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Development Of Ultra High Performance Concrete Incorporating Blend Of Slag And Silica Fume As Cement Replacement

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Abstract: **Ultra high performance concrete (UHPC), even though a construction material with excellent performance is deemed to be unsustainable as per many opinions owing to its high cement content which raises the cost and pollution. This paper looks into the possibility of development of UHPC with high amount of cement replacement (around 70%) by two supplementary cementitous materials, slag and silica fume. The combination has been found to raise the early strength and late strength by approximately 10% and 17% compared to a control mix as opposed to low early strength development when only slag is used and lower late strength (than the blended mix) when only silica fume is incorporated. The scope of this paper also covers the effect of curing method on strength development of the proposed UHPC mix and concludes that choice of curing medium and method highly influence strength development. It also addresses the optimal fineness combination of slag and silica fume which contributes highest strength. The promising point is that for a fixed water-binder ratio, even with such low cement content, concrete can show appreciable strength improvement when blended with two admixtures given that proper curing method and fineness of admixtures are properly chosen.**

Keyword: **Ultrahigh performance concrete, Silica fume, GGBS, Mineral admixtures, Fineness.**

I. INTRODUCTION

Ultra high performance concrete (UHPC), as new cement based material, has been rapidly developed and utilized especially in bridges and some other special structures recently [1] , [2], [3].Mineral admixtures which finely divided siliceous materials are added to concrete in relatively large amounts, generally in the range 20 to 70 percent by mass of the total cementitious material . By investigating the mechanical properties of UHPC with cement replacement by mineral admixtures under different curing conditions, Yazici *et al* [4], [5], [6], [7]. found that mineral admixtures can substitute a part of the cement by still maintaining or improving the properties with reduced cost. From the aspect of development of UHPC over past few years, use of mineral admixtures especially ground granulated blast furnace slag (GGBS) has been increasing. Such incorporation reduces the cost of production and contributes to environmental benefits. GGBS improves workability, reduce the heat of hydration and imparts excellent resistance to alkali silica reaction and sulphate attack. On the other hand, strength development of GGBS concrete is greatly reduced as GGBS hydrates very slowly. Therefore, to enhance early strength development with similar improvement in late strength as well, silica fume (SF) was chosen as the second admixture to blend with GGBS for the study. Silicafume is a by-product of the manufacture of silicon metal or ferro-silicon alloys and is a very fine powder of specific surface area ranging between 10,000- 30,000 m^2/kg. However, there are a few challenges that could be encountered while using it in concrete: the quality of silica fume is hard to control and in some countries (for example, Singapore) the yield is not as high to maintain the growing demands of concrete industry. Nevertheless, addition of even small percentage of SF can enhance the performance of UHPC which makes it use with superplasticizer a usual way to develop UHPC [8].

Many authors claim that SF brings improvement to the strength between matrix and aggregates in concrete [9-13]. However, researchers also have varying opinions about the definition of optimal content of SF which enables to obtain highest strength. From some past works [14], [15], the replacement is around 15% to be optimal whereas to some researchers [16],[17] increase in compressive strength have been witnessed at even 20% to 40% cement replacement by SF. Based on past works, study and research needs, this paper has been aimed at researching on the amount of SF than can be used alongside high replacement percentage of GGBS (around 60%) to develop UHPC with strength enhancement. Also, fineness of SF and GGBS play important role in the strength development process and thus study has been conducted with variable fineness combination of the two. Curing is an important factor when it comes to reaction of

pozzolans. Curing method and medium highly influences strength and therefore a brief study on the effect of curing has been performed taking into consideration the actual curing practices followed at any construction site.

II. RESEARCH SIGNIFICANCE

Usually UHPC mix mainly constitutes high percentage of cement, low amount of water and mineral admixture. In fact the water-binder ratio of UHPC ranges from 0.10-0.25 by weight. According to past researches, the degree of hydration in UHPC has been estimated in the range of 31 to 60% [18]. The anhydrous cores of cement particles then work as micro-aggregates which actually mean that the unhydrated particles act as filler materials only. This strongly suggests the use of mineral microfillers to replace expensive cement still maintaining the workability of the mix. Thus silica fume owing to high specific surface area was chosen with the logic that the unhydrated cement particles together with finer particles of pozzolanic mineral provide an enhanced packing effect and increase the strength and durability of concrete. Effectively, smaller particles of silica fume promote large Van Der Waals attraction improving the bonding of particles. GGBS, on the other hand, owing to high calcium oxide content contribute to calcium silicate hydrate formation thus largely contributing to strength development. For both the mineral admixtures, particle fineness would play a major role in deciding the rate of reaction and strength development. Therefore this paper also aims at studying the strength development for different fineness of the slag and silicafume particles. UHPC in last one decade has found wide application in bridge pier constructions. Such application as these demands fast strength development. There also lies the significance of using a very fine filler material that would help achieve high durability and mechanical performance. Slag is slow in gaining strength and therefore in early phase strength and durability may well be controlled by fine silica fume. From the experimental results, it is possible to suggest desirable combinations between the mineral admixtures in the mix that could be used in challenging and demanding construction areas.

III. EXPERIMENTAL PROGRAM

A. Properties of materials:

The GGBS used in the research comprises of three different specific surface area values as determined by Blaine method – 403 m^2/kg (FG1), 605 m^2/kg (FG2) and 797 m^2/kg (FG3). These three samples of GGBS were used along with silicafume of three fineness regime – 19,000 m^2/kg (FS1), 25,000 m^2/kg (FS2) and 30,000 m^2/kg (FS3). All the samples were produced from one source thus ensuring same composition. The cement used was ordinary Portland cement of grade 52.5 N and the sand was locally available sand with fineness modulus of 2.71. The properties of GGBS, OPC and silica fume are shown in the following tables (Table I and II).

TABLE I: COMPOSITION OF OPC

Type of cement	Density (g/cc)	Setting time, Vicat needle		MgO (%)	SO_3 (%)	Loss on ignition (%)	Chloride (%)	Sodium Oxide equivalent (%)
		Initial (mins)	Final (mins)					
CEM 1 52.5N	3.2	145	230	1.7	2.2	1.3	0.005	0.59

TABLE II: COMPOSITION OF SLAG AND SILICA FUME

Properties and elemental analysis	Silica Fume	GGBS
Fineness (m2/kg)	19,000(FS1)/25,000(FS2)/30,000(FS3)	403(FG1)/605(FG2)/797(FG3)
Bulk density (kg/m3)	1450	1200
Specific gravity	2.2	2.9
Silicon (%)	96.5	38
Aluminium (%)	1.8	11

Iron (%)	0.7	1
Calcium (%)	0.05	35
Magnesium (%)	0.04	12
Sodium (%)	0.2	0.5
Potassium(%)	0.23	0.4
Sulphate(%)	0.2	1.2
Chloride(%)	0.26	0.9

In modern concrete practice, to make UHPC it is practically impossible to achieve adequate workability without superplasticizer (SP) owing to very low water-binder ratio [19]. The workability of fresh concrete depends on the type of superplasticizer used. However, cement composition, variability in mix and mixing process and equipment play an important role, however it is well established that average molecular mass of superplasticizer is of prime importance for reducing water in concrete mix [20] The chemical nature of superplasticizer whether naphthalene based or melamine based , can also have effect on rheological behaviour of concrete mix. Hpwever, no definite trend could be identified from slump loss, retardation or air entrainment. So, there are some indications that some intrinsic properties of superplasticizer have effect on rheology.

