" EXPERIMENTAL STUDY OF A QUATERNARY BLEND FOR REACTIVE POWDER CONCRETE USING WET PACKING DENSITY METHOD FOR PARTICLE PACKING"

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Structural Engineering

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CERTIFICATE

This is to certify that the work which is being presented in the thesis titled **" EXPERIMENTAL STUDY OF A QUATERNARY BLEND FOR REACTIVE POWDER CONCRETE USING WET PACKING DENSITY METHOD FOR PARTICLE PACKING"** in partial fulfillment of the requirements for the award of the degree of Master of Technology in Civil Engineering with specialization in "**Structural Engineering**" and submitted to the Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat is an authentic record of work carried out by Mitali Gupta (152657) during a period from July 2016 to May 2017 under the supervision of Mr. Abhilash Shukla (Assistant Professor), Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

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ABSTRACT

In this study quaternary blend was used to obtain Ultra-high performance concrete or reactive powder concrete (RPC) by using wet packing density method for particle packing of pozzolanic materials fly ash and slag, calcined clay with OPC 53 grade which amongst all the parameters of producing RPC, the particle packing has an important role in achieving the desired properties such as having minimum void content and hence maximum packing density. 60 combinations of mixes were experimented on to achieve maximum packing density and to further increase the packing density and decrease the water to binder ratio use of high range water reducers or superplasticizer.

High packing density leads to a higher flowability at the same water content or allow the use of a lower W/CM ratio at the same flowability requirement because the water in excess of that needed to fill up the voids in the particle system lubricates the particles.

Since RPC does not involve the use of aggregates in it sands of different particle size was used for the mix design and compressive strength study was done for 28 days at cold water curing situation.

Keywords***: Quaternary mix, Water Solid ratio, Wet packing density, Solid concentration, Void ratio***

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LIST OF ABBREVIATION

W/CM	Water to Cementitious material ratio
W/B	Water Binder ratio
W/S	Water Solid ratio
L/D	Length to Diameter ratio
SF	Silica Fume
SP	Superplasticizer
SEM	Scanning Electron Microscope
RPC	Reactive Powder Concrete

CHAPTER 1: INTRODUCTION

1.1. GENERAL

Ultra high performance concrete differs from high strength concrete in terms of not strength only but increased durability, dimensional stability as well. The high strength for this concrete nessitiates using mineral admixtures such as fly ash, silica fume, slag, glass powder, brick powder, calcined clay, rice husk ash or any other material that show pozzolanic activity and has a finer particle size so as to fill in the voids between coarser particles. These admixtures have reactive silica and can react with lime in presence of water and produce C-S-H gel which accounts for strength of concrete. In addition to the reactivity they have finer particle size than cement that fill up the voids in concrete reducing the amount of water required to fill the voids giving a higher packing density to the mix. Water added must be sufficient to fill up the voids in the bulk volume of the cementitious materials in order to avoid entrapping air in the voids and therefore by having a higher packing density of the particle system, it allows to reduce the water/cementitious materials (W/CM) ratio and to increase the strength and durability of concrete.

1.2. PROJECT SPECIFIC

This study is aimed at making a quaternary mix of concrete to achieve high strength. Coarse aggregate is eliminated from the mix to achieve the objective of high strength. As discussed earlier the packing density is an important parameter to obtain high strength which is why the first step of the study is to find a combination of materials that gives the maximum packing of particles. The materials to be used in this study are Ordinary Portland Cement (OPC) 53, Ultra fine slag (Alccofine), High reactive Metakaolin, Fly ash, Rice husk ash, Quartz powder, Quartz sand, Manufactured sand.

This will be done by using the bulk density method or the wet packing density method which has been proven to be better than the dry packing density. Plotting the solid concentration and voids ratio against the W/S ratio, calculated from bulk volume of mixture, the maximum solid concentration and minimum voids ratio is determined. The maximum solid concentration is taken as the bulk packing density. It has been seen that at high packing density, percentage increase in packing density is less than the percentage decrease in voids ratio and the effects on the voids ratio should be studied. Compaction has proven to give better results rather than uncompacted mixes. Compaction will be done by vibration, which gives better packing than tamping as has been observed in previous studies as well. The use of low (W/CM) ratio necessitates use of chemical admixtures, the high range water reducers or superplasticizer, that is compatible with cement, which is important for the particles to disperse and not agglomerate as well as for the workability.

Different curing regimes have effect on the strength of concrete. Curing at lower temperature gave ultimate strength because higher temperature accelerates the hydration at the early age, which forms crystals of a poorer structure. Prolonged curing at lower temperatures gave better results.

1.3. OBJECTIVES

- To achieve high packing density for mixes by replacing OPC 53 grade with pozzolanic materials using bulk density method for a quaternary mix.
- To optimize the mixes with highest packing density for superplasticizer dosage.
- To test the mix for compressive strength for 28 days.

CHAPTER 2: LITERATURE REVIEW

2.1. Long et al. (2001) [1]: worked on very-high-performance concrete using ultra fine powders to study the compactness of binary and ternary mix containing SF, pulverized granulated blast furnace slag and PFA having mean diameter 0.2µm, 6.5µm, 5.8µm respectively for pastes and mortars by relative density method with OPC having strength of 56.4 MPa, quartz sand 0.63mm , 2 percent superplasticizer and were cast and stored in fog room at 20º C and bathed in 20º C for 72 h after demoulding and then cured at 95º C steam room for 72 hours. The relationships between relative density and fluidity of pastes were analyzed. Relative density of pastes increased with an increment in the content of powders. Since the apparent density of SF is smaller than that of PFA or PS, so its volume is larger at the same weight. SF was most effective in improving the relative densities of binary paste systems and for ternary paste its relative density further increased compared with binary pastes. With the decrease of W/B ratio, the relative density of fresh pastes increases rapidly. The fluidity of paste decreased with the increase in relative density and it improved when the relative density increase with the same W/B ratio. Good workability was obtained at W/B ratio of 0.16. The relationship between f/c and volume of steel fibers was found not to be simply linear but its value increases gradually with the addition of steel fibers. The compressive strength of VHPC confined by a steel tube went up to 300 MPa whereas compressive strength of concrete core was 198.2 MPa. Compressive strength of VHPC with ultrafine mineral powder up to 200 MPa was achieved. It was concluded that the brittleness of VHPC can be overcome by short steel fibers with greater L/D = 60.

2.2. Kwan and Fung (2009) [2]: wet packing method was applied to measure the packing densities of blended fine aggregates and mortars. Solid concentration of mortar was determined by:

$$V_s = \frac{M \ / V}{D_w U_w + D_a R_a + D_b R_b + D_c R_c + D_d R_d}$$

For both the blended fine aggregates and mortars, packing densities were measured and modeled and compared to the packing densities by two existing packing models, the linear packing models developed by Yu et al. (Model A) and DeLarrard (Model B). For Model A it was found that the effect of particle shape on particle interactions was insignificant and was neglected. When Model B was applied, it had the closest agreement with the measured results was achieved when the K-value, which accounts for the effect of compaction, was taken as infinity. The average absolute difference between the measured and predicted packing densities was 2.1% when Model A was employed and 1.3% when Model B was employed for the fine aggregate samples. For mortar samples, the absolute difference on an average between the measured and predicted packing densities was 1.1% when Model A was employed and 0.4% when Model B was employed.

2.3. Peng et al. (2009) [3]: analyzed the influence of mineral admixtures on the relative density of pastes with low W/B ratios for binary, ternary and quaternary mix and the relationship between compressive strength and paste density of the hardened mortars as well as their effect on packing density of in terms of minimum water requirement of cement. The minimum water requirement increased while the packing density decreased. The minimum water requirement for ternary composite was greater than that for the binary composite system. A quaternary composite system indicated that the introduction of SF further reduced the minimum water requirement. Optimal contents for UFFA, SS and SF were 10%, 17% and 15% by weight respectively, and the quaternary cementitious material possessed maximum packing density of 0.666. Compressive strength was determined after samples were cured at 90 ºC water for 72 hours, the strength included the contribution of the pozzolanic reaction effect of mineral admixtures and there was no direct relationship between the relative density and compressive strength.

2.4. Tam et al. (2010) [4]:did experimental work on optimal conditions for producing reactive powder concrete. Optimum quantity of materials was analyzed. Quartz sand of 3 classes were used to examine the best one. Microstructure and chemical composition of RPC were examined using a SEM and EDX.W/B ratio of 0.2, SP dosage 2.5% and 150–600 μm sized quartz sand cured at 27°C condition was best in terms of mechanical and composite properties. Quartz sand with particle size 150–300 μm displayed low compressive strength. Curing under 60°C in water and 60°C in mist condition resulted in a lower ultimate strength than that cured under 27°C in water condition. Heat treatment increased compressive strength whereas heat treatment duration had little effect on it.

2.5. Fennis (2012) [5]: Particle packing models and optimization methods were mentioned and their influence on concrete properties was discussed. Creep and shrinkage were conducted for 90 days at 20 ºC and 50% relative humidity. The two electrode method (TEM) determined the electrical resistance of concrete Particle size distribution was done using NEN 5950 and Dinger and Funk optimization curve for q value 0.37. Ecological mix using fine powders saved 57% cement that reduced 25% CO_2 emission. Cyclic design method used resulted in at least predicted strength 33 MPa. TEM results showed that W/B ratio and resistivity were not related to each other and creep and shrinkage decreased.

2.6. Matias et al. (2014) [6]: did experiment on recycled aggregate produced by crushing concrete having strength of 40 MPa. Effect of standard and high-performance superplasticizers on the durability related properties with different percentages of recycled coarse aggregates was studied. Specific density, capillarity properties were influenced by the superplasticizers. Higher RA particle density results in higher concrete's specific density. Compressive strength decreased, but superplasticizers could enhance it. RA concrete revealed higher shrinkage strains than normal concrete which can be improved quality of superplasticizer. Carbonation depth of RA concrete was lower than that of the RC at early ages because of superplasticizer. Efficiency of both superplasticizers decreased in the RA concrete with age. Mixes with RA and superplasticizers had better chloride penetration resistance than the normal concrete.

2.7. Kwan and Li (2014) [7] did an experiment on the dry and wet packing densities of concrete mixes under different combination of compactions and superplasticizer containing cementitious materials, fine and coarse aggregate using bulk density method and evaluated solid concentration of particles. Mixes with OPC, PFA and SF were made. Bulking effect was observed as W/S ratio increased. Maximum solid concentration was taken as the packing density of the sample which was tested under wet condition. Void ratio was more important parameter than packing density, the voids ratio decreased and solid concentration increased only until the W/S ratio reached an optimum value. Packing density was higher, the voids ratio was smaller and the filling effects of ultrafine supplementary cementitious materials were better revealed under wet condition than dry condition. After optimum cement content void ratio increased. In dry mix blend of OPC and CSF packing density decreased. Due to the ultrahigh fineness of CSF, the SP dosage per surface area decreased as the CSF content increased. Compared to the decrease in voids ratio due to blending with CSF, decrease in voids ratio due to blending with PFA was higher. The full potential of blending OPC with cementitious materials can be explored by setting the SP dosage according to the surface area and compaction should be applied. Water, compaction and SP all have significant effects on the particle packing of concrete mix. He concluded that the presence of water decreased the voids ratio by 46%. The compaction by tamping decreased the voids ratio by 36% under dry condition and 17% under wet condition. Under wet condition, compaction by vibration decreased the voids ratio by 27%, showing that vibration was more effective than tamping for compaction. The addition of SP decreased the voids ratio by 39%. The void ratio decreased initially as the cement content increased and then after reaching cement content by volume of about 15% to 20% increased, as the cement content further increased. Results indicate that use of wet packing method is better because if desired, the effect of SP and vibration can be simulated.

2.8. Kumar et al. (2015) [8]: worked on Reactive Powder Concrete with mineral admixtures. They analyzed different powder mixes with maximum packing density using alccofine and metakaolin as partial replacement of cement and studied the performance of concrete mixture in terms of split tensile strength, slump flow test for fresh concrete, compressive strength and flexural strength test at age of 3,7, 14 and 28 days. Test results indicated that blend containing 59% cement, 15% metakaolin and 26% alccofine achieved maximum packing density. Compressive strength of specimens increased with the increase in the percentage of alccofine in mixes with both with and without steel fibers. Split tensile strength of specimens increased with the increase in the percentage of alccofine compared to the OPC mix. Flexural strength of the cast beam increased with the increase in the percentage of alccofine percentage in both the mixes with steel fibers and without steel fibers. The strength gained was slightly less compared to the RPC 200 which can be achieved by using silica fume or quartz sand in the mixes.

2.9. Mehta and Patel (2015) [9] kept the quartz sand cement ratio constant at 1.5 and the silica fume cement ratio varied from 0.15 to 0.3. The value of water cement ratio was varied from 0.2 to 0.35. The dosage of super plasticizer depended upon the water cement ratio and dosage of other constituents. No relation was found between compressive strength or workability due to quartz sand. It was observed that even at low water cement ratio with comparatively low dosage of plasticizer, gave zero slump and zero flow displayed cohesiveness in the mix and the specimens could be casted easily as well as gave a higher value of compressive strength. Conclusion were made that the water cement ratio of 0.3 and silica fume cement ratio of 0.25

gave better results as compared to the other proportions for super plasticizer dosage of 8 ml with quartz sand cement ratio of 1.5.

2.10. Bandukwala and Sonkusare (2016) [10]: studied compressive strength of Plain Reactive Powder Concrete, Original Reactive Powder Concrete and Modified Reactive Powder Concrete and compared the strengths tested at 7 days normal curing and 48 hours 90 ºC accelerated curing. Modified Reactive Powder Concrete was casted by replacing sand by coarse aggregate up to 40%. Plain Reactive Powder Concrete gave the highest compressive strength as compared to MRPC and ORPC because it included steel fiber. Accelerated curing was better than normal curing because it required less time and gives higher strength also.

2.11. Qu et al. (2016) [11]: Investigated use of recycled powder from waste of clay bricks in reactive powder concrete. The recycled powder used to replace the silica fume in RPC indicated that as the replacement rate of silica fume in RPC by recycled powder increased, the flow of the mix decreased slightly, the compressive and flexural strengths decreased, the shrinkage reduced, and the chloride-penetration resistance of RPC decreased. The chloride penetration resistance of the mixture with recycled powder replacement of 100% was good. The recycled powder was used to replace the cement in RPC indicated that as the replacement rate of cement in RPC by recycled powder increased, the shrinkage reduced, the compressive strength changed slightly, the chloride-penetration resistance decreased, and the flexural strength of RPC decreased. The chloride-penetration resistance of the mixture with recycled powder replacement of 27% was good. It was observed that when RPC was made with recycled powder and GGBFS, as the replacement rate of cement in RPC by GGBFS increased, the flow, compressive and flexural strengths increased first and then decreased. The replacement rate of 10% was suggested. The standard curing was used for all the tests instead of steam curing normally required for RPC and the W/CM ratio was suggested between 0.18 and 0.20.

CHAPTER 3: EXPERIMENTAL PROGRAMME

3.1. MATERIALS USED: The materials used in the study are aimed at obtaining high packing density.

3.1.1. OPC 53: Ordinary Portland Cement 53 grade was used manufactured at Ambuja Cements Ltd., Darlaghat, Himachal Pradesh confirming to IS: 12269 (1987) [12].

Fig. 1. Ordinary Portland Cement (OPC) 53 grade

3.1.2. Fly Ash: Class F fly ash was used in this study. It is a low calcium pozzolanic material and its use as an admixture and Pozzolana conforms to IS: 3812 (1981) [13]. It an industrial by product obtained from PSPCL thermal power plant at Ghanauli, Ropar, Punjab.

Fig. 2. Fly Ash

3.1.3. Metakaolin: High Reactive Metakaolin by the name of KaoCem is being used in this study. It is manufactured for specific purpose under controlled conditions and not a byproduct of industry. The calcination done by heating kaolin, a natural clay, to temperature between 650-900 ºC modifies the particle structure making it a highly reactive, amorphous pozzolana. Its mineralogical composition is Kaolinite (Aluminum Silicate – Al_2O_3 SiO_2). Its use as a pozzolana is as per the specifications of IS: 1344-1981 [14].

Advantages:

- Concrete additive Mineral admixture
- Early age strengths and significant increase in Flexural Strength and Compressive strength
- Concrete durability enhances
- Reduction in permeability
- Chemical attack resistance
- Protection against corrosion
- Efflorescence & Shrinkage reduction or complete elimination
- Alkali Silica Reactivity (ASR) reduction or complete elimination

Recommendation as per Indian Standard - IS 1489 (Part–2):1991 [15].

