SUSTAINABLE APPROACH TO DEVELOP ULTRA HIGH PERFORMANCE CONCRETE USING INDUSTRIAL WASTES AND BY PRODUCTS

Shamanth Gowda T [1], Naveen A Katavi[1], Shashi Kiran M R[1], R V Ranganath[1]

1. BMS College of Engineering, Bengaluru, India.

ABSTRACT. This paper is an experimental report of an attempt made to develop High/ Ultra high performance concrete (UHPC) of strength greater than 100MPa by recording early strength gain behaviour as a key parameter. The paper accounts for the utilization of industrial wastes and by products such as Fly ash, Ground Granulated Blast furnace Slag (GGBS) and Ultra Fine Slag (UFS). The cement fine mineral admixtures such as Fly ash and GGBS are blended with UFS to evaluate the changes in concrete properties. Such combination is worked out at different percentage additions by weight of Ordinary Portland Cement (OPC) in achieving maximum strength in the early age, starting from the 16th hour after concrete preparation. The fresh and hardened properties are observed under each variation, mainly considering the compressive strength results. Based on the strength results, certain mixes were further tested for flexure strength, split tensile strength, water permeability and micro structural characteristics. The results have shown that incorporation of Ultra-fine mineral admixtures improves the concrete properties with a considerable enhancement in early strength. The microstructure is also improved with reduced porosity, thus contributing to the durability of concrete. It is possible to achieve nearly 40% strength increment on average by 16 hours of concrete casting in case of optimum mixes which is of great benefit towards faster construction cycles.

Keywords: Fly ash, GGBS, Ultra fine Slag, Early strength gain,Water permeability, Micro structure.

Mr ShamanthGowda T is a Research Scholar in the Department of Civil Engineering, BMS College of Engineering, Bengaluru, India. His research interests include Mineral admixtures in concrete, High/ Ultra high performance concrete, Fibre reinforced concrete etc.

Mr Naveen A Katavi and **Mr Shashi Kiran M R** have completed their Masters in Construction Technology from BMS College of Engineering, Bengaluru, India. Their research interests include Mineral admixtures in concrete and High / Ultra high performance concrete.

Dr R V Ranganath is a Professor of Civil Engineering at BMS College of Engineering, Bengaluru, India. His research interests are Geo-polymer Concrete, Self Compacting Concrete, High/ Ultra high performance concrete, Fibre reinforced concrete etc.

INTRODUCTION

The requirement of cement concrete is a never ending aspect in the current state of construction across the world. Every country's progress is dependent on concrete's consumption and the infrastructure development thereby. With such high demand, the carbon footprint of construction activity, especially that of cement concrete is also growing high and there is a need to bring down the same by utilizing available industrial wastes/ by products which can act as mineral admixtures in concrete. Out of many mineral admixtures available, which can bring out pozzalanic reaction when used in cement concrete, Fly ash and Ground Granulated Blast furnace Slag (GGBS) are more accepted and already in use by commercial Ready mix Concrete producers. However, when concrete of High strength is required, there is still a little hesitation towards blending OPC with mineral admixtures. In many cases higher cement content in the mix will be practised to maintain consistency in the desired strength. In order to address this practical situation, this study is focussed on to achieve a high/ ultra high performance concrete of strength greater than 100MPa by making use of Fly ash (class-F) and GGBS. As a possible performance enhancer, Ultra Fine Slag (UFS) which is nothing but further fine ground GGBS is incorporated to the concrete mixes to study any variations in the properties.

The need for high performance concrete is inevitable in the present scenario where the construction cycle needs to be faster and demands for early serviceability as compared to conventional concrete. Researchers across the world are studying the various possibilities of finding a sustainable concrete mix, proportioned with a least amount of cement content and maximum utilization of admixtures, which otherwise are wastes emitted into environment. In such cases the strength as well as durability aspects are to be studied repeatedly to arrive at a clear understanding of admixtures used to act as Supplementary Cementitious Materials (SCMs).

In an investigation by Caijun Shi et al [1], the mechanical and hydration properties of Ultra High Strength Concrete (UHSC) containing Cement and different SCMs such as Silica fume and Slag. The study proposes for a proper content of silica fume addition in order to improve the flow ability and compressive strength of UHSC. The porosity is observed to decrease with the increase of silica fume content due to the filling and pozzolanic effects of silica fume. Increasing Silica fume content up to an optimum of 15% has improved the 56day compressive strength from 108MPa to 125MPa.Slag, on the other hand is recorded to perform in a poor manner as compared to Silica fume, with strength in the range of 80MPa. High speed mixers are involved in concrete preparation. Maximum size of aggregates is limited to 2.36mm. In another study by Franqois de Larrad [2], Silica fume is used as a replacement option to OPC in production of High strength Concrete of 80MPa. OPC replacement by weight with 20 to 25% of silica fume is recorded to yield optimum results with improved strength. It is suggested by the study that instead of using OPC as a single binder, using ultrafine mineral additives improves the strength of concrete. Further in an attempt to develop Ultra High Performance Concrete (UHPC) C. Wang et al [3] have suggested simple methods and locally available raw materials so as to bring down the cost involved. The mixes are designed using Silica fume, GGBS and Limestone powder as SCMs by maintaining very low water to binder ratio of 0.12 to 0.18. Maximum slump of 268mm was obtained and highest compressive strength of 175.8 MPa at 90 days. Total cementitious material of 900 kg/m^3 with 50% of cement, 10% Silica Fume, 20% GGBS and 20% Limestone powder is observed to provide considerable improvement. Usage of super plasticizers with retarding agent together is considered to produce a pump able concrete for lower water binder ratio. Specialized mixer is used in this study as the powder content was high. Also in most cases where UHPC is proposed the OPC content is higher than 450kg/m3

with max size of aggregates being restricted to less than 10mm to achieve strength greater than 150MPa [1, 7, 10,11].
Since Fly ash and GGBS are produced in significant quantity by thermal power plants and industrial activities in India, it was intended to use such admixtures in the current study. Also Fly ash and Slag can be considered as a better option for replacing cement with silica fume, ultimately reducing the cost. Both Fly ash and GGBS at an optimum dosage are observed to have the ability to enhance the workability and resultant strength of concrete [4- 7].
There is no universally accepted definition for UHPC and varies based on the study. Usually defined as concrete with strength greater than 150MPa, it involves special constituent materials including fibres and preparation processes [8, 9]. For this study, Concrete with 28day strength greater than 100MPa is considered as UHPC, as the materials and methodology involved are simple and more practical.

