Grenze International Journal of Engineering and Technology, Jan Issue

Development of Mixture Design for Ultra-High Performance Concrete

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***Abstract*—Concrete is a composite material consisting of fine aggregates and coarse aggregates, these aggregates are bonded together with a fluid cement (cement paste) that hardens (cures) over time. There is increasing demand for construction and construction materials worldwide and for that concrete is the most widely used material. Because of the conflict between demand for high strength, high flowability and durability the emergence of Ultra High-Performance Concrete (UHPC) has occurred. In present investigation materials such as cement, silica fume, quartz powder, ennore sand, micro steel fibres and high range water reducer (HRWR)-polycarboxylic ether based superplasticizer was used. The mixing process of UHPC is quite different from that of the conventional concrete. For mixing UHPC digital mortar mixer machine was used. Properties of the UHPC mix were investigated such as flow table test, compressive strength test and flexural strength test. The results obtained from this study were compressive strength (136 MPa), flexural strength (25.60 MPa) and flow (115.33 %) respectively.**

***Index Terms*— Mixing Process, Mixing Time, Mortar Mixing Machine, Steel fibers, Compressive Strength, Flexural strength.**

I. Introduction

Ultra high performance concrete is new class of concrete that has been developed in recent decades due to its excellent properties of strength (Compressive strength greater than 150 MPa), durability and comparatively good tensile strength (about 5 MPa). Ultra High Performance Concrete mix generally consists of portland cement, supplementary cementitious materials, reactive powders, limestone and or quartz flour, fine sand, high-range water reducers, and water. And hence it is also known as reactive powder concrete (RPC). High rise buildings, bridges, dams etc. are endangered due to the increasing pollution level and possible events like earthquakes, gas explosions or any other natural or man-made disaster. Many times, conventional concrete is not sufficient to provide required strength and the size of the element is also restricted. Conventional reinforced concrete does not satisfy the construction of irregular shapes and facades which need high strength due to positioning of reinforcement. Considering the need of durability, safety and security of concrete structures leads to concrete development which pointed towards the advancement of concrete and hence there was a necessity of developing such concrete that has high durability and performance properties which would be useful in next generation construction of heavy structures like dams and bridges, precast elements and high rise building. Many advances are mad e in special concrete as per requirements from time to time i.e. from normal concrete to high strength

Grenze ID: 01.GIJET.7.1.523

concrete, high performance concrete, fiber reinforced concrete and finally towards the ultra high performance fiber reinforce concrete.

Table I shows comparison between normal concrete, high strength concrete, very high strength concrete and Ultra high performance concrete.

TABLE I. COMPARISON OF VARIOUS CONCRETE

	Normal Concrete	High Performance Concrete		
		High strength	Very high Strength	Ultra high performance concrete
Grade strength by cube (MPa)	≤ 50	55 -80	85 – 120	>120
W/c ratio	≥ 0.45	0.30 – 0.45	0.25 – 0.30	0.1 – 0.25
Chemical admixtures	Not required	Superplasticizer	Superplasticizer	Superplasticizer
Mineral admixtures	Not required	PFA/GGBS	Silica Fume	Silica fume/Nano material
Chloride permeability (Coulombs)	> 2,000	500 – 2,000	100 – 500	≤ 100
Tensile Strength (Mpa)	Not required	Not required	Not required	≥ 27