Fig. 3. High reactive Metakaolin

Table 1
Physical properties of High reactive Metakaolin

PHYSICAL PROPERTIES	
Color	Pink / Off-white
Pozzolana Reactivity mg Ca $(OH)_2$ / gm	900
Average Particle size	1.4 micron
Brightness (ISO)	75 ± 2
Bulk Density (Gm / Lt.)	320 to 370

3.1.4. Ultra Fine Slag (Alccofine1203): Ultrafine slag is a low calcium silicate mineral additive. results in unique particle size distribution owes to the controlled granulation process. Its pozzolanic reactivity results in enhanced hydration process. Its addition improves the packing density of paste component which results in lowering water demand, admixture dosage and improves strength and durability parameters of concrete at all ages. Its mixing time should be adequate to facilitate uniform inter dispersion in the concrete.

Advantages

- Refined pore structure, educes permeability improves durability parameters of concrete
- Improved resistance of concrete to aggressive environment
- Pump ability of concrete increases
- Enhanced slump and extended slump retention at low dosage of chemical admixtures
- With high pozzolanic material contents like fly ash exhibits higher strength of concrete.

Applicable standards - IRC SP: 70 [16], IS: 456 [17], IS: 12089 [18].

Fig. 4. Ultra fine slag

Table 2
Physical properties of Ultra fine slag

PHYSICAL PROPERTIES	
Particle Size Distribution(um) d10	1.7
d50	4.3
d90	8.8
Bulk Density (Kg / m^3)	680
Marsh Cone Flow (with water to ALCCOFINE 1203 ratio as 1.5)	28 sec
Average particle size	4 to 6 microns
Fineness	12000 cm^2/gm

3.1.5. Quartz Powder was procured from Surya Min Chem, Barwala, Delhi. with particle size range of 5-25 μm.

Fig. 5. Quartz Powder

3.1.6. Quartz sand was procured from Surya Min Chem, Barwala, Delhi.

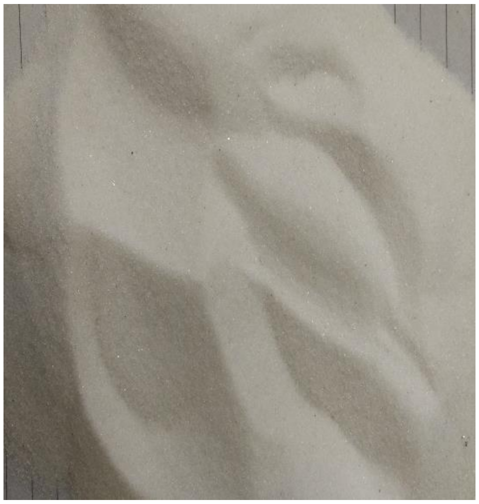


Fig. 6. Quartz sand

3.1.7. Manufactured sand was procured from Nangal, Punjab.

Fig. 7. Manufactured sand

Particle size distribution was done by laser diffraction analyzer at IIT Bombay for OPC and pozzolanic materials as shown in Fig. 8.

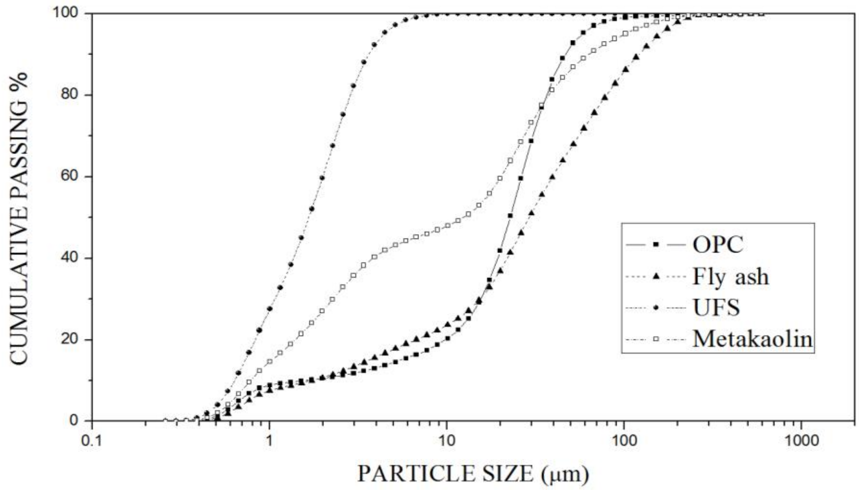


Fig. 8. Particle size distribution of OPC 53 grade and pozzolanic materials

Oxide composition of OPC 53 grade and pozzolanic materials was done by X-ray fluorescence test at IIT Bombay as shown in Table 3.

Table 3
Oxide composition of materials

MATERIALS	Al_2O_3	CaO	Fe_2O_3	K_2O	Na_2O	SiO_2	MgO
OPC 53	4.84	61.15	4.82	0.78	0.17	21.27	1.81
UFS	21.86	33.65	1.34	-	-	36.1	6.24
FLYASH	28.34	3.16	5.27	1.23	0.66	58.8	0.89
METAKAOLIN	41.28	0.03	0.56	0.62	-	54.6	-

3.2 METHODOLOGY:

3.2.1. PACKING DENSITY MEASUREMENT WITHOUT SUPERPLASTICIZER

The percentage replacement of OPC 53 grade was from 10 % and went up to 40% in steps of 5%. This percentage replacement was divided in 3 pozzolanic materials and they were arranged in order of their reactivity. Since fly ash has the least reactivity it was allotted least content in all the mixes. Ultrafine slag and metakaolin were varied by increasing one and decreasing the other. Wet packing density method was adopted for the achieving the maximum packing density of materials in this study. Under wet condition, the dispersion and solid concentration of solid particles depend on the water to solid ratio (W/S) ratio. At a W/S ratio lower than the optimum, the water added is not sufficient to fill up the voids, hence entrapping the air inside the voids and water bridges are formed between the particles, which cause the solid concentration to decrease as the W/S ratio decreases. Whereas, at a W/S ratio higher than optimum, the particles are dispersed in the water, causing the solid concentration to decrease as the W/S ratio increases. Hence, there at an optimum W/S ratio, called the basic W/S ratio, at which the voids are minimum, the particles are most closely packed, and the solid concentration reaches its maximum value. The maximum solid concentration therefore achieved is taken as the wet packing density. To determine the wet packing density, solid concentrations at different W/S ratios over a range needs to found out to cover the optimum W/S ratio. W/S is taken at the lowest value initially and increased gradually henceforth.

The test procedure of the wet packing test is as follows:

(a) Set the W/S ratio at which the test is to be carried out. Weigh the required quantities of OPC 53 grade, pozzolanic materials and water.

(b) Put all solids (cementitious and pozzolanic materials) into the mixing bowl and mix the solids to ensure uniformity of the sample for 3 minutes.

Fig. 9. Dry mix of solids

(c) Add the water into the mixing bowl and mix the contents to ensure uniformity of the sample.

Fig. 10. Wet mix at 0.26 W/S ratio

Fig. 11. Wet mix at 0.27 W/S ratio

Fig. 12. Wet mix at 0.28 W/S ratio

Fig. 13. Wet mix at 0.29 W/S ratio

(d) Transfer the mixture to the container of known volume for bulk density measurement and fill the container layer by layer and compact it on the vibrating table for 4 minutes.

(e) Fill the container to slight excess. Remove the excess with a steel rule and weigh the amount of mixture in the container to determine the bulk density.

Fig. 14. Compaction on vibrating table

Fig. 15. Levelling of the surface

(f) Pour the mixture into the mixing bowl, now add water to it corresponding to the next W/S ratio and mix it till a uniform mix is obtained.

(g) Repeat previous step (d-f) at successively higher W/S ratios by adding more water until the maximum solid concentration has been found as indicated by the solid concentration increasing to a certain maximum value and then decreasing with further increase in W/S ratio.

(h) Repeat all the above steps (a-g) for different mix proportions till maximum solid concentration is achieved.

From the bulk volume of the mixture (denoted by V), which is the volume of the container, and the solid volume of the particles (denoted by V_s), which is determined from the W/S ratio and the weight of the mixture, the solid concentration S_c, voids ratio u and void content ε can be determined as:

$$V_s = \frac{M / V}{D_w U_w + D_a R_a + D_b R_b + D_c R_c + D_d R_d}$$

$$S_c = \frac{V_s}{V}$$

$$u = \frac{V - V_s}{V_s}$$

$$\varepsilon = \frac{u}{1+u}$$

where,

D_w is the density of water, D_a, D_b, D_c and D_d are, respectively, the specific gravities of the cementitious and pozzolanic material a, b, c and d. U_w is the W/S ratio, and R_a, R_b and R_c are, respectively, the volumetric ratios of a, b, c and d to the total solids content.

The maximum solid concentration and minimum voids ratio can be determined by plotting the solid concentration S_c and voids ratio u against the W/S ratio.

Maximum solid concentration is taken as the wet packing density.

3.2.2. PACKING DENSITY MEASUREMENT WITH SUPERPLASTICIZER

The packing density measurement procedure is the same as described in section 3.2.1. with the difference of addition of superplasticizer. The packing density for 5 combinations having the highest packing density was tested by varying the superplasticizer dosage and keeping W/S ratio constant at 0.19. The only change in the procedure is to mix the superplasticizer with water and prepare a new mix every time for change in superplasticizer dosage.

3.3 TESTS PERFORMED

3.3.1. Tests on OPC 53:

The following results were obtained:

Normal consistency = 36%

Initial setting time = 110 min

Final setting time = 225min

Fineness of cement = 0.5%

Specific gravity = 3.15

Soundness = 2mm

3.3.2 Test for the specific gravity of materials: specific gravity of cement and other pozzolanic materials were done by Le Chatelier flask as per IS :1727 (1967) [19] and by Pycnometer for sands as per IS: 2386-3 (1963) [20].

Table 4
Specific gravity of materials

MATERIAL	SPECIFIC GRAVITY
OPC 53	3.15
ULTRA FINE SLAG	2.86
METAKAOLIN	2.5
FLY ASH	2.17
QUARTZ POWDER	2.65
QUARTZ SAND	2.34
MANUFACTURED SAND	2.6

3.3.3. Test for water absorption of sands: was done by Pycnometer for sands as per IS: 2386-3 (1963) [20]

Table 5
Water absorption of sands

MATERIAL	WATER ABSORPTION (%)
QUARTZ SAND	0.4
MANUFACTURED SAND	1

3.3.4. Sieve analysis of sands: to obtain the desired range of particles sieve analysis was done.

Table 6
Particle size distribution of sands

MATERIAL	Particle size range (μm)

QUARTZ SAND	150-300
MANUFACTURED SAND	300-600

3.4. MIX PROPORTIONS:

Mix proportions were tested for particle packing of OPC 53, Ultra-fine slag (Alccofine), Metakaolin, Fly ash so as to replace cement up to 70%. Cement was replaced in steps of 5% with other cementitious materials being replaced at an interval of 1%. The combinations were selected so as to not keep the percentage of fly ash less than 2%. For a particular percentage of cement replacement, keeping one of the material constant the other were varied.

The combinations are as follows, where the initials mean:

C: OPC 53

U: Alccofine

M: Metakaolin

F : Fly Ash

Table 7
Mix Proportions

COMBINATION NAME	PROPORTIONS
CUMF 1	(90:5:3:2)
CUMF 2	(90:3:5:2)
CUMF 3	(90:4:4:2)
CUMF 4	(85:6:6:3)
CUMF 5	(85:6:5:4)
CUMF 6	(85:7:5:3)
CUMF 7	(85:8:4:3)
CUMF 8	(85:5:6:4)
CUMF 9	(85:5:7:3)
CUMF 10	(80:7:7:6)
CUMF 11	(80:8:7:5)
CUMF 12	(80:9:6:5)
CUMF 13	(80:7:8:5)
CUMF 14	(80:6:9:5)

CUMF 15	(80:8:8:4)
CUMF 16	(80:9:7:4)
CUMF 17	(80:7:9:4)
CUMF 18	(75:9:9:7)
CUMF 19	(75:10:8:7)
CUMF 20	(75:8:10:7)
CUMF 21	(75:10:9:6)
CUMF 22	(75:9:10:6)
CUMF 23	(75:11:8:6)
CUMF 24	(75:8:11:6)
CUMF 25	(75:7:12:6)
CUMF 26	(75:12:7:6)
CUMF 27	(70:10:10:10)
CUMF 28	(70:11:10:9)
CUMF 29	(70:10:11:9)
CUMF 30	(70:11:11:8)
CUMF 31	(70:12:10:8)
CUMF 32	(70:13:9:8)
CUMF 33	(70:10:12:8)
CUMF 34	(70:9:13:8)
CUMF 35	(70:12:11:7)
CUMF 36	(70:13:10:7)
CUMF 37	(70:11:12:7)
CUMF 38	(70:10:13:7)
CUMF 39	(65:13:12:10)
CUMF 40	(65:14:11:10)
CUMF 41	(65:12:14:9)
CUMF 42	(65:15:11:9)
CUMF 43	(65:11:15:9)
CUMF 44	(65:14:13:8)
CUMF 45	(65:15:12:8)
CUMF 46	(65:13:11:11)
CUMF 47	(65:11:14:10)
CUMF 48	(65:14:12:9)
CUMF 49	(65:12:12:11)
CUMF 50	(65:12:13:10)
CUMF 51	(65:12:15:8)
CUMF 52	(65:13:14:8)
CUMF 53	(60:15:13:12)

CUMF 54	(60:15:14:11)
CUMF 55	(60:16:13:11)
CUMF 56	(60:17:12:11)
CUMF 57	(60:14:14:12)
CUMF 58	(60:13:15:12)
CUMF 59	(60:14:16:10)
CUMF 60	(60:13:17:10)

The five combinations for which highest packing density were obtained are mentioned in Table 8

Table 8
Mixes with highest packing density

COMBINATIONS	PACKING DENSITY
OPC 53(70%) + Ultra-fine slag(12%) + Metakaolin(10%) + Fly Ash (8%)	0.6949
OPC 53(70%) + Ultra-fine slag(10%) + Metakaolin(11%) + Fly Ash (9%)	0.6898
OPC 53(70%) + Ultra-fine slag(11%) + Metakaolin(10%) + Fly Ash (9%)	0.6874
OPC 53(70%) + Ultra-fine slag(13%) + Metakaolin(9%) + Fly Ash (8%)	0.6871
OPC 53(70%) + Ultra-fine slag(10%) + Metakaolin(12%) + Fly Ash (8%)	0.6867

CHAPTER 4: OPTIMIZATION OF SUPERPLASTICIZER

To achieve high strength of concrete a low W/S ratio is preferred but it does not provide enough workability hence at a low W/S ratio addition of superplasticizer ensures adequate workability of the mix. Optimization of dosage of superplasticizer was done to determine the compatibility of superplasticizer with cementitious paste. The optimization of superplasticizer for this study was done by marsh cone test. Optimization of the mix combinations having highest packing density was done using a third generation polycarboxylate ether superplasticizer. Superplasticizer dosage was varied for W/S ratio of 0.19.

The procedure followed for the Marsh cone test was:

1. All the pozzolanic and cementitious materials according to the mix proportion were dry mixed for 2 minutes in a planetary mixer (Hobart).
2. 50% superplasticizer and 50% water were then added to the mix and was mixed till 2 minutes.
3. Remaining 50% superplasticizer and 50% water were then added and mixed for 2 more minutes.
4. Marsh cone was filled with the paste while keeping the nozzle closed with the finger.
5. Once the cone was filled the paste was allowed to flow into a cylinder and simultaneously stop watch was started to record the time.
6. Watch was stopped when the paste was emptied in a cylinder.

Fig. 16. Planetary mixer (HOBART)

Fig. 17. Material filled in Marsh Cone **Fig. 18.** Flow through the hole

The test was repeated with an increase in superplasticizer at 0.5% steps till the decrease in time from the previous content was very less. From the calculations done (APPENDIX 2) the following results were obtained presented in Table 9.

Table 9
Optimized percentage of superplasticizer at W/S ratio 0.19

COMBINATION	PERCENTAGE SUPERPLASTICIZER
OPC 53(70%) + Ultra-fine slag(12%) + Metakaolin(10%) + Fly Ash (8%)	0.8%
OPC 53(70%) + Ultra-fine slag(10%) + Metakaolin(11%) + Fly Ash (9%)	0.8%
OPC 53(70%) + Ultra-fine slag(11%) + Metakaolin(10%) + Fly Ash (9%)	0.75%
OPC 53(70%) + Ultra-fine slag(13%) + Metakaolin(9%) + Fly Ash (8%)	0.8%
OPC 53(70%) + Ultra-fine slag(10%) + Metakaolin(12%) + Fly Ash (8%)	0.85%

CHAPTER 5: MIX DESIGN AND COMPRESSIVE STRENGTH

Reactive Powder Concrete as described earlier does not consist of coarse aggregate. Since coarse aggregates are removed from RPC its main composition consists of cementitious paste and sand. The sand used in this study are of two types quartz sand and the manufactured sand. Quartz powder was used to further increase the density of the mix.

