PRACTICAL APPLICATION OF HIGH STRENGTH CONCRETE MATRIX FOR USE IN DEFENCE ESTABLISHMENTS

Kasturi Bhuyan[1]**, Anil Kumar Sah**[1]**, Hrishikesh Sharma**[1]

1. Indian Institute of Technology Guwahati, India

ABSTRACT. High strength concrete (HSC) is a developing material that will allow the civil and defence construction industry to optimize the material use, generate economic benefits and build structures that are strong, durable, and sensitive to man-made and environmental hazards. It is used in civil and defence establishment where impact resistance, high durability and member size are governing factors in design. The current work focuses on achieving high compressive strength of HSC by practical execution of percentage content of materials like silica fume, quartz powder, fine aggregate and coarse aggregate. Material tests is conducted to determine their properties for arriving at the various trial mixes. In the current work, all the physical properties of materials are studied by conducting in-depth experiment such as XRD, FESEM and EDX. Different mixes are adopted with various percentage content of materials. The optimum content of the materials is determined based on the compressive strength test results done on the casted cubes at 7, 28 and 56 days from the day of casting. The mix proportion with better result is adopted for casting a floor slab at site. A practical implementation of the HSC is achieved with experimental value under feasible and realistic site condition which will be further useful in defence establishments.

Keywords: High strength concrete, Silica fume, Quartz, Material testing, Microstructural study

Kasturi Bhuyan is a Research Scholar in Structural Engineering of Civil Engineering Department, Indian Institute of Technology Guwahati, India. Her research interest includes high strength concrete and blast analysis.

Anil Kumar Sah, Masters in Structural Engineering of Civil Engineering Department, Indian Institute of Technology Guwahati, India. His research topic included study of high strength concrete matrix and its properties.

Dr Hrishikesh Sharma is an Assistant Professor of Civil Engineering Department at Indian Institute of Technology Guwahati, India. His research interests are Impact and blast resistant design, Reliability analysis and performance based engineering; and Design and optimization of protection measures.

INTRODUCTION

Development of high strength concrete (HSC) can be marked as an amazing progress in concrete technology. These developments help to optimize the use of materials in a broader way. Many materials are taken in research and development of what is also known as high performance concrete (HPC). Material selection process for the concrete requires proper understanding of the available materials, functions and their influence on fresh and hardened concrete properties. Proper study of such materials has thus become necessary to utilize the materials to their full potential.

High strength concrete has been used in bridges since many years and now is also finding its ways to defence and nuclear establishments. Dry mixed ultra-high performance concrete products are commercially available, and had been successfully applied for bridges and other spectacular structures in several countries. Iran recently developed an ultra-high performance concrete also known as “Smart concrete” to protect N-sites from US bunker busters. Sectors with high durability and strength demand are adopting HSC but due to it high cost, its use is limited.

The constituents usually used for the high strength concrete matrix are cement, fine aggregate, coarse aggregate, superplasticizer, low water-cement ratio and mineral admixtures like fly ash, ground granulated blast-furnace slag, silica fume, silica sand etc. As proper mix designs are not available for high strength concrete till date, trial mixes are very important in achieving the desired concrete performance. Knowing the effect of each material on the fresh as well as hardened concrete helps a lot in adopting the proportion in the trial mixes. Thus, the current paper summarises the outcome of the microstructural study of material and application of the materials in developing a high strength concrete mix by adopting compressive strength test. Also, with the understanding of results of the test conducted, a pragmatic application is done successfully on a floor slab under realistic circumstances.

CURRENT STATE OF HIGH STRENGTH CONCRETE

Many research works have been conducted over the years to achieve high mechanical performance with cementitious matrix materials. Eugene Freyssinet during the 1930s demonstrated that in order to improve the strength of concrete applying pressure to the fresh concrete is advantageous. During the 1960s, compressed samples were prepared and heat cured under elevated pressures which attained compressive strength of 650 MPa. Most of the research conducted on ultra-high performance concrete used cement, silica fume, quartz and superplasticizer along with fibers [1-4] and with various percentage of volume fraction [5-10].

High amount of superplasticizer in the mix causes the hydration reaction to start at 26 hours after water addition and gets retarded [2]. Yang et al. (2009) [11] investigated ultra-high performance concrete by replacing expensive silica sand by recycled glass cullet and two types of local natural sand; and some part of cement with ground granulated blast-furnace slag and silica fume. Addition of deformed fibers by volume lead to an increase direct tensile strength which was about three times more than that for UHP-FRC with smooth fibers [7, 9]. Higher fibre volume produced drastic changes in the cube strength, cylinder strength, post peak response, load-crack mouth opening displacement, fracture energy flexural strength, split tensile strength, residual strength and durability [8].