A. Literature Review

Ref. [14] Ahmed Tafreoui et al. (2009) discusses the effect of metakaolin in the formulation of UHPC. The materials used for the experimental program were cement, silica fumes, metakaolin, silica sand, superplasticizer and micro steel fiber. It was observed that flexural strength of concrete with metakaolin is almost equivalent to that with silica fumes but the compressive strength of concrete with metakaolin was found to be a bit lower than that with silica fumes. Also it was observed that the compressive strength was systematically improved due to the heat curing process. Ref. [11] B.A. Graybeal et al. (2007) focuses on the development of mixture design for ultra high performance concrete. The materials used were portland cement, fine sand, silica fumes, quartz powder, high range water reducing admixture and steel fibers. The results showed that heat curing played a very vital role in compressive strength, tensile cracking strength and modulus of elasticity. It also decreases the creep and also eliminates the subsequent shrinkage. Ref. [12] H.R. Sobuz et al. (2016) discusses steps in order to broaden and increase the application of UHPC by using cost effective manufacturing techniques for using commonly available materials and methods of production. Results showed that by using conventional natural and manufactured fine aggregates, including granulated slag, it is possible to produce concrete with good workability and compressive strengths in the range of 130–160 MPa without specialist mixing or curing regimes. Ref. [4] J.J. Chen et al. (2016) discusses increasing the packing density of the cementitious materials and providing room for further advancement of High Strength Concrete. A strength grade 52.5N Ordinary Portland Cement, Fly Ash Microsphere and Condensed Silica Fumes, superplasticizer were the materials used and totally 9 combinations of cementitious materials were adopted.The highest strength attained was 159 MPa for the mix with Fly Ash Microsphere content of 0% and Condensed Silica Fumes content of 20% and at a water/cementitious-material ratio of 0.16. It was observed that double blending of Ordinary Portland Cement with either Fly Ash Microsphere or Condensed Silica Fumes, and triple blending of Ordinary Portland Cement with both Fly Ash Microsphere and Condensed Silica Fumes can significantly increase the packing density and the addition of Fly Ash Microsphere and/or Condensed Silica Fumes would allow the water/cementitious-material ratio to be lowered in order to increase the strength. Ref,[10] P Richard et al. (1995) discusses the composition of reactive powder concrete. The materials used were portland cement, silica fumes, crushed quartz, superplasticizer and steel fibers.The results shows that the elimination of coarse aggregates combined to optimization of the granular mixtures results into dense cementitious matrix which exhibits high mechanical performances. Ref. [19] Prem Ref. [19] P.R. et al. (2013) discusses the influence of curing regimen on the compressive strength of ultra high performance concrete. The materials used for the experimental programme were Ordinary Portland Cement of 53 grade, silica fume, quartz powder, sand, superplasticizer and micro steel fibers.The results showed that for compressive strength the ennore sand was a better filer as compared to the quartz powder and also thermal regime is very important to activate silica fumes and quartz powered or else they will act as filler and not binder. Ref. [1] P.S.Ambily et al. (2015) emphasizes the behaviour of UHPC when incorporating copper slag as a fine aggregate. The materials used for the experimental program included Portland cement, silica fumes, quartz powder, fine aggregate(ennore sand, copper slag), superplasticizer and steel fibers. The results showed that using ennore sand as replacement showed increase in compressive strength also copper slag showed a positive effect of compressive strength of UHPC. Also specimens with ennore sand and copper slag as replacement and heat curing method showed a drastic increase in flexural strength of UHPC. Ref. [13] Yu Su et al. (2016) emphasize the effect of steel fibers on the dynamic strength of UHPC. The materials used for the experimental program included cement, silica fumes, silica flour, river sand, superplasticizer, nanoparticles and micro steel fibres. It was determined that a larger aspect ratio of length to diameter has a positive influence on crack control of UHPC. Also aspect ratio played a very important role in compressive strength and tensile properties of UHPC.

II. NEED OF STUDY

Over the past 50 years, there has been a continuous effort to protect civilian and military infrastructure, against impact and blast loading. Hence, extensive research is ongoing through several perspectives on building materials. The focus is on development of suitable construction products and technologies to save lives and protect infrastructure. Ultra High Performance Concrete (UHPC) is a potential material technology to meet the demand expected in terms of blast and ballistic resistance. The UHPC is known to have high strength, ductility and toughness suitable for impact resistant structures. As such there are no IS codal provisions for Ultra High Performance Concrete and therefore different mixture design have been proposed by various researchers and institutes. This paper deals with development to ultra high performance concrete with the target compressive strength of 120-150 MPa and flexural strength of 20-30 MPa which would help to achieve the performance aspects of concrete likely strength, durability, safety, heat insulation, consistency, elasticity, economy, etc.