MATERIALS AND METHODOLOGY USED IN THE STUDY

OPC 53 grade confirming to IS 12269 is used as the primary binding material. Class F Fly ash and GGBS along with UFS, all procured from commercial sources are used as Supplementary Cementitious Materials. Coarse Aggregate fraction of 20 and 12mm down size is used in combination with Crushed Stone Sand (CSS) as fine aggregate. Fine aggregate confirm to Zone II as per IS 383 specification. The material details of different ingredients used in the research are presented in table 1. Morphological study of Cement and SCMs are presented by the Scanning Electron Microscope (SEM) images from figure 1a to 1d. Cement, GGBS and UFS all show a rough angular surface texture whereas Fly ash consists of smooth spherical particles. UFS can be observed to have a similar texture of GGBS with much more fineness and particles present in a given space.

Table 1 Material properties

MATERIAL	SPECIFIC GRAVITY	FINENESS
OPC 53 GRADE	3.14	276 m^2/kg
FLY ASH	2.1	400 m^2/kg
GROUND GRANULATED BLAST FURNACE SLAG (GGBS)	2.9	386 m^2/kg
ULTRA FINE SLAG (UFS)	2.6	1000 m^2/kg
FINE AGGREGATES	2.62	-
COARSE AGGREGATES	2.67	-

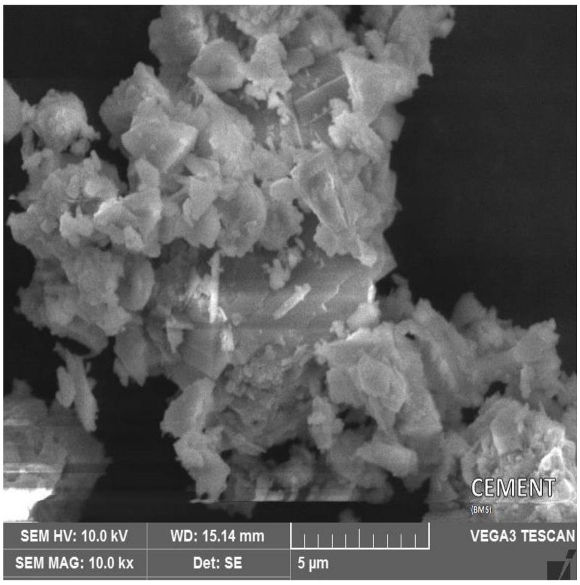

Figure 1a. SEM of Cement

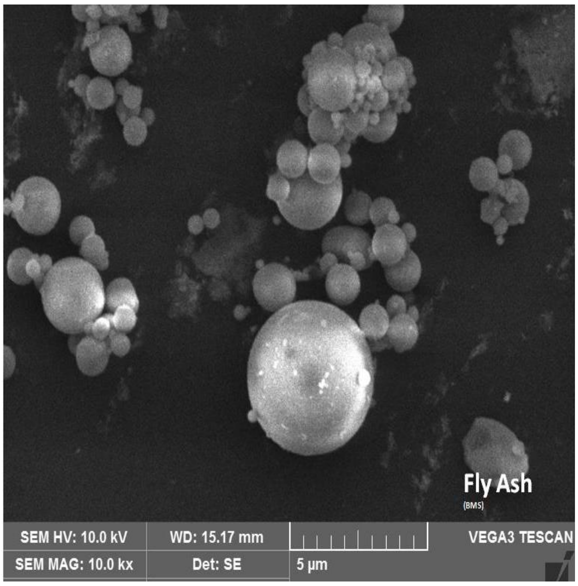

Figure 1b. SEM of Fly ash

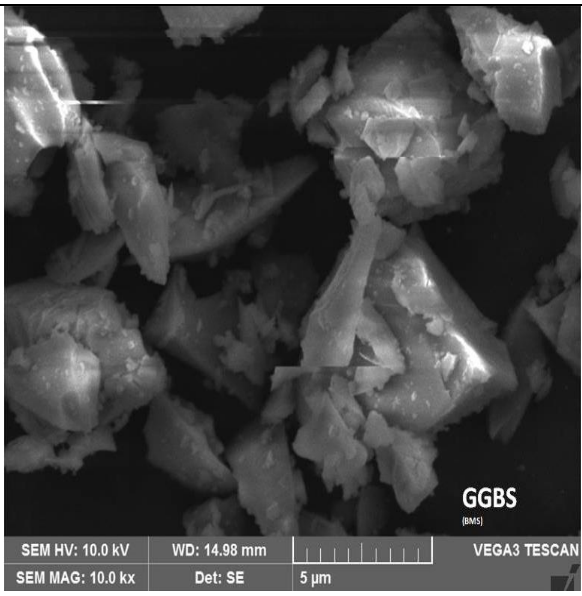

Figure 1c. SEM of GGBS

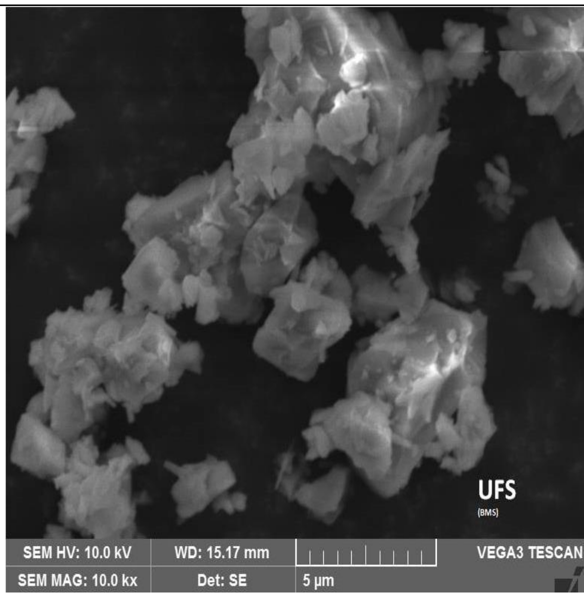

Figure 1d. SEM of UFS

The mix design is based on the method of least voids for aggregates and Paste volume (Vp) increment thereafter for concrete. In first stage, coarse aggregates (20mm and 12.5mm combination) were proportioned for least voids under compaction as per the guidelines of IS 2386. The percentage void so calculated for Coarse aggregate fractions reached a minimum value of 37.8% for a combination of 40: 60 parts of 12.5mm and 20mm aggregates respectively(Figure 2a). Later, to the least void proportion of coarse aggregate fractions, fine aggregate is added to obtain a minimum voids under compaction in similar manner (Figure 2b). Least value for % void obtained from the aggregate combination is 27%, which gives the minimum paste volume required to fill the void as 0.27 of concrete volume. Considering this minimum paste requirement, all trials are conducted by varying the paste volume between 0.3 to 0.4, there by satisfying the minimum paste content requirement and ensuring necessary cohesion.

