PRIORITIZATION OF RURAL ROADS MAINTENANCE IN HILLY TERRAIN

Thesis submitted in fulfilment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

by

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TABLE OF CONTENTS

DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled **"Prioritization of Rural Roads Maintenance in Hilly Terrain"** submitted at **Jaypee University of Information Technology, Waknaghat, Himachal Pradesh, India,** is an authentic record of my work carried out under the supervision of **Prof. Ashok Kumar Gupta and Prof. Ashish Kumar.** I have not submitted this work elsewhere for any degree or diploma. I am fully responsible for the contents of my Ph.D. Thesis.

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled **"Prioritization of Rural Roads Maintenance in Hilly Terrain"** submitted by **Aakash Gupta** at **Jaypee University of Information Technology, Waknaghat, Himachal Pradesh, India,** is a bonafide record of his/her original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

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Dedicated to my grandmother Late Smt. Mithlesh Gupta

And

my grandfather Shri. Naresh Kumar Gupta

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ABSTRACT

Pavements are imperative assets of highways which need timely maintenance for efficient use of road maintenance fund. The deferred pavement maintenance strategies results in huge economic loss and badly affects the development of any country. The available fund for road maintenance is also limited. Hence, for worthy utilization of road maintenance funds, it is required to assess the condition of pavements which needs to be maintained first and are in utter worst condition. Rural Roads of hilly terrain, India plays a vital role in the development of the country. For example, in state of Himachal Pradesh, with an increasing pace of rural road construction of 1000 kms per year and introduction of PMGSY, the total rural road network contribution in the state is approximately 26000 kms with 62% of tarred roads. In order to preserve this important asset, along with the rapid construction pace of this huge rural road network, simultaneous maintenance is also required in a timely manner. Prioritization of pavements is required in order to assess the pavement conditions and providing maintenance to the deprived one. Various pavement indexes such as Pavement Condition Index (PCI), Roughness Index (RI), etc, have been used to assess the condition of pavements. In the present study, an attempt has been made to develop Rural Road Maintenance Priority Index (RRMPI) for rural road network of hilly terrain, India. Rural Road Maintenance Priority Index (RRMPI) is a function of overall functional condition index (OFCI) and overall structural condition index (OSCI). The proposed index i.e. RRMPI is an index of scale 0-100, in which 0 signifies worst condition of pavement and 100 signifies best condition of pavement. The proposed index is expected to provide better reflection of pavement condition and helps in prioritizing maintenance strategies. In the present study, the developed RRMPI has been used to select maintenance strategy for the selected 12 rural road stretches of hilly terrain in Himachal Pradesh.

Also, the most important functional parameter of pavements i.e. International Roughness Index (IRI) plays an important role in developing maintenance strategies for the pavements. IRI depends upon various distress parameters such as cracking, ravelling, potholes, rutting, patching etc. In the present study, attempts has been made to correlate International Roughness Index with various distress parameters so as to eliminate the cost incurred in determining IRI using expensive equipments. The Weightage has been given to each distress parameter based on a questionnaire survey using Analytical Hierarchy Process (AHP). The pavement distress data collected on selected twelve rural road stretches in the hilly terrain of Himachal Pradesh is used to develop linear and non-linear regression model between IRI and distress parameters. Artificial Neural Network (ANN) is also used to develop the IRI model. All developed models have been studied, compared and it is found that non-linear regression model with a R^2 value of 0.84 and MSE of 0.16 is considered as best model for predicting International Roughness Index as compared to other models.

In addition, Structural Evaluation of pavements is essential to assess the structural strength of different layers of pavement. It also helps in determining the remaining life of a pavement and the thickness of overlay required. Surface Deflection is the structural response that is easy to measure and hence, commonly used parameter in structural evaluation. In the present study, an attempt has been made to develop a relationship between surface deflection and various structural parameters of pavements selected on low volume flexible rural roads of hilly terrain in Himachal Pradesh. Benkelman Beam has been used to determine characteristic deflection on selected 12 rural road stretches in hilly terrain of Himachal Pradesh. Because the conduction of Benkelman Beam Deflection (BBD) test is costly and difficult to carry out in the region of Himachal Pradesh due to hilly and narrow rural roads leading to disruption of traffic, hence, models have been developed to predict surface deflection value using Soaked CBR, Un-soaked CBR, Average Annual Daily Traffic (AADT) and Age of pavement from last overlay (in years). Another model has also been developed to estimate surface deflection using K-value, AADT and age of pavement. Multiple models have been developed using linear regression model. The various developed models have been studied, compared and best model is suggested supporting better coefficient of determination value and root mean square error (RMSE).

Keywords: Pavement distresses, roughness index, functional evaluation, structural evaluation, prioritization index

LIST OF ACCRONYMS AND ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphaltic Concrete
ADOT	Arizona Department of Transportation
ADT	Average Daily Traffic
AHP	Analytical Hierarchy Process
AI	Asphalt Institute
ALF	Accelerated Loading Facility
ANN	Artificial Neural Network
ARRB	Australian Road Research Board
ASTM	American Society for Testing and Materials
AVGRUT	Average Rut Depth
B/C	Benefit-Cost Ratio
BA	Budget Available
BB	Benkelman Beam
BBD	Benkelman Beam Deflection
BBDEF	Benkelman Beam Deflection
BI	Bump Integrator
BM	Bituminous Macadam
BOT	Buid-Operate-Transfer
BPNN	Back-Propagation Neural Network
CAD	Computer Aided Design
CBR	California Bearing Ratio
CD	Cross Drainage
CDOT	Colorado Department of Transportation
CESAL	Cumulative Equivalent Single Axle Load
CGRA	Canadian Good Roads Association
CI	Cracking Index
CI	Condition Index

CI	Composite Index
CI	Consistency Index
COPACES	Computerized Pavement Condition Evaluation System
CQ	Construction Quality
CR	Consistency Ratio
CRRI	Central Road Research Institute
CRS	Condition Rating Survey
CVPD	Commercial Vehicles Per Day
DA	Direct Assessment
DI	Distress Index
DMKD	Data Mining and Knowledge Discovery
DOT	Department of Transportation
DP	Depth of Pothole
DRAM	Decode and Repair Method
DRYDEN	Dry Density
DT	Destructive Techniques
EDK	Edge Break
EMTD	Estimated Mean Texture Depth
ESAL	Equivalent Standard Axle Load
FAA	Federal Aviation Administration
FCI	Fuzzy Condition Indices
FCI_{IRI}	Functional Condition Roughness Index
FCI_{SR}	Functional Condition Skid Resistance Index
FCI_{TPD}	Functional Condition Total Pavement Distress Index
FDI	Fuzzy Distress Index
FEM	Finite Element Method
FHWA	Federal Highway Administration
FIS	Fuzzy Inference System
FMCDM	Fuzzy Multi Criteria Decision Making
FPCI	Fuzzy Pavement Condition Index
FWD	Falling Weight Deflectometer
GA	Genetic Algorithm
GDOT	Georgia Department of Transportation

GIS	Geographic Information System
GoI	Government of India
GPS	Global Positioning System
GPS	General Pavement Study
HCM	Highway Cost Model
HDM	Highway Development and Maintenance Management System
HIPS	Highway Investment Programming System
HSI	High Severity Index
HWD	Heavy Falling Weight Deflectometer
IDOT	Illinois Department of Transportation
IRC	Indian Road Congress
IRI	International Roughness Index
IRR	Internal rate of Return
KDOT	Kansas Department of Transportation
LCCA	Life Cycle Cost Analysis
LD	Lacroix Deflectograph
LEB	Linear Empirical Bayesian
LLTP	Long Term Pavement Performance
LSI	Low Severity Index
LWSDEF	Loadman Deflection
M&R	Maintenance and Rehabilitation
MAE	Mean Absolute Error
MAE	Maximum Allowable Extent
MAUT	Multi Attribute Utility Theory
MCA	Multi-criteria Analysis
MCD	Municipal Corporation of Delhi
MDP	Mean Diameter of Pothole
MDR	Major District Road
M-E	Mechanistic Empirical
MED	Mechanistic Empirical Design
MERLIN	Machine for Evaluating Roughness using Low Cost Instrumentation
MIT	Massachusetts Institute of Technology
MMPI	Modified Maintenance Priority Index

MMS	Maintenance Management System
MnDOT	Minnesota Department of Transportation
MoRT&H	Ministry of Road Transport and Highways
MOST	Ministry of Surface Transport
MPA	Manpower Available
MPD	Mean Profile Depth
MPI	Maintenance Priority Index
MPR	Manpower Required
MSA	Million Standard Axles
MSE	Mean Square Error
MSI	Medium Severity Index
MSN	Modified Structural Number
MTD	Mean Texture Depth
NAPTF	National Airport Pavement Test Facility
NB	Negative Binomial
NCHRP	National Cooperative Highway Research Program
NDT	Non-Destructive Techniques
NH	National Highway
NOS	Network Optimization System
NPV	Net Present Value
NSI	Nebraska Serviceability Index
OAI	Overall Acceptability Index
OES	Option Evaluation System
OFCI	Overall Functional Condition Index
OLS	Ordinary Least Squares
OPC	Overall Pavement Condition
OPCI	Overall Pavement Condition Index
OSCI	Overall Structural Condition Index
PAVTHK	Pavement Thickness
PC	Premix Carpet
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PDA	Personal Digital Assistants

PDI	Pavement Distress Index
PEI	Prince Edward Island
PI	Priority Index
PIARC	Permanent International Association of Road Congress
PIM	Precise Integration Method
PIX	Priority Index
PM	Penalty Method
PMGSY	Pradhan Mantri Gram Sadak Yojna
PMIS	Pavement Management Information System
PMMS	Pavement Maintenance Management System
PMPI	Pavement Maintenance Prioritization Index
PMS	Pavement Management System
PMSC	Pavement Management for Small Communities
PPI	Pavement Performance Index
PPM	Pavement Preventive Maintenance
PPS	Pavement Performance Study
PQI	Pavement Quality Index
PRAM	Prioritized Resource Allocation Method
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
PSRT	Portable Skid Resistance Tester
PV	Pothole Volume
PWD	Public Works Department
QC	Quarter Car Model
QI	Quality Index
RCR	Ride Comfort Rating
RD	Rut Depth
RDBMS	Relational Database Management System
RDI	Rut Depth Index
ReLU	Rectifier Linear Unit
RI	Roughness Index
RI	Random Index
RIAM	Road Investment Analysis Model

RMSE	Root Mean Square Error
RQI	Ride Quality Index
RR	Rural Road
RRMPI	Rural Road Maintenance Priority Index
RSL	Remaining Service Life
RSMS	Road Surface Management System
RST	Road Surface Tester
RTIM	Road Transport Investment Model
RTRRMS	Response Type Road Roughness Measuring System
RUCS	Road User Cost Studies
RUGDL	Roughness Distress Level
RV	Ranking Values
SA	Structural Adequacy
SAR	Structural Adequacy Rating
SAS	Statistical Analysis System
SCI	Surface Condition Index
SCI	Structural Condition Index
$SCI_{K\text{-}value}$	Structural Condition K-value Index
SCI_{MSN}	Structural Condition MSN Index
SDC	Semi-Dense Carpet
SDI	Surface Distress Index
SF	Scale Factor
SH	State Highway
SHOWID	Shoulder Width
SHRP	Strategic Highway Research Programmes
SI	Serviceability Index
SIMS	Street Inventory and Management System
SN	Structural Number
SPS	Specific Pavement Study
SPSS	Statistical Package for Social Sciences
SRV	Skid Resistance Value
SSR	Sum of Squared Residuals
SVS	Subgrade Vertical Strain

TD	Travelling Deflectometer
TFN	Triangular Fuzzy Number
TIMMS	Transportation Infrastructure Maintenance Management System
TPM	Transition Probability Matrices
TRB	Transportation Research Board
TRRL	Transport and Road Research Laboratory
TxDOT	Texas Department of Transportation
UPDI	Unified Pavement Distress Index
UPMS	Urban Pavement Management System
URMS	Urban Roadway Management System
URUCS	Updated Road User Cost Studies
VEAPSC	Visual Evaluation of Asphalt Concrete Pavement Surface Condition
VMB	Vehicle Mounted Bump-Integrator
VOC	Vehicle Operating Cost
VR	Village Road
WASHO	Western Association of State Highway Organization
WMM	Wet Mix Macadam

LIST OF SYMBOLS

f	Coefficient of friction
$\mu(c_z)$	Membership of each condition measure z contained along membership function c_z
A	Amplitude
AGE	Age of pavement since construction
AGECRIN	Age of pavement at the time of cracking initiation in years
AGEPHIN	Age of pavement at the time of pothole initiation
AGERVIN	Age of pavement at the time of raveling initiation in years
A_i	Membership functions
A_l	Area enclosed to the left of the membership
AL_i	Acceptability level of any distress
A_r	Area enclosed to the right of membership function
AXLEYR	Number of vehicle axles per year (million)
C	Area of total cracks
c	Fuzzy set
CA_t	Progress crack area (%)
C_F	Cracked area of flexible pavement surface
C_R	Total linear cracks of rigid pavement surface
CR	Weighted area of cracking
CRG	Cracking (%)
CR_i	Initial cracked area (%)
CSA	Cumulative number of standard axles
CSALYR	Cumulative standard axles (msa) per year
C_t	Crack area (%)
c_z	Membership function describing overall pavement condition
D_a	Allowable deflection (mm)
D_c	Characteristic deflection (mm)
DEF_o	Initial rebound deflection in mm
DEF_t	Surface rebound deflection at time 't'
D_f	Final Deflection (mm)

D_i	Intermediate Deflection (mm)
D_o	Initial Deflection (mm)
DR	Distress grade
D_t	Corrected rebound deflection at time 't' in mm
e	Superelevation
FDD_{sub}	Field dry density of subgrade
F_j	Factor 'j' value out of 100
F_n	Normal force
F_s	Tangential frictional force
g	Acceleration due to gravity
h	Thickness of the pavement (mm)
H	Overlay thickness (mm)
iCA	Initial crack area (%)
iDEF	Initial deflection (mm)
IRI_{init}	Initial International Roughness Index
$IRI_{terminal}$	Terminal IRI of the pavement
k	Numeric constant
k-value	Modulus of subgrade reaction
MRD	Weighted mean rut depth
MTD	Weighted mean texture depth
N_t	Cumulative standard axles (millions)
P	Patched area of pavement surface
P%	First year rate of return
PAGE	Pavement age since last renewal
PC	Weighted area of patching
PDG	Ponding area
PH_i	Initial pothole area (%)
PT	Weighted volume of potholes
PTH	Area of potholes
R	Radius of horizontal curve
R^2	Coefficient of determination
RAV	Area of raveling
R_D	Mean value of rut depth in inches

RG_i	Initial Roughness mm/km
RI_a	Allowable value of roughness
RI_p	Present value of roughness
RSL_f	Remaining service life for fast lanes
RSL_s	Remaining service life for slow lanes
RV	Weighted area of raveling
RV_i	Initial raveled area (%)
S_CBR	Soaked CBR value
SCR_i	Min {CR_i, (100-CR_i)} and is sigmoid function of cracking
SHCAM	Camber of the shoulder
SNCK	1 + Modified Pavement Strength
SRV_i	Min {RV_i, (100-RV_i)} and is sigmoid function of raveling
STR	Current pavement structure number
S_V	Mean value of slope variance
THBM	Thickness of bituminous layer (mm)
UI_o	Initial Unevenness Index
UI_t	Unevenness Index at time ‘t’
v	Speed of vehicle
V	Traffic Volume (CVPD)
w_i	Weights
W_j	Factor ‘j’ weight of importance to priority ranking
z	Particular condition measure contained in fuzzy set c
ΔCR_t	Change in cracked area over a time
ΔPH_t	Change in pothole area over a time
ΔPT_t	Change in patched area over a time
ΔRG_t	Change in roughness over a time
ΔRV_t	Change in raveled area over a time
λ	Wavelength

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 General

The predicted service life of a pavement depends upon design parameters such as geological factors, water table fluctuations, construction variability and prevailing conditions such as intensity of traffic, drainage and climate taken into consideration while arriving at an estimate. The assessment of the deformations/distresses and other factors that affect the service life of pavements is a complex task, because of the occurrence of events causing them being uncertain and random in nature. It is inevitable; however, that these factors influence to degrade the predetermined performance of pavements leading to a reduction in their service lives. It becomes necessary, therefore, to investigate/examine or diagnose the existing conditions of pavements- both structural and functional/ to address their maintenance requirements with the available resources. The subject of pavement evaluation, which deals with the above aspect, is hence of considerable significance to the management of pavements. The functional performance of a pavement, assessed in terms of its strength and performance during its serviceable period, is based on the subjective measurement of its stiffness and roughness in different ways. An evaluation of the existing condition of the pavement by various evaluation methods is essential for:

a) Assessing the ride quality of the pavement and structural adequacy of the pavement structure
b) Prioritising maintenance activity by comparing the condition with allowable values of distresses/ loss of stiffness factors
c) Evolving an economical maintenance/repair strategy that best suits the distresses identified with the available funds. This may be linked to life cycle cost or long term and short term budget allocation
d) Estimating the remaining life of the pavement and developing performance/distress models for checking and updating the existing design and rehabilitation methods
e) Rescheduling maintenance activities based on the above updated predictions
f) Developing a database to serve as a reference for improving pavement maintenance management measures in future

1.2 Road Network in India and Scenario of Rural Roads

India's road network is the second largest in the world, with the total road length increased from 3.99 lakh kilometres as on 31st March 1951 to 55.55 lakh kilometres as on 31st March 2019. This increase is more than 11 times during the 68 year period from 1951 to 2019. The length of surface roads which was 1.57 lakh kilometres (39.35% of total road length) as on 31st March 1951 has increased to 28.25 lakh kilometres (56.83% of total road length) as on 31st March 2019. The road lengths as per road categories are given in Table 1-1.

Table 1-1 Road Lengths as per Road Categories

Road Categories	**Road Length (lakh km)**
National Highway	1.22
State Highways & PWD Roads	15.582
Urban Roads	29.674
Rural Roads	5.623
Project Roads	3.457
Total Road Length	55.556

Rural Roads are the lifelines of major proportion of population in India which connects them and provides accessibility to market centres and other facility centres. Rural Roads plays a major role in the economic and social development of the country. It provides a vital gain in agricultural incomes, employment opportunities and reduces the poverty in the country. Under Rural Roads development scheme, the Government of India introduces Pradhan Mantri Gram Sadak Yojna (PMGSY) scheme in order to enhance the growth and development of rural roads in India. The scheme was launched on 25th December, 2000 to provide all-weather roads as a goal to reduce poverty and to establish connection with all unconnected habitats with population up to 500 in plain terrain and up to 250 on hilly terrain with states like North-East, Jammu & Kashmir, Uttarakhand and Himachal Pradesh. The PMGSY scheme is running under stages and currently the PMGSY-III scheme (PMGSY-III scheme, GoI, August 2019 [214]) is under progress followed by PMGSY-II (PMGSY-II scheme, GoI, August 2013 [213]) and PMGSY-I [212].

The PMGSY-III envisages consolidation of the existing Rural Road Network by up gradation of through existing routes and Major Rural Links that connects habitat to- Gramin Agricultural Markets, Higher Secondary Schools and Hospitals. As per Transport Research Wing (2015) [274], Ministry of Road Transport & Highways, the total rural road network by the end of 31st March 2015 was 24,37,255 kms, out of which 14,86,609 kms comes under surfaced roads. As per Policy on Maintenance of Rural Roads in Himachal Pradesh, 2015

[239], the total rural tarred road was 15,567 kms and total un-tarred road was 9,456 kms. Also, it has been found that the maintenance cost of rural roads in Himachal Pradesh only, requires 526.55 crores per year. Similarly, the maintenance cost for all other states requires a handsome amount for their survival.

As per clause 17.5 (b) of PMGSY-III Programme Guidelines, August 2019, it has been indicated and urged a need of prioritization criteria for allocation of budgeted maintenance funds in order to use the road maintenance fund in a systematic manner without any misuse. Hence, this study represents a priority index method to prioritize the rural road network for better utilization of roads maintenance funds. The state wise rural road length distribution is given in Fig-1.1.

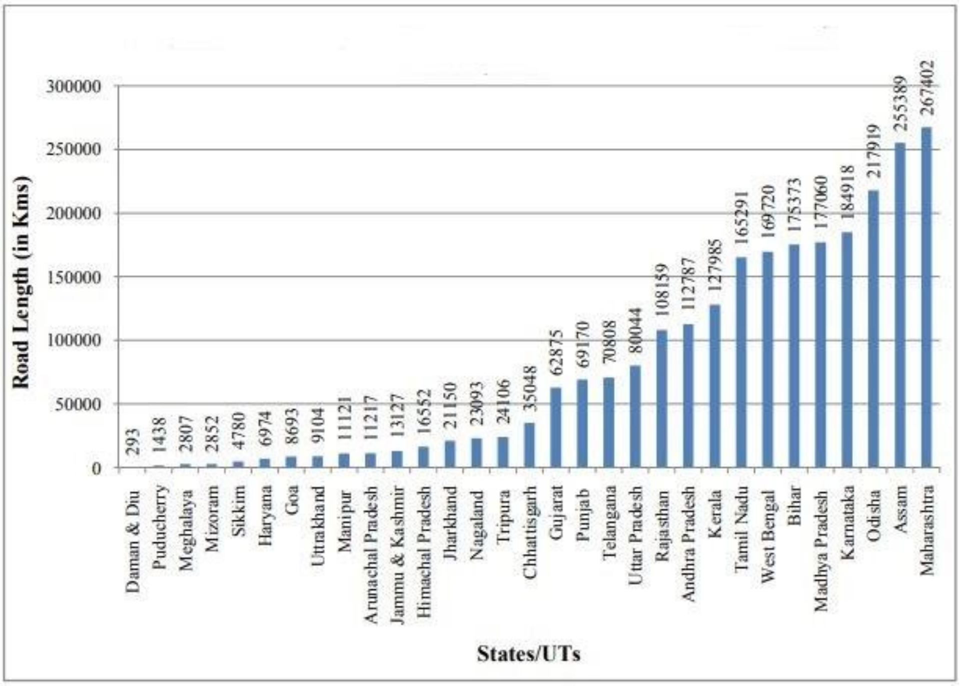


Figure 1.1 State wise rural road length distribution

1.3 Pavements Evaluation Methods

Pavement Evaluation is very necessary in order to maintain the second largest road network of India. Without maintenance, it would be a huge loss for the economy. In India, Pavement Evaluation is done by various government agencies such as NHAI, PMGSY etc for the better performance of roads. For the functional evaluation of roads, IRC: 82-2015 is followed and for the structural evaluation IRC: 81-1997 and IRC: 115-2014 is followed in India. Several methods are available for evaluation of pavements using equipment that serve specific purposes. Broadly, these methods can be categorised as (i) existing condition evaluation and

(ii) economic evaluation. The existing condition evaluation methods deal with either (i) functional evaluation or (ii) structural evaluation. Functional evaluation methods are further classified as distress evaluation methods and riding quality evaluation methods. The riding quality, again, may be evaluated in terms of surface roughness and safety criterion (measurement of skid resistance).

The technique adopted for structural pavement evaluation may be – (i) destructive technique (DT) or (ii) non-destructive technique (NDT). In destructive technique, it involves the extraction of in-situ samples of pavements from selected locations using core cutting methods. The extracted samples are tested for their engineering properties in the laboratory. Destructive techniques are preferred as they provide a more realistic picture of the pavement conditions such as pavements in-situ stiffness, density, drainage and climatic conditions of the location. But destructive testing technique are not widely used for routine evaluation of pavements because it disturbs the traffic flow during the testing period as well as post testing while repairs are carried out on the damaged surface. Also, it is uneconomical for longer lengths of pavements because it is a time consuming activity and the possibility of human errors is quite significant. The non-destructive technique tests the pavement surface without cutting/disturbing the existing surface using a variety of equipments for measuring different parameters. Some of the non-destructive technique equipment does not even require surface contact with the pavement under test. Using this technique, pavement performance in terms of riding quality (related to functional parameters) and structural strength are determined rapidly at a reasonable cost without disturbing the traffic flow, and there is no repair work involved either post testing. These qualities make NDT the preferred choice for routine monitoring or planned evaluation of pavements for most organizations dealing with pavements around the world.

1.3.1 Functional Evaluation

The functional condition of a pavement surface is related primarily to the riding quality, which may be measured in terms of parameters such as roughness or smoothness, skid resistance/surface texture, distress and any other parameter/coefficients that relate to unevenness. The assessment of the riding quality of pavement surface carried out using various NDT equipments is called as pavement surface condition survey. It consists of two parts: determination of distress by visual inspection along the surface of a road, considered the preliminary part of the survey, and mechanised measurement procedure following later, after the preliminary survey. Hence, road inventory data is often supplemented with data generated from NDT measurements.

1.3.2 Structural Evaluation

Structural Evaluation involves the application of standard load on the surface of pavement and measuring its response in terms of stress, strain or deflection. The structural strength or stiffness of pavements is determined using both destructive and non-destructive methods. The strength parameters so determined are related to the structural adequacy of the pavement structure as a whole, or to any individual component of the pavement.

1.3.3 Economic Evaluation of Pavements

The allocation of scarce resources in the most beneficial or optimal manner is an essential objective of any project. Cost is the main constraint governing most projects, and cost-benefits analysis form the basis of their feasibility studies. For a pavement project to be viable, cash flow is considered to be a crucial factor both during the initial stage of the construction as well as over the service life of the pavement. For this reason, the maintenance option best suited to different periods of time may not be the same, and for a given period the chosen option is guided by indicators relating financial returns to both economic and social benefits. In the case of BOT projects, for example, toll revenues form a part of the economic evaluation, the concession period being dependent on the investment involved. The maintenance option selected from the available alternatives is based on the importance of the project, the engineering practices and the policies of concern. Materials, method of construction, frequency of maintenance activities, level of service, and threshold values that trigger maintenance action are some of the main factors considered while preparing maintenance options. The proposed standards of specifications in each case are related to codes of practice approved by the funding authority.

1.4 Functional Evaluation- Purpose and Types

Uncertain parameters used as input to pavement design such as traffic intensity and volume, axle loading, subgrade strength, quality of construction, drainage and environmental and climatic conditions cause variations in the estimated service life of a pavement. As a result, the following outcomes may be expected- increase in the operating cost of vehicles, passenger discomfort, decreased operating speeds, potential increase in number of accidents, increase in damage to vehicles, induced road noise and accelerated deterioration of pavements.

Pavements are inherently prone to deterioration and need periodic evaluation surveys to ascertain supplementary maintenance activities required for keeping them in working condition.

1.4.1 Purpose of Functional Evaluation

The functional evaluation of pavements is carried out for the following purposes-

a) To evaluate the surface quality of newly constructed pavement surface and adjust its pay factor
b) To determine surface condition of pavement in terms of different forms of riding quality, by which the needs for maintenance measures are assessed
c) To measure the performance of a newly laid road through its road-roughness value, which is a good indicator
d) To provide engineering based decisions for allocating funds for maintenance
e) To decide a suitable maintenance option based on the type of roughness data
f) To develop deterioration models based on in-situ conditions, prevailing climatic conditions and axle load repetitions for estimating the pavement surface condition and its rate of deterioration
g) For reviewing and revising schemes/procedures of existing pavement maintenance management system in the light of the latest models of roughness
h) For evaluating safety of pavement surface in terms of skid resistance offered over diverse geometric conditions at different operating speeds. Such studies may also be used to determine geometric inconsistencies.
i) For recording pavement performance history with the help of roughness data gathered over a period of time

1.4.2 Types of Functional Evaluations

Surface characteristics which affect pavement riding quality related to safety, comfort and serviceability are the main concerns of functional evaluation of pavements. Attributes of surface condition decides surface-characteristics of interest as:

Serviceability: Roughness measured by several equipments are analysed by different methods. Typical examples of indicators are: International Roughness Index (IRI), Present Serviceability Index (PSI), Quality Index (QI), Bump Integrator values and others.

Safety: Surface Texture in terms of frictional resistance or skid resistance offered by the pavement surface. Typical examples of indicators are: coefficient of skid resistance, Skid Number and others.

Surface Distress: Usually, surface defects are denoted as condition data related to cracking, rutting, potholes, faulting and several other such failures.

In each case, several equipments and different methods are available for evaluation of surface characteristics in terms of indicators or indexes. Such attributes measured from different equipment can be compared using correlation equations.

1.5 The Concept of Serviceability

The pavement evaluation studies conducted by AASHO Road Test (1956-1961) are known as the "Serviceability Performance System". The present performance of a pavement in terms of surface roughness is subjectively rated by a panel of experienced drivers by riding over the pavement on a scale of 0 to 5 (Table 1-2). This numerical value is known as the present serviceability rating, PSR (Carey and Irick, 1962) [46].

Based on regression analysis, the PSR is satisfactorily related to an equivalent value of roughness-attribute termed as present serviceability index (PSI), which is derived from the measured performance of the same pavement sections in terms of objective measurement values, namely rutting, cracking, slope variance and patching. This concept of assessment of the current surface condition of pavement is called the serviceability concept. The serviceability record over a period of time is often referred to as the performance of a pavement. This AASHO system of serviceability has helped evolve numerous initiatives across the world for developing new paving materials, revised design methods, improved construction techniques, efficient evaluation and maintenance management systems. It has a significant impact on pavement technology.

Table 1-2: Guidelines on PSR

PSR	Section Evaluation	Description
0.1-1.0	Very Poor	Pavement surface is badly affected due to the presence of large, deep and wide cracks and potholes. The riding quality is drastically reduced, which drastically reduces speeds. The carriageway retains surface water during rainy season. Such distresses are observed over three fourth part of the pavement surface surveyed.
1.0-2.0	Poor	The ride quality is extremely deteriorated in such a way that it affects speed or free-flowing condition of the traffic due to the presence of deep-wide cracks, large potholes, considerable rutting and other typical distresses observed over half part of the flexible pavement surface surveyed. Rigid pavement distress includes, heavy cracking, faulting, joint failures and major failures of pumping.
2.0-3.0	Fair	The ride quality is found to be moderately inferior, which affects high speed traffic flow. Map cracking, rutting and extensive patching observed over the surface of the flexible pavement. In case of rigid pavement, cracking, faulting, joint failures and minor failures of pumping are observed.
3.0-4.0	Good	Pavement surface may provide good riding comfort but fine-hairline random cracking, beginning of rutting and minor spalling (peculiar in case of rigid pavements) over the surface may observed as visible signs.
4.0-5.0	Very Good	New pavement surface or similar superior quality of surface have smooth surface and without any kind of visible-distress over the surface.

1.6 Pavement Roughness

Surface Roughness in a pavement is a kind of distortion of surface which occurs in a direction perpendicular to its plane, i.e. in the vertical plane. Roughness is an undesirable deviation of the pavement surface compared to its planar surface [286]. It induces vehicle vibrations- thereby riding discomfort- making travel unsafe (Hudson, 1978) [118]. The intensity of discomfort depends upon the amplitude and frequency of surface distortions, suspension characteristics of the vehicle and its speed. Typical values of wavelength and amplitude range from 0.1 m-100 m and 1 mm-100 mm respectively (Gillespie et al., 1980) [95]. Further, any neglect of roughness leads to unrealistic, rapid and progressive deteriorations of the pavement, causing severe loading effect, long term cracking (NAPA, 1996) [184] and consequently degradation of surface-drainage conditions.

1.6.1 Classification of Roughness Measuring Equipments

There are several methods and equipments available for the measurement of roughness of pavements. They are classified as-

1. Contact Type – (a) Absolute Type : Static Type (For ex. Vertical staff and level, MERLIN, Straightedge etc.) and Non-Static Type (For ex. CHLOE, Michigan DOT profilometer, Walker Roughness Device etc.) and (b) Response Type road roughness measuring system (RTRRMS) (For ex. TRRL Bump Integrator, Roughometers, ROMDAS Bump Integrator etc.)
2. Non-Contact Type – (a) Laser, (b) Infrared, (c) Ultrasonic (Foe ex. Lightweight Profiler)

1.6.2 International Roughness Index (IRI)

To overcome the limitations or drawbacks of different roughness indices obtained at different operating speeds, a standard procedure is recommended for calibrating high-speed testing and conversion of the measured roughness profile to a standard roughness scale, termed the International Roughness Index (IRI). The IRI is correlated with different indices obtained from a variety of methods and equipment used by different countries. This facilitates the conversion of all other indices of roughness measurements also on to a common, uniform and consistent standard scale throughout the world.

The method of computation of IRI from the measured roughness profile is defined by Quarter-Car (QC) model. The QC model comprises a mathematical model of equations that simulate typical response of RTRRMS of a single wheel with standard values of spring stiffness and dampening effect (Fig. 1.2). The computer simulated suspension deflection of the single-wheel mechanical system is similar to the suspension deflection of the single-wheel of a passenger car (Fig. 1.3 (a)), travelling at a standard speed of 80 kmph. The simulated suspension deflection is linearly accumulated over the length of the measured profile to yield IRI. The standard unit of reporting IRI value as slope is m/km.

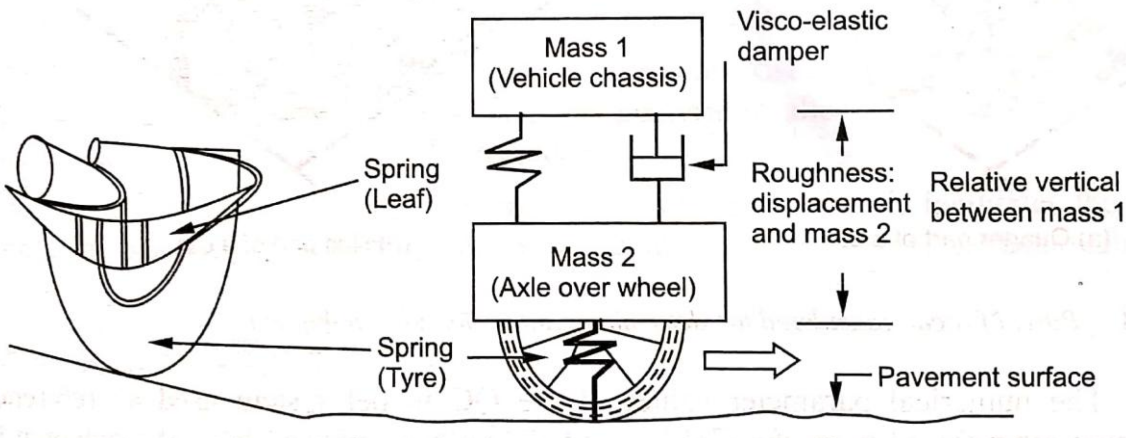


Figure 1.2 Schematic Diagram of Quarter-Car Model

The mathematical model of the Quarter-car simulation comprises a series of differential equation that describes the motion of the QC: it is used for running the software over the road profile data for the reference vehicle at a simulated speed of 80 km/h. The accumulated motion or relative displacements between the maas-1 and mass-2 (Fig. 1.3 (b)) are normalised by the length of the measured profile.

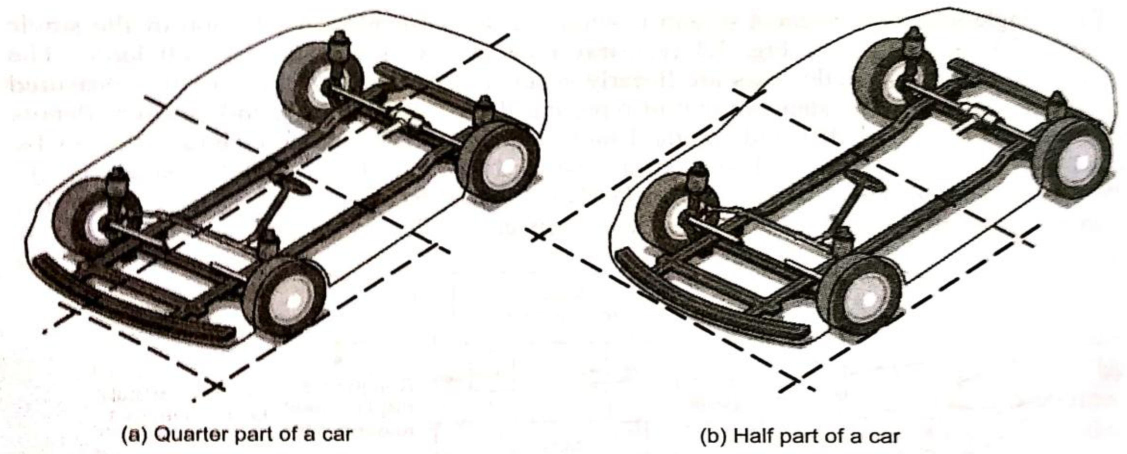


Figure 1.3 Parts of a Car considered for determining IRI

1.6.3 Advantages of using IRI

The following are the merits of using the IRI as a standard method of representing roughness compared with other roughness statistics-

1. The IRI is reproducible and stable with time.
2. The IRI value is independent of the equipment used for measurement (unlike measures made using RTRRMS). Hence, the output of IRI is consistent, which also facilitates the measurement of roughness by any device that is cost effectiveness.
3. As the IRI value is correlated with different types of existing indices such as PSR, PSI, BI, RQI and D value of MERLIN, it is possible to allocate funds equitably based on a common platform of roughness index.
4. As the IRI is purely dependent on the profile characteristics, it facilitates the use of optional maintenance treatment and related control of the finished surface quality.

1.6.4 Disadvantages of using IRI

The following are the disadvantages of using IRI value compared to other roughness statistics-

1. The IRI value is computed based on characteristics of profile measured along a single or two-wheel path only, which do not consider the overall surface roughness of the pavement unlike PSR or PSI measures.
2. The quarter-car model parameters representing higher dampening effect are insensitive to shorter wavelengths, which may not closely represent all situations, e.g., commercial trucks.

1.7 Frictional Evaluation of Pavements

The pavement surface condition is evaluated in terms of (a) skid-resistance as a safety measure and (b) surface texture characterisation under wet condition as a performance indicator. For both these, one of the main objectives is to determine safe braking distance under different operating conditions related to surface, climate, speed and tyre tread designs. Different types of NDT equipment and methods are available to measure surface frictional characteristics in terms of skid resistance. Such data can be analyzed for determining the skid-hazard sections of pavements, monitoring skid resistance in order to maintain vehicle control, stopping distance in emergency breaking situations, and for prioritising pavement rehabilitation activities at the network level.

The skid resistance of pavement surface is essentially a resistive force that develops opposite to the direction of motion in the contact plane between the tyre and the surface of the pavement under a locked or non- rotating wheel. Skidding occurs when the available frictional resistance is less than the frictional demand at the interface between the tyre and surface of the pavement (Kennedy et al, 1990) [142]. The resistive force can be quantified as coefficient of friction (f), and is expressed as the ratio between the tangential frictional force acting between the contact planes of the rubber tyre and pavement surface (F_s) to the normal force or load applied by the wheel (F_n) (Fig. 1.4).

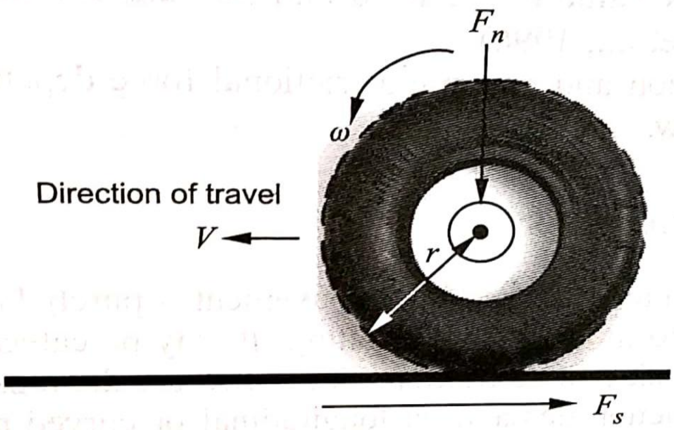


Figure 1.4 Free-Body Diagram of forces acting on a rolling wheel

1.7.1 Types of Frictions

1. **Longitudinal Friction**

The longitudinal frictional resistance or skid resistance is developed when (a) the pneumatic tyre rolls freely over a pavement surface without any type of braking and (b) the brake is applied constantly to the rolling tyre (Meyer, 1982) [170]. In case of free rolling (no braking mode), the relative speed between the tyre and the travelled surface at middle of the contact area of the tyre (referred to as the slip speed) is zero. That means, when slip speed value is equal to zero, vehicle speed and average peripheral speed of its tyre are equal. In case of locked wheel mode, value of the slip speed increases from zero to a maximum of the speed of the vehicle. Skid resistance as a safety measure is characterized by the coefficient of friction developed at the complete slippage of a locked wheel under standard test conditions.

As the slip value changes from 0 to 100%, the value of *f*, the coefficient of friction between the tyre and the surface of pavement, varies (Henry, 2000) [108]. It increases rapidly to a peak value with increasing slip of tyre, usually in the range of 10 to 20% (this slip value is referred to as critical slip, Fig. 1.5). As the wheel is fully locked, the *f* value then decreases to a certain value at 100% slip, referred to as the coefficient of sliding friction. The value of the coefficient of sliding friction in the longitudinal direction is considered as the minimum required friction factor with regard to safety. The numerical difference between the peak coefficient of friction and the sliding coefficient of friction may be equal to up to 50% of the slip value. The difference is significantly greater for wet pavements.

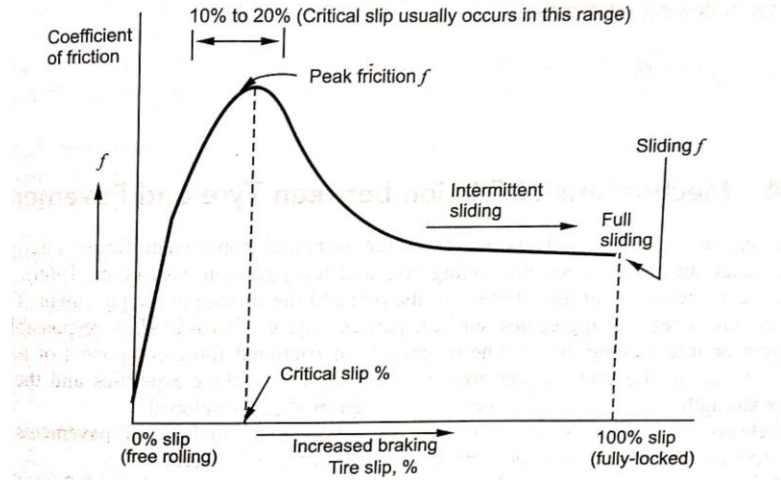


Figure 1.5 Relationship between pavement friction and tyre slip (Hall et al, 2009) [103]

2. Lateral or Side-force friction

To compensate for the sliding out of a vehicle when traversing a horizontal curve, a side force friction is developed between the tyre and pavement surface on a transverse/super-elevated slope. The relationship between f_s, the side friction force, e, the superelevation, R, the radius of horizontal curve, v, the speed of the vehicle, and g, the acceleration due to gravity is given in equation (1.1) –

$$f_s = \frac{v^2}{gR} - e \qquad (1.1)$$

On curves, camber surface and lane changes, a combination of longitudinal and lateral friction forces will come into play between the tyre and its contact surface area on the pavement.

1.7.2 Factors affecting Surface Friction/Skid Resistance

1. Factors related to test wheel and tyre

The test tyre measures different friction values on the same surface of pavement because of the difference in tyre properties. The properties related to test tyre are: inflated air pressure, pressure applied on the tyres, material composition of the tyre relating to tyre elasticity, and tyre geometry such as tread pattern, outer diameter, contact area and tread depth. It may be noted that the occurrence of critical slip ratio is greatly influenced by the hardness property of the tyre. Therefore, creep recovery and elastic properties of the tyre material are important. Due to this reason, skid resistance testers operating at low slip ratio (particularly fixed slip ratio less than 17% or slip speed less than 17 km/h) should strictly specify the test tyre characteristics and implement recommendations stringently (Rado, 2000) [220].

The skid resistance data obtained by the smooth tyre test evaluates safety better than the data obtained from ribbed tyre test. However, it is noted that the prediction of accident frequency also depends on other factors prevailing at the site. The smooth tyre surface is sensitive to the microtexture as well as the macrotexture since its smooth surface does not provide any channels (like ribbed tyre) to let water escape from the tyre-pavement interface. In the case of ribbed tyre, and therefore, it is insensitive to macrotexture. In both cases, skid resistance will be predominantly influenced by microtexture (Henry and Saito, 1983) [107].

2. Factors related to pavement characteristics and materials

The factors affecting coefficient of friction in this regard are the microtexture and macrotexture of pavement surfaces, mineral composition of the aggregate, aggregate gradation, shape of the aggregate, bitumen content and the type of bituminous mix. The mineral composition of aggregate is an important factor because if the aggregate is composed of soft materials, they get polished off by traffic flow and the surface becomes smooth. Likewise, in the case of hard miners, the aggregates have high resistance to polishing and maintain skid resistance. Limestone is an example of soft mineral aggregate and sandstone that of hard mineral aggregate. In general, sedimentary rocks provide better skid resistance than igneous and metamorphic rocks. The key characteristic of sandstone is that its small particle get worn off, exposing layers of sharp crystals to the tyres. In case of igneous and tough rocks, as the stone get polished, their smoothened surfaces present poor skid resistance.

A study of the Virginia Smart Road reveals that the skid number determined using smooth tyre is lower than that using ribbed tyre when tested on finer mixtures in which the nominal maximum size of aggregate is less than 9.5 mm (Michelle, 2001) [171].

3. **Factors related to driving dynamics**

Linear and curvilinear speeds (on horizontal curves that depend on the radius of curvature and superelevation), slip speed, slip ratio, brake efficiency, acceleration, deceleration, braking speed, location of drive wheel with reference to configuration of vehicle axles, load on test wheel and unsymmetrical loading by wheels are the factors that affect friction coefficient.

4. **Factors related to climate**

The intensity of moisture level or wetness of pavement surface or dryness or dryness of surface, snow, ice or the presence of precipitation in any form and intensity of wind are factors that affect coefficient of friction. The frictional resistance between the tyre and the pavement surface will be drastically reduced when the pavement surface is wet, increasing the risk of skidding. Due to this reason, the test pavement surface is deliberately made wet while testing for skid resistance. The nominal water film thickness is defined as the average depth above a smooth texture, and its value ranges from 0.25 mm and 1.0 mm.

5. **Other factors**

Other factors affecting skid resistance includes the present of dirt, mud, debris, grease, oil spillage, salt, sand, spray and any other material that influence surface friction on the pavement surface.

1.8 Pavement Surface Texture

Pavement surface texture consists of deviations in its surface with reference to a true planar surface. Based on the surface deviations, the Permanent International Association of Road Congress (PIARC, 1995) [209] has classified texture as microtexture, macrotexture, megatexture and profile roughness (Fig. 1.6 – Fig. 1.8). The deviations along the surface profile are characterised by wavelength (λ) and peak-to-peak amplitude (A). The PIARC recommended standard range of values of λ and A as depicted in Fig. 1.6.

Texture measurements are useful for a wide variety of purposes such as routine survey, accident analysis, and quality of construction, rehabilitation and pavement management.

Measurement of pavement texture is an important investigation by which macro and micro characteristics can be quantified, it may also be related to the condition of skidding, noise, tyre friction and roughness. Surface texture is quantified by different parameters such as mean texture depth (MTD), estimated mean texture depth (EMTD), mean profile depth (MPD) etc. Mean Texture Depth (MTD) is the output determined from the sand patch test belonging to volumetric technique of macrotexture measurement methods. A specific volume of standard sand or tiny glass spheres are spread in a circle by flushing on a pavement surface and MTD is calculated by dividing the volume of sand by the circular area.

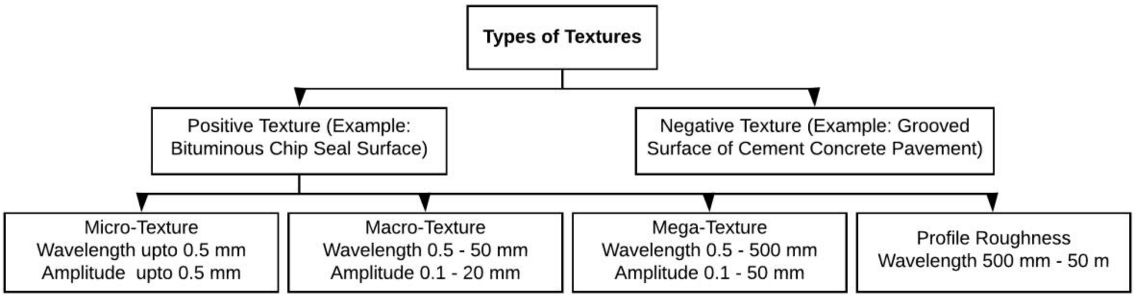


Figure 1.6 Texture Classification

Microtexture- It is a function of surface characteristics of aggregates used for paving works at the microscopic level. Aggregate surface fracture characteristics like sharpness, edges, flakiness and irregularity are important for defining pavement roughness at the microtexture level; they impact tyre friction at low speeds. Microtexture facilitates the penetration of thin films of water, and the resulting interaction between the tyre and the pavement surface are better evaluated at low speeds.

Macrotexture- Macrotexture contributes predominantly to skid resistance at high speeds in wet weather condition. The roughness quality of the pavement surface is attributed to aggregate mixture properties of materials- the shape, size, gradation and finished texture. Providing adequate depth of macrotexture improves the resistance of the surface to skidding at high speeds. The macrotexture facilitates the draining of runoff water by channelization, which depends on the nature of spacing, alignment and depth of the macrotexture and adhesive component of the microtexture breaking the film of water. Preventing hydroplaning by effectively expelling water between the tyre and pavement surface is also a function of macrotexture.

Microtexture and macrotexture are influenced by the quality and quantity of binder by which the aggregates are held in position under the weathering and abrasive action induced by traffic loading.

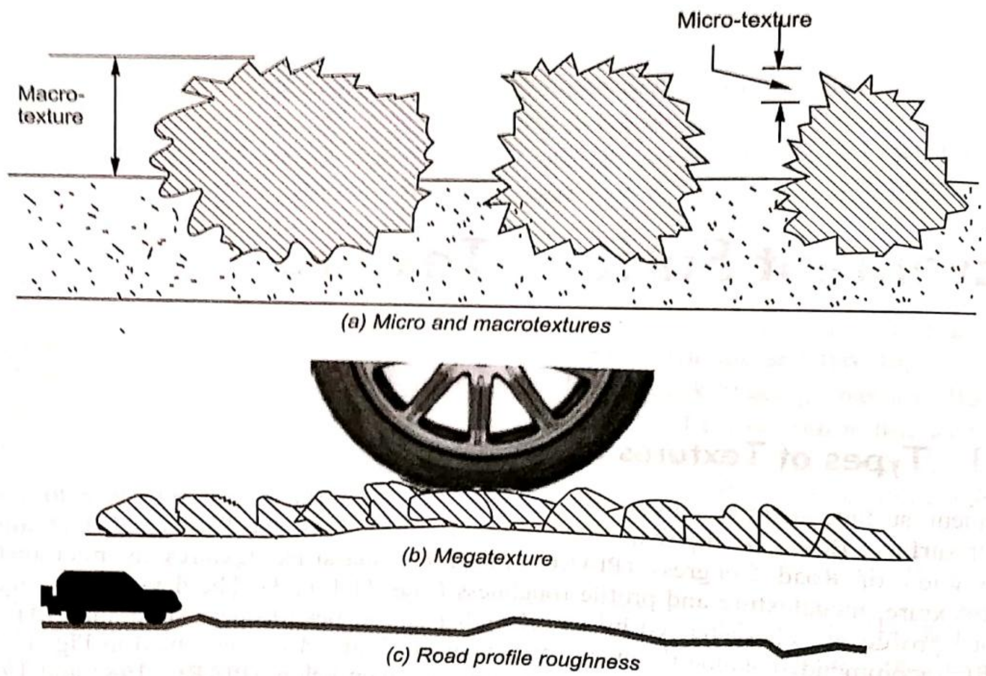


Figure 1.7 Different Types of Pavement Textures

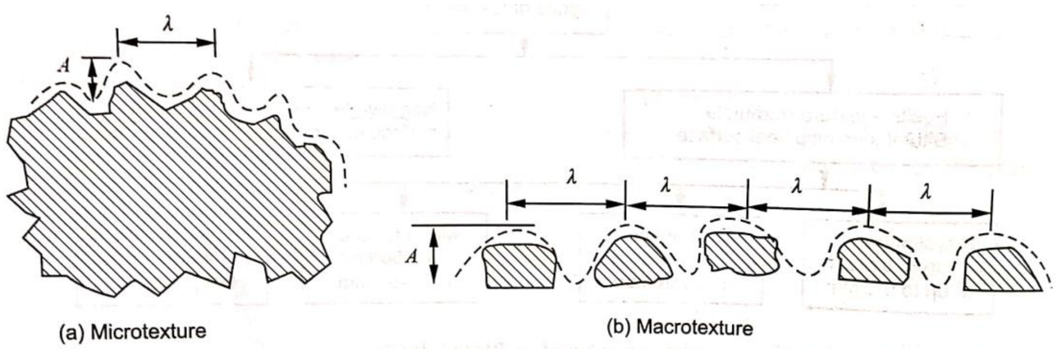


Figure 1.8 Wavelength and Amplitude of Microtexture

Megatexture- It has the typical wavelengths of the order of the size of tyre-pavement interface (Fig. 1.7 (b)). Megatexture of pavement surface is largely defined by undulations and distresses like potholes, ruts, ravelling, cracking and other defects present on the surface.

Roughness- Uneven surfaces comprising longer wavelengths (Fig. 1.7 (c)) exceeding 500 mm (i.e. the upper limit of megatexture) represents roughness or unevenness.

1.9 Pavement Distress

The visible signs of pavement deterioration called pavement distresses include all types of surface deformations such as cracks, patches, potholes and others. Basically distress is a sign of impending failure. Distress may also be defined as physical manifestation of defects in a pavement. These symptoms are useful for categorising the measured data, which can be used for rating the pavements in order to determine strategic action plan for the management of pavement maintenance activities, i.e. for PMS (Pavement Management System). Pavement distress is caused by various factors such as-

- Inadequate thickness of pavement layers
- Inadequate mix of ingredients
- Poor quality of construction practices
- Excessive loading and wearing by traffic
- Poor drainage conditions
- Unfavourable weather conditions, particularly rainfall and pavement temperature
- Contamination of pavement surface due to fuel or oil or chemical spills

1.9.1 Distress Surveys

Identifying and understanding the various types of failures of pavements is one of the preliminary process in determining the corrective action to be taken up before any repair work. Understanding the root causes of failures helps in taking timely corrective action and making sound judgements with regard to the required intervention to prevent the recurrence of failures.

The design life of a flexible pavement can be considered as 20 years, or even up to 30 years for the special cases. However, pavements fail to retain their serviceability condition till the end of their design period due to uncertainty in several factors considered as design parameters, which include traffic repetitions, axle loads, weather conditions, variable subgrade strength, and drainage conditions along the roadway, rainfall and variability in construction of different layers of pavements. Any one of the above factors or their combinations can influence the serviceability of a pavement. Because of this, maintenance and repair of pavements are inevitable for correcting failures and prolonging service life.

1.9.2 Types of Distresses

There are various types of pavement distresses which are described below-

1. **Alligator or Crocodile or Fatigue Cracking**

This is very common type of distress found in asphalt pavements, wherein a series of interconnected cracks forming a group of small cells spread over an area, resembling the skin of an alligator or in the form of chicken wire (Fig. 1.9) develops. The average size of each cell may be up to 300 mm, but are typically less than 150 mm on the shortest side. Alligator cracking is caused by repeated flexing of the asphalt layer due to excessive deflection of asphalt surface. Excessive application of axle loads over the asphalt surface is one of the main reasons for such deflections. These cracks originate at the bottom fibre of the asphalt surface where the tensile strain exceeds the allowable limit under repeated application of wheel loads. It indicates that the pavement structure has exhausted its fatigue life. The structural inadequacy of asphalt surfaces in such situations may be due to excessive tensile strain, insufficient thickness of asphalt layer, poor stability of the mix and unstable lower layers that are susceptible to moisture changes. The criteria adopted for measurement of alligator cracks is the extent of cracking i.e. the area of spread of cracks in sq.m. and the severity levels.

Figure 1.9 Alligator Cracking on Flexible Pavement

2. Longitudinal Cracking

Longitudinal cracks occur in pavements along the direction of traffic flow and may be found in the wheel path or outside the wheel path (Fig. 1.10). The depth of cracking may be partial or full. The longitudinal cracks within wheel path are of serious concern because the main reason for it is the structural failure of the pavement. Such structural failure may be attributed to several factors such as loss of adequate support due to accumulation of water in lower layers, deficient thickness of layers and excessive deflection of surface due to loading. The criteria adopted for measuring longitudinal cracks is the length of cracking in meters and severity levels with reference to crack widths.

Figure 1.10 Longitudinal Cracking

3. Transverse Cracking

Transverse cracking occurs predominantly in the direction perpendicular to the traffic flow and extends partially or fully along the width of the pavement (Fig. 1.11). The criteria of mean width as measurement for longitudinal cracking may be considered. The severity levels and the description of transverse cracking are also applicable for distress rating of block cracking and reflection cracking at joints. The severity levels as applicable to longitudinal cracking are considered for the measurement of transverse cracking also.


Figure 1.11 Transverse Cracking

4. Block Cracking

In block cracking, rectangular pattern cracks form on the pavement surface with average size ranging from approximately 25 cm X 25 cm to 1.5 m X 1.5 m (Fig. 1.12). One of the main reasons for this is the binder present in the asphalt layer has lost its elasticity under normal temperature variations due to ageing, or the quality of binder is poor. For measuring block cracking, the criteria of mean crack width as adopted for measurement of transverse cracking is to be considered in calculating the area of each block of crack.


Figure 1.12 Block Cracking on Flexible Pavements

5. **Edge Cracking**

These are inclined longitudinal cracks observed adjacent to the shoulder and outside of the wheel path of pavements with unpaved shoulders (Fig. 1.13). The crack pattern may be continuous or crescent shaped, within a bandwidth of 0.5 to 0.6 m along the edge of the carriageway. The causes of edge cracking could be poor subgrade support with unstable shoulders, poor drainage condition along the edge or shoulder or weak structure of pavement layers. The criteria adopted for measurement of edge cracking are length of cracking in meters among various severity levels of low, medium and high.

Figure 1.13 Edge Cracking

6. **Delamination or Peeling**

Poor interlayer bond is one of the root causes of delamination or peeling distress in asphalt pavements (Fig. 1.14). If rain water enters through cracks, it seeps through the interface between top and the supporting wearing course. As the seeped water freezes, it expands and pushes out the top layer. Then, such portions of the asphalt layer de-bond, become loose and peel out from the supporting asphalt layer. In addition to this, delamination also takes place due to weathering or ageing effect, poor quality of mix ingredients and insufficient quantity of binder. The extent of delaminated area in sq.m. is the criteria adopted for the measurement of this type of distress.

Figure 1.14 Delamination or Peeling of Asphalt Layer

7. Deterioration of Patch Surface

A patch is an area of pavement (greater than 300 mm X 300 mm) where certain portion of the original material has been removed and replaced with new material, compacted and surface finished (Fig. 1.15). Utility cuts, skin patching and blade patch covered with additional material are also considered as patches. Any type of distress present in such patch areas (sq.m.) of the surface is defined in terms of the severity level as low, medium or high. Any distress noted within the patch boundary should be included in rating severity levels. Include only distressed patches other than utility patches. In case of very large patches, the severity levels are to be recorded separately. Rate the entire patch as highest level in severity if it is not possible to define any distress perfectly due to variations.

Figure 1.15 Patching of Pavement Surface

8. **Bleeding or Flushing**

Bleeding of asphalt or bitumen takes place due to migration of excess asphalt binder on the pavement surface, resulting in formation of fatty surface or a film of bitumen (Fig. 1.16). This distress is common to wheel paths, wherein the surface looses texture and becomes smooth. No severity level is considered for bleeding, and the extent of its spread on the surface is measured in sq.m. The main reason for bleeding is the presence of excess content of asphalt binder and deficient gradation of mineral aggregates in the mix.

Figure 1.16 Bleeding on Pavement Surface

9. **Corrugations and Shoving**

Shoving is a form of plastic deformation that results in upward movement or vertical displacement of localised area of the pavement surface material (mostly in longitudinal direction) by which ultimately bulging takes place like a wound in pavement surface in wet weather conditions. Poor mix design, poor drainage coupled with breaking or accelerating vehicles and structural failure of pavement surfaces, usually associated with rutting, are the common causes of shoving. The shoved area is recorded in sq.m. No severity levels are associated while recording this distress.

Corrugations are the deformations on the pavement surface that becomes evident after successive shoving at regular intervals (i.e. closely spaced crests and valleys) in the direction of traffic (Fig. 1.17). The shallow corrugations (> 75 mm) of asphalt pavement can be corrected locally by cold milling followed by surface treatment or asphalt overlay.

Figure 1.17 Corrugations

10. Rutting

Rutting is the primary distress mode in asphalt pavements. It is a result of plastic deformation of the pavement surface by repeated application of load along the wheel paths (Fig. 1.18). Such pavement deterioration will be further aggravated by saturation of soils and intrusion of moisture in the pavement. It can be observed as a localized area of distress of length ranging from 3 metres to a couple of hundred metres. The criteria adopted for measurement of rutting is defined by depth of rutting in mm and severity levels as prescribed by IRC: 82-2015 [124] as low, medium or high.

Figure 1.18 Rutted Surface of Bituminous Concrete Surface

11. Potholes

Potholes are bowl shaped holes or pits of various sizes found on pavement surfaces (Fig. 1.19). These holes usually contain ravelled edges. As water seeps or penetrates through incipient cracks in the surface of pavement during rainy season, it softens the supporting layers. The seeped water retained freezes, expands and pushes up the asphalt layer during winters. The weak portion of the asphalt starts breaking up and ravelling under wheel loads during dry season. In addition to these causes, poor workmanship during construction/repair, poor reinstatement of service trenches, the lack of prime coat, stripping of asphalt, truck passes over weak spots, thin structural layers, poor adhesion between the base and the surfacing and non-structural causes such as diesel spillage, mechanical damage due to vehicle rims or accidents and fires, damage due to falling of rocks while being cut, all contributes to potholes. The criteria adopted for the measurement of potholes is described in terms of depth and width of pothole and severity levels as specified in IRC: 82-2015 as low, medium or high.

Figure 1.19 Potholes

12. Ravelling

The loss of or dislodgement of fine and coarse aggregates from the asphalt surface due to ageing effect or stripping of asphalt (Fig. 1.20) is called ravelling. As a result of ravelling, a very rough and pitted texture will form on the surface of pavement. Some of the causes of this kind of failure are wearing of pavement surface due to the use of aged and inadequate quantity of binder, damp aggregate, poor compaction of asphalt layer at a non-standard temperature and problems with aggregate segregation. It is to be noted that rutted surfaces due to studding action, which does not roughen up the texture significantly, should not be rated as ravelling. Ravelling occurs most commonly in wheel paths, but can also be elsewhere on the surface of pavement. The ravelling is measured as percentage of aggregate ravelled in sq.m. along the direction of traffic flow. It is noted that if ravelling is widely spread and covers the entire lane width, low asphalt content may be the root cause and if ravelling occurs sporadically, aggregate segregation or poor construction may be the main cause of ravelling.

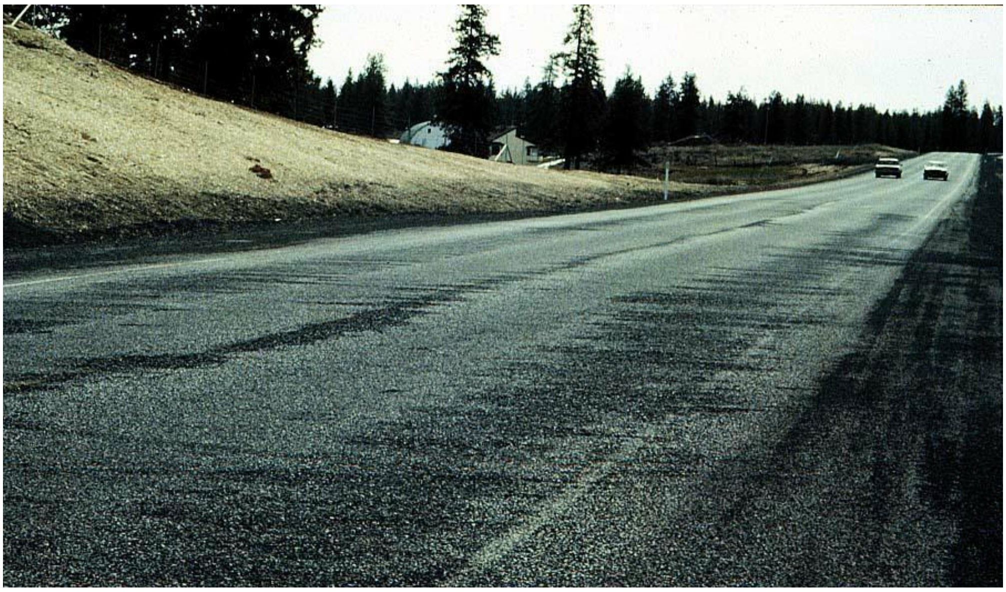


Figure 1.20 Ravelling of aggregates

1.10 Structural Evaluation- Purpose, Types and Equipments

Pavement evaluation is carried out to determine the existing condition of pavements in terms of its surface and structural adequacy. The data obtained from such studies are used for deciding the type of maintenance operations required, prioritisation of maintenance works and for establishing a pavement maintenance management system. Diagnosing the existing structural condition of individual layers of pavement as well as examining the overall pavement strength is termed structural evaluation.

In the structural evaluation method, the response of a pavement to a test load is observed. While structural response of the pavement can be measured in terms of stress, strain and deflections, surface deflection is the most common parameter used in almost all pavement evaluation systems, as it is easy to measure. Measurement of surface deflection is rapid, relatively inexpensive and non-destructive. The early full scale road tests conducted in USA by WASHO and AASHO resulted in correlations between Benkelman Beam (BB) deflections and pavement performance under ultimate loading conditions. Since then, efforts have been made and directed by different research groups in different countries to develop deflection-based procedures that can be used to evaluate pavements. Therefore, NDT equipments capable of measuring surface rebound deflections are widely in use today for structural evaluation of pavements.

Equipments used for structural evaluation of pavements should be able to measure appropriate responses of the pavement subjected to a given loading conditions that are similar to those applied by vehicular traffic. The main features of the loading conditions consist of number of loads, magnitude of load, shape and contact area of load and loading time. Other operational features of the equipment include data acquisition, methodology, adopted for calibration and mobility of the equipment.

1.10.1 Purpose of Structural Evaluation of Pavements

The necessary requirements of conducting structural evaluation includes-

- To examine the structural adequacy of pavement
- To determine the RSL "Remaining Service Life" of pavement
- To design the overlay thickness
- To generate a PMS "Pavement management System" based on structural condition of pavement

1.10.2 Types of Structural Evaluation Methods

Structural evaluation of pavements is generally carried out by two methods- (a) destructive testing (DT) (b) non-destructive testing (NDT)

Destructive Testing- In the destructive testing method, in situ pavement layers are cut open at different levels of the pavement structure to determine individual layer strengths. Other properties are determined either by in situ testing or by extracting layer samples for testing in the laboratory. As the pavement is cut at different levels and at regular intervals, the road will be heavily damaged. Huge funding would be required to restore such damaged pavements. Due to this reason, destructive testing techniques have become an unpopular practice and are generally abandoned.

Non-Destructive Testing- In the non-destructive testing method, the pavement is not subjected to any kind of damage. Determination of strength parameters of the pavement layers is carried out without disturbing their existing conditions. Pavement surface rebound deflections are generally measured by employing different NDT equipments. This is more easy and convenient than directly measuring stress and strains. Due to this reason, many standard institutions insist on using NDT equipment for structural evaluation of pavements.

However, for physical examination, the pavement may be drilled to collect in situ samples at selected locations along the test section.

1.10.3 Structural Evaluation Equipments

1. Structural Evaluation by static loading- Equipments that are in use for evaluating flexible pavements under this category are: the Benkelman Beam (BB), the Lacroix deflectograph (LD) and the travelling deflectometer (TD). These equipments are very popular because of their low costs and simplicity of operation. The external loads applied are either static or moving at creep speed.
2. Structural Evaluation by Steady-State Vibratory Loading- Any NDT device that produces a sinusoidal vibration in the pavement with a dynamic force generator is categorized under this group. The most widely known devices are dynaflects and various models of the road rater. In these devices, a static load is placed over the pavement surface and a steady-state sinusoidal vibration is induced in the pavement with the help of a pulsating dynamic force generator.
3. Structural Evaluation by Impulse Loading- In this type of loading, a transient impulse force is applied on to the pavement surface and the deflected shape of the surface is measured. These equipments are capable of producing load pulses in the range of those applied by wheels of commercial vehicles. Different models of impulse loading equipment which are widely known as falling weight deflectometers (FWD) are available.

1.11 Pavement Condition Rating Methods

Pavement condition changes frequently as the road ages. It is essential to have a simple method of determining a numerical indicator which provides a measure of the present condition of pavement based on the type of distresses and their extent and severity. Such a numerical indicator provides an objective and rational basis for prioritising and triggering maintenance work. The numerical indicator is basically an index value which can be used to provide feedback on pavement performance over a period of time, and the trend of deterioration with time can be used for validating and improving the current procedures of pavement design and maintenance management.