The mix design has been prepared for the 5 mixes having highest packing densities by keeping cement content at 1100 kg/m^3 and 900 kg/m^3 respectively as shown in Table 10 and Table 11. The water to solid ratio was kept 0.19 for all the mix designs. the procedure adopted for mixing and casting was as follows:

1. The materials were weighed according to their proportions in the mix design.
2. All the constituents were mixed in dry state in Planetary Mixer (HOBART) for approximately 1.5 minutes at first gear.
3. Half of the water mixed with superplasticizer was then added to the mixer and mixed for another 2 minutes at first gear.
4. Remaining water and superplasticizer were added to the mixer for 1 minute at first gear.
5. Then the mixer was made to run on second gear for 2.5 minutes.
6. Lastly the mix was blended for 1 minute at first gear.
7. The mixture was added to the 3 moulds to take an average reading and vibrated on mechanical vibrating table.
8. Compaction by vibration was done for 4 minutes.

The cubes were cured in water tank which had temperature less than 18 ºC and were demoulded after 28 days for compressive strength testing in Universal Testing Machine (UTM).

Table 10

Mix design for OPC 53 content 1100 kg/m^3

Combination no.	TCM	OPC 53 (g)	Alccofine (g)	Metakaolin (g)	FA(g)	QS (50%) (g)	MS(50%) (g)	QP(5%) (g)	SP	Corrected water
CUMF 34	1778.70	1245.09	213.44	177.87	142.30	208.21	231.35	24.82	14.23	331.99
CUMF 36	1778.70	1245.09	177.87	195.66	160.08	205.02	227.80	24.44	14.23	331.94
CUMF 37	1778.70	1245.09	195.66	177.87	160.08	206.02	228.91	24.56	14.23	331.96
CUMF 35	1778.70	1245.09	231.23	160.08	142.30	209.21	232.46	24.94	14.23	332.01
CUMF 32	1778.70	1245.09	177.87	213.44	142.30	206.22	229.14	24.58	15.12	331.39

Table 11

Mix design for OPC 53 content 900 kg/m^3

Combination no.	TCM	OPC 53 (g)	Alccofine (g)	Metakaolin (g)	FA(g)	QS (50%) (g)	MS(50%) (g)	QP(5%) (g)	SP	Corrected water
CUMF 34	1455.30	1018.71	174.64	145.53	116.42	399.10	443.45	47.58	13.83	273.69
CUMF 36	1455.30	1018.71	145.53	160.08	130.98	396.49	440.55	47.27	13.83	273.69
CUMF 37	1455.30	1018.71	160.08	145.53	130.98	397.31	441.45	47.36	13.10	274.13

CHAPTER 6: RESULTS AND DISCUSSION

6.1. RESULTS: The packing density obtained for mix proportions are as follows:

Table 12
Packing density, Void Ratio, Void Content of combinations tested without superplasticizer

Mix Number	Proportions	Packing Density	Void Ratio	Void Content
CUMF 1	(90:3:5:2)	0.6723	0.4764	0.3227
CUMF 2	(90:4:4:2)	0.6731	0.4789	0.3238
CUMF 3	(90:5:3:2)	0.6588	0.4890	0.3284
CUMF 4	(85:5:7:3)	0.6817	0.4728	0.3210
CUMF 5	(85:6:6:3)	0.6597	0.4900	0.3289
CUMF 6	(85:7:5:3)	0.6793	0.4737	0.3214
CUMF 7	(85:8:4:3)	0.6742	0.4806	0.3246
CUMF 8	(85:5:6:4)	0.6752	0.4618	0.3159
CUMF 9	(85:6:5:4)	0.6805	0.4802	0.3244
CUMF 10	(80:7:9:4)	0.6780	0.4764	0.3227
CUMF 11	(80:8:8:4)	0.6786	0.4624	0.3162
CUMF 12	(80:9:7:4)	0.6756	0.4739	0.3215
CUMF 13	(80:6:9:5)	0.6763	0.4687	0.3191
CUMF 14	(80:7:8:5)	0.6858	0.4568	0.3136
CUMF 15	(80:8:7:5)	0.6833	0.4597	0.3149
CUMF 16	(80:9:6:5)	0.6822	0.4472	0.3090
CUMF 17	(80:7:7:6)	0.6845	0.4571	0.3137
CUMF 18	(75:7:12:6)	0.6705	0.4626	0.3163
CUMF 19	(75:8:11:6)	0.6797	0.4600	0.3150
CUMF 20	(75:9:10:6)	0.6777	0.4732	0.3212
CUMF 21	(75:10:9:6)	0.6778	0.4738	0.3215
CUMF 22	(75:11:8:6)	0.6777	0.4777	0.3233
CUMF 23	(75:12:7:6)	0.6767	0.4848	0.3265
CUMF 24	(75:8:10:7)	0.6782	0.4739	0.3215
CUMF 25	(75:9:9:7)	0.6759	0.4811	0.3248
CUMF 26	(75:10:8:7)	0.6882	0.4706	0.3200
CUMF 27	(70:10:13:7)	0.6733	0.4771	0.3230
CUMF 28	(70:11:12:7)	0.6770	0.4805	0.3246
CUMF 29	(70:12:11:7)	0.6862	0.4792	0.3240
CUMF 30	(70:13:10:7)	0.6798	0.4743	0.3217
CUMF 31	(70:9:13:8)	0.6830	0.4662	0.3180
CUMF 32	(70:10:12:8)	0.6867	0.4720	0.3207
CUMF 33	(70:11:11:8)	0.6859	0.4691	0.3193
CUMF 34	(70:12:10:8)	0.6949	0.4715	0.3204
CUMF 35	(70:13:9:8)	0.6871	0.4802	0.3244
CUMF 36	(70:10:11:9)	0.6898	0.4745	0.3218
CUMF 37	(70:11:10:9)	0.6874	0.4772	0.3231

CUMF 38	(70:10:10:10)	0.6793	0.4806	0.3246
CUMF 39	(65:12:15:8)	0.6788	0.4830	0.3257
CUMF 40	(65:13:14:8)	0.6763	0.4860	0.3270
CUMF 41	(65:14:13:8)	0.6719	0.4956	0.3314
CUMF 42	(65:15:12:8)	0.6786	0.4770	0.3229
CUMF 43	(65:11:15:9)	0.6748	1.4818	0.5971
CUMF 44	(65:12:14:9)	0.6762	1.4789	0.5966
CUMF 45	(65:14:12:9)	0.6788	1.4732	0.5957
CUMF 46	(65:15:11:9)	0.6747	1.4822	0.5971
CUMF 47	(65:11:14:10)	0.6712	1.4900	0.5984
CUMF 48	(65:12:13:10)	0.6775	1.4760	0.5961
CUMF 49	(65:13:12:10)	0.6816	1.4672	0.5947
CUMF 50	(65:14:11:10)	0.6758	1.4796	0.5967
CUMF 51	(65:12:12:11)	0.6782	1.4745	0.5959
CUMF 52	(65:13:11:11)	0.6724	1.4873	0.5979
CUMF 53	(60:13:17:10)	0.6701	1.4924	0.5988
CUMF 54	(60:14:16:10)	0.6727	1.4866	0.5978
CUMF 55	(60:15:14:11)	0.6720	1.4882	0.5981
CUMF 56	(60:16:13:11)	0.6736	1.4847	0.5975
CUMF 57	(60:17:12:11)	0.6721	1.4878	0.5980
CUMF 58	(60:13:15:12)	0.6713	1.4896	0.5983
CUMF 59	(60:14:14:12)	0.6670	1.4992	0.5999
CUMF 60	(60:15:13:12)	0.6763	1.4786	0.5965

Table 13
Packing density results of mixes with superplasticizer

MIX NAME	PACKING DENSITY
CUMF 34	0.7277
CUMF 36	0.7266
CUMF 37	0.7259
CUMF 35	0.7227
CUMF 32	0.7223

6.2. DISCUSSION

6.2.1 PACKING DENSITY

- Maximum packing density of 0.6949 is obtained for combination CUMF 29 which is Cement (70%) + Ultra fine slag (12%)+ Metakaolin (10%) + Fly ash (8%)
- The packing density increases as the percentage replacement of cement with Ultra-fine slag, Metakaolin, Fly ash increases.
- At a low water solid ratio (W/S) the paste formed is powdery and does not give high packing and the paste required to fill the container is less as the volume is occupied by air.
- At a high water solid ratio (W/S) the paste formed has a higher water content making the paste required to fill the container less and decreasing the packing density.
- At an optimum water solid ratio (W/S) the packing density is maximum as was observed by maximum paste required to fill the container.
- The optimum water content for each mix was different, as it not only depended on the amount of cement but on the amount of each of the fine material in the mix.
- To obtain a paste (not powdery mix), a minimum water content is required so that it can be compacted trials were done starting from lowest water solid ratio 0.25 for mix proportions with 90% cement.
- To obtain a paste, the lowest water solid ratio increased as the percentage of cement in the mix decreased. This is attributed to the increase in fine content of the mix as they increase water requirement.
- At 85% cement content in the mix paste was formed at 0.26 water solid ratio.
- At further decrease in cement content paste was formed at 0.28 water solid ratio.
- Packing density increased till 30 % replacement and decreased after further replacement at 35% and 40% as shown in Fig. 20.
- Packing density increased on addition of superplasticizer by 4.72 % to 5.6%.

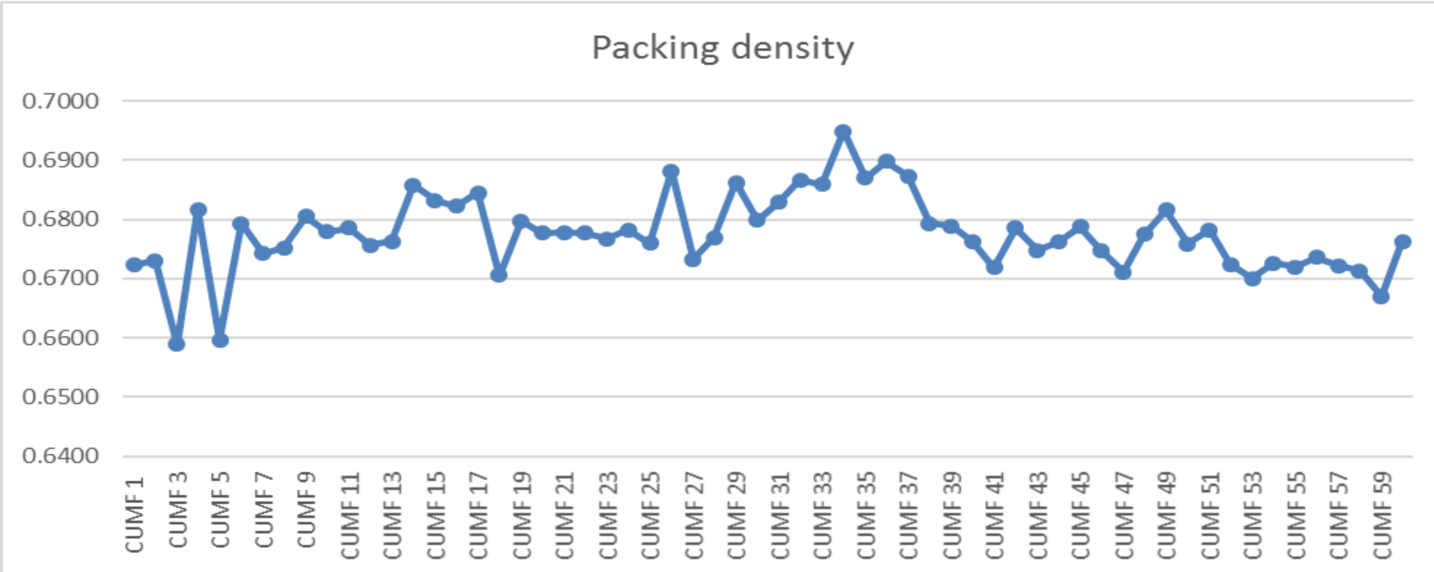


Fig. 19. Packing density variation for each combination

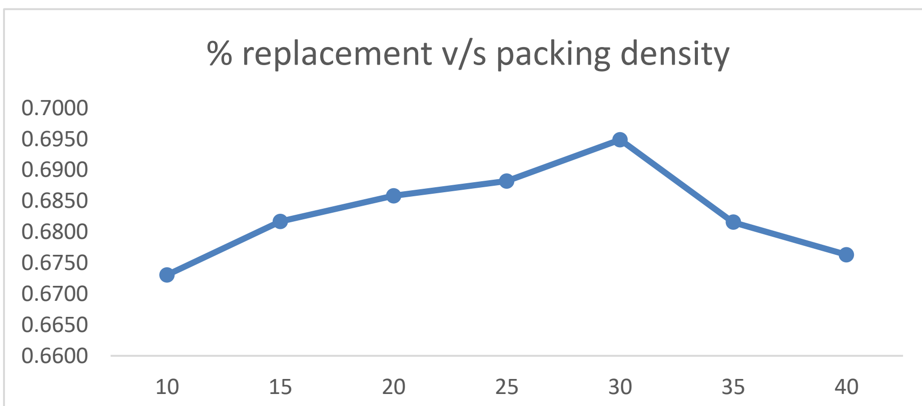


Fig. 20. Packing density as per increase in percentage replacement

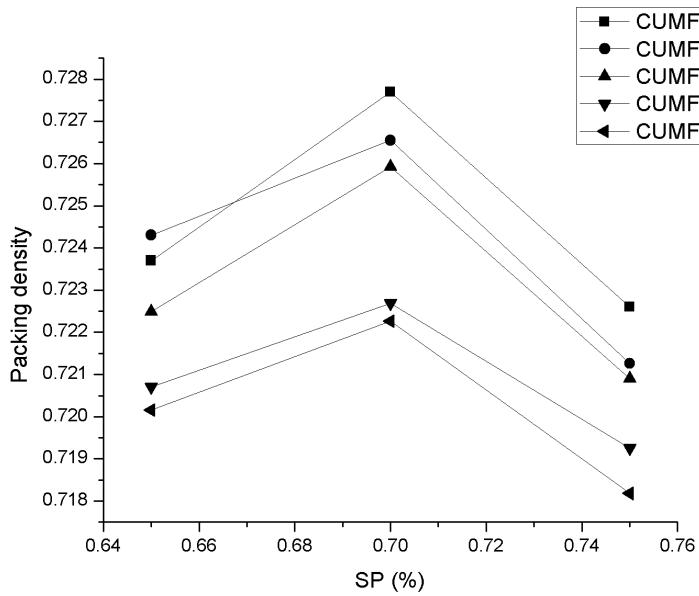


Fig. 21. Packing density with varying superplasticizer percentage

6.2.2. OPTIMIZATION OF SUPERPLASTICIZER

- Superplasticizer dosage decreases as fly ash content increases.
- Superplasticizer dosage increases as Metakaolin content increases.

6.2.3 COMPRESSIVE STRENGTH

- Compressive strength of the cubes was lower than expected as the temperature of the curing tank was quite low ranging between 10 ºC to 18 ºC and hydration was not proper
- Mechanical vibrating table was used for the compaction instead of mortar cube vibrating machine and since the plates of the mould were not in proper contact with each other it contributed to low compressive strength.
- The failure of the cubes was of de-fragmentation type or brittle failure.

