Experimental study on effective utilization of industrial solid wastes in developing Ultra-High Performance Geopolymer Concrete

M Sathyanarayanan[1], D Brindha[2]

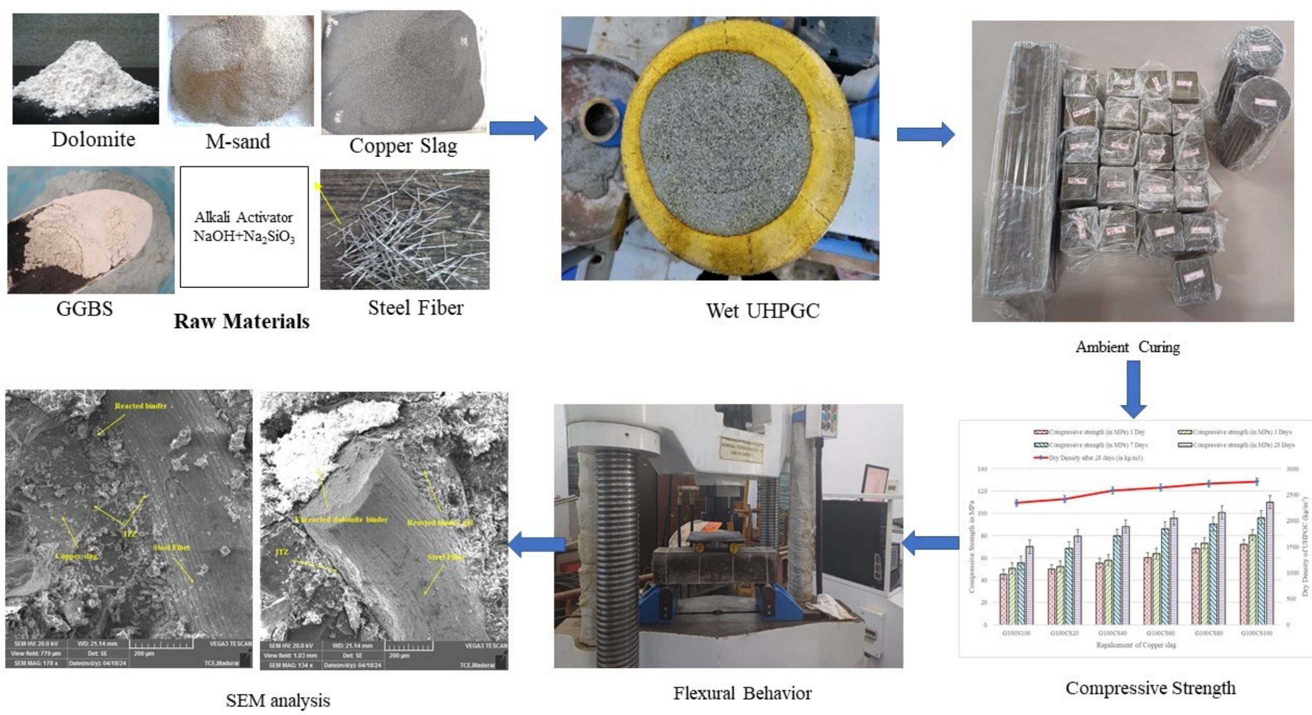
[1]Thiagarajar College of Engineering, Madurai, Tamil Nadu, India.

[2] Thiagarajar College of Engineering, Madurai, Tamil Nadu, India.

*Corresponding author: M Sathyanarayanan

E-mail: sathya15289@gmail.com, tel: 9994548417

Graphical abstract:



Abstract:

This experimental study explores the use of Ground Granulated Blast Furnace Slag(GGBS) and dolomite as alkali activated binders and copper slag as aggregate to achieve a cost-effective and sustainable Ultra-High-Performance Geopolymer Concrete(UHPGC). Several concrete compositions utilizing copper slag as a substitute for natural aggregates were formulated. Tests have shown that the inclusion of 100% copper slag fine aggregate leads to significant improvements in the mechanical properties and density of geopolymer concrete. Specifically, the compressive strength increased by 56.8% and the density increased by 17.5%. To understand the influence of dolomite in GGBS binder, several mixes varying dolomite proportion in GGBS were examined. The compressive strength of the 80% GGBS/20% dolomite geopolymer matrix is 32.8% higher compared to the compressive strength of UHPGC with 100% GGBS. The UHPGC mixture containing 1% crimped steel fibers showed the highest compressive strength, measuring 146.6 MPa. The split tensile and flexural strengths of the 20% dolomite matrix show a significant increase of 30.55% and 30.24% respectively compared to the 100% GGBS matrix. The water absorption and porosity of the 100% GGBS specimen were found to be lower compared to the 20% dolomite UHPGC specimen. The microscopic study reveals the positive impact of dolomite and GGBS on enhancing the bonding of the geopolymer matrix along with decreasing permeability. This study highlights the potential of geopolymer technology in producing ultra-high-performance concrete using GGBS, dolomite, and copper slag.