1.11.1 Visual Distress Condition Surveys

Pavement condition surveys aid in monitoring pavement deterioration. Common indicators of deterioration are physical distress observed by visual surveys, ride quality as roughness and safety as skid resistance. Visual surveys collect distress information of pavements using a systematic procedure and standard notations so that the collected information can be summarised, analysed and used for various applications uniformly. During visual surveys, following may be used-

- Blank forms or data sheets for recording distress data
- Field manual and site location map
- Stationary Material- Clip board, pencil, eraser, mini-calculator
- Camera for taking photographs and video
- Scale and tapes with least count of 1mm for taking linear measurements
- Hand odometer wheel, straightedge, thermometer, pocket GPS, fault meter, Dipstick or any walking profiler
- Piece of chalk, colour paint, chisel and hammer, safety jackets

1.11.2 Need for Distress Condition Rating

The distress data collected from the field surveys needs to be summarised in terms of appropriate numerical values such as index values that categorise and rank the current condition of the pavement surface. Different agencies have developed index values for ranking distress condition of pavement surfaces. These index values are useful for categorising pavement sections based on their deterioration, judging appropriate time of maintenance or for triggering treatments, adopting suitable method of maintenance repair, calculating life cycle cost analysis, forecasting pavement performance, evaluating pavement network conditions, comparing road surfaces with simiklar distress levels and evolving and revising the pavement management system (PMS) that ultimately facilitates allocation of funds for long term as well as short term maintenance needs.

1.11.3 Methods of Conducting Pavement Condition Surveys

These methods can be broadly classified as manual pavement condition surveys and automated pavement condition surveys. The manual pavement surveys can be conducted as (i) walkover surveys or (ii) windshield surveys. Both are commonly combined to record detailed pavement distress condition data, particularly at network level surveys.

1. **Manual Pavement Condition Surveys**

Walkover surveys provide more detailed and precise distress data of a rated pavement as compared to any other survey, but the time and efforts consumed will be more. In addition, manual surveys are potentially dangerous to conduct during traffic flow. However, the field measurements obtained by the Walkover surveys are considered as 'truth' for the development of acceptable criteria or mathematical algorithm for analysis of data obtained by automated pavement condition surveys. These surveys comprise the least subjective of procedures in which the individual distress items are rated by type, extent and severity. Finally, the Pavement Condition Index (PCI) score is calculated from deducts values. It is noted that the greater the number of details incorporated in walkover survey, the more extreme is the objectivity of the survey method (Livneh, 1994) [157]. Trained and experienced engineers are essential for getting consistent and reliable output, especially to identify representative condition over a network of pavement. Therefore, a sufficient sample size with an average output result can provide a representative condition of distress over a network pavement.

Windshield surveys comprise the collection of distress data from a slowly driven vehicle on the pavement or on its shoulder. It is essentially a subjective procedure in which the rater assigns a final numerical score on a predefined scale for the state of overall distress of a pavement section under consideration. The pavement condition is rated through the windshield of the vehicle so that the time and efforts involved is lesser than manual surveys, but the rater has to be trusted for the quality of data collected, particularly when surveyed on a large network pavement. To overcome such limitation, walkover survey and windshield survey are combined so that reasonably precise data can be obtained.

2. **Automated Pavement Condition Surveys**

A vehicle equipped with several sensors is run over a test section of pavement at highway speeds. The acquired data is stored online in an onboard computer and the data is analysed by software for detecting and classifying surface distress extent over a length of road and ultimately, for computing surface condition index. The automated data collection vehicle should essentially be equipped with high resolution digital line-scan and digital area-scan cameras, GPS, laser sensors, light focussing bulbs and an onboard high capacity computer.

The difficulties with the automated systems are-

- High performance computers are essential for real-time detection and classification of different distresses from the images captured at traffic speeds
- Noise filtering and image processing using specific mathematical algorithms are still an evolving technology
- It is very difficult to detect and classify the distresses if the pavement surface has foreign objects, contaminants, dust, surface texture, stains and discoloured stones
- Standard common indices and their statistically validated criteria still need to be standardised
- Research targeted towards development of compatible combination of hardware devices with software supplied by different vendors for consistent output results are still on.

Despite the above difficulties, it is observed that automated pavement condition surveys are more rapid, efficient, cost effective and safer than the manual pavement surface condition surveys.

1.11.4 Pavement Condition Indices and Rating Methods

Pavement distress condition is numerically represented by different agencies in USA, Canada, UK, Australia, Europe and other parts of the world using different terminology like Pavement Condition Index (PCI), Distress Index (DI), Overall Pavement Condition (OPC), Nebraska Serviceability Index (NSI), Condition Rating Survey (CRS) value, Surface Condition Index (SCI), Surface Rating (SR), Pavement Quality Index (PQI), Surface Distress Index (SDI), Present Serviceability Rating (PSR) and Pavement Serviceability Index (PSI). Whatever be the terminology used, the core concept is that the numerical index varies between 0% to 100%, wherein 100% is defined as excellent pavement condition and 0% as the worst condition of the pavement.

In Condition Rating Survey (CRS) used by the Illinois Department of Transportation (IDOT) to evaluate pavement condition, a value range from 1 to 9 in 0.1 increments is used. A CRS rating of 1 indicates total failure of surface and 9 indicates a newly constructed surface of pavement. The other categories of CRS rating system are: Poor- 1 to 4.5; Fair- 4.6 to 6.0; Satisfactory 6.1 to 7.5; and excellent 7.6 to 9.0.

1.11.5 Interpretation of a Condition Rating

The condition rating provides a rationale basis for ranking the maintenance of member pavement sections considered according to their current condition index values with regard to its performance curve (Fig. 1.21). In this process the PCI can be used in PMS to provide a benchmark to compare the relative condition of a group of pavements in a road network. The PCI is primarily used to support pavement management initiatives of the state and local government agencies. This will help avoid ambiguous conditions, particularly when there is a paucity of funding. Programming and long term budgeting is possible with reference to the list of such rankings. In addition, the index value assigned by the condition rating provides the appropriate method of repair with suitable construction technology.

The condition index along with condition rating provides the preliminary indication of the type of repair work necessary, the time suitable for it and the extent of maintenance needs (Fig. 1.21). Subsequently, long term and short term maintenance activities with their schedules can be worked out under the framework of budgetary allocation and available resources. Ultimately, the condition rating concept can be used to evolve innovative approaches to tackle complex combinations of maintenance needs with distress condition of pavement, which is influenced by inconsistent parameters related to traffic, weather, drainage, material characteristics and construction quality. The trend of performance curves, which depends of rate of deterioration due to these factors, will suggest the timely management of several activities, especially for cost effective maintenance. As a whole, the above concept of pavement maintenance with reference to measured performance over a period of time is called PMS (Pavement Management Systems).

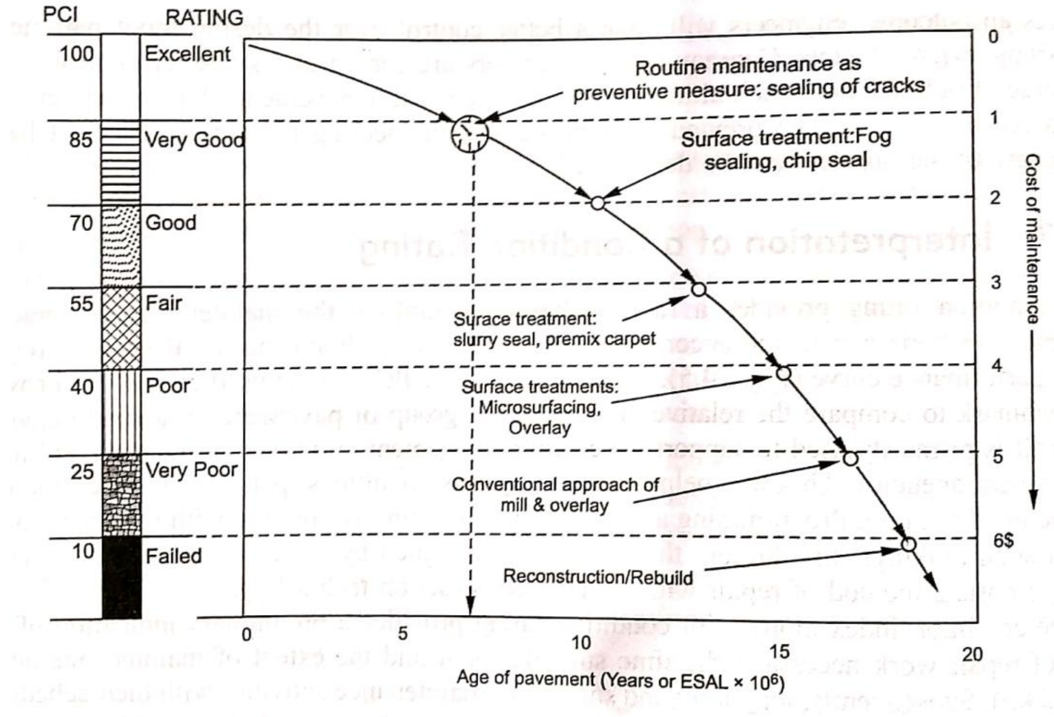


Figure 1.21 Interpretation of condition rating with performance and maintenance needs of pavement (Coplantz., 2010) [59]

1.12 Pavement Maintenance Management System (PMS)

Pavement management system (PMS) is a systematic process of planning various activities involved with timely maintenance and repair of a road network. PMS is widely used as a software-based planning tool in order to optimise the cost component with regard to feasible maintenance alternatives and desired conditions of pavement over an entire network. PMS focuses mainly on maintain current or improved pavement system condition, identifying future needs with their associated efforts, and prioritising future maintenance and rehabilitation activities.

The software neither manages pavements nor makes decisions. The personnel involved in the pavement management activities are responsible for decision making and implementing the PMS. The software assists in the management of massive amounts of information and calculations and support decisions made by pavement managers. The software can store, update, and analyze multiple complex calculations quickly and logically to satisfy the given criteria. Ultimately, the analysed data can be retrieved as understandable reports with a set of feasible maintenance alternatives applicable to a distress condition.

The PMS incorporates life cycle costs in a sequential order in order to undertake repair, maintenance and reconstruction works scheduled under short term funding and long-term budget projections. Pavement management encompasses several activities which are necessary to predict the performance of pavement, prioritise pavement projects and maintain timely agency-desired quality of pavement based on inventory of roadway features, condition data, structural requirement, drainage, weather data and traffic data.

Ultimately, the PMS is useful as an aid to scientifically support pavement management decisions towards preventive maintenance rather than delaying maintenance work which will lead to further deterioration taking place, adding to the cost heavily. Due to this reason, the PMS places priority on preventive maintenance of roads in good condition rather than rectifying roads in poor condition, i.e., the PMS aims to try preserving good roads at a low cost and not them deteriorate to condition where it will cost heavily to repair.

1.12.1 Need for Pavement Maintenance

It is not uncommon that a pavement fails prematurely before its design life because the assumptions and the input conditions presumed at the time of design, construction and maintenance are subject to unavoidable uncertainties, particularly, occurrence of traffic, variations in subgrade strength along the pavement, drainage conditions, rainfall, weather condition, and also as a result of non-uniform construction leading to variations in the degree of compaction and thickness of compacted layers, as well as due to the quality of ingredients used. This is the reason why most of the pavements need maintenance and rehabilitation.

1.12.2 Purposes of PMS

The following are the primary purposes of the PMS-

- Store, retrieve, update and analyse a variety of data systematically
- Support pavement managers with scientific information and improve the efficiency of decisions
- Ensure consistency and uniformity in decisions taken at different levels of administration within an organisation
- Improve effectiveness of all decisions in terms of efficiency of achieving results

- Provide feedback as a consequence of decisions taken earlier
- Assist engineers responsible for maintaining a specified road network and the department authorities responsible for allocating funds in making cost-effective decisions for preserving a pavement network. Cost-effectiveness is a measure used to relate costs to performance.
- Improve communication between different consulting groups working in the department and with road users.

1.12.3 Uses of Pavement Management System (PMS)

The PMS as a tool can be used for meeting the following management objectives-

- Fundamental Principle: The PMS provides the ability to identify a pavement problem while it is in minor state so that preventive maintenance treatments can be implemented in time without having to resort to expensive treatments in the later course of time. In effect, the overall condition of the pavement can be maintained at a higher level of performance at the best possible funding.
- Inventory of Pavement Features: The stored data regarding a pavement's condition can be easily updated and assessed to address pavement management problems. The updated information has got importance for tracking maintenance works and is used as a reference for preparing reports.
- Planning maintenance works related to budgets: The PMS facilitates preparation of a series of budgets over a period of time, called Life Cycle Cost Analysis (LCCA) [296]. The LCCA provides economic analysis of expenditures incurred in maintenance works as short term and long term budgets. During this analysis, an optimal selection of alternatives or a list of suitable options of maintenance works related to current and predicted performance (it could be PCI with traffic parameters) of pavement can be presented to budget deciders.
- Prioritisation and financial planning: The prioritisation of maintenance of candidates projects at the network level based on PCI, traffic and cost of selected option from various maintenance works is facilitated by the PMS. Planning and scheduling of such maintenance activities can be assigned with regard to the upcoming budget year as well as for long term financial funding.
- Feedback System: The PMS allow the modelling of performance of individual candidate projects or a group of projects having similar characteristics or an overall

road network based on the past and present data. Prediction of PCI value is commonly considered the crucial parameter to account for the rate of deterioration per year or over a period of time. Statistically-based prediction equation are developed using data of the past and present distress condition, traffic volume, existing pavement layer composition and relevant weather conditions. With reference to this predicted performance (may be as PCI), the maintenance manager will have the option to continue with earlier plan of maintenance work in existence or implement other type of maintenance which may be opted from any standard recommended list of feasible alternatives. This is termed as improved decision making.

- The pavement management programs provide a systematic approach for financing agencies to monitor utilisation of funds and ensure accountability of work in progress.
- The PMS provide an idea of the pavement's condition status over its service life by conducting impact analysis using past and projected performance data, decisions on treatments, government policies, politically influenced decisions and other factors including the overall condition of pavements in a locality.

1.13 Objectives of the Research

Following are the objectives of the current research based on the literature review and current research gaps-

- To evaluate the functional evaluation parameters which includes road roughness, mean texture depth, skid resistance, various pavement distresses such as cracking, ravelling, potholes, patching and rutting

- To evaluate the structural evaluation parameters of study area in hilly terrain which includes California bearing ratio, Pavement surface deflection, Modulus of subgrade reaction.

- To develop relationship between pavement roughness (i.e. IRI) and distress parameters which includes cracking, ravelling, potholes, patching and rutting for rural roads in hilly terrain

- To develop a pothole model to predict volume of pothole using depth and mean diameter of pothole as input parameter

- To develop relationship between Benkelman Beam Deflection and other structural parameters which includes soaked CBR, un-soaked CBR and Modulus of subgrade reaction for rural roads in hilly terrain
- To develop Rural Road Maintenance Priority Index (RRMPI) for Maintenance Prioritization of rural roads in hilly terrain which incorporates both functional and structural parameters

1.14 Organization of Thesis

- The first chapter provides the insight of the pavement evaluation methods. It gives a brief introduction about the functional evaluation and structural evaluation of pavements, their purpose, types and various equipments used in their study. It also explains various pavement distresses present on the pavements, pavement condition rating methods and a brief concept of pavement management system.
- The second chapter incorporates a detailed literature review with regards to the functional evaluation and structural evaluation of pavements. It explains the research work carried out by various researchers in the field of pavement evaluation in context of the various parameters affecting pavement roughness, pavement performance prediction models such as pavement deflection prediction model, pavement roughness prediction model. It also includes the indexes developed by researchers in order to prioritise the pavement maintenance decisions.
- The third chapter deals with the detailed information of field data collection and the corresponding methodology adopted to conduct the test related to pavement evaluation, standard procedures followed to obtain precise results. It represents the data collected and methodology followed on selected rural road sections of hilly terrain in Himachal Pradesh regarding pavement parameters such as road roughness, pavement deflection, rutting, patching, skid resistance etc.
- The fourth chapter presents the mathematical regression models developed and Artificial Neural Network (ANN) technique used for the development of road roughness model to predict the International Roughness Index (IRI) on hilly terrain in m/km based on various parameters such as cracking, ravelling, patching, potholes etc. It also presents the development of pavement surface deflection model using regression analysis.

- The fifth chapter proposed a methodology to determine Rural Road Maintenance Priority Index (RRMPI) for hilly terrain roads in order to prioritize the pavement maintenance decisions so that road maintenance fund can be utilized appropriately. It represents the development of RRMPI based on both functional and structural parameters of pavements.
- The sixth chapter deals with the conclusions derived from functional and structural evaluation of pavements, development of road roughness model and pavement surface deflection model and developed Rural Road Maintenance Priority Index (RRMPI).

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter incorporates a detailed literature review with regards to the functional evaluation and structural evaluation of pavements. It explains the research work carried out by various researchers in the field of pavement evaluation in context of the various parameters affecting pavement roughness, pavement performance prediction models such as pavement deflection prediction model, pavement roughness prediction model. It also includes the indexes developed by researchers in order to prioritise the pavement maintenance decisions. An extensive literature survey has been carried out and presented here to keep abreast with the latest techniques used for modelling the different component of PMMS viz. pavement evaluation i.e. functional and structural evaluation, pavement performance prediction models, optimization of resource allocation, and prioritization methods for maintenance. Many organizations have made recognized contributions in form of documentations and reports presenting the process of successful development and implementation of PMMS all over the world. Following are some of them presented below with their salient features.

2.2 PMMS Concept

The pavement maintenance management system (PMMS) is a methodical system for inspection and rating the pavement condition in a given area. The system also performs a cost effectiveness analysis of various maintenance and rehabilitation strategies. Finally the system prioritize and recommend pavement rehabilitation and maintenance to maximize results within a given budget amount. Many countries have implemented a pavement maintenance management system(PMMS), in which this system will help the decision makers such as pavement engineers to apply the best technique for pavement rehabilitation at perfect time, so the maximal use of available funds were done. Each system requires a procedure to prioritize maintenance processes, in which the effectiveness of each prioritization will direct affect the obtainable funds efficiency.

2.2.1 American Association of State Highway & Transportation Officials (AASHTO)

AASHTO is an association representing highway and transportation departments in USA. Its primary goal is to foster the development, operation and maintenance of an integrated national transportation system. Some standards issued for PMMS are mentioned below.

A pavement evaluation study was conducted by AASHTO during 1956 to 1961 that introduced the first available comprehensive report on the fundamental of "Serviceability Performance System" and procedures of their measurements **[1]**. This methodology and concept was followed by freeway and highway construction program all through the United States of America.

This AASHTO system of serviceability has helped evolve numerous initiatives across the world for developing new paving materials, revising design methods, improved construction techniques, efficient evaluation and maintenance management systems. Stated simply, it has had a significant impact on pavement technology.

The regression equations developed from AASHTO road test data are given below-

For flexible pavement:

$$PSI = 5.03 - 1.91\ X\ log_{10}\ (1 + S_V\ ) - 0.01\ X\ (C_F\ + P)^{0.5} - 1.38\ {R_D}^2 \quad (2.1)$$

For rigid pavement:

$$PSI = 5.41 - 1.78\ X\ log_{10}\ (1 + S_V) - 0.09\ X\ (C_R + P)^{0.5} \quad (2.2)$$

Alternatively, the following equation is applicable when roughness index (R) value (inches/mile) was measured using Bureau of Public Roads Roughometer employed at the speed of 10 miles/hour.

$$PSI = 5.41 - 1.80\ X\ log_{10}\ (0.4R - 33) - 0.09\ X\ (C_R + P)^{0.5} \quad (2.3)$$

Where,

PSI = present serviceability index

C_F = cracked area (sq. Ft. per 1000 sq. Ft) of flexible pavement surface

C_R = total linear cracks (ft. per 1000 sq. Ft) of rigid pavement surface

P = patched area (sq. Ft. per 1000 sq. Ft) of pavement surface

R_D = mean value of rut depth (in inches) measured on both wheel paths using a 4-ft straight edge

S_V = mean value of slope variance ($X10^6$) measured along both wheel paths (using profilometer of AASHTO)

The following equation may be used to determine the value of S_V when a series of elevations are measured-

$$S_V = \frac{\sum_{i=1}^{n} d_i{}^2 - \frac{1}{n}\left(\sum_{i=1}^{n} d_i\right)^2}{n-1} \qquad (2.4)$$

Where, d_i is the difference in elevation obtained between two successive points spaced at an interval of one foot, and n is the value of the total number of d_i values obtained.

The initial or newly constructed AASHTO test section's average value of PSI was determined as 4.2. These test sections were then opened for traffic till failure, and the mean terminal PSI was determined as 1.5. The numerical difference between initial and terminal PSI is termed as loss of PSI. For the design of flexible pavements according to AASHTO, at failure conditions or terminal PSI value, may be taken as 2.5 and 2.0 for high and low volume roads respectively. The AASHTO design method was basically developed from the results obtained from AASHTO test results constructed at Ottawa and Illinois in 1958-60 and later revised in 1981, 1986 and 1993. The AASHTO road test results showed that roughness alone contributed about 95% of the information related to the value of the serviceability of a pavement (Hudson, 1979) [117]. The AASHTO design concepts influence many pavement design methods developed all over the world.

AASHTO, 1985 [2] described that a Pavement Management System is an entrenched, documented technique considering all activities involved in management of pavement such as planning, design, budgeting and programming, construction, monitoring, research, maintenance, rehabilitation and reconstruction in an organized and integrated manner. In 1990 AASHTO issued guidelines for developing a PMS. These guidelines included: (i) Description of the PMS components, (ii) steps for development or enhancement of an existing PMS, (iii) use of a PMS at the network level for strategic planning and project level for engineering applications, and (iv) applications of PMS **[3]**. In 1993 the guidelines on design of pavement structures was published by AASHTO where a section on pavement rehabilitation with and without overlays was included **[4]**. Also information on pavement management and its process at project level & network level was added. AASHTO, 2001 presented a comprehensive guide for pavement management that documented the state of practice and identified state-of-art technologies and processes pertaining to section, collection, management and analysis of data used in PMS **[5]**.

2.2.2 The Federal Highway Administration (FHWA)

The Federal Highway Administration (FHWA), a branch of the U.S Department of Transportation in Washington, D.C.; carries out the federation highway programs in association with the State and local authorities to match the Nation's transportation requisites. FHWA's contribution in development of PMMS is summarized as below:

In 1989 FHWA issues a policy which required all state Highway agencies in U.S. to implement basic PMS by 1993 **[78]**. A policy to select, design and manage federal –aid highway pavement in a cost-effective way as well as to identify pavement work eligible for federal –aid funding was set forth. **(Holt, F.B. et.al.1992) [113].**

FHWA, 2000 & 2001 [79,80] disseminated a document specifically addressing the flexible pavement preventive maintenance (PPM), the available treatments and their suitability, their cost efficiency, the aspects to be considered in selecting the suitable management strategy and a methodology to ascertain the best suitable treatment for a specific pavement. The analysis of PMS data explained various aspects like engineering application of PMS, database need & elements, performance and pavement modelling, pavement preservation strategies and effect of pavement maintenance on performance **[81]**.

FHWA, 2008 documented a catalogue containing the information about sixteen pavement management software developed by private companies and public agencies **[82]**. It also presented the information about various equipment like ground penetrating radar, falling weight and rolling wheel deflectometers, road profilers, skid testers and multifunction data collection systems that collect pavement data to support PMS. FHWA, 2009 **[83]** provides various pavement distresses and enlighten the identification, causes and measurement of various pavement distresses such as cracking, ravelling, potholes, patching, bleeding etc. It also suggests the distress survey procedures and measurement practices adopted in different countries around the world. The observed distresses have been numerically summarized for indexing or rating of the pavement's distress condition.

2.2.3 National Cooperative Highway Research Program (NCHRP)

The National Cooperative Highway Research Program (NCHRP) was established in 1962 under Transportation Research Board in cooperation with AASHTO and FHWA, to carry out research in acute problem areas that affect highway planning and design, highway construction, and their operation and maintenance nationally. Ann extensive work has been reported on PMS and is given below:

NCHRP, 1968 [187] defined various application of system approach for pavement design and different concept of PMS.

NCHRP, 1979 [188] released "how to" guide for the development of PMS.

NCHRP, 1981 [189] grouped pavement condition data as roughness, surface distress, deflection and skid resistance. It also described the equipment used by various highway agencies to measure the same.

NCHRP, 1985 [190] first presented information on how life cycle cost analysis (LCCA) of pavement can be used to select an M&R alternative that is least expensive over the designed life of the pavement.

NCHRP, 1987 [191] accounted for the state of affairs with regards to PMS and described the features, applicability and use of PMS.

NCHRP, 1994 [192] published information on the various practice in use for the collection, reporting and applications of pavement condition data.

NCHRP, 1995 [193] released a document on pavement management methodologies to select project and recommend the suitable preservation treatments.

NCHRP, 2004 (a) [194] presented a study on the current practices for identifying, measuring and articulating the public benefits of highway system maintenance and operation. It also presented that the benefits to be communicated in such a way that are comprehensible and simple to understood to stakeholders like road users, officials, and others who have an interest in highway system's performance.

NCHRP, 2004 (b) [195] documented research and development efforts in the automated method for collection and processing and pavement condition data techniques usually used in the management of network-level pavement system.

NCHRP, 2004 (c) [196] documented the state of practice and knowledge of PMS using GIS and other spatial technologies and discussed their integration to enhance the highway management process.

NCHRP, 2004 (d) [197] explained the procedure to determine the optimum timing for the application of precautionary maintenance treatment techniques to flexible and rigid pavements, based on the comparison of pavement performance and its costs associated with treatment applications at different ages.

NCHRP, 2009 (a) [198] outlined the development framework for applying asset-management principles and practices to manage interstate highway system investments.

NCHRP, 2009 (b) [199] developed procedures and guidelines for managing the quality of pavement data collected either, automatically, semi-automatically or manually to ensures the needs of the pavement management process.

2.2.4 The Australian Road Research Board (ARRB)

The purpose of the research works carried by ARRB are to develop equipment that collects road and traffic information and software that assists in decision making across road network. Some of the research reports on PMS and application of HDM-4 are given below:

A review of existing pavement performance models was deiscussed and evaluated by ARRB, 1996 which describes their applicability to different Australian road types, including local roads, at both network and project level **[24]**. Different state-of-art pavement performance models which are related to (a) the deterioration (roughness) of pavement at network level (b) rehabilitation (roughness & strength) of pavement at network level (c) the deterioration (roughness, strength, cracking, rutting and potholing) of pavement at project level were developed **[25]**.

ARRB, 2004 **[26]** documented the calibration of HDM-4 deterioration models. It reported (a) effects of various maintenance treatments using the accelerated loading facility (ALF), (b) estimates of the actual rates of deterioration at long term pavement performance(LLTP) maintenance sites and (c) the calibration factors for roughness and rutting progression of the road deterioration models of HDM-4 for various conditions of maintenance, environment and loading.

2.2.5 Transport and Road Research Laboratory (TRRL)

TRRL research is a leading edge for transport by generating and applying science, knowledge and understanding to develop innovative solution and software around the world. The research which includes PMS as one of the area and has documented some reports on PMMS as given below:

A detailed guidance on the design and operation of computer based road management system for engineers & managers was provided by TRRL in 1998 that involved in road maintenance **[271]**. In 1999, guidance on road pavement evaluation techniques (non-destructive and destructive) suitable for bituminous surfaced roads in tropical and sub-tropical climates and reviewed alternative suitable methods for maintenance and repair was introduced **[272]**. TRRL, 2005 is a single resource which provided advice on the construction works, evaluation and maintenance of pavement that are not anticipated to experience structural deterioration, frequently termed as long life pavements **[273]**.

2.2.6 Documentation of other Organization

PMM, 1982 [215] is the manual on pavement maintenance management using PAVER software released for public use by department of army, USA. It consisted of components like (a) network identification (b) pavement condition inspection (c) M&R alternatives determination (d) economic analysis of M&R alternatives and (e) data management.

UK Pavement Management System (UKPMS), 2005 [277]: the principal use of UKPMS was to facilitate the local agencies to plan and organize the maintenance of the local road network by conducting the systematic pavement condition data collection and analysis.

MnDOT, 2008 [174]: Minnesota Department of Transportation (MnDOT) outlined best practices for the selection of asphalt pavement recycling techniques. The procedure included selection rehabilitation method, pavement thickness design, materials mixture design and construction.

MnDOT, 2009 [175] presented a method that uses Global Positioning system (GPS) and GIS software to make accurate distress measurements in the field and to manipulate and analyze the data in the office.

2.2.7 Ministry of Road Transport & Highways (MoRT&H)

MoRT&H is a GoI undertaking organization responsible for framing policies for Road Transport, National Highway and Transport research with a view to increase the mobility and efficiency of the Road Transport system in India. MoRT&H published following documents related to maintenance management of roads network.

MoRT&H 2004 [179] documented the policies and guidelines relating to maintenance and management of primary, secondary and urban roads. The fundamental maintenance norms/practices for various road categories are summarized in the guidelines. The details relating to data collection methodology and analysis are also been reviewed and mentioned. The approaches for selection of optimal maintenance approaches and prioritization of selection for road maintenance are also demonstrated.

2.3 Studies on Pavement Condition Evaluation and Analysis

Pavement Condition Evaluation is an integrated and important part of pavement management techniques since it provides the means for deciding the effectiveness and accomplishment of the planning, design and construction objectives. Pavement condition evaluation encompasses the functional as well as structural evaluation of the pavement. Pavement evaluation studies done in India and abroad are briefly described below.

2.3.1 Functional & Structural Evaluation

The pavement deflections were measured by using Benkelman Beam, Falling weight deflectometer (FWD) and vibratory road rater and various vehicular loadings were used to check the pavement response relevant to structural evaluation on diverse loading conditions **[112]**. It has been found that Falling Weight Deflectometer simulates the best structural response. The quasi-static loading of the Benkelman Beam induces the highest deflections in maximum pavements. A new procedure for measuring pavement profile, deflection, and texture from a moving vehicle has been proposed and derived by **Elton and Harr (1988) [74]**.

An automatic pavement-distress-survey system that used laser, video and image processing techniques was explained which consisted of a survey vehicle and a data-processing system **[86]**. The survey vehicle could measure cracking, rutting and longitudinal profile simultaneously, continuously, rapidly and accurately moving at a speed of 60km/hr. The data-processing system converted the measured data automatically into pre-defined format the can be used in the pavement data bank. The potential application of digital image processing methods to automate the manual data collection and visual rating of the pavement surface condition was recognized by **Ritchie et al. (1990) [236]**. The recommended for a cost effective automated system which captures and extract pavement surface distress from video image with consistency and uniformity of data.

Kaseko and Ritchie (1993) [140] presented a methodology for automatic processing of highway pavement video image using an integrated Artificial Neural Network (ANN) models with conventional image processing techniques. The approach was divided into five major steps viz. (1) image segmentation, (2) features extraction, (3) decomposition of the image into tiles and identification of tiles with cracking, (4) integration of the result from steps {3} and classification of cracking type in each image and (5) computation of the severities and extents of cracking detection in each image.

An automated pavement distress survey system was described by Chua et al. (1994) which was developed at the University of New Mexico **[58]**. In the system, pavement image were captured using video cameras mounted on a moving vehicle and then using a computer program to recognize and quantify the pavement distresses from the video image. They described automated survey system was capable of accurately analyzing image captured at a vehicle speed of 24km/h (15mps) and below.

Bennet (1994) [36] studied the effect of using a sand pad, effect of different operators and effect of temperature on Loadman readings. Also, the deflection readings measured with Loadman and Benkelman beam (BB) were compared. The equation (2.5) was developed for converting the deflection values measured from loadman to BB. The application of Loadman for PMS project was also discussed.

$$BBDEF = -0.3381 + 2.0393 * LWSDEF \qquad (2.5)$$

Where BBDEF= Benkelman beam deflection (mm), LWSDEF= loadman deflection (mm).

The relationship between rut depth, deflection and other distress modes for flexible pavements was reported, and recommended that the correlation between rut-depth and deflection is useful for design of new flexible pavement and overlays to extend the life of existing pavement **[98]**.

For functional and structural evaluation of roads some analytical algorithms are also available that converts the subjective rating values of distress attributes to a rational weight scale. It provides quantified measurements of effects close to distress type on pavement damage and riding quality **[56]**.

Rio et al. (1997) [235] explained the methodology for pavement evaluation with a multifunction device called a video-laser road surface tester (RST). It was used to evaluate about 20000 km of highways in Spain. The RST is a pavement evaluation device with high precision output and repeatability that is installed in a powerful van. The versatility of the system allows testing to be performed under all traffic conditions including very low speeds or up to 90kps (60mps) without affecting the measurements. The data collected was then converted into IRI (roughness), texture, rut and cracking indices to represent the pavement condition in quantifiable terms. The collection of stage data is needed at both project and network level for application **[260]**. This is to establish an approach that provides the requisite data for minimizing the cost of data collection.

Several methodology was recognized for sample size determination in collection of pavement performance data, consisting of characteristic deflection, rut depth, uneven index and riding comfort index, so that it could adequately predict the structural and functional condition of the pavement **[228]**.

To study the distresses in flexible pavements due to over loading, computation of the load equivalence factors are important. Mehndiratta and Reddy (1999) **[169]** computed the load equivalence factors using alternative incremental analysis. A computer program was developed which required structural number of pavement, percentage of total number of axles each wheel-load category and wheel-load magnitude (KN) as input. The result provides total number of repetitions required for 0.1 decrement of present serviceability index equivalence factor corresponding to legal axle load of 10.2 T.

The use of Loadman and Benkelman beam deflection (BBD) for the measurement of pavement structural condition was deliberated by Sharma (2000) **[253]**. It also developed a relationship between them with a view to facilitate quick deflection measurement with much lesser manpower, without causing inconvenience to traffic movements especially on the urban road sections and on all other road section carrying medium to very heavy traffic volume. The general forms of the models developed for different road class are given Table 2-1

Table 2-1 Relationship between Loadman and Benkelman Beam Deflection values

Sr. No.	**Road Type**	**Model Equation**	**Notation**
1	National Highway	Y = 0.751X + 0.3174	Where, Y = Loadman Deflection (mm), X = Benkelman Beam Deflection (mm)
2	Urban Road Section	Y = 0.6966X + 0.3879	
3	MDR	Y = 0.0956X + 1.2303	
4	VR	Y = 0.2897X + 0.6046	

Linear regression models were proposed to predict IRI based on initial IRI reading, percentage cracking and average rut depth **[161]**. The relationship is given in equation (2.6) with R^2 value of 0.71.

$$IRI = 0.597\ (IRI_{init}) + 0.0094\ (\text{fatigue percentage}) + 0.00847\ (\text{Rut Depth}) + 0.382 \qquad (2.6)$$

Where IRI_{init} = Initial International roughness index (m/km), Rut depth in mm

A computerized pavement condition evaluation system (COPACES) was formulated that consist of four main modules: distress identification, data entry and management, COPACES Manual with COPACES Tutorial **[276]**.

R.D. McQueen et al. (2001) [166] performed non-destructive tests at various times on flexible pavement test items at the Federal Aviation Administration's (FAA) National Airport Pavement Test Facility (NAPTF) located at the William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The NDTs were performed with both falling weight deflectometer (FWD) and heavy falling weight deflectometer (HWD) equipment to document the uniformity of pavement and subgrade construction, as well as to acquire data on pavement response over time and increasing numbers of full-scale load repetitions. ANN modelling was also used for precise prediction of characteristic deflection profiles of flexible pavements depending upon traffic loadings **[48]**

The sensitivity of different structural estimator was analysed by Zhang et al. (2003) for pavement deterioration process and was categorized in terms of changes in the Pavement Management Information system (PMIS) score **[299]**. Furthermore, a new method using

FWD based structural condition indicators primarily, the structural number (SN) and the structural condition index (SCI) was presented as a selection parameter for network level decisions regarding pavement M&R.

Das and Pandey (2003) [69] evaluated the structural condition of pavements on selected stretches of National Highway around Delhi using Falling Weight Deflectometer (FWD). Using the test result the overlay design charts for the region under study were developed. The deflection values measured by FWD were also compared with Benkelman Beam deflection results.

Indiana experience was presented using FWD and GRP for evaluating pavement condition at the network level **[201]**. An updated record of pavement layer thicknesses, pavement surface deflections and mechanistic behaviour of pavement layer that can be retrieved knowing road section name, route of travel and reference position was prepared using the data evaluated from this equipment. These data was used to inspect inconsistency in pavement structural indicators. The qualification of remaining service life (RSL), necessary overlay thickness and required details for structural reliability and safety factor analysis for Indiana Highway Road sections was also done.

For the prediction of IRI for Chinese Pavement Network some algorithms were formulated using regression methods and Artificial Neural Networks. It was found that ANN better than regression analysis **[56]**. Jiaqi et al. (2005) **[134]** integrated the information technology in form of mobile devices such as Personal Digital Assistants (PDA) and Global Positioning System (GPS) to collect the data for PMS. The PDA has application like recording of type of distress identification, precise location of the distress and photo of capturing distress.

A gray system modelling theory was proposed to estimate the maximum, mean and minimum International Roughness Index based on data collected on Indiana Highways at different pavement ages **[133]**. It is found that large numbers of data sets are not required for gray system modelling and it discusses the effect of traffic volume on pavement riding quality.

Abaza (2004) [7] presented flexible pavement overlay design models constructed using performance curve parameters to provide an adequate overlay thickness at any given future time. The undertaken approach attempts to compensate an existing pavement structure for the loss in performance (strength) that it has endured over a specified service time. In essence, this approach is similar to the mechanistic methods of overlay design that make a compensation for the loss in a particular strength indicator such as the commonly used deflection method. Therefore, compensation is made for the loss in performance as represented by appropriately selected performance curve parameters.

The impact wave technique combined with cross spectral analysis was also used to characterize subgrade, WMM base course constructed in model pavement box as per MoRT&H **[181]**. the wave characteristics like phase velocity (VR), wavelength and attenuation coefficient were determined for different subgrade strengths characterized by density, static modulus and CBR.

Loizos and Plati (2008) [159] evaluated pavement roughness by using quarter-car model. The basic principle is automobile's body mass which acts as a sprung mass while the axle mass behaves as an unsprung mass. These two components are linked with the suspension system. As the vehicle travels along the road, pavement profile fluctuations cause a vertical response in the overall system.

The feasibility of using Dupont Clay as low-strength subgrade was studied by Garg and Hayhoe, and compared pavement performance over two different subgrade types **[90]**. The study showed that it is feasible to use DuPont clay as the low strength subgrade.

Hozayen and Alrukaibi (2008) [115] proposed polynomial equations to develop relationship between road roughness, cracking, ravelling, rutting and pavement condition rating (PCR) on account of regression analysis. Best model was finally proposed based on best value of R^2. Bogus et al. (2010) **[40]** presented a Kendall's correlation coefficient and illustrated its use in assessing variability in ordinal distress data collected through manual surveys. Using Kendall's correlation coefficient, variability between different raters and variability between multiple evaluations by one rater were determined for each individual distress type. This information can be useful when used to develop training programs to reduce data variability.

A methodology using fuzzy logic was presented for the categorization of distresses **[147]**. Also an expert system was developed in C language using fuzzy logic for reasoning. It was developed to use automated techniques for quick, efficient and consistent classification for flexible pavement distresses based on data obtained from the automated distress measuring system. The implementation and comparison of the falling weight deflectometer (FWD) and Benkelman Beam (BB) for pavement evaluation was computed **[303]**. Field measurements were made at an in-service pavement A30 in Shanghai, China. Based on the deflections measured by FWD and BB, the exact relation between the results of FWD and BB was established. It is believed that the dynamic modulus back-calculated from FWD test results can be used as a stiffness modulus for the subgrade of new pavement construction in China.

Aguiar-Moya et al. (2011) [18] developed IRI model using ordinary least squares (OLS). They have analysed long term pavement performance data which fits the mechanistic-empirical IRI model for flexible pavements. The model was estimated by analysing possible bias which indicated various changes in parameters affecting IRI through time.

Gupta et al. (2011) [99] developed deterioration models using regression analysis and ANN using structural and functional data collected on low volume road sections. They have used California Bearing Ratio (CBR) of subgrade, traffic volume, thickness of pavement and age of pavement as independent parameters to develop the equations. They found ANN modelling better than regression.

Khweir (2011) [145] discussed the process for determining most of the important parameters used in overlay design. These parameters are traffic loading, layer thickness, stiffness modulus, interface condition, and fatigue properties.

Monismith (2012) [177] briefly described few developments of the past 50 year. They were summarized as mechanistic analysis, materials characterization, mechanistic- empirical (M-E) pavement design methodologies, accelerated pavement testing, non- destructive pavement evaluation and overlay design, pavement management and lastly improved construction practices.

Peter Mucka (2012) [180] developed regression models between IRI and straightedge index. Five different straightedge indexes were used to develop the model. The tests were conducted on both flexible pavements and rigid pavements.

Satish Chandra et al. (2012) [51] developed relationship between roughness index and various distress parameters for Indian Highways. They considered four National highways (NH-49, NH-205, NH-6 and NH-15) to develop the relationship based on linear, non-linear regression and artificial neural networks. It is found that ANN model gives the best result taking the weightage and bias into account for predicting the IRI value, as the MAE (mean absolute error) was 18% and 11% less as compared to linear model and non-linear model respectively. Following equations (2.7, 2.8, 2.9 and 2.10) were generated-

Multiple Linear Regression equations-

$$IRI = 2.619 + 0.302 * RD + 0.088 * C + 0.149 * RAV \quad (2.7)$$

$$IRI = 2.061 + 0.436 * RD + 0.121 * C + 1.634 * PTH + 0.002 * P + 0.003 * RAV \quad (2.8)$$

$$IRI = 2.198 + 0.418 * RD + 0.122 * C + 0.518 * PTH + 0.002 * P + 0.002 * RAV \quad (2.9)$$

Non-Linear Regression equation-

$$IRI = 2.01 + 0.442(RD)^{0.92} + 0.092(C)^{1.032} + 0.575(PTH)^{0.168} + 0.046(P)^{0.539} + 0.174(RAV)^{0.13} \quad (2.10)$$

Where, RD = rut depth (mm), C = area of total cracks (m^2 per 3750 m^2); P = area of patching (m^2 per 3750 m^2); PTH = area of potholes (m^2 per 3750 m^2); RAV = area of ravelling (m^2 per 3750 m^2)

Meegoda and Gao (2014) [168] developed IRI model using long term pavement performance data which includes parameters as pavement age, structure number, traffic load, freezing index and annual precipitation. The optimization of the fit was achieved with the function lsqcurvefit based on the Levenberg-Marquardt algorithm in optimization toolbox of MATLAB.

Sahoo et al. (2014) [244] developed performance criterion considering vertical stress over subgrade for thin surfaced rural roads using the limited data available under this study. **N.R. Avinash et al. (2014) [29]** presented a typical case study of an urban road network of Tumkur city, Karnataka, India. Six roads stretches of the selected road network were investigated for traffic volume, functional and structural condition in terms of CBR value of the subgrade soil, rebound deflection from Benkelman Beam Deflection (BBD) survey, International Roughness Index(IRI) using Machine for Evaluating Roughness using Low-cost Instrumentation(MERLIN) and condition rating based on extent of cracking, patching, rutting and potholes. Modified Maintenance Priority Index (MMPI) was proposed and found to give realistic ranking of the maintenance priority requirement of the selected road network.

Li et al. (2018) [154] proposed precise integration method (PIM) to compute IRI in a time domain which is verified to be better than ASTM code and CEN code. Considering the computational efficiency, the PIM method is 2.69 times higher than the ASTM code and 3.91 times higher than the CEN code.

Rada et al (2018) [219] presented the use of traffic-speed deflection devices for the structural evaluation of pavements at the network level as part of an effort funded by the Federal Highway Administration. Highlights from three major efforts—gathering of information to identify viable devices, field trials at or near the MnROAD facility to evaluate viable devices, and data analyses to identify and select the best deflection indices.

Hossain et al. (2019) [114] proposed an IRI prediction model using Artificial Neural Network on long-term pavement performance database for pavements located in wet-freeze, wet-no freeze, dry freeze and dry-no freeze climatic zones. The lowest value of RMSE as 0.027 is reported in the study which predicts reasonable accurate results.

Li et al. (2019) [155] estimated the International Roughness Index using Inverse Pseudo excitation method for single source and multisource stationary random excitations. The dynamic responses of the planar vehicle model with four degrees of freedom were used. It was found that the proposed approach was independent of travelling speed, road roughness grade, and vehicle type.

2.3.2 Various Pavement Condition Indexes

The development of unified pavement distress index (UPDI) is based on the theory of fuzzy sets **[135]**. The UPDI was calculated using equation (2.11):

$$\mathrm{UPDI} = \left(\frac{\mathrm{A_1 - A_r + 1}}{2}\right) \qquad (2.11)$$

Where A_1 = area enclosed to the left of the membership function that depicts the final fuzzy set, A_r = area enclosed to the right of the membership function that depicts the final fuzzy set.

A model called the overall acceptability index (OAI) was developed based on fuzzy set theory for the formulation of a comprehensive ranking index for flexible pavements**[301]**. Four parameter viz. roughness, surface distress, structural capacity and skid resistance were considered for OAI. The membership value A_i was obtained from the membership curve and the OAI was expressed as given in equation (2.12):

$$OAI = \left(\frac{w_1}{\sum w_i}\right)A_1 + \left(\frac{w_2}{\sum w_i}\right)A_2 + \left(\frac{w_3}{\sum w_i}\right)A_3 + \left(\frac{w_4}{\sum w_i}\right)A_4 \qquad (2.12)$$

Where, A_i = membership functions, w_i = weight

One important advantage of this model was it ensured that sum of weighting values ($w_i/\sum w_i$) is equal to 1, even on deletion of any attribute from the model. The membership functions and weight so obtained from analysis are as given in Table 2-2.

Table 2-2 Membership Functions and Weights for Interstate and Secondary Roads

Attribute	**Membership Function**	**R-square**	**Weight**
For Interstate Roads			
Roughness (PSI)	$A = 1 - \exp(-0.008688 * PSI^4)$	0.995	0.344
Distress (D)	$A = \exp(-0.000002729 * D^2)$	0.965	0.203
Structural Capacity (SC)	$A = 1 - \exp(-0.104 * (SC/50)^5)$	0.972	0.222
Skid Resistance	$A = -0.32231 + 1.5582 * CF$	0.977	0.236
For Seondary Roads			
Roughness (PSI)	$A = 1 - \exp(-0.01274 * PSI^4)$	0.970	0.306
Distress (D)	$A = \exp(-0.00000185 * D^2)$	0.971	0.244
Structural Capacity (SC)	$A = 1 - \exp(-0.207 * (SC/50)^5)$	0.960	0.225
Skid Resistance	$A = -0.2246 + 1.6308 * CF$	0.979	0.231

A fuzzy logic approach was adopted to derive a universal pavement distress evaluator defined as Fuzzy Distress Index (FDI) and based on it pavement sections were ranked for maintenance needs **[257]**. The equation (2.13) was used to calculate the fuzzy distress index (FDI) from the final membership function, resulting in a ranking for each pavement section.

$$FDI = \frac{\int_{-\infty}^{\infty} \mu(c_z) \times z dz}{\int_{-\infty}^{\infty} \mu(c_z) dz} \qquad (2.13)$$

Where, c = a fuzzy set representing all distress conditions within the universe of distress condition; z = a particular condition measure contained in fuzzy set c; c_z = a membership function describing the overall pavement condition of the section; $\mu(c_z)$ = degree of membership of each condition measure z contained along membership function c_z.

A pavement distress image enhancement, analysis and classification algorithm was developed by Cheng and Miyojim (1998) **[55].** The enhancement algorithm eliminated the background lighting variations by calculating multiplication factors to correct the non-uniform background illumination. The new pavement distress classification algorithm builds a data structure storing the geometry of the skeleton obtained from the threshold image.

Pavement distress data was collected by several automated and manual methods used in Washington to calculate the pavement structure condition and in Oregon used for Pavement Condition Index (PCI). The indexes based on distress data collected by both methods were compared to indexes based on detailed distress surveys of selected test sections **[259]**.

The fuzzy pavement condition index (FPCI), a method to determine membership functions used in pavement condition assessment based on experts' opinions having range of values of in linguistic rating term of pavement parameters, was evaluated using following equation (2.14) **[23]**. The parameters considered were cracking, rutting and roughness.

$$FPCI = \left(\frac{A_L - A_R + 1}{2}\right) \times 10 \qquad (2.14)$$

Where, A_L=area of membership function enclosed to the left that represents the final assessment of pavement condition, A_R=area of membership function enclosed to the right that represents the final assessment of pavement condition.

Artificial neural network (ANN) was used in modelling the pavement serviceability rating (PSR) for the flexible pavements **[268]**. Using input variables which are longitudinal cracking, all cracking, patching, rut depth, slope variance and output as panel data of PSR an ANN (5,4,1) model was developed. The model was trained and tested using 74data sets obtained from AASHO test results. The comparison of PSR was done with ANN model and PSI obtained from AASHO equation. Coefficient of correlation (R^2) values of PSI and ANN model were obtained as 0.83 and 0.99 for training set, and 0.82 and 0.87 for testing set, respectively.

Gharaibeh et al. (2010) [94] compared the pavement condition indexes from five departments of transportation (DOTs) in United States, to ascertain the level of agreement among these indexes. A computational experiment was conducted where distress and ride equality data for 9,642 pavement sections (804m long) were obtained from the Pavement Management Information System (PMIS) of the Texas Department of Transportation (TxDOT). These sections were then rated using six pavement condition indexes from five DOTs and then compared. The result showed the significant differences among similar pavement condition indexes, which may be due to different distress types considered, weighting factors and the mathematical forms of the indexes, as conducted by the author.

Sarsam (2010) [246] evaluated the pavement sections using an expert system known as Visual Evaluation of Asphalt Concrete Pavement Surface Condition (VEAPSC) and determined the PCR. The severity and extent of each distress was assessed and PCR was calculated. The required maintenance action was suggested for each section based on the PCR.

Nayak et al (2012) [186] proposed a data analytic application for assessing the road pavement condition. The data analytics process includes acquisition and integration of data from multiple sources, pre-processing the data and mining the useful information from the data. The generated data mining models were able to demonstrate factors that affect pavement deflection data.

2.4 Studies on Pavement Performance/Deterioration Prediction Models

The next part of PMMS includes the development of prediction models for pavement deterioration using the existing time series pavement condition. It is very difficult to establish a universal and reliable performance prediction model for use in all regions. However, various prediction models have been developed on the basis of pavement type, structural design, paving materials, traffic levels, environmental and climatic condition and other factors.

The deterioration models applicable at different level of PMS can be classified as deterministic models and probabilistic model (**Hass & Hudson, 1994) [100, 106].** The deterministic models predict an average single value of a dependent variable (such as PCI, PSI, etc). Deterministic models can be further broken into three categories: mechanistic, empirical and mechanistic-empirical models, depending on which dependent and independent variables are included in the models and how their relationship is established. These models are established on the basis of extensive data collection and field tests along with experimental or naturally exposed pavements under different traffic and environment situations.

The probabilistic models predict a distribution and range of values for dependent variables, such as pavement condition state vectors [288, 292]. Probabilistic models are more utilized in pavement and other infrastructure network management concerning M&R priority programming. Various pavement deterioration prediction models as developed in India and globally have been summarized below.

2.4.1 Deterministic Models

Performance study on some full depth granular pavements sealed with thin bituminous surfacing was conducted on National Highways using Benkelman beam deflection survey for structural evaluation of pavements and adopted rutting and cracking as failure criterion **[224]**. A relationship (equation 2.15) was developed to estimate average rut depth as:

RD = -0.256 + 6.79*SVS + 3.08*ESAL (2.15)

Where, RD = mean rut depth (in), SVS= subgrade vertical strain (*10^{-3}), ESAL = equivalent standard axle load

The distress-prediction models was developed from local network data for load associated distress and climate/durability related distresses **[37]**.

Jain et al. (1992) [130] studied the parameters influencing efficient maintenance management of flexible pavements. Models were developed to predict the variation of deflection, rut depth, cracking and maintenance cost with time for flexible pavement in Uttar Pradesh and Haryana. An equation to predict the life of the overlay was also developed.

Lee et al. (1993) [153] predicted the PSR using parameters like pavement's age and structural number (SN), and cumulative equivalent single-axle loads. The developed model for estimating future PSR has been given below in equation 2.16.

$$PSR = PSR_i + a * STR^a * AGE^c * CESAL^d \qquad (2.16)$$

Where PSR_i = initial values of PSR at construction (4.5 used in analysis); STR = current pavement structure (structure number); AGE = age of pavement since construction or major rehabilitation (overlay) (years); and CESAL = cumulative equivalent single-axle loads of 18-kip on pavement in the heaviest traffic lane (millions).

Central Road Research Institute (**CRRI 1994) [62]** conducted the pavement performance study (PPS) comprising of two parts which are (i) Study on the existing pavement sections and (ii) study on new pavements sections. It was sponsored by the MOST, with the aim of developing pavement deterioration models and generating data for total transportation cost model. Four states Uttar Pradesh, Haryana, Rajasthan and Gujarat were considered for the study and the models were developed for different surface types viz. premix carpet, semi-dense carpet and asphaltic concrete surfacing. The models developed for various premix carpeting is as given in Table 2-3.

Table 2-3 Pavement Deterioration Models developed by CRRI (1994)

Sl. No	Model Description	Pavement Deterioration Models for PC Surfacing
1	Cracking Initiation	$AGECRIN = 2.74 * EXP\left[-2.57 * \frac{CSALYR}{MSN^2}\right]$
2	Cracking Progression	$\frac{\Delta CR_t}{t_i} = 5.41 * \left[\frac{CSALYR}{MSN}\right]^{0.54} SCR_i^{0.28}$
3	Ravelling Initiation	$AGERVIN = 3.18 * AXLEYR^{-0.138} * (CQ + 1)^{-0.38}$
4	Ravelling Progression	$\frac{\Delta RV_t}{t_i} = 3.94 * AXLEYR^{0.32} * SRV_i^{0.46}$
5	Potholing Initiation	$AGEPHIN = 0.21 * THBM^{0.23} * EXP[-0.18\ AXLEYR]$
6	Potholing Progression	$\frac{\Delta PH_t}{t_i} = 1.49 \frac{CR_i * AXLEYR\ (1 + CQ)}{THMB * MSN} + 3.60 * PH_i * AXLEYR\ (1 + CQ) + 3.47 \frac{RV_i * AXLEYR\ (1 + CQ)}{THMB * MSN}$
7	Roughness Progression	$\Delta RG_t = [58121\ (\Delta CSAL/SNCK^5)] * EXP\ (mPAGE) + [4.13\ \Delta\ CR_t] + [184.48\ \Delta\ PH_t] + [33.46\ \Delta PT_t] + [m\ RG_i * t_i] + [9.39\ \Delta RV_t]$

Where,

AGECRIN = Age of pavement at the time of cracking initiation in years

CSALYR = Cumulative standard axles (msa) per year

MSN = Modified Structural Number

$\frac{\Delta\ CR_t}{t_i}$ = Change in cracked area per year (%)

SCR_i = Min {CR_i, (100-CR_i)} and is sigmoid function of cracking

AGERVIN = Age of pavement at the time of ravelling initiation (years)

CQ = Construction Quality (0-Good, for NH; 1-Poor; for SH and MDR)

AXLEYR = Number of vehicle axles per year (million)

SRV_i = Min { RV_i, (100-RV_i)} and is sigmoid function of ravelling

RV_i = Initial Ravelled Area (%)

AGEPHIN = Age of pavement at the time of pothole initiation (years)

THBM = Thickness of bituminous layer (mm)

$\frac{\Delta PH_t}{t_i}$ = Change in pothole area per year (%)

CR_i = Initial cracking due to which change in potholes area occurred (%)

RV_i = Initial ravelling due to which change in potholes area occurred (%)

PH_i = Initial pothole due to which change in potholes area occurred (%)

ΔRG_t = Change in roughness (mm/km) over a time period t in years

ΔCR_t = Percentage change in cracked area over time't' years

ΔPH_t = Percentage change in potholed area over time'tʼ years

ΔPT_t = Percentage change in patched area over time'tʼ years

ΔRV_t = Percentage change in ravelled area over time'tʼ years

SNCK = 1 + Modified Pavement Strength

RG_i = Initial Roughness mm/km

PAGE = Pavement age since last renewal or overlay (years)

Various structural overlay life prediction models were developed having different subgrade viz., moorum, gravel and clayey for pavement performance study **[243]**. Also the structure deterioration and roughness deterioration models were developed and validated for NH-22, NH-2 and NH-24. The general forms of the developed models are given in equations 2.17, 2.18 and 2.19.

Overlay Life Prediction Model:

$$Overlay\ Life\ (months) = a_0 + a_1(h) + a_2(D_c) + a_3(h_0) + a_4(RDI) + a_5(V) + a_6(CI) + a_7(RI) \quad (2.17)$$

Where, h = thickness of the existing pavement (mm), D_c = characteristic deflection (mm), h_o = overlay thickness (mm), RDI = rut depth index, V = Traffic volume (CVPD), CI = cracking index, RI = roughness index.

Structural Deterioration Model:

$$D = D_0(1 + c * CSA/log_{10}(H)) \quad (2.18)$$

Where, D_0 =550 $log_{10}(\frac{D_c}{D_a})$, H = thickness in gravel material (mm), D_c = characteristic deflection (mm), D_a = Allowable deflection (mm), D = Deflection (mm), D_0 = initial deflection (mm), CSA = cumulative number of standard axles

Roughness Deterioration Model:

$$R = RI_0(1 + C_2 * CSA/log_{10}(H) \quad (2.19)$$

Where, H =$C_3 log_{10}(\frac{RI_p}{RI_a})$, H = overlay thickness (mm), RI_p = present value of roughness (mm/km), RI_a = allowable value of roughness (mm/km), C_2 and C_3 = constants

Reddy and Veeraragavan (1995) [233] developed a practical method for the maintenance management of rural (non-urban) highways and developed models for predicting structural condition and functional condition of the flexible pavement. The equations were developed for predicting the rebound deflection after an expected number of traffic load repetitions for the pavements overlaid with asphalt concrete and bituminous macadam (BM) surfacing.

The deterioration models were developed for Indian roadway and traffic situations, under a research project 'Pavement Performance Study – Study on Existing Pavement Sections' **[262]**. The models were developed for three pavement compositions viz. premix carpet (PC), Semi-dense carpet (SDC) and Asphaltic Concrete (AC). Various models for cracking, ravelling, pothole initiation and progression, and for roughness progression, were presented. **Vepa et al. (1996) [285]** proposed a procedure based on survivor curves for determination of RSL (Remaining Service Life) of flexible pavements.

Different multiple linear regression and ANN models were compared for predicting roughness distress level (RUGDL) probability for bituminous pavements as defined by Kansas Department of Transportation (KDOT) PMS **[116]**. The response variable used was binary i.e. 1 if pavements exists in a given roughness distress level or 0 if the pavement is in any other roughness distress level. It was conducted that the binary nature of the response variable created difficulty for regression analysis, hence ANNs proved to be much better predictors of RUGDL probability than traditional multiple regressions.

Reddy and Veeraragavan (1997) [229] constructed deterioration models and growth curves for rebound deflection, rut depth and crack area for two types of pavements surfacing. The predictive models for deflection, rut depth and depth and crack area progression with traffic were developed. They studied the effect of overloading and introduction of tandem axle trucks on pavement life. The deflection growth model (equation 2.20) has been developed using the historical data from six overlaid flexible pavement sub stretches with different initial deflection values.

$$DEF_t = 0.2386 \exp [CSA^{0.1713}] + 1.2445 (DEF_0) – 0.6071 \qquad (2.20)$$

Where, DEFt= surface rebound deflection at the time‘t’ in mm,

CSA= cumulative standard axle in millions at time‘t’, DEF_0= initial rebound deflection in mm

Roberts (1998) [237] used two types of ANN viz. quadratic function and dot product for predicting roughness based on different pavement characteristics and traffic. The 105 data sets were used, each set having 11 variables of 5 types viz. rutting, fatigue cracking, transverse cracking, block cracking equivalent axle loads and the International Roughness Index (IRI). The comparison model developed was named the quadratic function ANN model. The results showed that the quadratic function ANN model performed better than dot ANN model.

Reddy et al. (1999) [231] described a flexible pavement deterioration models for deflections increase with time, rutting and cracking representing structural condition and unevenness growth whereas PSR model representing functional condition. The RSL computation was also done based on critical condition performance criteria. The models developments are as shown below in Table 2-4 and 2-5. The applications of the developed deterioration models were also discussed.

Table 2-4 Deflection Growth Model

iDEF range (mm)	Model form
0.44 <iDEF< 0.61	$D_t = iDEF + 0.07884 [(N_t*Age)^{iDEF}]$
0.66 <iDEF< 0.8	$D_t = iDEF + 0.0027 \exp [(iDEF*N_t)^{iDEF}] + 0.0859 (Age)$
0.84 <iDEF<1.05	$D_t = iDEF + 0.04513(\exp N_t)^{0.45} + 0.0924 (\exp Age)^{logiDEF}$
1.10 <iDEF< 1.25	$D_t = iDEF + 0.03658 [\exp (iDEF*N_t)]0.5 + 0.19864 (Age)^{0.26}$

Table 2-5 Cracking Models

Model Type	Model Form
CRACK AREA	(BM+PMC) surfaced pavement $C_t = 1.8 [\log N_t + 0.115 (iDEF* N_t)^{1.48}]$
	(BM+AC) surfaced pavement $C_t = 3.49 [(iDEF* N_t)^{0.34} + 3.24* 10 -5* \exp (N_t)]$
CRACK AREA PROGRESSION	(BM+PMC) surfaced pavement $CA_t = iCA [1 + 0.744 (iDEF*N_t)*0.32 + 0.0054* \exp (N_t)]$
	(BM+AC) surfaced pavement $CA_t = iCA [1 + 1.49 (iDEF*N_t)*0.15 + 0.00547* \exp (N_t)]$

Where D_t = corrected characteristics rebound deflection (mm) at any time‘t’, iDEF = initial deflection (mm), Age = age of pavements at ‘t’ years, N_t = cumulative standard axles (millions) at ‘t’, C_t = crack area (%), CA_t = Progresses crack area in percent at time’t’, iCA = Initial crack area (%)

The three districts Pune, Raigarh, Yavatmal were selected on basis of different geographical, topographical and socio-economic status. Roughness was measured for paved and unpaved roads by using vehicle mounted bump integrator (VMB) and calibrated by using Dipstick **[63]**. The permissible limits for roughness considered in the study were 6500 mm/km for paved roads and 7500 mm/km for unpaved roads. Roughness Progression models are shown in Table 2-6.

Table 2-6 Roughness Progression Relationship

District	**Equations for Paved Roads**	**Equations for Unpaved Roads**
Pune	R= 86.43*Pavement Age +3119.8	R= 125.6*Pavement Age +5386.7
Raigarh	R= 68.417* Pavement Age+3066	R= 92.407*Pavement Age +4508.5
Yavatmal	R=103.41* Pavement Age+3379.9	R= 131.09*Pavement Age +5788

Where, R = number of revolutions per km (460), Pavement Age = pavement age in Months

Babu (2002) [30] compared various pavement performance models viz. HDM4, CRRI model, Bangalore model, etc. with the observed values of various distresses on the pavements sections. Various models for roughness, rutting, potholes and cracking were evaluated. **Roy et al. (2003) [238]** suggested regression equations as given in Table 2-7 for cracking initiation and progressions and roughness progressions for premix carpet surfaced pavements with a relationship between calibration factors, CSA, MSN and AXELYR.

Table 2-7 Cracking and Roughness Progression Models for Premix Carpet

Sl. No	Name	Model
1	Cracking Initiation	a_0 = 0.04124*CSA – 0.03059* MSN + 0.461
2	Cracking Progression	a_1 = 0.229*CSA – 0.07129* MSN + 0.537
3	Cracking Retardation Age	a_2 = 0.02825*CSA + 0.04123* MSN + 2.722
4	Roughness Environmental Coefficient	a_3 = -0.0176*AXELYR + 0.0460* MSN + 2.722
5	Roughness Progression	a_4 = -0.106*AXELYR + 0.481* MSN + 2.674

Where,

CSA = cumulative standard axles in millions at time't'

MSN = modified structural number

The RSL was estimated for slow and fast lines using the equation given below (2.21, 2.22 and 2.23) and taken as the difference between the age at which the roughness reaches its terminal value and the current age **[20]**.

$$RSL = \frac{1}{b}\ln\left\{\frac{IRI_{terminal}}{a}\right\} - current\ age \qquad (2.21)$$

$$RSL_s = \frac{1}{0.053}\ln\left\{\frac{3.0}{0.796}\right\} - current\ age \qquad (2.22)$$

$$RSL_f = \frac{1}{0.0359}\ln\left\{\frac{3.3}{0.824}\right\} - current\ age \qquad (2.23)$$

Where, RSL_s = remaining service life for slow lanes, RSL_f = remaining service life for fast lanes, $IRI_{terminal}$ = Terminal IRI of the pavement (mm/m or m/km); a = initial IRI value at age equal zero; b = Measures the curvature of the performance line.

Flexible pavement maintenance strategies which include the pavement deterioration modelling and unevenness progression model given in the study is given below in equation 2.24 **[283]**.

Unevenness Progression Models

$$UI_t = UI_0\,[1+0.065187*(CSA_t)^{1.22} + 0.184261*(Def * Age)^{0.61}] \qquad (2.24)$$

Where, UI_t = unevenness index (mm/km) at any time‘t’

UI_0 = initial unevenness index (mm/km), CSA_t = cumulative standard axle in million

at time ‘t’, Def= deflection (mm) at the time of UI_0, Age = age of pavement at ‘t’ years

The “analysis of data set obtained from the long-term pavement performance (LTPP) data observation to quantify the contribution of road material & construction variables of asphalt concrete on pavement performance (i.e., international roughness indicator) using a back-propagation neural network (BPNN) algorithm” **[56]**.

A deterministic performance prediction model was presented for use in rehabilitation and management of flexible pavement **[7]**. The model utilized the PSI concept adopted by AASHTO for use in flexible pavement design. The performance curves were developed for a pavement structural section and were used in several applications related to pavement rehabilitation and management. **Piyatrapoomi et al. (2005, 2006) [210,211]** described the variability of pavement strength significantly contributed to the variability in predicting road deterioration.

A study was performed to predict the performance of flexible pavement using two distress model in the KENLAYER computer program and eight deterioration models in HDM-4 **[92]**. The analysis of the test section indicated that the life of pavement predicted by HDM-4 is less than the predicted by KENLAYER. Also, only cracking and roughness have been found out to be critical, and as a result, condition-responsive maintenance has been carried out using HDM-4.

Mathew et al. (2008) [165] made efforts to develop the deterioration models for performance of rural road using ANN and were compared with regression techniques. It was concluded that the ANN models proves to be more suitable than the conventional regression models because of its ability to adjust to changing environment.

They developed deterioration models for ravelling initiation and progression, pothole progression and roughness progression using neural network and regression techniques. Eight sections of rural roads in Thiruvananthapuram districts were selected. The length of the study section was fixed as 0.5 km each study stretch was further divided into 50 sections of 10m each. Regression models are developed for rural roads given in equations 2.25, 2.26, 2.27, 2.28.

Ravelling Initiation Model

$$AGERVIN = 2 * AXLE^{0.113} * [CQ+1]^{0.997} * DR^{-0.26} \quad (2.25)$$

Ravelling Progression Model

$$RV_t/T_i = 6.47 * AXLE^{0.65} * SVR_t^{0.92} * DR^{-0.5} \quad (2.26)$$

Where, DR = drainage model= $1.2* (FDDsub)^{1.3} * SHCAM^{0.09} * PDG^{-0.118}$

AGERVIN = age of pavement in years, AXLE = number of vehicle axle per year (millions)

CQ = construction quality (0 good, 1 poor), RV_t = ravelling % at time 't'

T_i = time interval (years), SVR_t = Min. {RVi, (100-RVi)}

RVi = initial ravelling area (%), FDDsub = field dry density of subgrade (gm/cm^3)

SHCAM = camber of the shoulder, PDG = ponding area (m^2)

Pothole Progression Model

$$PH_t/t_i = 0.84 * PH_i * AXLE * (1+CQ) * DR + [\{0.12 * RV_i * AXLE * (1+CQ) * DR\}/\{THBM*MSN\}] \quad (2.27)$$

Where, PH_t= pothole area (%) at time't', PH_i= initial pothole area (%), AXLE= number of vehicle axle per year (millions), DR= drainage model

Roughness Progression Model

$$RG_t = [1.18* (CSAL/MSN) * e^{-0.3*PAGE}] + [0.48 * RG_i* t * DR * CQ] + [0.04*RV_i] + [0.14*PH_t] \quad (2.28)$$

Where, RG_t = roughness over time 't' in years, CSAL = cumulative standard axle in million at time 't', PAGE= pavement age since last renewal (years), RG_i = initial roughness (mm/km), DR = drainage model, RV_i = initial ravelling area (%) , CQ = construction quality (0 good, 1 poor), PH_t = pothole % area at time 't'

The mechanistic-empirical models were calbrated for flexible pavement using the WesTrack experiment **[279]**. **Shankar (2009) [250]** developed pavement deterioration models which can be used for reliable prediction of distresses of the in-service flexible pavements. Various models developed for different distresses are given below in Table 2-8.

Table 2-8 Models developed for National & State Highway of South India

Parameter	Model Form	Abbreviations
Cracking Model	$CRG = 3.123E-02 \times CBR + 4.689 \times DRYDEN + 3.583E-02 \times PAVTHK$	CRG = cracking(%), CBR = California Bearing Ratio (%), DRYDEN = Dry density (g/cc), PAVTHK = Pavement Thickness (mm)
Ravelling Model	$RAVELLING = IRI \times 1.480 - DR \times 0.722 - COMP \times 0.0516$	IRI = International Roughness Index (m/km), DR = Drainage rating, COMP = Relative Compaction of subgrade
Pothole Model	$PTHOLE = 8.558 \times DR + 3.176 \times CRG - 0.155 \times CSA$	PTHOLE = Pothole (Nos/km), DR = Drainage Rating, CRG = cumulative standard axle (msa)
Rutting Model	$AVGRUT = 2.714 \times IRI + 4.940E - 02 \times LTH$	AVGRUT = Average Rut Depth (mm), LTH = Length (Km)
Roughness Model	$IRI = CSA \times 0.06233 + CBR \times 0.362$	IRI = International Roughness Index (m/km)
Edge Break Model	$EDK = 7.225E-02 SHOWID + 0.180 PAVTHK + 6.204E-02 \times CSA$	EDK = Edge Break (m^2/km), SHOWID = Shoulder Width (m), PAVTHK = Pavement Thickness (mm)

Gaspar et al. (2009) [91], developed prediction models for India and Hungary and has been compared. The performance of Indian Highway pavements are evaluated considering bearing capacity, area of rut depth, cracking, ravelling and bleeding. Hungarian models were developed given in equations 2.29, 2.30, 2.31, 2.32, 2.33, 2.34 for surface defects, unevenness, rut depth, micro texture and macro texture as a function of age or traffic passed.