Table 14 Compressive strength results for mix design with OPC 53 content 1100 kg/m^3

Sr. No.	Combination name	Strength (N/mm^2)	Average Strength (N/mm^2)
1	CUMF 34	82.90	84.93
		87.10	
		84.81	
2	CUMF 36	81.00	84.03
		86.50	
		84.60	
3	CUMF 37	87.80	89.49
		89.67	
		91.00	
4	CUMF 35	85.39	87.807
		90.50	
		87.53	
5	CUMF 32	95.40	94.13
		92.57	
		94.33	

Table 15 Compressive strength results for mix design with OPC 53 content 900 kg/m^3

Sr. No.	Combination name	Strength (N/mm^2)	Average Strength (N/mm^2)
1	CUMF 34	87.13	86.89
		83.89	
		89.66	
2	CUMF 36	82.10	84.15
		84.11	
		86.28	
3	CUMF 37	76.37	79
		79.40	
		81.23	

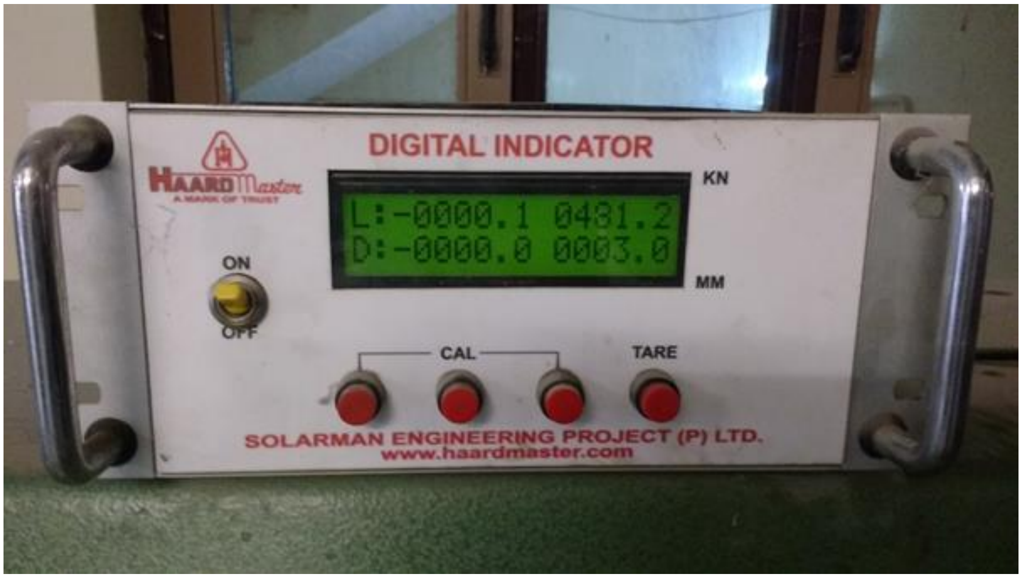


Fig. 22. Load readings on UTM

Fig. 13. Compressive strength testing on UTM

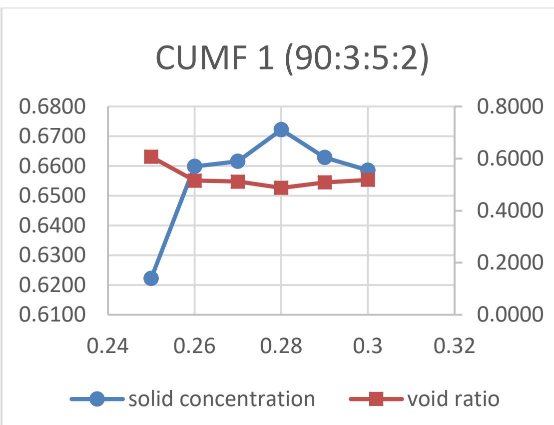
Fig. 24. Failure of the sample

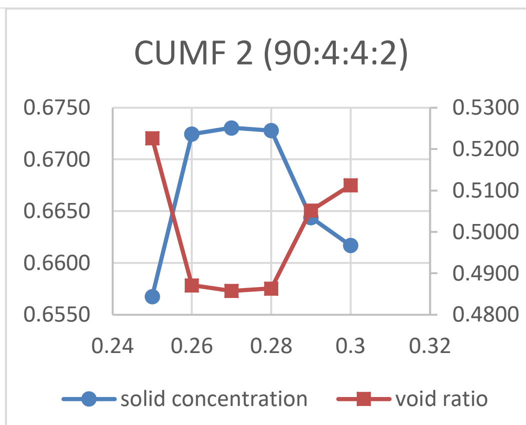
CONCLUSIONS

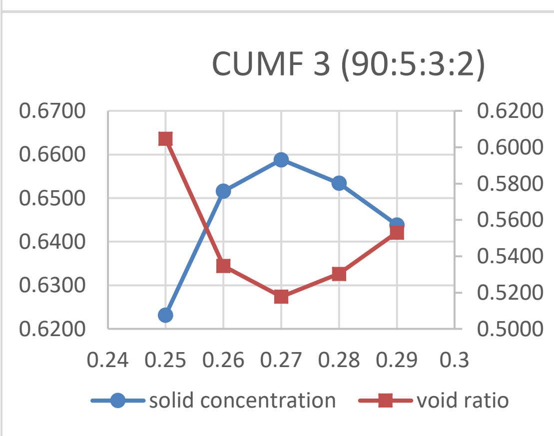
- From the experimental work till now it can be concluded that as fine content in the mix increases the packing density increases. The water content increases as well with increase in fine content, so to increase packing density at a low water solid ratio, use of superplasticizer is necessary.
- When cement and ultra-fine slag are constant packing density increases as fly ash content increases.
- When cement and metakaolin are constant, packing density decreases as alccofine content increases at higher cement proportion but increases with increase in alccofine content at 70% cement in a mix.
- When cement and fly ash are constant, packing density first increases and then decreases as the alccofine content increases.
- As fly ash content increases due to ball bearing action the workability increases and superplasticizer requirement decreases.
- Metakaolin being an ultra-fine material increases the superplasticizer percentage for sufficient flow, as its content increases.
- Since vibrating table was not found suitable for the casting of moulds for RPC, mortar cube vibrating machine should be used to for the casting of mixes.
- For a very low temperature the strength achieved is quite high and can further be increased by curing at a higher temperature.
- To avoid brittle failure of concrete steel fibers can be used.

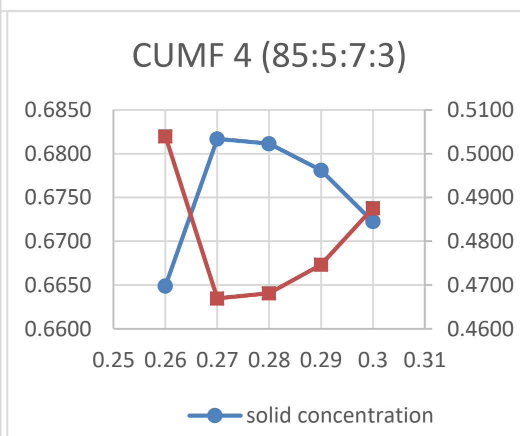
APPENDIX 1: Packing density calculations

C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
1	CUMF 1	207	6.9	11.5	4.6	0.25	354.4	249.35	0.6223	0.6070	0.3777
2	(90:3:5:2)	207	6.9	11.5	4.6	0.26	370.25	265.2	0.6599	0.5155	0.3401
3		207	6.9	11.5	4.6	0.27	371.75	266.7	0.6616	0.5115	0.3384
4		207	6.9	11.5	4.6	0.28	376.85	271.8	0.6723	0.4875	0.3277
5		207	6.9	11.5	4.6	0.29	373.85	268.8	0.6629	0.5086	0.3371
6		207	6.9	11.5	4.6	0.3	372.9	267.85	0.6586	0.5184	0.3414
7	CUMF 2	207	9.2	9.2	4.6	0.25	368.5	263.45	0.6568	0.5226	0.3432
8	(90:4:4:2)	207	9.2	9.2	4.6	0.26	375.6	270.55	0.6724	0.4871	0.3276
9		207	9.2	9.2	4.6	0.27	376.65	271.6	0.6731	0.4858	0.3269
10		207	9.2	9.2	4.6	0.28	377.35	272.3	0.6728	0.4864	0.3272
11		207	9.2	9.2	4.6	0.29	374.75	269.7	0.6644	0.5051	0.3356
12		207	9.2	9.2	4.6	0.3	374.45	269.4	0.6617	0.5113	0.3383
13	CUMF 3	180	10	6	4	0.25	355.3	250.25	0.6232	0.6047	0.3768
14	(90:5:3:2)	180	10	6	4	0.26	367.5	262.45	0.6516	0.5346	0.3484
15		180	10	6	4	0.27	371.2	266.15	0.6588	0.5178	0.3412
16		180	10	6	4	0.28	369.8	264.75	0.6534	0.5304	0.3466
17		180	10	6	4	0.29	366.7	261.65	0.6439	0.5531	0.3561
18	CUMF 4	204	12	16.8	7.2	0.26	370	264.95	0.6649	0.5040	0.3351
19	(85:5:7:3)	204	12	16.8	7.2	0.27	377.5	272.45	0.6817	0.4670	0.3183
20		204	12	16.8	7.2	0.28	378.1	273.05	0.6811	0.4681	0.3189
21		204	12	16.8	7.2	0.29	377.7	272.65	0.6781	0.4747	0.3219
22		204	12	16.8	7.2	0.3	376.15	271.1	0.6723	0.4875	0.3277

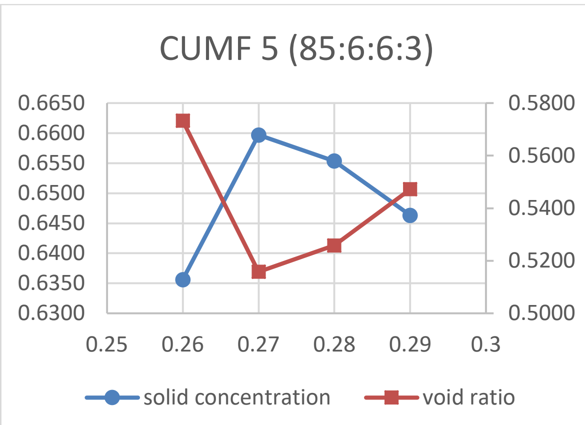


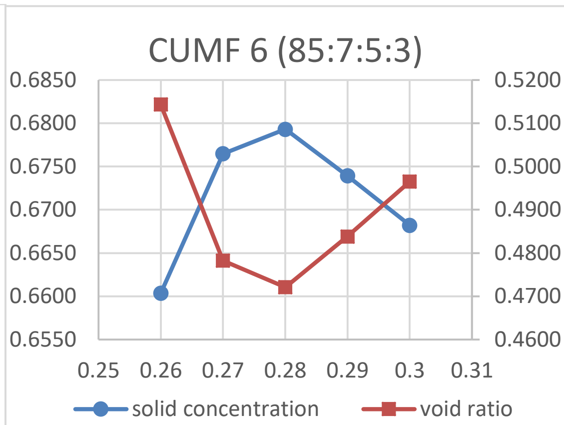


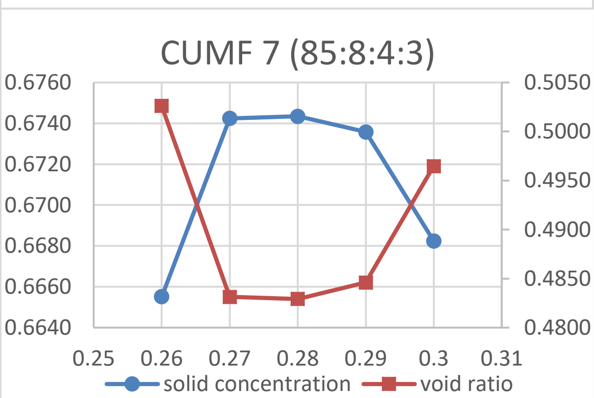


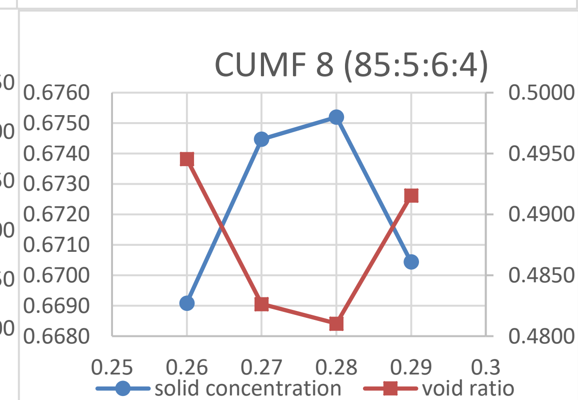


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm) OPC 53	UFS	METAKAOLIN	FLY ASH	W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
23	CUMF 5	195.5	13.8	13.8	6.9	0.26	358.6	253.55	0.6356	0.5733	0.3644
24	(85:6:6:3)	195.5	13.8	13.8	6.9	0.27	369	263.95	0.6597	0.5158	0.3403
25		195.5	13.8	13.8	6.9	0.28	368.05	263	0.6554	0.5259	0.3446
26		195.5	13.8	13.8	6.9	0.29	365.2	260.15	0.6463	0.5472	0.3537
27	CUMF 6	204	16.8	12	7.2	0.26	368.75	263.7	0.6603	0.5144	0.3397
28	(85:7:5:3)	204	16.8	12	7.2	0.27	376	270.95	0.6765	0.4783	0.3235
29		204	16.8	12	7.2	0.28	377.95	272.9	0.6793	0.4721	0.3207
30		204	16.8	12	7.2	0.29	376.6	271.55	0.6739	0.4838	0.3261
31		204	16.8	12	7.2	0.3	375.1	270.05	0.6682	0.4965	0.3318
32	CUMF 7	204	19.2	9.6	7.2	0.26	371.1	266.05	0.6655	0.5026	0.3345
33	(85:8:4:3)	204	19.2	9.6	7.2	0.27	375.4	270.35	0.6742	0.4831	0.3258
34		204	19.2	9.6	7.2	0.28	376.25	271.2	0.6743	0.4829	0.3257
35		204	19.2	9.6	7.2	0.29	376.75	271.7	0.6736	0.4846	0.3264
36		204	19.2	9.6	7.2	0.3	375.4	270.35	0.6682	0.4965	0.3318
37	CUMF 8	204	12	14.4	9.6	0.26	371.4	266.35	0.6691	0.4946	0.3309
38	(85:5:6:4)	204	12	14.4	9.6	0.27	374.35	269.3	0.6745	0.4826	0.3255
39		204	12	14.4	9.6	0.28	375.45	270.4	0.6752	0.4811	0.3248
40		204	12	14.4	9.6	0.29	374.35	269.3	0.6704	0.4916	0.3296

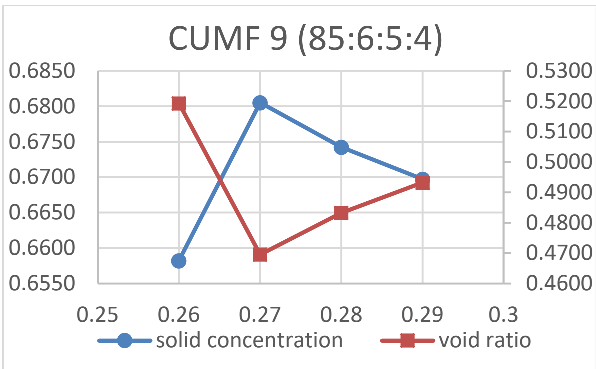


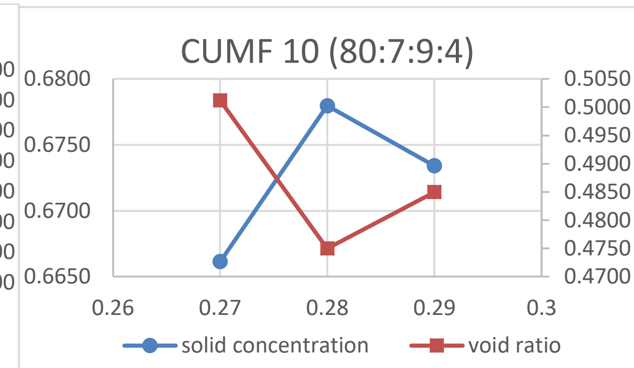


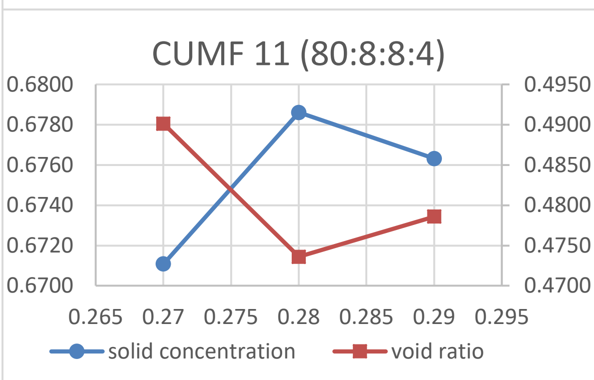


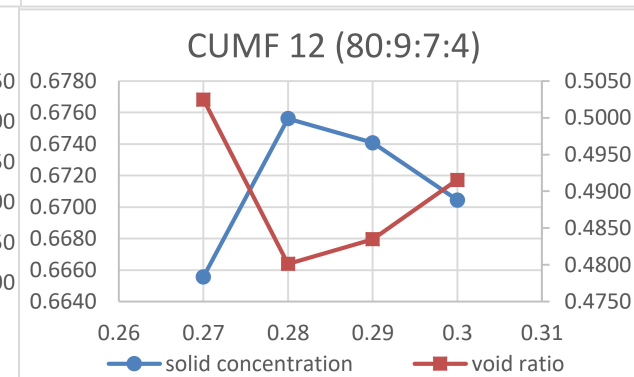


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
41	CUMF 9	204	14.4	12	9.6	0.26	367.35	262.3	0.6582	0.5193	0.3418
42	(85:6:5:4)	204	14.4	12	9.6	0.27	377.05	272	0.6805	0.4695	0.3195
43		204	14.4	12	9.6	0.28	375.35	270.3	0.6742	0.4832	0.3258
44		204	14.4	12	9.6	0.29	374.35	269.3	0.6697	0.4932	0.3303
45	CUMF 10	192	16.8	21.6	9.6	0.27	369	263.95	0.6661	0.5012	0.3339
46	(80:7:9:4)	192	16.8	21.6	9.6	0.28	374.5	269.45	0.6780	0.4750	0.3220
47		192	16.8	21.6	9.6	0.29	373.5	268.45	0.6734	0.4850	0.3266
48	CUMF 11	192	19.2	19.2	9.6	0.27	371.25	266.2	0.6711	0.4901	0.3289
49	(80:8:8:4)	192	19.2	19.2	9.6	0.28	375.05	270	0.6786	0.4736	0.3214
50		192	19.2	19.2	9.6	0.29	374.95	269.9	0.6763	0.4786	0.3237
51	CUMF 12	192	21.6	16.8	9.6	0.27	369.35	264.3	0.6656	0.5025	0.3344
52	(80:9:7:4)	192	21.6	16.8	9.6	0.28	374.15	269.1	0.6756	0.4801	0.3244
53		192	21.6	16.8	9.6	0.29	374.35	269.3	0.6741	0.4835	0.3259
54		192	21.6	16.8	9.6	0.3	373.7	268.65	0.6704	0.4915	0.3296