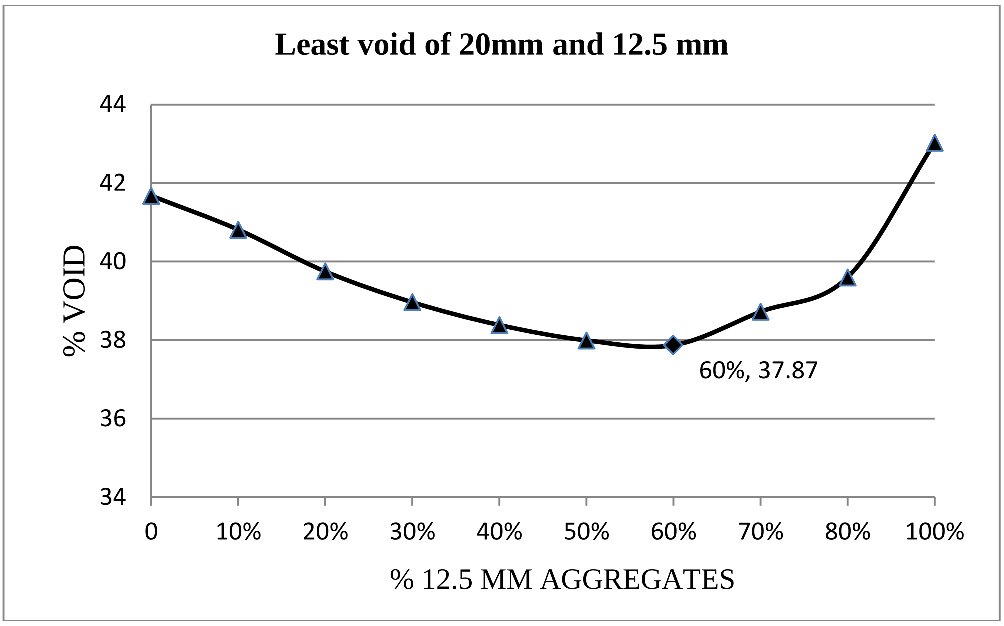

Figure 2a. Least void for coarse aggregate combination of 20mm and 12.5mm size

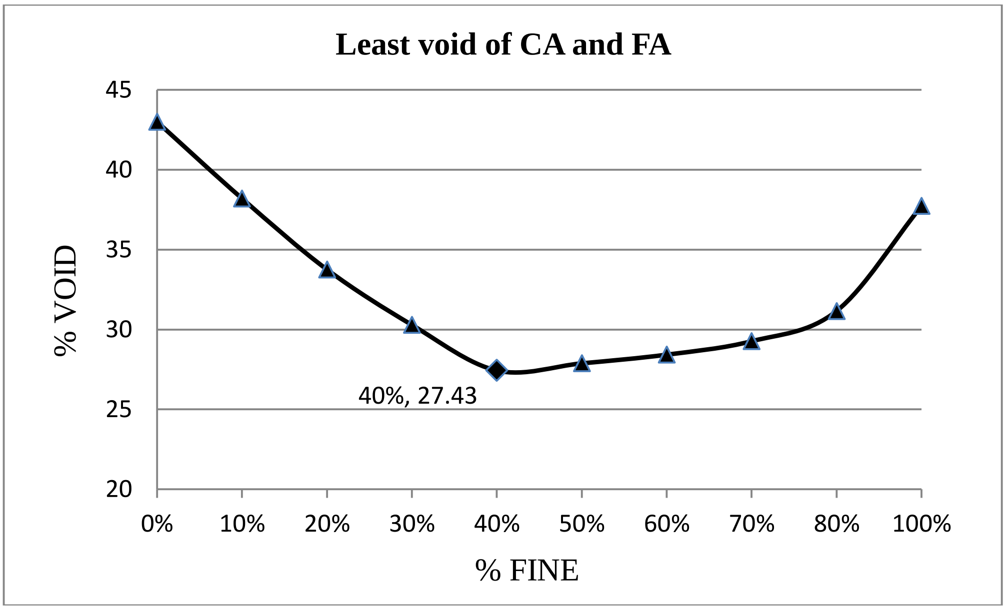

Figure 2b. Least void for coarse and fine aggregate combination

A primary mix with only OPC, limited to 450kg/m^3, is established as control. Under the first set of concrete trial mixes, binary blends of OPC with Fly ash and ternary blends of OPC with Fly ash and UFS is prepared to study the fresh and hardened properties. Based on the optimum results obtained from binary blended mixes, one reference mix was selected for incorporation of UFS at a dosage of 2, 4, 6 and 8% by weight of Cement. Similarly binary blends of OPC with GGBS and ternary blend of OPC, GGBS and UFS is prepared under set 2 concrete mixes. Water to cement ratio is maintained constant at 0.32 for all mixes. However water to binder ratio considering total powder content varies.

As the paste volume varied from 0.3 to 0.4, with higher powder content, addition of super plasticizer (SP) becomes necessary to maintain sufficient flow. PCE based SP at a dosage of 0.3wt% of Cement for Fly ash based Set 1 mixes and 0.6 wt% for GGBS based Set 2 mixes was used for blended concrete mixes. Dosage of SP is based on minimum requirement results established by marsh cone test.

Concrete mixing was done in laboratory pan mixer for about 5 minutes after water addition and was maintained throughout. Conventional water curing method was practised. The mix details are as given in table 2. Specimen testing was done as per relevant IS guidelines and an average value from a minimum of 3 specimens is considered as test result. Water permeability test was conducted with respect to DIN 1048(5).