Deflection Progression Equation is given as :

$$Deft = 0.006\ Exp\ (iDef) + 0.153csa^{0.317} + 0.171age,\ (N=90;\ R^2 = 0.841;\ S.E. = 0.24) \quad (2.29)$$

Where, Deft = deflection at any time t, mm, iDef = initial deflection, mm,

csa = cumulative standard axles (millions),age = age of pavement from the time of construction, years.

Crack initiation $AGECRIN = 4Exp\ (-1.09CSALYR/MSN^2)$, $(R^2=0.45, SE=0.43)$ (2.30)

Crack Propagation $CR_t = 4.26(CSALYR/MSN)^{0.56}SCR_i^{0.32}$, $(R^2=0.25, SE=1.14)$ (2.31)

Where, AGECRIN = age of the pavement at the time of cracking initiation, years, CSALYR = cumulative standard axles per year (million), MSN = modified structural number, CR_t = percentage of the cracking at the time, t, SCR_i= initial cracking percentage

Ravelling Initiation

$$AGERVIN = 3.18 * AXLEYR^{-0.138} * (CQ+1)^{-0.38},\ (R^2=0.43,\ SE=0.38) \quad (2.32)$$

Ravelling Progression

$$RV_t = 3.94 * AXLEYR^{0.32} * SRV_i^{0.46},\ (R^2=0.43,\ SE=0.38) \quad (2.33)$$

Where, AGERVIN = age of pavement at the time of ravelling initiation (years), AXLEYR = number of vehicle axle per year (millions), CQ = construction quality (0 good, 1 poor), RV_t= ravelling % at time 't', SRV_i= initial ravelling %

Roughness Progression Equation

$$UI_t = UI_0 + 9.09\ csa^{iDEF} + 15.575age^{2.244},\quad (R^2=0.81,\ SE=0.237) \quad (2.34)$$

Where, UI_t= roughness (mm/km) at any time 't',UI_0 = initial roughness (mm/km), csa= cumulative standard axles, iDEF= initial deflection, mm, age= age of pavement from the time of construction, years

A neuro-fuzzy model was proposed by **Bianchini and Bandini (2010)** to predict the performance of flexible pavements using the parameters routinely collected by agencies to characterize the condition of an existing pavement **[38]**. The proposed hybrid model for predicting pavement performance was characterized by multilayer feed-forward neural networks that led the reasoning process of the IF-THEN fuzzy rules.

Khraibani et al. (2010) [144] presented a nonlinear mixed-effects model for the Evaluation and prediction of pavement Deterioration. They investigated and identified the structural and climatic factors that explain differences in the parameters between pavement sections, and quantify the impact of these factors on pavement evaluation.

Ullas et al. (2013) [278] identified the main distresses from the stretches of Kerala (five stretches, three from Kottayam-Kumili road and two from Varkala-Kallambalam) and Regression Models were developed (equations 2.35, 2.36, 2.37, 2.38, 2.39) for cracking, deflection, pothole, roughness, riding comfort index using SPSS Package. T test was used to check the reliability of models.

$$Def = 0.358Def_i + 0.009e^{VDF} - 0.002e^{MSN} + 0.653, \; (R^2 = 0.879; \; SE = 0.107) \quad (2.35)$$

Where, Def = deflection at time‘t’ in mm, Def_i= initial deflection, mm

VDF= vehicle damage factor, MSN= modified structural number

Cracking Progression $Cr = 0.985Cr_i + 0.269Def - 0.764(VDF/MSN) + 0.186$, ($R^2$=0.977, SE=0.367) (2.36)

Where, Cr = cracking area in percentage at time t, Cr_i = initial cracking area in percentage, Def = deflection at time t in mm

Pothole Progression

$$P_t = 1.075Pt_i + 0.013Age - 0.226(VDF/MSN) + 0.109 \quad (2.37)$$

Where, P_t = pothole area in percentage at time t, Pt_i= initial pothole area in percentage, Age= pavement age in years

Roughness Progression

$$RG_t = -0.159*RG_i + 0.347*RV*(VDF/MSN)^{AGE} + 3.24*Pt*(VDF/MSN)^{AGE} + 1.171*Cr + 0.553*(VDF/MSN)^{AGE} + 3.211, \quad (R^2=0.748, SE=0.725) \quad (2.38)$$

Where, RG_t= roughness at time ‘t’ in m/km, RG_i= initial roughness in m/km, RV= ravelling area in % at time ‘t’, Cr= cracking area in % at time ‘t’, AGE= pavement age in years

RCI Model: $RCI = 2.9897 \ln(u) - 22.902$, ($R^2$=0.873) (2.39)

Where, RCI = riding comfort index, u = unevenness in mm/km

Luo (2013) [160] proposed the application of an auto-regression method to pavement performance modelling to improve the predictive accuracy of predictions when there are only limited or incomplete data available. The International Roughness Prediction model was developed by **Dalla Rosa et al. (2017)** for network level PMS (Pavement Management System) over time which is a function of initial IRI and pavement age **[68]**. The pavement data has been selected from Texas Department of Transportation (TxDOT) from a ten year pavement management database. The model has been validated by observing the IRI values for year 2015 and IRI values calculated from the model for year 2015. **Inkoom et al. (2019) [120]** proposed deep machine learning methods to assess the pavement crack deterioration based on selected time variant and previous condition rating of pavements by using partitioning bootstrap forest, Naive Bayes, K-nearest neighbours and boosted trees methodologies.

A pavement deterioration index based on negative binomial (NB) regression model was predicted by **Pantuso et al. (2019) [206]** which is a function of pavement age. Pavement condition models were developed for various pavement families and compared with previous non-linear regression models. The linear empirical Bayesian (LEB) approach was used to further improve the prediction power of the models.

2.4.2 Probabilistic models

Markov process is a specific performance prediction model used for network-level based on stochastic concept treating pavement deterioration as Markov process **[208]**. **Golabi (1982) [96]** developed a PMS for State of Arizona to produce optimal maintenance policies. The system used a mathematical model which captured the dynamic and probabilistic aspects of pavement maintenance. The model integrated management policy decisions, budgetary policy, environmental factors and engineering decisions. A cumulative damage model was predicted by **Camahan (1987)** based upon a Markov process to predict pavement deterioration **[45]**. The optimal repair action for each possible pavement state in the planning horizon was found by means of probabilistic dynamic programming. Sample sequences of repair actions were generated during a simulation in which the optimal repair policy was applied to sample pavement condition histories. Several sensitivity studies were performed to study the variation in expected cost, including the effect of delaying the optimal program.

An analysis of pavement crack initiation data based on the duration modelling techniques was presented by **Shin and Madanat (2003) [256]**. These duration models enable the stochastic nature of pavement crack initiation. The stochastic duration model and hazard model were compared with AASHO model for crack initiation. Various advantage of using stochastic model over AASHO model was listed. **Abaza et al. (2004a) [9]** applied a discrete-time Markovian model to predict pavement deterioration with the inclusion of pavement improvement resulting from M&R actions. The model for optimum M&R associated with the case of random selection of pavement project candidates and models for worst-first selection of optimum M&R were developed.

Markovian technique was used for prediction for pavement condition by constructing the probability transition matrix **[269]**. A matrix of 10*10 was constructed where each matrix predicts pavement condition with some deviation from actual condition. The matrix with least deviation was considered for application.

Ortiz-Garcia et al. (2006) [202] focused on the prediction of deterioration using three probabilistic techniques at the network level. The first method assumed that the historical condition data for each of the sites in the network is readily available. The second utilized the regression curve obtained from the original data, and the third assumes that the yearly distributions of condition are available to assist in the process.

2.4.3 International Scenario

A number of pavement deterioration studies related to flexible pavements have been conducted globally. A brief description of some of the notable studies is given below:

AASHO Road Test

The AASHO Road test was the first major landmark, wherein the concept of pavement serviceability was developed. The test was an accelerated-controlled trafficking experiment, conducted in USA using typically road vehicles on specially constructed pavements, over a period of 2 years (1958-60). The primary objective of the AASHO Road test was to determine the relationship between number of axle transits of different loadings and pavement performance. Pavement condition data collected included slope variance, rut depth, cracking and patching area. Pavement strength was expressed in terms of structural number. Relationships developed are based on accelerated loadings under controlled conditions and don’t reflect the actual traffic loading situations in the field. No separate relationship for prediction of roughness, rut depth and cracking were developed. The limitations of this study were-

(i) The serviceability indices evolved in this study are subjective in nature, being based on user expectancy levels.

(ii) The tests under accelerated controlled trafficking did not provide any information on behaviour under mixed traffic conditions.

(iii) The correlations developed are for freezing environment only.

(iv) The tests were limited to thick asphalt concrete on one weak subgrade only.

Kenya Study

In 1969, Massachusetts Institute of Technology (MIT) under the sponsorship of World Bank, initiated the development of a model to be used for the economic evaluation of investments in roads. This program was concluded in 1971 and resulted in integral relationships which considers the cost of highway construction, maintenance and utilization by the users. Phase-I of this program produced the Highway Cost Model (HCM). These results encouraged the world bank and a study was completed by TRRL, UK in Kenya during 1971-74 with the specific objectives of measuring the deterioration characteristics of some roads and the operating costs of the vehicles that used them. A computer model "Road Transport Investment Model (RTIM)" was developed in 1975.

Relationships for change of roughness, cracking and rut depth were developed in non-freezing climate over a narrow range of pavement strength, mixed traffic loadings and under different maintenance standards. The relationships developed are for individual modes of distress and are independent of affects of other distresses types. The major limitation of this study included that correlations developed were mostly with cement stabilized base and had a narrow range of pavement strength and that the data base was very narrow.

In 1976, World Bank, MIT and TRRL joined together with the objective of producing a single model that would combine the HCM and RTIM. Another version through these efforts came into being and was designated as Road Investment Analysis Model (RIAM).

Brazil Study

In 1975, The Brazilian Government and UNDP undertook a highway research project designated as "research on the-relationships between costs of highway construction, maintenance and utilization (PICR)". One of the product of PICR was model to be used in economic evaluation of highway investments and was designated as Highway Cost Model (MICR). The Brazil Study was completed during 1977-82. A number of levels of pavement age and pavement types were considered. A wide range of pavement strength from MSN 1.5 to 7.0 was covered. A large degree of scatter in the data was observed primarily from the inherent variability of construction quality, materials properties, materials behaviour and partly measurement error. The Brazil study builds on the causalities of events but introduces formulation discontinuities, which increases the computation effort. Models for prediction of cracking, ravelling, potholing, rutting and roughness were developed. The major limitations of these models are that conditions like thick bituminous pavements, granular base, low rainfall and the affect of pavement widths were not covered.

All India Present Serviceability Rating Study

In early 1970's, an All India Serviceability Rating Study was carried out under which Pavement Serviceability Index (PSI) correlations based on the concept developed at the AASHO Road Test were evolved, both for flexible and rigid pavements, separately at zonal as well as national level. The assessment of distress was subjective in nature. The various parameters included in the development of PSI equations were total surface distress and the unevenness index. The correlations suffered from limitations that important factors like pavement composition, its structural adequacy and the affect of traffic etc. were not considered.

US-SHRP LTPP Studies

Long Term Pavement Performance (LTPP) study is one of the four research programmes undertaken under the Strategic Highway Research Programmes (SHRP) of USA during 1987-92, with a view to better understanding of pavement materials and performance of structure, and to rationalize the design procedures. This study which has following two parts, is planned to be conducted over a period of 20 years.

(a) General Pavement Study (GPS)
(b) Specific Pavement Study (SPS)

GPS studies are restricted pavements that incorporate materials and designs that represents good engineering practice and that have strategic future importance. GPS studies are limited to pavements in common use and are divide into 4 climatic zones, viz. wet-freeze, wet non-freeze, dry-freeze and dry non-freeze. GPS has 10 different studies covering aspects related to different materials and specifications. There are a total of about 780 sections, 437 on flexible pavements and 340 on rigid pavements. Products that are expected to evolve from GPS data analysis include:

- Improved design equations
- Improved design and analysis techniques
- Distress-specific performance models
- Construction variability
- Factors important in rutting initiation

- A technique for re-evaluating load equivalency factors

SPS will study the effects of certain important factors on pavement performance. SPS include specially constructed pavements and will explore options for construction of new pavements, the application of maintenance treatments to existing pavements and the rehabilitation of distressed pavements. SPS include 9 experiments covering design, maintenance and rehabilitation of flexible and rigid pavements, and validation of SHRP asphalt specifications and mix design. Early analysis of the available LTPP data has established the following:

- Both flexible and rigid AASHTO design equations are poor prediction equations
- AASHTO design equations frequently lead to un-conservative design
- Response to loads and environments vary seasonally and that the manifestation of distress also vary seasonally
- Accelerated trafficking to failure at the Road Test is not representative of in-service asphalt pavements
- Future design equations should either be capable of taking climate into account or individual equation should be used for different climatic zones

2.5 Studies on Optimization Techniques and LCCA

The optimal allocation of the available resources is necessary when the available maintenance funds are limited. Identifying the best maintenance strategy for a large highway network with resource constraints is a highly complex problem. The optimization approaches require the formulation of the decision problem as a mathematical model. In this the objective one wished to pursue (i.e. maximizing improvement) and the constraints one has to satisfy (i.e budget, manpower, equipment etc.) and is stated as mathematical decision techniques. Many different approaches have been proposed to carry out this task.

Some of the studies have been presented in this section.

2.5.1 Work Done in India

A simplified approach for maintenance of highway system was recommended by **Bhanwala (1995) [162]**. Based on detailed pre-monsoon and post-monsoon field study, optimum maintenance norms and strategies were suggested for different test sections. **Nagaraja et al. (1996) [182]** developed the Transition Probability Matrices (TPM) on the basis of subjective judgment of the highway experts for the rural roads in Karnataka. The optimal M&R decisions were made based on these TPM.

Arya et al. (1999) [27] conducted a maintenance cost study for pavement under different rainfall and traffic condition on NH-4 sections. Based on extensive field data collected, maintenance norms, related to choice of renewal specifications, norms of ordinary repairs and periodic renewal surfacing for pavements test sections were developed.

Ramesh et al. (2001) [222] developed a computer program to compute the life-cycle cost duly considering the first stage strengthening cost, pavement maintenance cost, vehicle operating cost, user delay cost and salvage value during the design life. The suggested approach was used in selection of optimal maintenance strategies, to prioritize road sections for maintenance and planning of the maintenance budget during the expected design life.

Reddy et al. (2002) [232] presented a method of allocation of pavement cost viz. pavement overlay construction costs and maintenance cost depending upon the volume of commercial vehicle and the performance of pavements. The cost allocation was based on statistical models developed for unevenness progression and its relationship with PSR.

Aggarwal et al. (2004) [17] compared the total life-cycle cost considering highway agency costs and road user cost using the program analysis tool of HDM-4. The condition responsive M&R alternative was considered for the analysis for predicting these costs. The LCCA was carried out for selected sections of National Highways.

Agarwal (2005) [14] proposed the methodology for optimal allocation of the available resources for highway maintenance. A mathematical program was formulated with an attempt to maximize (or minimize) an objective (expressed as a function) subject to various constraints (expressed as inequalities). The final form of developed program was as given in equations (2.40 and 2.41) below.

Objective Function:

$$Z = \sum_{\forall S}[\sum_{\forall d}\{\sum_{\forall c}(\sum_{\forall a} X_a^S \,.\, IC_{ac})\,.\, ID_{cd}^S\}\,(CI_d^S . W_d)].PI^S \qquad (2.40)$$

Subject to:

$$\sum_{\forall S}\sum_{\forall a}(CR_d^S \times X_a^s) \le BA, \qquad \sum_{\forall S}\sum_{\forall a}(ER_{la}^S \times X_a^S) \le BA, \forall l$$

$$\sum_{\forall S}\sum_{\forall a}(MTR_{ma}^S \times X_a^S) \le MTA_m \quad \forall m, \qquad \sum_{\forall S}\sum_{\forall a}(MPR_{na}^s \times X_a^s) \le MPA_n \quad \forall n,$$

$$\sum_{\forall S} IC_{ac} \times X_a^S \le 1 \qquad \forall c, \forall s \qquad (2.41)$$

Where, CI_d^S = Condition Index of dth distress at section s, W_d = Weight of dth type of distress in improving the condition of any section, ID_{cd}^S = improvement in the condition of the dth distress due to improvement in the condition of the cth distress component, PI^s is the urgency or priority index of section s, BA = Budget available, ER = equipment hours required, EA = equipment available, MTR = quality required for material type, MTA = quality available for material type, MPR = manpower required, MPA = manpower available

2.5.2 Work Done in Abroad

A procedure for making optimal maintenance decision for a deteriorating highway network using Markov Decision Process (MDP) was described by **Carnahan (1988) [47]**. The MDP has a merit as an approach to optimal budgeting. It could represent the quantitative framework for an expert system designed to advise the budgeting process. The work done in Arizona has shown that a proper state definition can provide the predictive accuracy required for optimizing decisions for pavement management.

Kanto (1993) [138] presented the Highway Investment Programming System (HIPS) developed at network level to optimize pavement rehabilitation policy and budgeting. HIPS consisted of two models (i) long-term to find a pavement condition level and maintenance policy which minimizes total social cost and (ii) short-term to find the quickest practical means of achieving the optimal pavement condition level defined by the long-term model.

Mijuskovic et al. (1994) [172] established a mathematical model that presented the impact of the amount of the available budget for the network quality as a whole in a sample and realistic way. A non-homogeneous markov chains was applied for this model. **Harper (1996) [104]** discussed two optimization model viz. optimal steady-state model and multi-year model for minimizing the maintenance cost while maintain the high standards as desired by the Kingdom of Saudi Arabia. The linear programming concept integrated with Lagrange Multiplier, for optimization was used.

The performance of current network optimization system (NOS) model used by Arizona Department of Transportation to minimize the annual cost over the planning period was presented by **Liu and Wang (1996) [156]**. In relation to annual budget the pavement condition, two types of analysis were conducted. In the first analysis, only annual budget was applied as the constraint for the model and in the second analysis both annual budget and pavement performance requirements were introduced as the constraints. **Wang and Liu**

(1997) [287] described the application of fuzzy set representations for different pavement factors introduced to determine the pavement performance ratings for various pavement condition states which are necessary to generate the objective function.

Fwa et al (2000) [89] presented a genetic-algorithm-based procedure for solving multi-objective network level pavement maintenance programming problems. The concept of Pareto optimal solution set and rank-based fitness evaluation and two methods for selecting an optimal solution were adopted. Genetic Algorithm (GA) was applied by **Chan et al. (2001) [49]** for optimizing the resource allocation for pavement maintenance programming. The performance of the various constraint handling methods viz. prioritized resource allocation method (PRAM), decode and repair method (DRAM) and penalty method (PM) were compared.

Mamlouk and Zaniewski (2001) [163] presented a step-by-step procedure for selecting the appropriate preventive maintenance treatment for asphalt pavement. It also evaluates the optimal timing for that treatment under different pavements, traffic and climatic conditions. A model was presented to provide the basis for the analysis of the cost-effectiveness of a pavement preventive maintenance program. **Abaza (2002) [6]** developed a flexible pavement life-cycle model to yield an optimum M&R plan. The model incorporated both performance and cost associated optimization process with a life-cycle analysis period for a given pavement structure (project). A single life-cycle indicator called life-cycle disutility was introduced and defined as the ratio of cost to performance.

Ferreira et al. (2002) [77] presented an optimization model with an objective to minimize the expected total discounted costs of the pavement M&R actions over a given planning time span. This is used within a network-level PMS together with a genetic-algorithm heuristic to solve the model. The probabilistic segment-linked mixed integer optimization model was applied to three test problems involving the road network of Coimbra, Portuguese city.

Chan et al. (2003) [50] used genetic-algorithm (GA) optimization technique to allocate the total funds available to the district or regional agencies in order to best achieve specified central and regional agencies' goals subject to operational and resource constraints.

Abaza et al. (2004a) [9] developed an effective practical decision policy for use in the selection of an optimum M&R program with an objective of optimizing pavement condition under constrained budgets. The developed policy utilized a discrete-time Markovian model with five condition states labelled a, b, c, d, e and f where ‘State a’ represented pavements in excellent condition, and ‘State f’ indicated pavements in bad condition.

Herabat et al. (2005) [109] selected the flexible road sections for the study in the Pathumthan province, Thailand. The single and multi-objective optimization models using genetic algorithm which are used to develop the multiyear maintenance plan considering the characteristics of network.

Bosurgia and Trifiroa (2005) [41] defined a procedure to make use of the available economic resources in the best way possible for interventions of resurfacing on flexible pavements by using artificial neural network and genetic algorithms. The optimization problem was resolved by means of an opportunely defined genetic algorithm using the results of the neural networks designed. The procedure was applied to the all motorway of the Eastern Sicily road network”.

A comprehensive procedure to carry out the strategy analysis using option evaluation system (OES) with dynamic sectioning (called SDS) for a nationwide road network including sound trade-off analysis of all constituent sub-networks under a uniform annual network budget constraint over the planning period **[111]**. **Abaza and Ashur (2009) [8]** formulated- “an optimum microscopic linear integer programming model that incorporated integer variables representing the number of pavement sections to be treated by the applicable M&R actions. The optimization model was developed to maximize pavement conditions or minimize M&R costs. **Zongzhi et al. (2010) [304]** proposed a stochastic model approach formulated as the zero/one integer doubly constrained multidimensional knapsack problem and an efficient heuristic solution algorithm developed using the Lagrange relaxation technique. It was developed for system wide highway project selection. An optimal Maintenance and Rehabilitation (M&R) strategy for a designed flexible pavement by integrating Life-Cycle Cost Analysis (LCCA) and California Mechanistic-Empirical (M-E) design procedures (CalME) **[164]**.

Fwa and Farhan (2012) [88] proposed a two-stage approach in resolving the dual-level multiasset, multi-objective pavement network maintenance optimal budget allocation problem. The first stage of the approach analyzes the individual multi-objective asset systems independently to establish for each a family of optimal Pareto solutions, whereas in second stage it adopts an optimal algorithm to allocate budget to individual assets by performing a cross-asset trade-off to achieve the optimal budget solution for the given overall system-level objectives.

2.6 Studies on Prioritization Methods for Maintenance

The final aim of any PMMS is to establish a priority order to execute maintenance by using a method that will lead to a more realistic and rational way at the network-level. Priorities can be determined by many methods, ranging from simple subjective ranking to the true optimization method (**Hass et al. 1994) [106].** The application of various techniques for maintenance prioritization has been presented in this section.

2.6.1 Prioritization based on Subjective Rating Methods

The feasibility of using ANN models for priority assessment of highway pavement maintenance needs a simple back-propagation neural network with three different priority setting schemes **[87]**. Where a linear function relating priority ratings to pavement conditions, a nonlinear function, and subjective priority assessments obtained from a pavement engineer, was tested using general purpose micro-computer based neural network software known as Neural Works.

Prioritization procedure are a part of an Urban Roadway Management System (URMS) at network level. The procedure combined two matrices and an equation for computing priority index (PIX). PIX were taken as a function of PCI, pavement age, mixed traffic and street class **[54]**. **Sharaf (1993) [252]** compared three models for priority ranking. In the first model the priority index was estimated as follows equation (2.42):

$$Priority\ Index = \frac{Defect\ Length}{Traffic\ Factor \times Defect\ Factor} \quad (2.42)$$

The traffic factors were selected as 1.0, 0.5 and 0.1 based on traffic levels. The defect factor (values between 0.1to1.0) was assigned on the basis of the distress type and required treatment (lower values for major treatments). The sections were then ranked in descending order after calculating the section priority index, and converted to a unit cost using appropriate maintenance treatment. The second model was a modification of the first, where the pavement sections were arranged according to road type (i.e. desert or agricultural roads) and traffic level into four classes. In the third model, the distribution of budget among all sections was done on the basis of optimization method.

Jain and Gupta (1996) [131] conducted studies on four sections of flexible pavement on NH-21 & NH-22 in state of Himachal Pradesh and eight sections in state of U.P on NH-2, SH-45 & MDR-121 for prioritizing maintenance strategies. Several field data collection was done on the selected roads and it was suggested to invest for a design life of five years. Priority fixation for M&R was done based on following factors which includes- importance of road (i.e. road type and commercial traffic); characteristic deflection (D_{cs}) value; road condition based on roughness, cracks, rutting, potholes and investment needs for M&R.

A simple ranking technique was derived to prioritize the pavement maintenance strategies by considering various pavement distresses i.e. cracking, patching with their extent and severity levels, roughness value and pavement condition rating **[265]**. The weightage factors were allotted to each distress parameter on the basis of their extent and severity levels. Finally, a “Pavement Condition Index” was generated to prioritize or rank the pavement sections for their maintenance. **Zhang (2004) [298]** presented an “Analytical Hierarchy Process (AHP)” technique for prioritization of data necessities for pavement management system. The ranking score was obtained based on the weighted sum technique by combining the importance and frequency of usage of data items. **Agarwal et al. (2004) [15]** presented a logical way using AHP for prioritization of roadway sections depending on the current pavement condition, estimated pavement condition and the important roadway for maintenance. The functional condition of road sections was estimated considering the safety, efficiency if traffic operation and riding comfort. A total of 15 parameters were considered. These factors have been given relative weights as obtain from the expert’s of field engineers, which were analysed using AHP. The developed approach was employed for prioritizing the road sections of a small road network for maintenance.

Chandran et al. (2007) [52] utilized the concept of fuzzy logic in order to design the prioritization method for low volume roads. Eight pavement sections each of 500m length with different deterioration levels were selected in the Trivandrum and Kollam Districts in Kerala State. Fuzzy prioritizing methods were used to develop – “Fuzzy Condition Indices (FCI)” which further indicates the prioritization process of pavement sections. Fuzzy functions were designed for “severity, extent and relative importance of each distress with respect to maintenance”.

A special approach known as- “Fuzzy Multi Criteria Decision Making (FMCDM) approach” was developed by **Sandra et al. (2007) [245]** for ranking various pavement sections of NH, SH and Major District Roads (MDR). The gravity or importance of various pavement distresses in view of their severity and extent on the functional condition of pavement was judged and verified by conducting an expert poll. The fuzzy matrix method developed in MATLAB was used to finally generate a Priority Index (PI) whose higher value indicates that a particular pavement stretch has highest priority for maintenance.

Farhan and Fwa (2009) [75] made an attempt to explore the use of Analytical Hierarchy Process for prioritizing pavement rehabilitation activities. Three models of AHP were tested, viz., "the distributive-mode relative AHP, the ideal-mode relative AHP, and the absolute AHP". For analysis purpose, three components each from- "road functional classes, distress types and levels of distress severity" were observed. It gave as many as 27 different pool of rehabilitation strategies. The study concluded that the absolute AHP was suitable for the pavement maintenance prioritization process. Analytical Hierarchy process and fuzzy network were used for prioritizing the maintenance strategies. The developed models were executed for 131 sections of urban streets of district No. 6 of Tehran municipality. The modelling was done in two steps. In the first step, AHP was employed to compute the relative weights of parameters. In the next step, fuzzy logic modelling was used to obtain satisfactory precision **[176]**.

Abu-Samra et al. (2017) [13] proposed a pavement condition rating system for the flexible road network of Canada and USA using Multi-attribute utility theory (MAUT). All the supposed factors affecting pavement condition had been incorporated to develop the pavement condition rating model and questionnaires had been prepared which suggests that transverse cracks has the highest impact on condition of flexible pavements.

Al-Haddad et al. (2018) [19] developed pavement condition index by using Micro-Paver 5.2 software for Al-Samawah-Nasiriyah roadway in Iraq which possess extensive pavement distresses using soft computing fuzzy logic technique by taking densities of deterioration for different severity levels as the input. The output of proposed Fuzzy Inference System (FIS) shows an error of only 4%.

Long Term Pavement Performance (LTPP) database was used by Elhadidy et al. to correlate the Pavement Condition Index with International Roughness Index using simple regression analysis. A total of 1208 pavement section data had been analysed and a sigmoid function was used to determine the relationship between International Roughness Index and Pavement

Condition Index with a coefficient of determination value of 0.992 which shows a very good correlation between the parameters **[72]**.

2.6.2 Prioritization based on Composite Condition Index

The pavement management implementation project for Prince Edward Island (PEI), Canada covers a road network of 500 km **[139]**. The Condition Index (CI) was computed considering the severity of 10 different distresses on road sections. The Overall Serviceability Index (SI) was calculated for all road sections using following equation (2.43).

$$SI = a(RCI) + b(SAR) \tag{2.43}$$

Where, SI = serviceability index (Rating Scale: 0-10 where 0 – totally unacceptable pavement and 10 is perfectly smooth and strong pavement), RCI = Riding Comfort Index (Rating Scale: 0-10 here 0 is worst riding comfort & 10 is perfectly smooth pavement), SAR = structural adequacy rating (Rating Score: 0-10 where 0-4.9 indicates structural adequate pavement, 5-10 indicates structural inadequate pavement), a and b = weighting factors (where a + b = 1.0)

A mathematical-optimization (linear-programming) model was adopted to set priorities based on benefits maximization and budget constraints. **Andres (1994) [22]** detailed the prioritization methodology of local roadway improvements for the town of Eastharm, Massachusetts. The system used a composite performance based index to assess priorities. The prioritization was done considering different budget scenarios like zero funding, full funding, moderate budget cut and severe budget cuts. The method for prioritizing pavement rehabilitation projects depending on expert's survey was used for 5 years pavement preservation program of Arizona Department of Transportation (ADOT). The parameters like cracking; roughness, rutting, and maintenance cost and road classification were considered for prioritizing pavement sections **[84]**.

Ramadhan et al. (1999) [221] used AHP for priority ranking of pavement maintenance. The Priority Index (PI) given by following equation (2.44) was adopted to compute the priority ranking for pavement maintenance. The factor weights were computed using the AHP method by analyzing the data collected.

$$PI = \sum W_j \times F_j \tag{2.44}$$

Where, PI = “Priority Index for any section (out of 100)”; W_j = “factor “j” weight of importance to priority ranking”; F_j = “Factor “j” value (out of 100) and sum of W_j = 1.0”.

In a study carried by Ramesh et al. , detailed pavement data pertaining to performance from the selected National Highways in Karnataka was collected and this has been used to determine deterioration models and in the determination of “Life Cycle Cost” **[223]**. The objective of the study includes developing Present Serviceability Index (PSI) model based on pavement evaluation data. A relationship (equation 2.45) was derived for pavement serviceability index as given below-

$$PSI = 14.79 - 0.029(C_t) - 0.0086\,(RD)^{1.85} - 0.642\,(UI)^{0.4} \qquad (2.45)$$

“C_t =Cracking in percentage, RD= rut depth in mm, UI= unevenness index in cm/km”

Bandara and Gunarante (2001) [33] worked for the main road network of Sri Lanka to develop a methodology for the prioritization of maintenance strategies for the huge road network using visual surveys and fuzzy logic. The concept of triangular fuzzy numbers (TFNs) with a linear membership function was used for analysis. This concept proposed priority ranking methodology based on combined distress index model and traffic regulation factors **[230]**. The surface condition for pavement sections was assessed in form of acceptability and relative weightage, defined in terms of Pavement Distress Index (PDI) as equation (2.46):

$$PDI = [1 - \sum(AL_i * w_i)\,/\sum w_i]\;100 \qquad (2.46)$$

Where AL_i = Acceptability level of any distress, i, w_i = weightage of distress i. based on above equation, PDI value have been assigned as 0 to very good pavement and 100 to completely deteriorated pavement. The Priority Index (PI) for a road section was computed as equation (2.47):

$$PI = F \times PDI = F \times [1 - \sum(AL_i * w_i)\,/\sum w_i]\;100 \qquad (2.47)$$

Where, PDI = Pavement Distress Index, F = Prioritization factor depending on functional class and average daily traffic.

Cafiso et al. (2002) [44] provided a Multicriteria Analysis (MCA) framework for pavement maintenance management. An AHP method of MCA was implemented to compute the ranking values (RV) for the maintenance alternatives. The HDM-4 was used to produce outputs that can be used as attributes for each road section and investment alternative.

Narasimha (2003) [185] defined a procedure to prioritize the periodic maintenance of road network on the basis of subjective rating as per the recommendations of "Asphalt Institute (AI), USA". The field surveys and data collection were conducted on different categories of roads (SH, MDR & ODR). Data pertaining to present serviceability conditions were collected for about 22km of road length from a total of 160.334 km under study area, in Tamil Nadu. The pavement condition survey was carried out, by identifying and evaluating thirteen types of distresses as defined by AI and then the pavement condition rating (PCR) of each stretch of road was computed. Finally, the PCI value was calculated using the charts given in AI and the prioritization of maintenance for road sections was done.

Kumar and Kumar (2004) [149] developed a method to prioritize the maintenance strategies of highways for certain roads in Thiruvananthapuram city based on composite criteria. The approach included the opinions from the users in first step and opinions from the experts in the second step. The questionnaire for user opinion survey consisted two parts one with trip information and second with pavement condition. Based on functional evaluation indices second questionnaire was prepared and expert opinion were taken for fixing priority for maintenance. Finally the priority obtained from user and experts were compared.

Vasudev et al, (2007) [282] studied "Pavement Management for Rural Roads" to develop pavement serviceability models (equation 2.48). 19 test sections were selected; detailed data collection has been done on these stretches.

$$PSI = 5.03 - 0.01 * (C+P)^{0.5} - 1.386 * RD^2 - 1.91 * \log(1+SV) \quad (2.48)$$

C= cracking (ft^2/ 1000 ft^2), P= patching (ft^2/ 1000 ft^2), RD= mean rut depth (in), SV= mean of slope variance in the wheel path

Pantha et al. (2010) [205] proposed a "GIS-based Highway Maintenance Prioritization Model" for major link of 53.2 km for the city of Kathmandu, Nepal. The highway sections were prioritized considering the pavement and roadside slope stability condition. The weighted PMPI i.e. Pavement Maintenance Prioritization Index and weighted RMPI i.e. Roadside Slope Maintenance Prioritization Index were added to finally arrive at MPI i.e.

maintenance Prioritization Index, as given in following expression (2.49). The selection of maintenance sections were done based on these calculated MPI.

$$MPI = PMPI * W_p + RMPI * W_r \quad (2.49)$$

Where, PMPI is the pavement maintenance prioritization index, RMPI is the roadside slope maintenance prioritization index, W_p is the weight given to pavement maintenance and W_r is the weight given to roadside slope maintenance.

Khademi and Sheikholeslami (2009) [143] presented a mixed "Conference-Delphi-AHP" model developed to maintain and rank the low-class roads in Gilan, Iran. The main three objectives defined for this study was to determine the "high-priority low-class roads" for maintenance (MA), improvement (IM), and upgrading (UP).

Kaysi et al. (2010) [141] prioritized the National Road sections using a multi-criteria analysis (MCA) method, the linear additive model. Three level hierarchies were generated by dividing the each main criterion into primary criteria and secondary criteria, as given in Figure 2.1. in the next step the relative weights of each criterion were derived using AHP method by developing the questionnaire. The following Linear Additive model (equation 2.50) was used to calculate the combined value score of a road network by adding its weighted score on a set of criteria:

$$S_i = \sum_{j=1}^{n} w_j S_{ij} = w_1 S_{i1} + w_2 S_{i2} + \cdots + w_n S_{in} \quad (2.50)$$

Where S_i is the total value score of scheme i; w_j is the relative weight of criterion j; S_{ij} is the value score of scheme i on criterion j; and n is the total number of criteria. The schemes were then ranked based on the calculated total scores.

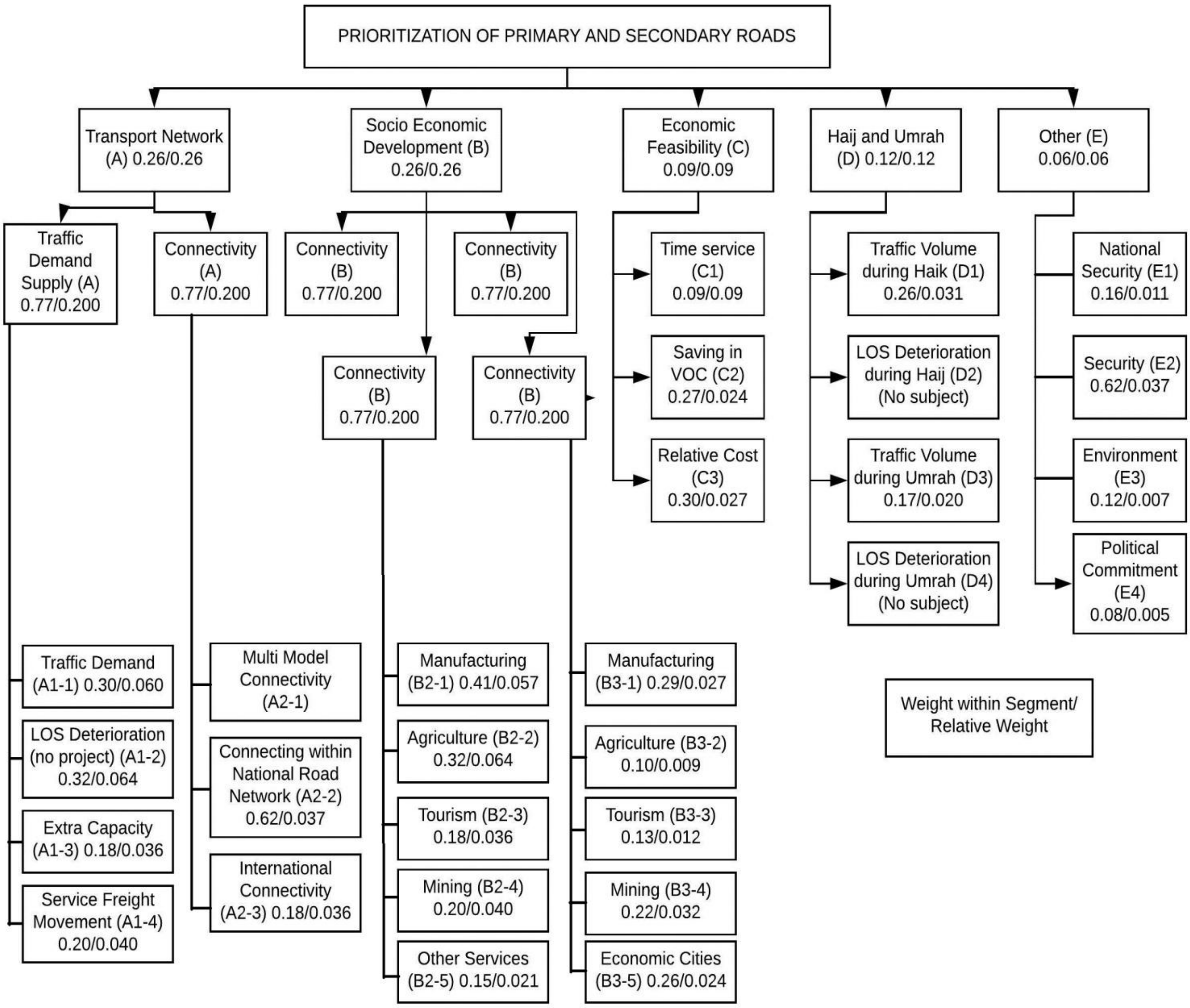


Figure 2.1 Hierarchy for Set of Criteria for Prioritization Model

Shah et al. (2013) [249] proposed an "overall pavement condition index (OPCI)" in order to prioritize the urban road network of Noida City with study conducted on 29.92 km of road length. Field data collection was done including "pavement inventory data, functional evaluation of pavement, structural evaluation of pavement, and measuring various thickness of pavement". Individual – "pavement condition distress index, roughness index, skid resistance index and structural capacity index" had been determined and at last, a combined final "overall pavement condition index (OPCI)" was developed which assumed to be a good indicator of a road condition and has been used to prioritize the maintenance strategies.

Prakasan et al. (2015) [216] used AHP (Analytical Hierarchy Process) to prioritize the urban road maintenance strategies by developing a priority ranking model. The developed priority ranking model was compared with direct assessment method (DA). The attributes used to develop the questionnaire included: PSR, Road Class, Riding Quality, Safety conditions, Traffic Volume, Drainage conditions, Structural adequacy and importance to community. The experts were asked to rate the importance based on Saaty's scale of 1 to 9 and based on the results weightage had been determined and assigned to individual parameters to develop the Priority Ranking Model.

Tawalare and Raju (2016) [267] developed pavement performance index (PPI) for Indian rural road network. Various pavement parameters have been considered such as longitudinal unevenness, transverse unevenness, skid resistance texture, bearing capacity, potholes, ravelling, rutting, alligator cracking, transverse cracking, block cracking, bleeding, patching, carriageway width, drainage characteristics, land use, roughness survey, vehicle damage factor, edge break, camber, condition of shoulders etc and expert opinions suggestions were incorporated to select or reject a parameter for rural roads specifically. Rating and weightage has been assigned based on the visual inspection and AHP process respectively to the selected pavement parameters and a final formula (2.51) has been suggested to determine the Pavement Performance Index ranging between 0-5 with "0" indicates the bad road condition and "5" indicates the best road condition.

$$PPI = \sum(R_i * W_i) \tag{2.51}$$

Where, PPI = pavement performance index, R_i = rating of each parameter by visual inspection and W_i = weightage determined using AHP for each pavement parameter

Pavement condition rating uses evidential reasoning theory based on pavement distresses. The original pavement condition for further assessment was represented by a "belief value" which was determined by using "Dempster–Shafer theory of evidence" **[12]**.

2.6.3 Prioritization based on Economic Analysis

Livneh and Craus (1990) [158] suggested an economic-based model for prioritizing the maintenance of pavement sections. The model had a following mathematical form equation (2.52):

$$P\% = k \times SN^{3.72} \times (5 - PSI) \times (\frac{AADT}{1000}) \tag{2.52}$$

Where P% = the first year rate of return, SN = structural number = 5-0.04DR, where DR is a distress grade (0-100), PSI = serviceability grade (0-5), AADT = annual average daily traffic, and k = numeric constant.

Three techniques for priority setting were compared. The first method was a simple ranking depending on four ranking measures like least life cycle cost, worst condition first, maximum traffic and maximum benefit/cost ratio. The second method was a collective ranking method based on relative weights given to the above mentioned four ranking parameters. Finally, the third method was optimization using linear programming which considered both times (present and future) and space (entire network). The results revealed a substantial variation in future network performance under the three methods with the optimization method produced the best results **[251]**. A prioritizing tool used to prioritize the maintenance strategies for pavements using the functional parameters and structural parameters of the pavements. The economic evaluation method was used to determine the "benefit/cost ratio and net present value" **[284]**. The pavement sections indicated with higher value of Benefit/Cost Ration or Net Present Value, was considered at first rank and given top priority for its maintenance.

Roy et al. (2003) [238] evaluate the uses of HDM-4 as a versatile tool to study the economic viability of alternative road projects and to prepare road investment programmes for the selected sections of state highways of Kerala. The M&R strategies were selected for sections based on IRR and B/C values.

The yearly M&R works for the National Highway was prioritized based on the decreasing NPV/Cost ratio. The "Project Analysis" component of HDM-4 software has been used for doing analysis and computing of NPV/cost ratio for different pavement sections of NH, under study **[17]**. A section with "higher NPV/Cost ratio" has been considered first for the maintenance. HDM-4 software was used for prioritizing maintenance of road sections, under different budget scenarios. The NPV/Cost ratios were determined for all candidate sections and were prioritized accordingly **[258]**.

2.7 Studies on GIS Applications to PMMS

The amalgamation of "Geographical Information System (GIS) technique with PMMS" helps in effective PMMS. Pavement Maintenance Management System includes identification of road network, data collection, prioritizing M&R strategies, and follow-ups. On the other hand, GIS includes data entry, developing important maps and a final decision. Various Indian and Abroad case studies based on GIS integrated PMMS have been presented.

2.7.1 GIS and PMMS Integration – Indian Case Studies

Yoagentharan et al. (2002) [295] illustrated the selection of strategies for improvement integrated with GIS for Chennai city roads. The study identifies the important links requiring immediate attention and proposed the improvements for the critical links. It also proposed the road condition database for the roads of Chennai City using Geographic Information System. The Arc/Info application of GIS software was used for database creation.

Jain et al. (2003) [129] developed a PMS system incorporated in GIS for a total road network of 360 km situated in New Delhi, under the supervision of PWD and MCD. The road condition data was collected after conducting various pavement surveys. The GIS software that was developed shows maps which clearly indicates the condition of pavement, road roughness, axle load and traffic etc. The M&R strategies for ten years for the selected road network were suggested and presented graphically on the maps.

Aggarwal (2003) [16] and Parida et al. (2005) [207] attempted to develop PMS for the National Highway Network by combining the network level pavement management system with the "Arc View GIS" which is commercially available in the markets. The different process of GIS integration involves: (i) "Creation of spatial map" (ii) "Attaching the attribute data to spatial map" (iii) "Locating basic data of a pavement section" (iv) "Query analysis" (v) "Viewing pavement condition of selected section".

Niju (2006) [200] aimed to develop a "GIS based PMMS (GPMMS)" in which the management system was capable of providing adequzte data and knowledge about the rehabilitation and maintenance strategies, and economical construction process. It has enlightened the pavement design process by incorporating the current traffic and predicted future traffic, predicted deteriorations, in a durable manner. The conceptual approach as shown in Figure 2.2 was used to develop GPMMS. An illustrated example using "GPMMS analysis" was presented for the Calicut district.

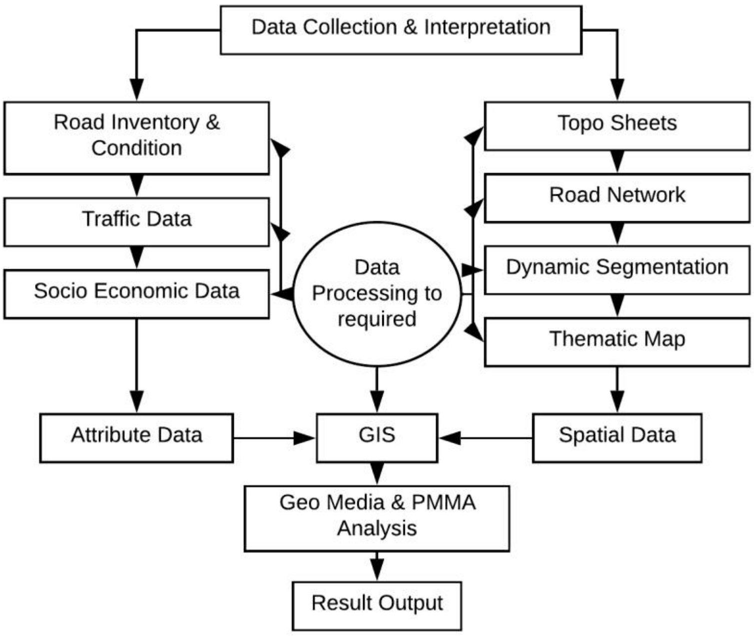


Figure 2.2 Conceptual Representation of PMMS

Pratap et al. (2006) [218] utilizes Arc Info software which works in GIS environment to develop the Pavement management System using pavement condition data. The evaluation of selected pavement section was done in two manners. The first one was done on the basis of PSI calculation and the other one was on the basis of simple visual surveys and measuring rut depths. This data and calculations were then stored in the GIS database. The optimum M&R suggested were displayed graphically using Arc Info software.

Rao et al. (2006) [225] presented the GIS based Maintenance Management System (GMMS) for main roads of Delhi. The entire GMMS was planned into two main divisions of a GIS based system which are the Spatial and Non-Spatial data (Figure 2.3).

The collected pavement condition data were added to road network map of Delhi, which was made in GIS platform. The recommendation for M&R of pavement network for design period of 10 years were planned with options for flexible overlay in two stages and cement concrete overlay in a single stage. The two stage maintenance alternatives with their respective years of application were graphically indicated on the separate maps.

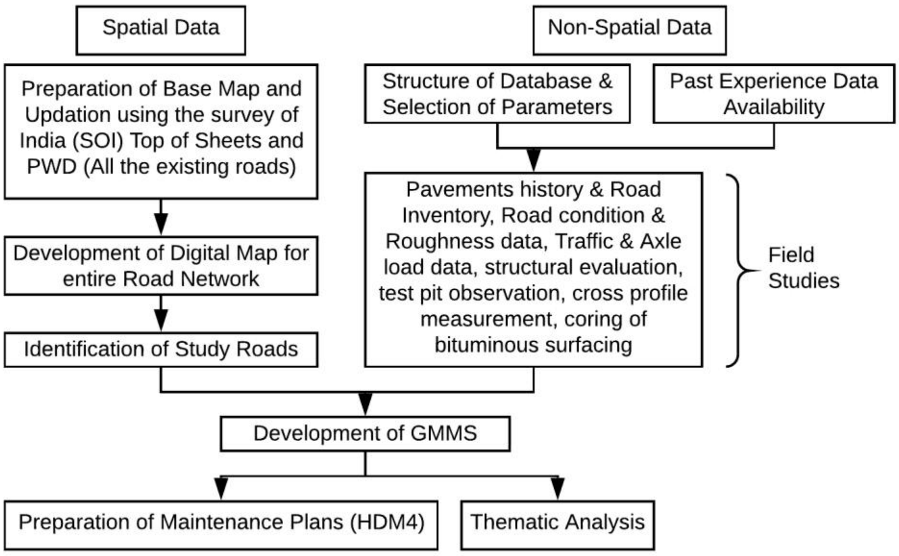


Figure 2.3 Flow Chart for Development of Maintenance Management System

Rao et al. (2007) [226] developed a Pavement Management System based on GPS and GIS using the concept of "Total Integration" approach. As a first step, detailed road network of IIT Bombay campus was incorporated in "GIS software Trans CAD" and further transferred to the GPS Palmtop using software "GIS pathfinder". Using the GPS palmtop, road condition data dictionary was prepared. A spatial data dictionary for line features, such as roadway networks, route numbers, number lanes, type of terrain, road width, etc. was also prepared. So, prepared dictionaries were attached as an attributes to the digitized map in GIS software. User friendly strip charts were prepared and maintenance requirements have been found based on "Priority Index" (PI), which depends on "Pavement Distress Index" and "present traffic".

Balkrishnan (2009) [32] represented a "Road Information and Maintenance Management System" for the region of Ooty, Tamil Nadu. The study area covers about 24km of road stretch. The entire database was created using Arc View 3.2 GIS Software. The IRS 1C (LISS III) satellite data was used for land use and land cover mapping. Attributes of road & cross drainage (CD) works were prepared through various ways such as maps, reports, total station and GPS surveys. A Relational Database (RDBMS) was developed from above details for the entire road network. The prepared database was then used to get outputs in form of reports and maps for the queries fed into the system for taking decisions related to maintenance works.

2.7.2 GIS and PMMS Integration- Abroad Case Studies

Abkowitz et al. (1990) [10] presented many parameters i.e. (i) “highway management applications that can benefit from adaptation to GIS” (ii) “key GIS concepts affecting highway transportation” and (iii) “issues affecting GIS design and implementation within and between highway agencies”. GIS applications in different sectors viz. “pavement management, traffic engineering, planning and research, bridge maintenance and field office support” was explained in brief. A brief outline of Geographic Information System, GIS element which is applicable to the transportation division (GIS-T) was described.

Osman and Hayashi (1994) [203] coupled a highway PMS with GIS for a study area in Japan and studied the different applications of such a system. Output representing various analysis stages and methods related to maintenance decisions were presented.

Lee et al. (1996) [152] described a “GIS based PMS (G-PMS)” for the City of Salt Lake, Utah. G-PMS was developed using programming language i.e. MapInfo and Map-Basic. G-PMS improved decision-making strategies and the software database in City of Salt Lake.

Rio et al. (1997) [235] explained the methodology used in the production of a GIS using Arc/CAD, for the management of 20000 km of highways in Spain. The pavement evaluation data was collected with a multifunction device called a vedio-laser road surface tester (RST). A base map for road network was prepared and 6 different maps generated from the results were presented and a final detailed map of mean results of all different parameters.

Al-Swailmi and Al-Mulhem (1998) [21] combined the PMS database with GIS for the Riyadh City, Saudi Arabia. The technical aspects of displaying the results of database queries are analysis report and viewing the pavement conditions through multi-lane dynamic segmentation and colour-coded system.

Medina et al. (1999) [167] described a prototype developed for low-volume roads PMS using a GIS platform for Fountain Hills, Arizona. The Road Surface Management System (RSMS) was used for PMS portion developed at Arizona State University and MapInfo package of GIS was used to link the PMS. The RSMS software had two module which are information management module and analysis module. The RSMS software was run in menu driven MapInfo application and the pavement M&R program was imported and displayed through coloured maps.

Ferreira (2001) [76] developed “SIGPAV a GIS based PMS” for the main road network of Coimbra (254 segments), the third-largest Portuguese city. The maintenance strategies executed as analysed through SIGPAV were detailed on the maps created in GIS. The system consisted of three basic modules viz. Road Network Database, Quality Evaluation Tool and Decision-Aid Tool.

Zhang et al. (2001) [302] utilizes a “three-stage implementation” notion to develop the management system of pavements in the “Texas Department of Transportation” (TxDOT). The three stages included assessment of current status, intermediate solution and ideal stage.

Tsai and Gratton (2004) [275] improved a total length of 28,962 km road network by implementing GIS based PMS that was initially devised by “Georgia Department of Transportation” (GDOT). The system so developed was capable of integrating data, determining the priority & scheduling the projects to be surveyed, monitoring the progress of field surveys for each district and identifying the projects with unusual pavement conditions that require reconfirmation.

Abo-Hashema et al. (2006) [11] combined the concept of Geographic Information System and Pavement Maintenance Management System through the current maintenance project of Al Ain City, Abu Dhabi. The general workflow of the PMMS project and the GIS workflow are represented in Figure 2.4 & Figure 2.5 respectively. The distress maps, thematic maps showing the prioritized list, etc. were presented graphically on the maps using GIS.

El-Mowafy et al. (2008) [73] improved the effectiveness of pavement maintenance decision-support system by combining it with GIS/GPS in the road network of Abu Dhabi Island. The road network maps indicating location of various distresses and emergency failures locations (e.g. potholes, depressions, etc.) were developed using GIS which facilitated distress analysis and pavement condition evaluation.

Elhadi, A.H.M. (2009) [71] performed two tests viz. determining the “International Roughness Index” IRI to assess the riding quality of the pavement and determination of rebound deflection using non-destructive “Falling Weight Deflectometer”, FWD to assess the structural adequacy of the selected pavement sections. The results which were analysed from the two tests conducted had been used to develop Pavement Management System using GIS technology. Geographic Information System analyses more accurate results through visualization technique.

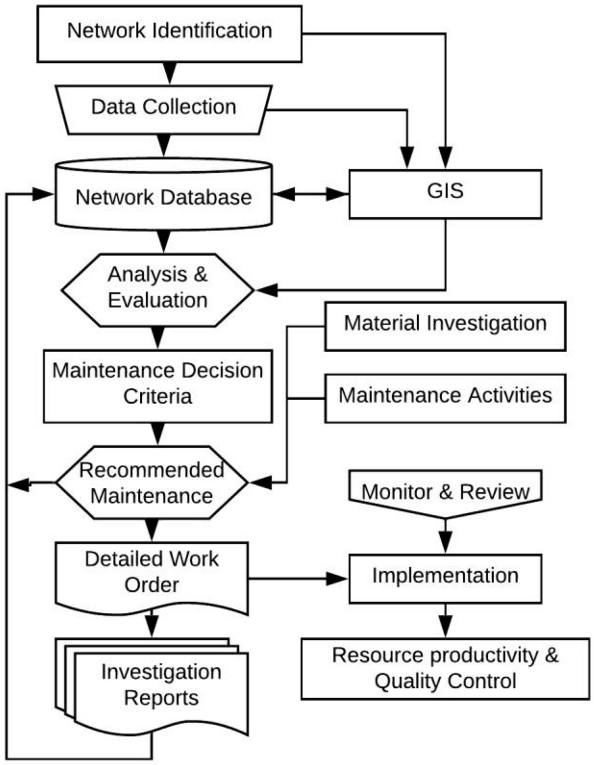


Figure 2.4 General Workflow of GIS/GPS Integration for PMMS

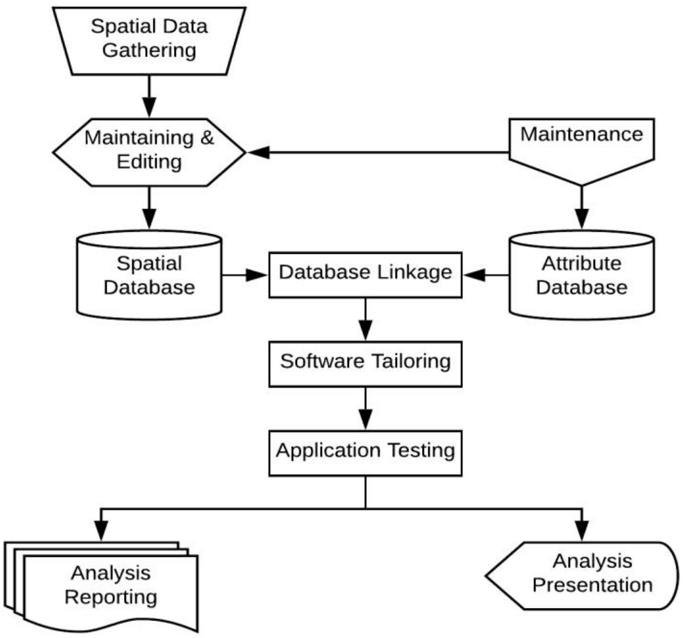


Figure 2.5 General Workflow of GPS Integration for GIS

Pantha et al. (2010) [205] considered pavement and roadside slope stability conditions of major link and developed the GIS based maintenance model for capital city of Kathmandu, Nepal. Three GIS based maps were prepared viz. pavement maintenance priority map showing pavement condition, priority map for prioritizing the stability of the slope condition of roadside, and finally, a combination of previous two i.e. pavement prioritizing map and prioritization map of roadside slope.

Xie and Li (2010) [294], Xie, F. (2010) [293] introduced the use of WebGIS in order to maintain the highways. The designed system linked various pavement or roadway geographic parameters using dynamic segmentation technology. The model processed the road condition data and predicted the future condition. The establishment of this system enhanced the efficiency of highway maintenance strategies in order to eradicate the contradiction between fast development of roadways/highways and their maintenance requirements.

Zhou (2010) [303] explored the application of data mining and knowledge discovery (DMKD) integrated with GIS techniques and pavement management. It was developed to prioritize the maintenance priorities, applying best rehabilitation activities and predicting decisions for money investment. The decisions making process for M&R is based on data mining included five steps viz. problem identification, knowledge acquisition, knowledge representation, implementation and validation.

Ibraheem and Falih (2012) [119] developed a Pavement Maintenance Management System based on GIS for the 23 pavement stretches/sections of "Nahrain University, Iraq". The M&R strategies were implemented based on the Pavement Serviceability Index, which was used as indicator of pavement performance for each selected section of pavement. Using GIS interface, many thematic maps were generated to make the maintenance decision module more effective and easy.

2.8 Road User Cost Studies (RUCS)

In order to execute any road project, it is very necessary to conduct the benefit and cost analysis of the concerned road project. The benefit and cost analysis is further required in order to rank or prioritize the various road projects for its implementation. Various researchers have their contribution in India to develop the relationships between the RUC "Road User Cost" and the geometric design parameters.

2.8.1 RUCS Studies

"Ministry of Surface Transport" (MOST), Government of India, initiated the first project related to RUCS in the year 1982 and sponsored it to the "Central Road research Institute" (CRRI) (**CRRI 1982**) [61]. Under this study, a large sample of vehicle which includes commercial vehicles and private vehicles were surveyed and the data pertaining to vehicle operating cost was collected including the geometric design features of the roads on which the surveyed vehicles were plying. The mathematical models or relationships were proposed between the geometric design parameters and VOC after analysing the collected data. As the new types and new axle configuration of vehicles entered in India, hence the study was further updated in the year 1992 (**Kadiyali 1992, 1993**) [136, 137].

Hence, in continuation to the above study, a further study was conducted to update the models or relationships between RUC and geometric design parameters by CRRI "Central Road Research Institute" sponsored by "Ministry of Road Transport & Highways", Government of India, in order to incorporate the new models of passenger car models which then recently introduced to Indian markets. In the study which was concluded in 2001, the speed measurements were also incorporated to develop relationships for vehicle operating cost (**CRRI 2001, Reddy 2003**) [64, 234].

2.8.2 Road Development and Maintenance Investment Decision Model

The "Updated Road User Cost Study" (URUCS) and the "Pavement Performance Study" (PPS) done on the pavements of Indian conditions introduced extensive research backup and various relationships to propose a "Total Transportation Cost Model". The "Road Development and Maintenance Investment Decision Model" was assumed to be a refinement model as compared to other highway economic evaluation methods. The developed and updated model helped the highway agencies to predict better accuracy of economic analysis of highways for Indian conditions, which incorporated pavement deterioration models and updated vehicle operating cost. The main drawback of developed model was that it can only be applied to the project level (**Sharma and Pandey 1997**) [254].

2.9 PMMS Studies on Urban and Rural Roads

2.9.1 Studies done in India

Traffic studies and pavement condition surveys on the roads at different areas of New Delhi to propose a Pavement Management System for such urban roads was conducted **[227, 132]**.

The proposed Pavement Management System was capable of determininng appropriate maintenance rehabilitation strategies, analyzing life cycle cost of the roads, and utilizes the software HDM-III for prioritizing the roads maintenance. The economic analysis method i.e. “Net Present Worth” method was used to prioritize the road sections maintenance. The road section having high Net Present Worth value was selected for prioritization and maintenance.

Yoagentharan et al. (2002) [295] applied the spatial analytical hierarchy process (AHP) method (integrating the GIS database with AHP) for selecting the critical link for improvement for urban streets of Chennai city. The Composite Index (CI) for each road was estimated using equation 2.53, by adding all the relative weightings (RIW) at every level of the hierarchy.

$$CI = 5.5R_{i1} + 1.89R_{i2} + 1.57R_{i3} + 0.68R_{i4} + 0.35R_{i5} \qquad (2.53)$$

Where, R_{i1-5} = “standard value for j^{th} parameter for route i”, i = “selected routes from 1 to n”. And the critical links is determined depending on the index value in such a way that link will be more critical if the index value is less and a suitable improvement is suggested. **Naidu et al. (2005) [183]** attempted and draw an effort to optimize the M&R strategies and proposed “Pavement Maintenance Management System” (PMMS) for Delhi Roads (Inner Ring Road) by using HDM-4 based on life cycle cost analysis. The Road Network considered for the study includes a total length of 96 kms in both directions with dual three lane carriageway of the major arterial inner ring road of Delhi. HDM-4 components viz. “Project analysis and programme analysis” components of HDM-4 were used for developing Pavement Maintenance Management System.

Prakash et al. (2009) [217] used HDM-4 to propose a “Maintenance Management System” (MMS) for the Patna City area which lies under urban road network. MMS included various components like analyzing appropriate maintenance strategy, RSL of each pavement stretch, life-cycle cost analysis for both M&R and Drainage Work, and an unconstrained works program. Special consideration on drainage condition was given in the analysis by developing a scale to assign type of drainage work based on drainage quality corresponding to their adopted drainage factors.

2.9.2 Studies done in Abroad

Curtayne and Scullion (1981) [67] focused about the implementation of an Urban PMS in the city of Johannesburg. The system was capable of giving three computer outputs viz. (i) assessment of maintenance requirements- type of treatment, urgency of priority treatment, amount of work in terms of area and cost, opinion of the inspector (ii) Summary of maintenance requirements- amount (cost) of various types of maintenance treatment for each priority level, (iii) Recommended Inspection Schedule

Sheppard and Blank (1983) [255] described the design, development and use of "Street Inventory and Management System" (SIMS) for City of San Antonio, Texas and for the County of Bexar. The software was implemented using Statistical Analysis System (SAS) which performs tasks which includes process of data collection, rectification or checking the collected data for any error, updating and processing of collected data, and exporting the prepared data reports.

Tavakoli et al. (1992) [266] presented the details of PMS for Small Communities (PMSC). The methodology integrated the main activities like pavement inventory, pavement condition rating, and selection of annual M&R strategies, determining the requirements of all sections, realize the standard needs, and developing the needs of budget for the requisite measures. The various tabular reports including (i) indicating pavement sections by numbers or their names, (ii) inventory data collection by section name or number, (iii) the section requirements for first year determined by sorting through priority index, (iv) Predicted strategies or planning, and (v) predicted costs have been generated.

Chen at al. (1993) [54] explained an implementation of graphical urban roadway management system (URMS). URMS functions in graphic system and was well described and presented by its easiness, user-friendly and handy ability. Analysis include, pavement condition index derived from seven types of distress, and various pavement condition indexes which includes the age of pavement, average mixed daily traffic and truck traffic. The arrangement of Maintenance and Rehabilitation strategy to each and every section was done by means of a decision tress. The project prioritization was achieved by adopting a method of amalgamation of dual matrix and an equation. The system and its various functions were validated with the data collected from Austin, Texas.

Zhang et al. (1993a) [300] explained the necessity for efficient pavement management and other infrastructure in the urban cities and detailed the efforts to apply GIS for the same. Under this study, some issues related to develop an implementable GIS application were considered and a user friendly GIS-URMS program was developed.

Battiato et al. (1994) [35] conducted a study and implemented the PMS for the main urban roads in the municipality of Padua, Italy. The test included over 40 km of roads, most of it around the centre of Padua, and they were subjected to heavy traffic volume. The pavement evaluation was done using FWD, Laser profilometer and SCRIM. Various deterioration models were developed. The sections were prioritized based on average condition of the homogenous pavement sections and also for pavement sections based on considerations and a cost benefit ratio analysis.

Chen et al. (1994) [53] described the second part of URMS which is the project-level pavement design and maintenance subsystems. A linear programming model was developed for selecting the cost-effective distress repair methods. Each distress type was related to a maximum of three variables viz. Severity, density and traffic where each variable has maximum another three levels viz. Low, medium and high or light and heavy. The advantage of this system was that it was simplified expert system which can be applied for pavement routine maintenance without any coding.

Sohail and Hudson (1996) [261] discussed about the next part of URMS which is the network-level implementation for two cities of Texas viz. Lampasas and Terrell. The paper documents the implementation of URMS in Lampasas only. A road network of 114 km was considered in city of Lampasas which was divided into 428 sections for evaluation module of URMS. Priority index model was prepared based on PCI and ADT. Maintenance programme summary was given for both M&R needs and M&R requirements for next 5 years for all sections.

Scazziga and Meyer (1998) [247] implemented the Pavement Management System (PMS) adjusted for the urban conditions of city Schaffhausen, situated at north end of Switzerland. The maintenance budget was allocated in an appropriate manner using proposed Pavement Management System. **Jiaqi et al. (2005) [134]** used the technique in which data was collected using mobile which includes PDA and GPS data of the region and developed an "Urban Pavement Management System" (UPMS) for Nanjing, China. The Pavement Management System was also combined with Geographic Information System.

"Transportation Infrastructure Maintenance Management System" (TIMMS) which includes footpaths, railway crossing, street lighting, guardrails, traffic signals, road markings, drainage arrangements of the pavement, etc. for an urban city Uintah, Utah was developed **[60]**. The inadequacy of finance budget and time resources were correlated to the acute scarcity of manpower during the development of TIMMS. The scarcity of manpower requirement required to be maximized. The main objective of the study was to minimize the complaints of residents and maximize the maintenance of infrastructure.

To assess the effects of pavement maintenance treatments applied using low cost instruments to the low volume roads, a case study had been conducted on Roads of Colorado using previous pavement database from Colorado Department of transportation (CDOT) **[101]**. It has been found that some pavement treatments like fatigue cracking, longitudinal and transverse cracking were most effective treatments.

2.10 Summary of Literature Review

This chapter incorporates a detailed literature review with regards to the functional evaluation and structural evaluation of pavements. It explains the research work carried out by various researchers in the field of pavement evaluation in context of the various parameters affecting pavement roughness, pavement performance prediction models such as pavement deflection prediction model, pavement roughness prediction model. It also includes the indexes developed by researchers which emphasises on pavement maintenance prioritization. In various countries, the PMS (Pavement Management Systems) is accompanied by various HDM-4 and AASHTO models developed by highway organizations. Various researchers developed and proposed ANN (Artificial Neural Network), Fuzzy Logic, Regression models in areas of pavement engineering, along with the use of computer softwares like ANSYS, HDM-4, IITPAVE, KGPBACK etc. An ample work has also been reported related to the progression models or deterioration models corresponding to various pavement distresses, however, it has been observed that further studies are required for effective and accurate results. The roughness index plays a very important role in determining condition of pavement for which various roughness prediction models have been generated and compared. The deflection studies of pavement especially in hilly terrain shows that it is difficult to conduct Benkelman beam studies due to narrow roads and frequent traffic. Hence, an alternative is required to determine the structural adequacy of rural roads in hilly terrain. After a critical review of all the published research papers, it can be concluded that limited work has been done for rural roads of hilly terrain and for their pavement management systems.

CHAPTER 3

FIELD DATA COLLECTION AND METHODOLOGY

3.1 General

In this chapter, the methodology for field data collection with respect to achieve the objectives of present study has been presented which are strictly adhered with the standard procedures and codes recommended by IRC and other highway agencies. The field data has been collected in order to develop various models which would help in the maintenance of rural road network in hilly terrain. The field data has been collected based on the functional parameters which are predominantly prevailing on the rural road sections of hilly terrain in the state of Himachal Pradesh. The functional parameter which has been evaluated includes-road roughness, pavement distresses such as cracking, ravelling, potholes, patching, rutting and mean texture depth with respective severity levels of low, medium and high. Skid Resistance which indicates the resisting power of pavement surface against friction has also been computed using Skid Resistance Portable Pendulum Tester.