Excellent mechanical performance and A very dense and homogeneous microstructure is reported even when no pressure was applied to fresh high performance concrete mixtures including calcined bauxite [6]. Ultra-high performance concrete (UHPC) mixtures with respect to that of HPC and conventional concrete showed very small microcracks in the vicinity of the aggregate particles with no CH crystals and very small thickness of the transition zone [12,13].

MATERIALS FOR HIGH STRENGTH CONCRETE

All materials used in a concrete mix has its significance. Optimizing the particle size distribution of the cementitious materials increases the potential packing density and can also reduce the capillary porosity as it also favours the formation of fine-textured hydration products that have a higher strength than the coarser equivalents. It is assumed that small aggregate particles will contain less internal flaws and hence produce a higher concrete strength. Ingredients of high strength concrete matrix should possess these properties to ensure maximum particle density and minimum flaws.

Cement

In the present work, Ordinary Portland cement (OPC) of 53-grade conforming to IS: 8112-2013 (Specific gravity = 3.15) was used in the preparation of concrete mixes. Cement was selected based C_3A content; lower the content means less water demand. The physical properties of cement are as follows:

- Standard consistency = 30%
- Initial setting time = 93 min
- Final setting time = 6 h
- 28 day compressive strength = 53.4 N/mm^2
- Fineness = 96%
- Specific surface area = 2.152 m^2/g

Silica Fume

Silica fume is a by-product from manufacturing of Silicon metal and alloys in electric arc furnace. Papadakis et al. (1999) [14] investigated that silica fume has particle diameters of about 0.1 micron. Two particle shapes are present, one spheroid and one cylindrical. and further added that, this particular shape can help in SF identification in cement paste during the hydration process. The silica fume agglomerations are almost spherical. The agglomeration consists of much ultra-fine silica. Some agglomerations have sizes larger than 100 mm. Due to the spherical particles, lubrication effect is developed which improves the rheological characteristics; and it also reacts (pozzolanic reaction) with the lime resulting from primary hydration producing secondary hydrates.

Microsilica® Grade 920 D was adopted as a mineral admixture in the mixes for filling the voids between the next larger class particles (cement). The image obtained from scanning electron microscope (SEM) is presented in Figure 1(a), where the spherical particles of varying diameter are clearly visible. The specific surface area of the material is 16.085 m^2/g with specific gravity of 2.22.

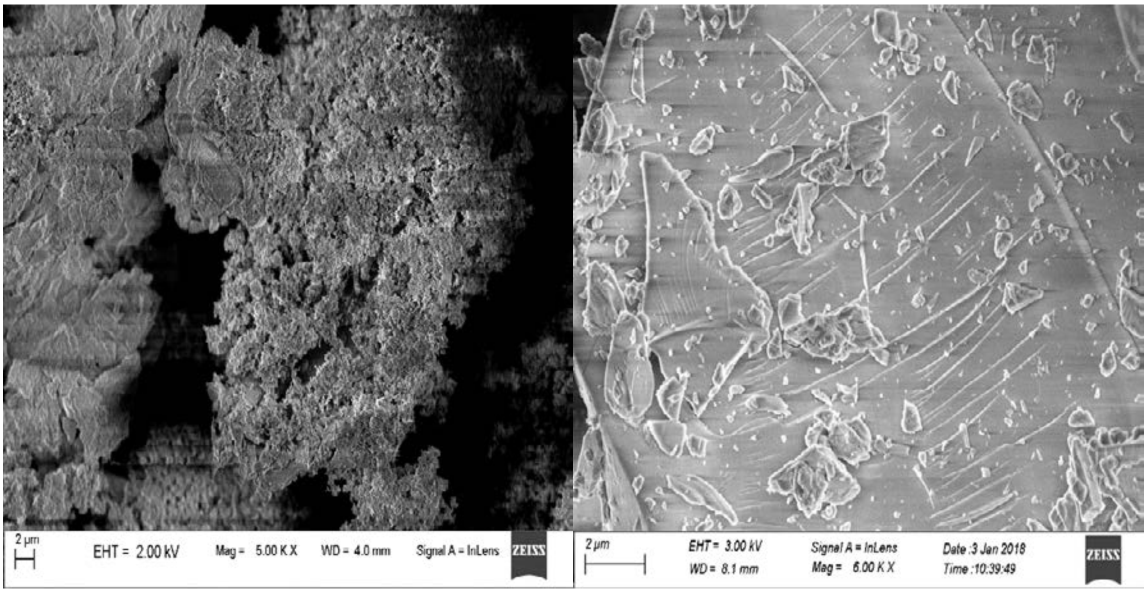


Figure 1 SEM image of (a) silica fume and (b) quartz.