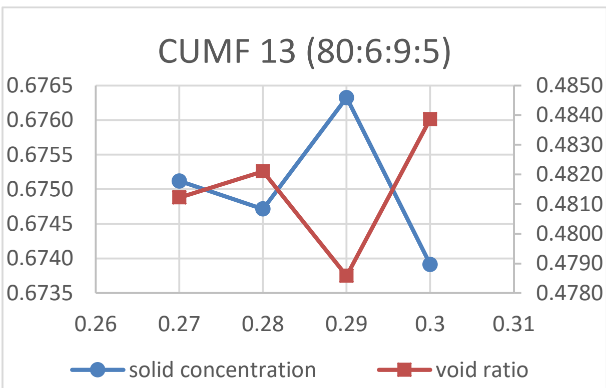


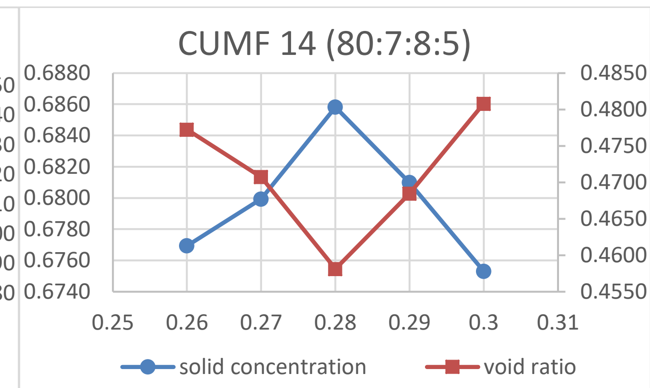


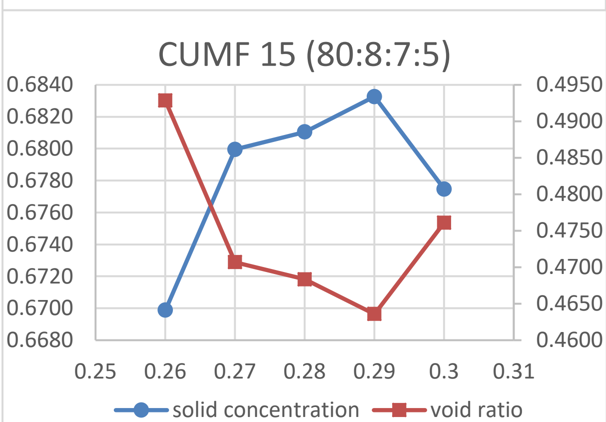


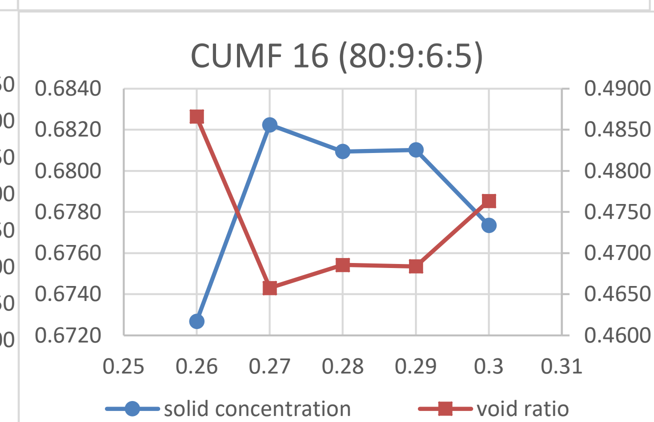


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
54	CUMF 13	192	14.4	21.6	12	0.27	372	266.95	0.6751	0.4812	0.3249
55	(80:6:9:5)	192	14.4	21.6	12	0.28	372.65	267.6	0.6747	0.4821	0.3253
56		192	14.4	21.6	12	0.29	374.1	269.05	0.6763	0.4786	0.3237
57		192	14.4	21.6	12	0.3	373.95	268.9	0.6739	0.4839	0.3261
58	CUMF 14	192	16.8	19.2	12	0.26	372.2	267.15	0.6769	0.4772	0.3231
59	(80:7:8:5)	192	16.8	19.2	12	0.27	374.2	269.15	0.6799	0.4707	0.3201
60		192	16.8	19.2	12	0.28	377.35	272.3	0.6858	0.4581	0.3142
61		192	16.8	19.2	12	0.29	376.25	271.2	0.6810	0.4685	0.3190
62		192	16.8	19.2	12	0.3	374.8	269.75	0.6753	0.4808	0.3247
63	CUMF 15	192	19.2	16.8	12	0.26	369.7	264.65	0.6699	0.4928	0.3301
64	(80:8:7:5)	192	19.2	16.8	12	0.27	374.5	269.45	0.6800	0.4707	0.3200
65		192	19.2	16.8	12	0.28	375.75	270.7	0.6810	0.4683	0.3190
66		192	19.2	16.8	12	0.29	377.45	272.4	0.6833	0.4636	0.3167
67		192	19.2	16.8	12	0.3	375.95	270.9	0.6775	0.4761	0.3225
68	CUMF 16	192	21.6	14.4	12	0.26	371.1	266.05	0.6727	0.4866	0.3273
69	(80:9:6:5)	192	21.6	14.4	12	0.27	375.7	270.65	0.6822	0.4658	0.3178
70		192	21.6	14.4	12	0.28	376	270.95	0.6809	0.4686	0.3191
71		192	21.6	14.4	12	0.29	376.85	271.8	0.6810	0.4684	0.3190
72		192	21.6	14.4	12	0.3	376.2	271.15	0.6774	0.4763	0.3226

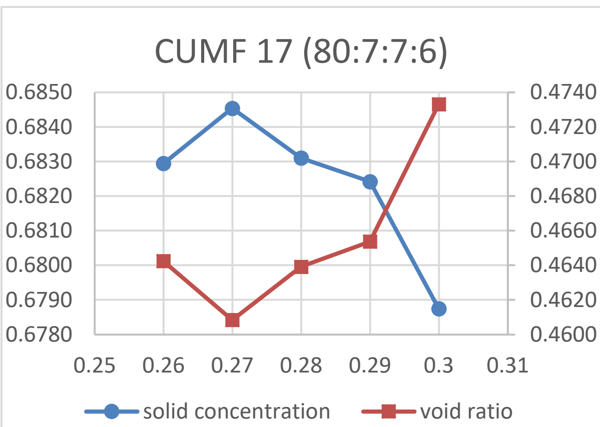


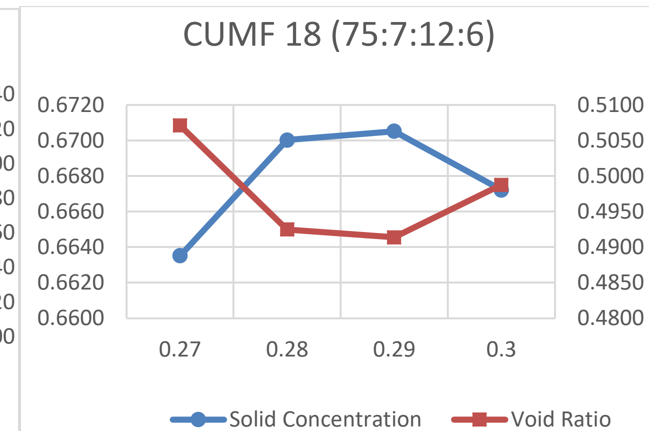


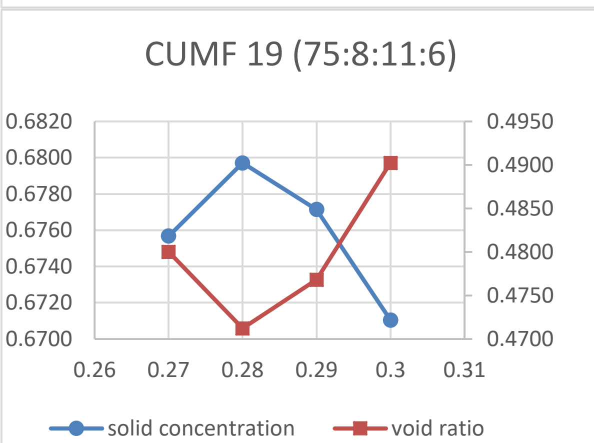


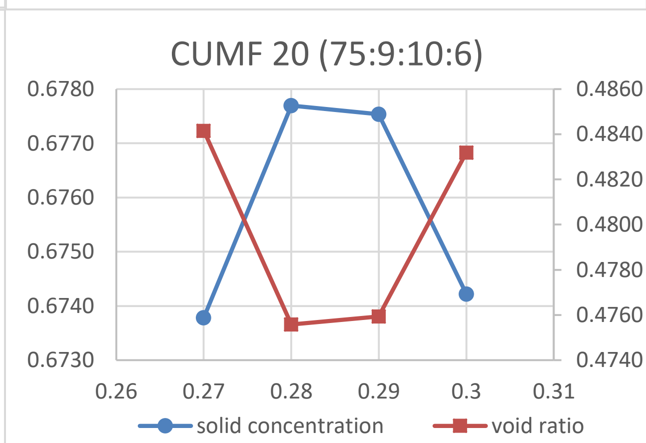


		C:U:M:F (QUARTANARY MIX)									
SR		Wt. of materials (gm)					Wt. (container + paste)	Wt. of compacted	Solid		
No.	OPC 53:UFS:METAKAOLIN:FLY ASH	OPC 53	UFS	METAKAOLIN	FLY ASH	W/S ratio	(gm)	mix(gm)	concentration	Void Ratio	Void content (ε)
73	CUMF 17	192	16.8	16.8	14.4	0.26	374.3	269.25	0.6829	0.4642	0.3171
74	(80:7:7:6)	192	16.8	16.8	14.4	0.27	375.75	270.7	0.6845	0.4608	0.3155
75		192	16.8	16.8	14.4	0.28	376	270.95	0.6831	0.4639	0.3169
76		192	16.8	16.8	14.4	0.29	376.55	271.5	0.6824	0.4654	0.3176
77		192	16.8	16.8	14.4	0.3	375.9	270.85	0.6787	0.4733	0.3213
78	CUMF 18	180	16.8	28.8	14.4	0.27	364.85	259.8	0.6635	0.5071	0.3365
79	(75:7:12:6)	180	16.8	28.8	14.4	0.28	368.2	263.15	0.6700	0.4925	0.3300
80		180	16.8	28.8	14.4	0.29	369.2	264.15	0.6705	0.4914	0.3295
81		180	16.8	28.8	14.4	0.3	368.7	263.65	0.6672	0.4988	0.3328
82	CUMF 19	180	19.2	26.4	14.4	0.27	369.9	264.85	0.6757	0.4800	0.3243
83	(75:8:11:6)	180	19.2	26.4	14.4	0.28	372.3	267.25	0.6797	0.4712	0.3203
84		180	19.2	26.4	14.4	0.29	372.1	267.05	0.6771	0.4768	0.3229
85		180	19.2	26.4	14.4	0.3	370.5	265.45	0.6710	0.4902	0.3290
86	CUMF 20	180	21.6	24	14.4	0.27	369.45	264.4	0.6738	0.4842	0.3262
87	(75:9:10:6)	180	21.6	24	14.4	0.28	371.8	266.75	0.6777	0.4756	0.3223
88		180	21.6	24	14.4	0.29	372.55	267.5	0.6775	0.4759	0.3225
89		180	21.6	24	14.4	0.3	372.05	267	0.6742	0.4832	0.3258

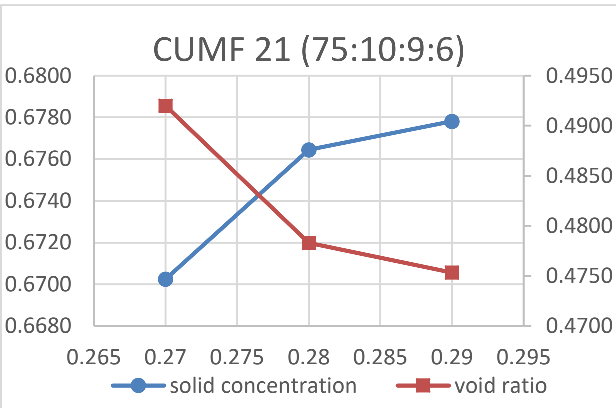


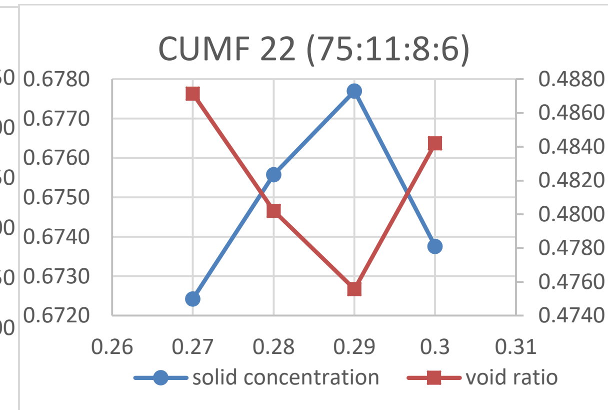


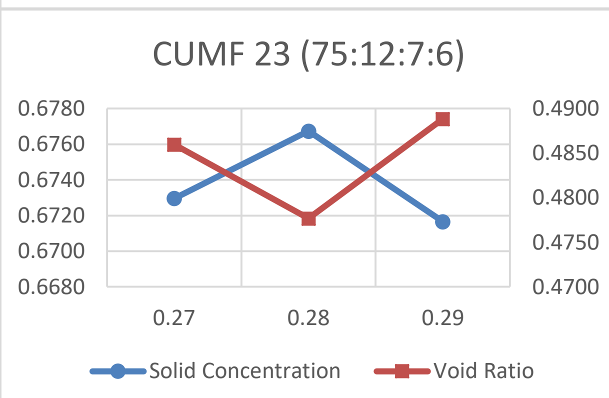


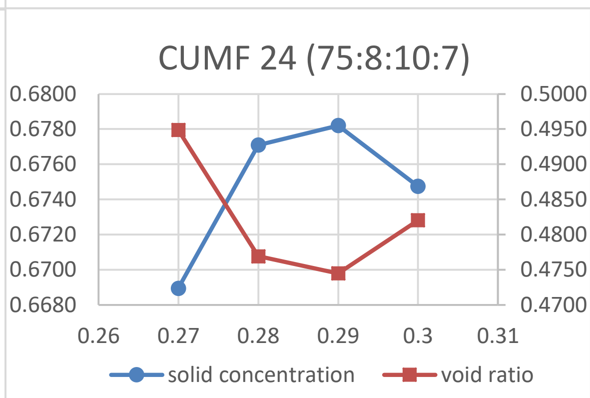


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
90	CUMF 21	180	24	21.6	14.4	0.27	368.35	263.3	0.6702	0.4920	0.3298
91	(75:10:9:6)	180	24	21.6	14.4	0.28	371.6	266.55	0.6764	0.4783	0.3236
92		180	24	21.6	14.4	0.29	372.95	267.9	0.6778	0.4753	0.3222
93	CUMF 22	180	26.4	19.2	14.4	0.27	369.5	264.45	0.6724	0.4871	0.3276
94	(75:11:8:6)	180	26.4	19.2	14.4	0.28	371.55	266.5	0.6756	0.4802	0.3244
95		180	26.4	19.2	14.4	0.29	373.2	268.15	0.6777	0.4756	0.3223
96		180	26.4	19.2	14.4	0.3	372.45	267.4	0.6738	0.4842	0.3262
97	CUMF 23	180	28.8	16.8	14.4	0.27	370	264.95	0.6730	0.4860	0.3270
98	(75:12:7:6)	180	28.8	16.8	14.4	0.28	372.3	267.25	0.6767	0.4777	0.3233
99		180	28.8	16.8	14.4	0.29	371.1	266.05	0.6717	0.4888	0.3283
100	CUMF 24	180	19.2	24	16.8	0.27	367	261.95	0.6689	0.4949	0.3311
101	(75:8:10:7)	180	19.2	24	16.8	0.28	371	265.95	0.6771	0.4769	0.3229
102		180	19.2	24	16.8	0.29	372.25	267.2	0.6782	0.4745	0.3218
103		180	19.2	24	16.8	0.3	371.7	266.65	0.6747	0.4820	0.3253