It also includes the standard procedure followed to conduct the Benkelman Beam Deflections which represents the structural behaviour of the pavement. In order to implement corrections in the Benkelman Beam Deflection values, the data pertaining to pavement temperature, type of subgrade soil, plasticity index of soil, moisture content of subgrade soil and annual rainfall data has also been collected in the present study.

The California Bearing Ratio (CBR) test has also been conducted indicating both soaked CBR and unsoaked CBR on the subgrade soil samples taken from the selected rural road sections of hilly terrain. The K-value i.e. Modulus of subgrade reaction has been determined using the correlation chart given between soaked CBR and K-value in IRC: 58-2015 [122].

The classified traffic volume survey has been conducted manually for both lean season and peak season of the hilly region and Average Annual Daily Traffic has been determined using standard code of IRC: SP:72-2015 [125].

3.2 Selection of Road Sections

In the present study, 12 rural roads stretches in hilly region of Himachal Pradesh, India each of 2.5 km length and average width of 3 metre has been selected as shown in Table 3-1 for collecting the pavement distress data, pavement roughness data and pavement structural data. The 12 rural road sections of hilly region have been selected in the vicinity of Shimla and Solan Districts of Himachal Pradesh, India. Each section (as shown in Fig. 3.1 and Fig. 3.2) has been chosen in such a way that it represents as a whole length of the stretch in terms of traffic and climatic conditions. The width of each selected rural road stretch is 3.5 metre. The field data has been collected in terms of Pavement Inventory, Functional condition of roads, Structural condition of roads, CBR of roads, K-value and classified traffic volume of selected rural road sections is presented in the below sections. A summary of all data parameters; equipment used; number of data points collected and procedure followed has been given in Table 3-3.

Table 3-1 Selected Rural Road Stretches

Road ID	Road Name	Road ID	Road Name
RR-1	Domehar-Waknaghat Road	RR-7	Shoghi-Heon Road
RR-2	Salogra-Ashwini Khad Road	RR-8	Shoghi-JaogRoad
RR-3	Kyari Bangla-Dera Road	RR-9	Kandaghat-Kot Road
RR-4	Basha Road	RR-10	Chail Road
RR-5	Khawara Chowki-Mashru Road	RR-11	Nain Basal Road
RR-6	Shoghi-Dooh Road	RR-12	Solan-Malaun Road

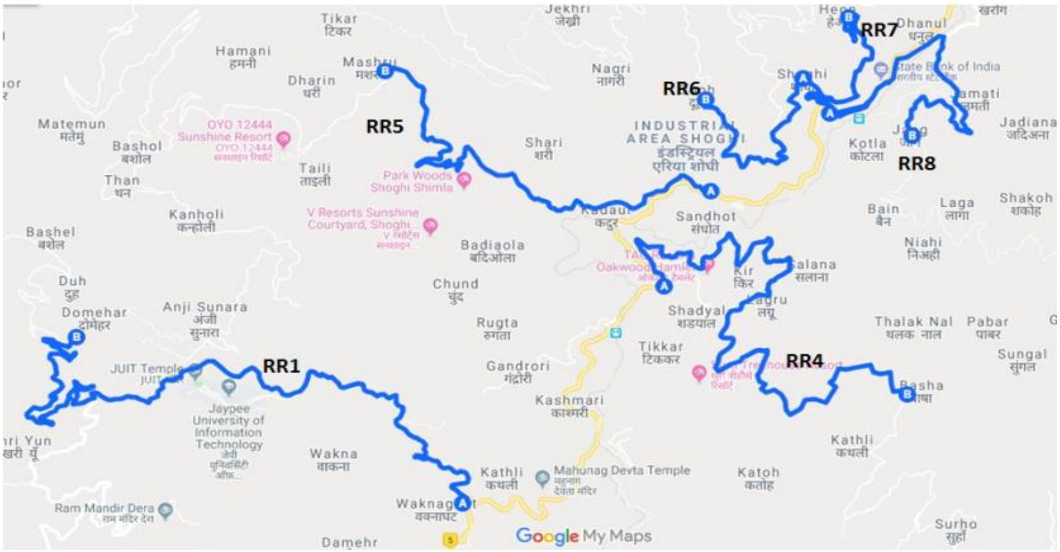


Figure 3.1 Selected Rural Road Stretches (Ref: Google Map)

Figure 3.2 Selected Rural Road Stretches (Ref: Google Map)

3.3 Pavement Inventory Data

Pavement inventory details include Name of the road, Category of the road viz. rural road, NH or SH, number of lanes, carriageway width of the road, surface type, maintenance and construction history of the roads, given in Table 3-2.

Table 3-2 Pavement Inventory Data of selected Rural Road Sections

Rural Road ID	Name of Road	Category of Road	Number of Lanes	Carriageway Width	Surface Type	Age of pavement from last overlay in years
RR1	Domehar-Waknaghat Road	Rural	One	3.5 metre	Premix Carpet	7
RR2	Salogra-Ashwini Khad Road	Rural	One	3.5 metre	Premix Carpet	5
RR3	Kyari Bangla-Dera Road	Rural	One	3.5 metre	Premix Carpet	7
RR4	Basha Road	Rural	One	3.5 metre	Premix Carpet	6
RR5	Khawara Chowki-Mashru Road	Rural	One	3.5 metre	Premix Carpet	6
RR6	Shoghi-Dooh Road	Rural	One	3.5 metre	Premix Carpet	7
RR7	Shoghi-Heon Road	Rural	One	3.5 metre	Premix Carpet	5

RR8	Shoghi-JaogRoad	Rural	One	3.5 metre	Premix Carpet	6
RR9	Kandaghat-Kot Road	Rural	One	3.5 metre	Premix Carpet	7
RR10	Chail Road	Rural	One	3.5 metre	Premix Carpet	7
RR11	Nain Basal Road	Rural	One	3.5 metre	Premix Carpet	6
RR12	Solan-Malaun Road	Rural	One	3.5 metre	Premix Carpet	7

3.4 Functional Evaluation Data

The functional evaluation has been done on the selected 12 rural road sections which includes the collection of functional parameters of pavements i.e. pavement distresses (cracking, ravelling, potholes, patching, rutting) which are predominantly prevailing on the selected rural road sections in hilly region of Himachal Pradesh, pavement roughness in terms of IRI, Mean Texture Depth (MTD), Skid Resistance. All functional parameters data has been collected over a span of one year.

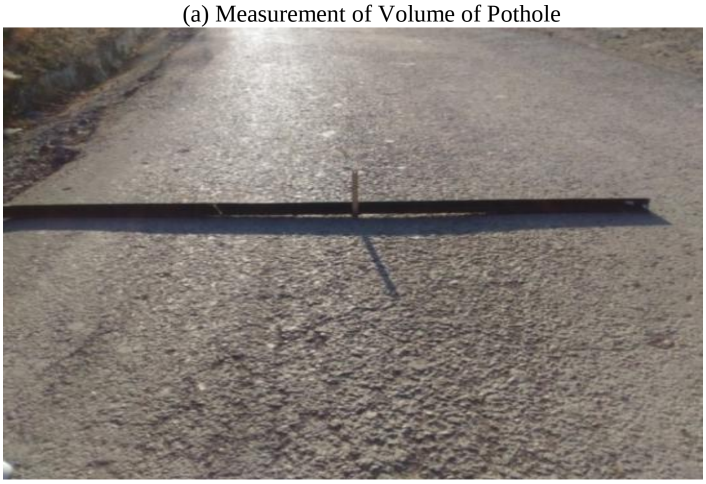
3.4.1 Pavement Distresses

The pavement distress data has been collected on the selected 12 rural road section of hilly terrain in Himachal Pradesh. The pavement distresses which are mostly prevailing in the region include- pavement cracking, ravelling, potholes, patching and rutting. The distresses like pavement cracking, ravelling and patching have been measured using simple measuring instruments such as tape and scale as shown in Fig 3.3, which in turn converted into percentages expressed as the total area of pavement surface. The cracking has been further recorded as longitudinal cracking, transverse cracking and alligator cracking with respective severity levels of low, medium and high.

Figure 3.3 Measurement of Ravelling, Patching and Cracking on selected Rural Road Sections

Potholes which resemble a bowl like pavement distress has been measured in terms of volume in the present study. Each pothole is filled with a known volume of sand as shown in Fig. 3.4 (a) and the average diameter of the pothole, average depth of the pothole has been measured in order to derive a correlation between the volume of pothole and its depth and diameter which is described in next chapter.

(a) Measurement of Volume of Pothole



(b) Measurement of Rutting using straight edge

Figure 3.4 Measuring Volume of Pothole and Rut Depth

Rutting which is the longitudinal displacement in the wheel path due to the wheel load has also been studied in the present study and the mean rut depth has been measured using 3 metre straight edge with the procedure followed as per IRC: 82-2015 [124] as shown in Fig. 3.4 (b). All the ruts present on the selected rural road sections in hilly region of Himachal Pradesh has been determined.

Table 3-3 Summary of Equipment used, data points collected and procedure followed for various pavement parameters

Parameter	**Equipment Used**	**Number of Data Points Collected**	**Procedure Followed**
Cracking	Simple measuring equipment	Length, Width and Area of All Cracked surface (with severity)	IRC-82:2015
Ravelling	Simple measuring equipment	All ravelled area (with severity)	IRC-82:2015
Patching	Simple measuring equipment	All patched area (with severity)	IRC-82:2015
Rutting	3 m Straight Edge	All rut depth data prevailing in 2.5 km section	IRC-82:2015
Potholes	Simple measuring equipment and sand replacement method to determine volume of pothole	All pothole data (with severity)	IRC-82:2015
Road Roughness	MERLIN	Four passes of MERLIN in each 500 m section	IRC-82:2015 & TRL MERLIN Report 229
Skid Resistance	Skid Resistance Pendulum Tester	Three Skid resistance values (wet & dry) at every 50 m interval	IRC-82:2015 & ASTM-274 [28]
Mean Texture Depth	Sand Patch Apparatus	Mean texture depth at every 50 m interval	BS 598 Part 105 & ASTM E 965
Pavement Deflection	Benkelman Beam	25 deflection points on each 2.5 km road section	IRC: 81-1997
CBR value	CBR Apparatus	Three samples from each road section	IRC: 36-2010 and IS2720
K-value	--	One value for each road using average CBR value	IRC: 58-2015
Traffic Volume	Manually	7 days traffic count	IRC:SP: 72-2015

3.4.2 Pavement Roughness

Pavement Roughness has been measured on all the selected rural road sections using TRL MERLIN (Fig 3.5). The Machine for Evaluating Roughness using Low-cost INstrumentation (MERLIN) is a road-roughness measuring apparatus that comes with the advantages of being simple to operate, robust, easy to fabricate, reasonably accurate, reliable and almost maintenance free (Fig 3.6). It was designed by the Transportation Research Laboratory (TRL) [65], UK, for providing a simple and low-cost method of calibration of roughness measuring equipments or for direct measurement of roughness of roads in developing countries (Cundill, 1996) [66].

Figure 3.5 MERLIN test conducted on RR-6

MERLIN Structure

It consists of a metal frame 1.8 m long with a wheel at the front and a probe mid-way resting on the road surface. The probe is attached to a moving arm which is weighted so that the probe moves downwards either till it touches the road surface or till the limit of the transverse of the arm is reached; the other end of the arm is a pointer that moves over a chart (Fig. 3.6). The machine is wheeled along the road and at regular intervals the position of the pointer is recorded on the chart [148]. The variability in displacements recorded on the chart will be more for rougher surfaces of the road. The displacements are plotted as a histogram, and it is found that the width of the histogram gives a good estimate of the roughness in terms of the IRI.

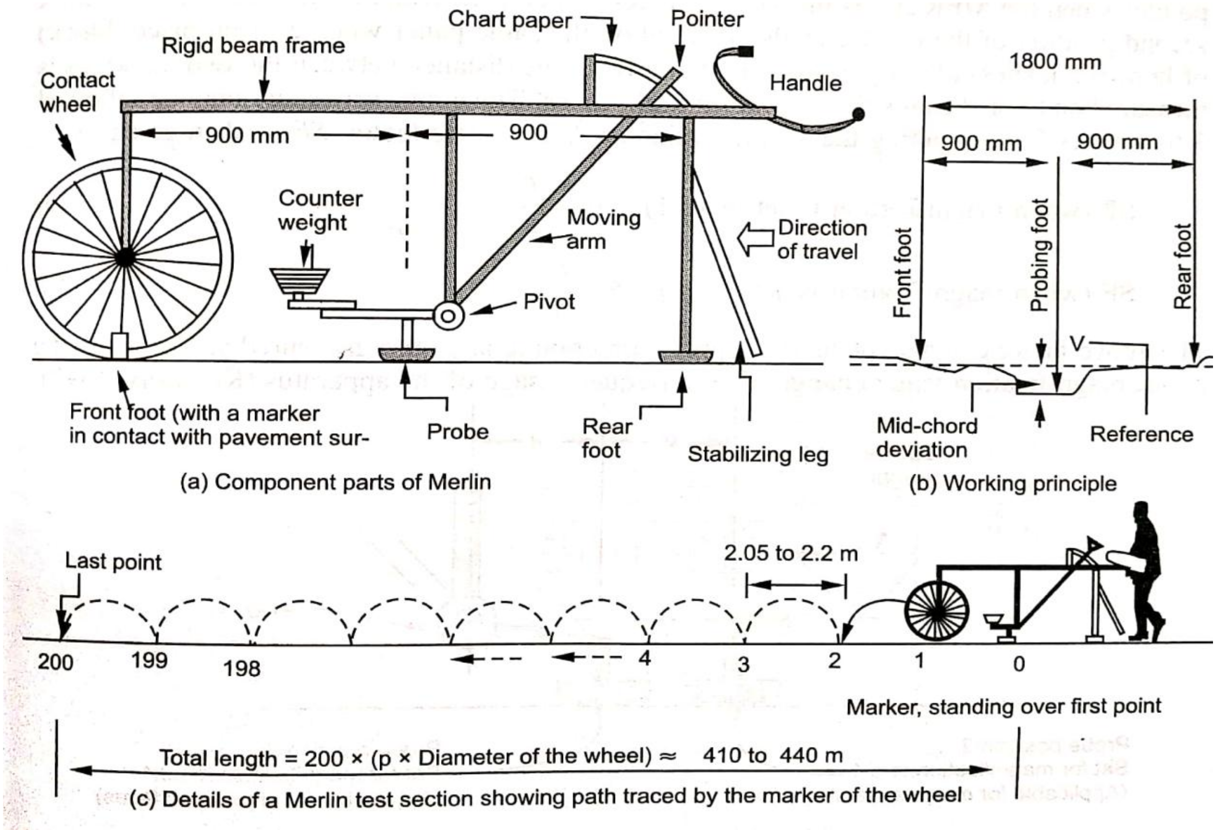


Figure 3.6 Schematic Diagram of TRL MERLIN

MERLIN Operation

The MERLIN is operated with any one of the position of the probe shown in Fig. 3.7. Probe position-1 is used on smooth surfaces where magnification of the reading is set to 10:1 and the probe position-2 is set to magnify the reading to 5:1, used for measuring on rough surfaces. The above sets of magnification may slightly change based on the exact position of the probe. Therefore, prior to use, a scale factor (SF) is determined by calibration to obtain the exact magnification value of the chart pointer.

The calibration procedure adopted for the position of the probe is simple. For a given position of the probe, initially, draw a mark on the chart paper to indicate the first position of pointer when the MERLIN is placed over very smooth flooring, such as an office floor. A second position of the pointer is also marked on the same paper when a metal piece or block of known thickness (T) is placed under the probe. The distance between the two markings is measured and noted as displacement S in mm. The same procedure may be followed 3 to 4 times for computing the average value of S. The scale factor SF, is given by equation 3.1 and 3.2-

SF (when magnification is set to 10:1) = 10 * (T/S) (3.1)

SF (when magnification is set to 5:1) = 5 * (T/S) (3.2)

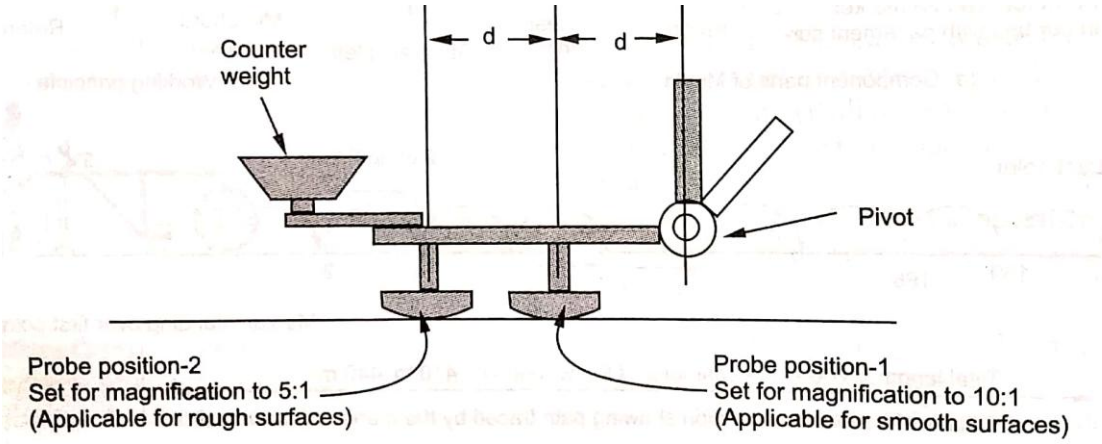


Figure 3.7 Different Positions of Probe set to magnify the readings of MERLIN

In addition to the calibration check, the following should be taken care of for the better results-

- Before recording each point of measurement, care should be taken to stop the wheel (front foot) exactly at its normal position.
- The wheel should be exactly circular with constant radius and without any bends on its rim.
- The roughness of the contact surfaces of the probe and rear foot should be checked for the TRL standard shape.

Field Measurement

The MERLIN is placed over the pavement surface while in standing position with the wheel marker touching the surface and its whole body resting over the probe, rear foot and stabilising leg. The wheel position with the wheel marker touching the surface is termed as normal position. The MERLIN is manually operated along the left and right wheel paths separately. A sample of the marked chart of the TRL-MERLIN for a section of RR-7 has been shown in Fig 3.8. A cross is marked on the chart paper as the position indicated by the pointer. Approximately two hundred such readings are taken and checked with the help of a tally box. The chart consists of grids of size 5 mm.

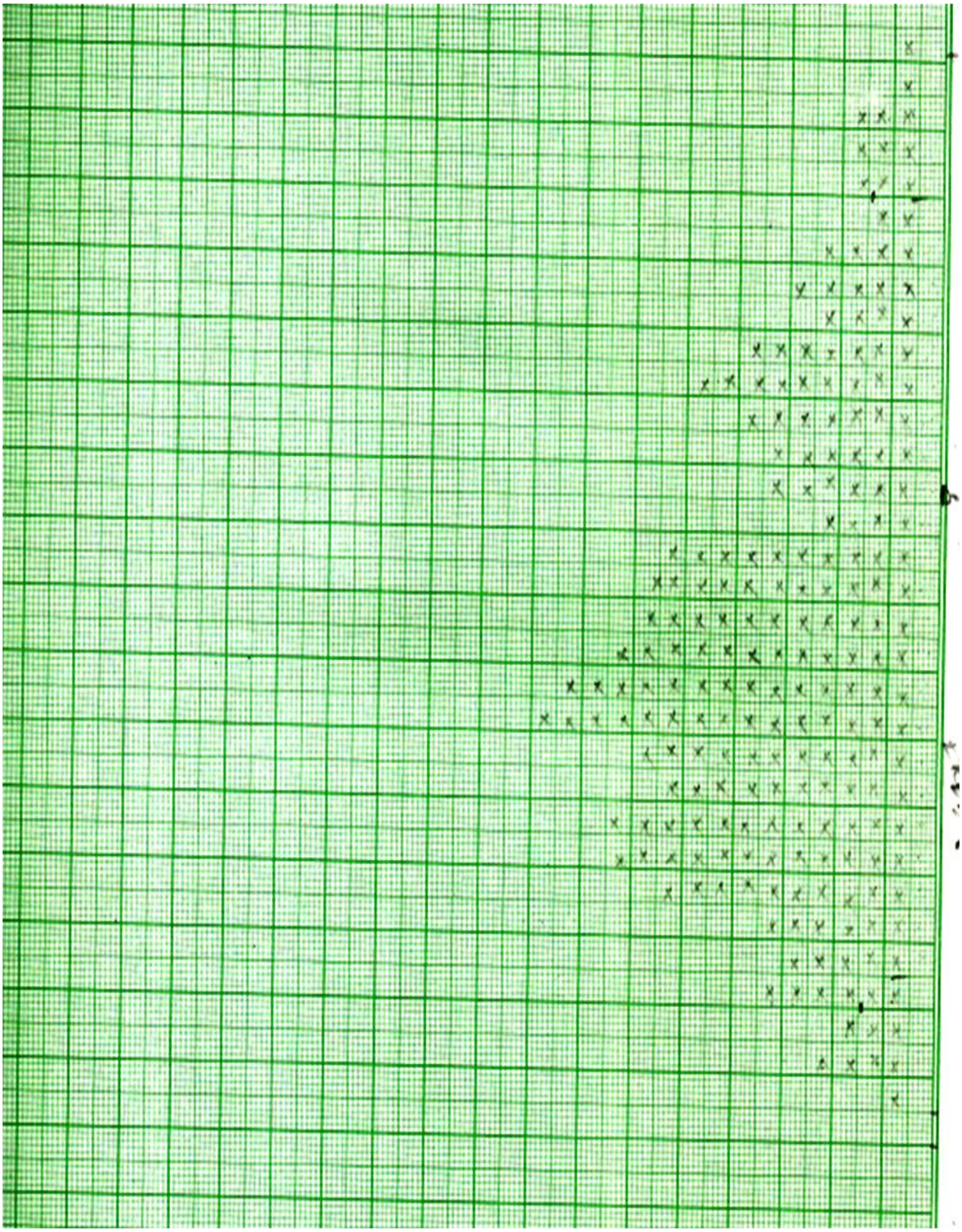


Figure 3.8 Sample Histogram Chart Prepared for a section of RR-7

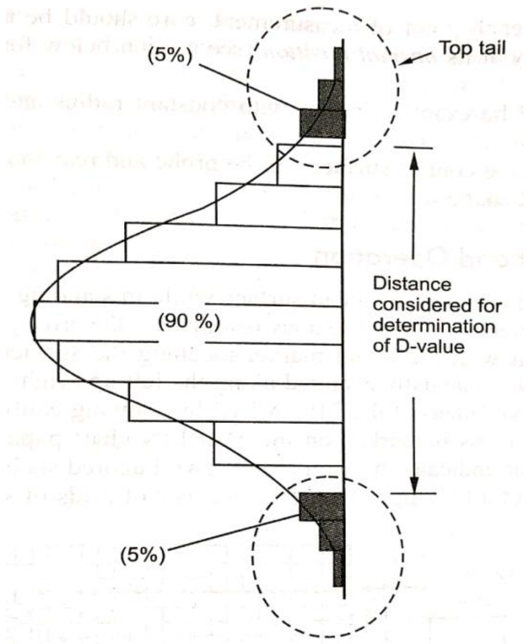


Figure 3.9 Normal Distribution Curve Resembling recorded chart of TRL MERLIN used for determination of D-value

Circle off 5% of the total number of markings at bottom and top tails of the histogram (Fig 3.9). The D value of the MERLIN roughness statistic is determined by multiplying the inner distance between the markings of the circle borders to SF. This exclusion of 5% of the markings on both tails of the MERLIN histogram resembles the 90% area enclosed by curve of the normal distribution (Fig 3.9). The IRI value has been determined from the D value using TRL recommended equation 3.3 (Cundill, 1991 and 1996) [65, 66].

$$IRI\ (in\ mm) = 0.593 + 0.0471 * D \tag{3.3}$$

Applicable Range: 42<D<312 or (2.4<IRI<15.9)

All the data corresponding to road roughness of selected 12 rural road sections of hilly region in Himachal Pradesh has been presented in Appendix A. It includes the IRI obtained at each MERLIN pass on the pavement section. Four passes of MERLIN were conducted at each section of 500 m and its average value is depicted as final IRI in m/km.

3.4.3 Mean Texture Depth (MTD)

The Mean Texture Depth has also been accounted in the current study which influences the road roughness at macro level corresponding to pavement surface aggregates characteristics such as flakiness, sharpness, irregularities etc. The Mean Texture Depth has been calculated using standard test method “Sand Patch Method” given in ASTM E965 [263] and BS 598 Part 105 [43] as shown in Fig 3.10.

Figure 3.10 Sample data point collected of Sand Patch Test on RR-2

Sand Patch Method

The sand patch test assesses the macrotextural characteristics of pavement surfaces. The details of sand patch test are explained in Fig 3.11. Dry sand of standard size (0.6 to 0.15 mm), 50 ml in volume, is poured in a heap over a dry surface of pavement (preferably beside the wheel path) which has been cleaned by a soft hand brush. The sand heap is spread in a circular patch of largest diameter using a wooden flat disc of 65 mm diameter (with hard rubber sheet of 1.5 mm thickness stuck to its bottom face). It is ensured that the surface depressions are filled with sand to the level of the surface peaks. Later four readings of the patch diameter are measured at every 45^0, to the nearest mm, and an average value of the patch diameter is calculated as D_{mean}. The following expression (3.4) is used to calculate the texture depth reported to the nearest 0.01 mm.

Mean Texture Depth, MTD (mm) =

$$\left(\frac{Volume\ of\ Sand}{Area\ of\ Patch}\right) = \left(\frac{50ml*1000}{\left(\frac{\pi * D_{mean}{}^2}{4}\right)}\right) \tag{3.4}$$

Pavement surface texture is classified based on the mean texture depth (MTD) value as follows: (a) up to 0.25 mm- Fine, (b) between 0.25 and 0.5 mm – Medium, (c) greater than 0.5 mm – Open. A study (Larsen, 1999) [151] reports that wet-crashes increased greatly when the mean texture depth was less than 0.4 mm. The target minimum value of MTD considered for the purpose of intervention level for texture in various countries is: (a) New Zealand- 0.6 mm for National Highways System, (b) Quebec- 0.6 mm, (c) South Australia- 0.4 – 0.8 mm for Motorways and 0.2 – 0.4 mm for any other, and (d) Great Britain- 1.5 mm for new pavements (Henry, 2000; Sullivan, 2005) [108, 264]. For providing adequate surface friction, another study (Hibbs and Larsen, 1996) [110] recommends an average value of 0.8 mm for MTD and the minimum value of MTD for an individual test as 0.5 mm.

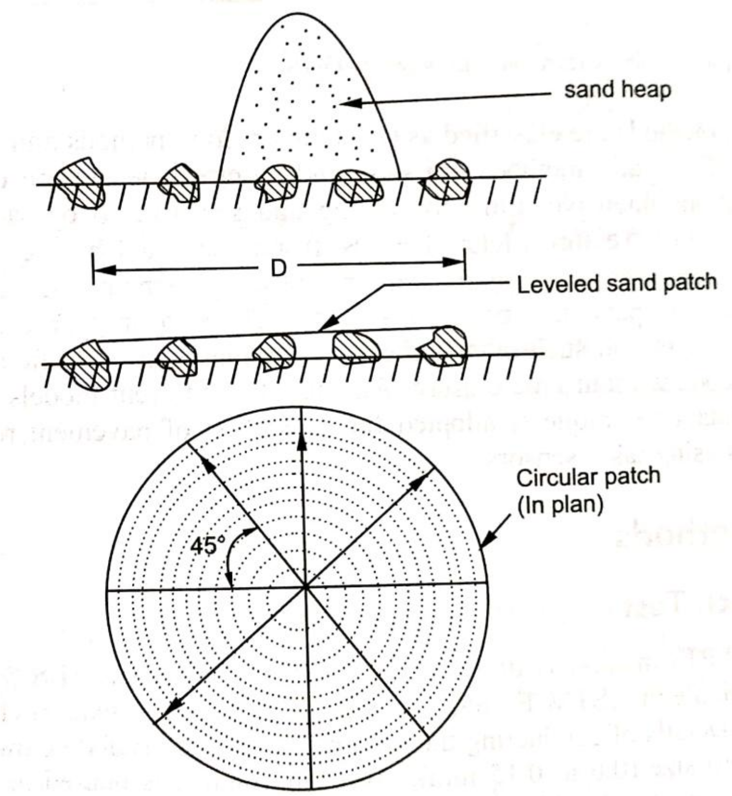


Figure 3.11 Texture Depth Determination by sand patch method

The following three points should be noted during conducting Sand Patch Test-

- In case of smooth surfaces having texture depth less than 1 mm, the volume of the sand may be taken as 25 ml or less.
- Care should be taken to interpret the texture depth, particularly in the range of 0.5 mm to 5 mm, in the case of open-graded porous and deeply-grooved surfaces.
- Protection against wind is required while conducting the experiment for ensuring the accuracy of measurements. At least a minimum of three test values may be considered to calculate the mean texture depth (MTD) of each test surface.

3.4.4 Skid-Resistance Measurement

The Portable Skid Resistance Tester (PSRT), also known as the British Pendulum Tester (Fig 3.12) which was developed by the Transport Research Laboratory (TRL), UK and described in ASTM E303 [204] and IRC: 82-2015 has been used in the present study to determine the skid resistance value (both on wet surface and dry surface) on the selected rural road sections of hilly terrain of Himachal Pradesh. The final reading is taken as the average of three successive readings taken at every 50 m interval on the selected rural road sections of 2.5 km each. This device is capable of simulating skid resistance as offered by a pavement surface to a rubber-tyres vehicle when travelling at a speed of 50km/h. The frictional resistance of the pavement surface can be determined on site or in the laboratory on a sample of the surface. This test can also be conducted on wet floors of pedestrian walkways, profiled road markings, iron works, sport surfaces, floors of offices, factories and toilets.

This test is based on Izod principle. The PSRT consists of a known mass of a pendulum which rotates about a vertical spindle. A spring loaded rubber slider is attached to the pendulum on its head. The rubber slider is characterized by standard specification of hardness and resilience.

Figure 3.12 Skid Resistance Test conducted on RR-1

Before conducting the test, a few adjustments should be carried out [270]-

- The PSRT should be set on the road in such a way that its slider swings in the direction of traffic flow.
- Levelling screws are to be adjusted to set the pendulum supporting column vertical

- The pendulum is calibrated to its full free swing so that the pointer indicates zero reading. During the swinging operation, the height of the pendulum with the rubber slider is adjusted so that the slider does not touch the road
- While hanging the pendulum free and vertical, its height is adjusted by placing a spacer under it so that the rubber slider just touches the road surface. Later, the height of the pendulum is clamped and the spacer is removed.
- Finally, the pendulum height is further adjusted vertically to just strike and have contact with rubber slider at a predetermined prescribed length along the surface of the sample. The prescribed standard value of sliding length should be between 125 and 127 mm for road surface test and 76 mm for a laboratory test.
- The test site should be free from loose grit and dust. The pendulum arm should be held by a catch to prevent it from striking back on its return swing.

The condition of pavement corresponding to skid resistance value prescribed by IRC: 82-2015 is given in Table 3-4.

Table 3-4 Suggested Minimum values of Skid Resistance measured with Portable Skid Resistance Tester (IRC: 82-2015)

Skid Resistance Value (SN by ASTM-274) (Minimum Desirable)	**Condition of Pavement**
65	Good
55	Fair
45	Poor

3.5 Structural Evaluation Data

The structural evaluation of the selected 12 rural road sections of hilly terrain in Himachal Pradesh has been carried out. The structural parameters i.e. pavement deflection, California Bearing Ratio (CBR) test and Modulus of subgrade value (K-value) has been determined under the section of structural evaluation. The static load has been applied on the pavement surface and its rebound deflection has been measured using Benkelman Beam. The detailed procedure followed to determine pavement deflection, CBR and K-value has been presented in the below sections.

3.5.1 Pavement Benkelman Beam Deflection Test

In the present study, in order to determine the pavement deflection values on the selected 12 rural road sections of hilly terrain in Himachal Pradesh, the Benkelman Beam (Fig 3.13) has been used. It was decided that 10 measurement points per kilometre will be taken for data collection. Hence, 25 points per road stretch were selected to determine the characteristic deflection as per the procedure laid down in IRC: 81-1997 [123] "Guidelines for strengthening of flexible road pavements using Benkelman Beam Deflection Technique". A standard two axle truck having rear axle load of 8.16 tonnes and tyre pressure of 5.6 kg/cm^2 was used for measurement of initial reading, intermediate reading and final reading at each selected point 60 cm away from the pavement edge. The temperature correction was not applied because the average day temperature in the selected stretch region is less than 20^o C for more than four months in a year. All the deflection measurements have been made when the ambient temperature was greater than 20^o as suggested by IRC: 81-1997. Subgrade soil samples were taken from the test pits evaluation for determining the subgrade moisture content. These soil samples were oven dried in the laboratory for finding out the moisture content needed for applying moisture correction factor in characteristic deflection calculations.

To measure the response of a flexible pavement in terms of surface rebound deflections under static standard axle truck wheel loading, A.C. Benkelman introduced the Benkelman Beam (BB) in 1953. The beam was especially made for the road tests conducted by the Western Association of State Highway Organization (WASHO). The BB method played a major role in the evaluation of the overlay design using surface rebound deflections measured under standard axle loads similar to truck traffic loading. The Benkelman Beam is simple, inexpensive and reliable equipment uses to assess the structural adequacy of a flexible pavement.

Figure 3.13 Benkelman Beam Deflection study on selected stretches (RR-2 and RR-12)

The BB test has been done as per the procedure laid in IRC: 81-1997. The details of the Benkelman Beam test as recommended by the IRC: 81-1997 are presented below.

The Benkelman Beam consists of a probe of slender beam 3.66 m in length. It is pivoted at a distance of 2.44 m from the probe point (Fig 3.14). The probe beam is mounted in position by a reference beam of length 2.66 m. The reference beam is equipped with front and rear legs for initial horizontal adjustment using a spirit level. A dial gauge is installed on the reference beam 1.22 m away from the pivot and its spindle is in contact with the other end of the probe beam.

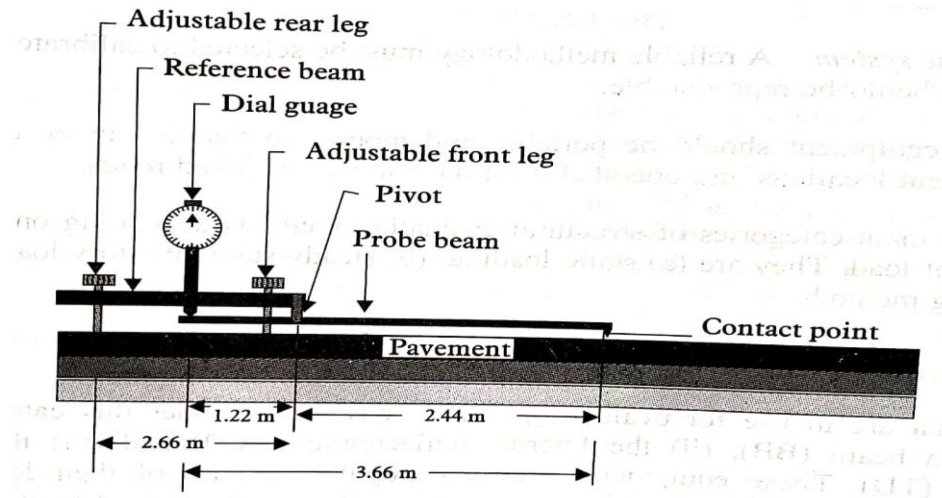


Figure 3.14 Salient features of a Benkelman Beam

Calibration of Benkelman Beam

Before using the Benkelman Beam, its dial gauge should be calibrated by placing its probe point on a metallic plate of known thickness (Fig 3.15). The reading on the dial gauge should be checked as one-half of the thickness of the metallic plate, since the distance between the pivot to the spindle of the dial gauge is one-half the distance between the pivot and the probe point. While calibrating, the reference beam should be horizontal and there should be no vibrations in the ground. Free movement of the probe beam should be ensured at the pivot.

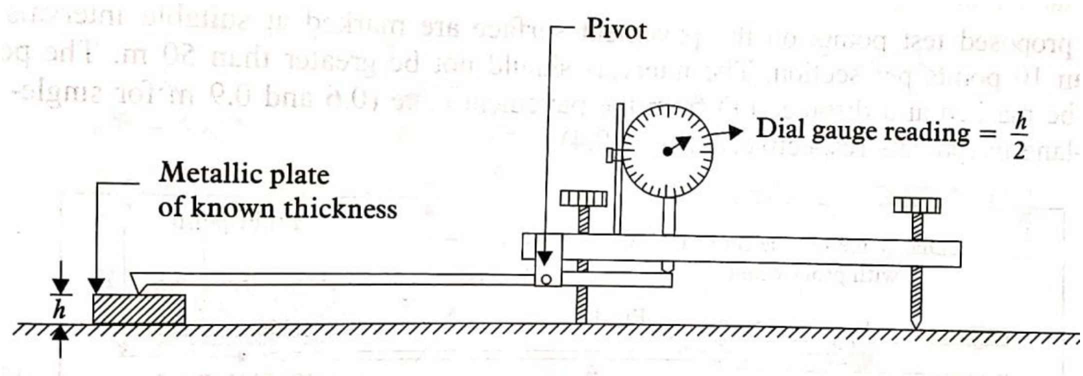


Figure 3.15 Calibration of Benkelman Beam

Pavement Condition Survey

The test sections of the pavement are subjectively rated by visual examination of surface distress in terms of cracking and rut depth. The test sections may be classified into the following three types-

- Good: No cracks and rut depth less than 10 mm
- Fair: No or very little hair cracks and rut depth between 10 mm to 20 mm
- Poor: Considerable cracks on the surface and rut depth more than 20 mm

Additional information such as existing pavement crust thickness, individual layers thickness and prevailing drainage conditions should be recorded separately. The above information should be collected at suitable intervals based upon the condition of the test section and requirement.

Method of Measurement of Rebound Surface Deflections

The Canadian Good Roads Association (CGRA) procedure has been adopted for measurement of pavement surface deflection. Initially, the BB probe point is inserted between the dual tyres of a standing truck's rear axle (Fig 3.16). The standard values of truck rear axle weight and the inflated tyre pressure has been taken as 8170 kg and 5.6 kg/cm^2 respectively. During the test, the rear axle load and the tyres pressure should not change beyond a tolerance limit of ± 1 and ± 5% respectively (IRC: 81-1997).

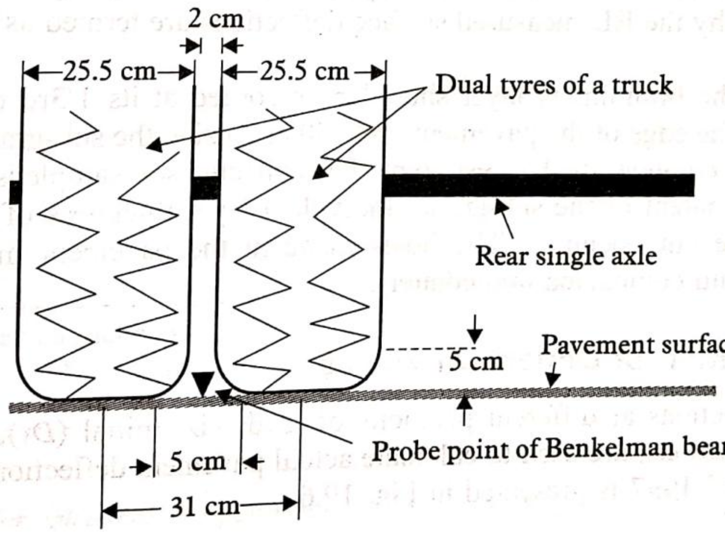


Figure 3.16 Initial Position of the Benkelman Beam probe point in between the dual wheels of a track

The proposed test points on the pavement surface are marked at suitable intervals not less than 10 points per section. The intervals should not be less than 50 m. The points should be marked at a distance (Y) from the pavement edge (0.6 and 0.9 m for single and double lane respectively) (Fig 3.17).

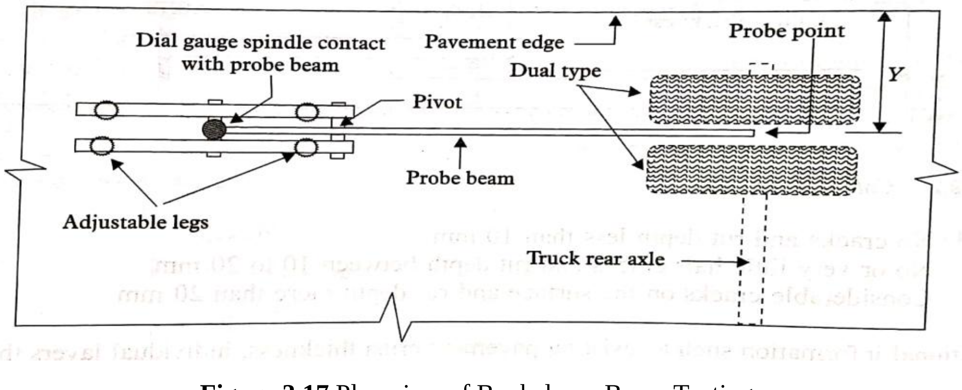


Figure 3.17 Plan view of Benkelman Beam Testing

Horizontality of the reference beam should be checked and the dial gauge's initial reading (D_o) recorded when the probe is deflected under the given standard loading conditions (Fig 3.18 (a)). Second reading or intermediate reading (D_i) is recorded when the truck is driven at a creep speed (≤ 2 km/h) and stopped 2.7 m from the initial position (Fig 3.18 (b)). Finally, the truck is allowed to move further by 9 m and the third reading or final reading (D_f) is recorded (Fig 3.18 (c)). The above readings should be recorded when the rate of deformation of pavement is less than or equal to 0.025 mm per minute.
It is observed from Fig. 3.18 that initially the pavement surface is deflected under the loading. As the truck moves away, the pavement surface gradually regains its original level. This is the reason why the BB measured surface deflections are termed as rebound or elastic deflections.

Temperature of the bituminous layer should be recorded at its 1/3rd depth. A small pit should be cut from the edge of the pavement up to 50 cm inside the subgrade and a sample of the subgrade collected under the BB test point. The collected soil sample is used to determine the field moisture content of the subgrade. Individual layer thickness of pavements has been obtained from these cut openings. The holes made in the pavement must be filled with suitable materials and compacted immediately.

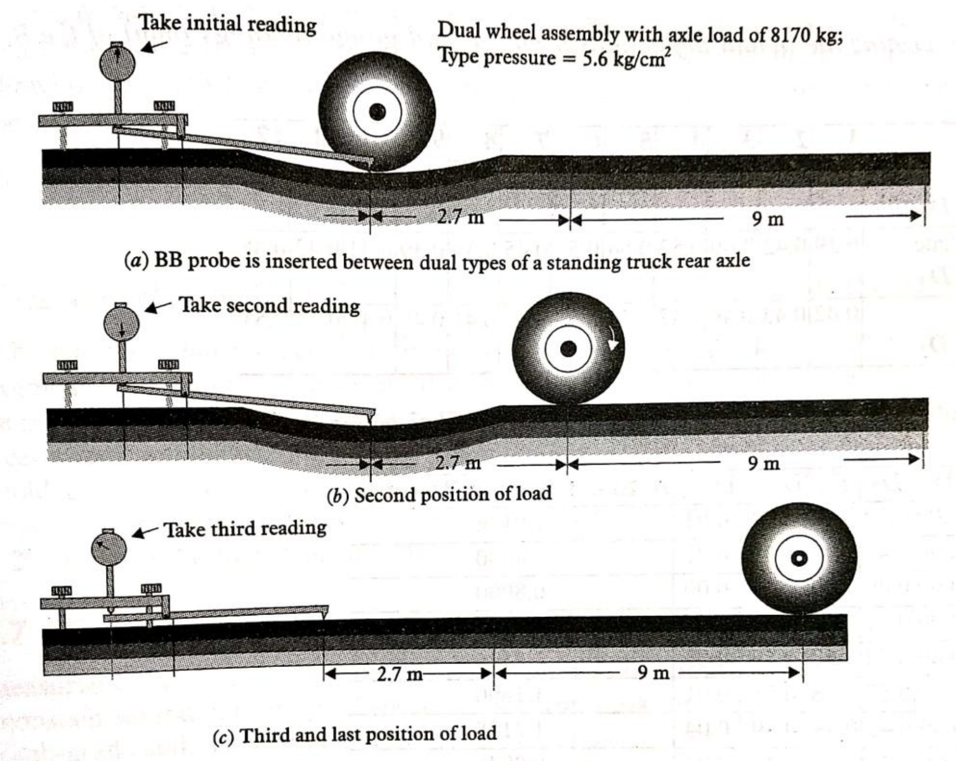


Figure 3.18 Measurement of pavement surface rebound deflection using Benkelman Beam

The recorded deflections at different positions of load, viz. initial reading (D_o), intermediate reading (D_i) and final reading (D_f), have been used to calculate actual pavement deflections and the standard procedure of IRC: 81-1997 has been presented in Fig 3.19.

As the pavement surface deflections will be influenced by variations in the temperature of the bituminous layer, hence, all the measured deflections should be corrected to a standard temperature. The temperature correction has been applied as per the recommendation given in IRC: 81-1997. In the present study, the temperature correction has not been applied due to the following two reasons-

- The thickness of the bituminous layer on all the selected rural road sections of hilly region is less than 40 mm.
- The average temperature remains less than 20 ^{0}C for more than four months in a year for the hilly region in which the roads has been selected. However, all the deflection readings has been taken when the ambient temperature is more than 20 ^{0}C.

The measured deflections are sensitive to the magnitude of strength of the subgrade. During post-monsoon season, the subgrade becomes soft or weak due to accumulation of moisture in the subgrade soil. Hence, if the deflections are measured during dry months, they should be corrected using seasonal correction factors given in six charts from IRC: 81-1997, using simple input parameters like subgrade soil type, plasticity index and annual rainfall of the region. All the BBD data calculations of the selected 12 rural road sections in hilly region of Himachal Pradesh have been presented in Appendix D.

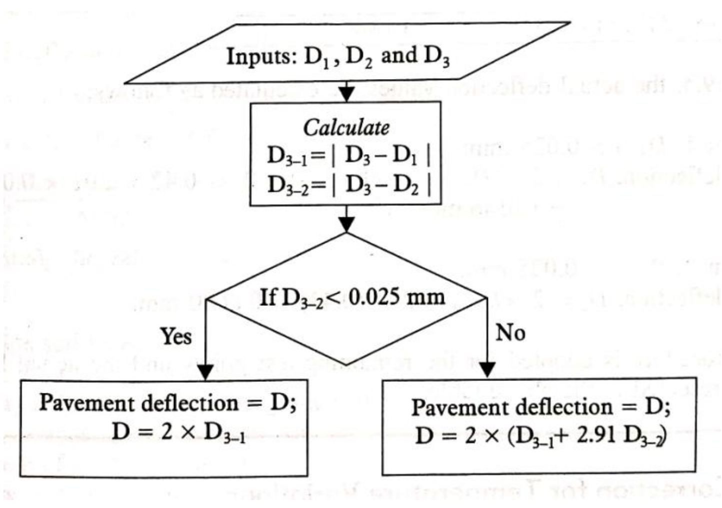


Figure 3.19 Procedure for calculating the pavement deflection from the Benkelman Deflection Data

3.5.2 California Bearing Ratio Test

California Bearing Ratio (CBR) Test has been conducted as per the standard procedure recommended in IRC: 36-2010 [121] and IS 2720 [126] on the disturbed subgrade soil samples taken from selected 12 rural road stretches. Three subgrade soil samples were taken from each selected road stretch. All soil samples were tested in laboratory (Fig. 3.20) to determine the Soaked CBR value and Unsoaked CBR value. The average value of the three soil samples has been taken as shown in Table 3-5. The load vs penetration curves for soaked CBR value and unsoaked CBR value of all the selected 12 rural road stretches of all the subgrade soil samples has been shown in Appendix B.

Figure 3.20 California Bearing Ratio Test in Laboratory

Table 3-5 Unsoaked CBR and Soaked CBR Values of all soil samples

	Unsoaked CBR				**Soaked CBR**			
Roads	**CBR-1**	**CBR-2**	**CBR-3**	**Average CBR (%)**	**CBR-1**	**CBR-2**	**CBR-3**	**Average CBR (%)**
RR1	26.58	28.32	27.93	27.61	18.54	19.01	20.14	19.23
RR2	24.54	25.01	27.52	25.69	15.24	15.97	18.11	16.44
RR3	19.89	22.41	20.85	21.05	10.22	11.58	14.41	12.07
RR4	28.69	29.11	30.85	29.55	18.64	19.41	20	19.35
RR5	17.68	19.21	18.16	18.35	9.73	11.52	9.26	10.17
RR6	27.85	26.35	30.49	28.23	18.26	19.71	20.47	19.48
RR7	26.25	28.95	26.13	27.11	15.65	16.87	21.06	17.86
RR8	27.36	28.34	31.15	28.95	19.22	20.35	21.21	20.26
RR9	25.06	27.47	28.2	26.91	15.74	16.46	17.45	16.55
RR10	19.27	23.18	25.29	22.58	11.84	12.12	14.11	12.69
RR11	25.88	26.41	26.43	26.24	15.98	16.48	19.32	17.26
RR12	22.91	24.75	23.95	23.87	14.21	15.49	16.29	15.33

3.5.3 Modulus of Subgrade Reaction (K-value)

The modulus of subgrade reaction (K-value) has also been determined approximately corresponding to the soaked CBR value using IRC: 58-2015 [122] "Guidelines for the design of plain jointed Rigid Pavements for highways" as shown in Table 3-6.

Table 3-6 K-value of all selected stretches

Road ID	RR1	RR2	RR3	RR4	RR5	RR6	RR7	RR8	RR9	RR10	RR11	RR12
K-Value	6.79	6.40	5.79	6.81	5.52	6.83	6.60	6.96	6.42	5.88	6.52	6.25

3.6 Age of Pavement

The age of pavement i.e. the number of years from last overlay till the year in which the Benkelman Beam study conducted was taken from DPR of the selected road sections available with PWD, Himachal Pradesh and shown in Table 3-7.

Table 3-7 Age of Pavement from last overlay (in years) of all selected stretches

Road ID	RR1	RR2	RR3	RR4	RR5	RR6	RR7	RR8	RR9	RR10	RR11	RR12
Age (years)	7	5	7	6	6	7	5	6	7	7	6	7

3.7 Traffic Volume Survey

Classified traffic volume surveys were conducted manually for 7 days (12 hours on each day), by employing skilled enumerators, covering all types of vehicles viz: Buses, two-axle Trucks, multi-axle trucks, light commercial vehicles, light passenger vehicles and Two-wheelers. The traffic volume survey was done twice i.e. in lean season and in peak season, both for 7 days as shown in Fig. 3.21 and 3.22 respectively.

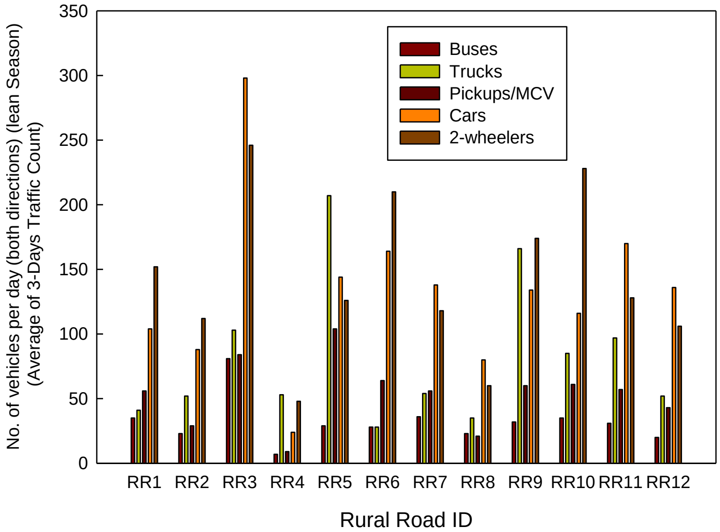


Figure 3.21 Traffic Volume Survey for Lean Season

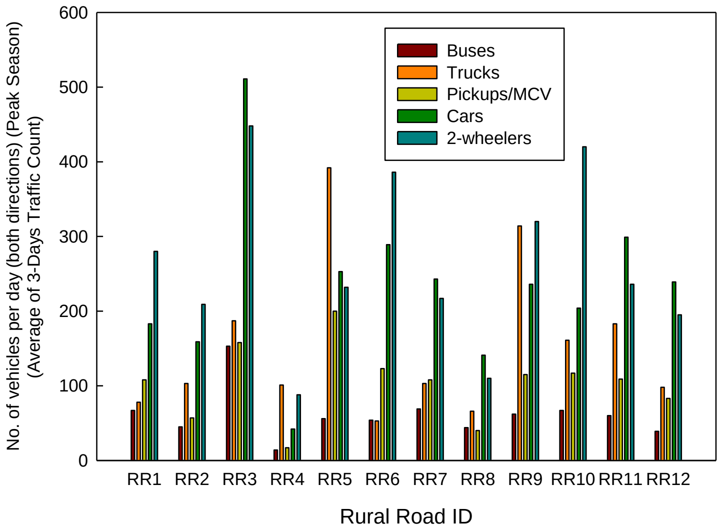


Figure 3.22 Traffic Volume Survey for Peak Season

The traffic volume has been determined in terms of Average Annual Daily Traffic (AADT) on all the selected rural road stretches using IRC: SP: 72-2015 [125] "Guidelines for the design of Flexible Pavements for Low Volume Rural Roads". The classified traffic volume data for all the selected rural road section of hilly region in Himachal Pradesh has been presented in Appendix C.

CHAPTER 4

DVELOPMENT OF RURAL ROAD ROUGHNESS MODEL AND SURFACE DEFLECTION MODEL

4.1 General

Pavements are important asset of highways which needs routine or periodic maintenance. The performance of pavements needs to be monitored regularly to meet the service life expectancy corresponding to the intensity of traffic and prevailing environmental conditions. The proper pavement maintenance strategies lead to better economic returns. Now days, Maintenance of highways is monitored either by functional evaluation or by structural evaluation of pavements. Functional evaluation of pavements mainly deals with the smoothness of road and the distresses present on them such as ravelling, cracking, potholes, patching, bleeding, delamination, rutting, corrugation, overlay bumps etc which can be easily visible on any highway whereas structural evaluation deals with the structural parameters of road such as deflection of road, bearing capacity etc.

In view of functional evaluation, road roughness is an important parameter which is required by any highway agencies or pavement engineers to monitor the smoothness of roads. Road Roughness is also required to categorize different roads in order to strategize the maintenance priorities. Road Roughness itself is a function of various pavement distresses present on roads which proves to be hurdle in the comfort zone of road users. It also affects the vehicle operating cost when road roughness is ample. Hence, road roughness plays a vital role in the design and maintenance of highways.

In this chapter, an attempt has been made to achieve the objective to develop a road roughness model for rural road network of hilly terrain of Himachal Pradesh which can predict the value of road roughness on the basis of various distresses present on roads with the help of functional evaluation data collected in previous chapter. All the pavement distresses do not participate equally in the cause of road roughness. Hence, the weightage to various distresses is given based on surveys conducted using Analytical Hierarchy Approach (AHP). The weighted distress parameters have been used to develop models using linear, non-linear regression and Artificial Neural Network technique. Three models have been developed and compared with each other. The best model is finally suggested to predict road roughness value which can be very useful for pavement engineers and highway agencies to define maintenance strategies based on pavement distresses which in turn reduces the time consumed in determining road roughness value with the help of costly equipments.

Also, the pavement performance can be ascertained by structural evaluation of pavements. Structural evaluation can be of two types, Destructive type and Non-Destructive type. In the present study, non-destructive technique has been used to evaluate the surface characteristic deflection of selected flexible rural road stretch using Benkelman Beam.

The study has been conducted on the rural roads of Himachal Pradesh of hilly terrain which plays vital role in the development of the state. The total length of rural roads in Himachal Pradesh contributes around 81% of the total road network in the state. Out of total rural road network, 63% are tarred roads which need to be maintained timely for their better performance. These roads are not only subjected to heavy traffic loads but also suffer diverse weather of the hills throughout the year leading to heavy wear and tear.

The other objective of the present study is to eradicate the use of costly equipments such as Benkelman Beam, Falling Weight Deflectometer etc. and their cumbersome process of determining surface deflection on narrow and hilly rural roads which leads to disruption of traffic. Hence, attempts have been made to develop a mathematical model using the structural data collected in previous chapter which can predict pavement characteristic deflection corresponding to traffic volume, age of pavement (number of years from last overlay), soaked CBR and Un-soaked CBR. Another model has also developed to estimate pavement surface deflection corresponding to traffic volume, age of pavement and K-value. The multiple mathematical models developed have been compared and best model is suggested based on various statistical parameters.

4.2 Analytical Hierarchy Process (AHP)

4.2.1 Basics of AHP

Analytical Hierarchy Process (AHP) is one of the simplest and most useful processes in this field which is appropriate for approximate usages. This method has been a tool in the hands of decision makers and researchers since its introduction. It is still one of the most widely used tools when assessing decisions in bridge and road construction (Zavadskas et al., 2008) [297]. The AHP is a process that uses hierarchical decomposition to deal with complex information in multi-criterion decision making. It is a theory, developed by Saaty in 1970s, for dealing with complex technological, economic, and socio-political problems. AHP aims at quantifying relative priorities for a given set of alternatives on a ratio scale (Saaty, 1980 and Vargas, 1990) [240, 281].

Principle of AHP- There are three principles which one can recognize in problem solving. They are the principles of decomposition, comparative judgements and synthesis of priorities. The decomposition principle calls for structuring the hierarchy to capture the basic elements of the problem (Saaty, 1986) [242]. In AHP, a hierarchy is an abstraction of the structure of a system to study the functional interactions of its components and their impact on the entire system. This abstraction can take several related forms, all of which essentially descends from an apex (an overall objective), down to sub-objectives, down further to forces, down to objective of the people who influences these forces, down to the objectives of the people and then to their policies, still further down to the strategies, and finally the outcomes which results from these strategies (Saaty, 1980) [240]. Figure 4.1 shows a typical schematic hierarchy of weightage determination and prioritization process. After the design of the problem components (hierarchy) is made, the second phase of the AHP is the evaluation which is based on the concept of paired comparisons. The elements in a level of the hierarchy are compared in relative terms as their importance or contribution to a given criterion that occupies the level immediately above the elements being compared. This process of comparison yields a relative scale of measurements of priorities or weights of the elements. These relative weights sum to unity (Vargas, 1990) [281].

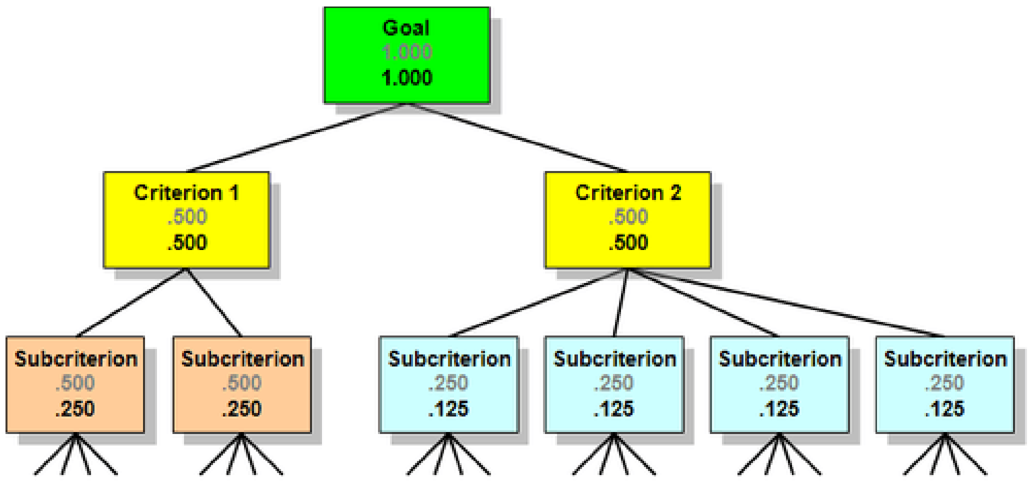


Figure 4.1 Typical Hierarchy Structure for Weightage Determination and Prioritization

A useful feature of the AHP is its applicability to the measurements of intangible criteria along with the tangible ones through a ratio scale. In AHP, a ratio scale between 1 and 9 is used to give the relative preference between two alternatives as shown in Table 4-1. This scale is able to capture a great deal of information and has proven to be extremely useful due to the fact that the AHP is somewhat scale independent.

Table 4-1 Intensity of Importance Scale of AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one activity over another
5	Essential importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed between two

The AHP incorporates judgements and personal values in a logical way. It depends on imagination, experience, and knowledge to structure the hierarchy of the problem. It also depends on logic, intuition and experience to provide judgements. Once accepted and followed, the AHP shows how to connect elements of one part of the problem with those of another to obtain the combines outcome (Saaty, 1982) [241].

The process of AHP is much different from conventional methods provided as follows (Hagquist, 1994) [102]-

- AHP uses a set of one-to-one comparison to evaluate alternatives under each criterion. These pair-wise comparisons are the smallest in decisions.
- AHP uses one-to-one comparisons to assign criteria importance weights.
- AHP does alternative comparisons and criteria weighting in separate steps.

- AHP includes both objective measure and subjective preferences in the form of criteria weights. Typically, only one objective is quantified.

AHP has many advantages over the conventional scoring methods such as increase in accuracy and consistency. Even the subjective consideration is quantified in a structured framework. However, the major drawback in the use of AHP is the effort required to make all pair-wise comparisons (Millet and Harker, 1990) [173]. As the size of the hierarchy increases, the number of required pair-wise comparisons increases exponentially.

Also, the AHP has its complexity in terms of higher level of details required by the evaluators when asked for their preferences and opinions. In pavement management, usually many factors are considered in any modelling process (e.g. prioritization). For a huge pavement network the comparison based on 9-pont scale for many factors is a difficult task. However, at project-level evaluations where a few sections are to be considered simultaneously, AHP is an effective method for analysis.

4.2.2 Principles and Background of AHP

Principle of AHP- Consider *n* elements to be compared, C_1.........C_n and denote the relative weight (or priority or significance) of C_i with respect to C_j by a_{ij} and form a square matrix A = (a_{ij}) of order *n* with the constraints that $a_{ij} = 1/ a_{ij}$, for $i \neq j$, and $a_{ij} = 1$, all i. Such a matrix is said to be a reciprocal matrix. The weights are consistent if they are transitive, that is $a_{ik} = a_{ij} * a_{jk}$ for all i, j and k. Such a matrix might exit if the a_{ij} are calculated from exactly measured data. Then a vector *w* is formed of order *n* such that $A*w = \lambda*w$. For such a matrix, *w* is said to be an eigenvector (of order *n*) and λ is an eigen value. For a consistent matrix, $\lambda = n$. For matrices involving human judgement, the condition $a_{ik} = a_{ij} * a_{jk}$ does not hold, as human judgements are inconsistent to a greater or lesser degree. In such a case the *w* vector satisfies the equation $A*w = \lambda_{max}*w$ and $\lambda_{max} \geq n$. The difference, if any, between λ_{max} and n is an indication of the inconsistency of the judgements. If $\lambda_{max} = n$ then the judgements have turned out to be consistent. Finally, a consistent Index (CI) is calculated from ($\lambda_{max} = n/(n-1)$). That needs to be assessed against judgements made completely at random and Saaty, 1980 has calculated large samples of random matrices of increasing order and the Consistency Indices of those matrices. A true Consistency Ratio (CR) is calculated by dividing the CI for the set of judgements by the index for the corresponding random matrix called as Random Index (RI) (Table 4-2). Saaty suggest that if that ratio exceeds 0.1 the set of judgements may be too inconsistent to be reliable. In practice, CRs of more than 0.1 sometimes have to be accepted. If CR equals 0 then that means that the judgements are perfectly consistent.

Table 4-2 Random Consistency Index based on Matrix Size (Saaty, 1980) [240]

Matrix size	Random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

4.2.3 Weightage Determination using AHP

Analytical Hierarchy Process is a structured tool which is useful in complex decision making. In this process, the problem is first dissolved into a hierarchy and then sub-structured into different groups. It can solve any complex problem related to decision making which involves expert opinions and perceptions. The AHP incorporates the imagination, knowledge and experience of each individual into the analysis of any problem. It synthesizes the numerous decisions or perceptions mathematically for which the consistency of the judgements is checked to evaluate each decision and finally the output is arrived to model the concerned problem statement.

In the present study, the technique of Analytical Hierarchy Process is used to determine the Weightage of different distress parameters which have a considerable effect on International Roughness Index. For this a questionnaire has been prepared as given in Appendix-E in which various distress parameters have been compared for their relative importance. The questionnaire has been dispersed into Highway Engineers, Scientists, Academicians and Research Scholars for their individual perception based on their experience and knowledge.

A total of 150 questionnaires have been distributed out of which 119 responded and used to determine the relative Weightage of various distress parameters. To check the Consistency Ratio (CR) of 119 responses Expert Choice 11 software [34, 127] has been used as shown in Fig. 4.2 and Fig. 4.3.

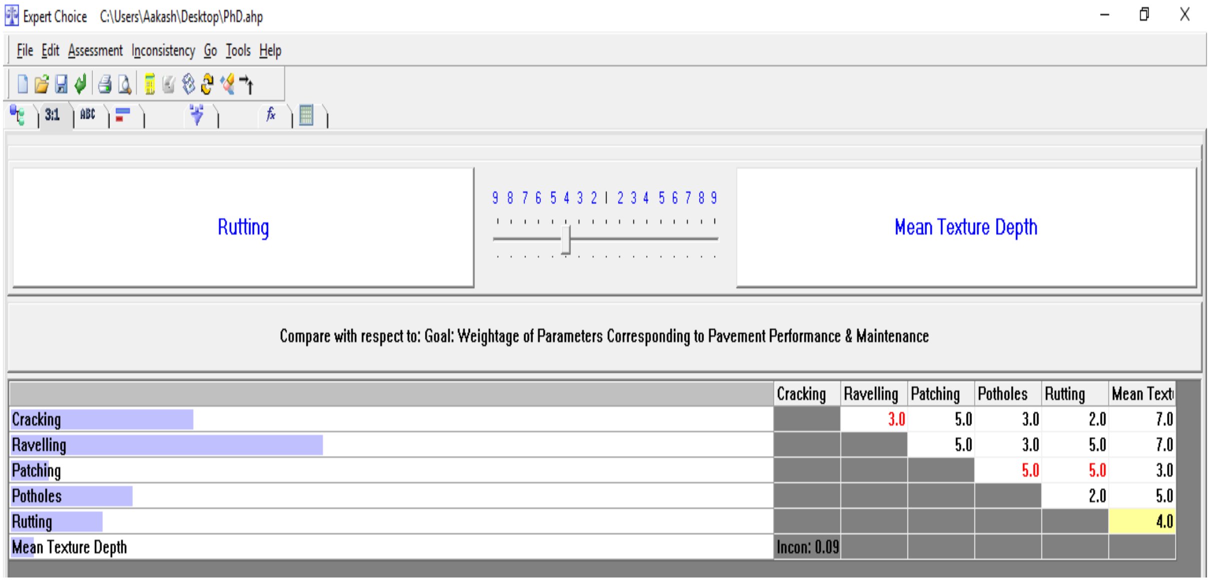


Figure 4.2 Rating Input in Expert Choice Software based on various questionnaires

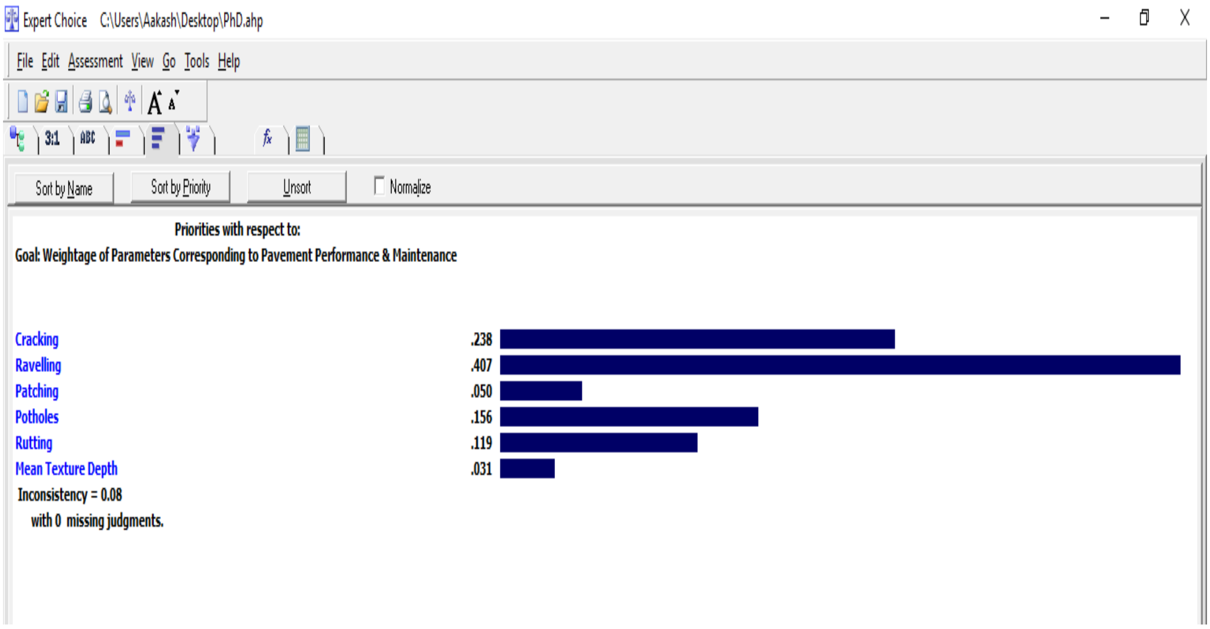


Figure 4.3 Consistency Ratio Calculation using Expert Choice Software

If the consistency ratio of any response is more than 0.1 than that particular response has been discarded. Hence out of total 119 responses, 21 responses whose consistency ratio greater than 0.1 has been discarded and the Weightage has been calculated based on remaining 98 responses. The final weightage of each pavement distress parameter which has appreciable effect on IRI after considering 98 responses whose inconsistency is less than 0.1 are given in Table 4-3.