III. EXPERIMENTAL STUDY

A. Material Properties

Cement:
The grade of cement used in mixture design is OPC 53 and properties are shown in the corresponding to IS: 12269 (2019). Table II. shows mechanical and physical properties of cement.

Silica fume:
Standard silica fume was used in the mixture design which had below mentioned properties. Table III. shows physical properties of silica fume.

Quartz Powder:
The replacement of cement was done by quartz powder in the mixture design of UHPC. Table IV. shows physical characteristics of quartz powder.

Ennore Sand:
Fine aggregate used for mixture design of Ultra High Performance Fibre Reinforced Concrete is standard Ennore sand of Grade- Ⅰ and Grade-Ⅲ were used according to IS 650:1991. Table V. shows the physical properties of ennore sand.

Micro Steel Fibres:
Brass coated low carbon micro steel fiber of 13 mm length and 0.22 mm diameter were used for the mixture design. Table VI. shows the physical properties of Micro Steel Fibres used.

Super Plasticizer:
High range water reducer (HRWR) Polycarboxylic Ether based superplasticizer, namely MasterGlenium Sky 8777 was used in the mixture design to decrease the w/c ratio and to increase the workability. Table VII. shows the performance test data for the superplasticizer.

TABLE II. MECHANICAL & PHYSICAL PROPERTIES OF CEMENT

Sr. No	Properties	Result Obtained	Specifications (IS:12269)
1	Compressive Strength (MPa)		
	3 days	29.17	27 (MPa)
	7 days	40.02	37 (MPa)
	28 days	55.19	53 (MPa)
2	Fineness (m^2/Kg)	308.47	225 (m^2/Kg)
3	Setting time (min)		
	Initial setting time	128	30 (min)
	Final setting time	218	600 (min)
4	Specific gravity	3.2	NA
5	Standard consistency	27.50%	IS 4031 (Part 4 – 1998)

TABLE III. PHYSICAL PROPERTIES OF SILICA FUME

Sr. no	Properties	Value
1	Average particle size (µm)	1.5
2	Bulk density (gm/ltr)	300
3	Physical formation	Grey
4	Specific gravity	2.5

TABLE IV. PHYSICAL PROPERTIES OF QUARTZ POWDER

Sr. no	Properties	Value
1	Particle size (µm)	(1.3 - 5.3)
2	Appearance	White
3	Odour	None
4	Melting point	1710^{o}C
5	Boiling point	2230^{o}C
6	Hardness (Moh's scale)	7
7	Specific gravity	2.65

TABLE V. PHYSICAL PROPERTIES OF ENNORE SAND

Sr no.	Properties	Value
1	Particle size of Grade-□ (mm)	1-2
2	Particle size of Grade-□ (mm)	0.5-0.9
3	Colour	Greyish White
4	Shape of grains	Subangular
5	Specific Gravity	2.64
6	Absorption (in 24 hours)	0.80%

TABLE VI.. PHYSICAL PROPERTIES OF MICRO STEEL FIBER

Sr no.	Properties	Values
1	Material	C76D
2	Appearance	Brass Coated
3	Cross Section	Round
4	Length (mm)	13
5	Diameter (mm)	0.22
6	Aspect Ratio	60
7	Tensile Strength (MPa)	>2000
8	Melting Point (□)	1500

TABLE VII. PHYSICAL PROPERTIES OF SUPER PLASTICIZER

Sr no.	Parameter	Observation
1	Appearance	Light Brown Liquid
2	Specific Gravity (at 25□)	1.10
3	pH	≥ 6
4	Chloride Content (%)	≤ 0.2

B. Mixture Design

After referring different literatures of UHPC, final mixture design for UHPC was prepared. According to which the constituents were taken and mixed in digital mortar mixture for high shear mixing and further preparation of cube samples (70.6 mm × 70.6 mm × 70.6 mm conforming to IS:10080 - 1982) and beam samples (40 mm × 40 mm × 160 mm conforming to BS-EN-196-1) was done. The next process was the normal water curing of all specimens at (27 +/- 2) ^{o}C for 28 days. Different tests of fresh and hardened concrete were also performed during the time. Table VIII shows different mix design was used by Richard and Cheyrezy [10], Benjamin A Graybeal

[11] and PR Prem et al. [9]. Based on available information in literature for present study mixture design of UHPC was prepared as shown in Table VIII.