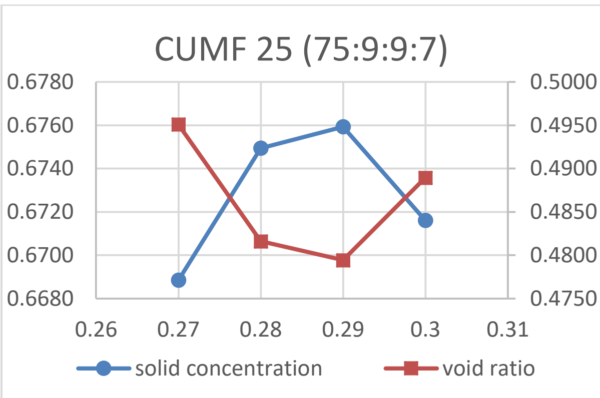


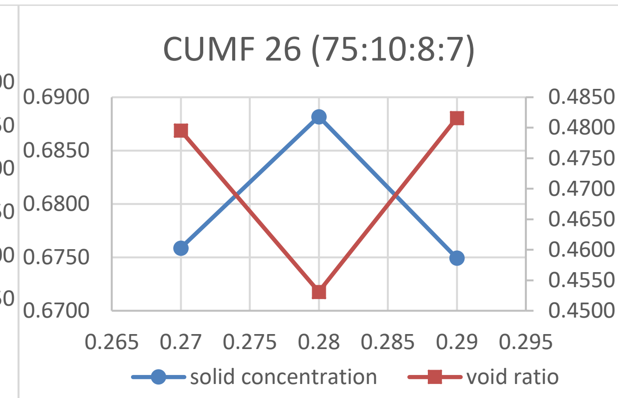


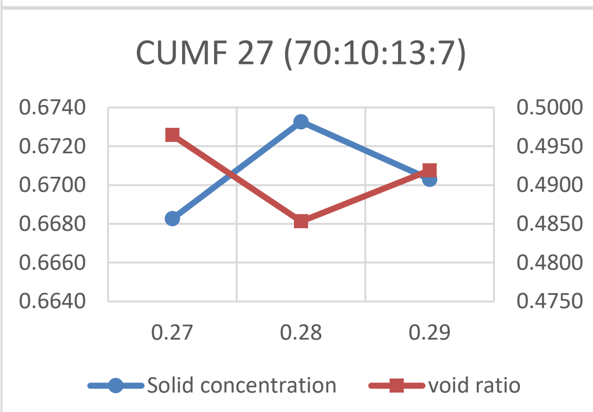


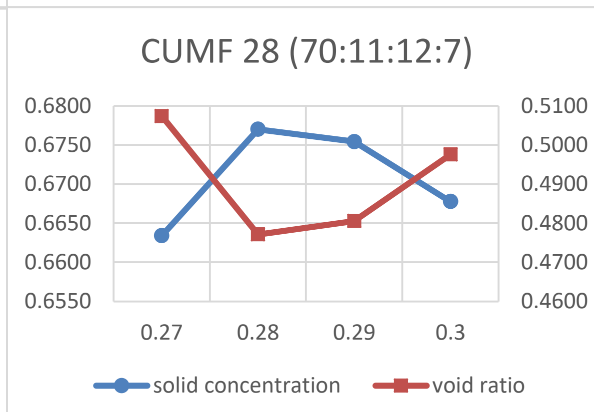


SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	C:U:M:F (QUARTANARY MIX) Wt. of materials (gm) OPC 53	UFS	METAKAOLIN	FLY ASH	W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
104	CUMF 25	180	21.6	21.6	16.8	0.27	367.25	262.2	0.6689	0.4951	0.3311
105	(75:9:9:7)	180	21.6	21.6	16.8	0.28	370.45	265.4	0.6749	0.4816	0.3251
106		180	21.6	21.6	16.8	0.29	371.65	266.6	0.6759	0.4794	0.3241
107		180	21.6	21.6	16.8	0.3	370.75	265.7	0.6716	0.4890	0.3284
108	CUMF 26	180	24	19.2	16.8	0.27	370.3	265.25	0.6759	0.4795	0.3241
109	(75:10:8:7)	180	24	19.2	16.8	0.28	375.95	270.9	0.6882	0.4531	0.3118
110		180	24	19.2	16.8	0.29	371.55	266.5	0.6749	0.4816	0.3251
111	CUMF 27	168	24	31.2	16.8	0.27	364.7	259.65	0.6683	0.4964	0.3317
112	(70:10:13:7)	168	24	31.2	16.8	0.28	367.45	262.4	0.6733	0.4853	0.3267
113		168	24	31.2	16.8	0.29	367.1	262.05	0.6703	0.4919	0.3297
114	CUMF 28	168	26.4	28.8	16.8	0.27	363.1	258.05	0.6634	0.5074	0.3366
115	(70:11:12:7)	168	26.4	28.8	16.8	0.28	369.2	264.15	0.6770	0.4771	0.3230
116		168	26.4	28.8	16.8	0.29	369.4	264.35	0.6754	0.4805	0.3246
117		168	26.4	28.8	16.8	0.3	367.2	262.15	0.6678	0.4975	0.3322

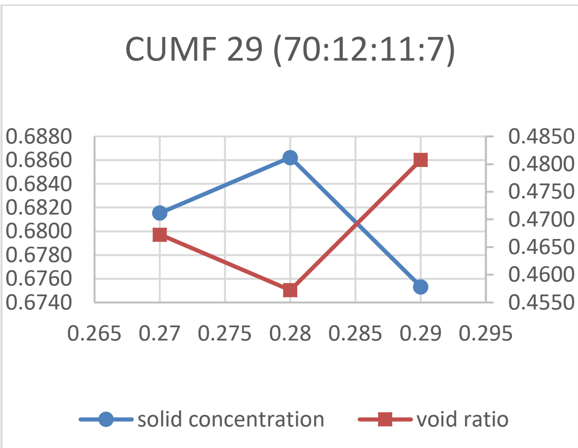


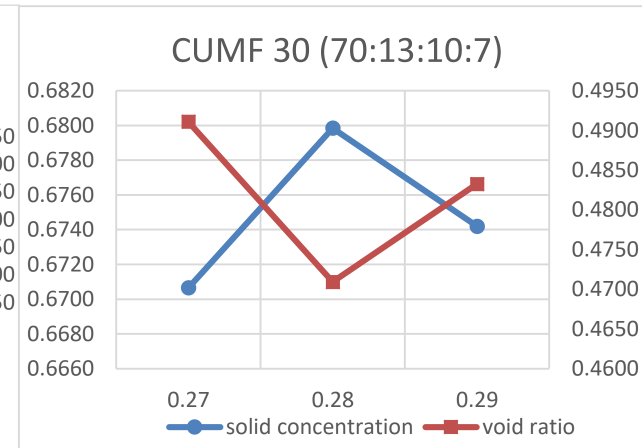


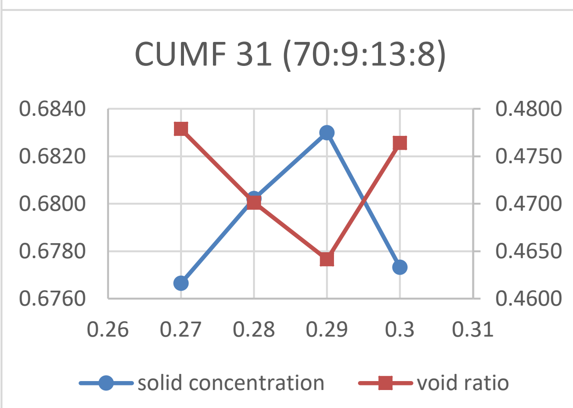


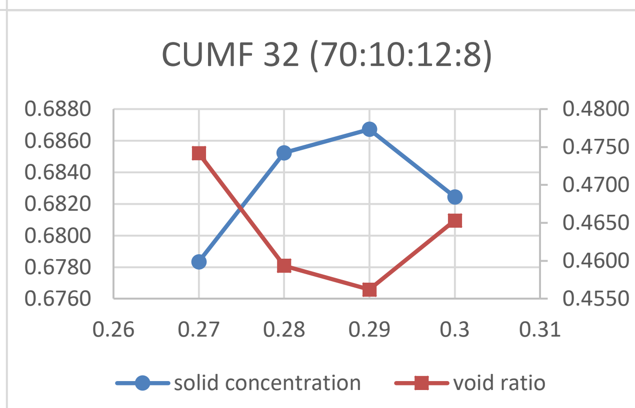


C:U:M:F (QUARTANARY MIX)											
SR		Wt. of materials (gm)					Wt. (container + paste)	Wt. of compacted	Solid		
No.	OPC 53:UFS:METAKAOLIN:FLY ASH	OPC 53	UFS	METAKAOLIN	FLY ASH	W/S ratio	(gm)	mix(gm)	concentration	Void Ratio	Void content (ε)
118	CUMF 29	168	28.8	26.4	16.8	0.27	370.45	265.4	0.6815	0.4673	0.3185
119	(70:12:11:7)	168	28.8	26.4	16.8	0.28	373.1	268.05	0.6862	0.4572	0.3138
120		168	28.8	26.4	16.8	0.29	369.65	264.6	0.6753	0.4808	0.3247
121	CUMF 30	168	31.2	24	16.8	0.27	366.5	261.45	0.6707	0.4911	0.3293
122	(70:13:10:7)	168	31.2	24	16.8	0.28	370.9	265.85	0.6798	0.4709	0.3202
123		168	31.2	24	16.8	0.29	369.5	264.45	0.6742	0.4832	0.3258
124	CUMF 31	168	21.6	31.2	19.2	0.27	367.4	262.35	0.6766	0.4779	0.3234
125	(70:9:13:8)	168	21.6	31.2	19.2	0.28	369.6	264.55	0.6802	0.4701	0.3198
126		168	21.6	31.2	19.2	0.29	371.5	266.45	0.6830	0.4641	0.3170
127		168	21.6	31.2	19.2	0.3	370.1	265.05	0.6773	0.4764	0.3227
128	CUMF 32	168	24	28.8	19.2	0.27	368.35	263.3	0.6783	0.4742	0.3217
129	(70:10:12:8)	168	24	28.8	19.2	0.28	371.85	266.8	0.6852	0.4593	0.3148
130		168	24	28.8	19.2	0.29	373.25	268.2	0.6867	0.4562	0.3133
131		168	24	28.8	19.2	0.3	372.4	267.35	0.6824	0.4653	0.3176

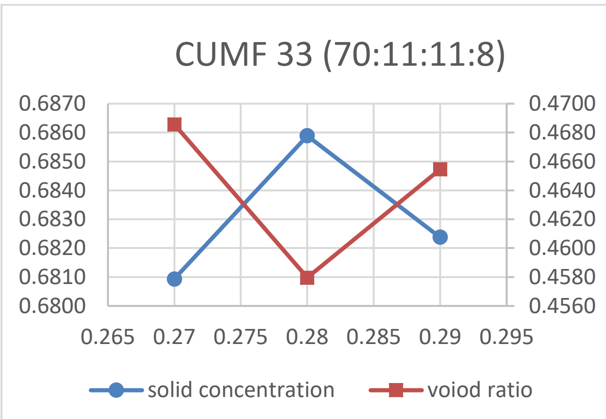


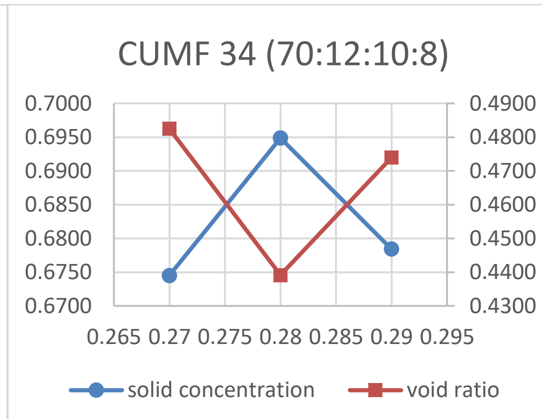


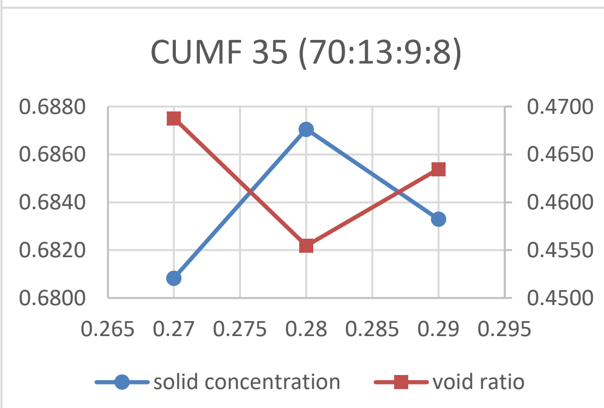


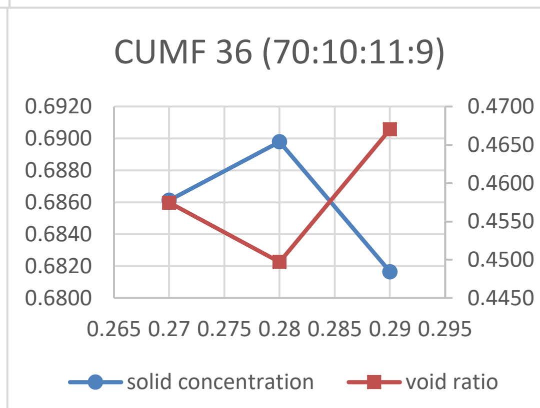


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
132	CUMF 33	168	26.4	26.4	19.2	0.27	369.65	264.6	0.6809	0.4686	0.3191
133	(70:11:11:8)	168	26.4	26.4	19.2	0.28	372.4	267.35	0.6859	0.4580	0.3141
134		168	26.4	26.4	19.2	0.29	371.85	266.8	0.6824	0.4655	0.3176
135	CUMF 34	168	28.8	24	19.2	0.27	367.45	262.4	0.6745	0.4825	0.3255
136	(70:12:10:8)	168	28.8	24	19.2	0.28	376.2	271.15	0.6949	0.4391	0.3051
137		168	28.8	24	19.2	0.29	370.6	265.55	0.6784	0.4740	0.3216
138	CUMF 35	168	31.2	21.6	19.2	0.27	370.2	265.15	0.6808	0.4688	0.3192
139	(70:13:9:8)	168	31.2	21.6	19.2	0.28	373.45	268.4	0.6871	0.4555	0.3129
140		168	31.2	21.6	19.2	0.29	372.8	267.75	0.6833	0.4635	0.3167
141	CUMF 36	168	24	26.4	21.6	0.27	371.1	266.05	0.6861	0.4575	0.3139
142	(70:10:11:9)	168	24	26.4	21.6	0.28	373.35	268.3	0.6898	0.4497	0.3102
143		168	24	26.4	21.6	0.29	371	265.95	0.6817	0.4670	0.3183