Keywords: Geopolymer concrete, GGBS, Dolomite, Copper slag, Fine aggregate, Mechanical properties, Durability, Sustainable construction.

1. Introduction

Ultra-High-Performance Concrete (UHPC) is an emerging construction composite with superior compressive strength (typically greater than 120 MPa), high flexural strength, remarkable toughness, and durability requirements (X.-H. Wang et al., 2017; Yoo et al., 2016). These outstanding performances are made possible through rapid mixing, peculiar proportioning and special curing techniques. The important aspect in developing UHPC is the heavy consumption of Portland Cement (PC). UHPC contains typically 850 to 1200 kg/m^3 of PC which is thrice the quantity required for conventional concrete. As a result, UHPC's extensive use is limited because to its high energy consumption and ensuing rise in materials cost (Habert et al., 2013). Research has been made to find a suitable alternate binding material for PC-based binding system. Utilizing Supplementary Cementitious Materials (SCM) derived from industrial leftovers such as metakaolin, fly ash, ground granulated blast furnace slag (GGBS), Alccofine, and Rice Husk Ash (RHA) as a partial substitute for PC in UHPC offers a methodical strategy that effectively minimizes trash accumulation in landfills (Kavitha and Felix Kala, 2016; Sharma and Sivapullaiah, 2016; R and J, 2019; Ansari and Bandewar, 2022).

Geopolymer binders, are the clinker free binders utilizing 100% SCM which achieves comparable mechanical properties and superior durability properties(Singh et al., 2015; Sontakki and Cholekar, 2015; de Oliveira et al., 2022; Wong, 2022). Geopolymer Concrete (GPC) is produced when aluminosilicate minerals dissolve in the alkaline activation solution and repeatedly interact with Si–O–Al–O in an amorphous state. Joseph Davidovits developed three distinct varieties of geopolymers on the basis of the various shapes of chemical bonds that result from hydrothermal processes. It includes sialates (-Si-O-Al-), poly sialate (-Si-O-Al-O-)n, and poly-sialate siloxo (-Si-O-Al-O-Si-O-)n. (Davidovits, 1991). Being the most common and affordable aluminosilicate source, the low calcium flyash based geopolymer binders require heat curing for the polymerization process which makes the GPC technology less feasible in construction industry(Hardjito et al., 2005; Yunsheng and Wei, 2006). "Several attempts have been made to explore the potential of using solid crushed wastes such as recycled concrete waste powder and waste clay brick powder as alternative precursors for geopolymer binder. Huixia Wu et. al explored the use of recycled concrete powder (RCP) and recycled paste powder (RPP) in their study on high-ductility Engineered Geopolymer Composites (EGC) and UHPC(Wu, C. Liu, et al., 2024; Wu, X. Liu, et al., 2024). The clay brick waste, commonly used for filling, has proven to be a highly effective precursor for alkali activated composites(Wu, Gao, et al., 2024). At present, scholarly attention is focused on exploring the development of geopolymer concrete in ambient conditions as a way to reduce curing energy demands and enable the technology to be implemented for in-situ concreting. Despite the fact that numerous alternative SCMs can enhance their strength during elevated curing, ambient cured geopolymer concrete can be formulated only by using GGBS as the primary binder. (Patil, Karikatti and Chitawadagi, 2018; Amar et al., 2023; Chithambar Ganesh et al., 2023).

The GGBS is a by-product resulted from the molten iron in the smelting process of iron ore. Being the second largest by-product produced in India after flyash, GGBS is mainly utilized as a partial replacement of cement in the conventional concrete(Sharma and Sivapullaiah, 2016). It was reported that the quantity of GGBS dissolved is greater than that of fly ash dissolved in a geopolymer medium(Panagiotopoulou et al., 2007). It is generally observed that the compressive strength of geopolymer concrete tends to increase with higher slag content. The limited dissociation of the glass phase in fly ash results in a minimal production of C-(A)-S-H. Due to the utilization of GGBS as its primary binder, GPC has garnered considerable interest in recent years on account of its superior chemical and temperature resistance, low permeability, and high initial compressive strength. Studies reveals that Ultra-High Performance Geopolymer Concrete (UHPGC) can be developed by using GGBS and silica fume as binding precursors(Ambily et al., 2014). A.Wetzel et al.(2019) summarized the superior effect of metakaolin and silica fume in GGBS for higher polymerization degree in the reaction products(Wetzel and Middendorf, 2019). The study also revealed the possibility of balancing workability and strength parameters. Liu et al. (2020) reports the development of Ultra-High Performance Geopolymer Concrete (UHPGC) using GGBS and overcoming the brittleness feature of geopolymer matrix by using different steel fibers(Ding, Shi and Li, 2018; Liu et al., 2020a). It is widely recognized that augmenting the source material dissolution results in a greater quantity of C-A-S-H gel, thereby enhancing the concrete's mechanical properties. Slag-based geopolymer concrete have practical obstacles, including quick setting (less than 30 minutes), which limits their application in mix-ready and pumped concretes(Dineshkumar and Umarani, 2020). The necessity for novel binders with equivalent strength performance as GGBS arose due to the workability and desired setting time needed for casting concrete. Studies reveal that high strength GPC may be produced from GGBS and dolomite(Saranya, Nagarajan and Shashikala, 2020). The inclusion of dolomite to slag-based GPC increases setting time and workability, and significantly improves early-age strength(Saranya, Nagarajan and Shashikala, 2019).