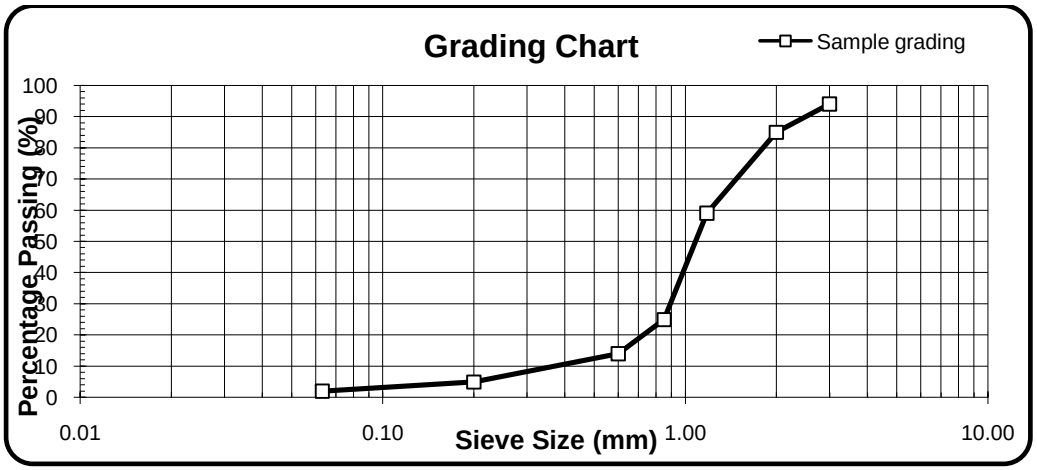
In this study, polycarboxylate based superplasticizer with 30% solid mass has been used to avoid particle aggregation and improve the rheological behaviour of the fresh mix. Because the side chain lengths have different effect on the particle dispersion [21] by comparing 5 kinds of SP, the one with the best effect was selected.

B. Mixture proportions:

B.1. Phase 1 testing at constant fineness:

The proportioning of mixture had to be selected carefully based on practical experiences and past researches. Samples were cast incorporating single mineral admixture at a time (GGBS and silica fume) to determine the optimum level of replacement of both separately which was useful to determine the percentage of replacement when both were incorporated together. For GGBS replacement, percentages varying from 40 to 80 (40, 60 and 80) were tried at three different water cement ratio. For first phase of testing, the fineness was kept constant at 605 m^2/kg. Silica fume replacement percentage was varied from 10 to 20 (10, 15 and 20) while fineness used was 25000m^2/kg. Same water-cement ratios as GGBS were used.

Cement used was CEM I (grade 52.5N as per SS EN 197-1:2008 specification) and normal sand available locally was used. The particle size distribution for the sand used is shown below.



Graph. 1. Particle size distribution of sand used

Sand to binder ratio (S/B) was fixed at 70% based on previous trial experiments done by the author. For each mix with admixture a control mix was cast at each water cement ratio with the mix proportion of cement: sand: water:: 1:0.7: (0.18-0.22 varied) to compare the strength development of UHPC with mineral admixtures There was no remarkable difference between workability of the control mix and the mixes with admixtures. A summary of the mix design is provided below. Superplasticizer as described before was used which was inevitable at low water cement ratio to make up for the water loss and produce flowable and workable concrete. However, the percentage by weight of superplasticizer for mixes was different owing to different binder and water content.

TABLE III: MIX PROPORTIONS AT CONSTANT FINENESS

Mix Name	Mix Proportion (Cement: GGBS:SF: Sand)	Water – binder ratios (W/B)	Percentage (%) of Superplasticizer (SP)	Flow range (mm)
FOR ONLY GGBS REPLACEMENT				
G1	0.60:40:0: 0.7	0.18/0.20/0.22	1.95/1.92/1.90	300-320
G2	0.40:0.60: 0 :0.7	0.18/0.20/0.22	1.91/1.88/1.84	315-330
G3	0.20:0.80 : 0: 0.7	0.18/0.20/0.22	1.87/1.86/1.83	320-340
MC1(control)	1: 0: 0: 0.7	0.18/0.20/0.22	2.05/2.04/2.00	270-290
FOR ONLY SILICA FUME (SF) REPLACEMENT				
S1	0.90:0:10:0.7	0.18/0.20/0.22	1.98/1.96/1.95	310-320
S2	0.85:0:0.15:0.7	0.18/0.20/0.22	1.94/1.93/1.90	315-330
S3	0.80:0:0.20 :0.7	0.18/0.20/0.22	1.93/1.88/1.87	325-345
MC1(control)	1: 0: 0: 0.7	0.18/0.20/0.22	2.05/2.04/2.00	270-290
FOR BLEND OF GGBS AND SILICA FUME				
B1	0.50: 0.40: 0.10 : 0.7	0.20	2.10	345
B2	0.30: 0.60:0.10: 0.7	0.20	2.03	358
B3	0.25:0.60:0.15:0.7	0.20	2.20	360
B4	0.20: 0.60: 0.20: 0.7	0.20	2.22	358

B.2. Phase 2 testing with variable fineness

To study the effect of fineness of GGBS and silica fume on strength development and workability different mixes were produced with varying fineness which was determined from the earlier test results. Testing every possible blend would be time consuming and therefore the author had to depend on the phase 1 result to arrive at the specific mixes to be tried. The mix proportions tried with variable fineness of GGBS and silica fume are tabulated below.

TABLE III: MIX PROPORTIONS WITH VARIABLE FINENESS

Mix Name	Mix Proportion (Cement: GGBS:SF: Sand)	Water – binder ratios (W/B)	Percentage (%) of Superplasticizer (SP)	Flow (mm)
FOR BLEND OF GGBS AND SILICA FUME WITH VARIABLE FINENESS				
B3	**0.25:0.60:0.15:0.7**	**0.20**		
FG1+FS1			1.92	340
FG3+FS3			2.25	362

FG1+FS3		1.96	345
FG3+FS1		1.94	342
FG2+FS3		2.02	365
FG3+FS2		2.00	355

B.3. Phase 3 testing for effect of curing methods

Analyzing the finding of the experiment on strength development of blended concrete with silica fume and slag , mixture B3 (fineness: FG1 and FS3) primarily because this mixture has been found to show high performance in terms of both compressive and flexural strength. Temperature and curing condition play very important roles in slag hydration and pozzolanic reaction and therefore doing a study on curing method of the developed UHPC was necessary. Also the control mix was subjected to same curing methods to do a comparison. For studying the effect of curing, three methods of curing were adopted as shown in the following table. Heat curing was not tried as one of the curing methods because for field application at original construction site except precast elements, this curing method is not a viable option.

TABLE IV: CURING METHODS ADOPTED FOR DEVELOPED UHPC

Mixture	Curing method	Description
B2 (FG2 + FS3)	Sealed	Samples were sealed using plastic foil and kept in the curing room at 27 degrees and RH= 95%.
	Air curing	Samples were left in open air at room temperature (27 degrees)
	Moist Curing	Samples were covered, kept in the curing room for 24 hours and transferred to water curing tank after 24 hours.