Table 2. Mix Details

	MIX	Vp	OPC kg/m^3	FLY ASH kg/m^3	GGBS kg/m^3	UFS kg/m^3	TOTAL POWDER	WATER kg/m^3	% SP	VOLUME OF AGGREGATES
Control	CC	0.29	450	-	-	-	450	144	0.3	0.71
SET 1: Fly ash based blends										
	Mix	Vp								
Binary blend (OPC+ Fly ash)	CF1	0.3	450	21	-	-	471	144	0.3	0.7
	CF2	0.32	450	78	-	-	528	144	0.3	0.68
	CF3	0.35	450	134	-	-	584	144	0.3	0.65
	CF4	0.38	450	191	-	-	641	144	0.3	0.62
	CF5	0.4	450	236	-	-	686	144	0.3	0.6
	Mix	%UFS								
Ternary blend (OPC+ Fly ash+ UFS)	Ref-CF3	0	450	134	-	-	584	144	0.3	0.65
	CFU1	2	450	134	-	9	593	144	0.3	0.65
	CFU2	4	450	134	-	18	602	144	0.3	0.64
	CFU3	6	450	134	-	27	611	144	0.3	0.64
	CFU4	8	450	134	-	36	620	144	0.3	0.64
SET 2: GGBS based blends										
	Mix	Vp								
Binary blend (OPC+ GGBS)	CG1	0.3	450	-	29	-	479	144	0.6	0.65
	CG2	0.32	450	-	107	-	557	144	0.6	0.65
	CG3	0.35	450	-	185	-	635	144	0.6	0.64
	CG4	0.38	450	-	264	-	714	144	0.6	0.64
	CG5	0.4	450	-	328	-	778	144	0.6	0.64
	Mix	%UFS								
Ternary blend (OPC+ GGBS+ UFS)	Ref-CG4	0	450	-	264	-	714	144	0.6	0.62
	CGU1	2	450	-	264	9	723	144	0.6	0.62
	CGU2	4	450	-	264	18	732	144	0.6	0.62
	CGU3	6	450	-	264	27	741	144	0.6	0.61
	CGU4	8	450	-	264	36	750	144	0.6	0.61

SUSTAINABLE APPROACH IN MIX DESIGN OF CONCRETE

Since the Strength of Concrete being explored is greater than 100MPa, there is a requirement of higher OPC content. Higher OPC content increases the carbon footprint of resultant concrete thereby reducing its sustainable factors for materials. Hence in this research, the OPC content is restricted to a maximum of 450kg/m^3 which otherwise requires a large quantity of OPC of the order of 600 to 800kg/m^3.Industrial wastes such as Fly ash and GGBS which possess a problem of disposal into environment is also used effectively in concrete mixes. Processed UFS is being explored to check for its effects on concrete. This can widen the sustainable options for concrete if found satisfactory. Further, use of Aggregates which is natural source without a proper packing method can also lead to over exploitation of the same. In the current study, the aggregates are proportioned to be used as per least voids packing method. Also, Crushed Stone Sand is used in place of Natural river aggregates as fine aggregate fraction. Using a well proportioned mix will not only reduce the cost of concrete in terms of materials but also reduces the cost of extraction/ manufacturing of same materials. The UHPC developed in the study involves simple mixing and curing method as well, which does not require a high energy input unlike high speed mixers and elevated curing method.

CONCRETE PERFORMANCE: RESULTS AND DISCUSSION

Fresh properties

Due to sufficient paste content in the trial mixes, the concrete mixes so obtained were cohesive enough to serve a pump able concrete. Workability results of trial mixes are given in table 3. The variations in flow behaviour observed upon ternary blending with UFS for set 1 and set 2 mixes is plotted in figure 3a and 3b.

Table 3 Workability results

		BINARY BLENDS						TERNARY BLENDS				
SET 1: Fly ash based blends	Mix	CF1	CF2	CF3	CF4	CF5	-	Ref. CF3	CFU1	CFU2	CFU3	CFU4
	% SP	0.3	0.3	0.3	0.3	0.3	-	0.3	0.3	0.3	0.3	0.3
	Flow, mm	340	430	540	525	510	-	540	560	550	510	470
SET 2: GGBS based blends	Mix	CG 1	CG 2	CG3	CG4	CG5	-	Ref. CG4	CGU 1	CGU 2	CGU 3	CGU 4
	% SP	0.6	0.6	0.6	0.6	0.6	-	0.6	0.6	0.6	0.6	0.6
	Flow, mm	560	585	570	520	465	-	520	530	510	475	410

Being a smooth surfaced spherical particle, Fly ash demands lesser SP dosage during mixing to attain sufficient mix consistency. It can be observed from the results (Table 3) that as the Fly ash content increases in the mix for Binary blend, the flow increases up to a certain limit after which it reduces. The initial increase can be attributed to the morphology of Fly ash which assists in flow. The later decrement in flow could be due to higher powder content which requires more water or SP to achieve a higher flow values. With UFS addition for a reference mix selected from binary blend mixes, the flow values sustained till 4% UFS addition after which the flow reduced. The flow variation is plotted in figure 3a. Maximum percentage reduction in flow by 13% is recorded at 8% UFS addition to Fly ash blend mixes.