The XRD pattern of silica fume is like a hump as the silica fume mainly consist of vitreous silica. Flatter the hump, more is the amorphous fume. The hump is located near 2θ=22°, which indicates the distribution of silicon tetrahedron in vitreous particles over a range of short distance. The XRD pattern of silica fume is shown in Figure 2(a). EDX analysis on silica fume has been done and it is observed that silicon, oxygen shows higher peaks (Figure 3).

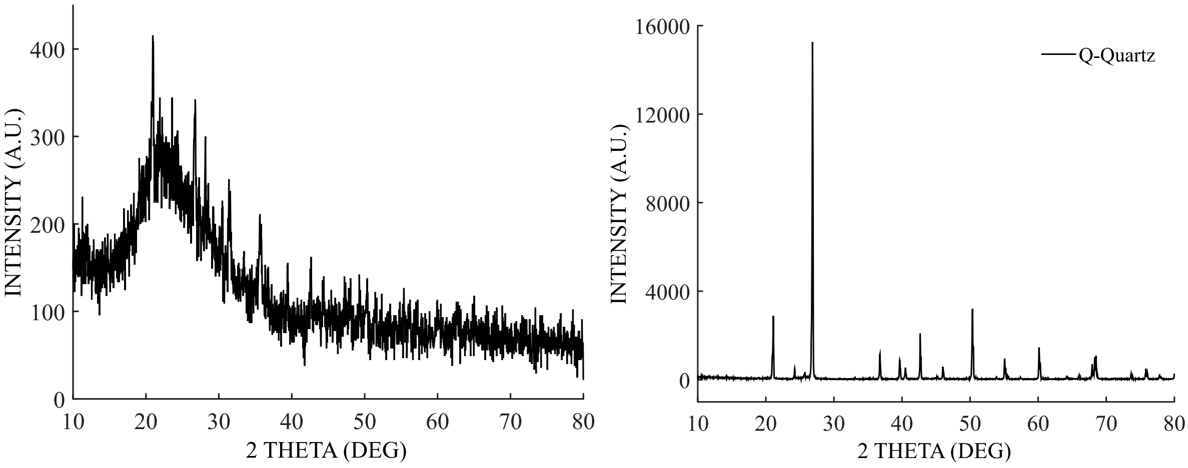


Figure 2 XRD pattern of (a) silica fume (b) quartz.

Quartz

Quartz is a very hard material and possesses excellent paste/aggregate interfaces. For heat-treated concretes crushed crystalline quartz powder is an essential ingredient as maximum reactivity is obtained for a mean particle size of between 5 and 25 μm during heat-treating. Locally available quartz powder is used as a filler material in the concrete mixes. SEM photograph of quartz presented in Figure 1(b) shows angular particles of different sizes. The particle size of quartz powder used is less than 75 μm with a specific gravity of 2.66. Figure 2(b) presents the XRD pattern obtained for quartz powder. The steep peak at 2θ=22°

indicates the presence of quartz. EDX pattern of quartz as shown in Figure 4 exhibits presence of impurities in the quartz sample.