Dolomite is a double carbonate of calcium and magnesium occurring naturally as a sedimentary rock. Dolomite predominantly consists of Calcium carbonate and Magnesium carbonate(Goldsmith and Graf, 1958). In 1792, Swiss naturalist Nicolas de Saussure discovered dolomite for the first time and designated it with the specific name "dolomite" in reference to its first describer, Dolimeu. Previous studies reveal that Waste Dolomite Powder (WDP) obtained as the by product from the dolomite rock crushing plant in the process of manufacturing dolomite products can be effectively utilized as precursor, fine aggregate and coarse aggregate in concrete(Hu, Yao and Wei, 2023). When $CaCO_3$ contributes early strength, $MgCO_3$ in conventional concrete makes the composites more workable as it dissolves easily than $CaCO_3$(Azimi et al., 2020). Similarly, in geopolymer concrete the dolomite reduces the quickness in the reactivity by providing high workability and comfortable setting time even for the lesser liquid binder ratio(Divekar and Sawant, 2023). That may overcome the disadvantage of GGBS based geopolymer composite which starts dehydrate rapidly. Understanding the function of precursors in developing UHPGC, through mechanical behavior and microstructural analysis is the primary aim of this study.

Meanwhile, the increasing demand for natural resources such as river sand and crushed aggregate poses a significant threat to the delicate ecological balance. Thus, the depletion of natural resources for building material sector leads to the associated many environmental effects like global warming and loss of bio diversity. The replacement of aggregates by industrial by products is a vast study in the civil engineering research. The ceramic waste, granite waste, copper slag, recycled aggregates and coral aggregates are the few alternate sources that can be replaced partially or completely in natural aggregates for the development of concrete composites (Shi, Meyer and Behnood, 2008; Brindha and Nagan, 2011; Rajasekar, Arunachalam and Kottaisamy, 2018; lyu et al., 2019; Wang et al., 2019). Brindha et al. (2011) revealed that replacement of copper slag in PC based concrete increased the self-weight by 20%. The also revealed that addition of copper slag up to 40% showed promising results in mechanical behavior. Many research studies show that copper slag as fine aggregate can also be utilized for UHPC. The compressive strength of 158 MPa was achieved by using copper slag fine aggregate(Ambily et al.,). Copper slag is a by-product that is acquired during the process of matte smelting and refining of copper. Utilizing copper slag offers both environmental and economic benefits. It helps reduce the need for landfill space and meets the growing demand for natural aggregates in the concrete industry(Vinotha Jenifer et al., 2023).

A thorough investigation has been conducted to examine the mechanical properties of UHPGC by incorporating varying quantities of copper slag instead of natural crushed aggregates in the phase-I of this study through flowability and compressive strength. Following the optimization of aggregates, the mechanical properties of the UHPGC samples that included dolomite as a partial substitute for GGBS were examined. The use of Scanning Electron Microscopy (SEM) analysis has greatly enhanced the analysis of this experiment at a microscopic level. Therefore, the research aimed to assess the practicality of using GGBS, dolomite, and copper slag in the production of UHPGC, making it more cost-effective for wider application.

2. Experimental program

2.1. Materials

2.1.1. Binder

The geopolymer binders were prepared by alkali activation of precursors like GGBS and dolomite. The GGBS was procured from JSW cement limited, Maharashtra, with 28 days Slag Activity Index being 89.80%. The chemical composition arrived from the XRF fluorescence analysis is displayed in Table 1, which confirms the chemical requirement recommended by IS 16714: 2018(IS 16714, 2018). The dolomite of size 800 US mesh varies from 8μ to 12μ was used as another precursor to optimize the binder materials to achieve better rheological properties. The chemical composition of dolomite as tabulated in Table 1 shows that the material composition is very similar to the GGBS except the content of Alumina and magnesia. The reactive CSH gels formation from the oxides of calcium ensures the uniform strength development by GGBS and dolomite. The GGBS and dolomite are shown in the Figure 1, where it can be seen that the color of GGBS is greyish white and dolomite being pure white in color.

a) b)