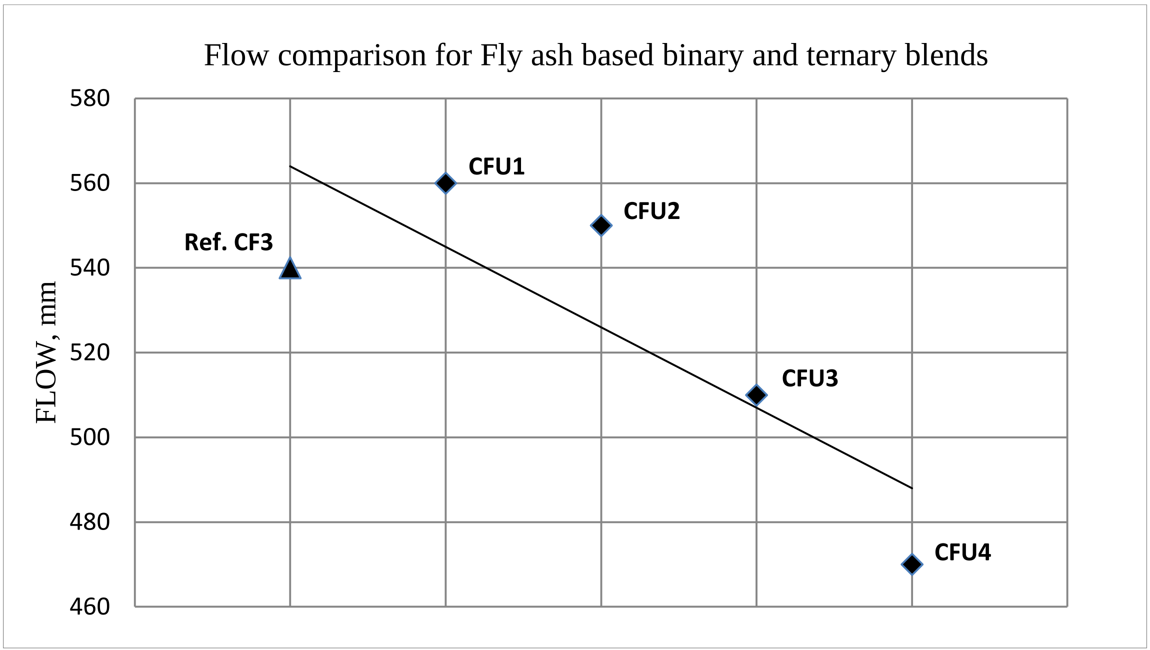

Figure 3a. Flow behaviour of Fly ash trial mixes

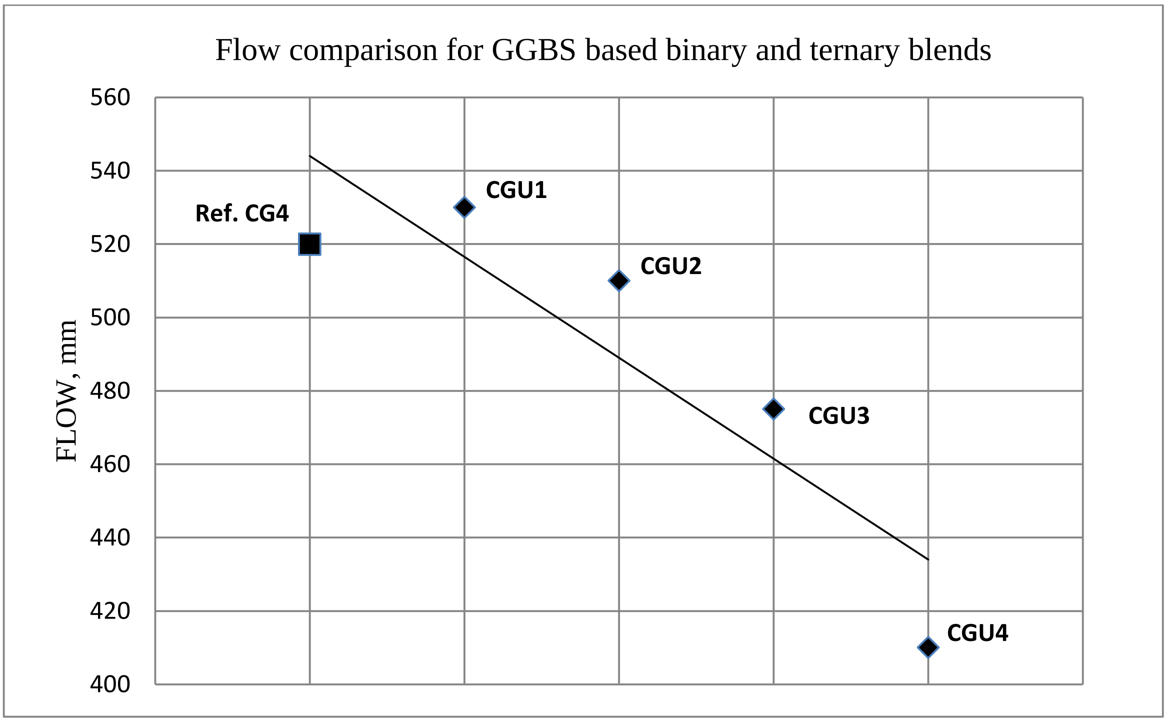

Figure 3b. Flow behaviour of GGBS trial mixes

Similar results are obtained for Set 2 concrete mixes with GGBS. Unlike Fly ash, GGBS did not yield a consistent mix at 0.3% of SP and the dosage was increased up to 0.6% weight of cement. At this point, the mixes with GGBS gave satisfactory cohesion. The flow parameter initially sustained and quickly started to reduce with increase in GGBS content for binary blend mixes (Table 3). The flow further reduced, when UFS was incorporated to a selected reference mix from GGBS binary blend trials. Maximum percentage reduction in flow by 22% is recorded at 8% UFS addition to GGBS blend mixes. The flow value is comparatively decreasing with UFS addition in both cases since no increment of SP is done. The decrease in flow is considerably high for GGBS-UFS ternary blends. Both GGBS and UFS are angular and rough textured particles (Figure 1c and 1d) which offer more resistance to flow. Thus the percentage variation in flow cab be linked to the quantity, shape and texture of fine particles being used in concrete

Hardened properties

The compressive strength is considered as a key parameter in assessing the hardened properties of concrete. It is measured as early as 16hours after casting and tracked up to 28days of curing. The results of compressive strength of different concrete mixes under study are presented in table 4a. Similar to workability the compressive strength has increased up to an optimum paste volume and started to sustain /reduce. This could be due to excess amount of SCMs present in the concrete mix which crossed the optimum quantity contributing to the formation of hydration products. Based on the test results of binary blend mixes, a reference mix yielding optimum values of compressive strength is selected as reference for further addition of UFS. The results are tabulated in table 4a and it can be observed from the results that as the powder content increased with binary and ternary blending, the strength at all duration has significantly improved compared to that of Control, with OPC as the only powder component limited to 450kg/m^3. Optimum mixes are identified based on the average strength results. Under Set 1 trial mixes with Fly ash binary blend, mix CF3 was selected as reference for ternary blending. Likewise, mix CG4 was selected from Set 2 Binary blends for addition of UFS.

The results reveal an increase in strength with the addition of UFS in both trial mixes containing Fly ash and GGBS (Figure 4a). An average of 30% strength gain can be observed within 24 hours for Fly ash and UFS ternary blend with 8% addition of UFS. The strength gain is not so prominent in case of GGBS blended with UFS, with an average of 16% increment within 24hours for 8% addition of UFS. At lesser percentage incorporation of UFS, the strength increment is not considerably improved, but has shown positive results in both cases of trials with Fly ash and GGBS. The ultimate strength after 28days of curing is observed to be higher in case of ternary blends of both Fly ash and GGBS with UFS. The 28th day strength of 112 MPa is recorded as highest for ternary blend of OPC, GGBS and UFS. This indicates that reactivity of UFS is more prominent with OPC and Fly ash in early strength increment and is equally beneficial in case of blending UFS with OPC and GGBS, considering the ultimate strength values.