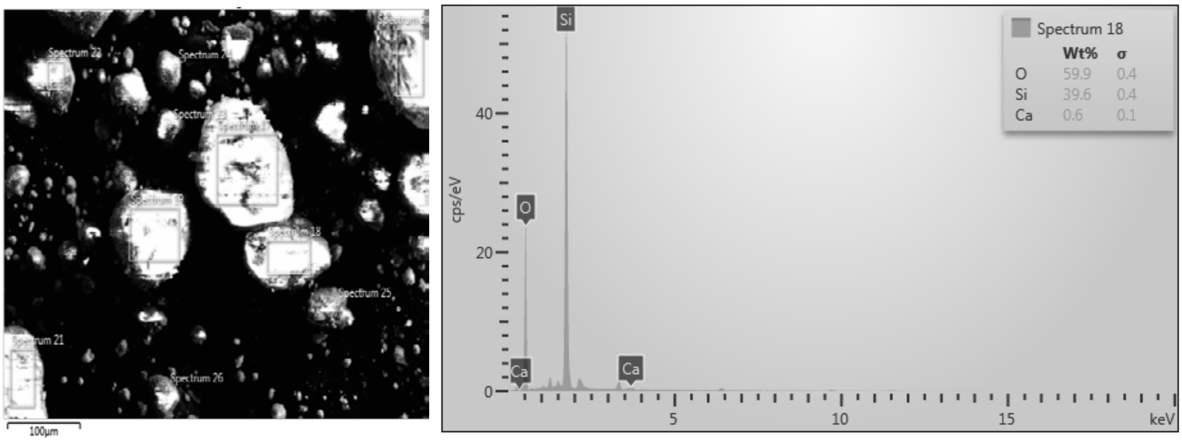


Figure 3 EDX pattern of silica fume.

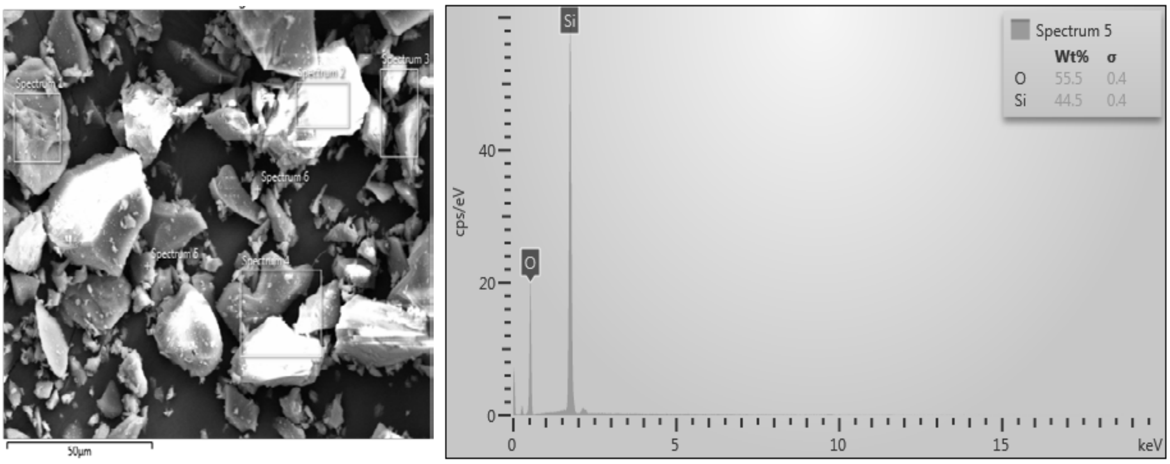


Figure 4 EDX pattern of quartz.

Fine Aggregate

Local river sand was adopted in this experiment conforming to Zone-II as per IS: 383-1970 with specific gravity of 2.65 and Fineness modulus (F.M.) as 2.75. Prior to mixing, the available sand was sieved by 600 µm sieve to maintain the particle size in the concrete matrix. The sieve analysis test results are shown in Table 1.

Coarse Aggregate

Mechanical properties of aggregate particles are a major cause of limitation of concrete strength achievable as they themselves are the weakest link. The improvement of transition zone between the paste and the aggregate causes the transfer of stresses more effective from the paste to the aggregate particles. In the current work, coarse aggregate (specific gravity = 2.67) of maximum size 10 mm was adopted in some mixes. The particle size distribution is presented in Table 1.

Table 1 Sieve Analysis of fine and coarse aggregate.

SIEVE SIZES (mm)	CUMULATIVE % WEIGHT PASSING
Fine Aggregate	
4.750	99.87
2.360	99.62
1.180	98.22
0.600	82.62
0.300	38.92
0.150	4.92
0.075	0.42
Coarse Aggregate	
12.50	99.97
10.00	97.39
4.75	18.33
2.36	3.10

Chemical Admixture

Superplasticizers plays an important role in high strength concrete production as it produces workable concrete at very low levels of water/cement ratios without needing high cement content. They also increase early and ultimate compressive strengths, offer better resistance to carbonation, reduce shrinkage and creep; and make concrete durable. Poly-carboxylate ether-based superplasticizer- FOSROC - Structuro 203 (Solid content of 34%) and MasterGlenium ACE 30UG (BASF- Solid content of 44.34%) both with specific gravity of 1.09 was used in the current study.