C. Mixing Process

The mixing process of Ultra High Performance Concrete is different from the conventional concrete because to mix all the contents at a lower w/c ratio high shear is required. Digital mortar mix er (5 lts) is used for the mixing process. Figure 1 shows Digital mortar mixer used for the casting. The speed of the mixer was varied from 140 rpm (low) to 280 rpm (high) for the process. All the dry materials are weighed and added to the mixture for dry mixing. This dry mixing is done for 3 minutes at low speed. Then 50% of the total amount of water is added and mixed for next 1.5 minutes at low speed. The remaining 50% of the water is added to the calculated amount of chemical admixture and the resulting solution is added in ⅓ rd proportion and mixed for 1.5 minutes at low speed. The remaining ⅔ rd proportion is added and mixed for 6 minutes at high speed. The Micro steel fibers are added to the mix and mixed for 3 minutes at low speed. Finally to make the mix attain proper flowability it is mixed for 3 minutes at high speed. Each mix takes about 21 minutes to complete the whole cycle. The time required for each mixing cycle plays an important role in producing UHPC of perfect consistency and to achieve required properties.

TABLE VIII. MIXTURE DESIGN OF UHPC

Composition kg/m^3	Richard and Cheyrezy (1995) [10]	Benjamin A Graybeal (2007) [11]	PR Prem et al (2013) [9]	Mix Design Present Study
Cement	865.1	712	788	800
Silica fume	199	231	197	212.5
Quartz powder	337.4	211	315	340
Fine aggregate	951.6	1020	866.8	654.5+289.85*
Water	147.1	109	173	202.5
S.P	20.21 (l/m^3)	31 (l/m^3)	14.77 (l/m^3)	15.19(l/m^3)
Micro steel fibers	-	156	157	163
w/c ratio	0.17	0.16	0.22	0.20

Figure 1. Digital mortar mixer

D. Properties of UHPC

Flowtable Test

Workability test for UHPC mix was done by Flowtable test as per IS 4031 (Part 7) as shown in Figure 2. By measuring four diameters after subjecting to flow table test and then average diameter of flow was taken. Equation for finding % flow of UHPC is given by Equation (1)

$$Flow(\%) = \left[\frac{Davg - Do}{Do}\right] \times 100 \qquad (1)$$

Do

Where,

Davg = Average flow diameter of mortar (mm)

Do = Inner base diameter of mould (mm)

Compressive Strength

Compression test for UHPC was done using the Compression Testing Machine (Total Capacity of 3000 kN) to estimate the compressive strength of UHPC. For this test 70.6 mm × 70.6 mm × 70.6 mm cube size was used as per IS 516 :1959. Figure 3 shows Compression Testing Machine used for testing of cube samples. For obtaining compressive strength of UHPC cube sample equation 2 is used.

$$Compresiive\ Strength\ \left(\frac{N}{mm^2}\right) = \left[\frac{P \times 1000}{A}\right] \quad (2)$$

Where,

Where,

P = Failure Load (kN)

A = Area of cube (mm^2)

iii. Flexural Strength

The flexural strength was performed in Universal Testing Machine (Capacity of 1000 kN) to assess the flexural strength of UHPC. For this test 40 mm × 40 mm × 160 mm beam was tested as per BS-EN-196-1. Figure 4 shows testing of beam specimens in Universal Testing Machine. For obtaining Flexural strength of UHPC equation 3 is used.