Figure 1. a) Ground Granulated Blast Furnace Slag (GGBS) b) Dolomite

Table 1. Physical and chemical properties of precursors

Oxide Composition (percentage by mass)	**GGBS**	**Dolomite**
CaO	37.63	36.32
SiO_2	34.81	19.23
Al_2O_3	17.92	8.24
Fe_2O_3	0.66	2.44
MgO	7.80	21.22
MnO	0.21	0.06
CL	0.004	0.03
SO_3	0.19	-
IR	0.20	0.09
Specific Gravity	2.91	2.86
Blaine's fineness(cm^2/g)	4032	3500
Colour	Greyish white	White

2.1.2. Aggregates

In order to achieve the ultrahigh strength confirming to ASTM C1856, the maximum aggregates size was restricted to 1.18 mm to ensure the homogeneity of the concrete(Ambily et al., 2014). The fine aggregates used in this study were natural crushed aggregates and copper slag of zone II grading confirming IS 383(1970)(Kisan and Sangathan, 1970). The physical properties of natural sand and copper slag are tabulated in Table 2. Copper slag was brought from Sterlite Industries India Limited, Tuticorin, Tamil Nadu, India. The copper slag and natural crushed aggregates received from the suppliers were sieved under 1.18 mm sieve and it was wetted to attain Saturated Surface Dry Condition (SSD) before casting.

Table 2. Physical properties of natural sand and copper slag

Physical Property	**Specific gravity**	**Bulk Density(g/cm^3)**	**Water Absorption (%)**	**Fineness modulus**	**Mean Size (Range)**
Natural Sand	2.603	1.811	4.2	3.21	925μ
Copper slag	3.570	2.044	0.52	3.74	1.03 mm

a) b)

Figure 2. a) Natural Crushed aggregates(M-Sand) b) Copper Slag

2.1.3. Alkali activators

The alkali activation of the precursors was done by Sodium Hydroxide (SH) and Sodium Silicate (SS). The sodium silicate solution's specific gravity was determined to be 1.54. A solution of sodium hydroxide was prepared by mixing caustic soda pellets with water. The pellets had a high purity level of 97%–98% and a specific gravity of 1.47. It is evident from the previous research findings that as the ratio of SH and

SS and molarity of SH increases, the compressive strength will be increased(Ahmed, Kumar and Nanda, 2021; Chithambar Ganesh et al., 2023). The consistency in Vicat apparatus and Flow table tests confirming to IS 4031(Part-4) - 1988 and IS 5512 – 1983 were performed to optimize the SH/SS and SH molarity for comfortable workability and reasonable setting time. The consistency and setting time of various mixes are illustrated graphically in Figure 3. From these preliminary tests and practical difficulties learnt, the liquid binder ratio was taken as 0.38, the ratio of Sodium hydroxide and sodium silicate and the molarity of sodium hydroxide was fixed as 1:2 and 14 M respectively to balance the strength and workability of the mix. For UHPGC with fibers, the matrix needs to be in a flowable consistency. Hence, the Polycarboxylate Ether (PCE) based superplasticizers were used to increase the workability without compromising the strength gain of concrete. The quantity of superplasticizers taken were restricted to 2% by weight of the of the binder.