Material Proportioning

In this experimental work, the mix proportioning of concrete matrix is carried out on the basis of literature review and thus carrying out several trial mixes. As reported in the literature for high strength concrete, the range of silica fume varies from 15% to 30% of mass of cement and quartz powder about 20-40% of mass of cement. Whereas, water/binder ratio fluctuates from 0.24 to 0.28. The range of the proportions of materials used in this study is given in Table 2. It is seen that water content or superplasticizer dosage needed increases with increase in silica or quartz content.

The standard guidelines for mix design of high strength concrete is not available. Mix design calculations are done as per conventional mix design techniques. Nine cubes of size 100 x 100 x 100 mm for each mix were casted for testing under compressive testing machine. Table 3 produces the composition of mixes adopted in this experiment.

Table 2 Range of different variable used in the mixes.

PARAMETERS	RANGE
Silica fume	15-30 %
Quartz	20-40 %
Fine Aggregate	0.8-1.4
Coarse Aggregate	0.9
Superplasticizer	0.6-1.8 %
Water-binder ratio	0.24-0.32

Table 3 Material composition of the concrete mixes.

MIX	W/B CONTENT	MATERIAL COMPOSITION (kg/m^3)					SP DOGAGE (%)
		Cement	Silica Fume	Quartz	F.A.	C.A.	
C1	0.24	829.83	124.47	207.46	912.81	-	1.60
C2	0.24	805.89	161.18	201.47	886.48	-	1.60
C3	0.24	783.30	195.83	195.83	861.63	-	1.60
C4	0.24	761.94	228.58	190.49	838.13	-	1.60
C5	0.24	846.57	211.64	-	931.23	-	1.60
C6	0.24	795.19	198.80	159.04	874.71	-	1.60
C7	0.24	771.76	192.94	231.53	848.94	-	1.60
C8	0.24	749.68	187.42	299.87	824.65	-	1.60
C9	0.24	781.76	156.35	195.44	938.11	-	1.60
C10	0.24	737.58	147.52	184.40	1032.61	-	1.60
C11	0.32	735.54	183.89	183.89	809.09	-	-
C12	0.28	757.33	189.33	189.33	833.06	-	1.00
C13	0.26	770.79	192.70	192.70	847.87	-	1.20
C14	0.24	781.87	195.47	195.47	860.06	-	1.80
C15	0.24	800.52	160.10	-	1080.70	-	0.06
C16	0.24	734.46	146.89	-	587.57	661.01	0.06
C17	0.24	734.46	146.89	-	587.57	661.01	0.06

Mixing and curing

In this experimental work, the mix proportioning of concrete matrix is carried out on the basis of literature review and thus carrying out several trial mixes. As reported in the literature for high strength concrete, the range of silica fume varies from 10% to 30% of mass of cement and quartz powder about 15-40%.

Most of the mixes were mixed manually without any mixing unit. Dry materials were mixed for about 5 minute until a homogenous mix was seen. Then water mixed with the superplasticizer dosage was added and again mixed for 10 minutes. 100 x 100 x 100 mm concrete moulds were then filled with the mix with proper vibration technique. The casted cubes were air cured for 3 days after removal of the moulds prior to the standard water curing. Mix C17 was machined mixed using a tilting mixer in the laboratory with same composition as mix C16. Curing procedure was kept similar to the other mixes.