C. Mixing, curing and testing method:

For preparation of materials after weighing a 20L Hobert mixer was used. Mix designs as shown in Table III were followed. Mixtures were cast into 50x50x50 mm cube moulds for compression test and 50x50x250 mm prism for flexural testing. The mixtures after being cast were vibrated using a vibratory table top with frequency of 2500 cycles/min. To test the effect of curing condition on strength development, two sets of samples were transferred to a fog room where temperature was maintained at 22±2 degrees and RH> 95%. Another set of samples were covered and kept intact in the casting area. Out of the two sets stored in fog room one set was subjected to water curing upon demolding after 24 hours while the other set was kept there until day of testing. The mixing procedure is shown in the form of a flowchart below.

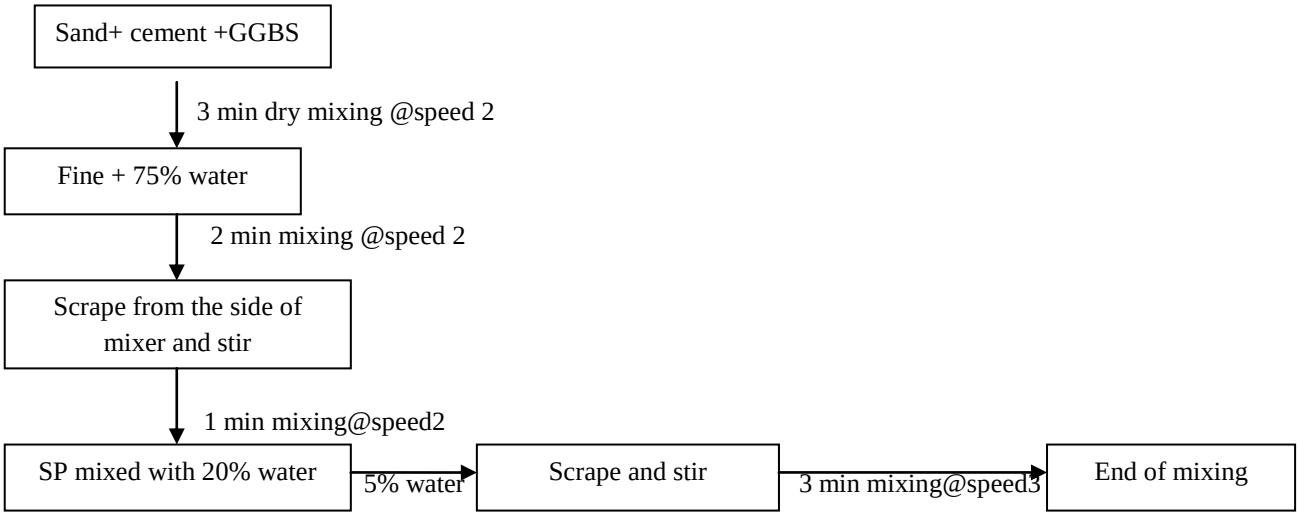


Fig. 1. Flowchart showing mixing steps for UHPC [22]

It is normally accepted that higher load rates will result in higher compression strength and modulus of elasticity results. For this reason, using the ASTM C39 load rate of 0.24 ±0.10 MPa/s (35 ±15 psi/s) is recommended for any standardized compression testing of concrete. However, the high strength results expected from UHPC mean that a single compression test on a concrete cylinder could take 15 to 20 minutes or more [23]. This objectionably long time led us to alter the loading rate. So, an altered loading rate of 1MPa/ s was used which could complete the testing in 3-5 mins depending on the strength. For flexural strength, Universal testing machine (UTM) was used with loading rate set at 0.5 mm/min and three point bending method adopted with distance between end supports 100 mm.

IV. RESULTS AND ANALYSIS

A) Influence of blended mineral admixtures on strength development:

The compressive strength test results for GGBS (only) mix has been produced in Table IV. In this case all the samples were moist cured by submerging in water after 24 hours. As expected, there was a drop in early compressive and flexural strength with higher percentage of slag replacement and an increase in late strength but for slag replacement of 80% proved to be an opposite case. The strengths did not increase with such higher replacement percentage but there was a slight reduction in 28 d strength for G3 at all water cement ratios. The beneficial effect of using GGBS replacement lies in the fact that it contributes low density calcium silicate hydrate (C-S-H) gel than OPC alone and the gel fills the capillary pores [24]. At 80% replacement there is no appreciable strength increase most probably owing to the fact that all the cement has been used up in the system and slag is acting only as filler material. Water-binder ratio (W/B) also plays an important role in strength development. For the mixes used, W/B of 0.2 was found to be optimal beyond which there was slight decrease in strength. This is possibly due to high cement replacement percentage which lowered the water demand. The percentage of superplasticizer needed to achieve the workability did not reduce drastically compared to other mixes as a result of which there was excess of water in the system which brought about reduction in strength.

TABLE V: STRENGTH RESULTS FOR ONLY GGBS MIX

MIX NAME		G1	G2	G3	MC1
WATER - CEMENT RATIO	0.18				
	% of GGBS replacement	40	60	80	0
	Compressive strength (MPa)				
	7 d	117.5	114	104	122
	28 d	140	142	138	135
	90 d	157	165	150	145
	Flexural Strength (MPa)				
	28 d	13.2	13.8	13	14
	90 d	15.6	16	15.5	15
WATER - CEMENT RATIO	0.20				
	% of GGBS replacement	40	60	80	0
	Compressive strength (MPa)				
	7 d	118.5	116	107	120
	28 d	148	153	142	138
	90 d	167	170	160	152
	Flexural Strength (MPa)				
	28 d	15.8	16.7	15.4	14.5
	90 d	22	22	19	16

WATER - CEMENT RATIO	0.22				
	% of GGBS replacement	40	60	80	0
	Compressive strength (MPa)				
	7 d	120	115.5	107	120
	28 d	143.2	146	146	131
	90 d	157	160	156	145
	Flexural Strength (MPa)				
	28 d	13.8	14.5	13.4	14
	90 d	16.8	17	15.5	16.9

As per the experimental program parallel mixes with silica fume replacement were tried to put an effort in finding out the optimum level of replacement which could aid in determining the blended mix design with both slag and silica fume. Table V and Graph 5 to 7 well explain the strength development due to silica fume addition and the comparison of strength development compared to the control mix at different timelines.

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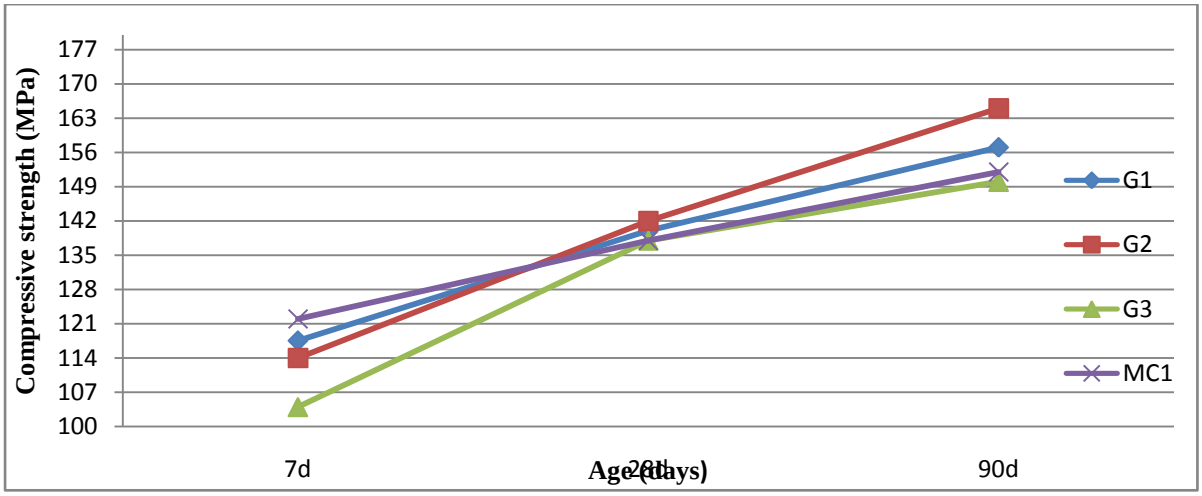
TABLE VI: STRENGTH RESULTS FOR ONLY SILICA FUME MIX