Table 4-3 Weightage of Different Pavement Distresses based on AHP

Pavement Distress Type	Weightage
Potholes	20.69%
Cracking	28.42%
Rut Depth/Rutting	10.86%
Ravelling	14.22%
Patching	22.27%
Mean Texture Depth	3.54%

4.3 Road Roughness Model Development

Efforts have been made to develop the mathematical models which can predict the value of International Roughness Index for the entire rural road network of hilly terrain in Himachal Pradesh. Various models have been generated based on the pavement distress data collected on the selected 12 rural road sections. Pavement distresses like cracking, ravelling, patching, potholes, rutting, mean texture depth which constitutes an appreciable effect on the value of IRI on rural roads in hilly terrain of Himachal Pradesh have been taken account for the IRI prediction model.

The data collected as per the methodology described in previous chapter has been divided into 60 data sets in which each data set represents data collected over a road length of 500 m which includes all the distress parameters and IRI. Each pavement distress parameter value collected during the survey has been multiplied with respective weightage factor arrived through AHP [150] (Table 4-3). The weighted distress data which represents actual response in pavement performance and maintenance have been used to generate models for better lucidity of International Roughness Index.

4.3.1 Multiple Linear Regression Model

Attempts have been made to develop a mathematical multiple linear regression [70, 146] model to predict the value of International Roughness Index based on weighted distress parameters. The data has been divided into test size and training size. 75% data has been used for training purpose to generate the multiple linear regression model and 25% data for testing purpose. The model have been developed using linear regression [178] with sklearn library of PYTHON [39]. All the distress parameters have been plotted as shown in Fig. 4.4 to check the correlation in between the parameters. Fig. 4.4 has been automatically generated using PYTHON programming which checks the dependency of each parameter by plotting each data point corresponding to the data points of other remaining parameters and because scattered plotting has been obtained at each level which shows that none of the selected parameter is correlated to any other parameter.

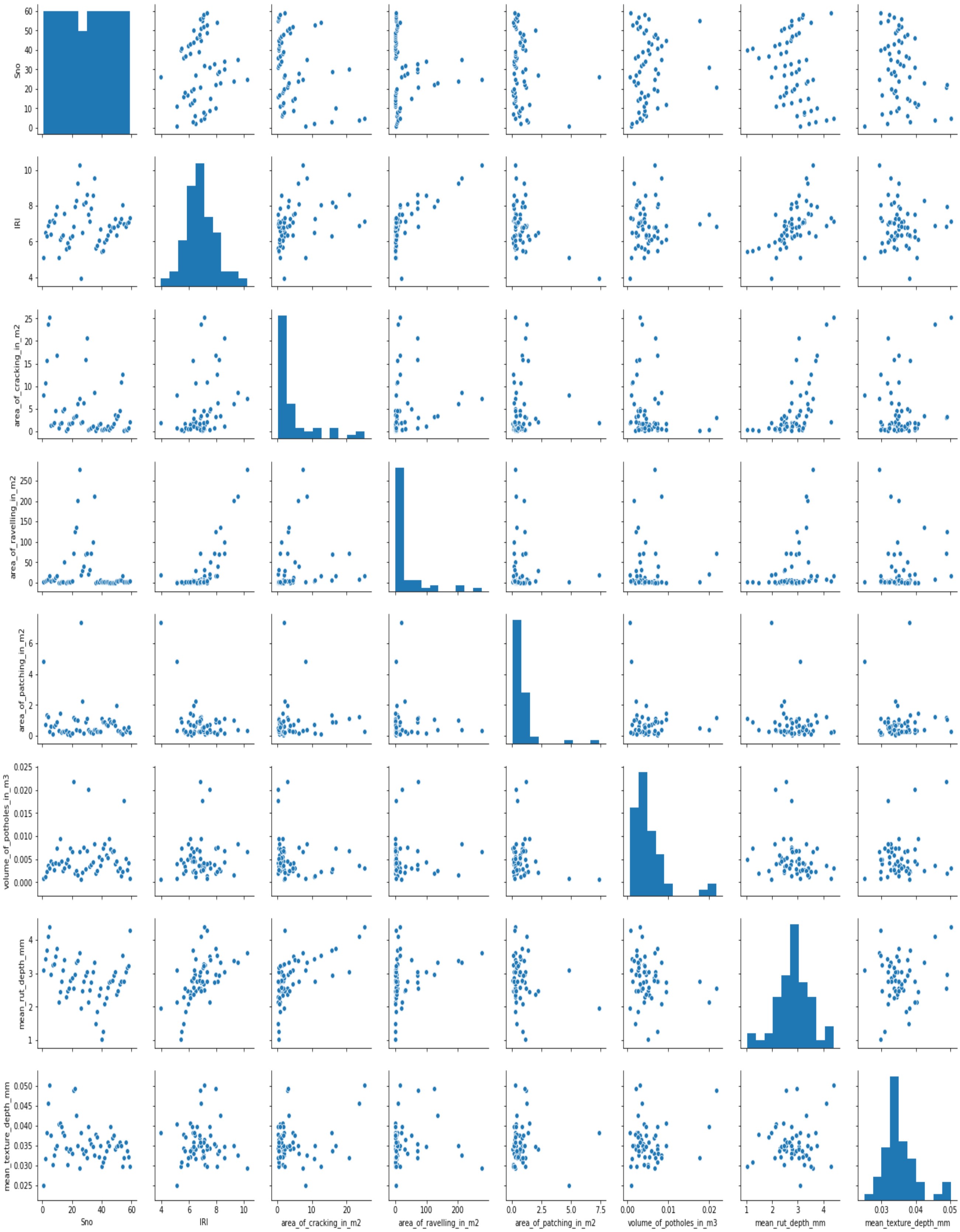


Figure 4.4 Correlation Between the Distress Parameters

PYTHON [280] is a high level programming language which has user friendly interface. Jupyter Notebook is the user interface which has been used as working environment of PYTHON. Python is dynamically typed and garbage-collected. It supports multiple programming paradigms, including procedural, object-oriented, and functional programming. Python is often described as a "batteries included" language due to its comprehensive standard library. Python uses dynamic typing, and a combination of reference counting and a cycle-detecting garbage collector for memory management. It also features dynamic name resolution (late binding), which binds method and variable names during program execution. Python is meant to be an easily readable language. Its formatting is visually uncluttered, and it often uses English keywords where other languages use punctuation. Unlike many other languages, it does not use curly brackets to delimit blocks, and semicolons after statements are optional. It has fewer syntactic exceptions and special cases than C or Pascal. Hence, because of its simplicity as compared to other computer languages, it has been used in the present study to deal with the regression model analysis and Artificial Neural Network model.

The correlation matrix has been developed as shown in Table 4-5 which shows that none of the distress parameter is correlated to each other and hence all parameters are used to develop the mathematical model.

The developed model is given in Eq. 4.1 and various statistical parameters of the models have been determined using sklearn library tools of PYTHON. The developed model was studied and tested with the actual training data and test data. The R^2 value has been determined for both training data and testing data which is 0.821 and 0.810 respectively as shown in Fig. 4.5 (a) and (b). The MSE (Mean Squared Error) of training data and testing data was found to be 0.24 and 0.19 respectively.

$$IRI = C_0 + C_1{*}CR + C_2{*}RV + C_3{*}PC + C_4{*}PT + C_5{*}MRD + C_6{*}MTD \qquad (4.1)$$

R^2=0.83

Where, C_0 = model constant, and C_1, C_2, C_3 ,C_4 ,C_5 ,C_6 = coefficients of Cracking (CR), Ravelling (RV), Patching (PC), Potholes (PT), Mean Rut Depth (MRD), Mean Texture Depth (MTD) respectively, Given in Table 4-4,

Table 4-4 Coefficients of Various Model Parameter

Model Parameter	Coefficients
Intercept	$C_0 = 6.191$
Area of Cracking	$C_1 = 0.034$
Area of Ravelling	$C_2 = -0.339$
Area of Patching	$C_3 = 0.012$
Volume of Potholes	$C_4 = 76.575$
Mean Rut Depth	$C_5 = 0.627$
Mean Texture Depth	$C_6 = -50.086$

Where, CR = weighted area of cracking (m^2 per 1500 m^2), RV = weighted area of ravelling (m^2 per 1500 m^2), PC = weighted area of patching (m^2 per 1500 m^2), PT = weighted volume of potholes (m^3 per 1500 m^2), MRD = weighted mean rut depth (mm per 1500 m^2), MTD = weighted mean texture depth (mm per 1500 m^2)

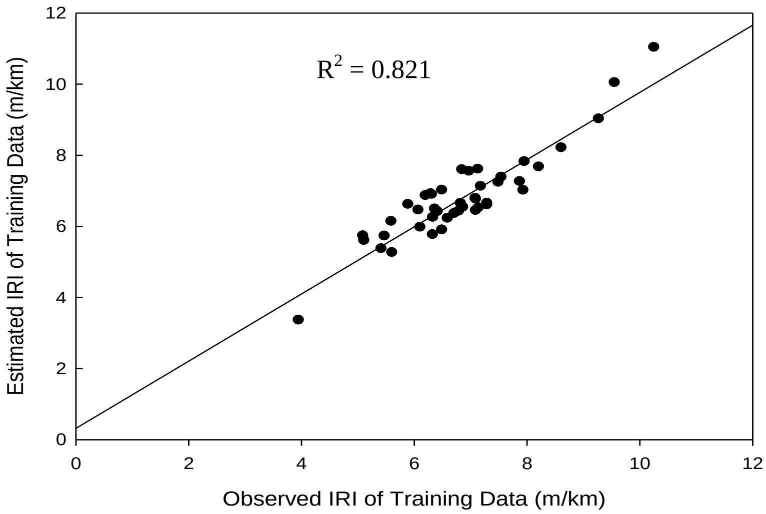
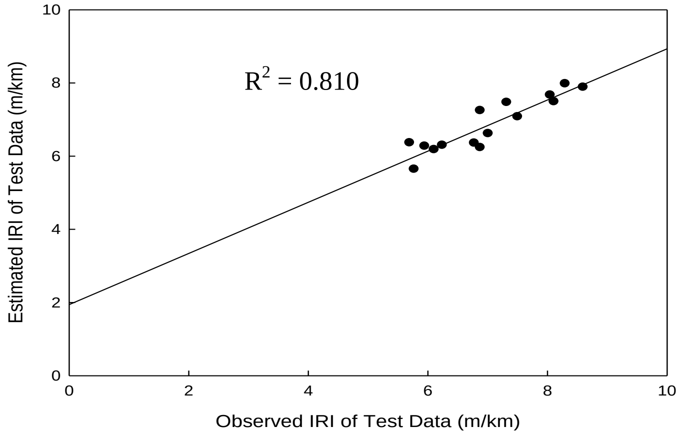


Fig 4.5 (a)



(b)

Figure 4.5 Validation of Linear Regression Model

Table 4-5 Correlation Matrix

	IRI (mm)	Weighted area of cracking (m^2)	Weighted area of ravelling (m^2)	Weighted area of patching (m^2)	Weighted volume of potholes (m^3)	Weighted mean rut depth (mm)	Weighted mean texture depth (mm)
IRI (mm)	1	0.34	0.75	-0.40	0.09	0.56	-0.01
Weighted area of cracking (m^2)	0.34	1	0.17	0.06	-0.17	0.59	0.19
Weighted area of ravelling (m^2)	0.75	0.17	1	-0.04	0.04	0.26	0.05
Weighted area of patching (m^2)	-0.40	0.06	-0.04	1	-0.13	-0.14	-0.01
Weighted volume of potholes (m^3)	0.09	-0.17	0.04	-0.13	1	-0.20	0.16
Weighted mean rut depth (mm)	0.56	0.59	0.26	-0.14	-0.20	1	0.11
Weighted mean texture depth (mm)	-0.01	0.19	0.05	-0.01	0.16	0.11	1

4.3.2 Non-Linear Regression Model

Another model has also been developed based on Non-Linear Regression Analysis [42] to predict International Roughness Index corresponding to pavement distresses. Again, the model has been developed using 75% training data and 25% testing data. The developed non-linear model is presented in Eq. 4.2. The non-linear analysis has been done in Excel and the coefficients have been determined using SOLVER [105, 290] function by minimizing the Sum of Squared Residuals (SSR) depending upon the coefficients of model parameters. The R^2 value has been determined for both training data and testing data which is 0.844 and 0.837 respectively as shown in Fig. 4.6 (a) and (b). The MSE (Mean Squared Error) of training data and testing data was found to be 0.22 and 0.16 respectively.

$$IRI = \beta_1 + \beta_2 * (CR)^{\beta_3} + \beta_4 (RV)^{\beta_5} + \beta_6 (PC)^{\beta_7} + \beta_8 (PT)^{\beta_9} + \beta_{10}(MRD)^{\beta_{11}} + \beta_{12}(MTD)^{\beta_{13}} \quad \text{(Eq. 4.2)}$$

Where, $\beta_1 = -227.01$, $\beta_2 = 0.031$, $\beta_3 = 0.903$, $\beta_4 = 0.108$, $\beta_5 = 0.607$, $\beta_6 = 107.315$, $\beta_7 = -0.002$, $\beta_8 = 120.981$, $\beta_9 = 0.003$, $\beta_{10} = 6.886$, $\beta_{11} = 0.168$, $\beta_{12} = -12.743$, $\beta_{13} = 0.677$

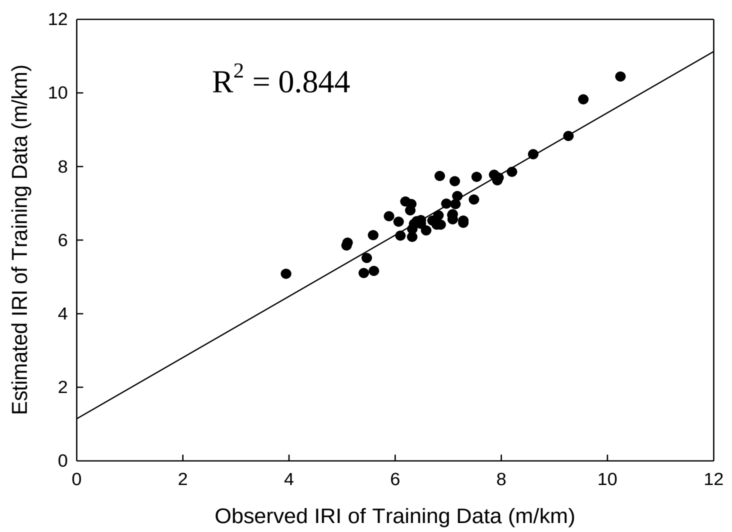
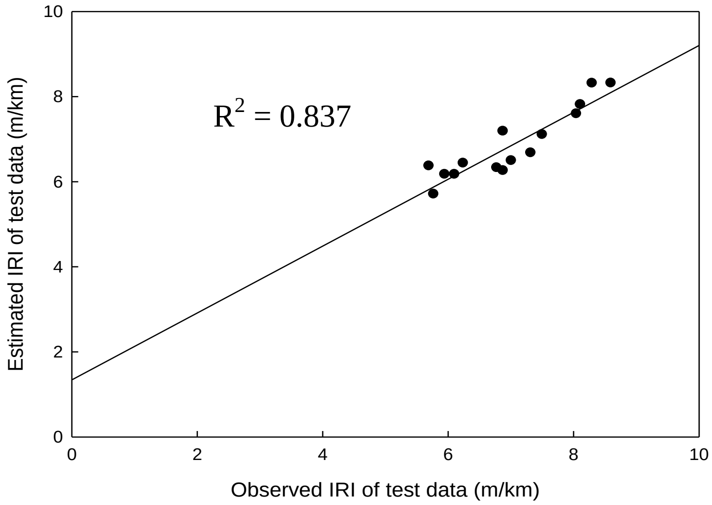


Fig. 4.6 (a)



(b)

Figure 4.6 Validation of Non-Linear Regression Model

4.3.3 Artificial Neural Network (ANN) Modelling

An artificial neural network is defined as a system based on the operation of biological neural networks. In other words, it is an emulation of biological neural system. An artificial neural network is modelled to resemble the human's brain capability to think and learn through perception, reasoning and interception [93, 97]. A brain is composed of networks of neurons that receive input signals from other neurons. When a certain level of excitation is reached, a neuron 'fires' an output signal that acts as an input to other connecting neurons. The type of relationship between the input and the output of a neuron can be described mathematically using a number of algorithms (Freeman and Skapura, 1991) [85].

The graphical representation of an ANN model is shown in Fig. 4.7. In comparison to a biological network, the neurons are replaced by artificial neurons also called processing elements (PEs) [289, 291]. ANN consists of at least three layers of interconnected PEs which are the input, hidden and output layers [128]. The number of PEs in the input layer is the same as the number of input variables that are used to predict the desired output (independent variables). The PEs in the output layer represents the variables to be predicted (dependent variables). The input and output layers are connected through one or several intermediate layers of PEs, also called hidden layers. The number of hidden PEs within these layers is decided by trial and error depending on the complexity of the problem.

Attempt has been made to use ANN to predict IRI based on various distress parameters. The model has been developed using ANN in PYTHON. Out of total data observations, 60% data has been used to train the ANN model and remaining 40% to test the model and for validation purpose to avoid any over fitting. One hundred epochs/iterations has been performed 10 times to arrive at MSE value of 0.371 and R^2 = 0.72. The MSE value decreased drastically as the number of iterations or epochs started increasing. The equation derived from the neural network used in this model is quite complex for the simple reason that four hidden layer each having 32 neurons have been accounted as shown in Fig. 4.7 and dense layer neural network has been used and hence, the connection between the input and hidden layers is quite complex. Also when the number of hidden layers or nodes in the hidden layer increases the number of computations increases and due to this, more central processing unit or graphical processing unit computations are required. The result computed by increasing the number of layers has been so much nexus that the calculation of equation derived from the neural network was very complex to write down. Rectified Linear Unit (ReLu) Activation functions have been used in the development of model. ADAM optimizer has been used for deep learning of the model to update the network weights on iterative basis.

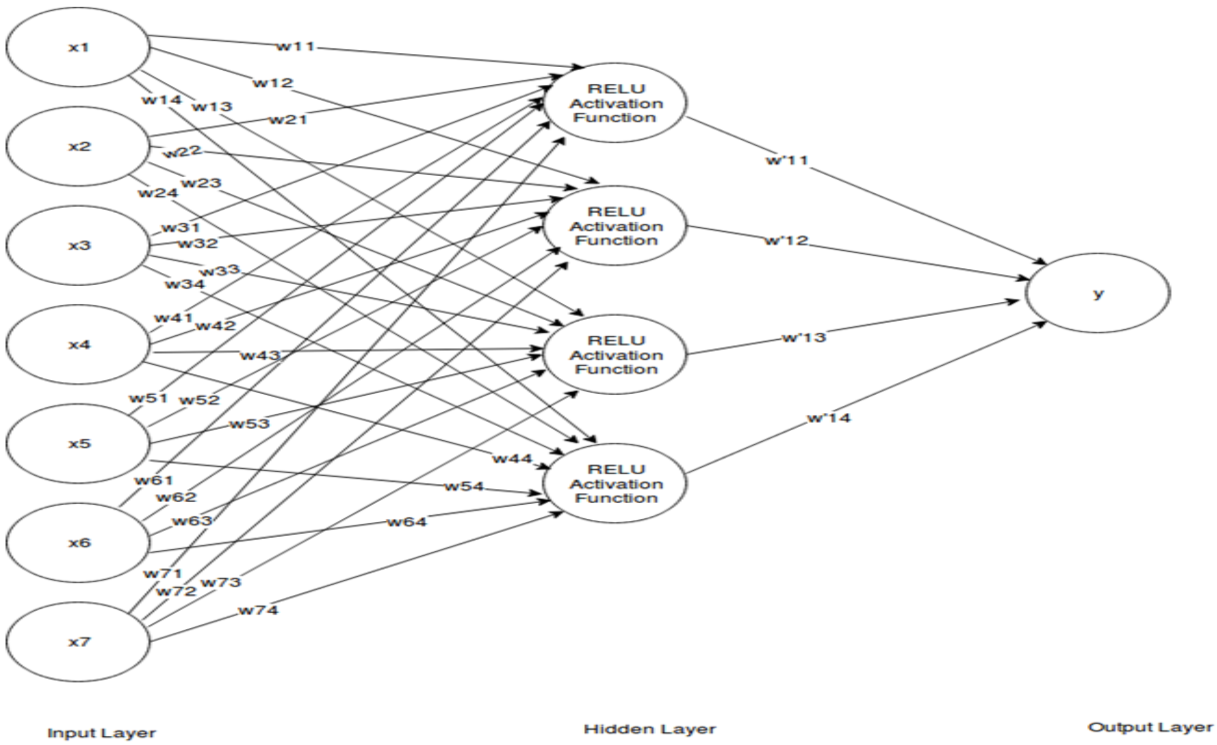


Figure 4.7 Artificial Neural Network

4.4 Pavement Surface Deflection Model Development

Attempts has been made to develop a mathematical model to predict the characteristic pavement deflection based on Soaked CBR value, Un-soaked CBR value, Average Annual Daily Traffic (AADT) and Age of pavement from last overlay (in years) as determined in the previous chapter. Another model has also been developed to estimate surface deflection using K-value, Average Annual Daily Traffic (AADT) and age of pavement (in years).

Multiple models have been developed using linear regression model in PYTHON. However, the data points in the development of deflection model is only 12, because of the limitation of conducting Benkelman beam test on such narrow roads. The various developed models have been studied, compared and best model is suggested based on various statistical parameters such as Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE) and R^2 value.

Two models have been developed using linear regression with sklearn library of PYTHON. All the parameters have been plotted as shown in Fig. 4.8 and Fig. 4.9 to check the correlation in between the parameters. Fig. 4.8 and Fig. 4.9 have been generated automatically using PYTHON programming to check the dependency of each parameter with the remaining parameters by plotting the data points and it can be clearly seen that soaked CBR and un-soaked CBR are highly correlated to each other. It can also be justified by the correlation matrix developed as shown in Table 4-6 and Table 4-7 which shows that soaked CBR and unsoaked CBR are highly correlated to each other and hence unsoaked CBR parameter has been removed to develop the final mathematical model.

The following two mathematical models (Eq. 4.3 & Eq. 4.4) has been suggested and various statistical parameters of the models have been determined using sklearn library tools of PYTHON-

$$D_c = 0.755147 + 0.001561 * AADT - 0.025788 * Age - 0.00681 * S\_CBR \qquad \text{(Eq. 4.3)}$$

MAE= 0.17, MSE= 0.06

RMSE= 0.19, R^2 = 0.76

$$D_c = 0.848226 + 0.001568 * AADT - 0.026334 * Age - 0.032537 * K\text{-}value \qquad \text{(Eq.4. 4)}$$

MAE= 0.18, MSE= 0.07

RMSE= 0.21, R^2 = 0.72

Where,

D_c = Pavement Characteristic Deflection (mm)

AADT = Average Annual Daily Traffic

Age = Age of pavement from last overlay (in Years)

S_CBR = Soaked CBR value (%)

K-value = Modulus of subgrade reaction (kg/cm^3)

MAE = Mean Absolute Error

MSE = Mean Squared Error

RMSE = Root Mean Squared Error

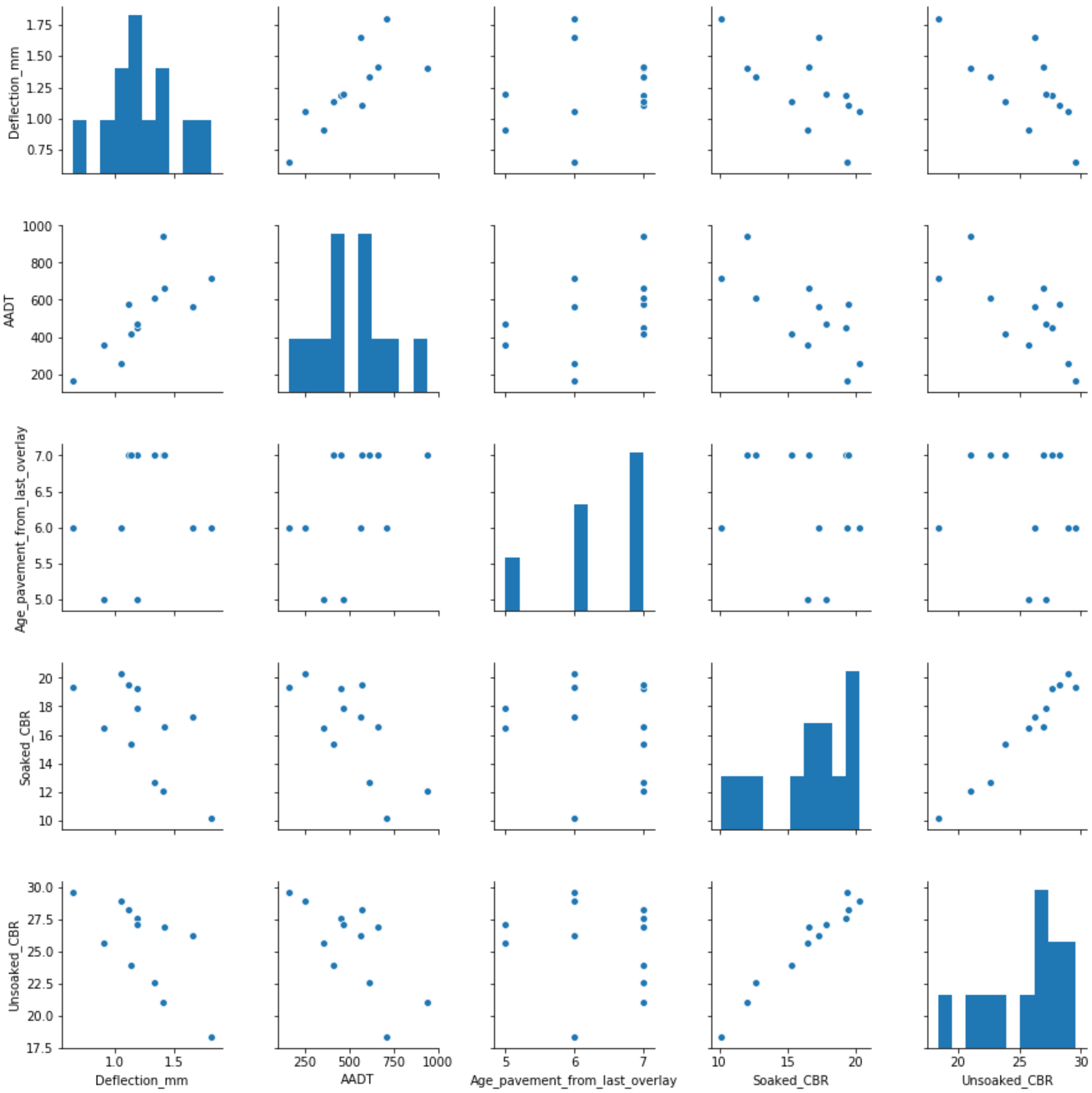


Figure 4.8 Correlation between the parameters

Table 4-6 Correleation Matrix

	Deflection_mm	AADT	Age of Pavement	Soaked_CBR	Unsoaked_CBR
Deflection_mm	1	0.759	0.200	-0.640	-0.679
AADT	0.759	1	0.427	-0.712	-0.707
Age of Pavement	0.200	0.427	1	-0.161	-0.157
Soaked_CBR	-0.640	-0.712	-0.161	1	0.978
Unsoaked_CBR	-0.679	-0.707	-0.157	0.978	1

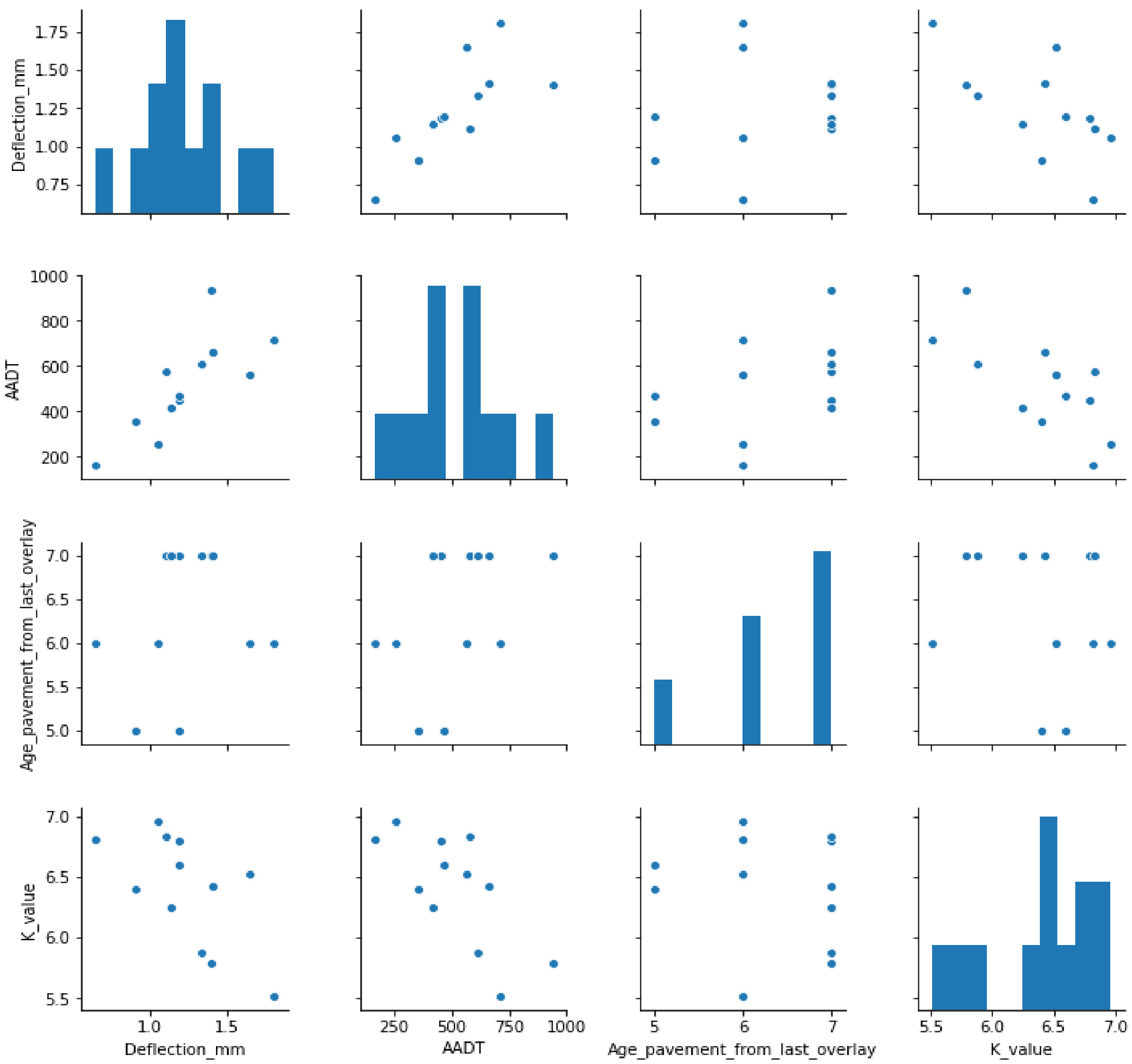


Figure 4.9 Correlation between the parameters

Table 4-7 Correleation Matrix

	Deflection_mm	AADT	Age of Pavement	K_value
Deflection_mm	1	0.759	0.200	-0.639
AADT	0.759	1	0.427	-0.713
Age of Pavement	0.200	0.427	1	-0.160
K_value	-0.639	-0.713	-0.160	1

4.5 Development of Pothole Volume Prediction Model

Attempts have been made to generate a prediction mathematical model which can predict the volume of pothole when physical dimension parameters of potholes i.e. mean diameter and maximum depth of pothole are given as input parameter. As many as 250 pothole data has been collected which includes pothole volume determined by using sand replacing the bowl of pothole, mean diameter and depth of pothole.

70% of the pothole data has been used to generate the regression model and remaining 30% has been used for testing. Linear regression model and non-linear regression model has been generated and it has been found that non-linear model predicts better results than linear model. The R^2 value i.e. the coefficient of determination has been determined for both linear regression model and non-linear regression model as 0.87 and 0.85 respectively as shown in Fig. 4.10 and 4.11 has been achieved in case of non-linear model which shows a good model prediction. The linear and non-linear model has been presented in Eq. 4.5 and 4.6 respectively.

4.5.1 Linear Regression Model

PV = -2445.07 + 103.56 * (MDP) + 544.51 *(DP) (Eq. 4.5)

Where,

PV = volume of the pothole in ml (which can be further converted into m^3) ($1m^3 = 10^6$ ml)

MDP = mean diameter of pothole in mm

And, DP = depth of pothole in mm.

4.5.2 Non-Linear Regression Model

$$\mathbf{PV} = 3548.22 + 15.58*(\mathbf{MDP})^{1.43} + (-5164.34)*(\mathbf{DP})^{-0.40} \qquad \text{(Eq. 4.6)}$$

Where,

PV = volume of the pothole in ml (which can be further converted into m^3)

MDP = mean diameter of pothole in mm

And, DP = depth of pothole in mm

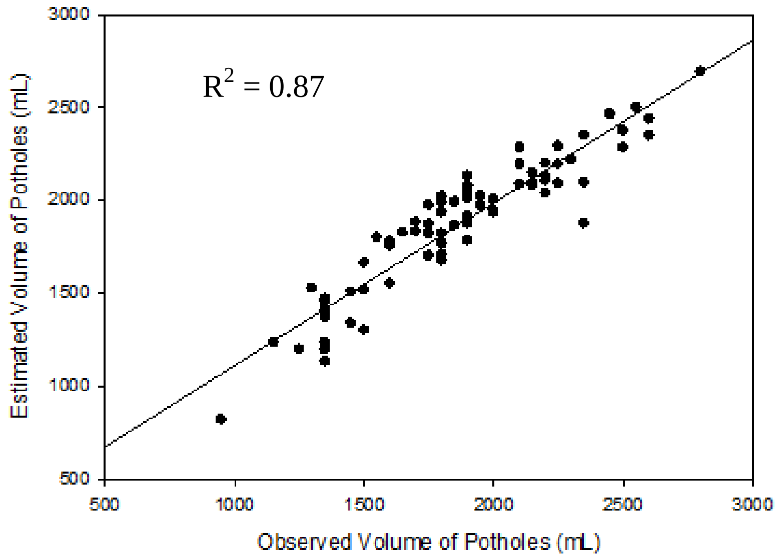


Figure 4.10 Validation of Linear Regression Pothole Volume Prediction Model

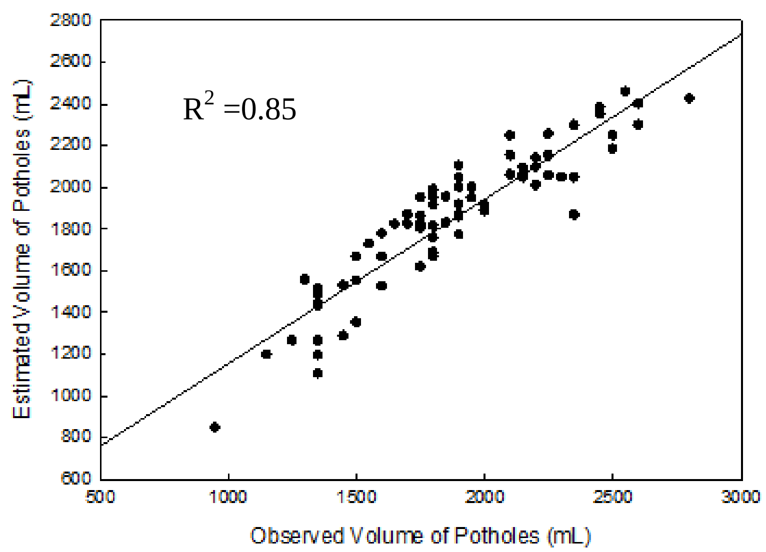


Figure 4.11 Validation of Non-Linear Regression Pothole Volume Prediction Model

4.6 Results and Discussion

1. The percentage cracking is found to be lowest (0.14%) in RR9 whereas it is highest in rural road stretch of RR1 with 5.36% as shown in Fig. 4.12.

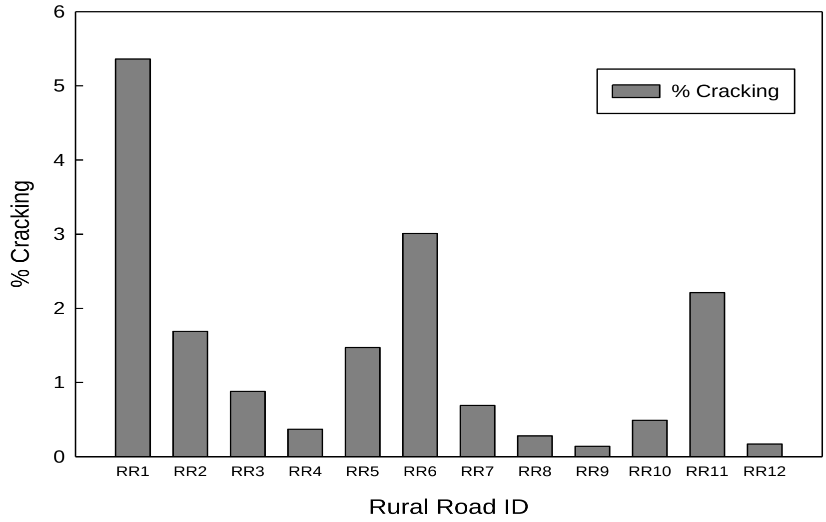


Figure 4.12 Percentage Cracking of selected road stretches

2. Also, the percentage ravelling is found to be lowest in RR9 with 0.28% and shown a significant effect in RR5 with 38.74% as shown in Fig. 4.13.

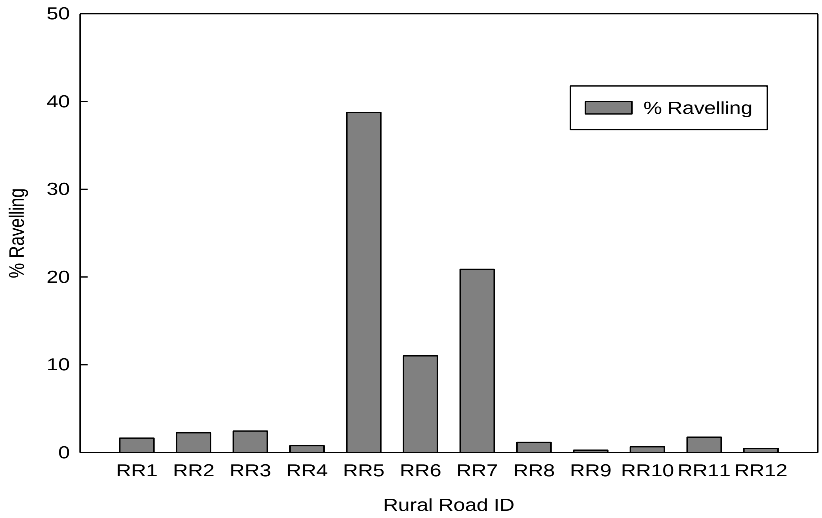


Figure 4.13 Percentage Ravelling of selected road stretches

3. The distress patching is found to be very low on all the roads in a range of 0.22% - 2.68% as shown in Fig. 4.14. The highest percentage patching is found to be on RR6.

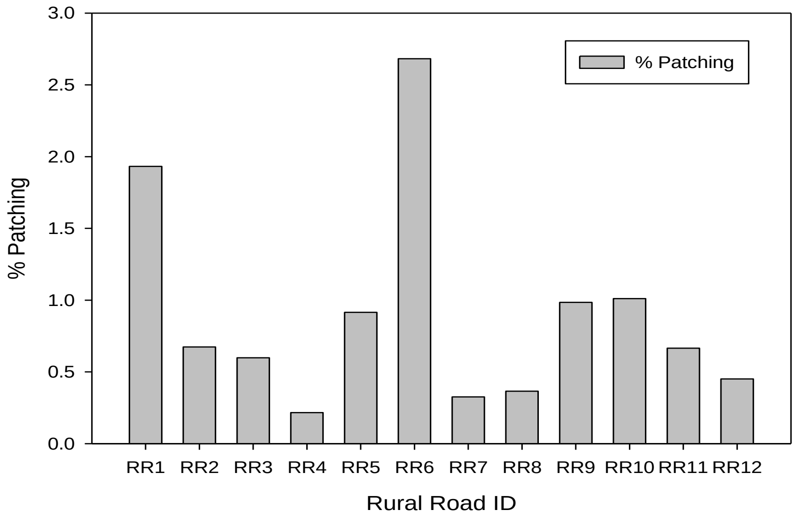


Figure 4.14 Percentage Patching of selected road stretches

4. The total volume of potholes measured through replacing a known volume of sand with the pothole bowl is found to be significant on RR7 with 0.28 m^3 of volume (Fig. 4.15). However, least volume of pothole is found to be on RR1 with 0.076 m^3 of volume (Fig. 4.15).

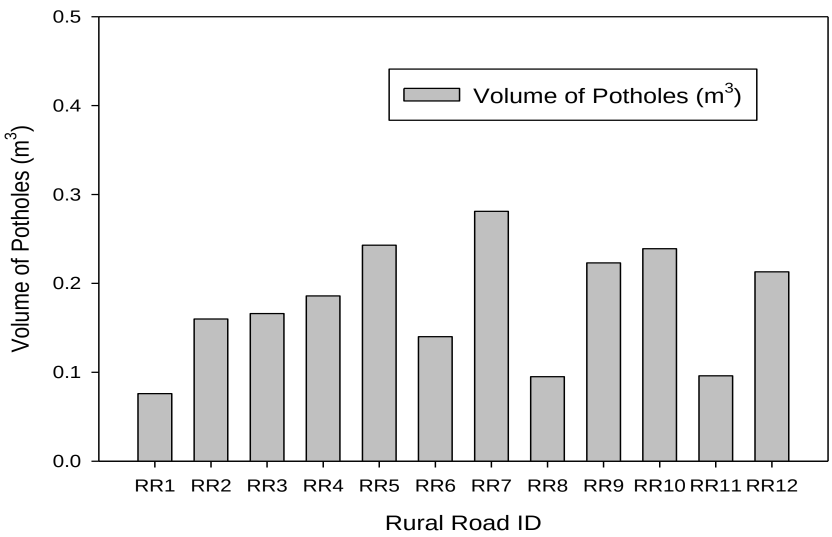


Figure 4.15 Total Volume of Potholes on selected road stretches

5. Also, the mean rut depth is found to be highest on RR1 with a value of 16.8 mm and RR9 secures lowest 8.26 mm mean rut depth as shown in Fig. 4.16.

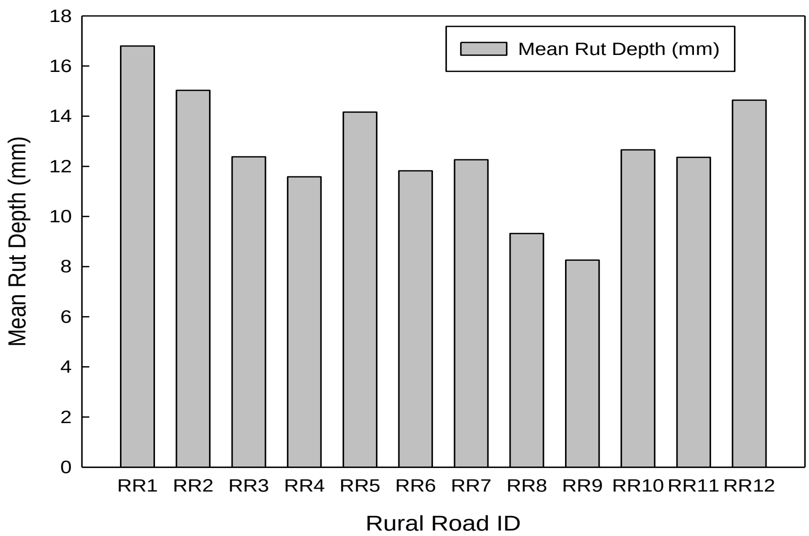


Figure 4.16 Mean Rut Depth on selected road stretches

6. The mean texture depth obtained by sand patch method is found to be significant on RR5 with 1.16 mm (Fig. 4.17).

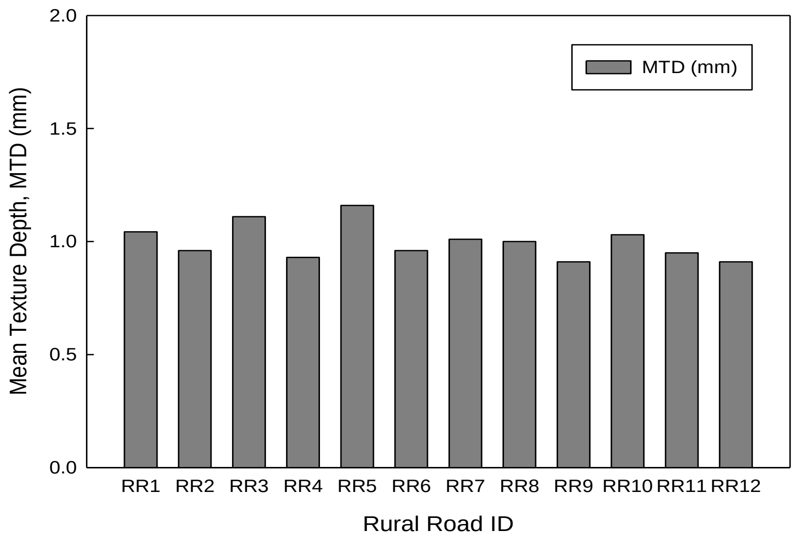


Figure 4.17 Mean Texture Depth on selected road stretches

7. The International Roughness Index derived by MERLIN is obtained by taking the average of four reading per 500 m stretch and found to be highest on RR5 with 8.5 mm/km whereas it is lowest on RR4 with 5.9 mm/km as shown in Fig. 4.18.

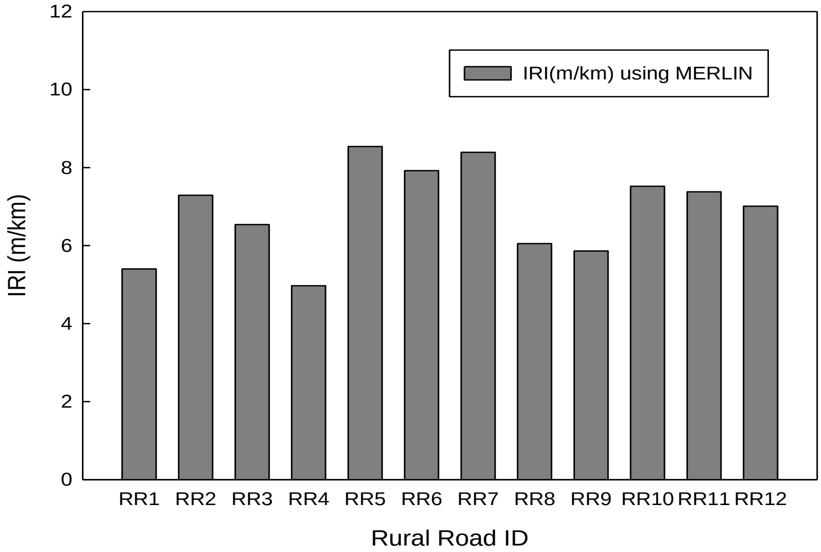


Figure 4.18 IRI on selected road stretches

8. As the dry skid resistance value for all the selected stretches is more than 65 as shown in Fig. 4.19, hence all the roads are in good condition with respect to skid resistance value.

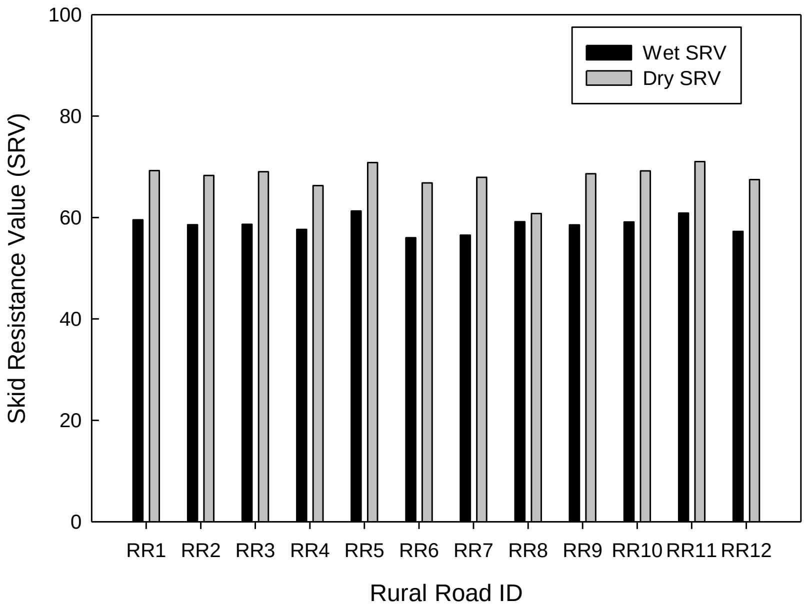


Figure 4.19 Skid Resistance Value on selected road stretches

9. The weightage given to various distresses as shown in Table 4-3 using Analytical Hierarchy Process shows that as per the experts cracking has greater importance relative to other distress parameters and mean texture depth leads to least important parameter in pavement performance and maintenance.
10. The R^2 value in linear regression model of road roughness model for both training data and testing data is 0.821 and 0.810 respectively which shows a good correlation as shown in Fig. 4.5. The MSE (Mean Squared Error) of linear regression model for training and tested data is found to be 0.24 and 0.19 respectively which shows estimated values of IRI using this model are very close to the observed values of IRI.
11. The R^2 value in non linear regression model of road roughness model for both training data and testing data is 0.844 and 0.837 respectively which also shows a good correlation as shown in Fig. 4.6.
12. The MSE of Non linear regression road roughness model for training and tested data is found to be 0.22 and 0.16 respectively whereas the MSE value of model developed using Artificial Neural Network is found to be very high as 0.371.
13. The Benkelman beam study conducted on all the twelve selected rural road stretches shows that RR5 has the most characteristic deflection value of 1.8 mm and RR4 has the least deflection value of 0.65 mm (Fig. 4.20). Hence RR5 needs to be maintained first out of the twelve selected stretches corresponding to low structural strength.

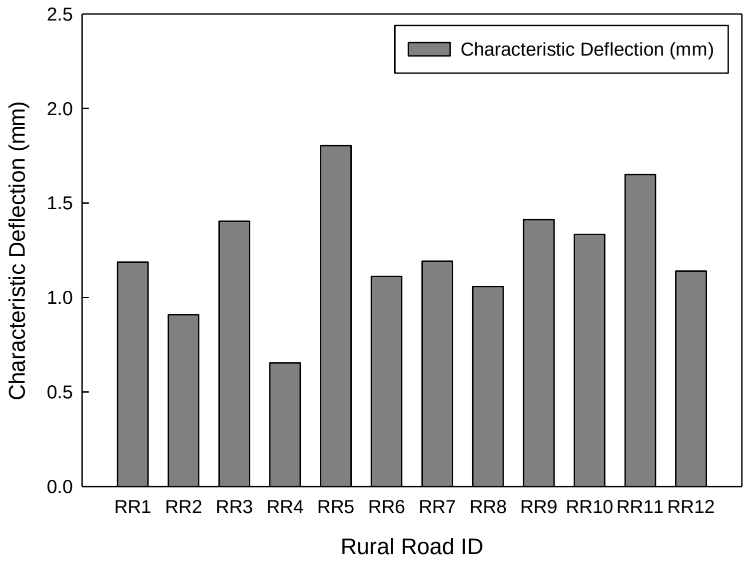


Figure 4.20 Characteristic Deflection of all selected stretches

14. The average unsoaked and soaked CBR value of RR5 is 18.35% and 10.17% (Fig. 4.21) which is least among all the selected roads which show poor subgrade strength.

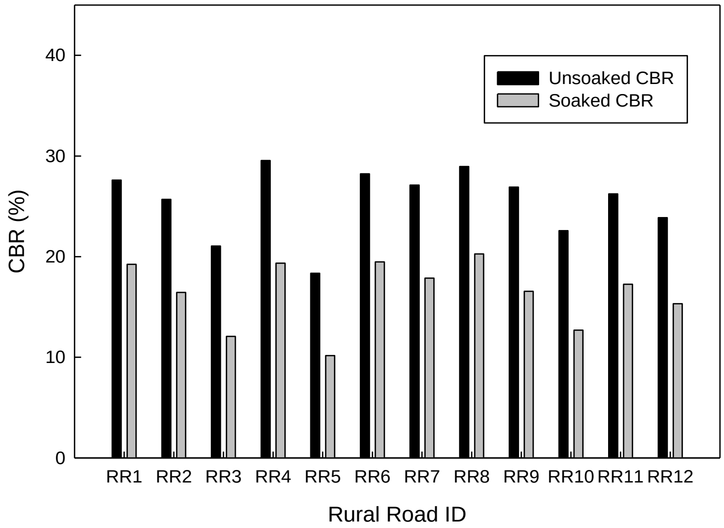


Figure 4.21 Unsoaked CBR and Soaked CBR Values of selected stretches

15. The average annual daily traffic (AADT) of 940 is maximum on RR3 followed by RR5 with an AADT of 713 (Fig. 4.22), hence the traffic volume on RR5 has significant contribution to the pavement deflection value of 1.8 mm.

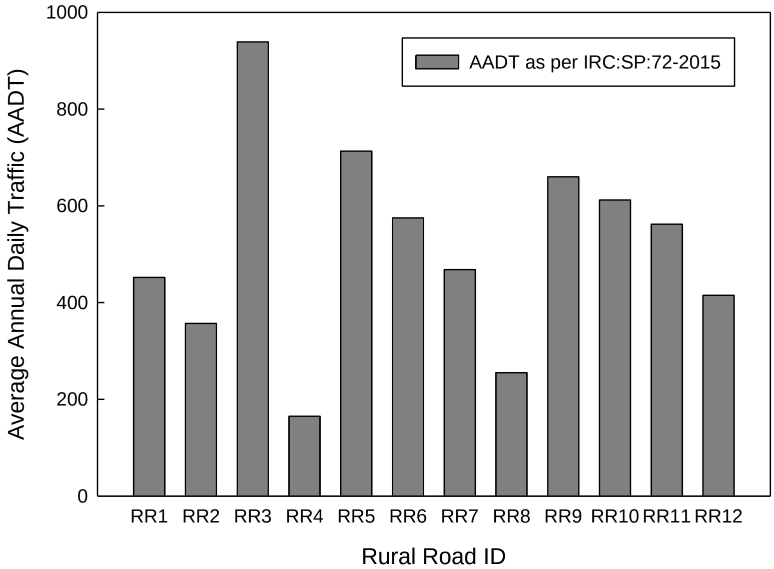


Figure 4.22 Average Annual Daily Traffic of selected stretches

16. The age of pavement from last overlay is in the range of 5-7 years as given in Table 3-7.
17. The two mathematical models of pavement surface deflection prediction models developed are evaluated using statistical parameters such as Mean Absolute Error (MAE), Mean Squared Error (MSE) and Root Mean Squared Error (RMSE) as shown in Eq. 4.3 and Eq. 4.4. The model developed in Eq. 4.3 is found to be better than model developed in Eq. 4.4 depending upon better RMSE value and R^2 value of 0.19 and 0.76 as compared to 0.21 and 0.72 respectively of Eq. 4.4.
18. The two models developed for pothole volume prediction as given in Eq. 4.5 and Eq. 4.6 suggests that the linear regression model with R^2 value of 0.87 provides better results as compared to the non-linear regression model with R^2 value of 0.85 as shown in Fig 4.10 and Fig 4.11 respectively.

CHAPTER 5

DEVELOPMENT OF RURAL ROAD MAINTENANCE PRIORITY INDEX

5.1 General

Prioritization of roads in respect to their pavement condition is requisite in order to utilize the available road maintenance fund fruitfully. Pavement Maintenance Prioritization can be done by solely using the models developed in previous chapter by considering the International Roughness Index (IRI) or by using Benkelman Beam Deflection values. However, Pavement condition needs to be assessed both functionally and structurally. Functional evaluation implies the analysis of exterior road surface conditions such as International Roughness Index (IRI), pavement distresses, skid resistance etc. Pavement distresses such as cracking, ravelling, rutting, potholes, patching, etc, majorly affects the pavement condition. Pavement Roughness also affects the riding quality or riding comfort of the passengers.

Apart from Functional evaluation, Structural condition of pavements also contributes a major role in determining the maintenance strategies. The characteristic deflection values determined by conducting Benkelman Beam Study helps in determining the thickness of overlay required. Modified Structural Number (MSN) has been found to be a good indicator of structural condition of pavement. The modulus of subgrade reaction (K) is also described as a structural parameter of pavements.

In this chapter, an attempt has been made to prioritize the rural roads in hilly terrain of Himachal Pradesh, India regarding their functional and structural conditions, in order to provide timely maintenance as required using Rural Road Maintenance Priority Index (RRMPI). RRMPI is a function of overall functional condition index (OFCI) and overall structural condition index (OSCI) and having a scale of 0-100, in which 0 signifies worst condition of pavement and 100 signifies best condition of pavement.

OFCI depends on International Roughness Index, total pavement distress and skid resistance. Hence, OFCI is a function of Functional Condition Roughness Index (FCI_{IRI}), Functional Condition Total Pavement Distress Index (FCI_{TPD}) and Functional Condition Skid Resistance Index (FCI_{SR}). Also, OSCI depends upon modified structural number (MSN) and Modulus of subgrade reaction (K-value). Hence, OSCI is a function of Structural Condition MSN Index

(SCI_{MSN}) and Structural Condition K-value Index ($SCI_{K\text{-}value}$). The weightage has been given to each parameter using Analytical Hierarchy Process (AHP). The final predicted RRMPI is a useful tool for various highway agencies and engineers in order to prioritize the maintenance strategies for rural road network in Himachal Pradesh for efficient use of road maintenance fund in a genuine manner.

5.2 Analysis for Development of Rural Road Maintenance Priority Index (RRMPI)

The overall flowchart of the methodology adopted in order to develop Rural Road Maintenance Priority Index (RRMPI) is presented in Fig. 5.1. In the present study, 12 rural road sections of hilly terrain have been studied in order to develop the Rural Road Maintenance Priority Index (RRMPI).

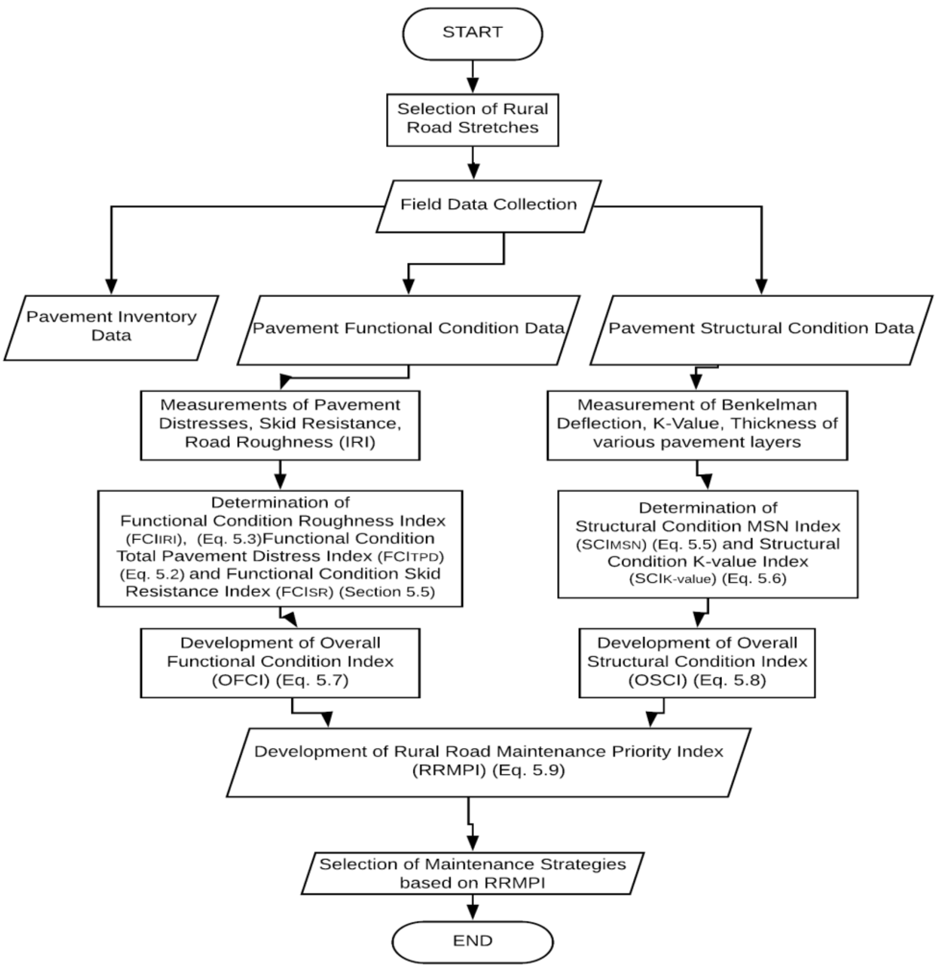


Figure 5.1 Flowchart showing detailed methodology to develop RRMPI

5.3 Functional Condition Total Pavement Distress Index (FCI_{TPD})

Various pavement distresses such as cracking, ravelling, patching, potholes, rutting etc. have been observed on the selected 12 rural road sections of hilly terrain in Himachal Pradesh. The functional condition total pavement distress index (FCI_{TPD}) has been generated using concept of Maximum Allowable Extent (MAE) [31].

The maximum allowable extents (MAE) of different pavement distresses with their severity levels and corresponding illustrations have been given in Table 5-1 [248, 249]. In the present study the threshold value for the rural road sections in Himachal Pradesh has been taken as 50. The threshold value indicates that the pavement has reached in a state where preventive and corrective measures are required for its rehabilitation.

Analytical Hierarchy Process (AHP), a complex decision making tool has also been used to give weightages to various distress parameters in order of their relative importance to each other. The AHP incorporates the imagination, knowledge and experience of each individual into the analysis of any problem. It synthesizes the numerous decisions or perceptions mathematically for which the consistency of the judgements is checked to evaluate each decision and finally the output is arrived to model the concerned problem statement. A sample of weightage determination of various parameters is shown in Fig. 5.2.

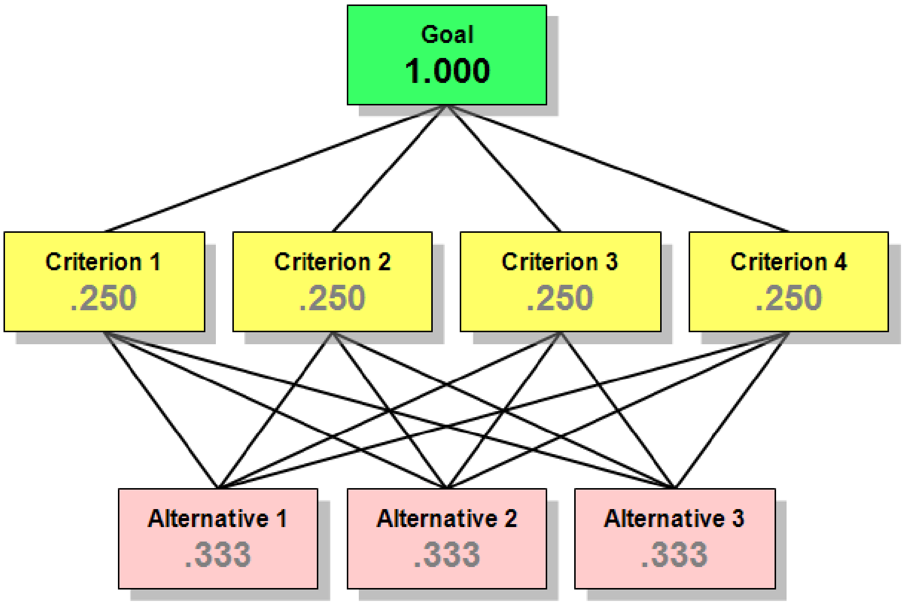


Figure 5.2 Sample Weightage for AHP

Table 5-1 Illustration of Severity levels and MAE for different pavement distresses

Sl. No.	Pavement Distress	Severity	Illustration	Maximum Allowable Extent
1	Longitudinal & Transverse Cracking	L	Crack mean width < 3 mm	25
		M	> 3 mm and < 6 mm	20
		H	> 6 mm	10
2	Alligator Cracking	L	Few connected cracks with width between 1 to 3 mm	50
		M	Moderate connected cracks width between 3 to 6 mm	25
		H	Extensive connected mapped cracking with width > 6mm	15
3	Potholes	L	< 25 mm deep and < 200 mm wide	50
		M	25-50 mm deep and 200-500 mm wide	30
		H	> 50 mm deep and >500 mm wide	10
4	Patching	L	Patching with low distress of any type and rutting < 4mm	50
		M	Patching with moderate distress and rut depth 4-10 mm	15
		H	Patching with extensive distress and rut depth > 10 mm	10
5	Rutting	L	Rut depth <4 mm	80
		M	4-10 mm	60
		H	> 10 mm	30
6	Ravelling	L	Loss of aggregate is low and ride quality affected low	70
		M	Loss of aggregates moderate and ride quality appreciably affected	30
		H	Loss of aggregates extensive and ride quality is poor	20
7	Mean Texture Depth	L	0-0.25 mm	90
		M	0.25-0.50 mm	65
		H	> 0.50 mm	40

The questionnaire given in Appendix-E has been disseminated into Highway Engineers, Scientists, Academicians and Research Scholars for their individual perception based on their experience and knowledge. A total of 157 questionnaires have been distributed out of which 123 responded and used to determine the relative Weightages of various distress parameters.
To check the Consistency Ratio (CR) of 123 responses Expert Choice 11 software has been used as shown in Fig. 5.3 and Fig. 5.4. If the consistency ratio of any response is more than 0.1 than that particular response has been discarded. Hence out of total 123 responses, 31 responses whose consistency ratio greater than 0.1 has been discarded and the Weightages has been calculated based on remaining 92 responses.

The final average weightages of each pavement distress after incorporating 92 responses whose inconsistency is less than 0.1 are given in Table 5-2. The weightages to different severity levels of distresses has also been taken as 1, 0.75 and 0.50 to high (H), medium (M) and Low (L) Severity respectively.

Table 5-2 Weightages determined using AHP Expert Choice 11 software

Pavement Distress Type	Weightage (W_i)
Longitudinal Cracking	0.15
Transverse Cracking	0.12
Alligator Cracking	0.23
Potholes	0.14
Rutting	0.22
Ravelling	0.05
Patching	0.07
Mean Texture Depth	0.02

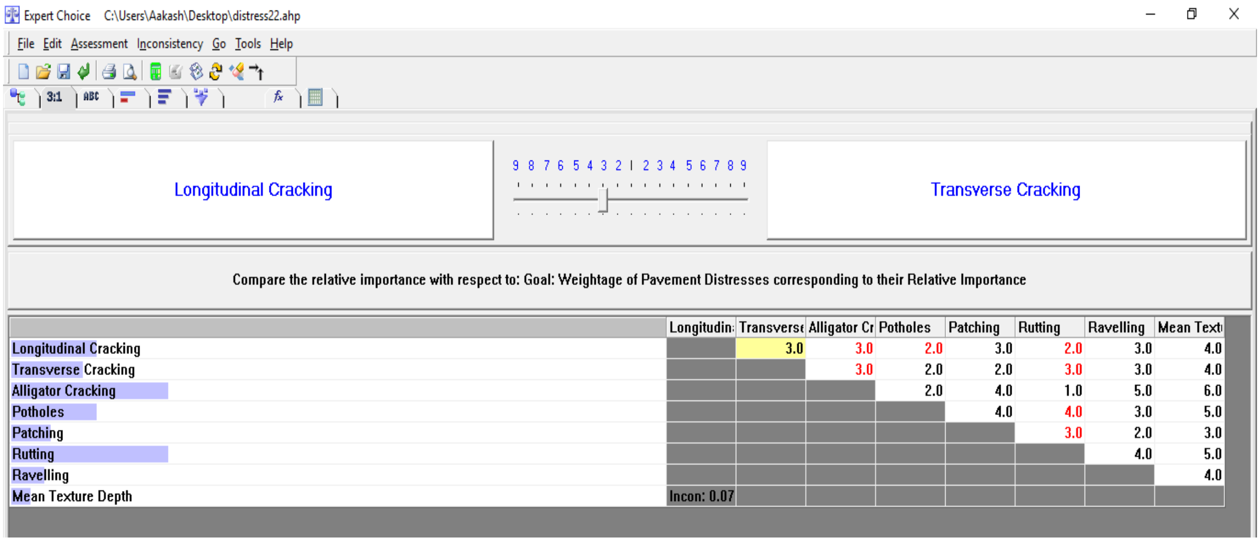


Figure 5.3 Expert Choice 11 software using questionnaire data

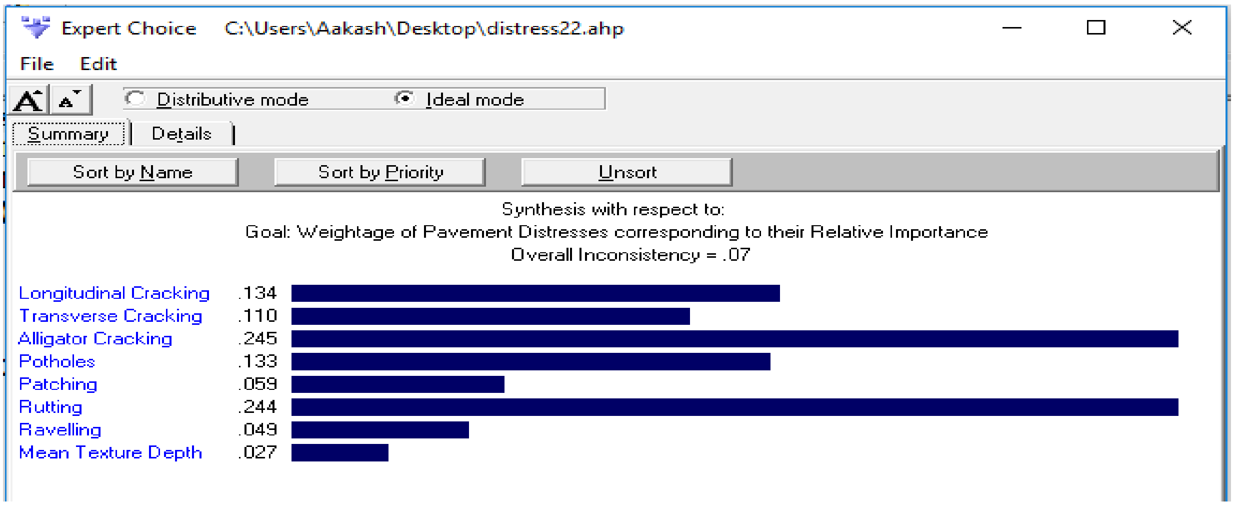


Figure 5.4 Sample weightages determined using a questionnaire in Expert Choice 11 software

The distress index calculated using equations given in Table 5-3 are subjected to a minimum value of 0 and maximum value of 100 where %L, %M and %H indicated the percentage of distress area measured using simple measuring tape (longitudinal cracking, transverse cracking, alligator cracking, patching, and ravelling) with low, medium and high severity respectively.