Table 4a.Compressive strength results

	MIX	VP	16HR	24HR	3DAY	7DAY	28DAY
Control	CC	0.29	8	16	47	63	72
SET 1: Fly ash based blends							
	Mix	Vp	16hr	24hr	3day	7day	28day
Binary blends (OPC+ Fly ash)	CF1	0.3	12	28	52	72	91
	CF2	0.32	12	30	66	80	95
	CF3	0.35	15	30	68	81	98
	CF4	0.38	13	27	56	77	96
	CF5	0.4	10	25	48	62	89
	Mix	%UFS	16hr	24hr	3day	7day	28day
Ternary blends (OPC+ Fly ash+ UFS)	Ref. CF3	0	15	30	68	81	98
	CFU1	2	18	34	60	75	93
	CFU2	4	17	35	67	76	93
	CFU3	6	18	37	73	84	101
	CFU4	8	20	39	74	87	103
SET 2: GGBS based blends							
	Mix	Vp	16hr	24hr	3day	7day	28day
Binary blends (OPC+ GGBS)	CG1	0.3	15	28	59	71	90
	CG2	0.32	17	31	67	80	98
	CG3	0.35	16	34	71	85	95
	CG4	0.38	19	35	74	89	105
	CG5	0.4	18	32	70	84	100
	Mix	%UFS	16hr	24hr	3day	7day	28day
Ternary blends (OPC+ GGBS+ UFS)	Ref. CG4	0	19	35	74	89	105
	CGU1	2	18	32	72	86	108
	CGU2	4	19	34	70	84	106
	CGU3	6	20	38	72	90	108
	CGU4	8	23	39	79	94	112

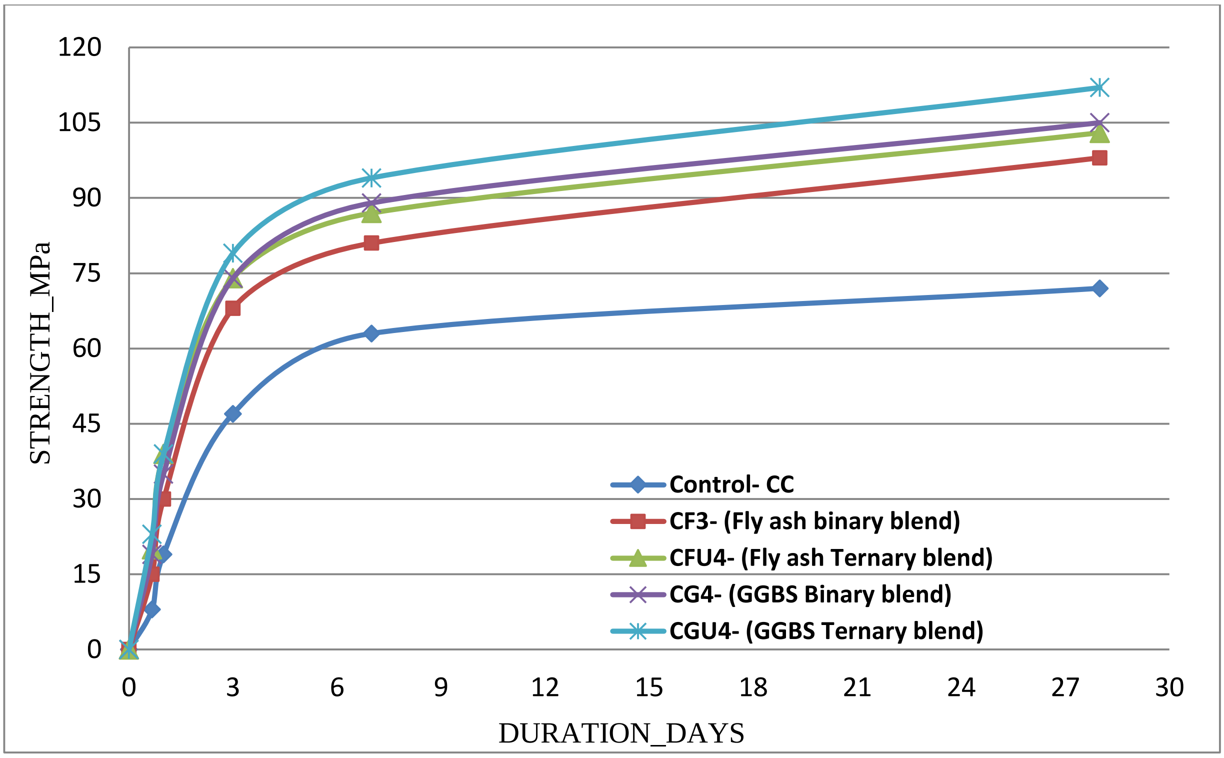

Figure 4a. Compressive strength comparison

Further, flexural strength, tensile strength, water permeability and micro-structural studies are conducted on selected concrete mixes from Set 1 and Set 2 based on compressive strength performance. Control mix with only OPC; mix CF3 from only Fly ash blend, mixCG4 from only GGBS blend, mix CFU4 from Fly ash-UFS ternary blend and Mix CGU4 from GGBS-UFS ternary blend are selected for further studies. The results so obtained are given in table 4b.