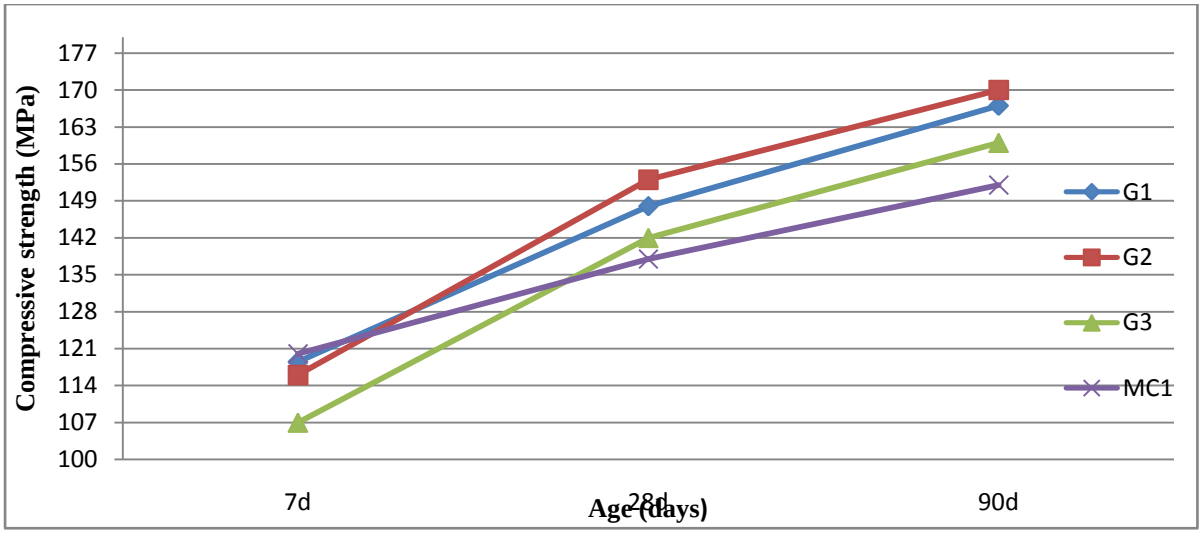
MIX NAME		**S1**	**S2**	**S3**
WATER - CEMENT RATIO	0.18			
	% of SF replacement	10	15	20
	Compressive strength(MPa)			
	7 d	136	137	137.5
	28 d	150	155	159
	90 d	164	172	177
	Flexural Strength (MPa)			
	28 d	14.2	15	16
	90 d	19.2	20	22
WATER - CEMENT RATIO	0.20			
	% of SF replacement	10	15	20
	Compressive strength (MPa)			
	7 d	136.7	138	144
	28 d	154	159	162
	90 d	167	175	180
	Flexural Strength (MPa)			
	28 d	15.2	17	18.5
	90 d	19.8	20	23
WATER – CEMENT RATIO	0.22			
	% of SF replacement	10	15	20
	Compressive strength (MPa)			
	7 d	136.7	137	138

	28 d	147	149	153
	90 d	156	163	167
	Flexural Strength (MPa)			
	28 d	14.9	16	18
	90 d	18	19.6	22

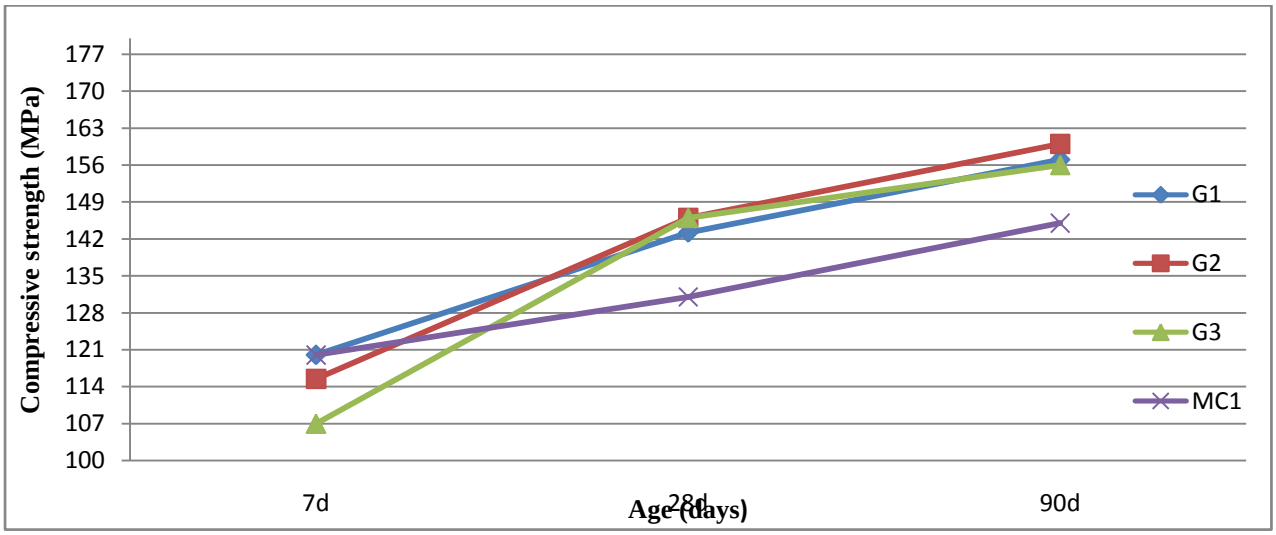
Compressive and flexural strength of the samples increased with increased replacement of silica fume but very much like in the case of GGBS, the strengths decreased with W/B above 0.2 although on average strength development with 20% silica fume replacement was higher than slag replacement of 60% due to the fact that silica fume acts as a better filler material than slag due to its smaller particle size (and high specific area) and simultaneously forming more stable C-S-H than weak calcium hydroxide (C-H). The graphs depicts the strength development while GGBS and silica fume are used separately from which the author arrived at the blended mixes as listed in Table. III.