Table 5-3 Distress Index corresponding to Low, Medium and High Severity

Distress	Low Severity Index (LSI)	Medium Severity Index (MSI)	High Severity Index (HSI)
Longitudinal Cracking	**100- 50* (%L/25)**	**100- 50* (%M/20)**	**100- 50* (%H/10)**
Transverse Cracking	**100- 50* (%L/25)**	**100- 50* (%M/20)**	**100- 50* (%H/10)**
Alligator Cracking	**100- 50* (%L/50)**	**100- 50* (%M/25)**	**100- 50* (%H/15)**
Potholes	**100- 50* (%L/50)**	**100- 50* (%M/30)**	**100- 50* (%H/10)**
Patching	**100- 50* (%L/50)**	**100- 50* (%M/15)**	**100- 50* (%H/10)**
Rutting	**100- 50* (%L/80)**	**100- 50* (%M/60)**	**100- 50* (%H/30)**
Ravelling	**100- 50* (%L/70)**	**100- 50* (%M/30)**	**100- 50* (%H/20)**
Mean Texture Depth	**100- 50* (%L/90)**	**100- 50* (%M/65)**	**100- 50* (%H/40)**

Percent of rut depth and potholes within each severity is measured using the following equation-

(Number of ruts or potholes within each severity/15)* 100

Percent of mean texture depth within each severity is measured using the following equation-

{Number of sand patch test results (test conducted subjected to 15 sample per 100 m length of road and 3.5 m wide) within each severity/Total Number of test conducted} * 100

Further, each pavement distress index has been calculated by incorporating the weight factors of different severity levels. The distress index for each distress of pavement can be calculated using equation (5.1).

$$\text{Each Pavement Distress Index (PDI)} = \frac{\lfloor 0.50*LSI+0.75*MSI+1.0*HSI \rfloor}{\lfloor 0.50+0.75+1.0 \rfloor} \qquad \text{(Eq. 5.1)}$$

The functional condition Total Pavement Distress has been calculated by incorporating the weightages determined by Analytical Hierarchy Process (AHP) using Expert Choice 11 software given in Table 5-2. The functional condition total pavement distress has been determined by using equation (5.2).

$$FCI_{TPD} = \sum w_i * PDI \qquad \text{(Eq. 5.2)}$$

Where, w_i = weightages given in Table 5-2

PDI = Each Pavement Distress Index corresponding to longitudinal cracking, transverse cracking, alligator cracking, potholes, patching, rutting, ravelling and mean texture depth calculated from equation (5.1).

5.4 Functional Condition Roughness Index (FCI_{IRI})

The functional condition roughness index has been determined by correlating the International Roughness Index (IRI) and Ride Comfort Rating (RCR) as given by non-linear regression equation (5.3). The International Roughness Index (IRI) has been calculated using MERLIN on the selected rural road sections of hilly terrain. The Ride Comfort Rating (RCR) survey has been done by a panel of four members on the selected road sections and their average rating depending upon the guidelines given in Table 5-4 and their personal perception has been considered in the study.

$$FCI_{IRI} = RCR = -606.40 + 848.80 * (IRI)^{(-0.14)} \quad (R^2 = 0.85) \qquad \text{(Eq. 5.3)}$$

Where,

RCR = Ride Comfort Rating subjected to Minimum value 0 and Maximum value 100

IRI = International Roughness Index in (m/km)

5.5 Functional Condition Skid Resistance Index (FCI_{SR})

The skid resistance has been obtained by using skid resistance pendulum testing machine. The scale of skid resistance pendulum testing machine is between 0-100 in which higher value depicts a good pavement surface with high skid resistant surface and low value depicts that pavement surface is slippery and skid resistant is low. Hence, the functional condition skid resistance index (FCI_{SR}) has been taken directly from the result obtained by the skid resistant pendulum testing machine.

Table 5-4 Guidelines for Panel Conducting Ride Comfort Rating (RCR)

Ride Comfort Rating (RCR)	Section Evaluation	Description
0-20	Very Poor	More than 75% of the pavement section is drastically affected by presence of large, deep and wide cracks and potholes. The riding quality/comfort is drastically affected and speed is reduced. The pavement surface possesses water logging problem in rainy season.
20-40	Poor	About 50% of the pavement surface is affected with deep and wide cracks, large potholes, free flowing speed reduced drastically and other type of high severity distresses are prevailing on the section surveyed.
40-60	Fair	Ride comfort quality is moderately affected which affects high-speed flow of traffic. Moderate alligator cracking, patching, rutting observed over the surface.
60-80	Good	Riding Comfort may be good but apart from it, very low severity visible micro-cracks and initiation of rutting or ravelling over the surface observed.
80-100	Very Good	Conditions similar to a newly constructed pavement having smooth surface and no visible pavement distress on the surface.

5.6 Structural Condition MSN Index (SCI_{MSN})

The best indicator of structural condition of pavement is its structural number which depends on the rebound deflection of the surface of the pavement, layer coefficients, and thickness composition of each layer of pavement. The characteristic deflection of the surface of pavement has been measured using Benkelman beam as per the procedure recommended in IRC 81:1997.

AASHTO test developed the concept of Structural Number (SN) which is the indicator of strength of any pavement. Further the Structural Number has been modified after incorporating the California Bearing Ratio (CBR) of subgrade and defined as Modified Structural Number (MSN). The Modified Structural Number is calculated using equation (5.4).

$$MSN = SN + 3.51\,(\log_{10} CBR) - 0.85(\log_{10} CBR)^2 - 1.43 \qquad \text{(Eq. 5.4)}$$

Where, $SN = \sum_{i=1}^{n} a_n * t_n$

Where, a_n = layer coefficients of n layers, t_n = thickness of n layers of pavement in inches

CBR = California Bearing Ratio of pavement subgrade (%)

The layer coefficients of different layers as prescribed by Central Road Research Institute [61], New Delhi have been used in the present study. The structural condition MSN Index has been determined using equation (5.5).

$$SCI_{MSN} = \left(\frac{MSN}{SN_{effective}}\right) X\ 100 \qquad \text{(Eq. 5.5)}$$

Where,

$SN_{effective} = 3.2 * (Characteristic\ Deflection\ in\ mm\ using\ Benkelman\ Beam) - 0.63$

MSN = Modified Structural Number from equation (5.4)

5.7 Structural Condition K-Value Index ($SCI_{K\text{-}value}$)

The modulus of subgrade reaction is an important structural parameter which indicates the structural adequacy of the concerned pavement. The K-value can be obtained by conducting plate bearing test but the test being too expensive, hence the required K-value for the selected 12 rural road sections of hilly region has been obtained using the relationship given between soaked CBR and K-value in IRC 58-2015.

The range of K-value for a soaked CBR range of 2% - 100% is 21 – 220 MPa/m. Since, the subgrade CBR value of 15% is considered very good for rural road sections of hilly region in Himachal Pradesh and 2% CBR as very poor as per IRC-SP: 72-2015; hence, the subgrade CBR value of 15% is taken as the upper limit and the structural condition K-value index has been obtained by normalizing it in range of 0-100 by using the formula given in equation

(5.6), where high value of index depicts stiffer and good structural adequacy of pavement whereas low value directs a poor structural adequacy of pavement.

$$SCI_{K\text{-value}} = 100 * \frac{(K_{value} - 21)}{(62-21)} = 2.44 * (K_{value} - 21) \qquad \text{(Eq. 5.6)}$$

5.8 Development of Overall Functional Condition Index (OFCI) and Overall Structural Condition Index (OSCI)

The overall functional condition index (OFCI) is dependent on Functional Condition Total Pavement Distress Index (FCI_{TPD}), Roughness Index (FCI_{IRI}) and Skid Resistance Index (FCI_{SR}) where as overall structural condition index (OSCI) depends upon Structural Condition MSN Index (SCI_{MSN}) and K-Value Index ($SCI_{K\text{-value}}$). Hence, weightages need to be determined for various parameters depending upon OFCI and OSCI to develop respective indexes. The same sample data of 92 responses has been used corresponding to questionnaire given in Appendix-E. Expert Choice 11 software has been used and the structured tree of OFCI and OSCI has been shown in Fig. 5.5. The dynamic sensitivity of nodes has also been done using the software shown in Fig. 5.6. The average weightage of 55%, 30% and 15% has been obtained for OFCI parameters of Total Pavement Distress Index (FCI_{TPD}), Roughness Index (FCI_{IRI}) and Skid Resistance Index (FCI_{SR}) respectively and the average weightage of 65% and 35% has been assigned to OSCI parameters of Structural Condition MSN Index (SCI_{MSN}) and K-Value Index ($SCI_{K\text{-value}}$) respectively. Hence, the Overall Functional Condition Index (OFCI) and Overall Structural Condition Index (OSCI) has been determined using equations (5.7) and (5.8) respectively.

$$OFCI = 0.55 * FCI_{TPD} + 0.30 * FCI_{IRI} + 0.15 * FCI_{SR} \qquad \text{(Eq. 5.7)}$$

Where, FCI_{TPD} = Functional Condition Total Pavement Distress Index

FCI_{IRI} = Functional Condition Roughness Index

FCI_{SR} = Functional Condition Skid Resistance Index

$$OSCI = 0.65 * SCI_{MSN} + 0.35 * SCI_{K-value} \qquad \text{(Eq. 5.8)}$$

Where, SCI_{MSN} = Structural Condition MSN Index

$SCI_{K\text{-value}}$= Structural Condition K-Value Index

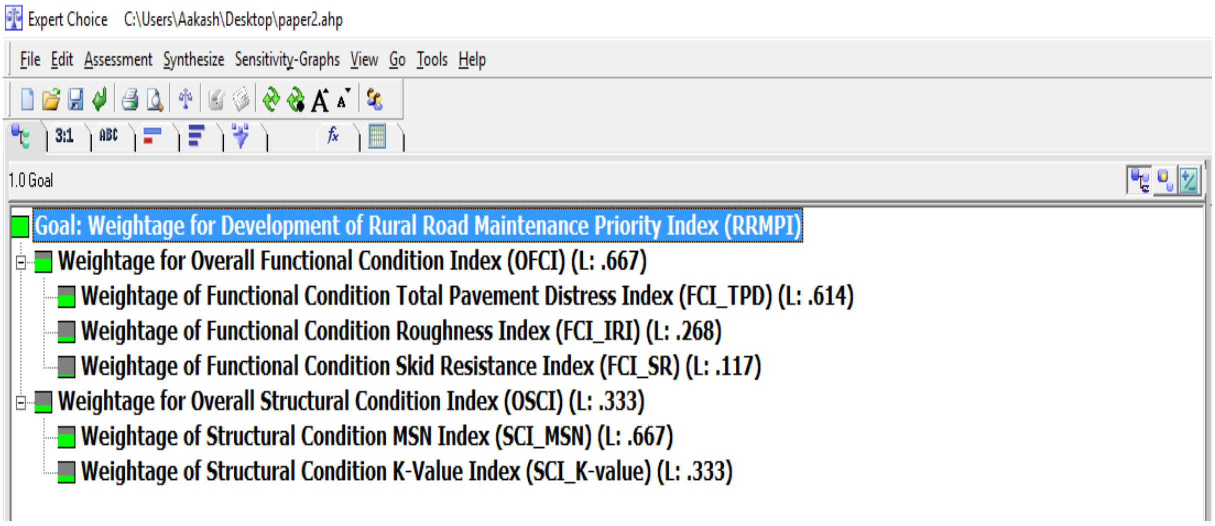


Figure 5.5 Weightage determination using Expert Choice 11 software

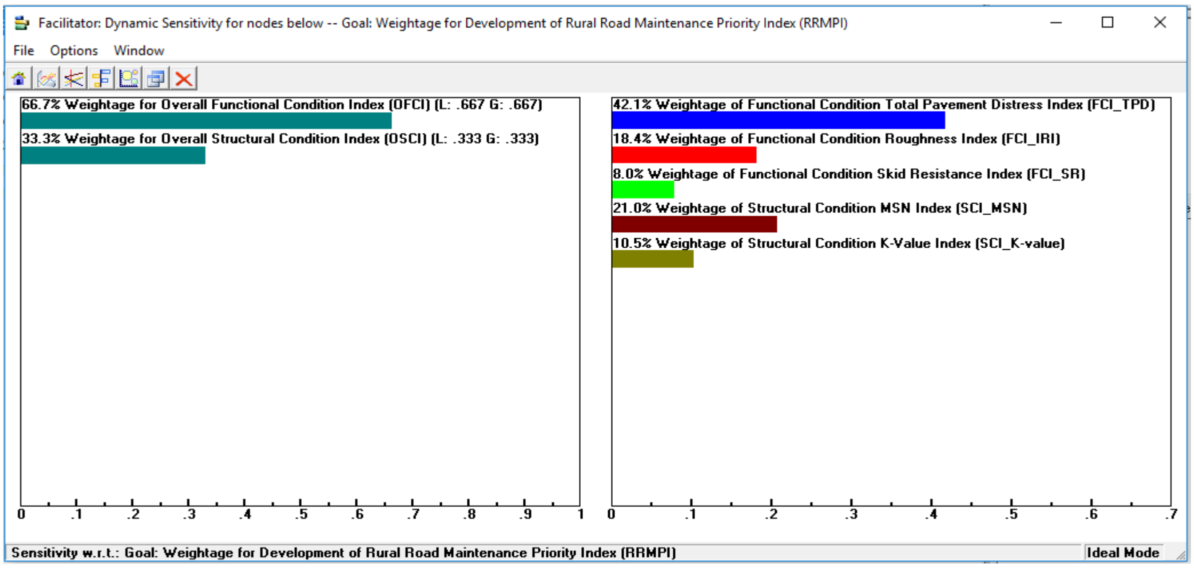


Figure 5.6 Dynamic Sensitivity of nodes using Expert Choice 11 software

5.9 Development of Rural Road Maintenance Priority Index (RRMPI)

The Rural Road Maintenance Priority Index (RRMPI) has been developed which is based on overall functional condition index (OFCI) and overall structural condition index (OSCI) which has been determined using equations (5.7) and (5.8) respectively. The weights have been assigned to functional parameters and structural parameters of pavement separately in order to articulate the final Rural Road Maintenance Priority Index (RRMPI) for best results. The weights have been determined using Expert Choice 11 software based on Analytical Hierarchy Process as shown in Fig. 5.6 using questionnaire given in Appendix-E. After processing 92 questionnaires, the average weightage of 60% has been assigned to functional parameters and 40% to structural parameters. Hence, final RRMPI has been determined using equation (5.9).

$$RRMPI = 0.6 * (OFCI) + 0.4 * (OSCI) \qquad \text{(Eq. 5.9)}$$

Where, OFCI and OSCI are overall functional condition index and overall structural condition index respectively.

5.10 Maintenance and Repair Strategies based on RRMPI

Some maintenance and repair strategies has been suggested in the present study for the preventive and corrective measures of rural road sections depending upon various ranges of Rural Road Maintenance Priority Index (RRMPI) values. Since, the Rural Road Maintenance Priority Index (RRMPI) has been evolved considering the functional parameters and structural parameters of the rural roads; hence it is expected to be a best indicator of pavement condition. The Maintenance and Repair strategies corresponding to various ranges of RRMPI values have been recommended in Table 5-5.

Table 5-5 Maintenance and Repair strategies based on RRMPI Values

RRMPI Range	Pavement Rating	Maintenance and Repair Strategies
0-15	Very Poor	Full Depth Reconstruction, Reclaimed Asphalt Pavement Recycling
15-30	Poor	Thick overlays, Premix Carpet, Surface Dressing
30-50	Fair	Thick overlays, Full Depth Patching, Pothole filling
50-65	Good	Thin Overlays, patching, fog seal
65-80	Very Good	Thin Overlays, Chip Seal, Micro-surfacing
80-100	Excellent	Routine Maintenance that includes micro crack sealing, patching

5.11 Results and Discussions

1. The individual functional condition indexes of total pavement distress, International Roughness Index, Skid Resistance and structural condition indexes of Modified structural number and K-value parameter has been shown in Fig. 5.7.

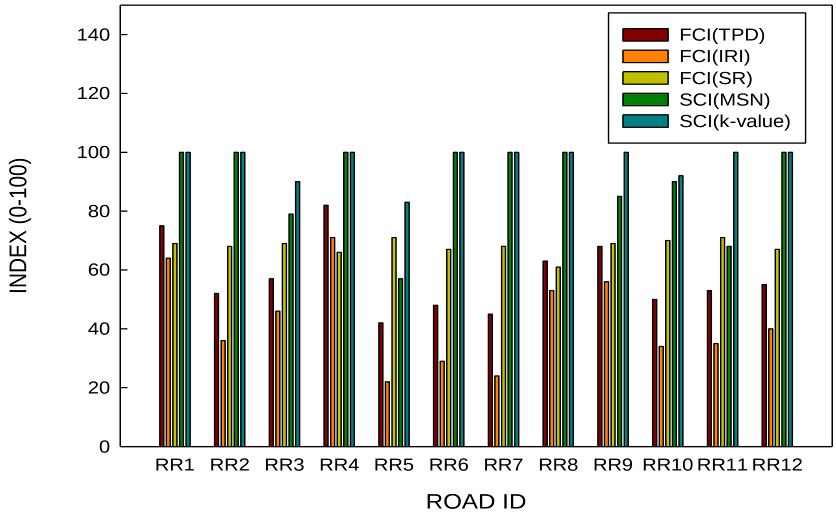


Figure 5.7 Individual Functional and Structural Indexes

2. The overall functional condition index (OFCI), overall structural condition index (OSCI) and The Rural Road Maintenance Priority Index (RRMPI) has been determined for all the 12 selected rural road sections of hilly terrain in Himachal Pradesh which has been depicted in Fig. 5.8.

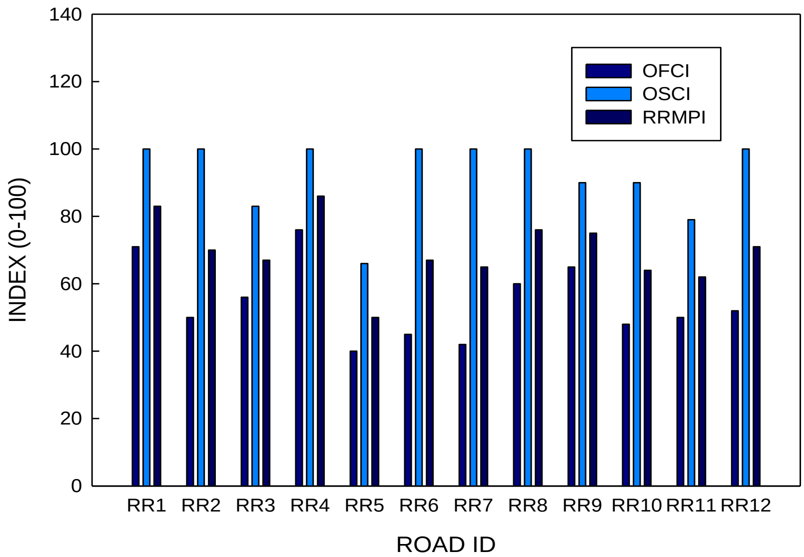


Figure 5.8 OFCI, OSCI and RRMPI Indexes of selected Rural Roads

3. Also, the calculated Indexes based on functional and structural parameters, OFCI, OSCI, RRMPI, Ranking based on IRI, BBD and RRMPI for selected rural road sections of hilly terrain are presented in Table 5-6.
4. It shows that there is a significant difference in the indexes calculated based on structural and functional parameters of the rural roads of hilly terrain. As per OFCI (Table 5-6), RR5 needs to be maintained first with an Overall functional condition index of 40 and RR4 maintenance can be deferred as compared to other rural road sections with an OFCI value of 76.
5. As far as OSCI is concerned (Table 5-6), RR5 with an overall structural condition index of 66 needs to be maintained first, having lowest value of OSCI. However, it shows that RR1, RR2, RR4, RR6, RR7, RR8, and RR12 have very good structural strength with an OSCI value of 100 and do not need any maintenance whereas same rural road sections have different priority need of maintenance corresponding to OFCI values.
6. If prioritization can be done solely on the basis of IRI measured using MERLIN (Table 5-6), then RR5 needs to be maintained first and RR4 maintenance can be deferred and can be maintained at later stage or at last as compared to other rural road sections.
7. As per prioritization of rural road sections based on Benkelman Beam deflection values, again RR5 needs to be maintained first and RR4 needs maintenance at last stage (Table 5-6).
8. If the prioritization ranking of RR6 is concerned, then it can be clearly concluded from Table 5-6 that RR6 has third, ninth and fifth priority ranking corresponding to IRI values, BBD values and RRMPI values respectively.
9. RRMPI can be proved to be cost efficient also as proper and strategic prioritization of maintenance will lead to cost effectiveness because deferred maintenance always lead to economic loss.
10. Hence from the above discussion, it can be clearly seen that Rural Road Maintenance Priority Index (RRMPI) is an accurate tool for determining the priority ranking for maintenance strategies of different rural road section in hilly terrain.

Table 5-6 Calculated Indexes based on functional and structural parameters, OFCI, OSCI, RRMPI, Ranking based on IRI, BBD and RRMPI for selected rural road sections of hilly terrain

Rural Road ID	FCI_{TPD}	FCI_{IRI}	FCI_{SR}	SCI_{MSN}	$SCI_{K\text{-}value}$	OFCI	OSCI	RRMPI	Ranking Based on IRI	Ranking Based on BBD Values	Ranking Based on RRMPI
RR1	75	64	69	100	100	71	100	83	11	7	11
RR2	52	36	68	100	100	50	100	70	6	11	7
RR3	57	46	69	79	90	56	83	68	8	4	6
RR4	82	71	66	100	100	76	100	86	12	12	12
RR5	42	22	71	57	83	40	66	50	1	1	1
RR6	48	29	67	100	100	45	100	67	3	9	5
RR7	45	24	68	100	100	42	100	65	2	6	4
RR8	63	53	61	100	100	60	100	76	9	10	10
RR9	68	56	69	85	100	65	90	75	10	3	9
RR10	50	34	70	90	92	48	90	64	4	5	3
RR11	53	35	71	68	100	50	79	62	5	2	2
RR12	55	40	67	100	100	52	100	71	7	8	8

CHAPTER 6

CONCLUSIONS

6.1 General

The chapter incorporates the conclusions derived from the functional and structural evaluation of pavements, development of road roughness model and pavement surface deflection model and developed Rural Road Maintenance Priority Index (RRMPI). The Rural Road Maintenance Priority Index (RRMPI) can be proved to be a powerful and handy tool for the highway engineers and road agencies, especially for the rural road sections of hilly terrain in order to prioritize the various pavement sections for their maintenance strategies. It also helps in appropriate allocation of road maintenance fund in a strategic manner without any economic loss.

6.2 Conclusions

Rural Roads of hilly terrain have been studied in the present study in order to prioritize the rural road network for the efficient management of road maintenance funds. Functional evaluation and structural evaluation of the same rural roads of hilly terrains has been conducted in the present study to evaluate the pavement maintenance. For this, 12 rural road stretches in hilly terrain of Himachal Pradesh has been selected for the development of International Roughness Index prediction model, Benkelman Beam Pavement Deflection model, pothole volume prediction model and Rural Road Maintenance Priority Index (RRMPI). From the results obtained in the present work, following conclusions can be drawn-

1. The objectives have been achieved after collection of vigorous data pertaining to functional and structural evaluation parameters which further helped in generation of roughness index models and pavement surface deflection models as a result of which RRMPI has been developed.
2. Various mathematical models have been generated to predict the value of International Roughness Index based on various distress parameters which are available and causes major affect on the roughness of rural roads present in Himachal Pradesh. The models have been developed using linear regression, non-linear regression and Artificial

Neural Networks which depicts that linear regression model and non-linear regression model gives very effective results when compared to Artificial Neural Network.

3. The R^2 value in case of linear model and non-linear model for tested data is found to be 0.810 and 0.837 respectively which shows a very good correlation between the observed IRI and predicted IRI. Both the models are very accurate; however, the R^2 value of non-linear model is on upper hand which is 3.34% more than that of linear regression model. Hence, it is suggested that non-linear model is more reliable than linear regression model.
4. The MSE values of linear regression model, non-linear regression model and ANN model for tested data are found to be 0.19, 0.16 and 0.67 respectively which again shows that linear regression and non-linear regression models are predicting far better results when compared to ANN model. It is due to because the number of data observations is quite less required for data training in Artificial Neural Network modelling. Hence, it is suggested that more number of data sets can be collected for better results of Artificial Neural Network model for further research scope on rural roads of Himachal Pradesh.
5. The structural evaluation data collected on the selected twelve rural road stretches of hilly terrain of Himachal Pradesh are used in the present study to develop mathematical models to predict Benkelman beam characteristic deflection based on Soaked CBR, Un-soaked CBR, Average Annual Daily Traffic (AADT), Age of pavement from last overlay (in years) and K-value. The models have been developed using linear regression analysis with the help of sklearn library in PYTHON. The correlation matrix has been formed to check the correlation within the parameters. Soaked CBR and Unsoaked CBR are found to be highly correlated to each other and hence either of these may be neglected. Hence, unsoaked CBR has been neglected in the modelling as soaked CBR being good representative of structural strength of pavement subgrade.
6. The developed models have been compared based on conventional statistical parameters such as MAE, MSE, RMSE and R^2 values. It has been found that the model developed to predict pavement deflection using soaked CBR, AADT and age of pavement is found to be more accurate as R^2 value of 0.76 and RMSE value of 0.19 being good as compared to other model. Modelling of characteristic deflection is very essential for the pavement maintenance management system and structural analysis of

pavements. Prediction of characteristic deflection value using mathematical models can give easy estimates of overlay design without carrying out actual Benkelman beam survey in the field which leads to disruption of traffic on narrow rural roads of hilly terrain and increase in cost of the project.

7. The two models developed for pothole volume prediction model suggests that the linear regression model provides better results as compared to the non-linear regression model with better R^2 value of 0.87 and can be proved to be an vital tool for highway engineers to directly calculate the pothole volume without actual measurements.
8. From the study of Rural Road Maintenance Priority Index (RRMPI), it has been found that RR1 and RR4 has RRMPI in range 80-100 hence pavement rating is excellent and RR5, RR7, RR10, RR11 are in range of 50-65 which are in good condition. It can be easily found that prioritization with respect to different parameters is different as distinct indexes has been determined in a scale of 0-100 which do not give a clear picture which can signify the worst or best condition of any road.
9. The RRMPI results in proper allocation of maintenance funds which can be proved to be a vital tool for the highway maintenance engineers and highway agencies. It also imparts sustainable development of the country.
10. Also, it can be clearly understood that prioritization cannot be done by simply considering the International Roughness value or Benkelman Beam deflection value alone as it gives haphazard results and the maintenance fund is not used appropriately.
11. It has been found that RR5 has the top priority ranking and needs to be maintained first and RR4 is the best road and needs least priority in maintenance with respect to IRI ranking, BBD ranking and RRMPI ranking. However, RR6 is considered at third, ninth and fifth priority in maintenance corresponding to ranking based on IRI, BBD values and RRMPI method. Hence, it shows that RRMPI signifies a clear and lucid condition of different roads.

6.3 Scope for future work

The scope for future work includes-

1. The number of rural road stretches selected in hilly terrain for collecting field data functional and structural parameters can be increased in further research work.

2. The road category can be altered to National Highway, State Highway which is of major importance in any hilly region or terrain.
3. The PWD highway authorities which are responsible for the maintenance of rural road network of any hilly terrain may develop and implement a PMS as per the methodology adopted in the present study.
4. The concerned field or highway engineers may be trained to successfully implement the current maintenance methodology.
5. The present study uses limited functional and structural parameters for predicting the road roughness model and pavement characteristic deflection model. Future study may include some more structural and functional parameters and more stretches may be selected of longer length in kilometres to further improve the present developed models.
6. During the study, some difficulties pertaining to data collection for Benkelman Beam were observed due to traffic congestion because of narrow roads. Hence, rapid technique of Falling Weight Deflectometer to determine deflection can be used in further study. Further, more data points can be used to develop the Pavement Surface Deflection Model.

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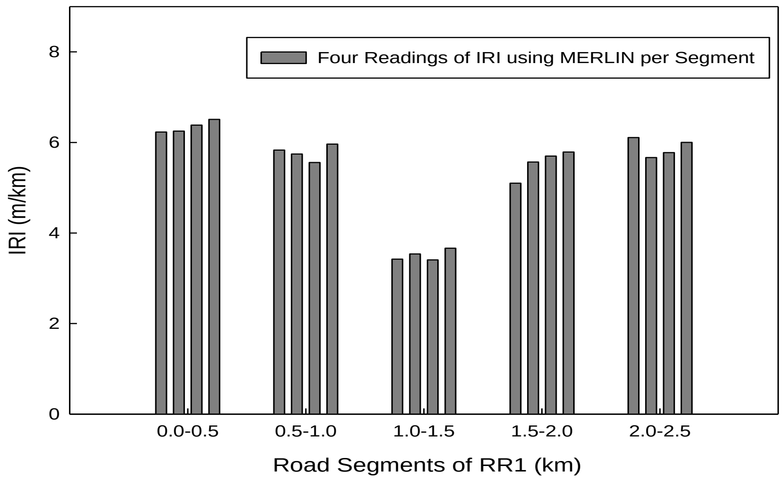
PUBLICATIONS

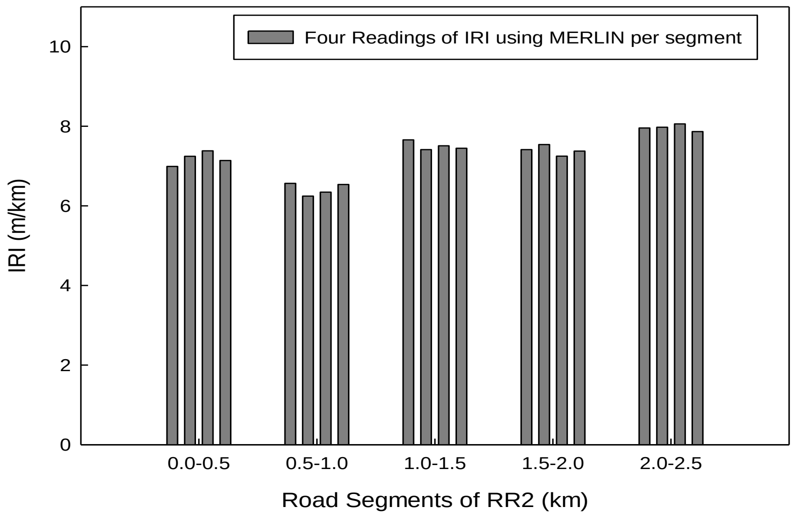
JOURNAL PUBLICATIONS

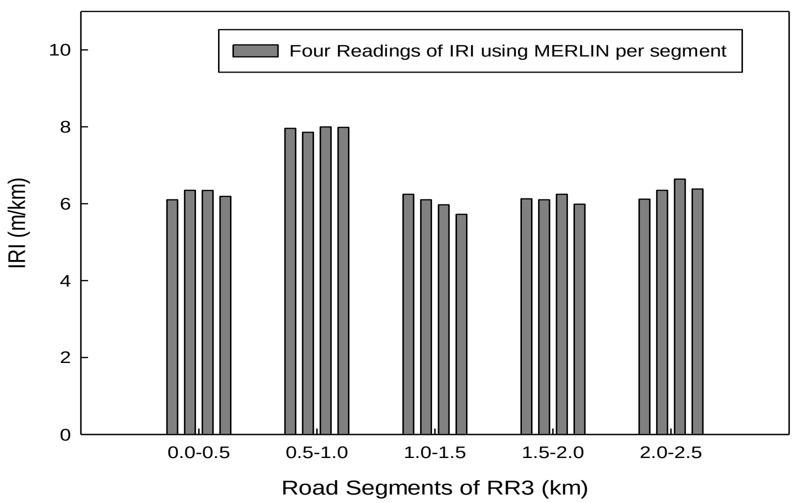
1. Aakash Gupta, Ashok Kumar Gupta, Ashish Kumar (2019). “Development of Maintenance Management System by Functional Evaluation for Rural Roads in Himachal Pradesh.” International Journal of Recent Technology and Engineering, 8 (1), 1682-1690 **(SCOPUS Indexed/ Published)**
2. Aakash Gupta, Ashok Kumar Gupta, Ashish Kumar (2018). ” Road Asset Management Using Pavement Performance Prediction Models.” Journal of Advanced Research in Dynamical and Control Systems, 10 (12), 300-310 **(SCOPUS Indexed/ Published)**
3. Aakash Gupta, Ashok Kumar Gupta, Ashish Kumar (2019). “A model for Pavement Characteristic Deflection for Rural Roads in Himachal Pradesh” Periodicals of Engineering and Natural Science **(SCOPUS Indexed/ Accepted)**
4. Aakash Gupta, Ashok Kumar Gupta, Ashish Kumar (2019). “Development of Road Roughness Model using Analytical Hierarchy Process for Rural Road Network in Himachal Pradesh” International Journal of Pavement Research and Technology **(Springer/ Submitted)**
5. Aakash Gupta, Ashok Kumar Gupta, Ashish Kumar (2019). “Rural Road Maintenance Prioritization Index based on Functional and Structural Parameters for Rural Road Network in Himachal Pradesh” International Journal of Pavement Research and Technology **(Springer/Re-Submitted after first review)**

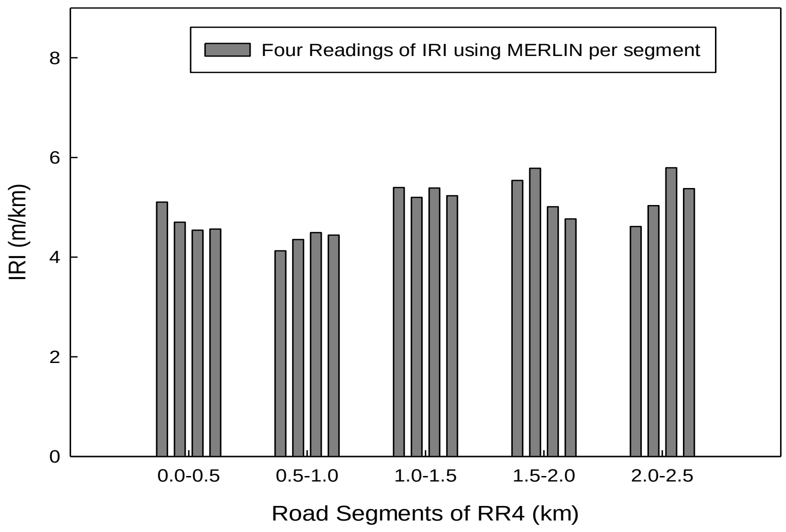
APPENDIX-A

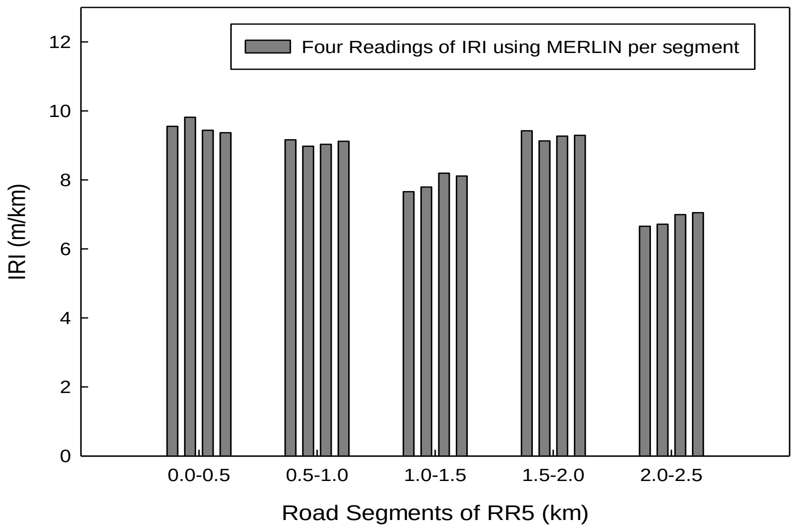
ROUGHNESS DATA

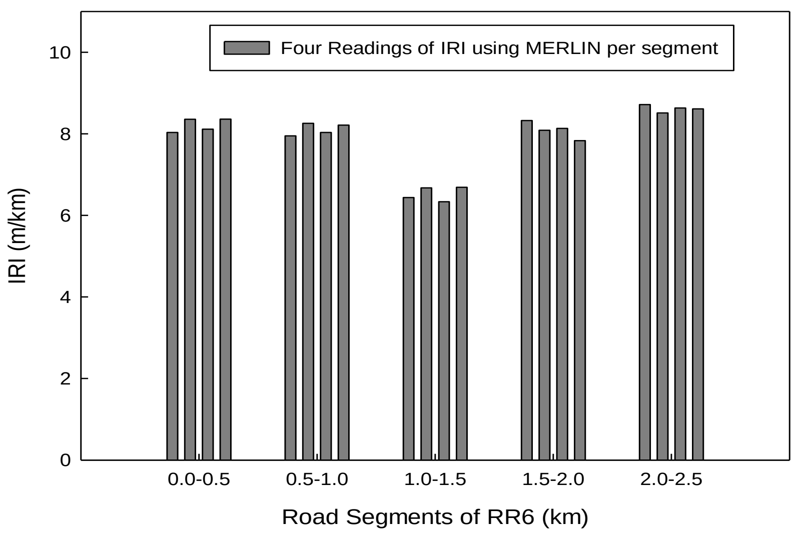

Four Readings of IRI using MERLIN per Segment
IRI (m/km)
0
2
4
6
8
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR1 (km)

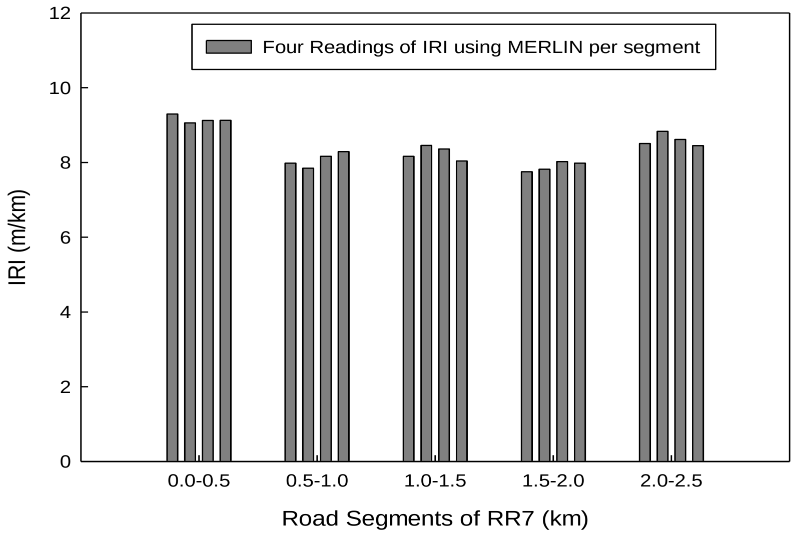

Four Readings of IRI using MERLIN per segment
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR2 (km)


Four Readings of IRI using MERLIN per segment
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR3 (km)

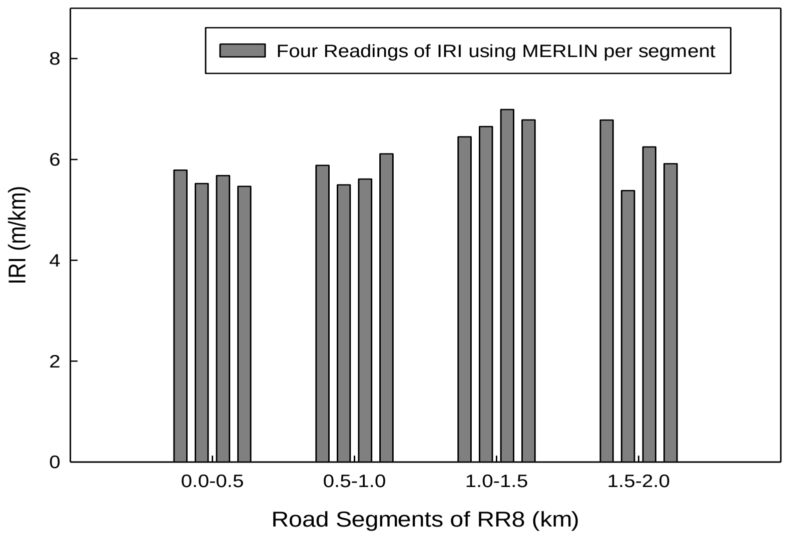

Four Readings of IRI using MERLIN per segment
IRI (m/km)
0
2
4
6
8
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR4 (km)


Four Readings of IRI using MERLIN per segment
IRI (m/km)
0
2
4
6
8
10
12
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR5 (km)

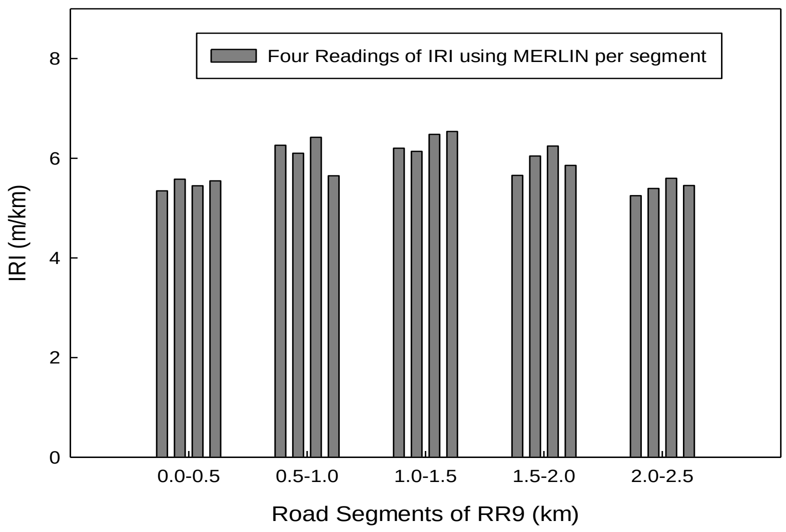

Four Readings of IRI using MERLIN per segment
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR6 (km)



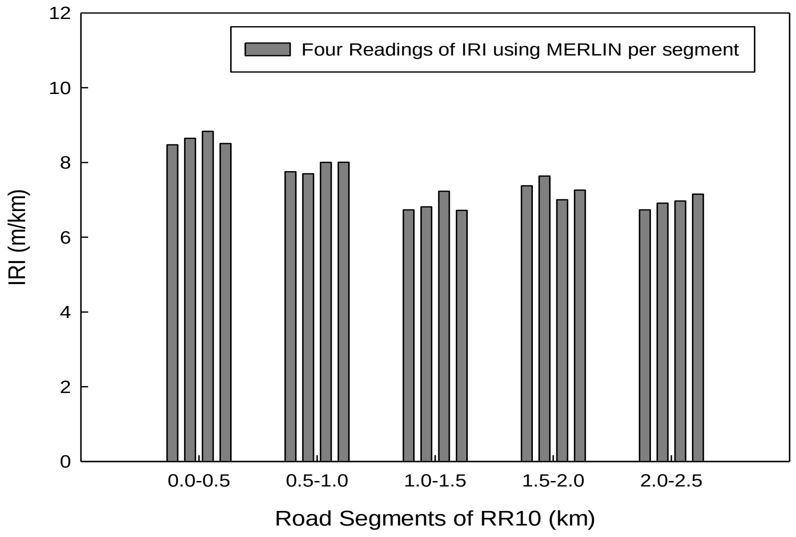
12
10
8
6
4
2
0
IRI (m/km)
Four Readings of IRI using MERLIN per segment
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR7 (km)



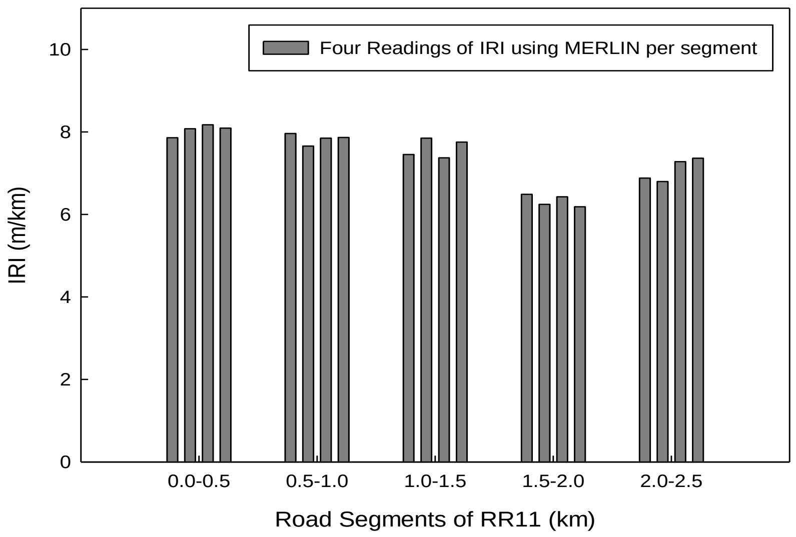
8
6
4
2
0
IRI (m/km)
Four Readings of IRI using MERLIN per segment
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
Road Segments of RR8 (km)



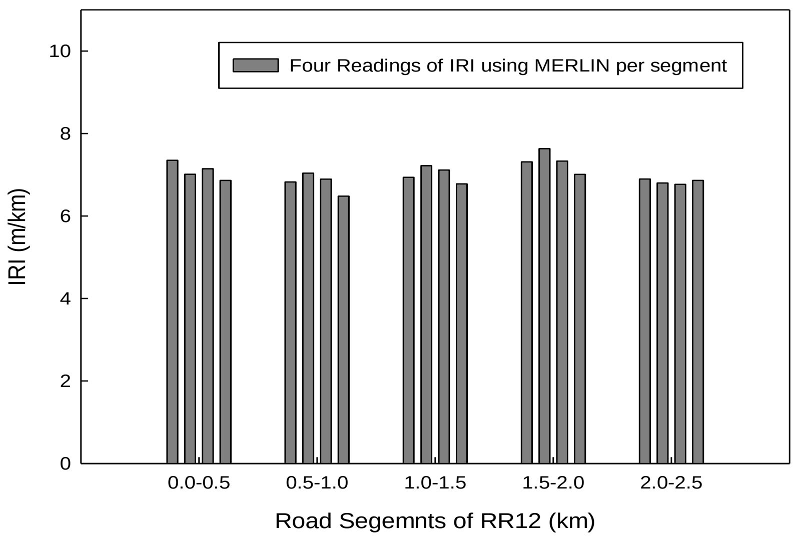
8
6
4
2
0
IRI (m/km)
Four Readings of IRI using MERLIN per segment
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR9 (km)



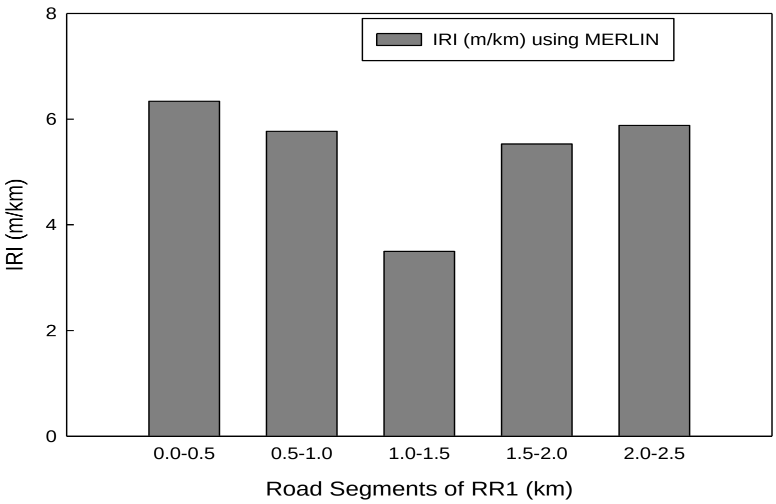
Four Readings of IRI using MERLIN per segment
IRI (m/km)
12
10
8
6
4
2
0
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR10 (km)

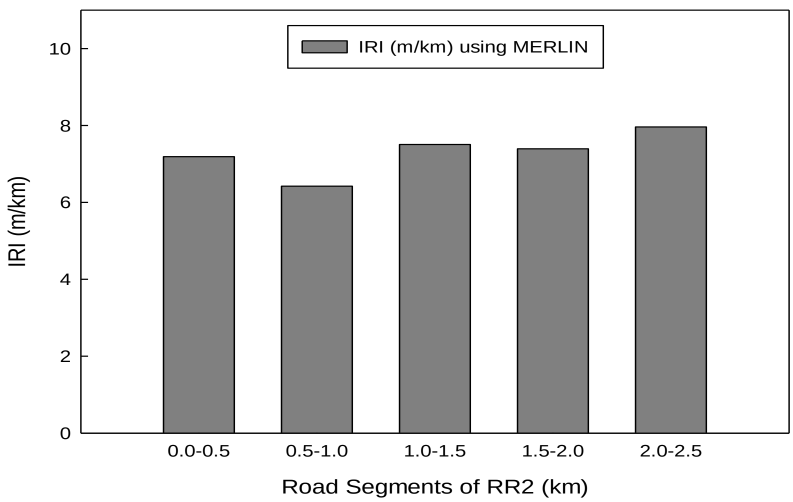


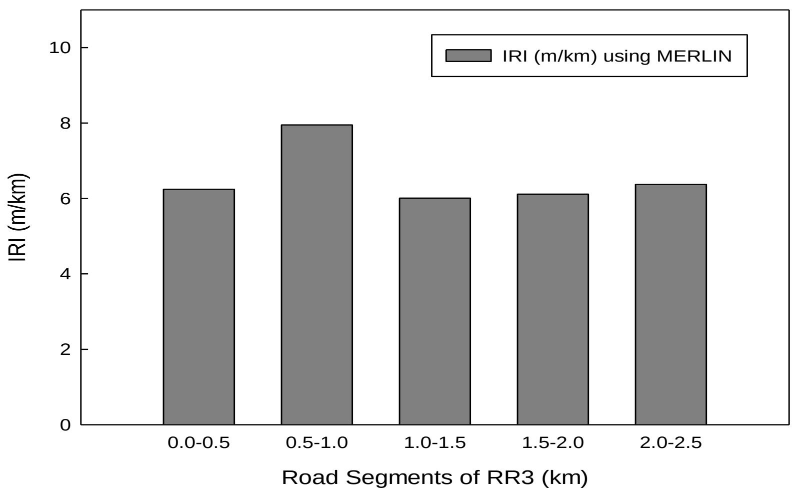
Four Readings of IRI using MERLIN per segment
IRI (m/km)
10
8
6
4
2
0
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR11 (km)

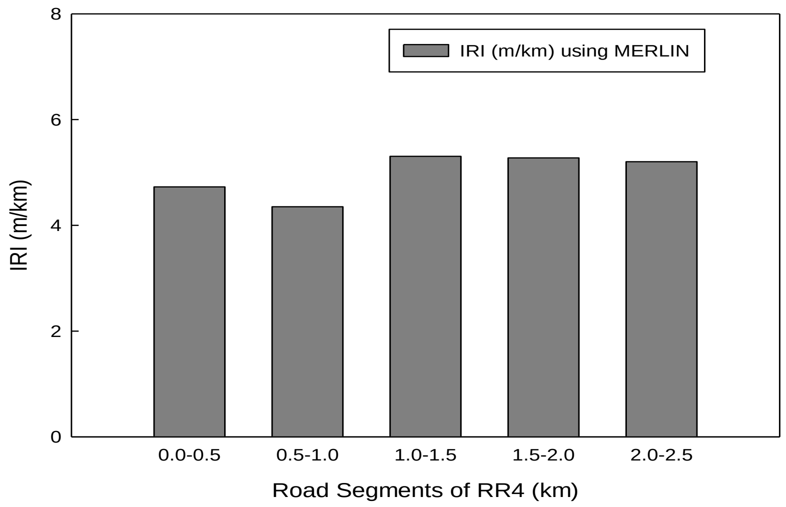


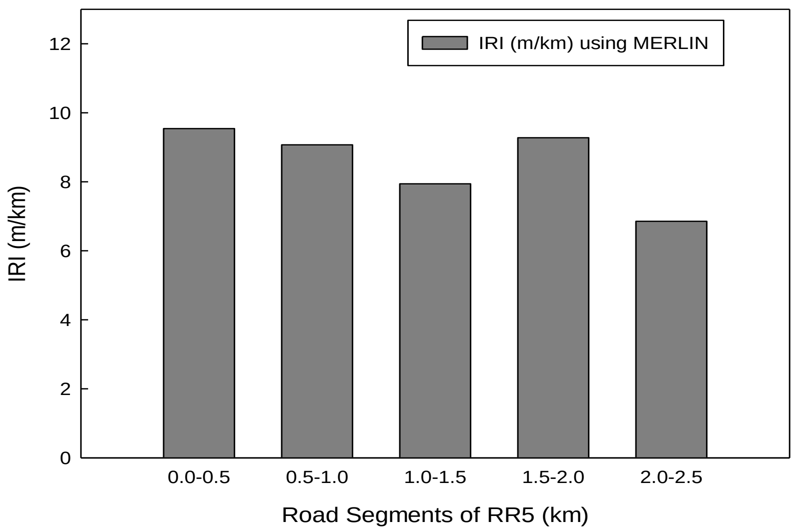
Four Readings of IRI using MERLIN per segment
IRI (m/km)
10
8
6
4
2
0
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segemnts of RR12 (km)

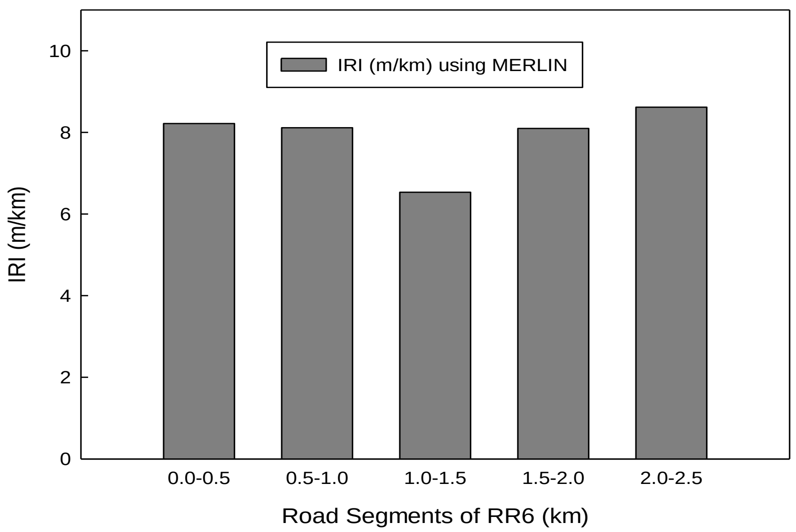

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR1 (km)

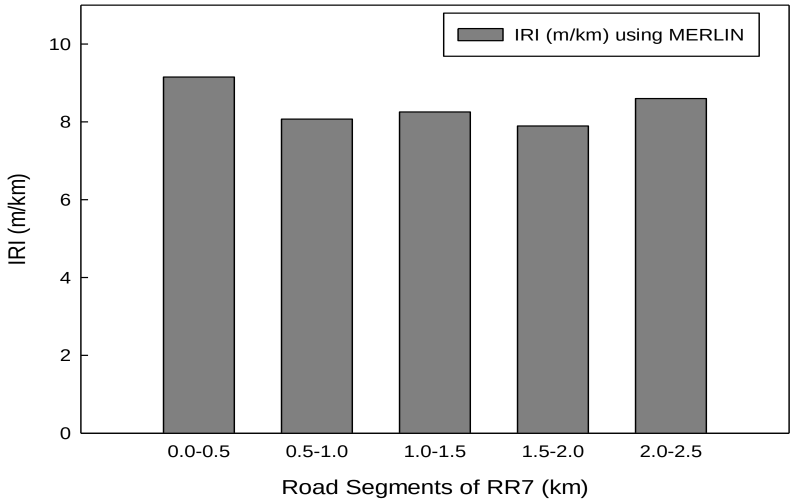

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR2 (km)

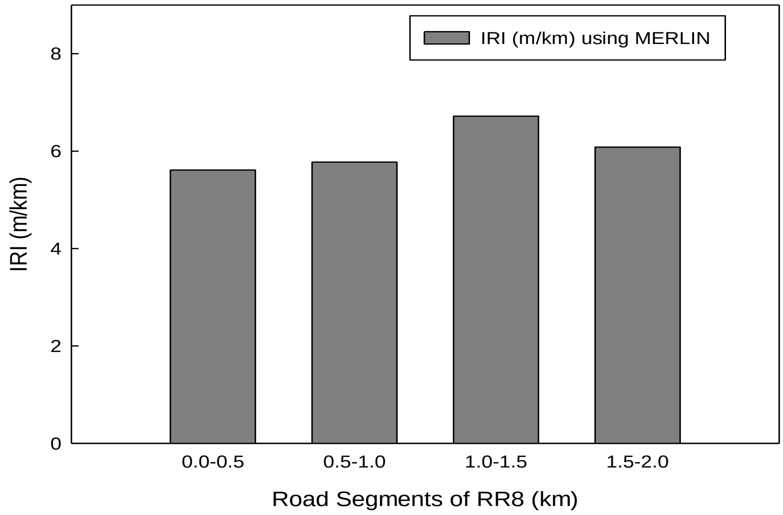

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR3 (km)

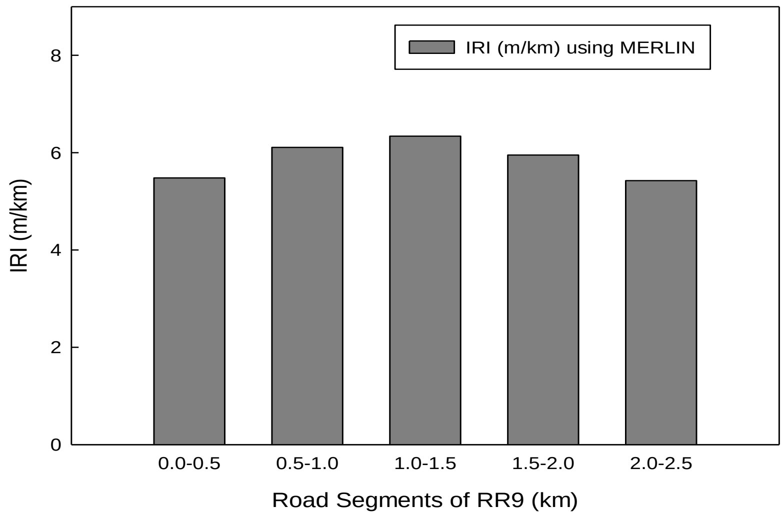

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR4 (km)

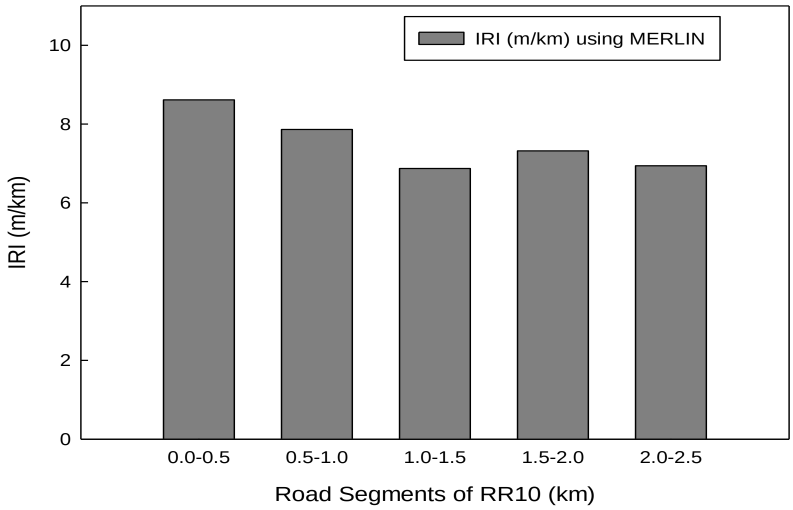

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
12
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR5 (km)

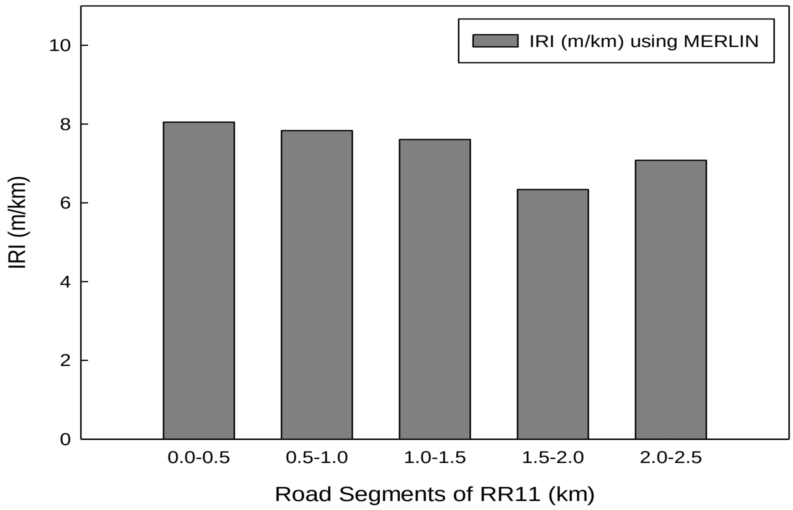

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR6 (km)

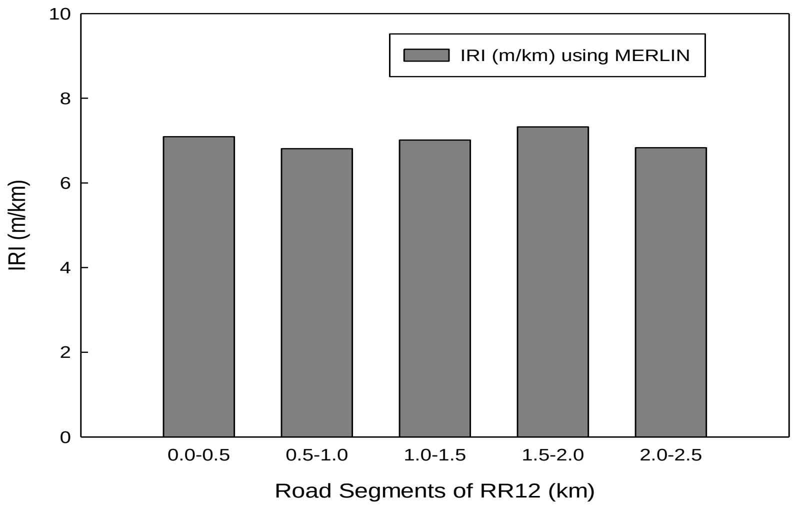

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR7 (km)


IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
Road Segments of RR8 (km)


IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR9 (km)

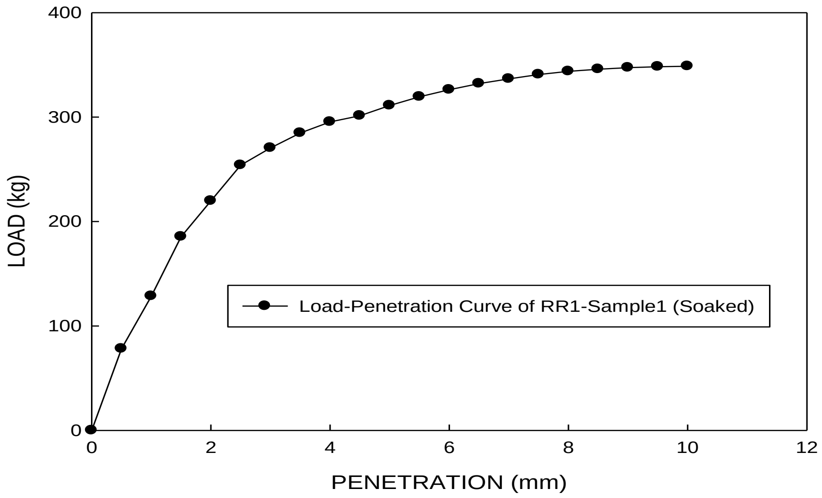

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR10 (km)

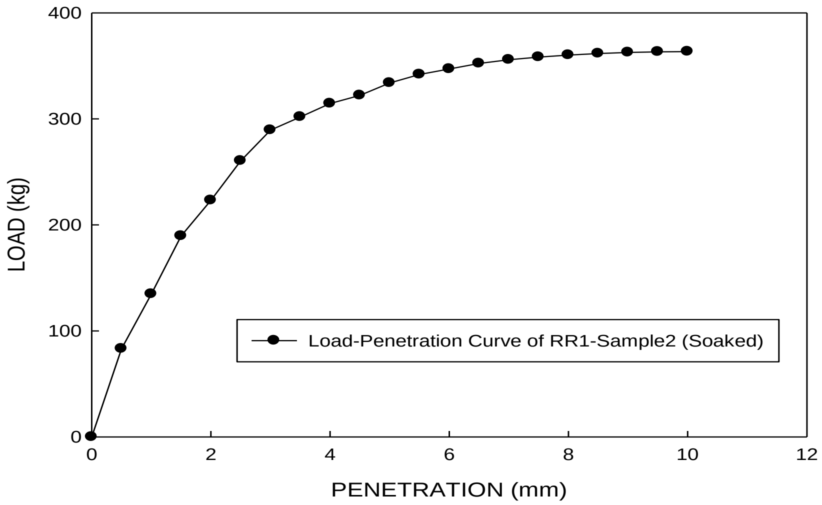

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR11 (km)

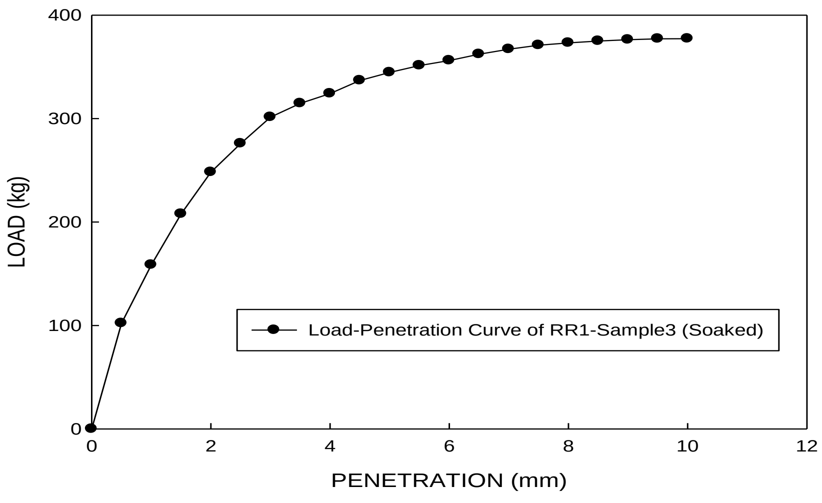

IRI (m/km) using MERLIN
IRI (m/km)
0
2
4
6
8
10
0.0-0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Road Segments of RR12 (km)