Table 4b. Hardened properties of optimum mixes

MIX	FLEXURAL STRENGTH, MPA	TENSILE STRENGTH, MPA	WATER PENETRATION, MM
CC	6.8	4.1	9
CF3	7.1	4.5	4
CFU4	7.4	5.2	1
CG4	7.5	5.0	5
CGU4	7.8	5.9	2

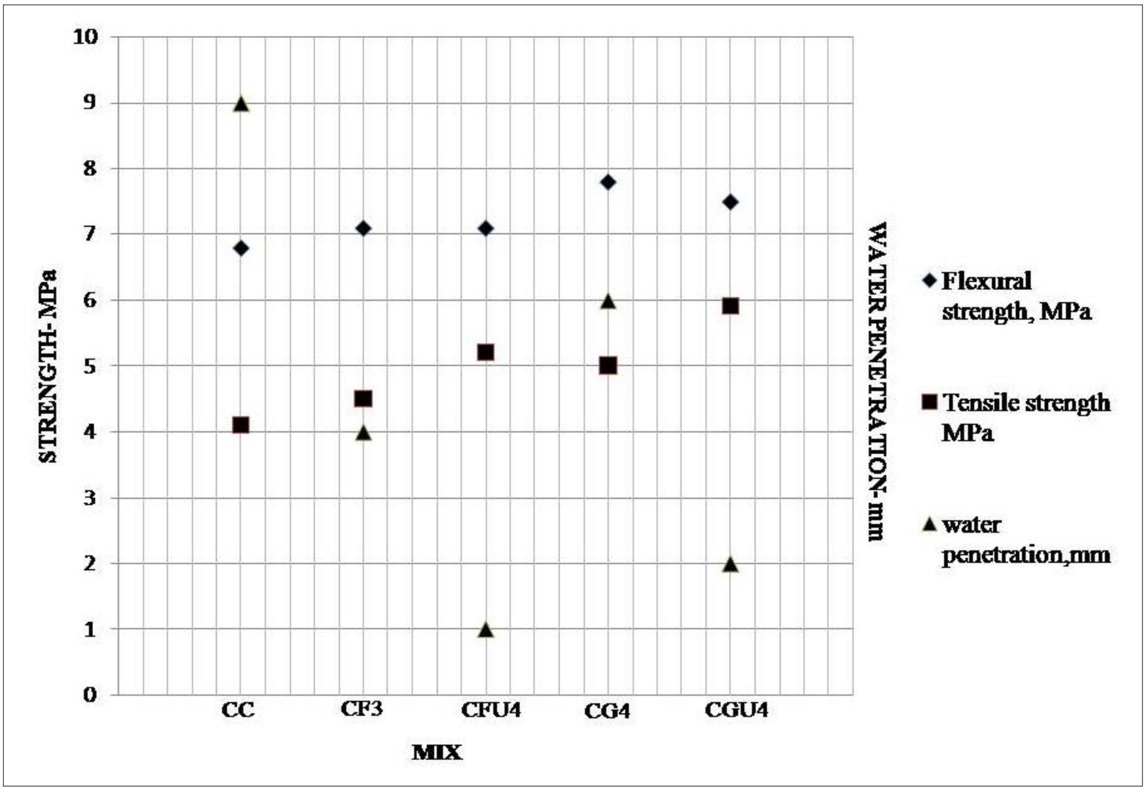

Figure 4b. Hardened properties of optimum mixes

The graph plotted for the test results obtained from optimum mixes (Figure 4b) can be used to understand the variation in concrete properties. On an average a 10% improvement in flexural strength from control is observed in case of binary/ternary blend mixes. However spilt tensile strength has increased by 25 to 40% for UFS added ternary mixes. The most positive effect of addition of SCMs is observed from the results of water permeability test. The depth of water penetration is brought down by 40 to 80% in case binary and ternary blending respectively. This indicates that the internal pores in concrete have reduced to a greater extent with the addition of UFS. This could be due to the pore-filling action and increase in the hydration products brought out by SCMs including UFS.

Microstructure study

Microscopic images from SEM reveal a dense microstructure consisting more of hydrated phases with observable reduction in CaOH crystalline structures in case of UFS blended concrete mixes (Figure 5c and 5e). The concrete matrix is packed with good amount of filler materials used. The control mix (Figure 5a) shows a loosely packed microstructure with the presence of flakes of CaOH and needle shaped ettringites. The amounts of CaOH and ettringites have visibly reduced in cases of Binary blended mixes (Figure 5b and 5d). The surface looks denser in case of GGBS blended binary mix than that of Fly ash blended mix. However, UFS addition has helped both Fly ash and GGBS blended ternary mixes to achieve a highly dense matrix as observed in Figure 5c and 5e.Fly ash particles can be seen embedded in the hydrated phases of concrete denoting an efficient process of hydration (Figure 5c). This indicates that UFS can aid in better hydration process which reduces the products of unhydrated phases within concrete microstructure thereby reducing the voids within.