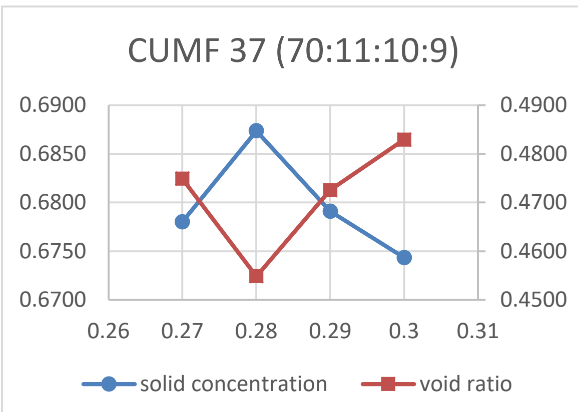


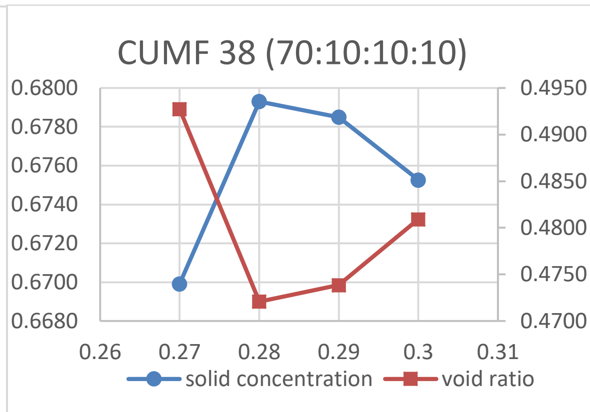


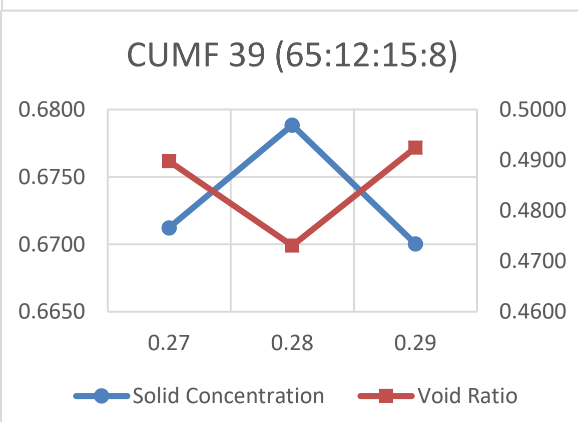


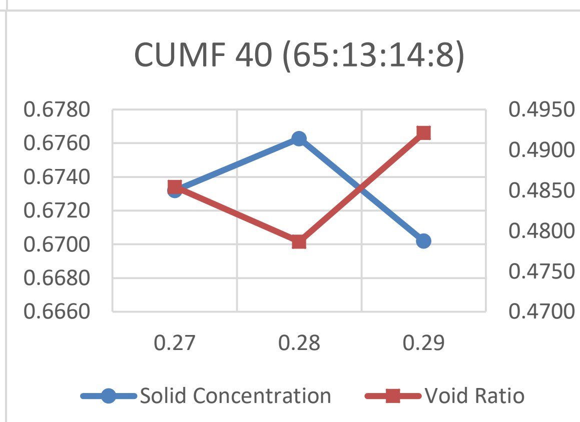


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
144	CUMF 37	168	26.4	24	21.6	0.27	368.25	263.2	0.6780	0.4749	0.3220
145	(70:11:10:9)	168	26.4	24	21.6	0.28	372.7	267.65	0.6874	0.4548	0.3126
146		168	26.4	24	21.6	0.29	370.3	265.25	0.6791	0.4725	0.3209
147		168	26.4	24	21.6	0.3	369.25	264.2	0.6743	0.4829	0.3257
148	CUMF 38	168	24	24	24	0.27	364.55	259.5	0.6699	0.4927	0.3301
149	(70:10:10:10)	168	24	24	24	0.28	369	263.95	0.6793	0.4721	0.3207
150		168	24	24	24	0.29	369.5	264.45	0.6785	0.4739	0.3215
151		168	24	24	24	0.3	369.05	264	0.6753	0.4809	0.3247
152	CUMF 39	156	28.8	36	19.2	0.27	363.55	258.5	0.6712	0.4898	0.3288
153	(65:12:15:8)	156	28.8	36	19.2	0.28	367.3	262.25	0.6788	0.4731	0.3212
154		156	28.8	36	19.2	0.29	364.7	259.65	0.6700	0.4925	0.3300
155	CUMF 40	156	31.2	33.6	19.2	0.27	364.6	259.55	0.6732	0.4854	0.3268
156	(65:13:14:8)	156	31.2	33.6	19.2	0.28	366.6	261.55	0.6763	0.4787	0.3237
157		156	31.2	33.6	19.2	0.29	365.05	260	0.6702	0.4921	0.3298

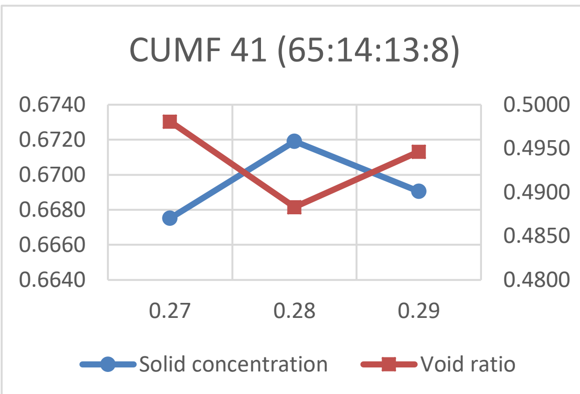


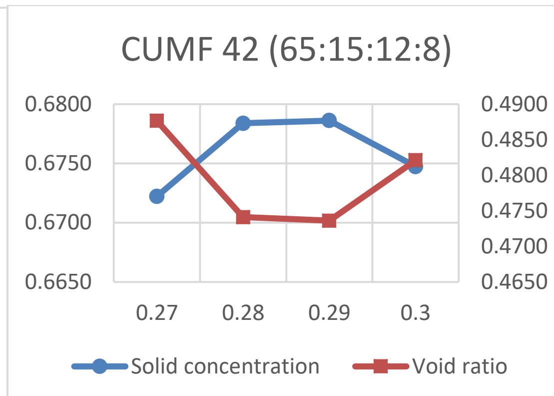


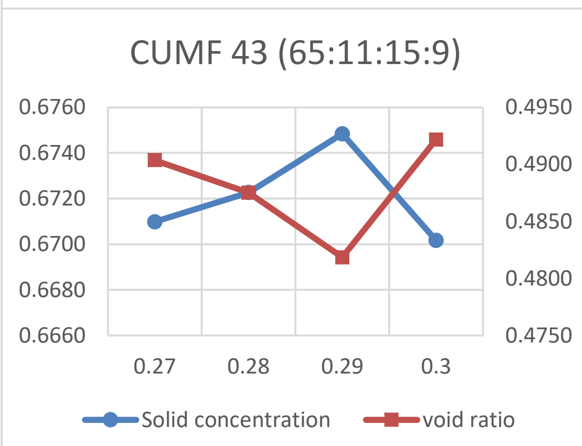


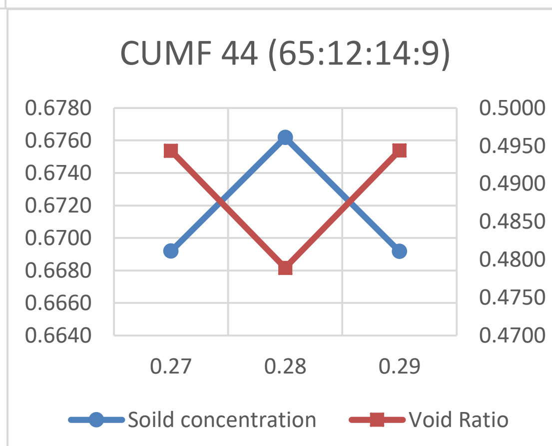


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
158	CUMF 41	156	33.6	31.2	19.2	0.27	362.7	257.65	0.6675	0.4981	0.3325
159	(65:14:13:8)	156	33.6	31.2	19.2	0.28	365.2	260.15	0.6719	0.4883	0.3281
160		156	33.6	31.2	19.2	0.29	364.9	259.85	0.6691	0.4946	0.3309
161	CUMF 42	156	36	28.8	19.2	0.27	364.8	259.75	0.6722	0.4876	0.3278
162	(65:15:12:8)	156	36	28.8	19.2	0.28	368	262.95	0.6784	0.4741	0.3216
163		156	36	28.8	19.2	0.29	368.9	263.85	0.6786	0.4736	0.3214
164		156	36	28.8	19.2	0.3	368.2	263.15	0.6747	0.4821	0.3253
165	CUMF 43	156	26.4	36	21.6	0.27	362.9	257.85	0.6710	0.4904	0.3290
166	(65:11:15:9)	156	26.4	36	21.6	0.28	364.2	259.15	0.6723	0.4875	0.3277
167		156	26.4	36	21.6	0.29	366	260.95	0.6748	0.4818	0.3252
168		156	26.4	36	21.6	0.3	365	259.95	0.6702	0.4922	0.3298
169	CUMF 44	156	28.8	33.6	21.6	0.27	362.5	257.45	0.6692	0.4943	0.3308
170	(65:12:14:9)	156	28.8	33.6	21.6	0.28	366	260.95	0.6762	0.4789	0.3238
171		156	28.8	33.6	21.6	0.29	364.1	259.05	0.6692	0.4944	0.3308

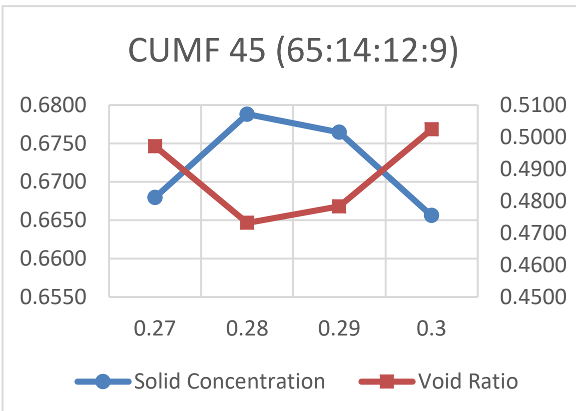


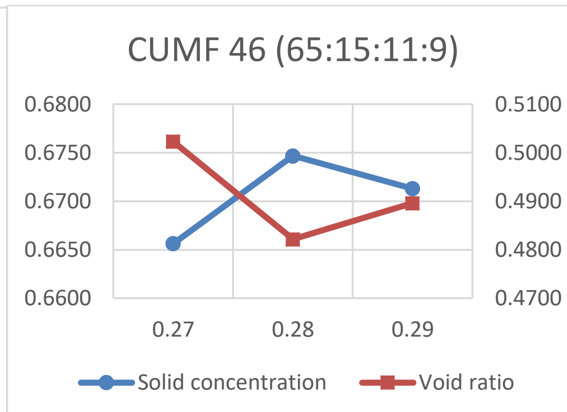


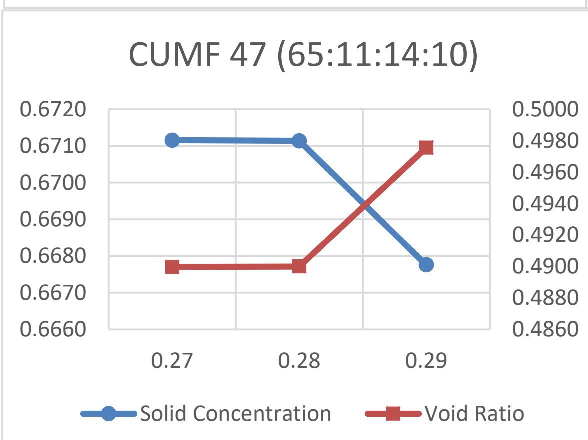


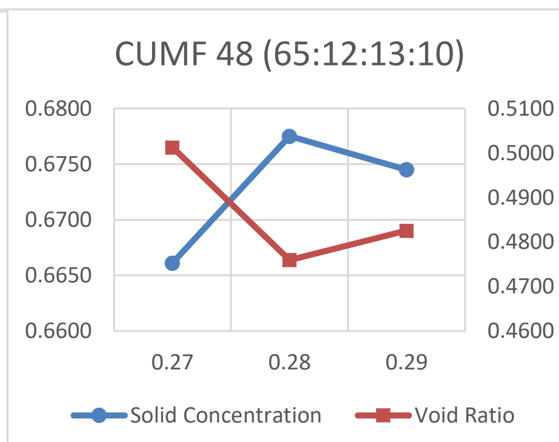


C:U:M:F (QUARTANARY MIX)												
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
172	CUMF 45	156	33.6	28.8	21.6	0.27	362.6	257.55	0.6679	0.4971	0.3321
173	(65:14:12:9)	156	33.6	28.8	21.6	0.28	367.6	262.55	0.6788	0.4732	0.3212
174		156	33.6	28.8	21.6	0.29	367.5	262.45	0.6764	0.4783	0.3236
175		156	33.6	28.8	21.6	0.3	364.1	259.05	0.6656	0.5024	0.3344
176	CUMF 46	156	36	26.4	21.6	0.27	362	256.95	0.6656	0.5023	0.3344
177	(65:15:11:9)	156	36	26.4	21.6	0.28	366.3	261.25	0.6747	0.4822	0.3253
178		156	36	26.4	21.6	0.29	365.8	260.75	0.6713	0.4896	0.3287
179	CUMF 47	156	26.4	33.6	24	0.27	362.7	257.65	0.6712	0.4900	0.3288
180	(65:11:14:10)	156	26.4	33.6	24	0.28	363.5	258.45	0.6711	0.4900	0.3289
181		156	26.4	33.6	24	0.29	363	257.95	0.6678	0.4975	0.3322
182	CUMF 48	156	28.8	31.2	24	0.27	361.05	256	0.6661	0.5013	0.3339
183	(65:12:13:10)	156	28.8	31.2	24	0.28	366.25	261.2	0.6775	0.4760	0.3225
184		156	28.8	31.2	24	0.29	365.9	260.85	0.6745	0.4826	0.3255