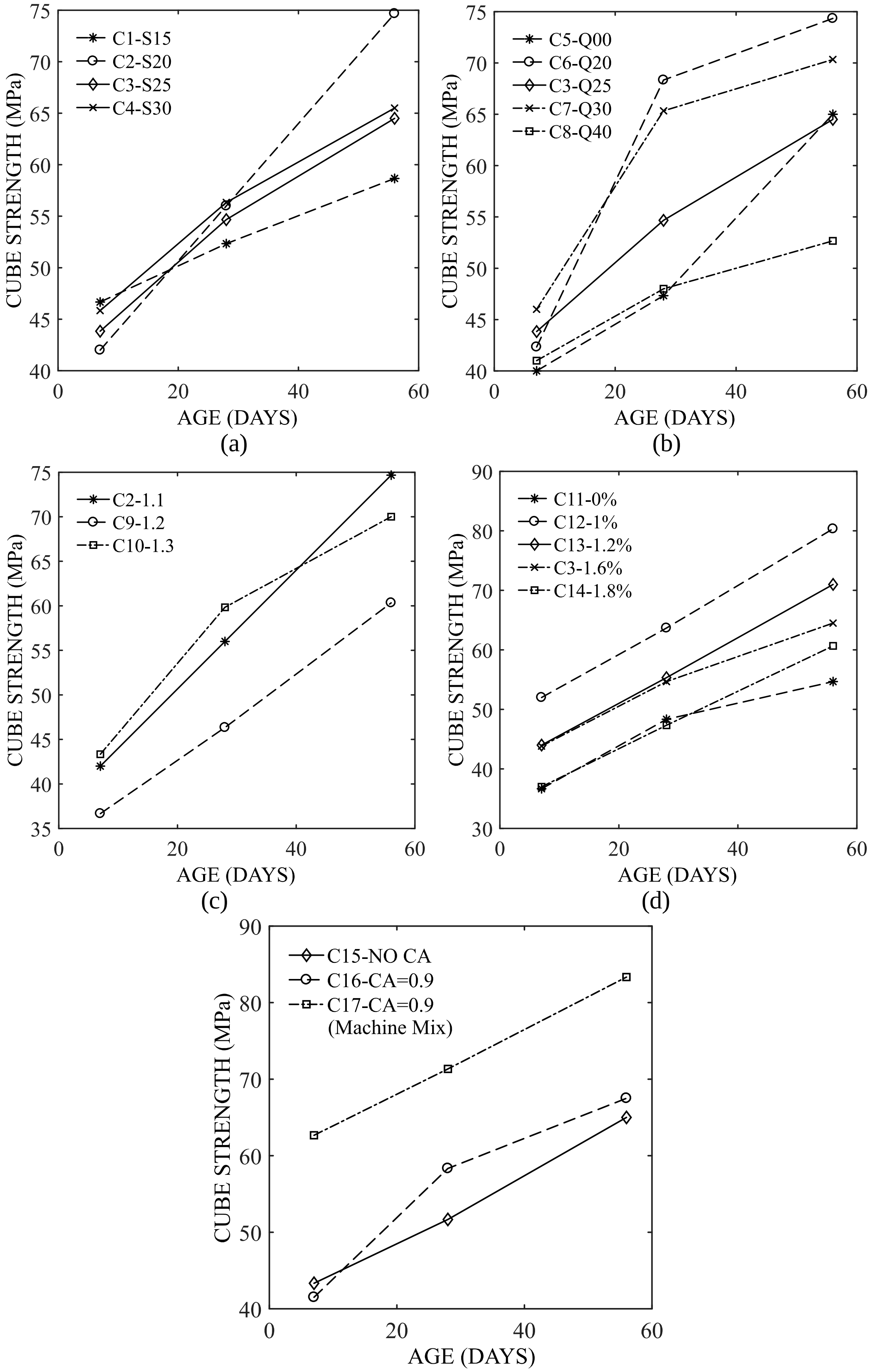
CONCRETE COMPRESSIVE STRENGTH TEST

After completion of curing, the cube specimens were removed from the curing tank. The compressive strength test was performed on the cube specimens in a compressive testing machine of capacity 2000 kN at the curing ages of 7, 28 and 56 days from the day of casting. Three cubes of each mix was tested from each curing age and the value of cube strength was recorded as the average value of three replicate cubes. Table 4 shows the cube compressive strength test results for all the ages of the concrete mix.

Table 4 Cube compressive strength results.

MIX	MATERIALS				SP DOSAGE (%)	W/B RATIO	AVERAGE CUBE STRENGTH (MPa)		
	Silica Fume	Quartz	F.A.	C.A.			7 D	28 D	56 D
C1	0.15	0.25	1.10	-	1.60	0.24	46.67	52.33	58.67
C2	0.20	0.25	1.10	-	1.60	0.24	42.00	56.00	74.67
C3	0.25	0.25	1.10	-	1.60	0.24	43.83	54.67	64.50
C4	0.30	0.25	1.10	-	1.60	0.24	45.83	56.33	65.50
C5	0.25	-	1.10	-	1.60	0.24	40.00	47.33	65.00
C6	0.25	0.20	1.10	-	1.60	0.24	42.33	68.33	74.33
C7	0.25	0.30	1.10	-	1.60	0.24	46.00	65.33	70.33
C8	0.25	0.40	1.10	-	1.60	0.24	41.00	48.00	52.67
C9	0.20	0.25	1.20	-	1.60	0.24	36.67	46.33	60.33
C10	0.20	0.25	1.40	-	1.60	0.24	43.33	59.83	70.00
C11	0.25	0.25	1.10	-	-	0.32	36.67	48.33	54.67
C12	0.25	0.25	1.10	-	1.00	0.28	52.00	63.67	80.33
C13	0.25	0.25	1.10	-	1.20	0.26	44.00	55.33	71.00
C14	0.25	0.25	1.10	-	1.80	0.24	37.00	47.33	60.67
C15	0.20	-	1.35	-	0.06	0.24	43.33	51.67	65.00
C16	0.20	-	0.80	0.9	0.06	0.24	41.50	58.33	67.50
C17	0.20	-	0.80	0.9	0.06	0.24	62.67	71.33	83.33