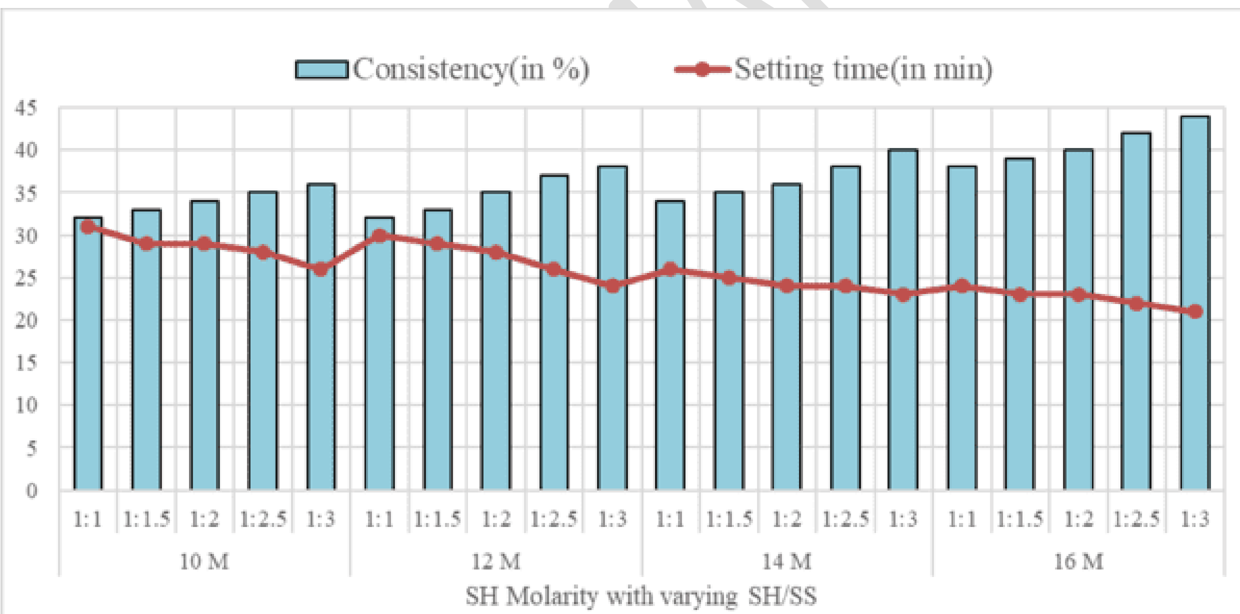


Figure 3. Consistency and Setting time vs Alkali activator concentration

2.1.4. Steel fibers

Micro steel fibers in geopolymer composites enhances the flexural behavior. The micro crimped steel fibers as shown in the Figure 4 was used in this experiment to enhance the ductile properties to UHPGC. The steel fibers length in this study was restricted to 20 mm as the longer steel fibers may affect the inter fiber spacing which may form a network of fibers that leads to week zone in concrete. The steel fibers of aspect ratio more than 50 was used. The mechanical behavior, particularly in terms of flexural strength, is significantly influenced by the deformation ratio (R_D) of the fibers. (Liu et al., 2020a). R_D for round crimped fibers is 1.33. The properties of steel fiber are listed in Table 3.

Figure 4. Crimped steel fibers

Table 3. Properties of steel fiber

Geometry	**Density (kg/m^3)**	**Length (mm)**	**Diameter (mm)**	**Aspect ratio (length/diameter)**	**Tensile strength (MPa)**	**Deformation ratio**
Crimped	7850	20	0.4	50	2820	1.33

2.2. Mix composition

As there are no standard method available for designing the mix proportion for UHPC and UHPGC, from the trial mixes and literature work the mix composition were derived. In order to make the mix denser with high packing density, the equal proportion of binder and aggregate were taken. The liquid binder ratio of 0.38 was maintained for all the mixes. Table 4 provides an overview of the mix composition of different mixes. A two-phase study was carried out to minimize material waste. In first phase the optimization of copper slag content in fine aggregate was investigated. The replacement of copper slag with varying percentage to natural aggregates (0-100%) were experimented for concrete compressive strength. After optimizing the copper slag content, the influence of dolomite as binder in mechanical and micro properties were studied. The crimped steel fibers by volumetric addition by 1.0 % were added.

Table 4. Mix composition of various mixes

Mix ID	**Binder**		**Aggregate**		**Alkali activator**		**Steel Fibers**	**SP**
	GGBS	**Dolomite**	**NA**	**CS**	**NaOH**	**Na_2SiO_3**		
Phase-I (Copper slag Optimization)								
N100	1195	0	1195	0	151.4	302.7	0	24
CS20	1195	0	956	239	151.4	302.7	0	24
CS40	1195	0	717	478	151.4	302.7	0	24
CS60	1195	0	478	717	151.4	302.7	0	24
CS80	1195	0	239	956	151.4	302.7	0	24
CS100	1195	0	0	1195	151.4	302.7	0	24
Phase-II (Dolomite Optimization)								
G100D0SF0	1195	0	0	1195	151.4	302.7	0	24
G100D0SF1	1195	0	0	1195	151.4	302.7	78.5	24
G90D10SF0	1075.5	119.5	0	1195	151.4	302.7	0	24
G90D10SF1	1075.5	119.5	0	1195	151.4	302.7	78.5	24
G80D20SF0	956	239	0	1195	151.4	302.7	0	24
G80D20SF1	956	239	0	1195	151.4	302.7	78.5	24
G70D30SF0	836.5	358.5	0	1195	151.4	302.7	0	24
G70D30SF1	836.5	358.5	0	1195	151.4	302.7	78.5	24
G60D40SF0	717	478	0	1195	151.4	302.7	0	24
G60D40SF1	717	478	0	1195	151.4	302.7	78.5	24