$$Flexural\ Strength\ (N/mm^2) = \left[\frac{Mmax}{W}\right] \quad (3)$$

Where,

Where,

M = Bending moment (Nmm)

W = Section of modulus (mm^2)

Figure 2. Flowtable Test assembly

Figure 3. Compressive strength testing in Compression Testing Machine

Figure 4. Testing of beam sample in Universal Testing Machine

IV. RESULT & DISCUSSION

A. Flowtable Test

Table IX shows the results of the flow table test. The average diameter of flow found was 215.33 mm which suggests that the concrete is much better in consistency, cohesiveness and less prone to segregation. The percentage flow measured was 115.33 which is due to the errorless mixing is done and the prepared mix was able to spread easily.

B. Compressive Strength

The Table X shows the result of compressive strength tests on cubes of dimensions 70.6 mm × 70.6 mm × 70.6 mm using a compressive strength testing machine at the rate of 140 kg/cm^2/minute without shocks during loading. The obtained values show that 28 days strength of concrete specimen was 136 MPa; which is due to addition of Supplementary Cementitious Materials and low water/cementitious-materials ratio of concrete and very much denser concrete microstructure was obtained. Obtained results were much better when compared to results of ordinary concrete.

C. Flexural Strength

The table XI shows the result of flexural strength tests on specimens of dimension 40 mm × 40 mm × 160 mm beams using two-point flexure test. Addition of steel fibres increases the flexure strength of beam specimens and in combination with steel reinforcement, the problem of tension cracks can be resolved. Steel fibres provide flexibility and also help minutely in compressive strength too. The 3 days Flexural strength was 8 MPa and 7 day strength was 17 MPa showing good bonding between steel fibres and concrete. The 28 days Flexural strength was 26 MPa which is much better when compared to ordinary concrete and high strength concrete.

TABLE IX. RESULTS OF FLOWTABLE TEST

Sr. No.	Diameter of Flow (mm)	Davg (mm)	% Flow
1.	216	215.33	115.33
2.	216		
3.	214		

TABLE X. RESULTS OF COMPRESSIVE STRENGTH

Sr. No.	Mass density (kg/m^3)	Age (days)	Compressive Strength (MPa)	Avg. Comp. Strength (MPa)
1	2624	3	62	63
2	2629		65	
3	2617		62	
4	2624	7	105	108
5	2631		111	
6	2615		108	
7	2624	28	137	136
8	2630		134	
9	2635		138	

TABLE XI. RESULTS OF FLEXURAL STRENGTH

Sr. No.	Days	Flexural Strength (MPa)	Avg. Flexural Strength (MPa)
1.	3	7.46	8
2.		8.00	
3.		7.28	
4.	7	16.76	17
5.		17.56	
6.		16.88	
7.	28	26.01	26
8.		24.20	
9.		26.60	

V. Conclusion

From the result of this experimental investigation, the following conclusions were made on the Ultra High Performance Concrete.

- Due to less water to binder ratio, addition of High Range Water Reducing Admixture is critical. Furthermore, the mixing has to be done in the given sequential order, within time constraints using digital mortar mixture.
- Prepared fresh concrete sample while testing on flow table test, shows excellent workability, high flow ability & uniform spread of prepared mix.
- Supplementary cementitious materials like silica fume, quartz powder was used as replacements to cement in concrete samples, which when tested under compressive test gave much superior values which is due to Supplementary Cementitious Materials' pozzolanic reactivity and much denser microstructure of concrete. Steel fibre effect will be minor on the improvement of compressive strength values.
- Similar effect on flexural strength was observed when a two point flexure test was performed. Addition of steel fibres in reinforced concrete flexural members increased ductility, tensile strength, moment capacity and stiffness which gave rise to flexural strength of concrete.
- Considering the advantages of UHPC, its widespread usage is expected in the upcoming future by using cost effective methods through which UHPC may find application in almost every civil engineering field. For example; nowadays modern high-speed railway tracks require the use of pre-fabricated UHPC sleepers which are very much better compared to the traditional wooden or ordinary concrete sleepers.

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