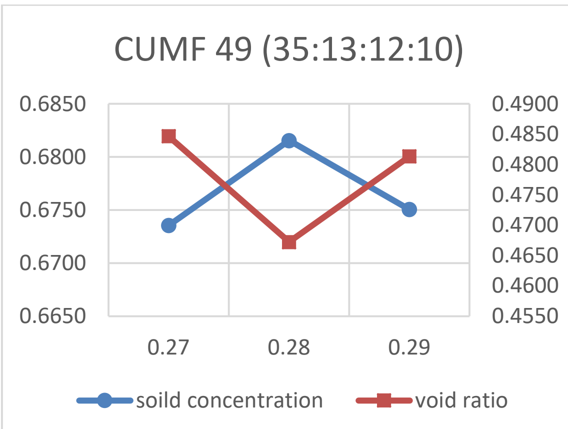


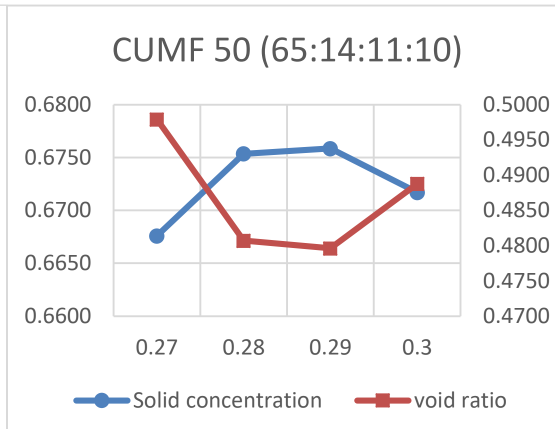


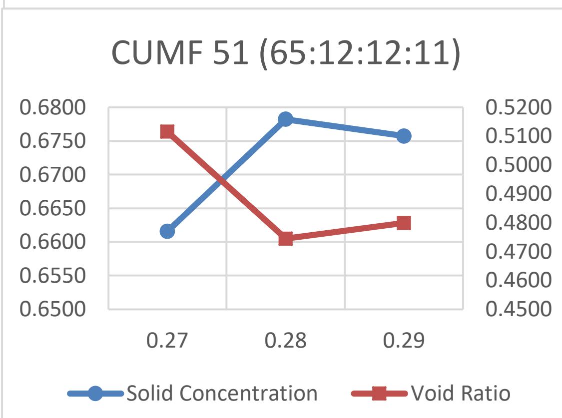


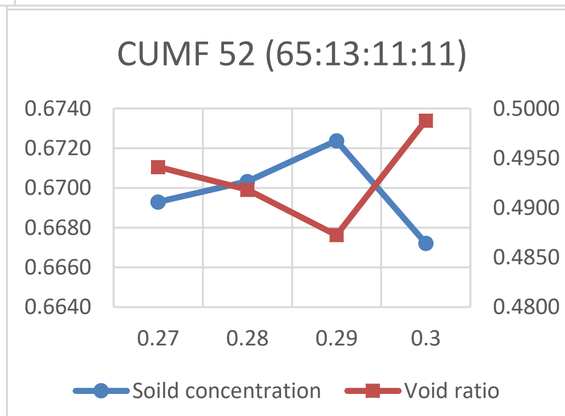


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm) OPC 53	UFS	METAKAOLIN	FLY ASH	W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
185	CUMF 49	156	31.2	28.8	24	0.27	364.2	259.15	0.6735	0.4847	0.3265
186	(65:13:12:10)	156	31.2	28.8	24	0.28	368.1	263.05	0.6816	0.4672	0.3184
187		156	31.2	28.8	24	0.29	366.4	261.35	0.6751	0.4814	0.3249
188	CUMF 50	156	33.6	26.4	24	0.27	362.2	257.15	0.6676	0.4979	0.3324
189	(65:14:11:10)	156	33.6	26.4	24	0.28	366	260.95	0.6754	0.4807	0.3246
190		156	33.6	26.4	24	0.29	367	261.95	0.6758	0.4796	0.3242
191		156	33.6	26.4	24	0.3	366.2	261.15	0.6717	0.4888	0.3283
192	CUMF 51	156	28.8	28.8	26.4	0.27	359.05	254	0.6616	0.5115	0.3384
193	(65:12:12:11)	156	28.8	28.8	26.4	0.28	366.25	261.2	0.6782	0.4745	0.3218
194		156	28.8	28.8	26.4	0.29	366.1	261.05	0.6757	0.4799	0.3243
195	CUMF 52	156	31.2	26.4	26.4	0.27	362.3	257.25	0.6693	0.4941	0.3307
196	(65:13:11:11)	156	31.2	26.4	26.4	0.28	363.5	258.45	0.6703	0.4918	0.3297
197		156	31.2	26.4	26.4	0.29	365.1	260.05	0.6724	0.4873	0.3276
198		156	31.2	26.4	26.4	0.3	363.9	258.85	0.6672	0.4988	0.3328

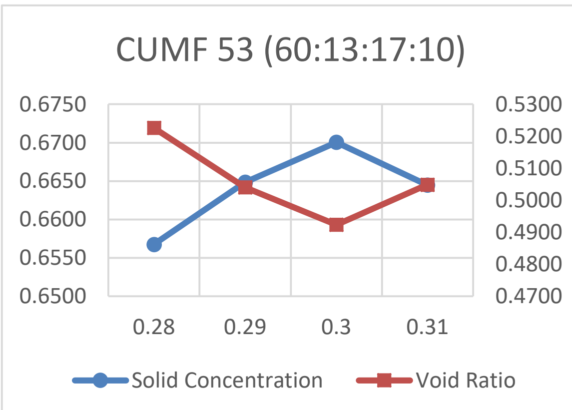


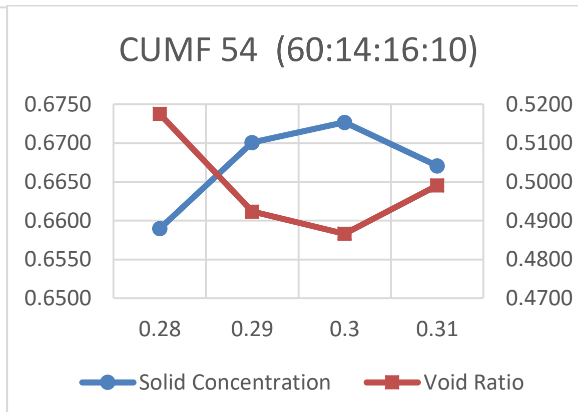


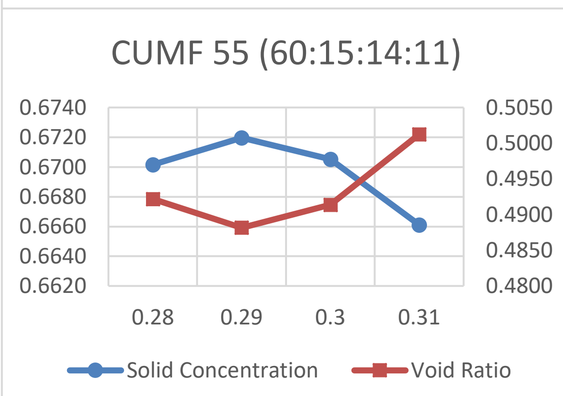


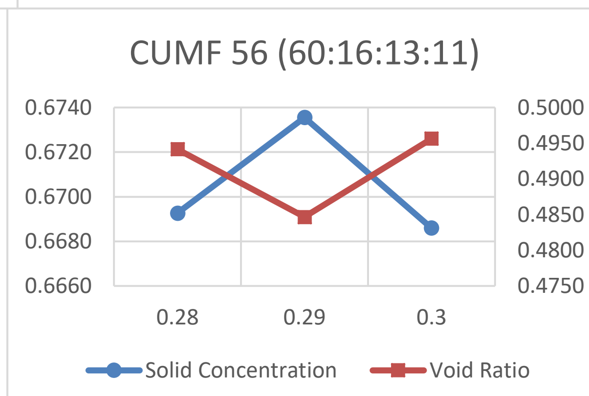


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm) OPC 53	UFS	METAKAOLIN	FLY ASH	W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
199	CUMF 53	144	33.6	38.4	24	0.28	356.25	251.2	0.6568	0.5226	0.3432
200	(60:13:17:10)	144	33.6	38.4	24	0.29	360.15	255.1	0.6649	0.5041	0.3351
201		144	33.6	38.4	24	0.3	362.95	257.9	0.6701	0.4924	0.3299
202		144	33.6	38.4	24	0.31	361.6	256.55	0.6645	0.5049	0.3355
203	CUMF 54	144	33.6	38.4	24	0.28	357.1	252.05	0.6590	0.5175	0.3410
204	(60:14:16:10)	144	33.6	38.4	24	0.29	362.15	257.1	0.6701	0.4924	0.3299
205		144	33.6	38.4	24	0.3	363.95	258.9	0.6727	0.4866	0.3273
206		144	33.6	38.4	24	0.31	362.6	257.55	0.6671	0.4991	0.3329
207	CUMF 55	144	36	33.6	26.4	0.28	361.4	256.35	0.6702	0.4922	0.3298
208	(60:15:14:11)	144	36	33.6	26.4	0.29	362.9	257.85	0.6720	0.4882	0.3280
209		144	36	33.6	26.4	0.3	363.15	258.1	0.6705	0.4914	0.3295
210		144	36	33.6	26.4	0.31	362.25	257.2	0.6661	0.5013	0.3339
211	CUMF 56	144	38.4	31.2	26.4	0.28	361.35	256.3	0.6693	0.4942	0.3307
212	(60:16:13:11)	144	38.4	31.2	26.4	0.29	363.8	258.75	0.6736	0.4847	0.3264
213		144	38.4	31.2	26.4	0.3	362.7	257.65	0.6686	0.4957	0.3314

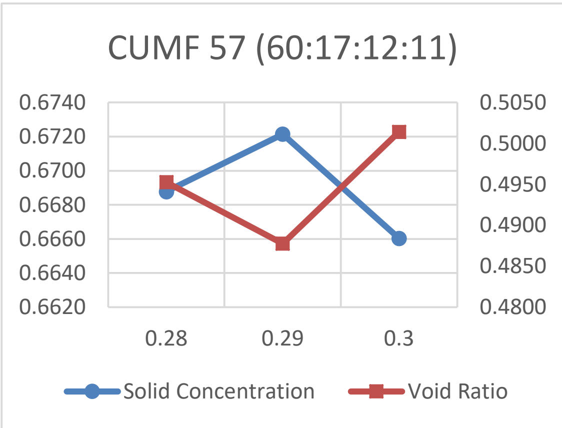


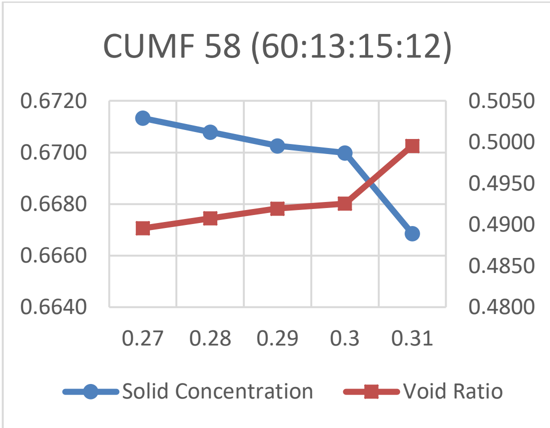


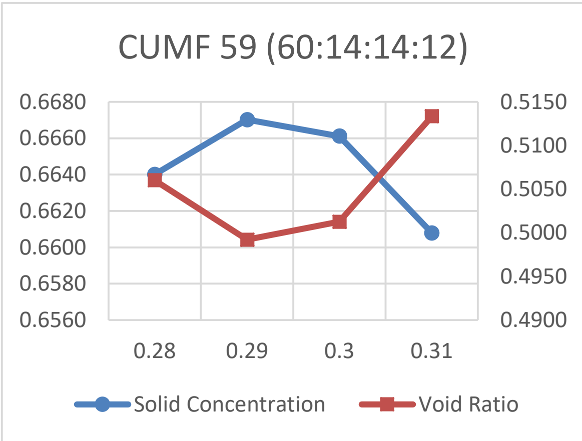


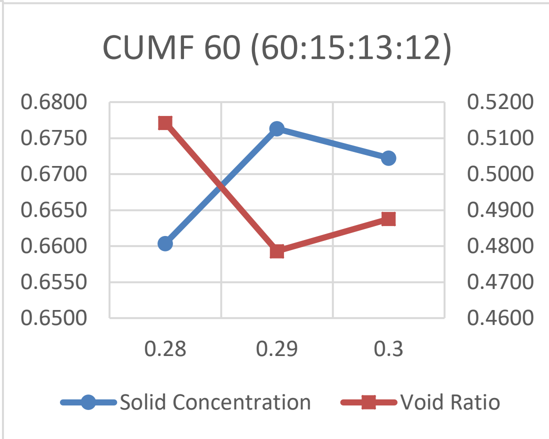


C:U:M:F (QUARTANARY MIX)											
SR No.	OPC 53:UFS:METAKAOLIN:FLY ASH	Wt. of materials (gm)				W/S ratio	Wt. (container + paste) (gm)	Wt. of compacted mix(gm)	Solid concentration	Void Ratio	Void content (ε)
		OPC 53	UFS	METAKAOLIN	FLY ASH						
214	CUMF 57	144	40.8	28.8	26.4	0.28	361.45	256.4	0.6688	0.4953	0.3312
215	(60:17:12:11)	144	40.8	28.8	26.4	0.29	363.55	258.5	0.6721	0.4878	0.3279
216		144	40.8	28.8	26.4	0.3	362	256.95	0.6660	0.5014	0.3340
217	CUMF 58	144	31.2	36	28.8	0.27	360.2	255.15	0.6713	0.4896	0.3287
218	(60:13:15:12)	144	31.2	36	28.8	0.28	360.8	255.75	0.6708	0.4908	0.3292
219		144	31.2	36	28.8	0.29	361.4	256.35	0.6703	0.4920	0.3297
220		144	31.2	36	28.8	0.3	362.1	257.05	0.6700	0.4926	0.3300
221		144	31.2	36	28.8	0.31	361.7	256.65	0.6669	0.4996	0.3331
222	CUMF 59	144	33.6	33.6	28.8	0.28	358.5	253.45	0.6640	0.5060	0.3360
223	(60:14:14:12)	144	33.6	33.6	28.8	0.29	360.45	255.4	0.6670	0.4992	0.3330
224		144	33.6	33.6	28.8	0.3	360.9	255.85	0.6661	0.5013	0.3339
225		144	33.6	33.6	28.8	0.31	359.65	254.6	0.6608	0.5133	0.3392
226	CUMF 60	144	36	31.2	28.8	0.28	357.4	252.35	0.6604	0.5143	0.3396
227	(60:15:13:12)	144	36	31.2	28.8	0.29	364.3	259.25	0.6763	0.4786	0.3237
228		144	36	31.2	28.8	0.3	363.55	258.5	0.6723	0.4875	0.3277









APPENDIX 2: Superplasticizer optimization calculations

	SP optimization for OPC (70%)+Ultra-fine slag (12%)+ Metakaolin (10%) + Fly Ash (8%) W/S Ratio=0.19							
1	Total Cementitious material (g)	water(g)	SP (%)	Solid content of SP in %	SP in ml	Solid content BWOC	Modified water content(g)	Marsh cone test (sec)
	1571.4	298.6	0.70	0.4	15.7	5.7	288.5	166
	1571.4	298.6	0.75	0.3	14.1	5.1	289.5	159
	1571.4	298.6	0.80	0.3	13.4	4.8	290.0	149
	1571.4	298.6	0.85	0.3	12.6	4.5	290.5	147
	1571.4	298.6	0.90	0.3	12.6	4.5	290.5	143
	1571.4	298.6	1.00	0.3	11.8	4.2	291.0	141

	SP optimization for OPC (70%)+Ultra-fine slag (10%)+ Metakaolin (11%) + Fly Ash (9%) W/S Ratio=0.19							
2	Total Cementitious material (g)	water(g)	SP (%)	Solid content of SP in %	SP in ml	Solid content BWOC	Modified water content(g)	Marsh cone test (sec)
	1571.4	298.6	0.70	0.4	15.7	5.7	288.5	169
	1571.4	298.6	0.75	0.3	14.1	5.1	289.5	161
	1571.4	298.6	0.80	0.3	13.4	4.8	290.0	155
	1571.4	298.6	0.95	0.3	12.6	4.5	290.5	152
	1571.4	298.6	0.90	0.3	12.6	4.5	290.5	151
	1571.4	298.6	1.00	0.3	11.8	4.2	291.0	148

	SP optimization for OPC (70%)+Ultra-fine slag (11%)+ Metakaolin (10%) + Fly Ash (9%) W/S Ratio=0.19							
3	Total Cementitious material (g)	water(g)	SP (%)	Solid content of SP in %	SP in ml	Solid content BWOC	Modified water content(g)	Marsh cone test (sec)
	1571.4	298.6	0.70	0.4	15.7	5.7	288.5	159
	1571.4	298.6	0.75	0.3	14.1	5.1	289.5	148
	1571.4	298.6	0.80	0.3	13.4	4.8	290.0	145
	1571.4	298.6	0.85	0.3	12.6	4.5	290.5	142
	1571.4	298.6	0.90	0.3	12.6	4.5	290.5	140

	1571.4	298.6	0.95	0.3	11.8	4.2	291.0	139
SP optimization for OPC (70%)+Ultra-fine slag (13%)+ Metakaolin (9%) + Fly Ash (8%) W/S Ratio=0.19								
4	Total Cementitious material (g)	water(g)	SP (%)	Solid content of SP in %	SP in ml	Solid content BWOC	Modified water content(g)	Marsh cone test (sec)
	1571.4	298.6	0.70	0.4	15.7	5.7	288.5	148
	1571.4	298.6	0.75	0.3	14.1	5.1	289.5	141
	1571.4	298.6	0.80	0.3	13.4	4.8	290.0	137
	1571.4	298.6	0.90	0.3	12.6	4.5	290.5	133
	1571.4	298.6	0.95	0.3	12.6	4.5	290.5	132
	1571.4	298.6	1.00	0.3	11.8	4.2	291.0	130
SP optimization for OPC (70%)+Ultra-fine slag (10%)+ Metakaolin (12%) + Fly Ash (8%) W/S Ratio=0.19								
5	Total Cementitious material (g)	water(g)	SP (%)	Solid content of SP in %	SP in ml	Solid content BWOC	Modified water content(g)	Marsh cone test (sec)
	1571.4	298.6	0.70	0.4	15.7	5.7	288.5	186
	1571.4	298.6	0.75	0.3	14.1	5.1	289.5	175
	1571.4	298.6	0.80	0.3	13.4	4.8	290.0	169
	1571.4	298.6	0.85	0.3	12.6	4.5	290.5	165
	1571.4	298.6	0.9	0.3	11.8	4.2	291.0	163

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