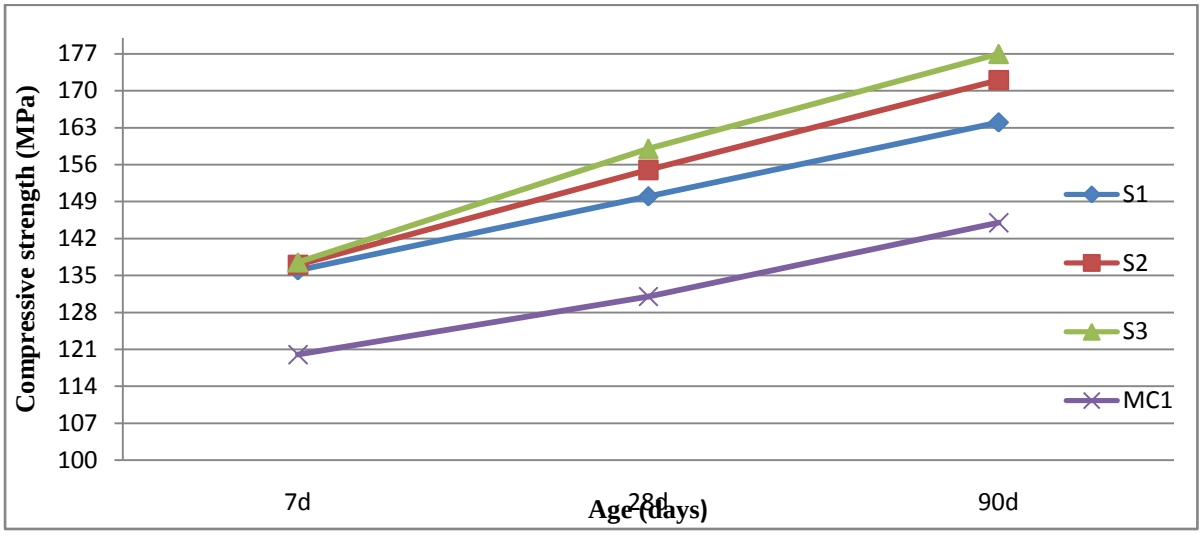
Graph. 2. Strength development of three GGBS mixes at W/B = 0.18



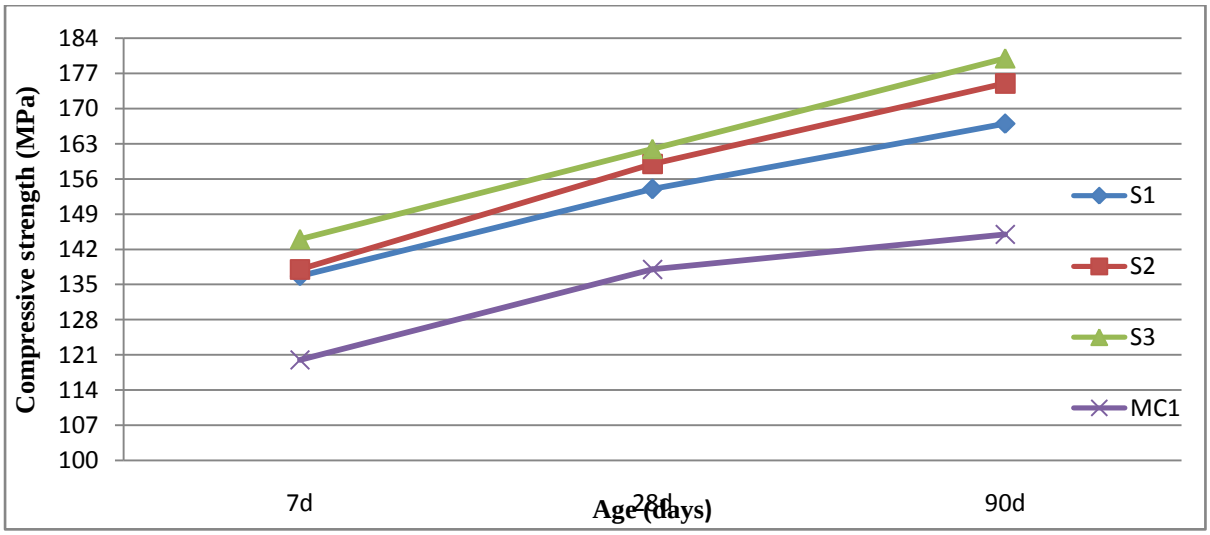
Graph 3. Strength development of three GGBS mixes at W/B = 0.20



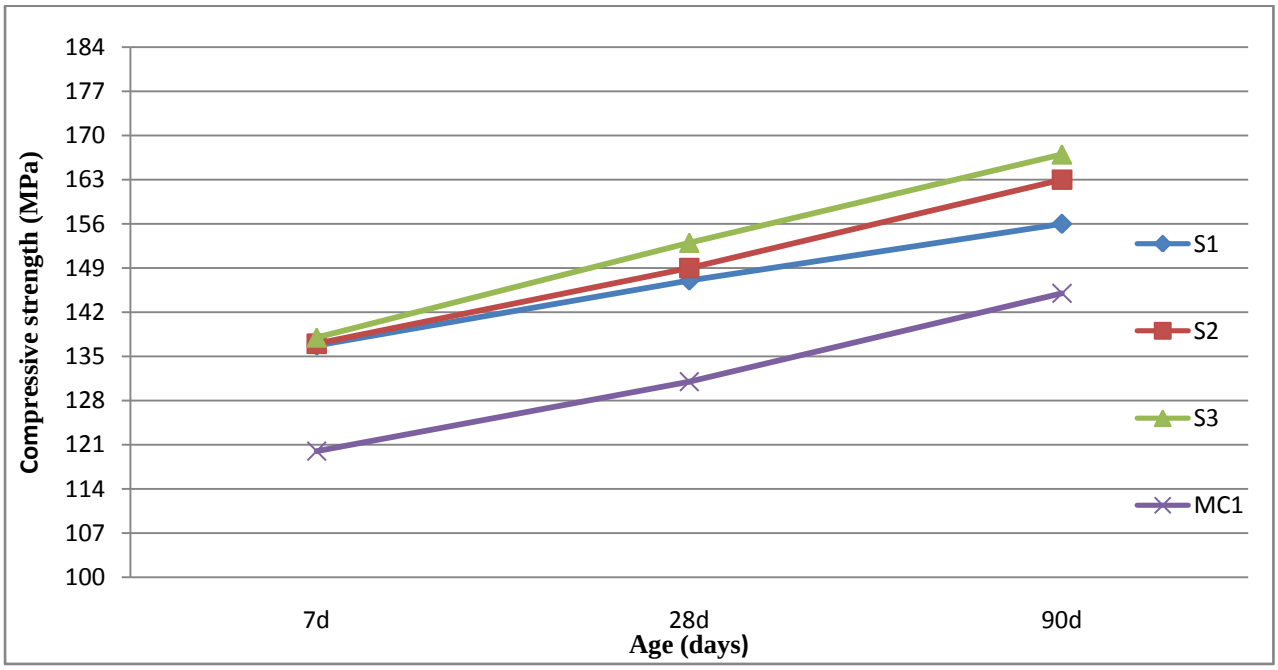
Graph 4. Strength development of three GGBS mixes at W/B = 0.22



Graph 5. Strength development of three Silica fume mixes at W/B = 0.18



Graph 6. Strength development of three Silica fume mixes at W/B = 0.20



Graph. 7. Strength development of three Silica fume mixes at W/B = 0.22

Upon analyzing all the graphs with GGBS and silica fume separately, it is clearly observed that the best strength performances are delivered by 60% GGBS replacement at W/B = 0.20 and 20% SF replacement at the same W/B. As the GGBS replacement percentage increases beyond 60% strength tends to go down as discussed before, therefore the author preferred to explore the experimental outcome with GGBS replacement of 40% along with silica fume as it could be observed that the optimal replacement percentage would be around 40 to 60% for the proposed mix. Also, in case of silica fume, late strength at 15% replacement was quite close to 20% and thus in the blended mix of GGBS and SF, both 15% and 20% replacement were tried. Based on these observations, the mix designs (B1, B2, B3 and B4) as provided in Table III were arrived at.