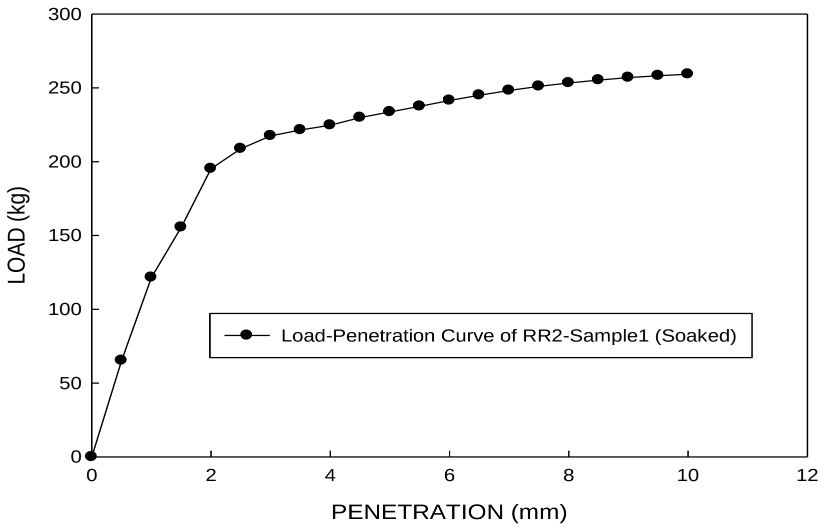
APPENDIX-B

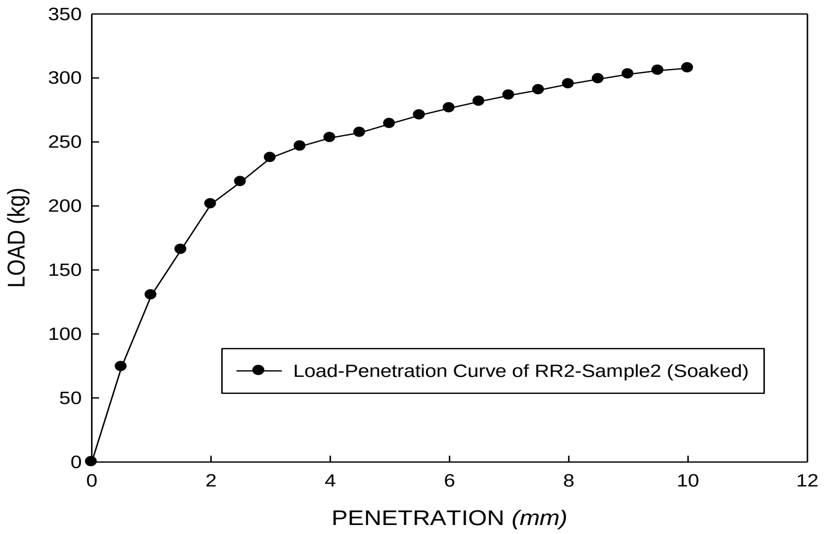
CBR DATA

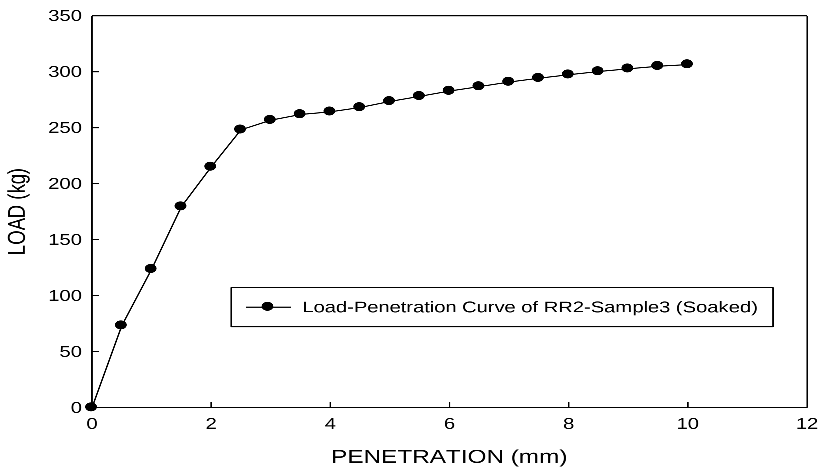

400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR1-Sample1 (Soaked)

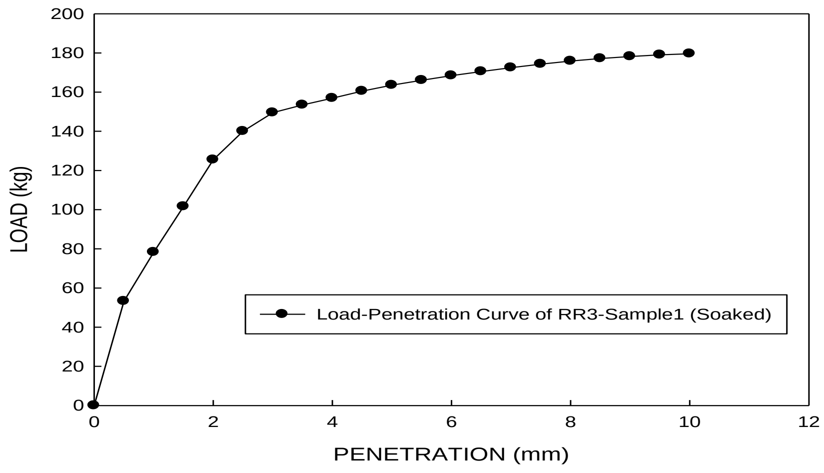

400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR1-Sample2 (Soaked)

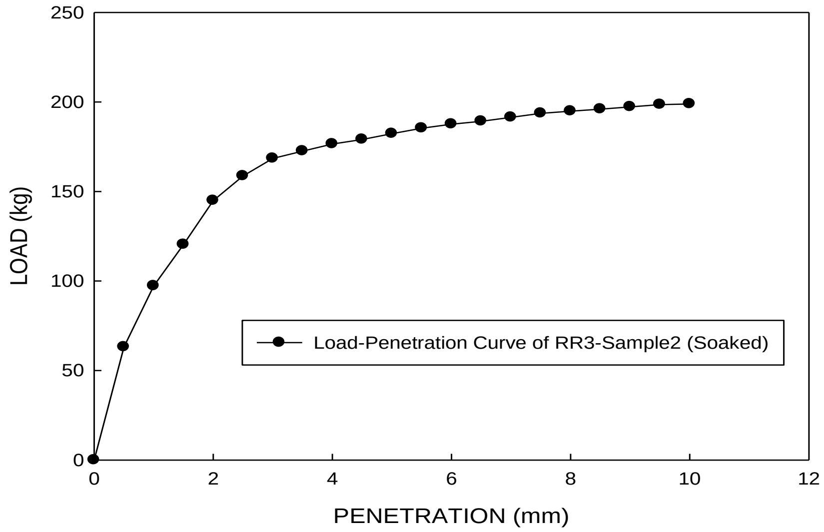

400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR1-Sample3 (Soaked)

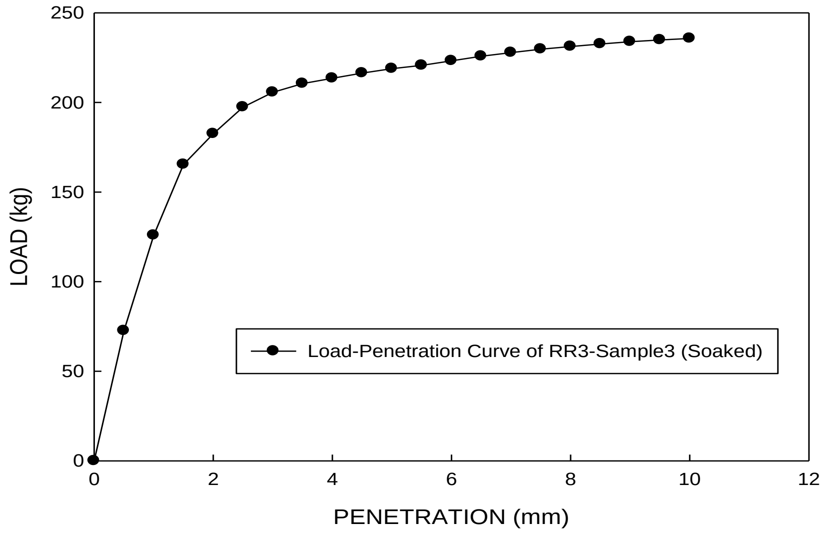

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR2-Sample1 (Soaked)
0
50
100
150
200
250
300
0
2
4
6
8
10
12

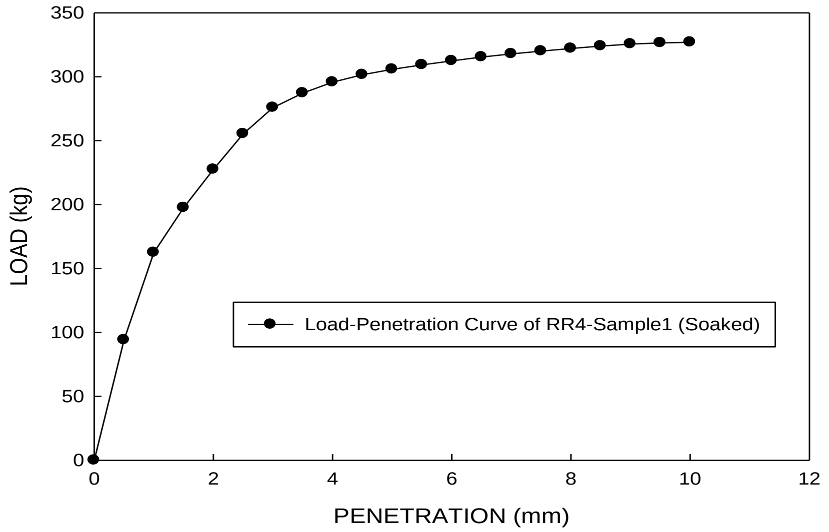

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR2-Sample2 (Soaked)
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12

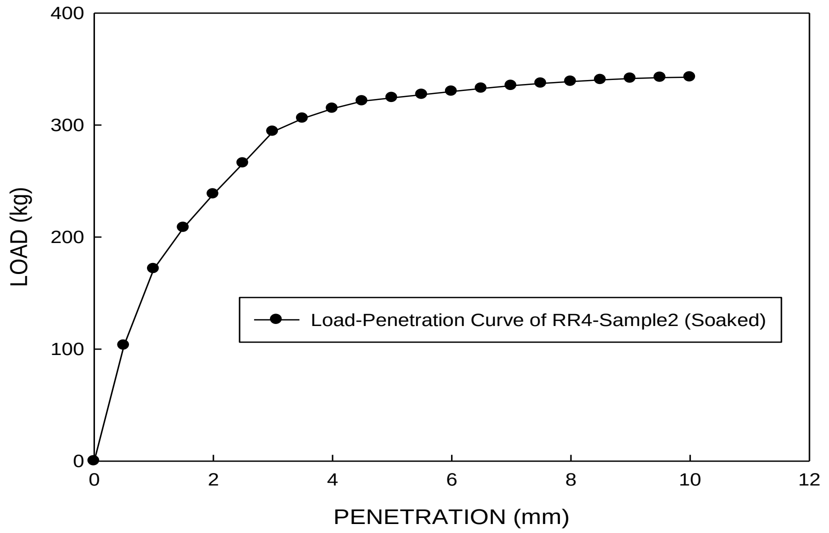

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR2-Sample3 (Soaked)
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12

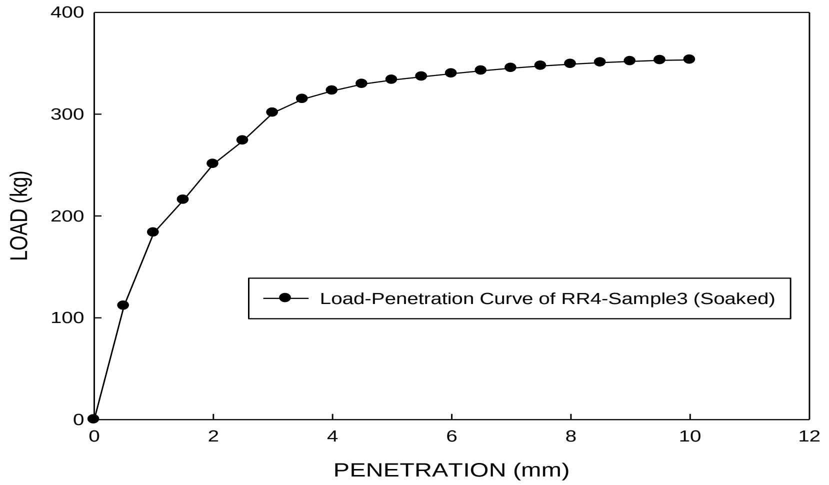

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR3-Sample1 (Soaked)

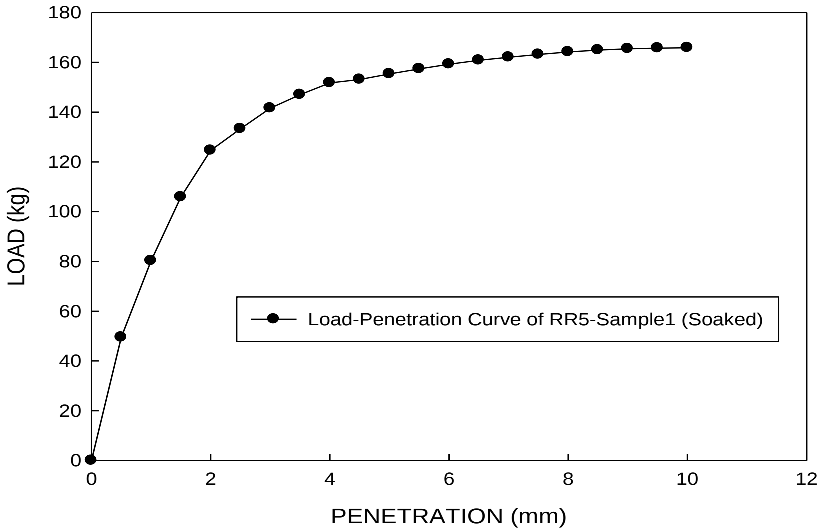

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR3-Sample2 (Soaked)

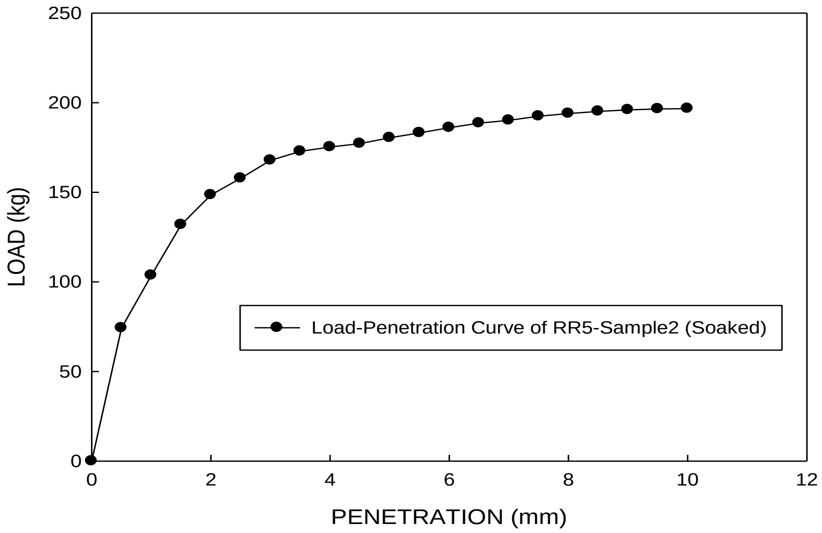

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR3-Sample3 (Soaked)

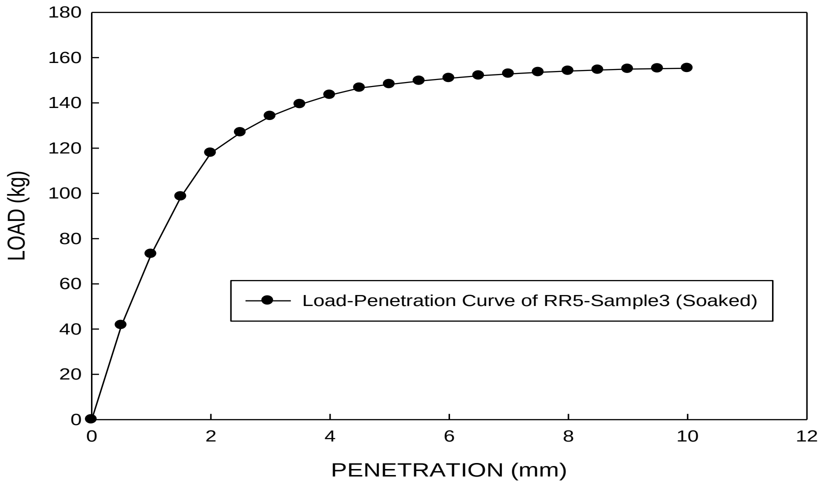

LOAD (kg)
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR4-Sample1 (Soaked)

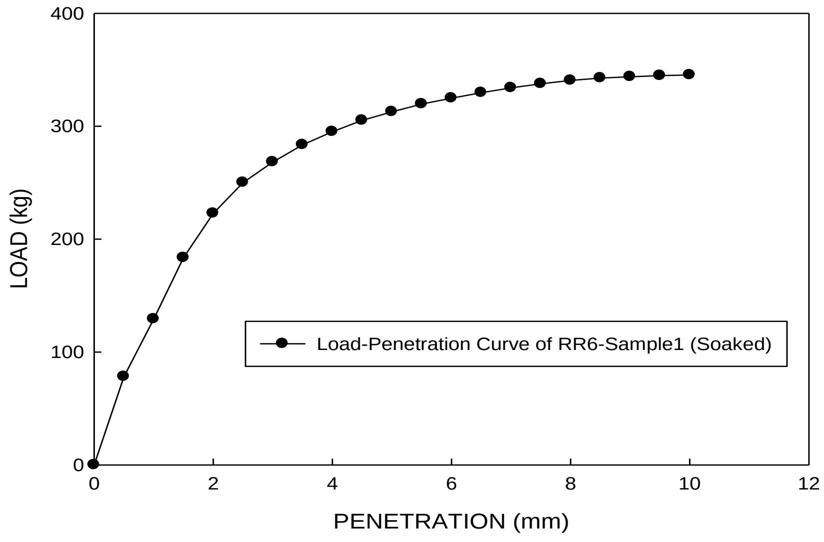

LOAD (kg)
400
300
200
100
0
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR4-Sample2 (Soaked)


LOAD (kg)
400
300
200
100
0
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR4-Sample3 (Soaked)

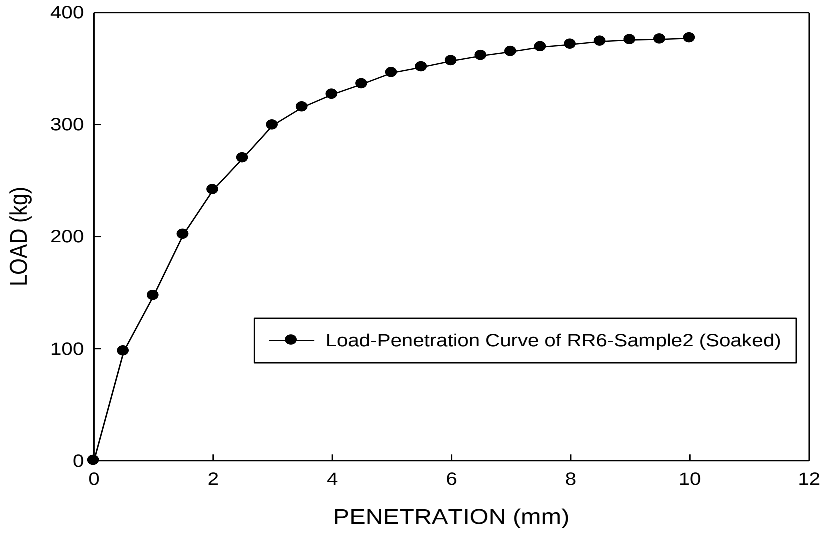

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR5-Sample1 (Soaked)


LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR5-Sample2 (Soaked)

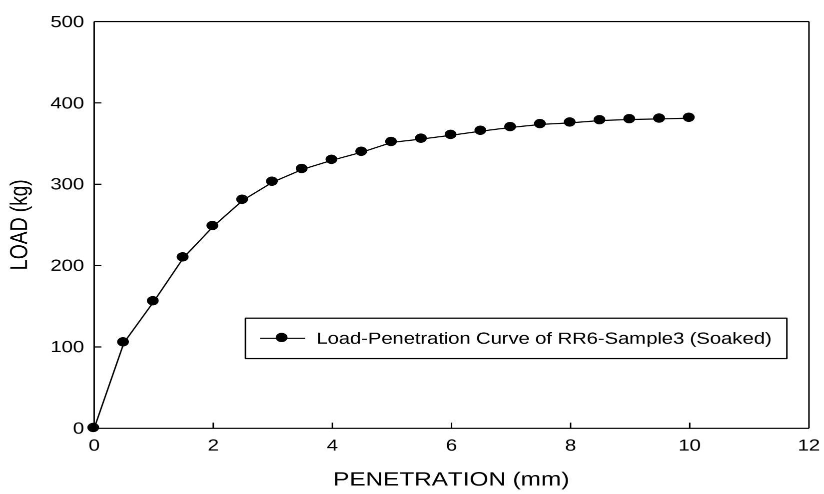

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR5-Sample3 (Soaked)



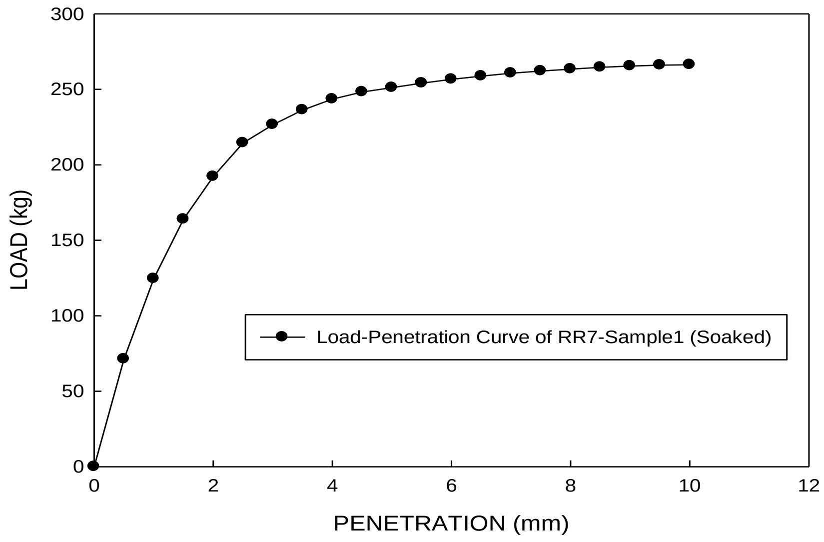
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR6-Sample1 (Soaked)

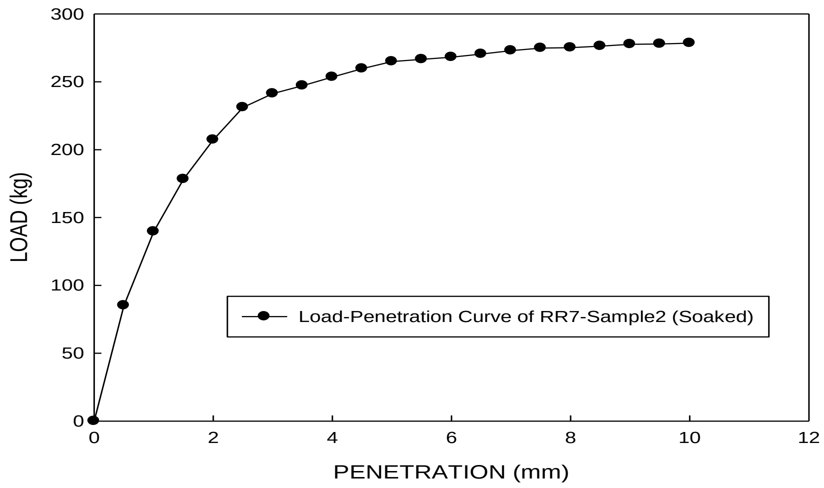


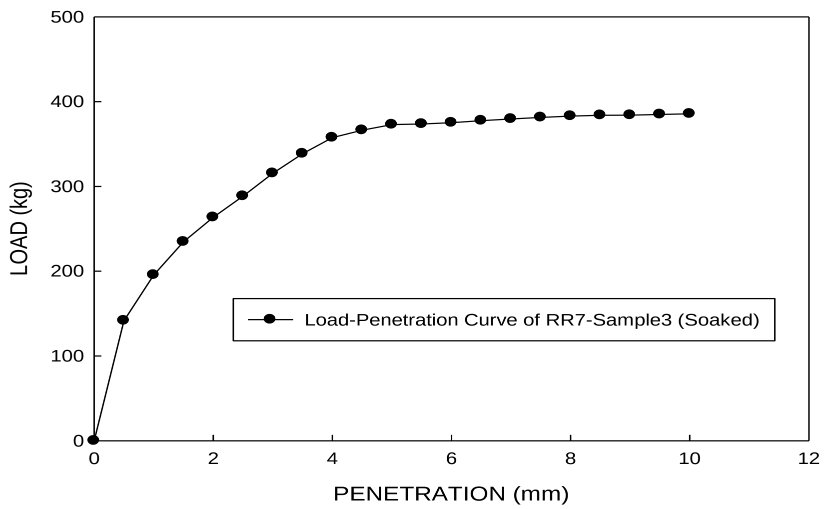
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR6-Sample2 (Soaked)

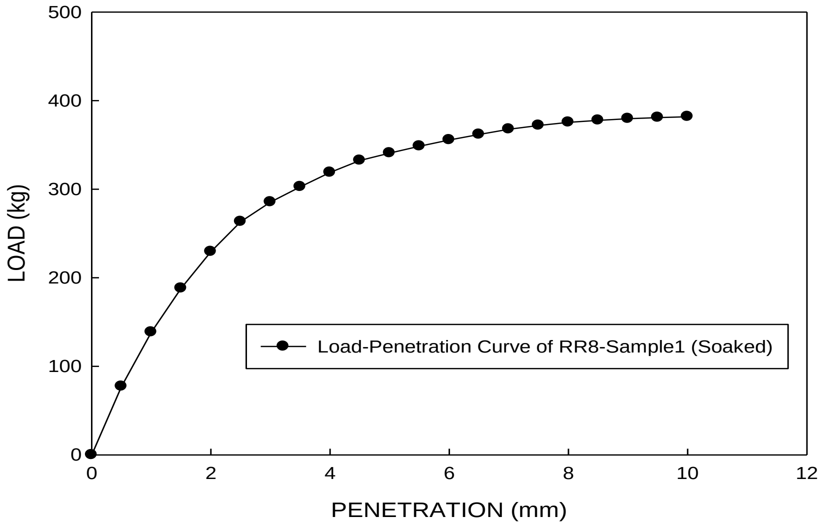


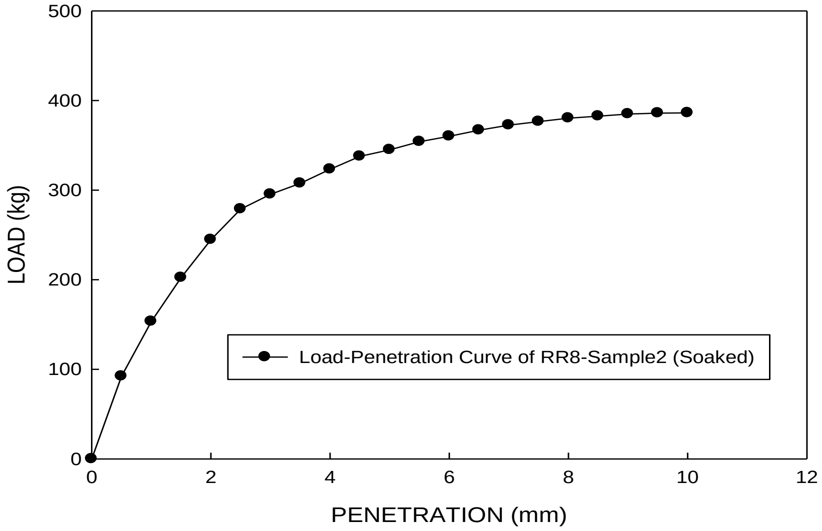
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR6-Sample3 (Soaked)

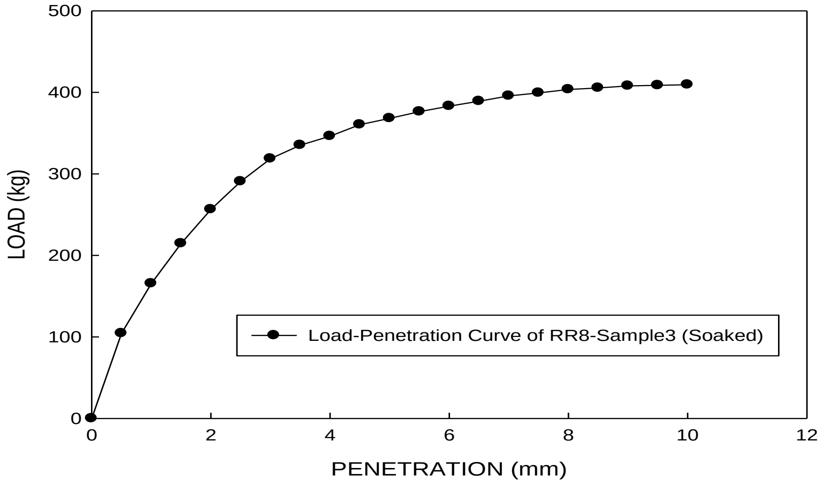

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR7-Sample1 (Soaked)

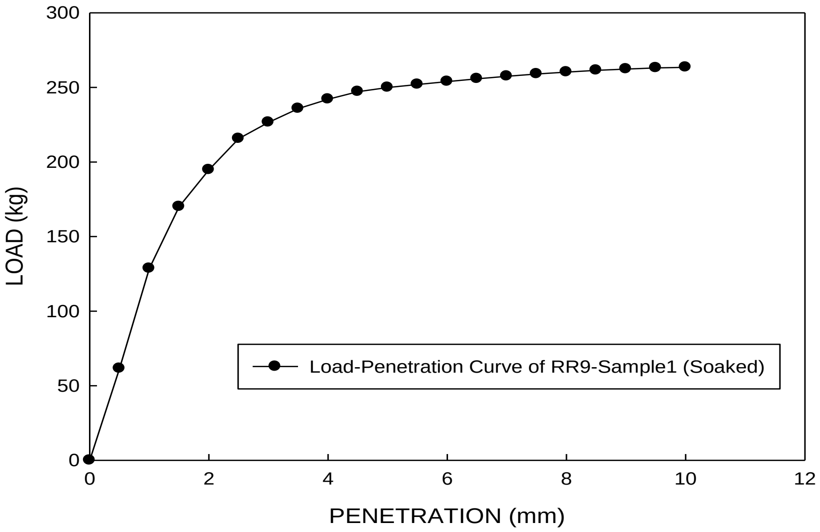

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR7-Sample2 (Soaked)

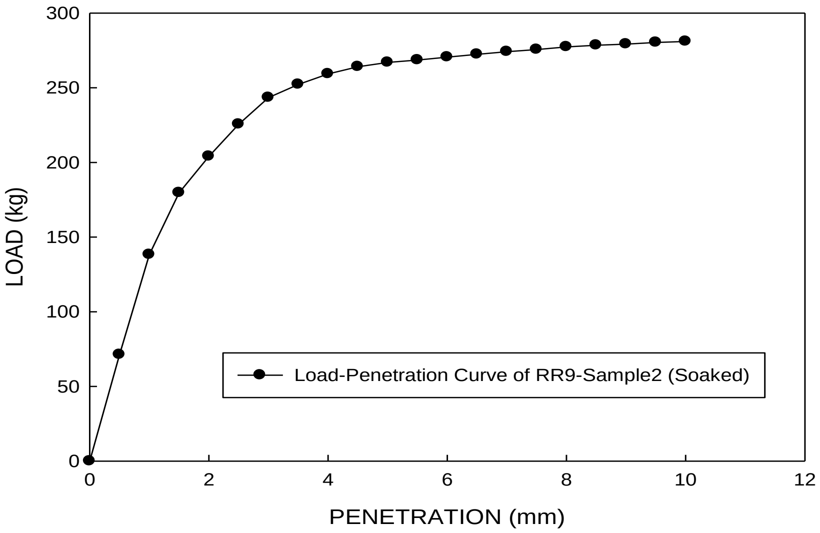

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR7-Sample3 (Soaked)

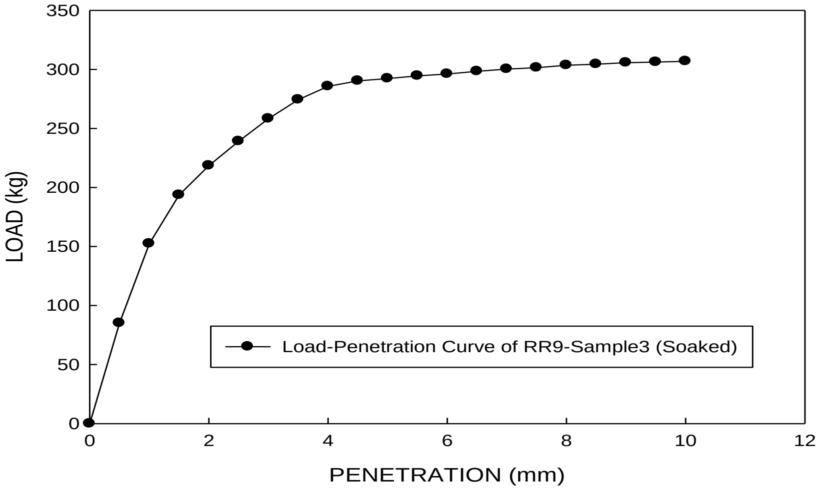

500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR8-Sample1 (Soaked)

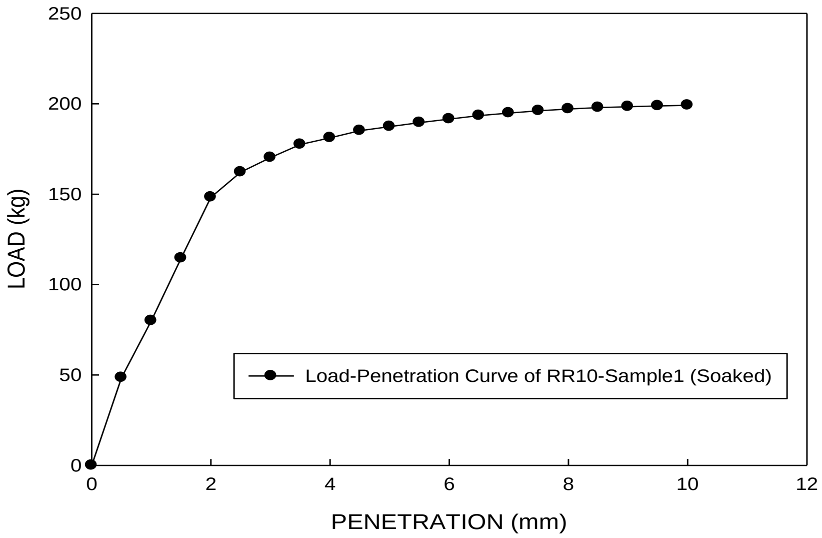

500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR8-Sample2 (Soaked)


500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR8-Sample3 (Soaked)

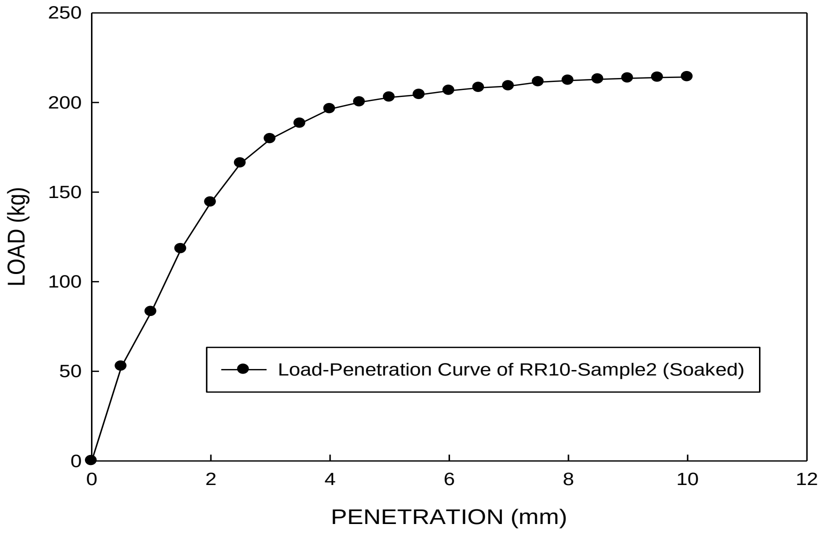

300
250
200
150
100
50
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR9-Sample1 (Soaked)


300
250
200
150
100
50
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR9-Sample2 (Soaked)

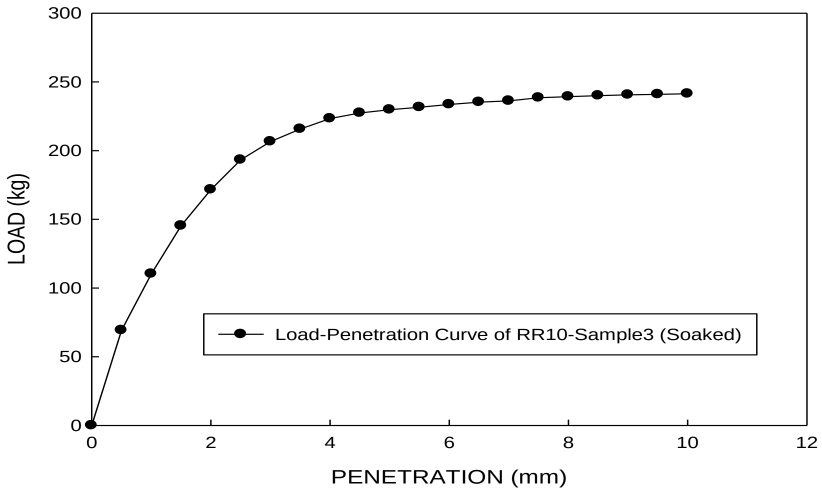

350
300
250
200
150
100
50
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR9-Sample3 (Soaked)



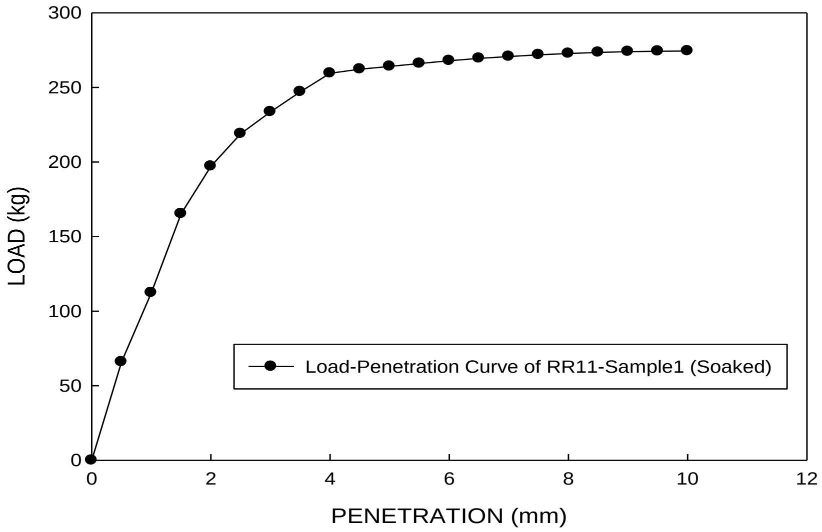
Load-Penetration Curve of RR10-Sample1 (Soaked)
LOAD (kg)
PENETRATION (mm)
0
50
100
150
200
250
0
2
4
6
8
10
12

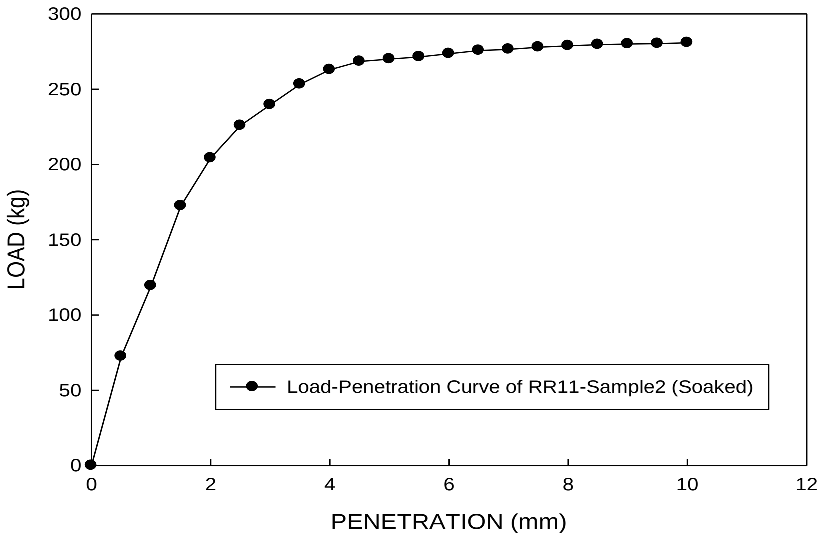


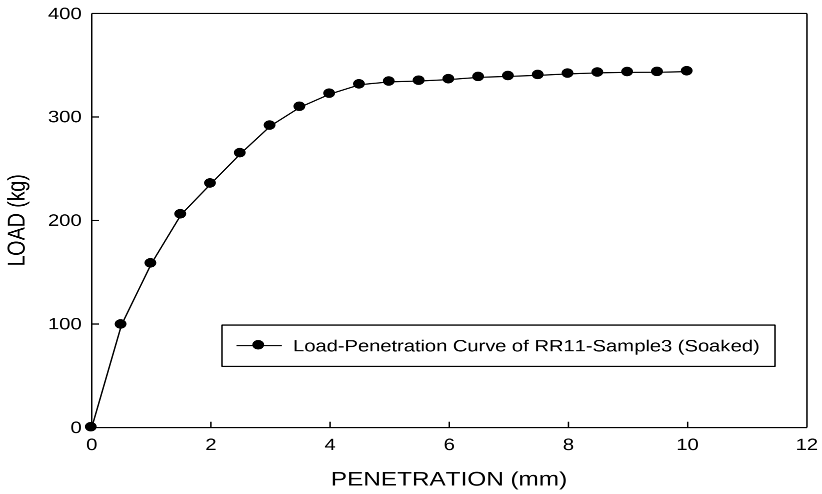
Load-Penetration Curve of RR10-Sample2 (Soaked)
LOAD (kg)
PENETRATION (mm)
0
50
100
150
200
250
0
2
4
6
8
10
12

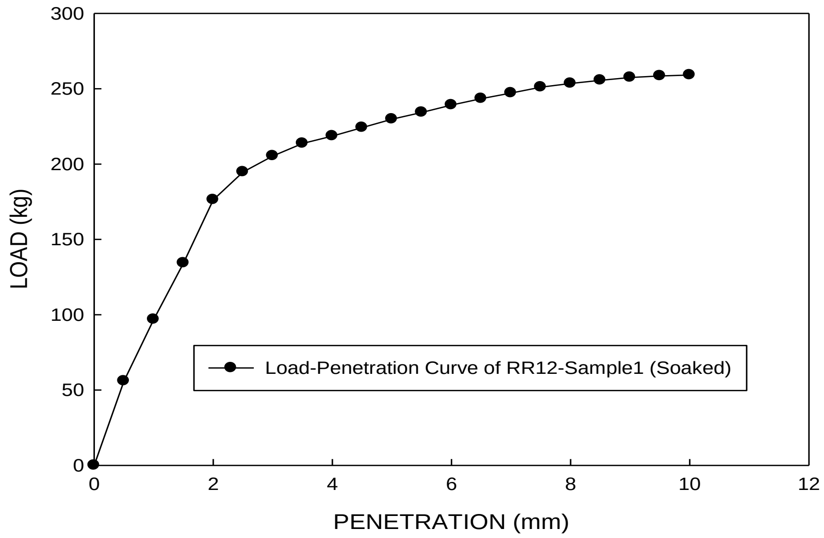


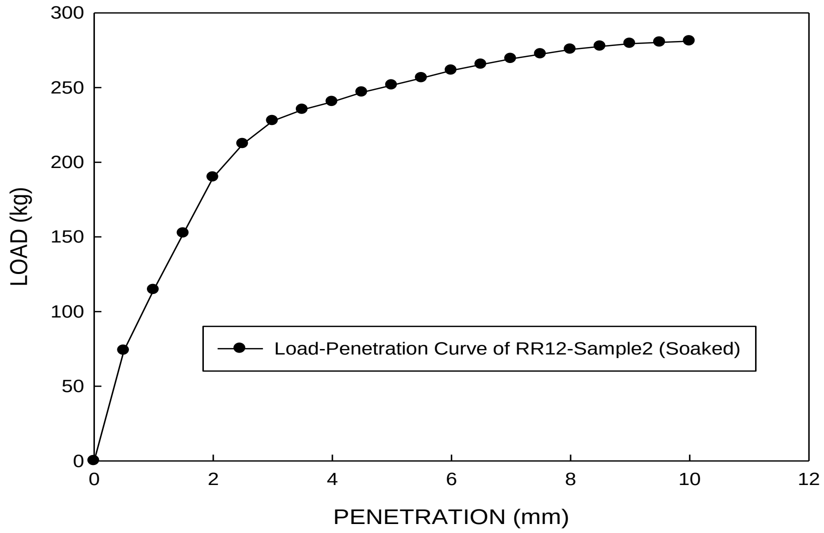
Load-Penetration Curve of RR10-Sample3 (Soaked)
LOAD (kg)
PENETRATION (mm)
0
50
100
150
200
250
300
0
2
4
6
8
10
12

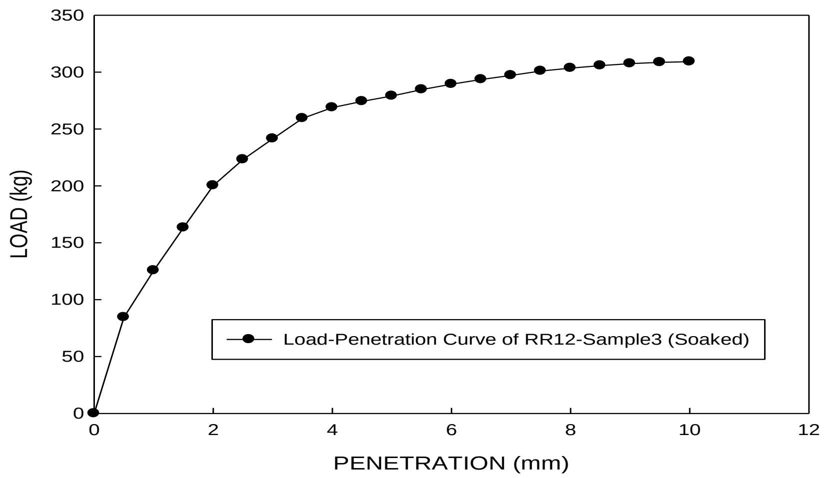

300
250
200
150
100
50
0
LOAD (kg)
Load-Penetration Curve of RR11-Sample1 (Soaked)
0
2
4
6
8
10
12
PENETRATION (mm)

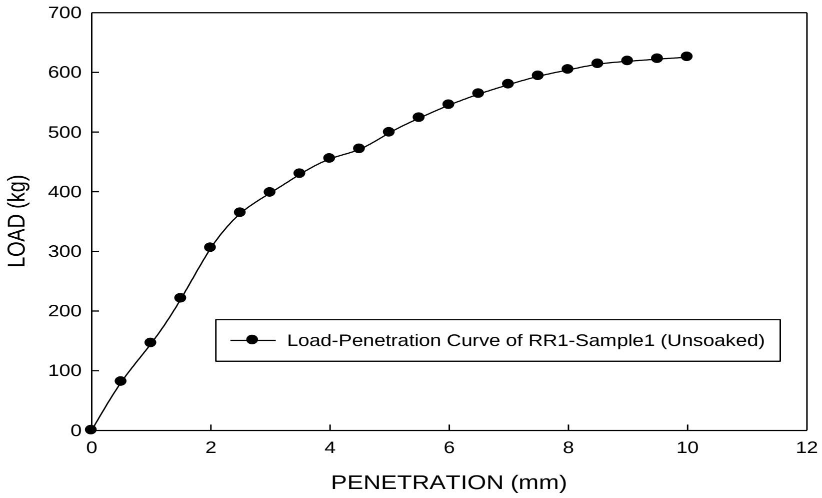

300
250
200
150
100
50
0
LOAD (kg)
Load-Penetration Curve of RR11-Sample2 (Soaked)
0
2
4
6
8
10
12
PENETRATION (mm)

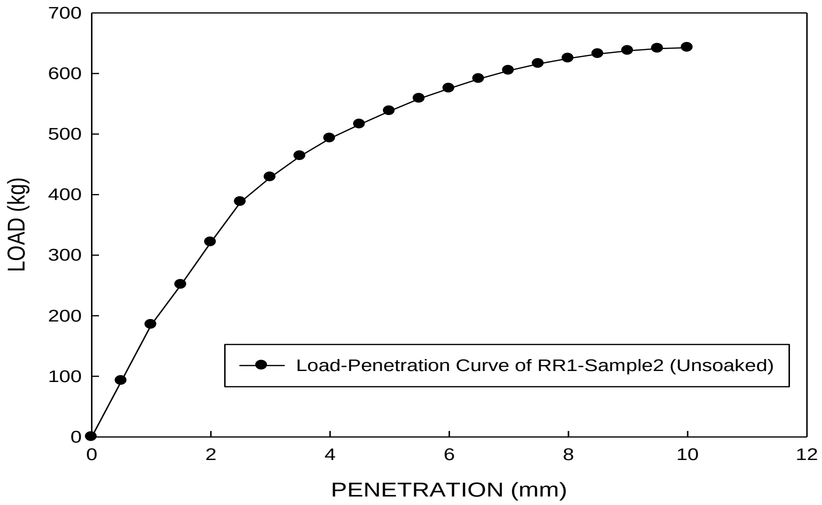

400
300
200
100
0
LOAD (kg)
Load-Penetration Curve of RR11-Sample3 (Soaked)
0
2
4
6
8
10
12
PENETRATION (mm)

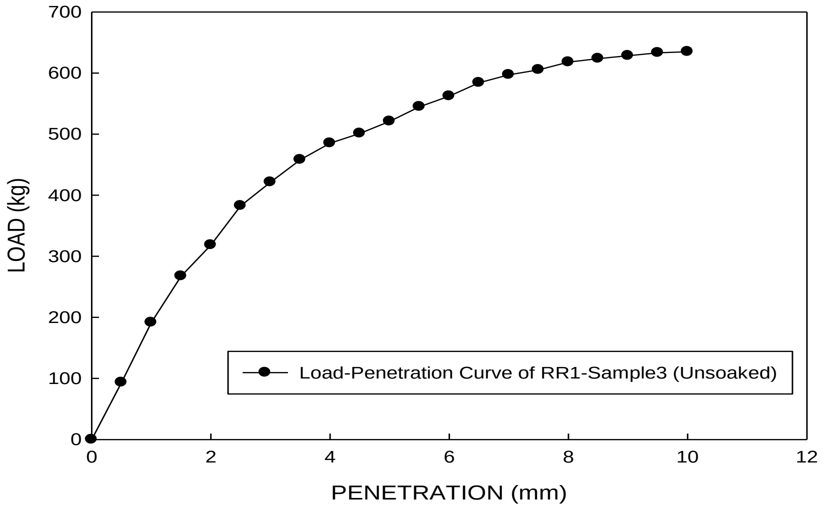

300
250
200
150
100
50
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR12-Sample1 (Soaked)

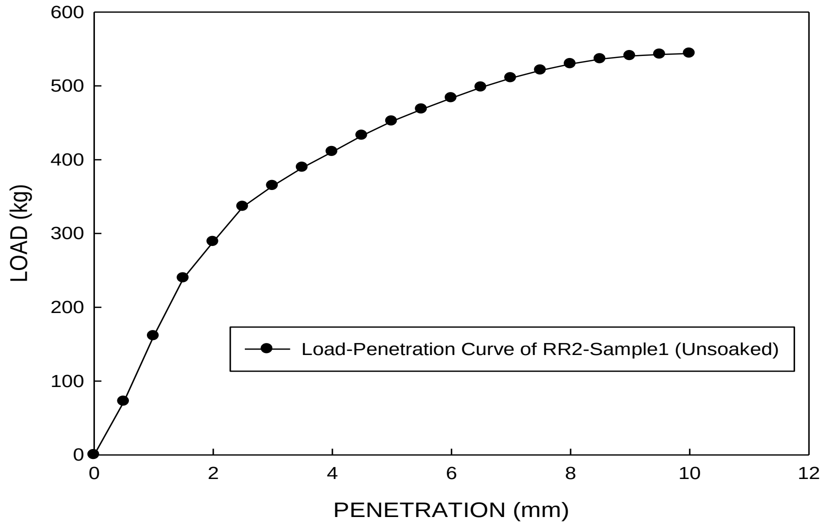

300
250
200
150
100
50
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR12-Sample2 (Soaked)

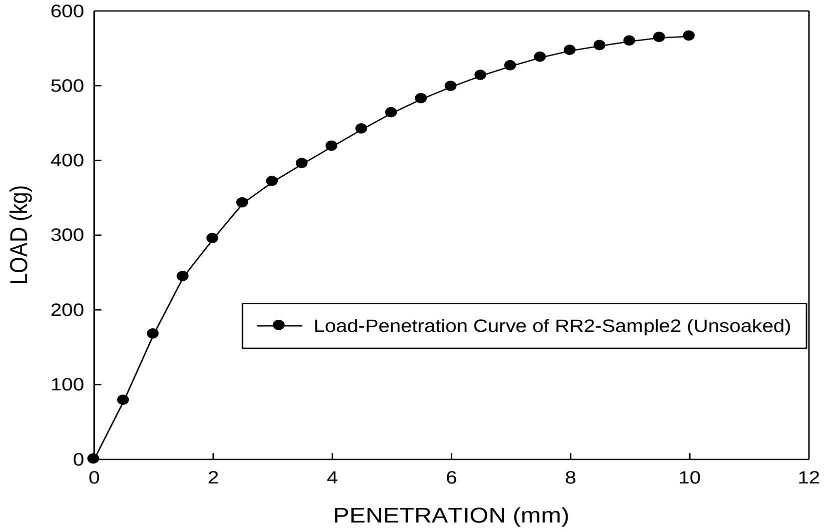

350
300
250
200
150
100
50
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR12-Sample3 (Soaked)

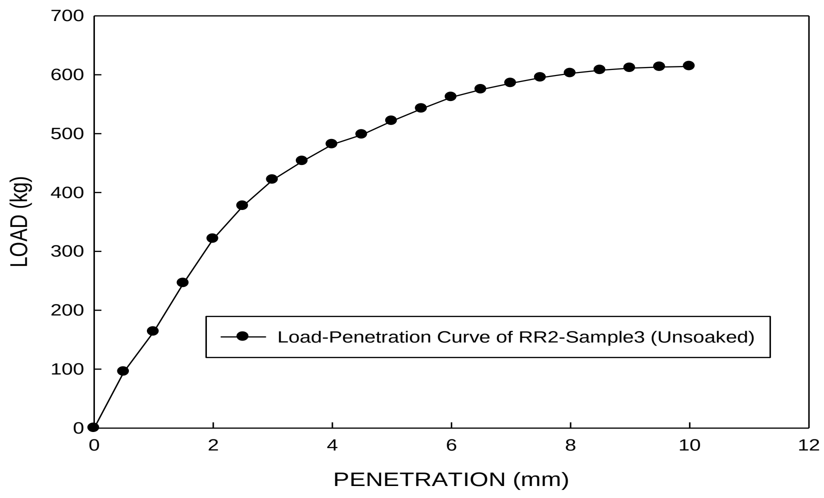

700
600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR1-Sample1 (Unsoaked)

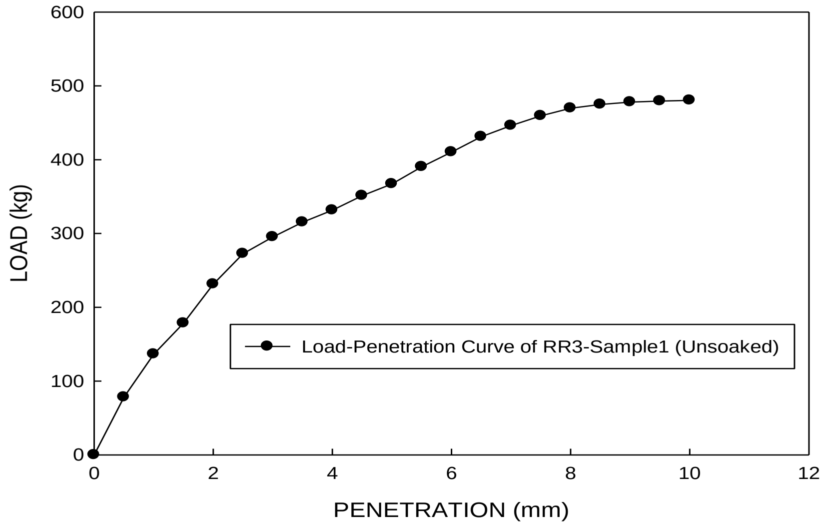

700
600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR1-Sample2 (Unsoaked)

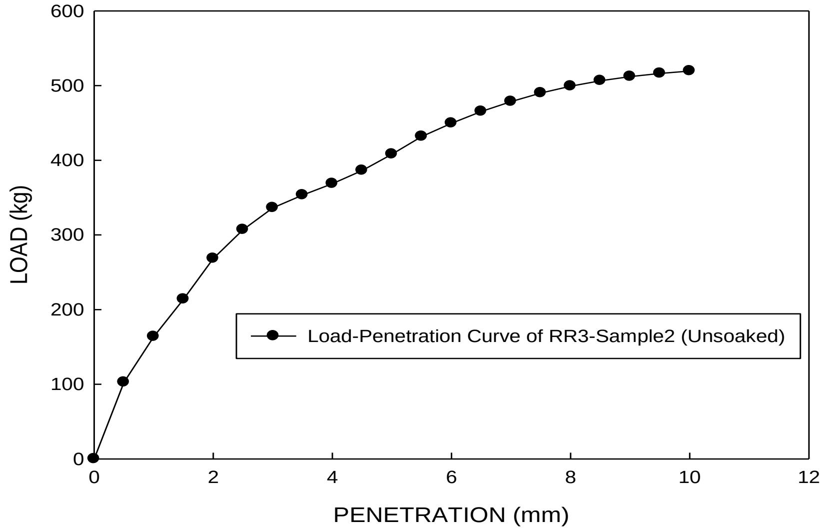

700
600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR1-Sample3 (Unsoaked)

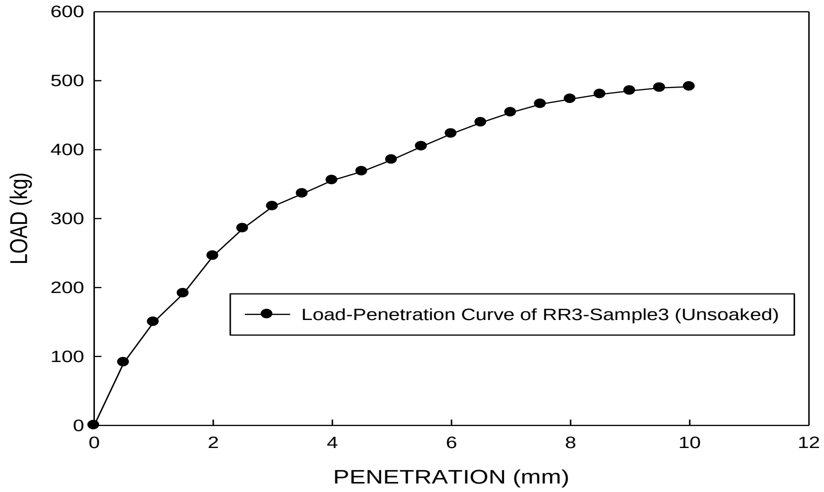

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR2-Sample1 (Unsoaked)
0
100
200
300
400
500
600
0
2
4
6
8
10
12

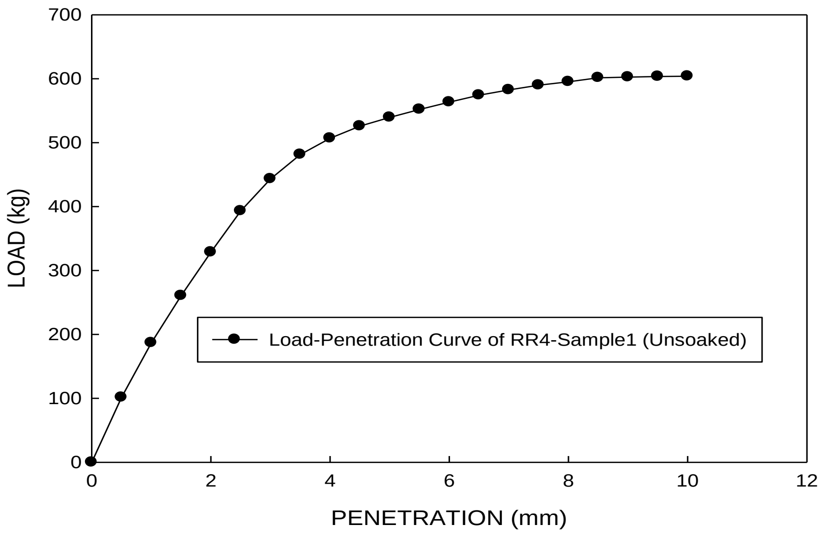

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR2-Sample2 (Unsoaked)
0
100
200
300
400
500
600
0
2
4
6
8
10
12


LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR2-Sample3 (Unsoaked)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

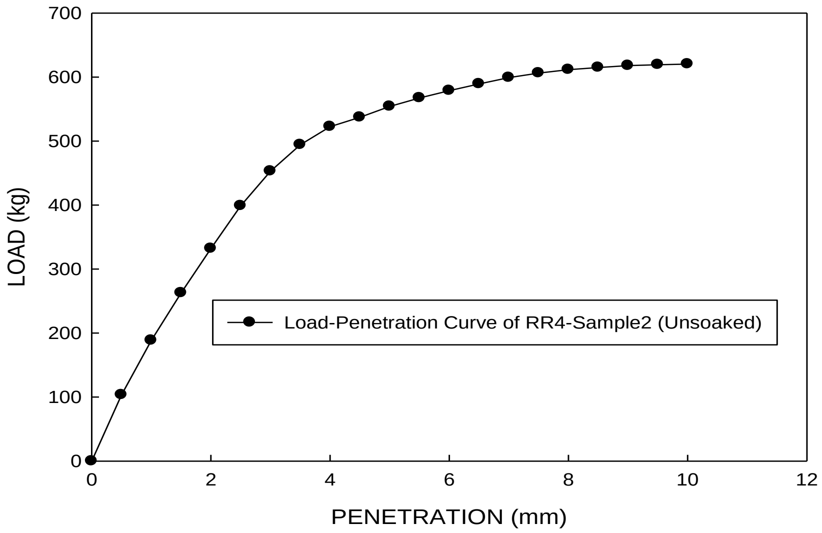

600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR3-Sample1 (Unsoaked)


600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR3-Sample2 (Unsoaked)

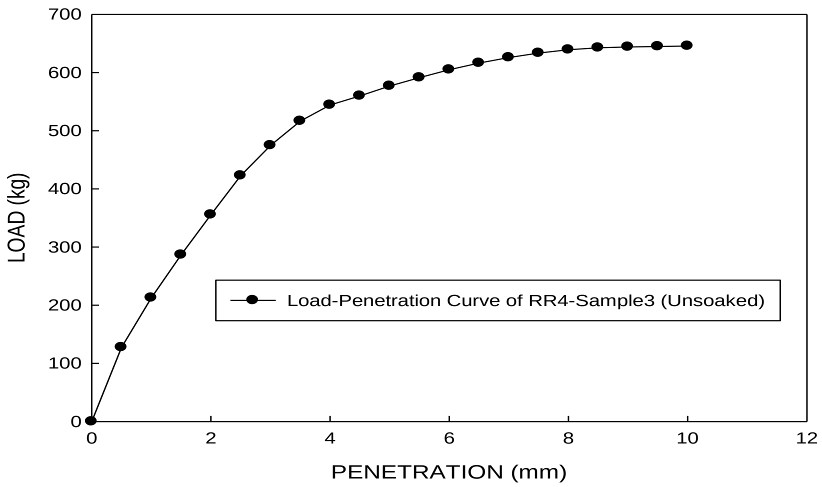

600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR3-Sample3 (Unsoaked)



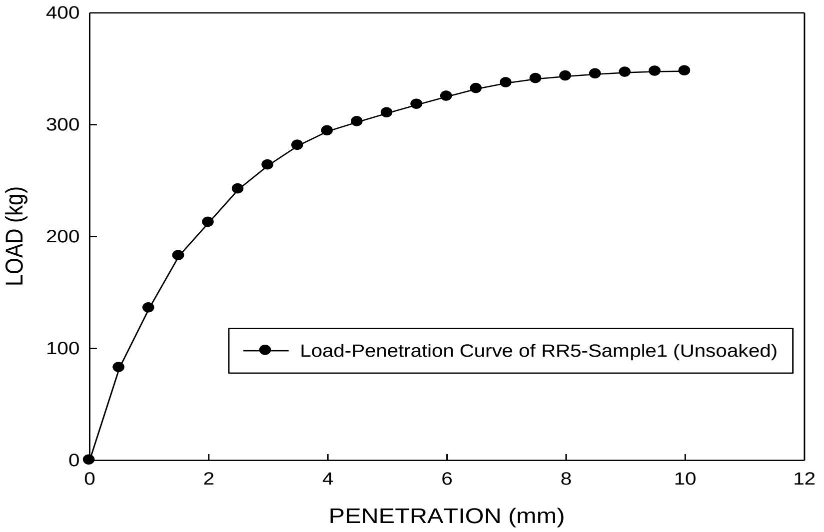
LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR4-Sample1 (Unsoaked)



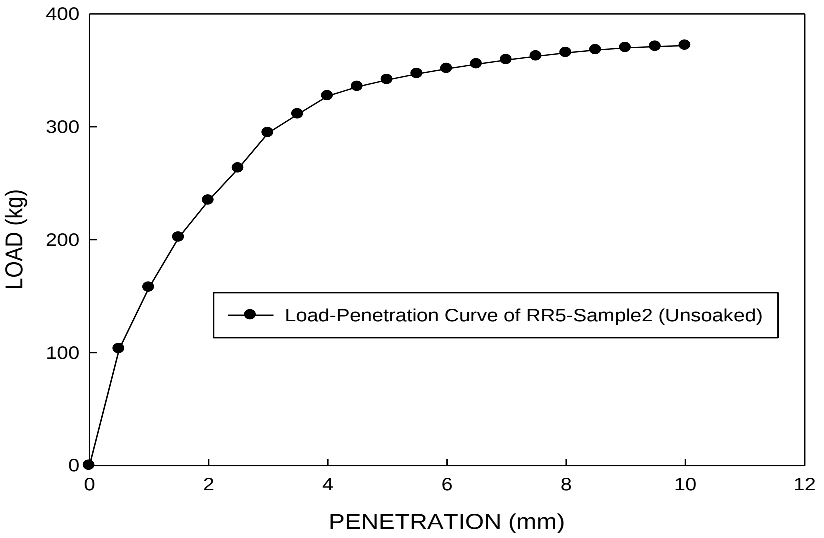
LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR4-Sample2 (Unsoaked)



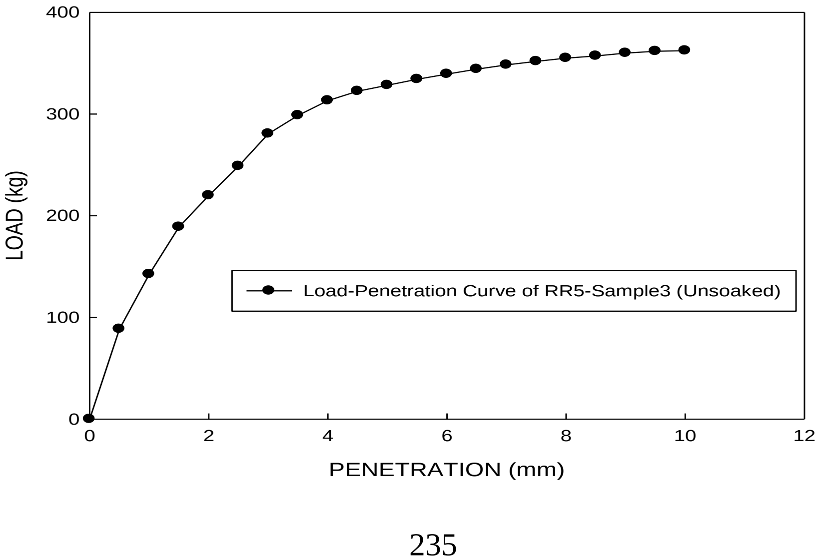
LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR4-Sample3 (Unsoaked)



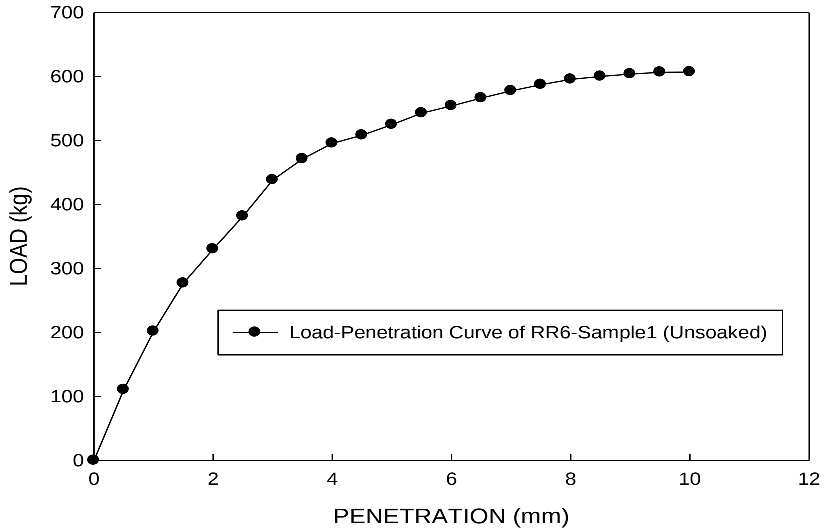
LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR5-Sample1 (Unsoaked)