NA-Natural Aggregate; CS-Copper Slag; SP-Superplasticizers

2.3. Preparation of samples and curing

Ensuring the workability of geopolymer concrete is crucial when using alkali activators. To prevent water absorption from the AAS, it is important to use aggregates in a saturated surface dry condition. The aggregate is allowed to immerse in the water and dried in room temperature in a large tray, so that there is no moisture in the surface of the aggregates. Instead of adding additional water during mixing process to achieve the minimum workability, this process would improve the workability in a healthy way which leads to the appropriate gel formation resulting better binding between powder material and aggregates(Kathirvel and Sreekumaran, 2021)A 20 L vertical vane type mixer with variable speed control was used for the mixing operation. The dry materials including binder and aggregates in SSD condition were mixed at 200 rpm speed for two minutes. Half of the alkali activating liquid prepared was added to the dry mixture and allowed to mix for another 2 minutes. Now the remaining liquid along with the diluted superplasticizers were added followed by the final mixing for 5 minutes at 450 rpm. The well mixed concrete is transferred to cube, cylinder and prism molds. Mixes with higher concentrations of dolomite and copper slag had a higher setting time and were easier to deal with because of their greater fluidity. The beneficial aspect of mixes with high workability without adding more liquid is that they may enhance the gel's binding capability with aggregates. Wan et al, investigated about the effect of steel fibers dispersion in the flexural strength of the concrete(Wan et al., 2020). The placement method of concrete decides the dispersion of steel fibers and fiber orientation. Concrete was poured in the center of the prism and allowed to spread out along its length by external vibration, as evidenced by earlier research showing that specimens produced by pouring concrete in the center had higher flexural strength. Once the surface is finished, the exposed surface of the cast specimen in mold was covered with wrapping sheet to avoid the rapid expelling of water to atmosphere. After 24 hours of casting the specimen was demolded. It is essential to promptly cover the specimen with a plastic sheet due to the usage of minimal amount of liquid and absence of bleed water in UHPGC. This surface drying can potentially affect the hardened properties.

The GGBS based geopolymer concrete does not require special curing regimes like heat curing and steam curing to achieve the desired strength. The high calcium GGBS leads to Calcium Alumina Silicate (CASH) gel in room temperature whereas the low calcium SCM based geopolymer composites (like fly ash, metakaolin and silica fume) requires high temperature curing for polymerization process. Hence all the specimens were left in room temperature in shade (22 to 29°C).

2.4. Testing

2.4.1. Flow properties

The flowability of fresh concrete was measured immediately after mixing using a standard flow table test apparatus, in line with ASTM C1437(ASTM C1437, 2020). As the copper slag is having least percentage of absorbing water from the liquid used for mixing, it makes the concrete more viscous. The flow test was conducted for the various mixes by varying dolomite content and percentage of steel fibers.

2.4.2. Compressive Strength

The typical Compression Testing Machine (CTM) with a 300-ton capacity is used to examine the compressive strength of the concrete using cubes measuring 70.7 mm by 70.7 mm by 70.7 mm. The load is applied at a rate of 5 kNs-^{1} (1.0 MPas^{-1}) as suggested by ASTM 1856M-17 (ASTM C1856, 2017). The tests were conducted after 1st, 3rd,7th and 28th day of casting to analyze the effect of binder in early and later strength.

2.4.3. Split Tensile strength

The tensile strength is an important parameter in developing Ultra-high performance in Geopolymer Concrete. Due to the challenges of determining direct tensile strength through experimental methods, we opted for the indirect approach of conducting Splitting tensile tests. These tests were performed on cylindrical specimens measuring 100 mm diameter and 200 mm length in the standard CTM of 300 Ton capacity. The cylinder is placed laterally and two metal strips were placed in the contact area of cylinder the load is applied at the rate of 1.2 N/mm^2/min in accordance with IS 5816(1999).

2.4.4. Flexural Strength

The assessment of flexural strength is experiment with prism specimens of size 100 mm x 100 mm x 400 mm. After 28-days curing the specimens were subjected to two-point loading in the UTM of 1000 kN capacity. The loading rate maintained is from 1.6 to 1.8 kN/minute.

2.4.5. Water absorption and porosity

The water absorption of hardened concrete is due to capillary forces between the voids as in the soil mass. The percentage of water absorption of the concrete sample measured will directly reflect the volume of air pores and its network. The presence of air pores leads to entry of moisture in to the concrete core resulting in corrosion of incorporated fibers and reinforcement. The water absorption is calculated by the percentage of weigh of the cubes. The porosity is the measure of total percentage of volume of voids compared to the specimen volume.

2.4.6. Micro properties

Microstructural properties of UHGPC samples with natural sand, copper slag, mix with optimal dolomite content, and steel fiber composites were analyzed using a scanning electron microscope (SEM). The SEM study was conducted using a third-generation TESCAN VEGA (LabIndia Instruments Pvt. Ltd, Mumbai, India) scanning electron microscope, which has an acceleration voltage of 30 kV.

4. Results and Discussion

4.1. Flow properties of fresh concrete

The flow percentage of mixes used in both Phase-I and Phase-II of the experiment is tabulated in Table 5. The flowability of the mixes depends on the water absorption capacity of aggregates of liquid from activating gel and reaction components of the precursors. Similarly, the steel fibers addition increased the density of the fresh concrete. The addition of dolomite decreases the density of the mixes up to 30% replacement of GGBS. The flow of various mixes was shown in Figure 5.