Same mixing procedure was followed (as shown in the flowchart, Fig. 1) for the blended mix and flow test following the methods stated in BS EN 12350: Part 8 was performed in similar ways as done for other samples. Vibration is not required as the concrete mix in the study was adequately flowable. Flow values are tabulated in Table. III. Following the same testing methods as before, compressive strength tests and flexural tests were performed and the results reveal a considerable improvement in both early and late strength development along with some results that are somewhat deviant from expected and worth analyzing. Although from Table.VI and Fig. 6 , it is clearly observed that 15% and 20% silica fume replacement contribute to higher strength than only 10% replacement, the blended mixes (along with 60% GGBS) especially B2, B3 and B4 offer different results. The experimental results suggest that blended sample B2 (with 10% SF) display higher strength compared to B3 and B4 where SF replacements are 15% and 20%, which has been explained later. Although B3 shows strengths quite close to B2 there was even little decrease in strength for B4. B3 and B4 mixes were sticky probably due to high amount of fines from higher silica fume replacement and this fact is also supported by the flow test.

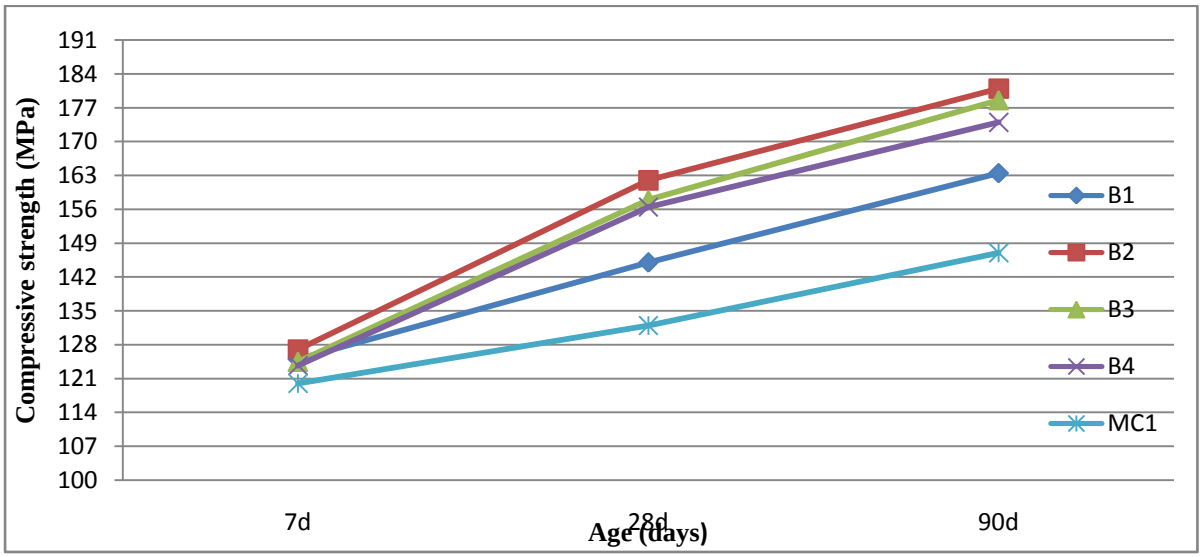
With nearly or more admixture dosage compared to other blends, B3 and B4 shows almost same flow value which might have affected the strengths as well. From another perspective, this might possible be due to one or more of the following reason:

a) Too low water- binder ratio because of which the hydration process was complete with satisfactory development of early strength and dense pore structure which obstructed any curing water to penetrate into the concrete thus reducing hydration and strength development at later stage. SF acted only as a filler material after there was no more secondary pozzolanic reaction.

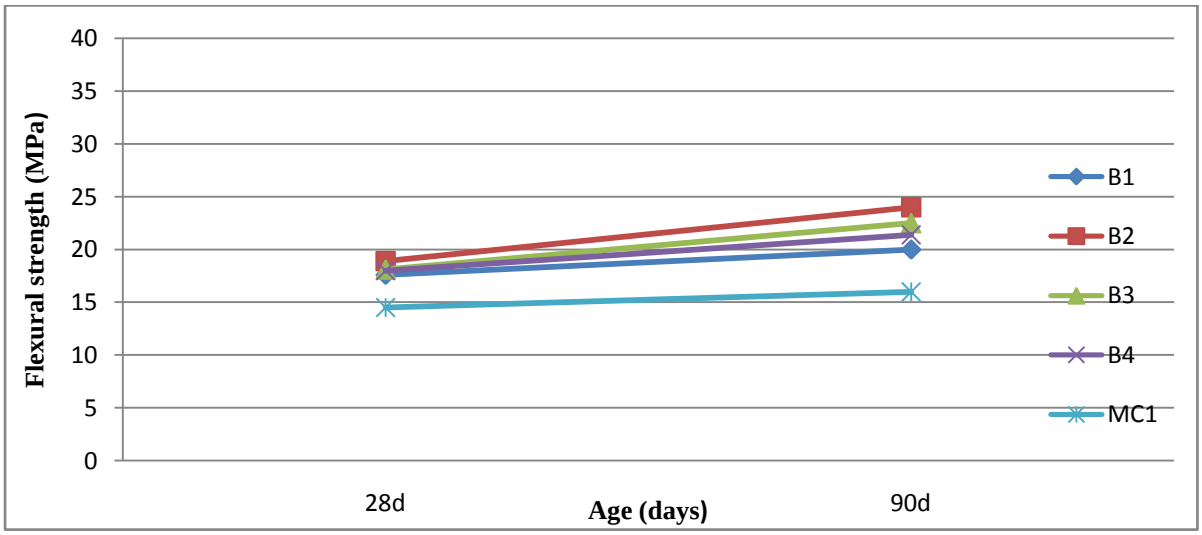
b) Considerable portion of SF was not properly dispersed in the mix and thus it might be essential to look into the mixing procedure when such high SF content is used along with GGBS.

TABLE VII: COMPRESSIVE AND FLEXURAL STRENGTH AS TESTED FOR BLENDED MIX OF GGBS AND SF

WATER - CEMENT RATIO		0.20		
Mixes	**B1**	**B2**	**B3**	**B4**
Compressive strength (MPa)				
7d	125	127	124.50	123.7
28d	145	162	158	156.50
90d	163.5	181	178.60	174
Flexural strength (MPa)				
28d	17.6	18.9	18.1	18
90d	20	24	22.5	21.4



Graph 8. Compressive strength Development of blended mix at W/B=0.20



Graph.9. Flexural strength Development of blended mix at W/B=0.20

B) Influence of fineness on strength development of UHPC

Mix B2 was selected as the mix to perform the tests to study the influence of fineness on strength development of UHPC primarily because at W/B = 0.20, this mix had been found the yield higher strength compared to other three. Six mixes were prepared with different fineness of GGBS and SF as listed in Table VIII. Each mix was tested at 7, 28, 56 and 90 days for compressive strength and 28, 56 and 90 d for flexural strength. Same test settings were followed like what has been done for previous samples (as described in section II).