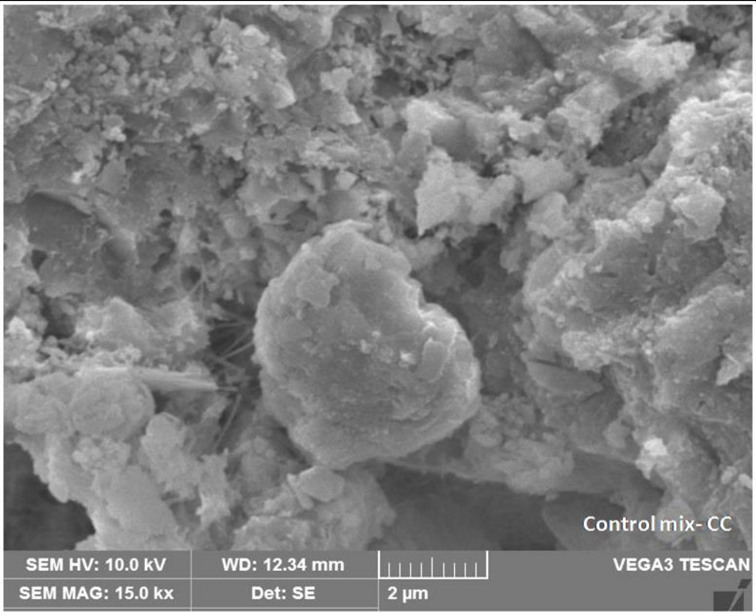

Figure 5a. SEM image of Control mix -CC

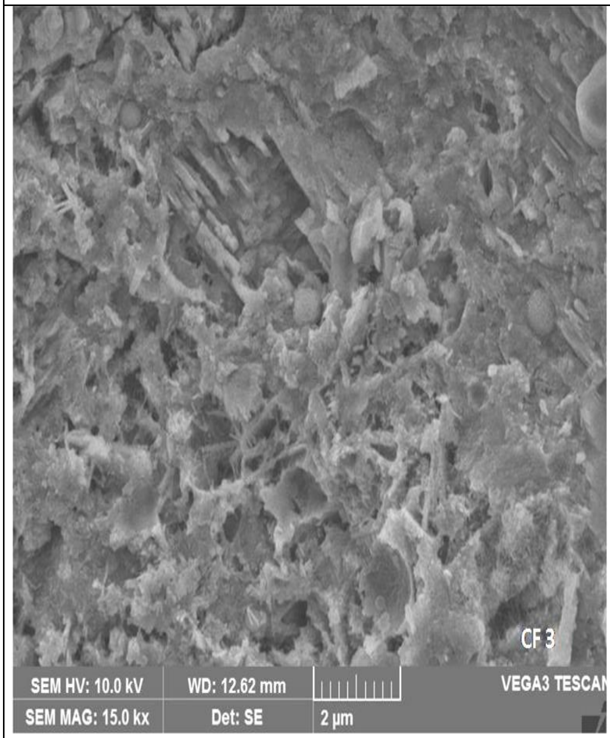

Figure 5b. SEM image of Fly ash Binary mix – CF3

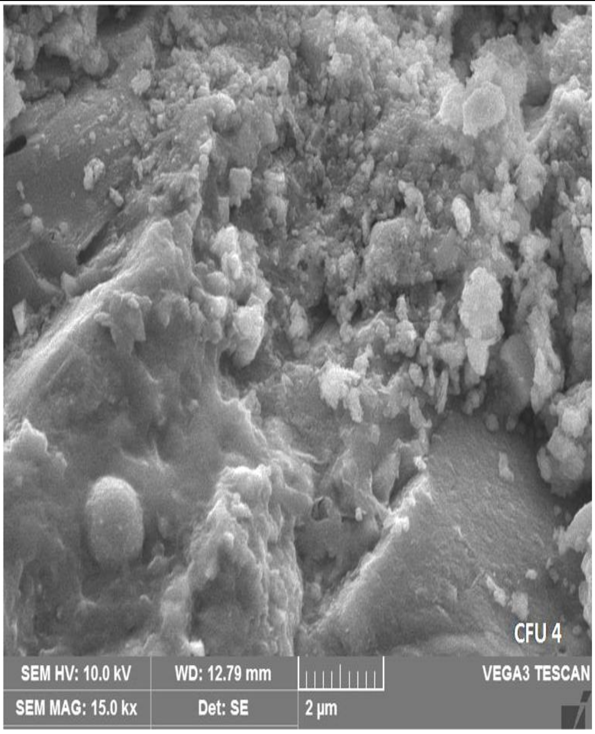

Figure 5c. SEM image of Fly ash Ternary mix – CFU4

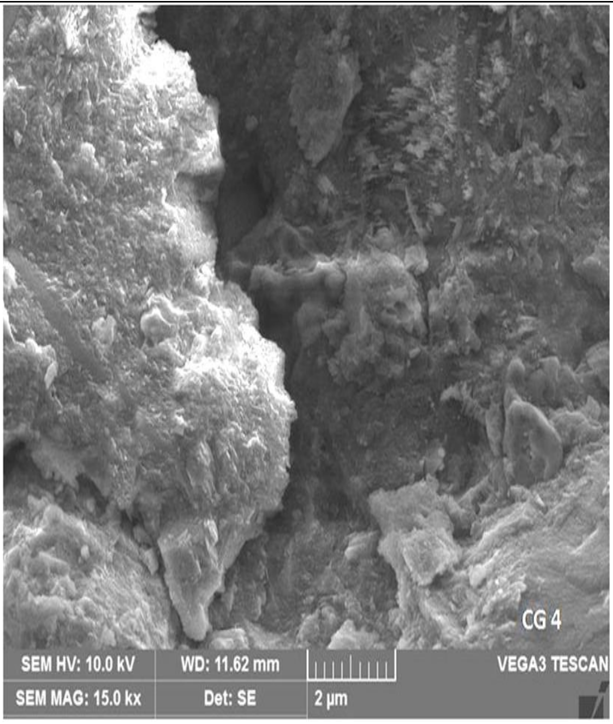

Figure 5d. SEM image of GGBS Binary mix – CG4

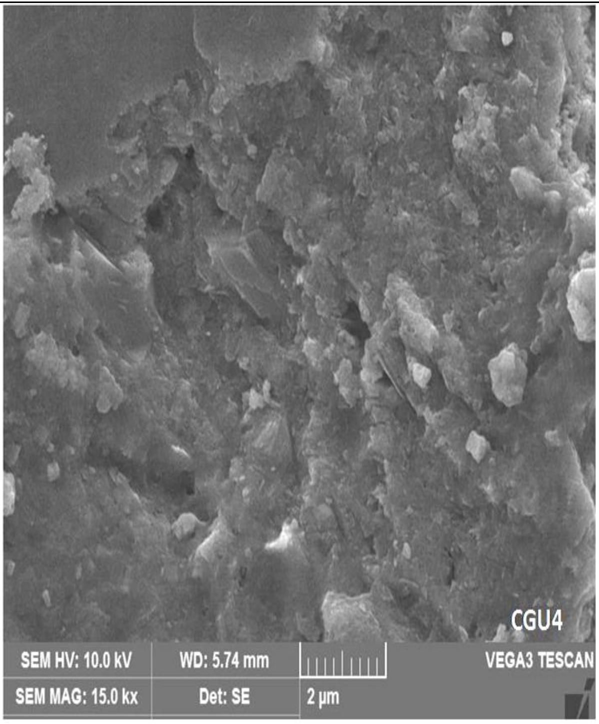

Figure 5e. SEM image of GGBS Ternary mix – CGU4

CONCLUDING REMARKS

From the findings of the research it can be concluded that, the requirement of high strength and performance can be achieved by using SCMs such as Fly ash and GGBS with simple method of mix design and mixing practice. Coarse aggregates of 20mm down size which is commonly not used in high strength concrete can also yield strength greater than 15MPa in 16 hours and 100MPa at 28 days if properly proportioned. Crushed stone sand is acceptable as fine aggregates to be used in UHPC. Early strength gain can be achieved with the addition of UFS when combined with Fly ash and GGBS. The ultimate strength however has remained on the same level as the concrete ages. Ultra fine additives can improve the microstructure by reducing the pores within thereby enhancing the strength and durability of resultant concrete. Reduction in pores has a long term benefit of resistance to environmental factors which can cause concrete deterioration. This paper suggests that concrete for ultra high performance can be made more reasonable and have a reduced toll on materials thereby making it more sustainable considering the complex materials, mixing and curing practices conventionally adopted in the production of the same.

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