Table 5. Fresh density and flowability of mix

Mix	Fresh Density(kg/m^3)	Flow (%)
G100N100	2342.6	85
G100CS20	2416.2	86
G100CS40	2582.0	90
G100CS60	2636.2	91

G100CS80	2712.1	93
G100CS100	2752.1	100
G100D0SF0	2752.1	105
G100D0SF1	2767.0	104
G90D10SF0	2758.1	115
G90D10SF1	2793.8	111
G80D20SF0	2808.4	118
G80D20SF1	2823.8	112
G70D30SF0	2810.0	119
G70D30SF1	2833.6	117
G60D40SF0	2781.2	123
G60D40SF1	2809.3	120

a) b) c) d) e)

Figure 5. Flow of various UHPGC mixes a) G100N100 b) G100D0 c) G80D20SF0 d) G60D40SF0 e) G80D20SF1

4.1.1. Effect of Copper slag

The copper slag, with its limited water absorption capacity, allows any excess water from the alkali liquid to remain in the matrix (Ambily et al., 2015; Rajasekar, Arunachalam and Kottaisamy, 2019). This free water makes the concrete more easily workable as the UHPGC needs nearly a self-compacting flowable mix. The aggregates entrapped water increases as the copper slag quantity increases. Figure 5a and Figure 5b shows the difference of flow between the UHPGC with natural aggregates and copper slag.

4.1.2. Effect of dolomite

The increase in dolomite content in the binder increased the flowability of the UHPGC. The workability of matrix where GGBS is the only precursor is very low compared to the matrix having 40% dolomite. The percentage of increase in flowability is nearly in 38% in the G60D40 matrix than G100D0 matrix. The fresh density is inversely proportional to the flowability as illustrated in Figure 6.

4.1.3. Effect of Steel fiber

In all the mixes irrespective of the aggregate and binder, the steel fiber addition decreased the flowability of the UHPGC.

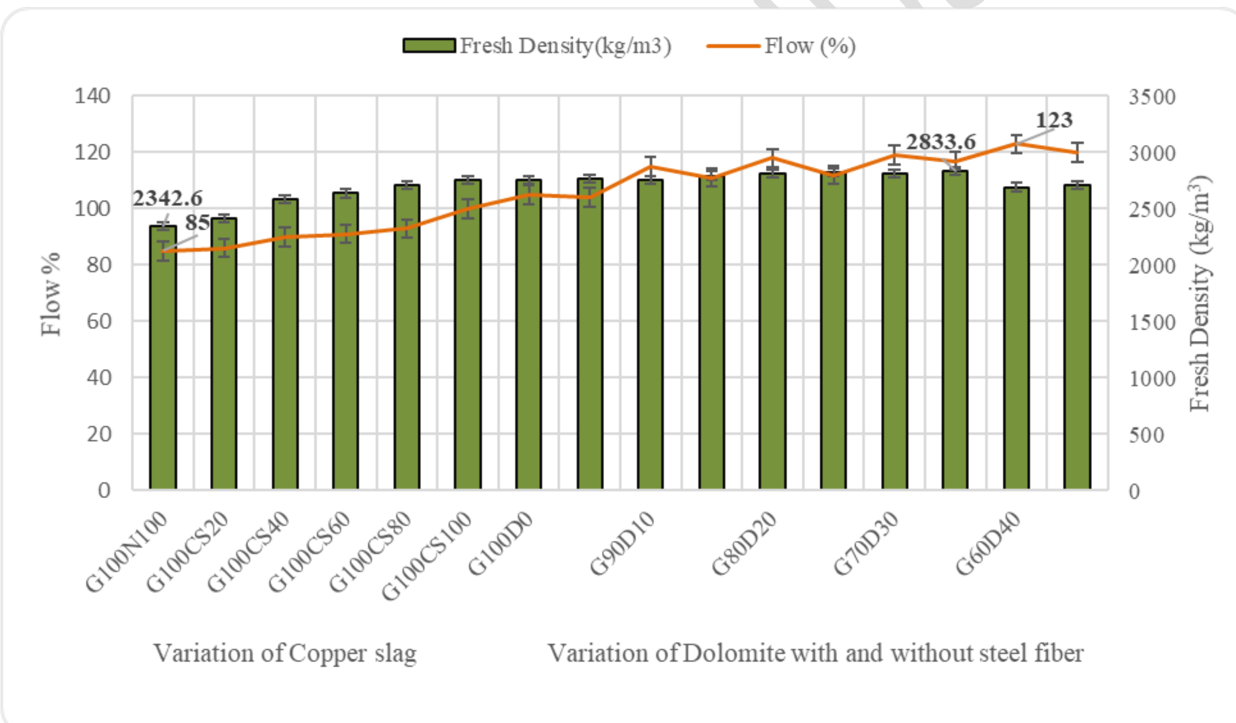


Figure 6. Fresh density and Flow percentage of UHPGC

4.2 Compressive strength

4.2.1. Effect of copper slag

The compressive strength of the UHPGC were tabulated in Table 6. The compressive strength results from Phase-I of the experiment showed that the replacement of copper slag with natural aggregates improves the compressive strength. The copper slag addition increases the fresh and hard density of concrete. Its uneven form, jagged edges, and rough surface, in addition to its unit weight, enhance the bonding properties with the binder substance. From this initial study, it is evident that the copper slag can be effectively used as aggregate to achieve the high strength up to 110 MPa. The mixes having copper slag as aggregate is having 63.8% more compressive strength than the mix with M-Sand as aggregates. The GGBS based geopolymer matrix is known for its high early strength. For 100% copper slag based UHPGC, the 1-day strength, 3-day strength, 7-day strength are 65.6%, 73.2% and 87.4% of the 28-day strength which is very higher than conventional UHPC. It can be noted from the Figure 7, that the addition of copper slag does not influence the speed of strength attainment.