The experimental results show that for short term hydration (7d), almost all the samples except FG2+FS3 show close strength development pattern confirming that fineness does only slightly affect short term strength. Only FG2 +FS3 shows comparatively high early strength (almost 8% higher than average of early strength of other 5 samples). This is attributable to the higher compactness achieved due to higher specific surface area. For long term behaviour (28d and above), the effect of fineness of strength development becomes more prominent and is maintained over time. Also, for the last four mixes in Table VIII increasing the fineness of GGBS keeping the fineness of SF lower does increase the strength but the increase is more when fineness of SF is increased even while the GGBS fineness is set comparatively lower. Thus, experimental results suggest that strength development is more sensitive to fineness of SF than GGBS although finer GGBS aid in higher raise in strength. The increase in strength with specific surface area is the result of two different physical phenomenon – the effect of particle size distribution and the second being heterogeneous nucleation [25]. When there is a blend of SF and GGBS in the sample both the mechanisms are believed to take place. The filler effect actually refers to the alteration of initial porosity which can in turn be related to density of the mix. SF being a very fine particle offers large packing density thus enhancing the filler effect. Heterogeneous nucleation is probably the effect associated with both fineness and quantity of mineral admixtures used and leads to a chemical activation of cement hydration. In other words, it refers to the nucleation of hydrates on mineral particles which helps in catalyzing the nucleation and reduces the energy barrier. As already found out [25], it depends on

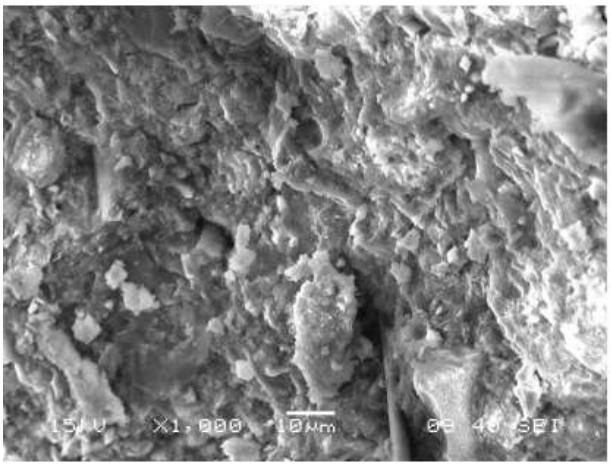
a) the fineness of admixture particles , since finer particles favour nucleation.

b) the amount of mineral admixture used since the probability of nucleation sites being closer to cement particles increase with replacement amount.

c) the affinity of mineral to cement hydrate although it depends on the mineral used.

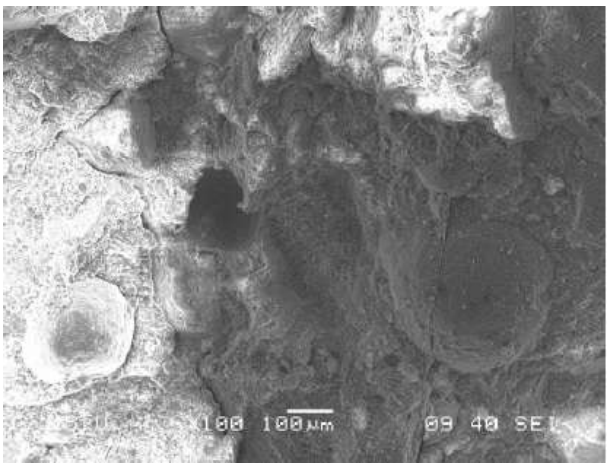
Silica fume when applied in optimal amount and quantity gets well dispersed and thus contributes to strength both by filling and nucleation effect whereas nucleation effect is more prominent in case of GGBS when used in high replacement quantity with more fineness. It explains in the blended sample FG2+FS3 we are able to achieve maximum strength values due to joint nucleation and filler effect.

However, test result and subsequent analysis present the fact that strength increase with increase in fineness is valid only up to a certain level of material fineness and does not maintain the increasing trend with increase of fineness beyond that point. When highest fineness of both GGBS and silica fume were used in the mix, the strength development showed a different trend. Although the early strength was satisfactory, decrease in late strength has been observed. To delve deeper into investigating the cause, SEM analysis was performed for mix FG2+FS3 and FG3+FS3 for comparison. The analysis images are shown below.



2 (a)

Fig. 2(a) SEM image for mix FG2+FS3



2 (b)

Fig. 2(b) SEM image for mix FG3+FS3

For FG2+FS3 the structure as shown in the image is very compact and dense with voids almost absent in the matrix. Very good bonding of the gel is observed. On the other hand, for the mix FG3+FS3 as shown in Fig. 2(b), voids could be

observed in the matrix with bond failure between gel matrix and mineral admixtures. This is believed to be due to intense cohesiveness developed from high fineness of both the admixtures (GGBS and SF) which prevented it from bonding properly with the matrix. Therefore decrease in strength could be believed to have resulted from too many voids and interfacial bond failure within the matrix.

TABLE VIII: IMPACT OF FINENESS ON STRENGTH DEVELOPMENT OF THE UHPC MIX

MIX: B2		W/B = 0.20	
Mix	**Age (days)**	**Compressive strength (MPa)**	**Flexural Strength (MPa)**
FG1+FS1	7	117.50	_
	28	136.70	17.20
	56	153.50	19.50
	90	165	21
FG3+FS3	7	125	_
	28	138	19
	56	152.50	19.60
	90	163	20.10
FG1+FS3	7	124.80	_
	28	145.40	18.10
	56	158	19.90
	90	168	21.50
FG3+FS1	7	119	_
	28	140	17
	56	156.50	18.20
	90	169	20
FG2+FS3	7	132	_
	28	168.50	19.50
	56	179.40	23.20
	90	190	25
FG3+FS2	7	124.80	_
	28	156	18.90
	56	167.60	20
	90	180	22

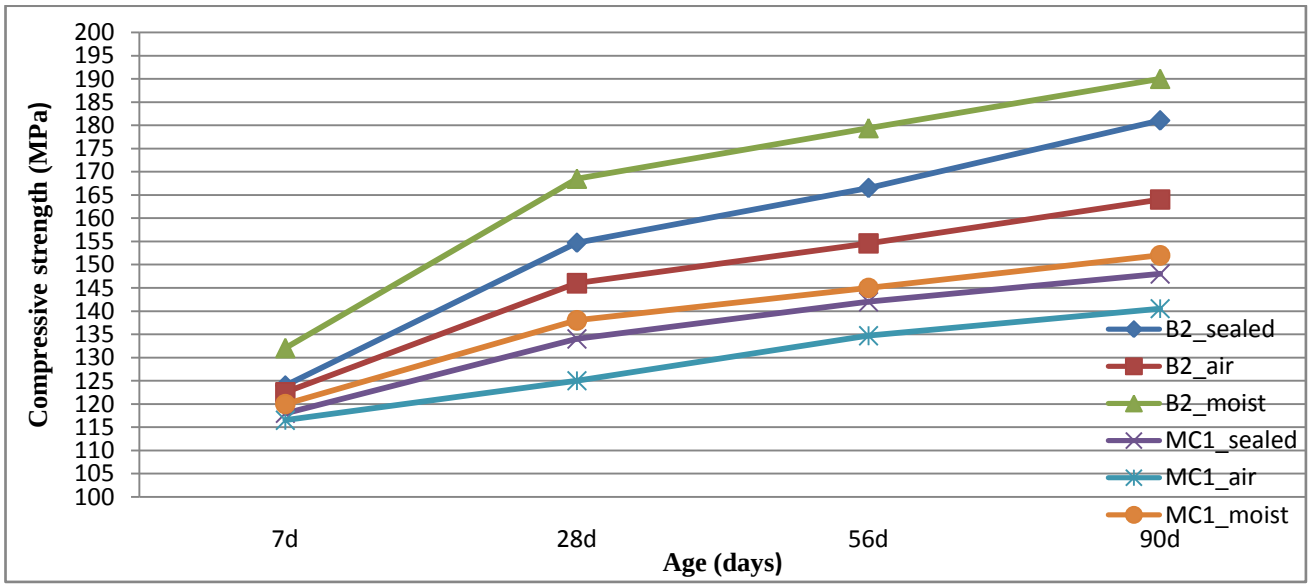
C) Influence of curing method on strength development of UHPC mix (blend B2)