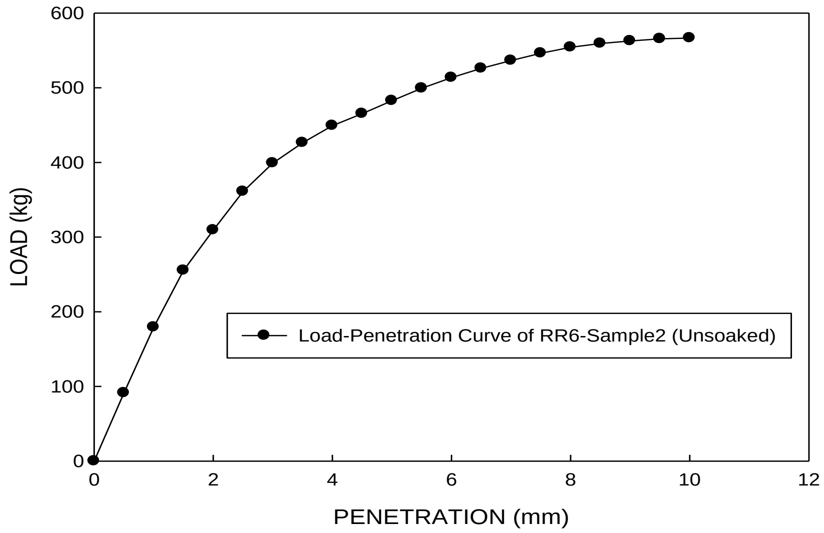


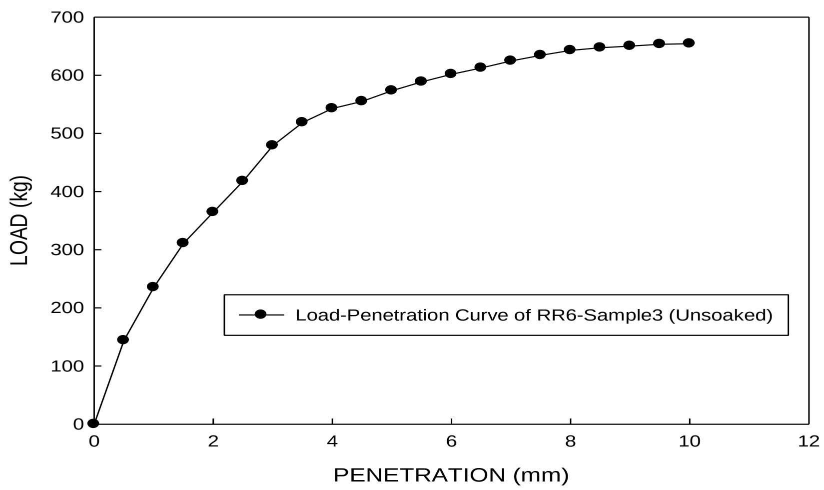
LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR5-Sample2 (Unsoaked)

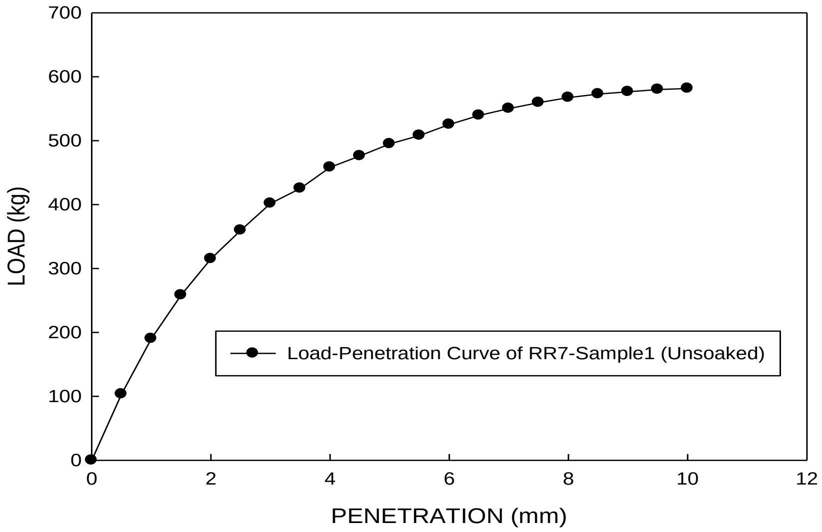


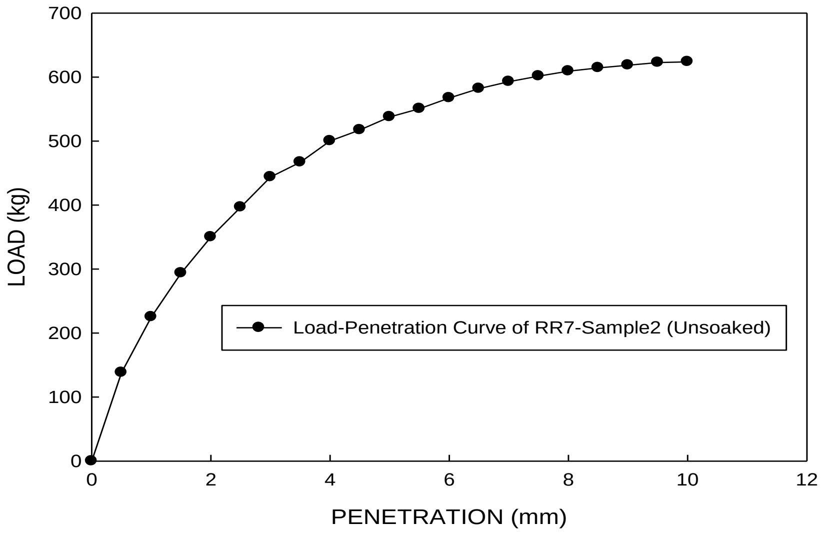
LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR5-Sample3 (Unsoaked)

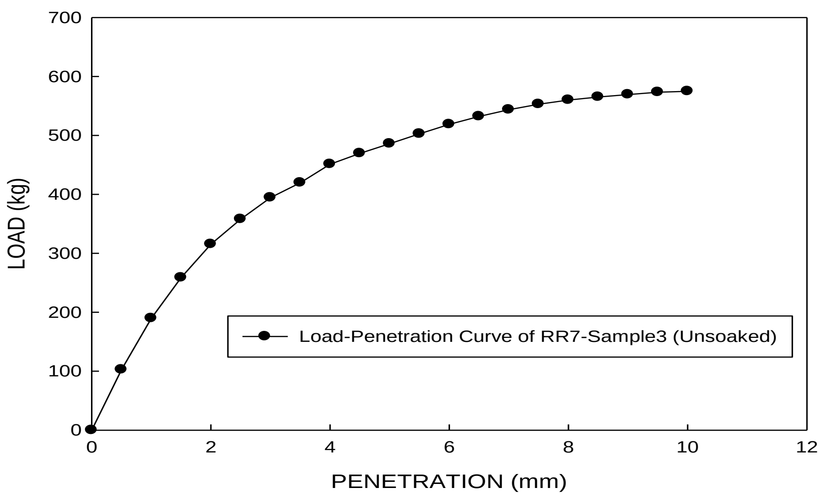

700
600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR6-Sample1 (Unsoaked)

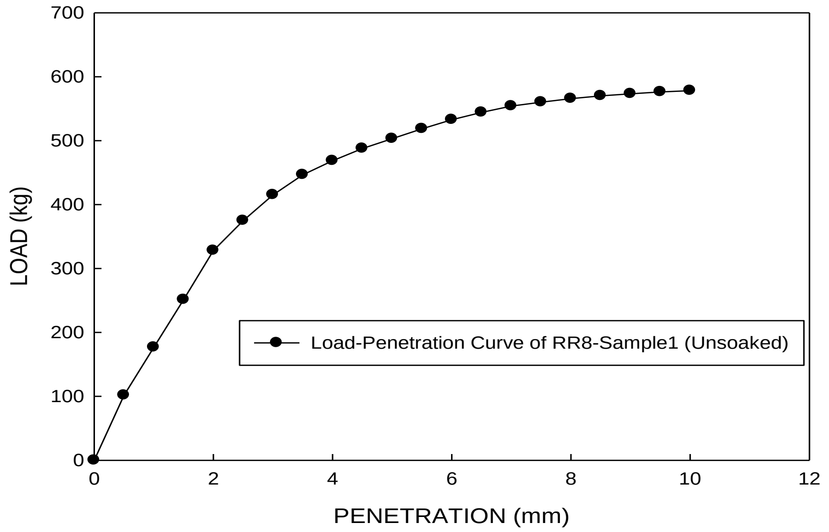

600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR6-Sample2 (Unsoaked)

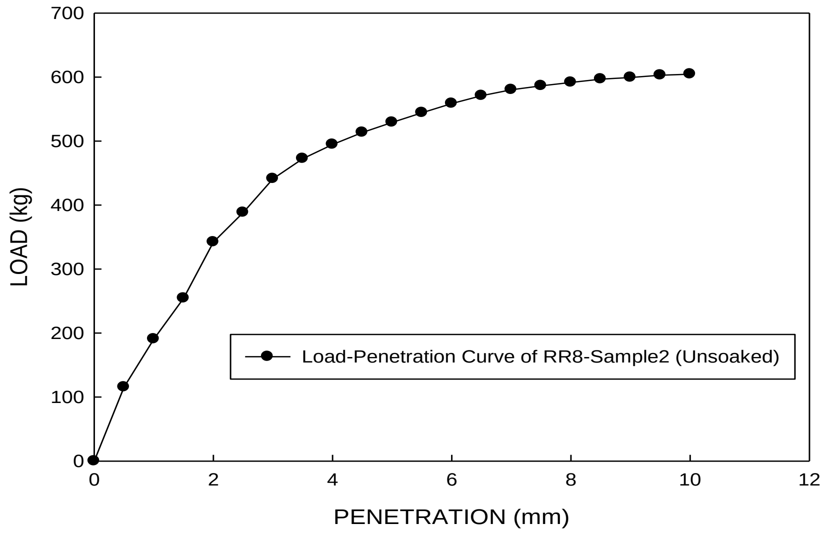

700
600
500
400
300
200
100
0
LOAD (kg)
0
2
4
6
8
10
12
PENETRATION (mm)
Load-Penetration Curve of RR6-Sample3 (Unsoaked)

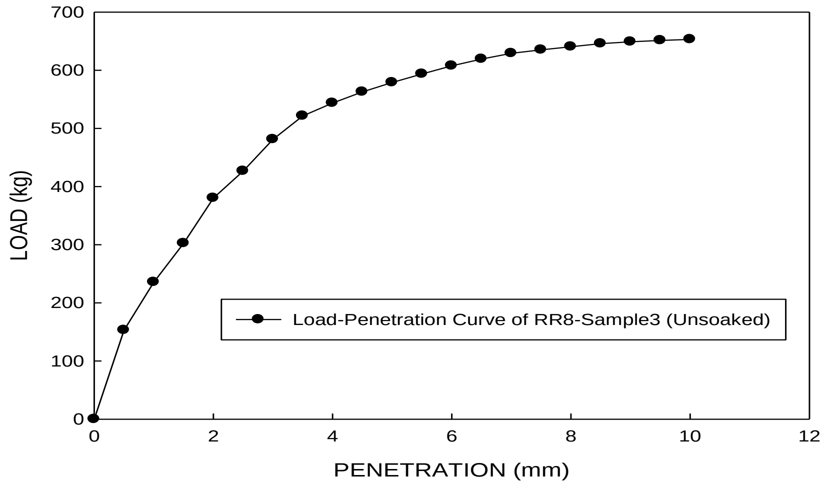

Load-Penetration Curve of RR7-Sample1 (Unsoaked)
LOAD (kg)
PENETRATION (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

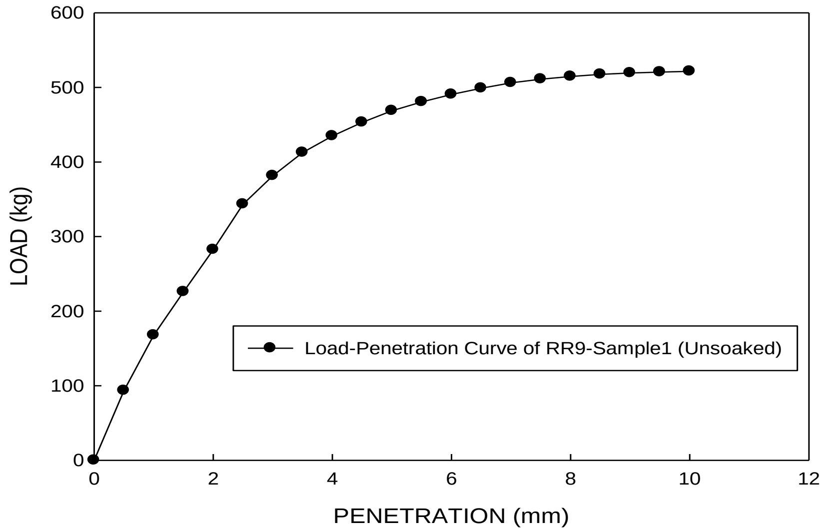

Load-Penetration Curve of RR7-Sample2 (Unsoaked)
LOAD (kg)
PENETRATION (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

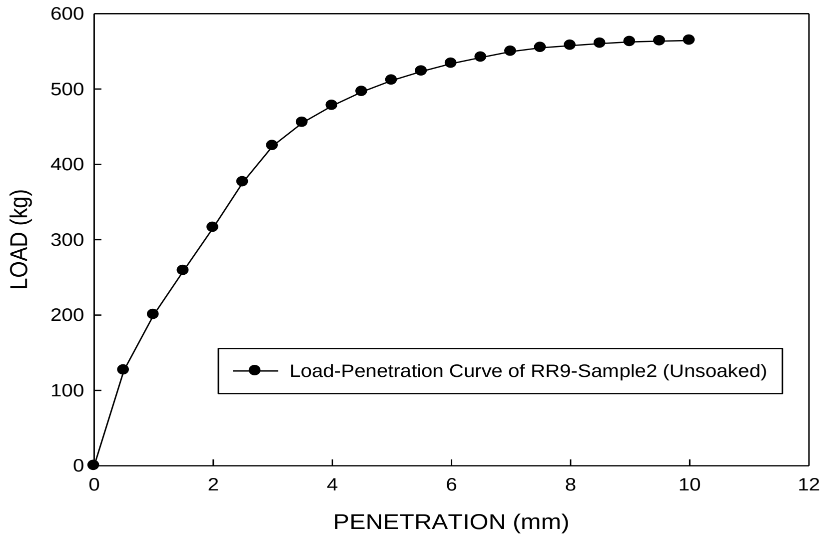

Load-Penetration Curve of RR7-Sample3 (Unsoaked)
LOAD (kg)
PENETRATION (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

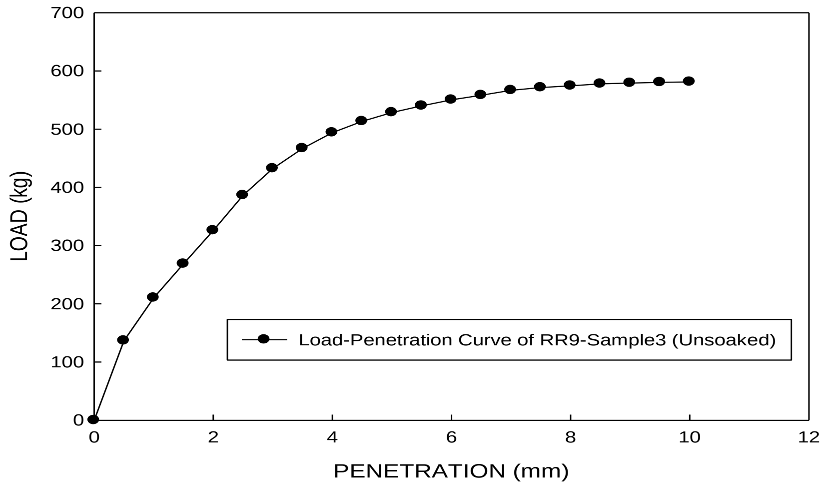

Load-Penetration Curve of RR8-Sample1 (Unsoaked)
LOAD (kg)
PENETRATION (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

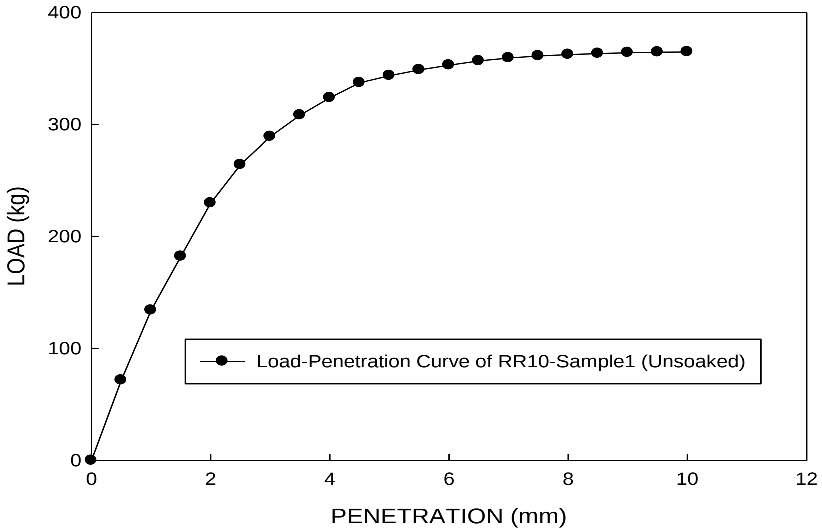

Load-Penetration Curve of RR8-Sample2 (Unsoaked)
LOAD (kg)
PENETRATION (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

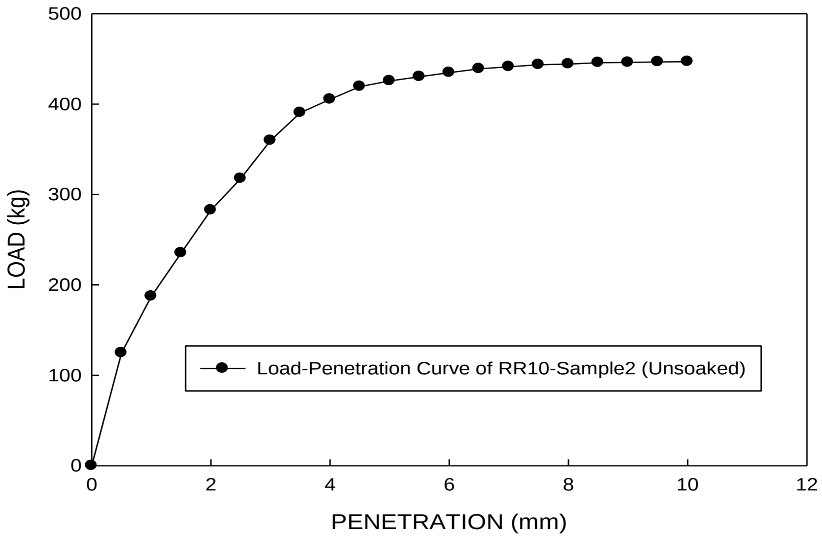

Load-Penetration Curve of RR8-Sample3 (Unsoaked)
LOAD (kg)
PENETRATION (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

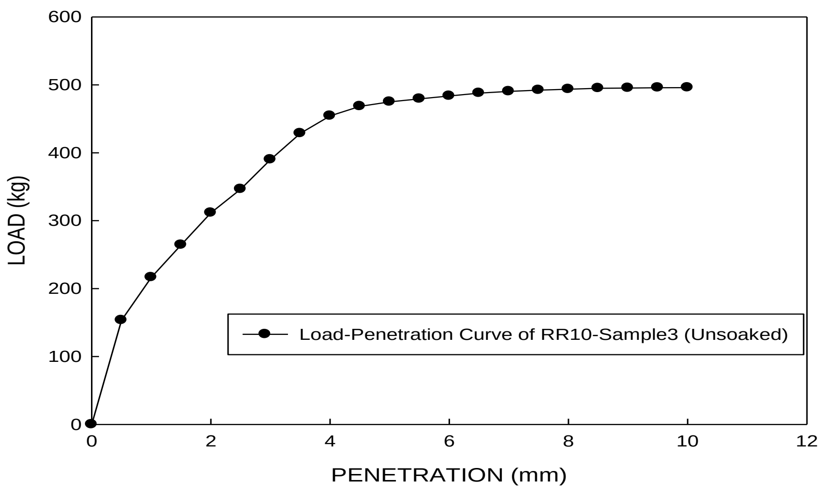

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR9-Sample1 (Unsoaked)
0
100
200
300
400
500
600
0
2
4
6
8
10
12

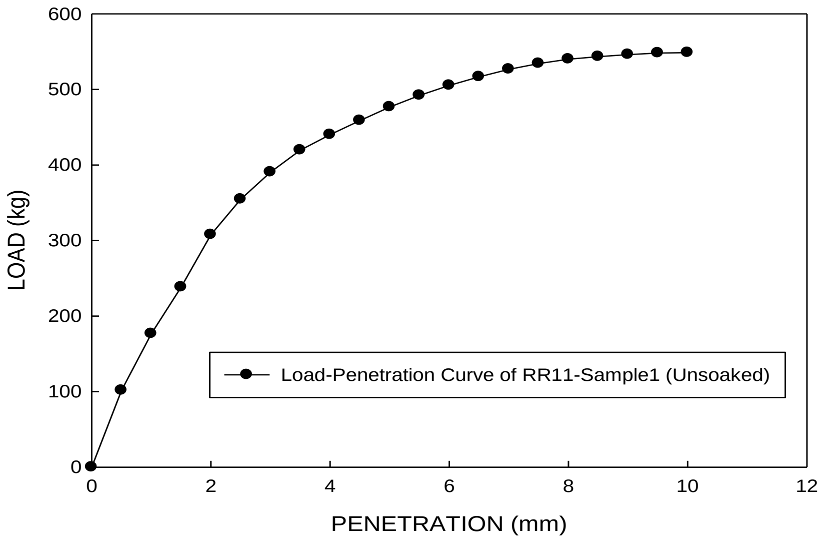

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR9-Sample2 (Unsoaked)
0
100
200
300
400
500
600
0
2
4
6
8
10
12

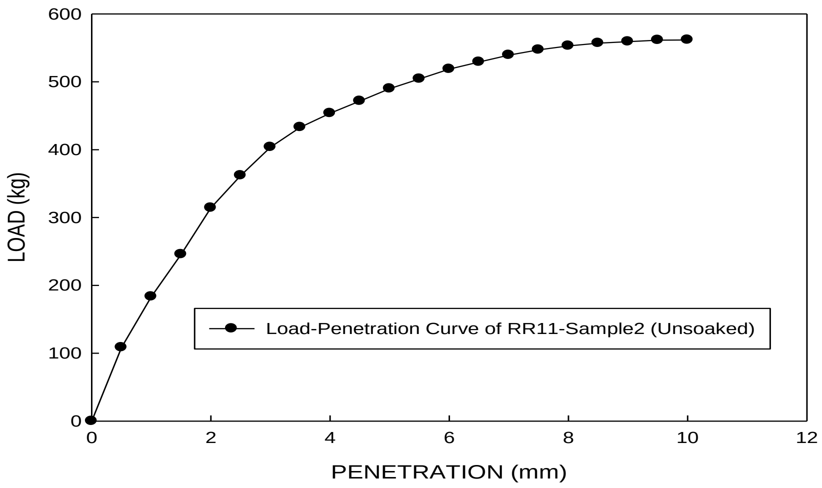

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR9-Sample3 (Unsoaked)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12

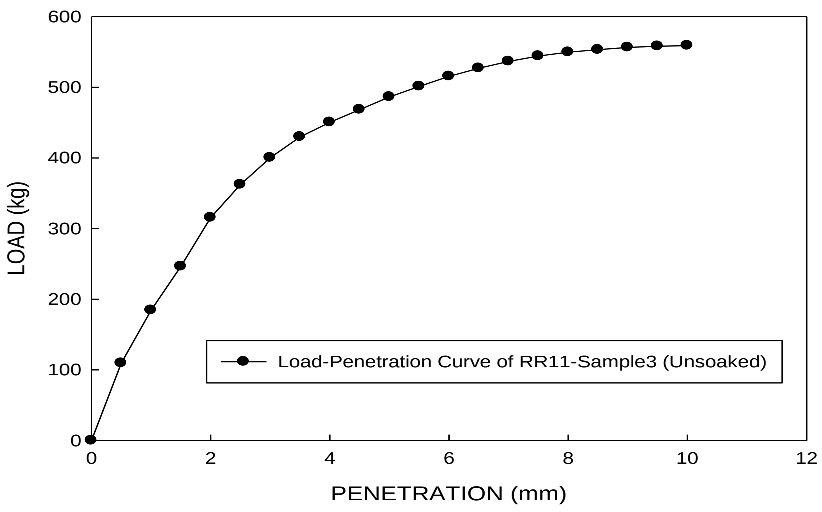

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR10-Sample1 (Unsoaked)
0
100
200
300
400
0
2
4
6
8
10
12

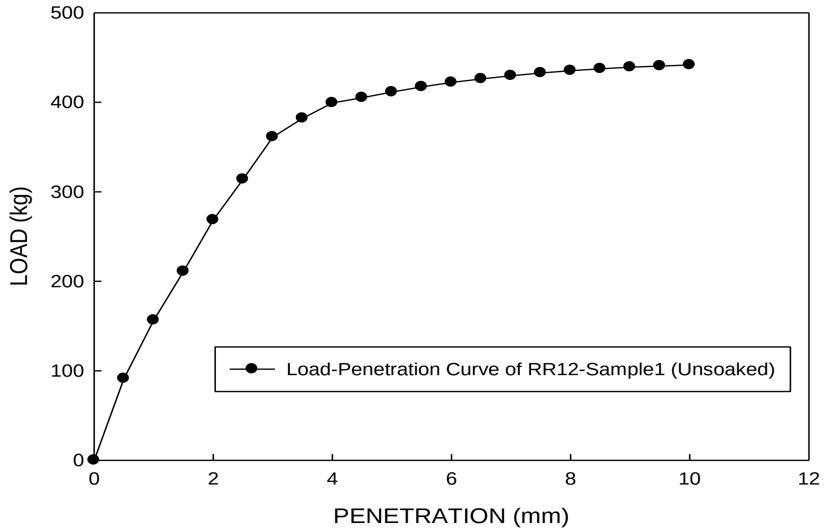

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR10-Sample2 (Unsoaked)
0
100
200
300
400
500
0
2
4
6
8
10
12

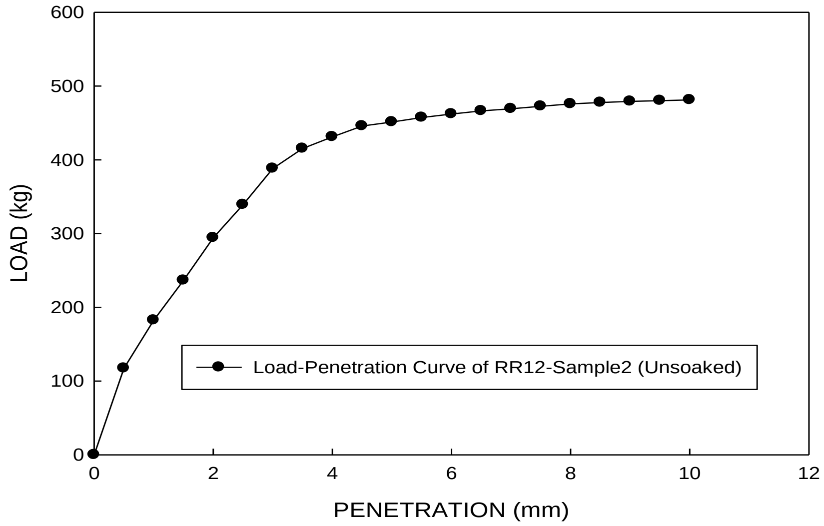

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR10-Sample3 (Unsoaked)
0
100
200
300
400
500
600
0
2
4
6
8
10
12

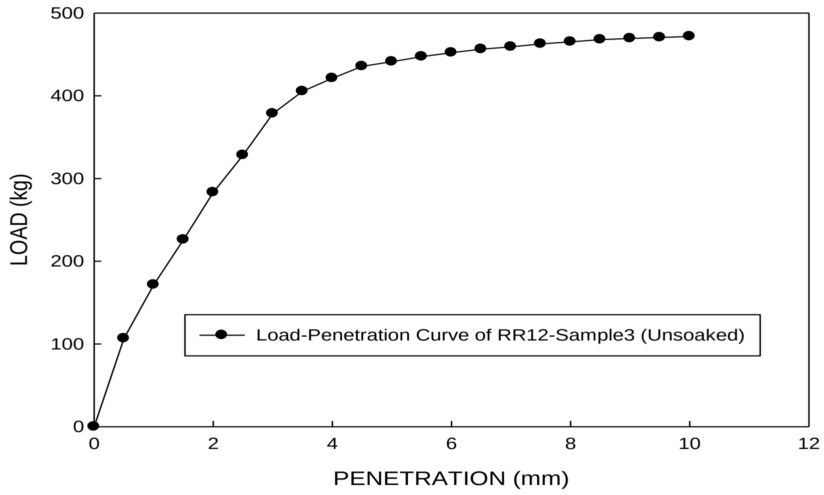

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR11-Sample1 (Unsoaked)


LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR11-Sample2 (Unsoaked)


LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR11-Sample3 (Unsoaked)

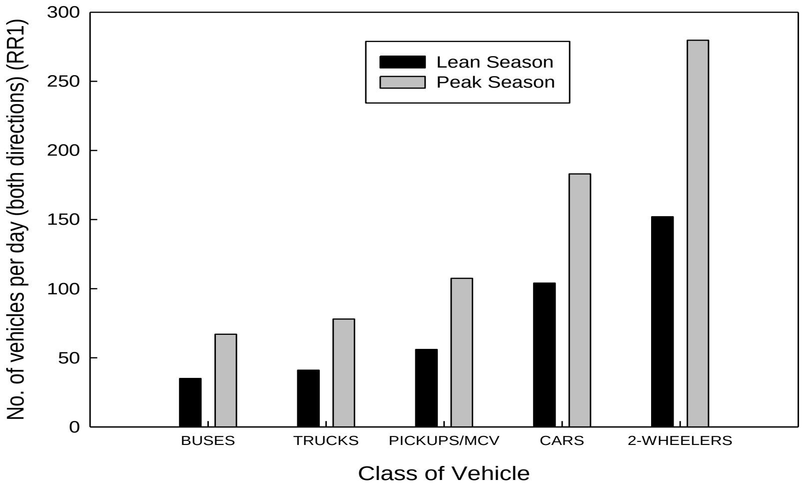

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR12-Sample1 (Unsoaked)


LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR12-Sample2 (Unsoaked)

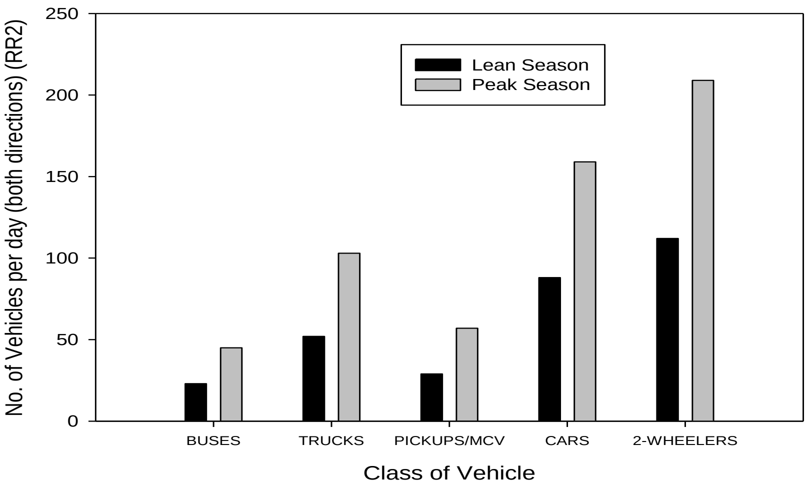

LOAD (kg)
PENETRATION (mm)
Load-Penetration Curve of RR12-Sample3 (Unsoaked)

APPENDIX-C

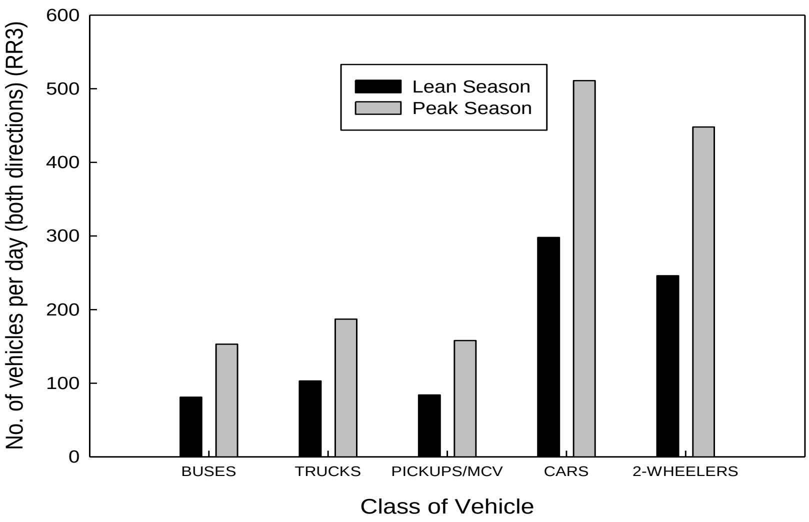
TRAFFIC VOLUME DATA



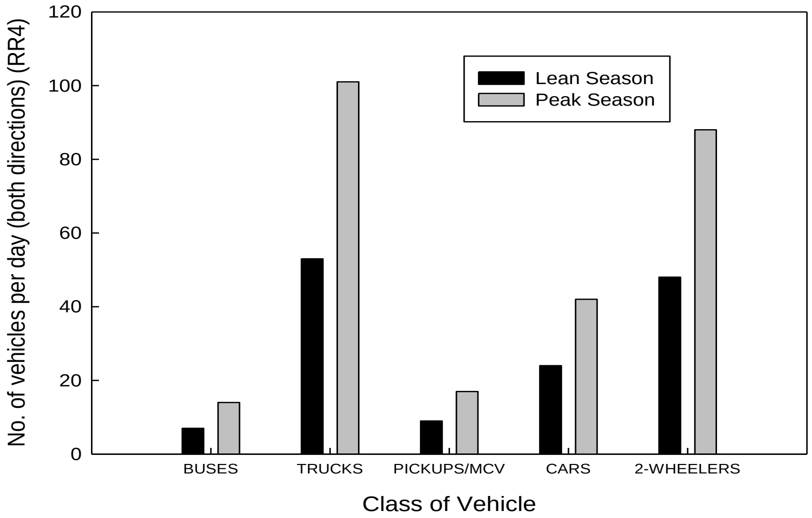
No. of vehicles per day (both directions) (RR1)
300
250
200
150
100
50
0
Lean Season
Peak Season
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle



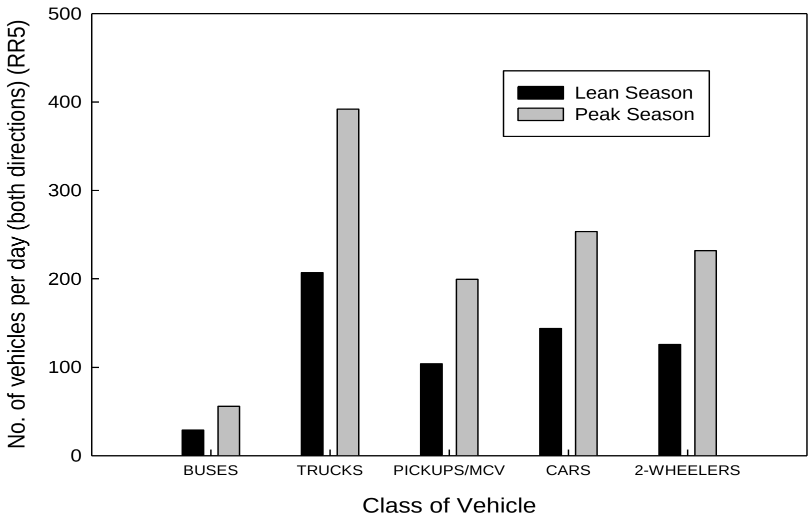
No. of Vehicles per day (both directions) (RR2)
250
200
150
100
50
0
Lean Season
Peak Season
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle



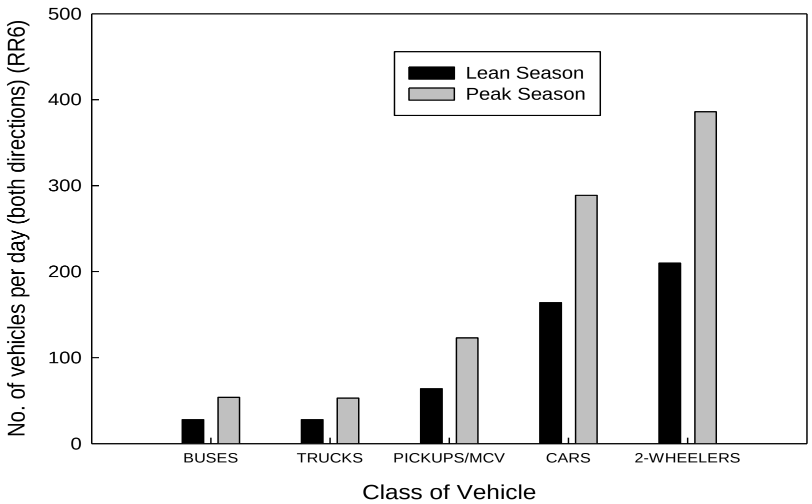
No. of vehicles per day (both directions) (RR3)
600
500
400
300
200
100
0
Lean Season
Peak Season
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle



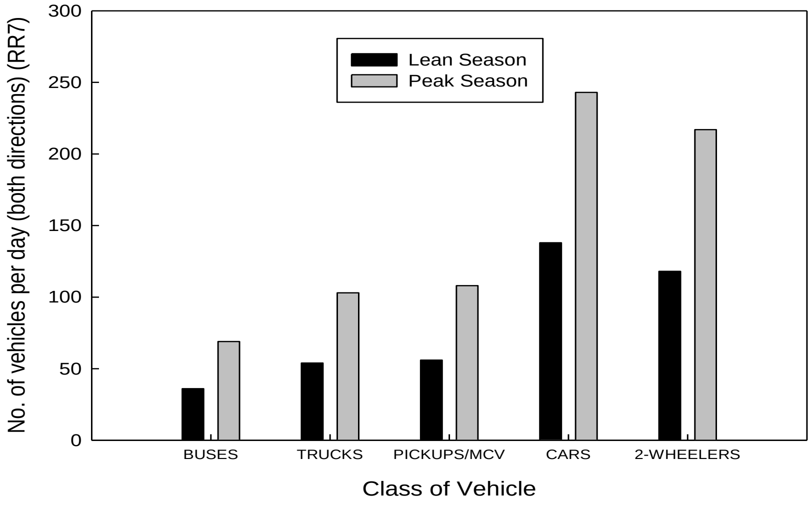
No. of vehicles per day (both directions) (RR4)
0
20
40
60
80
100
120
Lean Season
Peak Season
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle

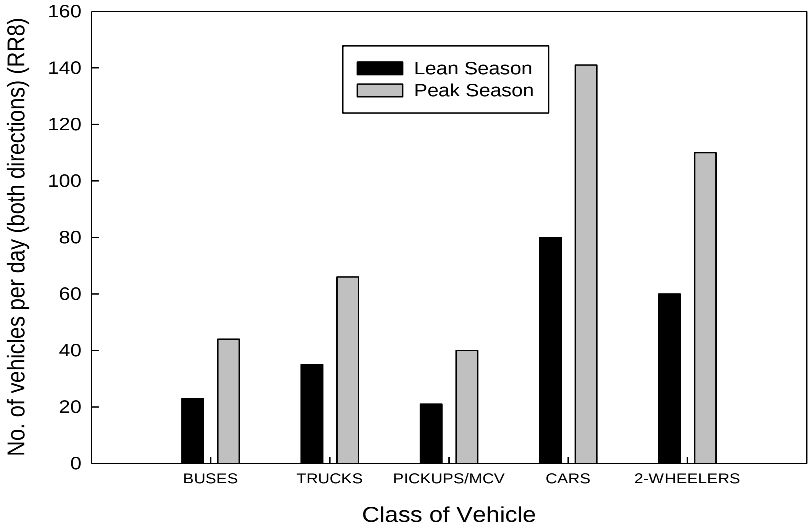


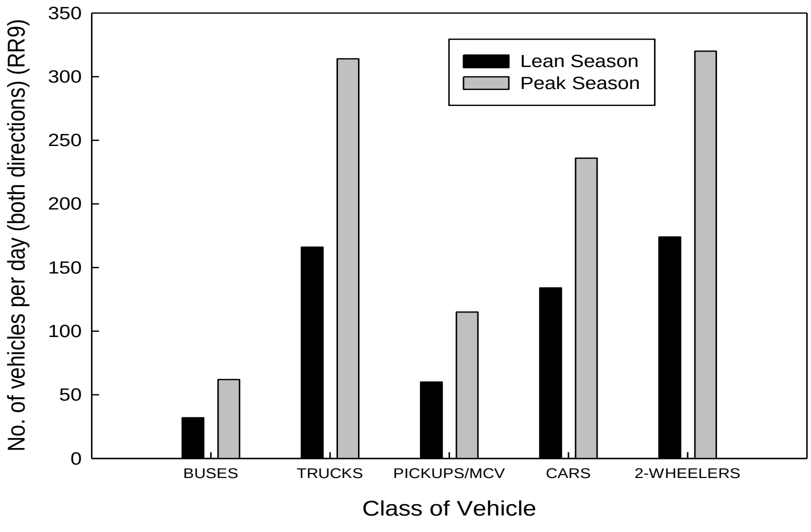
No. of vehicles per day (both directions) (RR5)
0
100
200
300
400
500
Lean Season
Peak Season
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle

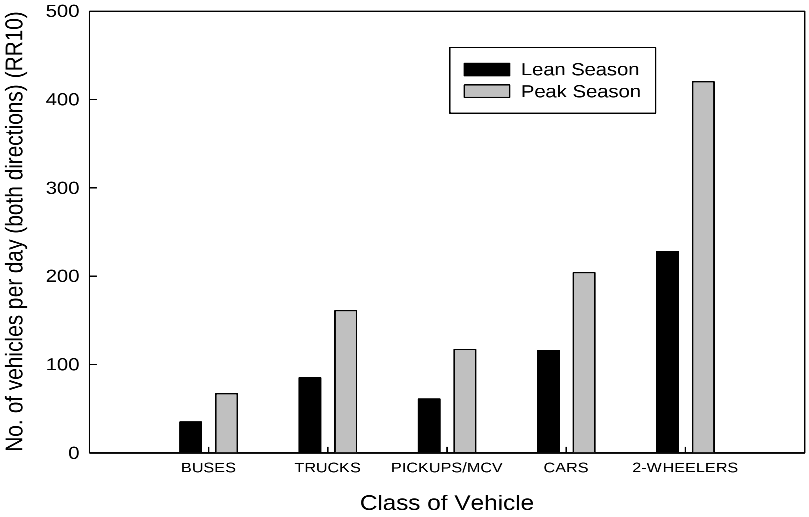


No. of vehicles per day (both directions) (RR6)
0
100
200
300
400
500
Lean Season
Peak Season
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle

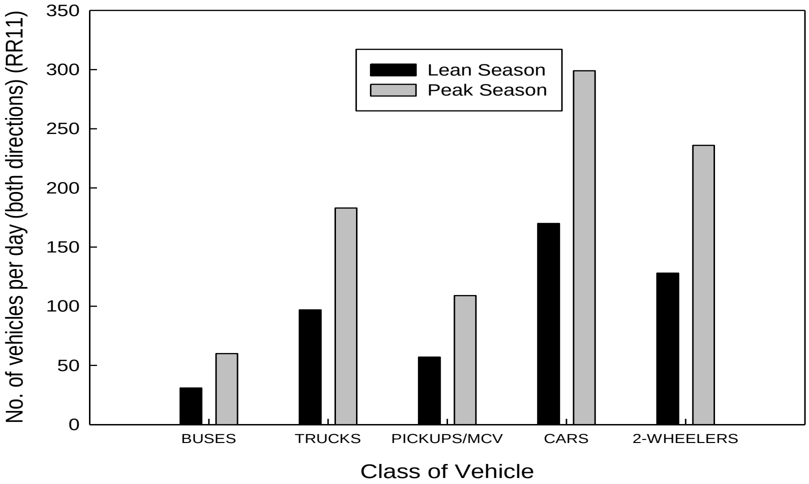

Lean Season
Peak Season
No. of vehicles per day (both directions) (RR7)
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle


Lean Season
Peak Season
No. of vehicles per day (both directions) (RR8)
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle

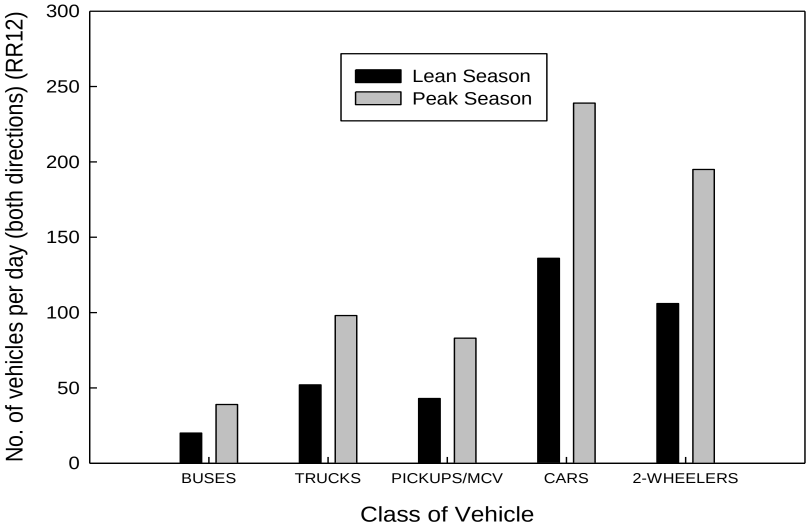

Lean Season
Peak Season
No. of vehicles per day (both directions) (RR9)
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle



Lean Season
Peak Season
No. of vehicles per day (both directions) (RR10)
0
100
200
300
400
500
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle



Lean Season
Peak Season
No. of vehicles per day (both directions) (RR11)
0
50
100
150
200
250
300
350
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle



Lean Season
Peak Season
No. of vehicles per day (both directions) (RR12)
0
50
100
150
200
250
300
BUSES
TRUCKS
PICKUPS/MCV
CARS
2-WHEELERS
Class of Vehicle

APPENDIX-D

BBD DATA

Benkelman Beam Characteristic Deflection Calculations for RR-1

RR1- Domehar-Waknaghat Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\,\sigma$	Moisture Correction Factor for 4%
0	0.352	0.355	0.003	0.355	0.71	0.645	0.14	0.86	**1.38**
0	0.217	0.219	0.002	0.219	0.438				
0	0.41	0.413	0.003	0.413	0.826				**Final D_c**
0	0.401	0.403	0.002	0.403	0.806				**1.18 mm**
0	0.302	0.304	0.002	0.304	0.608				Note: No temperature correction is required.
0	0.269	0.272	0.003	0.272	0.544				
0	0.215	0.217	0.002	0.217	0.434				
0	0.188	0.191	0.003	0.191	0.382				
0	0.361	0.364	0.003	0.364	0.728				
0	0.201	0.204	0.003	0.204	0.408				
0	0.415	0.417	0.002	0.417	0.834				
0	0.334	0.337	0.003	0.337	0.674				
0	0.381	0.384	0.003	0.384	0.768				
0	0.341	0.343	0.002	0.343	0.686				
0	0.271	0.274	0.003	0.274	0.548				
0	0.225	0.227	0.002	0.227	0.454				
0	0.358	0.361	0.003	0.361	0.722				
0	0.381	0.383	0.002	0.383	0.766				
0	0.396	0.399	0.003	0.399	0.798				
0	0.425	0.427	0.002	0.427	0.854				
0	0.332	0.335	0.003	0.335	0.67				
0	0.282	0.285	0.003	0.285	0.57				
0	0.303	0.306	0.003	0.306	0.612				
0	0.339	0.346	0.007	0.346	0.692				
0	0.297	0.299	0.002	0.299	0.598				

Benkelman Beam Characteristic Deflection Calculations for RR-2

RR2- Salogra-Ashwini Khad Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=CLAYEY
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.178	0.181	0.003	0.181	0.362	0.360	0.08	0.48	**1.86**
0	0.242	0.251	0.009	0.251	0.502				PI =13.7
0	0.277	0.279	0.002	0.279	0.558				**Final D_c**
0	0.153	0.163	0.01	0.163	0.326				**0.91 mm**
0	0.189	0.191	0.002	0.191	0.382				Note: No temperature correction is required.
0	0.221	0.223	0.002	0.223	0.446				
0	0.118	0.119	0.001	0.119	0.238				
0	0.221	0.224	0.003	0.224	0.448				
0	0.118	0.121	0.003	0.121	0.242				
0	0.185	0.189	0.004	0.189	0.378				
0	0.133	0.135	0.002	0.135	0.27				
0	0.232	0.233	0.001	0.233	0.466				
0	0.211	0.215	0.004	0.215	0.43				
0	0.176	0.178	0.002	0.178	0.356				
0	0.155	0.159	0.004	0.159	0.318				
0	0.123	0.125	0.002	0.125	0.25				
0	0.171	0.173	0.002	0.173	0.346				
0	0.188	0.19	0.002	0.19	0.38				
0	0.134	0.137	0.003	0.137	0.274				
0	0.165	0.169	0.004	0.169	0.338				
0	0.113	0.116	0.003	0.116	0.232				
0	0.175	0.176	0.001	0.176	0.352				
0	0.212	0.216	0.004	0.216	0.432				
0	0.161	0.163	0.002	0.163	0.326				
0	0.178	0.18	0.002	0.18	0.36				

Benkelman Beam Characteristic Deflection Calculations for RR-3

RR3- Kyari Bangla-Dera Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=CLAYEY
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.252	0.255	0.003	0.255	0.51	0.546	0.14	0.75	**1.86**
0	0.274	0.277	0.003	0.277	0.554				PI =12.22
0	0.187	0.19	0.003	0.19	0.38				**Final D_c**
0	0.219	0.222	0.003	0.222	0.444				**1.41 mm**
0	0.392	0.396	0.004	0.396	0.792				Note: No temperature correction is required.
0	0.321	0.325	0.004	0.325	0.65				
0	0.204	0.208	0.004	0.208	0.416				
0	0.291	0.294	0.003	0.294	0.588				
0	0.225	0.229	0.004	0.229	0.458				
0	0.162	0.165	0.003	0.165	0.33				
0	0.329	0.334	0.005	0.334	0.668				
0	0.205	0.206	0.001	0.206	0.412				
0	0.313	0.315	0.002	0.315	0.63				
0	0.301	0.303	0.002	0.303	0.606				
0	0.412	0.414	0.002	0.414	0.828				
0	0.209	0.213	0.004	0.213	0.426				
0	0.215	0.218	0.003	0.218	0.436				
0	0.325	0.327	0.002	0.327	0.654				
0	0.225	0.228	0.003	0.228	0.456				
0	0.261	0.263	0.002	0.263	0.526				
0	0.401	0.404	0.003	0.404	0.808				
0	0.264	0.265	0.001	0.265	0.53				
0	0.182	0.184	0.002	0.184	0.368				
0	0.31	0.313	0.003	0.313	0.626				
0	0.286	0.288	0.002	0.288	0.576				

Benkelman Beam Characteristic Deflection Calculations for RR-4

RR4- Basha Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.152	0.155	0.003	0.155	0.31	0.397	0.07	0.47	**1.38**
0	0.182	0.184	0.002	0.184	0.368				
0	0.19	0.191	0.001	0.191	0.382				**Final D_c**
0	0.212	0.214	0.002	0.214	0.428				**0.65 mm**
0	0.23	0.232	0.002	0.232	0.464				Note: No temperature correction is required.
0	0.162	0.165	0.003	0.165	0.33				
0	0.204	0.208	0.004	0.208	0.416				
0	0.178	0.182	0.004	0.182	0.364				
0	0.218	0.221	0.003	0.221	0.442				
0	0.251	0.253	0.002	0.253	0.506				
0	0.168	0.171	0.003	0.171	0.342				
0	0.139	0.141	0.002	0.141	0.282				
0	0.149	0.153	0.004	0.153	0.306				
0	0.229	0.233	0.004	0.233	0.466				
0	0.293	0.295	0.002	0.295	0.59				
0	0.146	0.149	0.003	0.149	0.298				
0	0.191	0.195	0.004	0.195	0.39				
0	0.211	0.214	0.003	0.214	0.428				
0	0.233	0.234	0.001	0.234	0.468				
0	0.161	0.165	0.004	0.165	0.33				
0	0.201	0.203	0.002	0.203	0.406				
0	0.218	0.22	0.002	0.22	0.44				
0	0.17	0.173	0.003	0.173	0.346				
0	0.245	0.249	0.004	0.249	0.498				
0	0.162	0.168	0.006	0.168	0.336				

Benkelman Beam Characteristic Deflection Calculations for RR-5

RR5- Khawara Chowki-Mashru Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=CLAYEY
D_o	D_i	D_f	D_i-D_f	D_o-D_f	$D= 2*(D_o-D_f)$	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.512	0.514	0.002	0.514	1.028	0.620	0.23	0.97	**1.86**
0	0.413	0.415	0.002	0.415	0.83				PI =14.17
0	0.404	0.407	0.003	0.407	0.814				**Final D_c**
0	0.359	0.362	0.003	0.362	0.724				**1.80 mm**
0	0.342	0.345	0.003	0.345	0.69				Note: No temperature correction is required.
0	0.362	0.365	0.003	0.365	0.73				
0	0.516	0.518	0.002	0.518	1.036				
0	0.558	0.563	0.005	0.563	1.126				
0	0.311	0.315	0.004	0.315	0.63				
0	0.269	0.272	0.003	0.272	0.544				
0	0.408	0.412	0.004	0.412	0.824				
0	0.192	0.195	0.003	0.195	0.39				
0	0.212	0.216	0.004	0.216	0.432				
0	0.234	0.237	0.003	0.237	0.474				
0	0.257	0.259	0.002	0.259	0.518				
0	0.318	0.321	0.003	0.321	0.642				
0	0.364	0.368	0.004	0.368	0.736				
0	0.252	0.255	0.003	0.255	0.51				
0	0.182	0.184	0.002	0.184	0.368				
0	0.152	0.155	0.003	0.155	0.31				
0	0.202	0.204	0.002	0.204	0.408				
0	0.162	0.163	0.001	0.163	0.326				
0	0.189	0.193	0.004	0.193	0.386				
0	0.195	0.197	0.002	0.197	0.394				
0	0.319	0.324	0.005	0.324	0.648				

Benkelman Beam Characteristic Deflection Calculations for RR-6

RR6- Shoghi-Dooh Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.413	0.418	0.005	0.418	0.836	0.553	0.17	0.81	**1.38**
0	0.162	0.167	0.005	0.167	0.334				
0	0.208	0.213	0.005	0.213	0.426				**Final D_c**
0	0.316	0.32	0.004	0.32	0.64				**1.11 mm**
0	0.18	0.181	0.001	0.181	0.362				Note: No temperature correction is required.
0	0.263	0.267	0.004	0.267	0.534				
0	0.144	0.15	0.006	0.15	0.3				
0	0.409	0.415	0.006	0.415	0.83				
0	0.315	0.317	0.002	0.317	0.634				
0	0.219	0.221	0.002	0.221	0.442				
0	0.243	0.244	0.001	0.244	0.488				
0	0.194	0.199	0.005	0.199	0.398				
0	0.318	0.321	0.003	0.321	0.642				
0	0.404	0.412	0.008	0.412	0.824				
0	0.161	0.164	0.003	0.164	0.328				
0	0.352	0.354	0.002	0.354	0.708				
0	0.234	0.238	0.004	0.238	0.476				
0	0.29	0.292	0.002	0.292	0.584				
0	0.338	0.34	0.002	0.34	0.68				
0	0.355	0.358	0.003	0.358	0.716				
0	0.225	0.227	0.002	0.227	0.454				
0	0.321	0.324	0.003	0.324	0.648				
0	0.36	0.363	0.003	0.363	0.726				
0	0.236	0.238	0.002	0.238	0.476				
0	0.174	0.177	0.003	0.177	0.354				

Benkelman Beam Characteristic Deflection Calculations for RR-7

RR7- Shoghi-Heon Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\sigma$	Moisture Correction Factor for 4%
0	0.312	0.314	0.002	0.314	0.628	0.654	0.14	0.86	**1.38**
0	0.321	0.324	0.003	0.324	0.648				
0	0.401	0.404	0.003	0.404	0.808				**Final D_c**
0	0.376	0.379	0.003	0.379	0.758				**1.19 mm**
0	0.381	0.385	0.004	0.385	0.77				Note: No temperature correction is required.
0	0.266	0.271	0.005	0.271	0.542				
0	0.251	0.257	0.006	0.257	0.514				
0	0.421	0.423	0.002	0.423	0.846				
0	0.439	0.443	0.004	0.443	0.886				
0	0.369	0.373	0.004	0.373	0.746				
0	0.26	0.263	0.003	0.263	0.526				
0	0.257	0.259	0.002	0.259	0.518				
0	0.328	0.333	0.005	0.333	0.666				
0	0.412	0.415	0.003	0.415	0.83				
0	0.352	0.355	0.003	0.355	0.71				
0	0.394	0.396	0.002	0.396	0.792				
0	0.315	0.319	0.004	0.319	0.638				
0	0.26	0.264	0.004	0.264	0.528				
0	0.193	0.197	0.004	0.197	0.394				
0	0.232	0.235	0.003	0.235	0.47				
0	0.334	0.336	0.002	0.336	0.672				
0	0.228	0.242	0.014	0.242	0.484				
0	0.257	0.259	0.002	0.259	0.518				
0	0.318	0.321	0.003	0.321	0.642				
0	0.413	0.417	0.004	0.417	0.834				

Benkelman Beam Characteristic Deflection Calculations for RR-8

RR8- Shoghi-Jaog Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.417	0.418	0.001	0.418	0.836	0.523	0.16	0.76	**1.38**
0	0.304	0.307	0.003	0.307	0.614				
0	0.329	0.336	0.007	0.336	0.672				**Final D_c**
0	0.269	0.271	0.002	0.271	0.542				**1.06 mm**
0	0.146	0.15	0.004	0.15	0.3				Note: No temperature correction is required.
0	0.186	0.189	0.003	0.189	0.378				
0	0.207	0.209	0.002	0.209	0.418				
0	0.242	0.245	0.003	0.245	0.49				
0	0.315	0.318	0.003	0.318	0.636				
0	0.202	0.205	0.003	0.205	0.41				
0	0.158	0.163	0.005	0.163	0.326				
0	0.167	0.169	0.002	0.169	0.338				
0	0.365	0.37	0.005	0.37	0.74				
0	0.154	0.16	0.006	0.16	0.32				
0	0.214	0.218	0.004	0.218	0.436				
0	0.404	0.408	0.004	0.408	0.816				
0	0.316	0.321	0.005	0.321	0.642				
0	0.172	0.176	0.004	0.176	0.352				
0	0.241	0.245	0.004	0.245	0.49				
0	0.343	0.349	0.006	0.349	0.698				
0	0.211	0.214	0.003	0.214	0.428				
0	0.183	0.187	0.004	0.187	0.374				
0	0.261	0.264	0.003	0.264	0.528				
0	0.337	0.341	0.004	0.341	0.682				
0	0.301	0.305	0.004	0.305	0.61				

Benkelman Beam Characteristic Deflection Calculations for RR-9

RR9- Kandaghat-Kot Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\,\sigma$	Moisture Correction Factor for 4%
0	0.414	0.417	0.003	0.417	0.834	0.831	0.13	1.02	**1.38**
0	0.432	0.438	0.006	0.438	0.876				
0	0.389	0.397	0.008	0.397	0.794				**Final D_c**
0	0.332	0.335	0.003	0.335	0.67				**1.41 mm**
0	0.357	0.36	0.003	0.36	0.72				Note: No temperature correction is required.
0	0.434	0.438	0.004	0.438	0.876				
0	0.407	0.41	0.003	0.41	0.82				
0	0.359	0.36	0.001	0.36	0.72				
0	0.377	0.381	0.004	0.381	0.762				
0	0.418	0.42	0.002	0.42	0.84				
0	0.447	0.45	0.003	0.45	0.9				
0	0.424	0.427	0.003	0.427	0.854				
0	0.511	0.516	0.005	0.516	1.032				
0	0.591	0.595	0.004	0.595	1.19				
0	0.417	0.419	0.002	0.419	0.838				
0	0.503	0.505	0.002	0.505	1.01				
0	0.466	0.467	0.001	0.467	0.934				
0	0.481	0.483	0.002	0.483	0.966				
0	0.36	0.369	0.009	0.369	0.738				
0	0.381	0.383	0.002	0.383	0.766				
0	0.401	0.402	0.001	0.402	0.804				
0	0.319	0.322	0.003	0.322	0.644				
0	0.378	0.38	0.002	0.38	0.76				
0	0.399	0.403	0.004	0.403	0.806				
0	0.313	0.315	0.002	0.315	0.63				

Benkelman Beam Characteristic Deflection Calculations for RR-10

RR10- Chail Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=CLAYEY
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.321	0.323	0.002	0.323	0.646	0.583	0.08	0.71	**1.86**
0	0.325	0.327	0.002	0.327	0.654				PI =13.26
0	0.285	0.289	0.004	0.289	0.578				**Final D_c**
0	0.261	0.263	0.002	0.263	0.526				**1.33 mm**
0	0.208	0.209	0.001	0.209	0.418				Note: No temperature correction is required.
0	0.255	0.258	0.003	0.258	0.516				
0	0.322	0.325	0.003	0.325	0.65				
0	0.303	0.306	0.003	0.306	0.612				
0	0.289	0.291	0.002	0.291	0.582				
0	0.207	0.21	0.003	0.21	0.42				
0	0.281	0.282	0.001	0.282	0.564				
0	0.352	0.357	0.005	0.357	0.714				
0	0.391	0.393	0.002	0.393	0.786				
0	0.252	0.254	0.002	0.254	0.508				
0	0.268	0.27	0.002	0.27	0.54				
0	0.297	0.299	0.002	0.299	0.598				
0	0.315	0.317	0.002	0.317	0.634				
0	0.269	0.271	0.002	0.271	0.542				
0	0.297	0.298	0.001	0.298	0.596				
0	0.286	0.287	0.001	0.287	0.574				
0	0.271	0.276	0.005	0.276	0.552				
0	0.309	0.31	0.001	0.31	0.62				
0	0.321	0.327	0.006	0.327	0.654				
0	0.339	0.341	0.002	0.341	0.682				
0	0.207	0.209	0.002	0.209	0.418				

Benkelman Beam Characteristic Deflection Calculations for RR-11

RR11- Nain-Basal Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=Gravely
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.521	0.524	0.003	0.524	1.048	1.063	0.08	1.19	**1.38**
0	0.563	0.567	0.004	0.567	1.134				
0	0.582	0.586	0.004	0.586	1.172				**Final D_c**
0	0.501	0.504	0.003	0.504	1.008				**1.65 mm**
0	0.483	0.485	0.002	0.485	0.97				Note: No temperature correction is required.
0	0.612	0.613	0.001	0.613	1.226				
0	0.552	0.554	0.002	0.554	1.108				
0	0.556	0.558	0.002	0.558	1.116				
0	0.421	0.424	0.003	0.424	0.848				
0	0.489	0.492	0.003	0.492	0.984				
0	0.561	0.563	0.002	0.563	1.126				
0	0.512	0.515	0.003	0.515	1.03				
0	0.525	0.527	0.002	0.527	1.054				
0	0.533	0.536	0.003	0.536	1.072				
0	0.53	0.532	0.002	0.532	1.064				
0	0.545	0.546	0.001	0.546	1.092				
0	0.549	0.551	0.002	0.551	1.102				
0	0.487	0.489	0.002	0.489	0.978				
0	0.561	0.564	0.003	0.564	1.128				
0	0.497	0.5	0.003	0.5	1				
0	0.449	0.452	0.003	0.452	0.904				
0	0.503	0.506	0.003	0.506	1.012				
0	0.602	0.604	0.002	0.604	1.208				
0	0.561	0.562	0.001	0.562	1.124				
0	0.532	0.534	0.002	0.534	1.068				

Benkelman Beam Characteristic Deflection Calculations for RR-12

RR12- Solan-Malaun Road					**Since, D_i-D_f<0.025mm**	**Mean**	**S.D.**	**For Rural Road**	Annual Rainfall=1570 mm, Type of soil=CLAYEY
D_o	D_i	D_f	D_i-D_f	D_o-D_f	D= 2*(D_o-D_f)	$\bar{D}$	σ	$D_c = \bar{D} + 1.5\ \sigma$	Moisture Correction Factor for 4%
0	0.352	0.354	0.002	0.354	0.708	0.436	0.12	0.61	**1.86**
0	0.212	0.214	0.002	0.214	0.428				PI =11.32
0	0.189	0.192	0.003	0.192	0.384				**Final D_c**
0	0.144	0.147	0.003	0.147	0.294				**1.14 mm**
0	0.232	0.237	0.005	0.237	0.474				Note: No temperature correction is required.
0	0.201	0.203	0.002	0.203	0.406				
0	0.26	0.263	0.003	0.263	0.526				
0	0.142	0.145	0.003	0.145	0.29				
0	0.305	0.306	0.001	0.306	0.612				
0	0.128	0.131	0.003	0.131	0.262				
0	0.207	0.21	0.003	0.21	0.42				
0	0.198	0.201	0.003	0.201	0.402				
0	0.169	0.171	0.002	0.171	0.342				
0	0.246	0.247	0.001	0.247	0.494				
0	0.252	0.254	0.002	0.254	0.508				
0	0.313	0.316	0.003	0.316	0.632				
0	0.144	0.147	0.003	0.147	0.294				
0	0.153	0.157	0.004	0.157	0.314				
0	0.223	0.226	0.003	0.226	0.452				
0	0.219	0.222	0.003	0.222	0.444				
0	0.205	0.207	0.002	0.207	0.414				
0	0.231	0.234	0.003	0.234	0.468				
0	0.19	0.193	0.003	0.193	0.386				
0	0.311	0.312	0.001	0.312	0.624				
0	0.168	0.171	0.003	0.171	0.342				

APPENDIX-E

QUESTIONNAIRES

QUESTIONNAIRE

Relative Importance of Parameters Corresponding to Pavement Performance & Maintenance

	Fundamental Scale
Intensity of Importance	**Definition**
1	Equal Importance
3	Somewhat more Important
5	Much More Important
7	Very Much More Important
9	Absolutely More Important
2,4,6,8	Intermediate Value when compromise is required between above

Please check the box with a tick (□) for the relative importance between Group 1 & Group 2 parameters.

SAMPLE

For Example : If you think that road cracking is 5 times more important than road ravelling then put (□) under 5 on left side towards cracking

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Cracking					□													Ravelling

For Example : If you think that road ravelling is 5 times more important than road cracking then put (□) under 5 on right side towards ravelling

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Cracking													□					Ravelling

For Example : If you think that road cracking has equal importance to road ravelling then put (□) under 1 in the centre

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Cracking									□									Ravelling

Start the Survey

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Cracking																		Ravelling
Cracking																		Patching
Cracking																		Potholes
Cracking																		Rutting
Cracking																		Mean Texture Depth
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Ravelling																		Patching
Ravelling																		Potholes
Ravelling																		Rutting
Ravelling																		Mean Texture Depth
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Patching																		Potholes
Patching																		Rutting
Patching																		Mean Texture Depth
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Potholes																		Rutting
Potholes																		Mean Texture Depth
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Rutting																		Mean Texture Depth

QUESTIONNAIRE

Relative Importance of Parameters Corresponding to Pavement Performance & Maintenance

	Fundamental Scale
Intensity of Importance	**Definition**
1	Equal Importance
3	Somewhat more Important
5	Much More Important
7	Very Much More Important
9	Absolutely More Important
2,4,6,8	Intermediate Value when compromise is required between above

PART-A

Please check the box with a tick (□) for the relative importance between Group 1 & Group 2 parameters.

SAMPLE

For Example : If you think that road rutting is 5 times more important than road ravelling then put (□) under 5 on left side towards cracking

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Rutting					□													Ravelling

For Example : If you think that road rutting is 5 times more important than road cracking then put (□) under 5 on right side towards ravelling

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Rutting													□					Ravelling

For Example : If you think that road rutting has equal importance to road ravelling then put (□) under 1 in the centre

Group 1 Parameter	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Group 2 Parameter
Rutting									□									Ravelling

Start the Survey																		
Group 1 Parameter	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Group 2 Parameter**
Longitudinal Cracking																		Ravelling
Longitudinal Cracking																		Patching
Longitudinal Cracking																		Potholes
Longitudinal Cracking																		Rutting
Longitudinal Cracking																		Mean Texture Depth
Longitudinal Cracking																		Transverse Cracking
Longitudinal Cracking																		Alligator Cracking
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Ravelling																		Patching
Ravelling																		Potholes
Ravelling																		Rutting
Ravelling																		Mean Texture Depth
Ravelling																		Transverse Cracking
Ravelling																		Alligator Cracking
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Patching																		Potholes
Patching																		Rutting
Patching																		Mean Texture Depth
Patching																		Transverse Cracking
Patching																		Alligator Cracking
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Potholes																		Rutting
Potholes																		Mean Texture Depth
Potholes																		Transverse Cracking

Potholes																		Alligator Cracking
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Rutting																		Mean Texture Depth
Rutting																		Transverse Cracking
Rutting																		Alligator Cracking
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Mean Texture Depth																		Transverse Cracking
Mean Texture Depth																		Alligator Cracking
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Transverse Cracking																		Alligator Cracking
									PART-B									
									LEVEL-1									
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Functional Condition																		Structural Condition
									LEVEL-2									
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Pavement Distresses																		Pavement Roughness
Pavement Distresses																		Pavement Skid Resistance
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Pavement Roughness																		Pavement Skid Resistance
									LEVEL-3									
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Pavement Modified Structural Number																		Pavement K-Value