Figure 5(a) demonstrates the effects of silica fume content on cube strength. Concrete mix with 20% silica fume shows better results of cube test. Although increase in its percent displays increase in strength, but with higher content, water requirement is more and the mix becomes unworkable. Excess of silica also delays the setting time of the concrete. Quartz effects the cube strength as depicted in Figure 5(b). Mixes without quartz and with 30% of its content exhibits almost similar cube strength at 56 days. 20% of quartz also proves to be the optimum quantity whereas increment to 40% did not improve the strength of concrete. Increase of quartz beyond a certain percentage content is not much of use.



(a)

(b)

(c)

(d)

(e)

Figure 5 Effect of (a) silica fume, (b) quartz, (c) fine aggregate, (d) superplasticizer dosage and (e) coarse aggregate content on cube strength.

Sand or fine aggregate using 1.1 times of cement content performed better than the other two mixes as seen in Figure 5(c). Sand content did not show any defined pattern of effect on cube strength. Superplasticizer dosage influences the water/binder ratio which in turn effects the concrete. Dosage of 1% of binder prove to be the optimum dosage with water/binder ratio of 0.28 than the other high dosage mix. As observed in Figure 5(d), with increase in superplasticizer content, the cube strength reduces. Cube strength of mix C15 without coarse aggregate (CA) and C16 with CA 0.9 times of cement are quite close to each other as shown in Figure 5(e). But mix C17 with similar material composition when machine mixed and tested, exhibits much higher strength. This may be due to homogeneity of the machine mixed concrete is way better than that of the hand mixed.

PRACTICAL APPLICATION

With the results obtained from all the mix, a proper floor slab (12 x 18 x 0.175 m) was casted. Concrete with the same composition as C17 was adopted for this application. Figure 6 shows the high strength concrete, the slab before and after casting. The casting was conducted in an uncontrolled manner. The local fine and coarse aggregates were used directly without sieving and mixing was done by labourer in a tilting mixing machine. The maximum compressive strength obtained from the concrete casted in the slab is 70 MPa in 28 days on an average.

Figure 6 Photographs of high strength concrete slab during casting.

The cost of high strength concrete is more due to which it is not considered in construction as much as normal strength concrete. The cost per unit volume of the current HSC is approximately 45% more than normal strength concrete, but the depth of slab required also reduces. The reduction in the depth of the slab leads to deduction in the demand of material which in turn reduces the cost of construction. Moreover, the cost of labour, formwork and all other ancillaries also minimizes as the dimension and time required for constructing a slender slab is less than that of a thicker one. Finally, the cost of construction of the slab with high strength concrete is approximately 50% less than normal strength concrete. Practical application of HSC mix showed that with proper consideration and planning done in mix design, high grade of concrete can also be obtained in construction field within the same overall construction cost. Thus, for civilian as well as defence establishments, where structures are huge and limited area is available for it, application of HSC will bring considerable changes in the present scenario of construction. This implementation will not only strengthen the structures but also will minimize the sections of the members required.

CONCLUDING REMARKS

Though both silica fume and quartz shows more good properties in microstructural studies due to its fineness water demand is high. This extra water added in turn reduces the cube strength. No significant improvement is seen on adding quartz. So, we casted some special mixes with coarse aggregates and without quartz. The concrete mixes with coarse aggregate aggregates (10 mm down) in an uncontrolled way gave us 63 MPa on an average at just 7 days from casting.