The compressive strength test results for three different curing methods (as usually adopted in construction practice) are shown in Table. VIII. The strength comparison for the same sample (B2, fineness: FG2+ FS3) has been shown in the graph labelled Fig. 9. According to the table and the comparison graph, it becomes evident that choice of curing method does not have significant bearing on early strength (7d strength) when the mixture proportion and temperature and humidity are kept identical. This is primarily because water necessary for continuing the hydration reaction still exists in the specimen for 7 days. Once the water in the system is used up, it becomes a hindrance to the hydration reaction and thus affects the strength development. The sample B2 contains relatively high percentage of slag replacement and since

slag hydrates over longer time compared to cement (which explains its slow strength development), presence of water becomes crucial for such slag content. This explains why the difference in strength becomes higher between samples subjected to separate curing methods with passage of time. The graph and the table below reveals that the late strength development for sealed curing is slightly lower than moist cured concrete whereas the strength for air cured concrete is much lower than moist cured ones; the reason can be attributed to the significant effect the curing method has on strength development beyond 7 days. The same holds valid for flexural strength development too. The relatively less difference in strength between sealed and moist cured specimens could be probably attributed to the fact that due to sealing the water is retained in the system for longer time while for only air curing a part of water dries up. Another fact for moist curing that can be taken note of in this context is the strength development slope is higher at early ages than later ages. For example, the increase in strength from 7d to 28 d is higher than 28 d to 56 d. For UHPC , the pore structure is much dense compared to normal concrete and therefore, even though there is supply of water from outside it cannot penetrate fully into the concrete owing to high density of pores thus slowing down the strength development at later ages. To summarize, based on the brief study on effect of curing on strength development, it can be demonstrated that air curing of UHPC concrete with mineral admixtures is not recommended and to achieve higher late strength some supply of water is necessary which, in fact, could be achieved at construction sites by spraying and wetting the UHPC members in the structure.

TABLE IX: COMPRESSIVE AND FLEXURAL STRENGTH AS TESTED FOR DIFFERENT CURING METHODS

Mix name	Curing Method	Age (days)	Compressive strength (MPa)	Flexural Strength (MPa)
B2 (fineness: FG2 and FS3)	Sealed Curing	7	124	_
		28	154.70	18.70
		56	166.50	22.90
		90	181	24
	Air Curing	7	122.50	_
		28	146	18.50
		56	154.60	20.60
		90	164	21.50
	Moist Curing	7	132	_
		28	168.50	19.50
		56	179.40	23.20
		90	190	25
MC 1 (Control mix)	Sealed Curing	7	118	_
		28	134	14.50
		56	142	14.90
		90	148	16
	Air Curing	7	116.5	_
		28	125	14
		56	134.70	14.70
		90	140.50	15
	Moist Curing	7	120	_
		28	138	14.50
		56	145	15
		90	152	16



Graph.10. Compressive strength comparison for different curing methods.

A summary table (Table. X) is prepared after all the experimental data are collected and tabulated in course of the study. The maximum strengths for each mix were picked and the maximum strength increase over the control mix at 28d and 90d (considering late strength) was enumerated. For blended mix B2 (FG2+FS3), further more calculation was done to present the percentage strength increase over their corresponding GGBS and SF sample yielding maximum strength. For example, GGBS and SF replacement in B2 were 60% and 10% respectively and therefore strength increase over mix G2 and S3 were calculated. The table shows considerable increase in compressive strength and flexural strength over the control mix. Silica fume and high GGBS replacement is known to highly contribute to late strength development but the blended mix displays compressive strength increase over the corresponding SF and GGBS sample by over 10% and 4% respectively and even better increase in flexural strength of over 13% and 5% respectively.

TABLE X: SUMMARY COMPARISON OF MAXIMUM STRENGTH INCREASE FOR INDIVIDUAL ADMIXTURE MIX AND BLENDED ADMIXTURE MIX

Percentage increase in compressive strength						
Mix	**Percentage increase over control mix (%)**		**Percentage increase over corresponding GGBS (only) mix (%)**		**Percentage increase over corresponding SF (only) mix (%)**	
	28d	**90d**	**28d**	**90d**	**28d**	**90d**
G2	10.87	11.84	_		_	
S3	17.89	18.42	_		_	
B2(FG2+FS3)	22.10	25	10.13	11.76	4.01	5.56
Percentage increase in flexural strength						
	28d	**90d**	**28d**	**90d**	**28d**	**90d**
G2	15.17	37.50	_		_	
S3	27.60	43.75	_		_	
B2(FG2+FS3)	34.48	56.25	16.77	13.64	5.41	8.70

V. CONCLUSION

This paper presents the possibility of using two admixtures to develop UHPC to rip the benefits of reduced cost and enhanced sustainability. From the study conducted with blend of two admixtures, the following inferences could be drawn:

a) Silica fume of around 10% when added to GGBS as a means of high amount cement replacement brings about improvement in compressive and flexural strength. Even, early strength which is lower when only GGBS is used can be raised through usage of silica fume along with it by around 6%. This is an indication of higher hydration reaction and thus can facilitate faster construction and also reduced reinforcement.

b) For maximum strength development determining the optimal percentage of mineral admixtures at a certain water-binder ratio in the mix is extremely important. Less than optimal or too high amount affect strength development negatively, about 4%-8% lower than maximum as per the research.

c) The fineness of GGBS and SF are equally determining factors for strength development. There is a notable point found out through this study - though strength increases with increase in fineness of mineral admixtures/ pozzolans, this might not necessarily be true when there is a mix of the admixtures / pozzolans. It should be noted that there was a considerable (around 13%) decrease in strength from maximum when highest fineness of GGBS and SF was used in the blended concrete mix.

The developed UHPC can be used in conjunction with steel to make composite columns. This would actually reduce member size, amount of steel thus facilitating faster construction and cost. Although the study shows that high strength can be reached, the material is brittle in failure. Therefore, some fiber reinforcement would add ductility to the concrete developed. Also, further research can be done to look into the durability and long term concrete properties of this developed UHPC which are supposed to be good owing to high cement replacement by minerals and low water-binder ratio. With good durability features and high strength, this could be excellent sustainable construction material for bridge construction and other special applications in foundation of high rise buildings.

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