Reduction in water/binder ratio causes closer packing of the cementitious particles in fresh concrete and produces a paste which has less capillary porosity in the hardened paste and so a greater strength can be achieved. Mineral admixtures attributes to improvement in packing density and reduction of capillary porosity. For the concrete matrix to attain high strength, water/binder ratio is kept well below the theoretical minimum for full cement hydration but hydration of cementitious particles within the paste is enough to pack the unhydrated cores of the particles together and to reduce the interstitial porosity between these hydrated particles. Here comes the critical role of superplasticizers of making concrete workable. The flocculation of Portland cement particles and distributing material such as silica fume homogeneously through the freshly mixed concrete is also taken care of by the superplasticizers making the paste homogeneous. Hand mixing of concrete in our case is leading to, inhomogeneity and capillary pores which are considered the weakest links and thus limiting the strength of the paste. The last special concrete mix with course aggregate is mixed in machine and has more homogeneity.

The outcome of the current work is that, at present conditions using cement, silica fume, fine aggregate, coarse aggregate and superplasticizer; higher grade of concrete which is practically implemented at the site under normal quality control condition and achieves an efficient reduction in the overall cost by approximately 50%, though the cost per unit volume increases by 45%. Higher grade of concrete can thus be applicable in defence establishments where structures require more strength to survive the unpredictable loading conditions that is both man-made and natural hazard.

ACKNOWLEDGMENTS

In the current work at IIT Guwahati, the authors are grateful to FOSROC Chemicals, India and BASF, India for giving the chemical admixtures required in this experiment. We also acknowledge Elkem for their support and proving us with micro-silica.

REFERENCES

1. MATTE V AND MORANVILLE M, Durability of reactive powder composites: influence of silica fume on the leaching properties of very low water/binder pastes, Cement and Concrete Composites 21, no. 1 (1999): 1-9.
2. HABEL K, MARCO V, EMMANUEL D AND EUGEN B, Development of the mechanical properties of an ultra-high performance fiber reinforced concrete (UHPFRC), Cement and Concrete Research 36, no. 7 (2006): 1362-1370.
3. WILLE K AND NAAMAN A E, Fracture energy of UHPFRC under direct tensile loading, In FraMCoS-7 International Conference, Jeju, Korea, 2010.
4. KIM, HEE S, WON J C, JEONG R C, YOUNG J K AND HYEJIN Y, An Experimental Study on the Behavior of Shear Keys According to the Curing Time of UHPC, Engineering 7, no. 04 (2015): 212.
5. RICHARD P, CHEYREZY M, MARET V, FROUIN L, DUGAT J, ROUX N AND BERNIER G, Les bétons de poudres réactives (BPR) à ultra haute résistance (200 à 800 MPa), In Annales de l'institut technique du bâtiment et des travaux publics, no. 532 (B-320), 1995.
6. REDA M M, SHRIVE N G AND GILLOTT J E, Microstructural investigation of innovative UHPC, Cement and Concrete Research 29, no. 3 (1999): 323-329.
7. WILLE K, DONG J K AND NAAMAN A, Strain-hardening UHP-FRC with low fiber contents, Materials and structures 44, no. 3 (2011): 583-598.
8. PREM P P, BHARATHKUMAR B H, AND NAGESH R I, Mechanical properties of ultra-high performance concrete, World academy of Science, Engineering and Technology 68 (2012): 1969-1978.
9. WILLE K, NAAMAN A E, SHERIF E T AND PARRA-MONTESINOS G J, Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing, Materials and structures 45, no. 3 (2012): 309-324.
10. COURTIAL M, M-N. DE NOIRFONTAINE, FREDERIC D, MARCEL S F, MOUNANGA P, KHALID C AND ABDELHAFID K, Effect of polycarboxylate and crushed quartz in UHPC: microstructural investigation, Construction and Building Materials 44 (2013): 699-705.
11. YANG S L, MILLARD S G, SOUTSOS M N, BARNETT S J AND THANH T L, Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC), Construction and Building Materials 23, no. 6(2009): 2291-2298.
12. SCHEYDT J C AND MÜLLER H S, Microstructure of ultra-high performance concrete (UHPC) and its impact on durability, In Proceedings of the 3rd International

Symposium on UHPC and Nanotechnology for High Performance Construction Materials, Kassel, Germany, pp. 349-356. 2012.

13. BAYARD O AND PLE O, Fracture mechanics of reactive powder concrete: material modelling and experimental investigations, Engineering Fracture Mechanics 70, no. 7 (2003): 839-851.

14. PAPADAKIS V G, PEDERSEN E J AND LINDGREEN H, An AFM-SEM investigation of the effect of silica fume and fly ash on cement paste microstructure, Journal of Materials Science34, no. 4 (1999): 683-690.