Table 6. Compressive strength of various UHPGC mixes

Mix	Dry Density after 28 days (in kg/m^3)	Compressive strength (in MPa)			
		1 Day	3 Days	7 Days	28 Days
G100N100	2342.6	45.3	50.6	55.5	70.2
G100CS20	2416.2	49.8	52.3	68.4	79.6
G100CS40	2582.0	55.2	58.0	79.7	88.2
G100CS60	2636.2	60.1	63.8	86.2	95.6
G100CS80	2712.1	68.5	73.2	90.4	100.8
G100CS100	2752.1	72.2	80.56	96.2	110.1
G100D0SF0	2752.1	72.2	80.56	96.2	110.1
G100D0SF1	2767.0	76.6	91.3	113.2	130.4
G90D10SF0	2758.1	64.0	73.2	102.0	115.8
G90D10SF1	2793.8	69.2	79.8	122.6	138.2
G80D20SF0	2808.4	63.9	77.6	106.8	119.2
G80D20SF1	2823.8	66.0	80.2	129.9	146.6
G70D30SF0	2810.0	52.6	66.8	106.0	114.6
G70D30SF1	2833.6	58.0	69.5	118.0	130.2
G60D40SF0	2781.2	45.3	55.2	90.2	105.0
G60D40SF1	2809.3	50.1	61.3	96.3	119.2

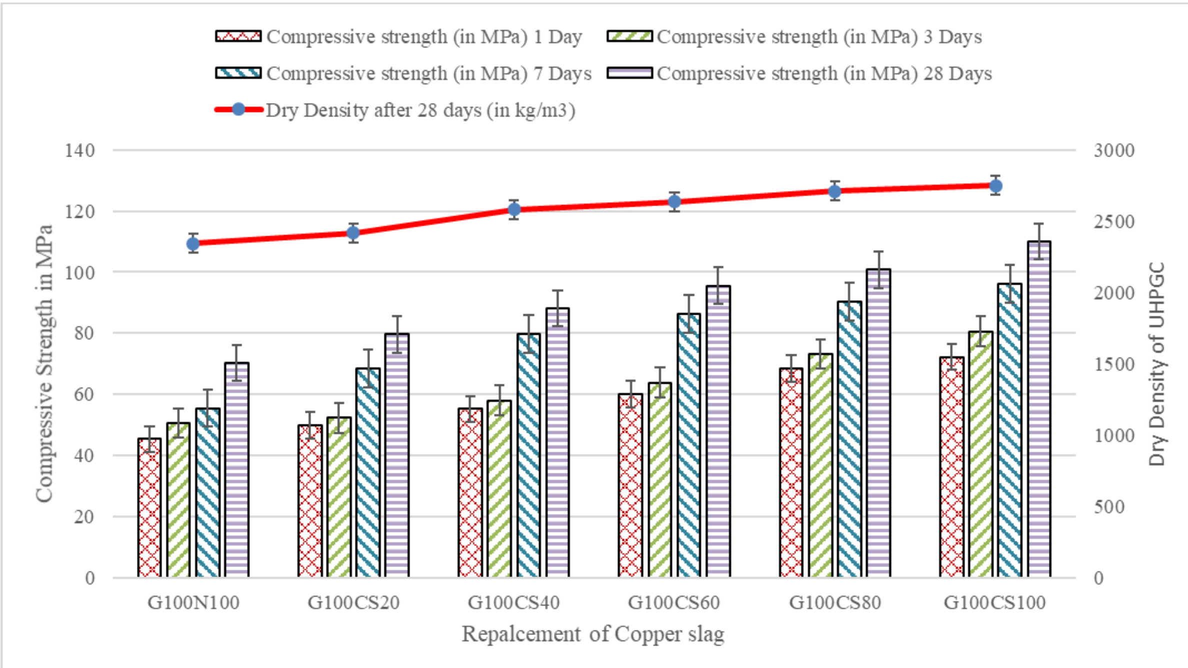


Figure 7. Dry density and Compressive Strength of UHPGC varying copper slag in fine aggregate

4.2.2. Effect of dolomite

Dolomite showed a superior performance in compressive strength up to 20% of replacement with GGBS. The dolomite with 30% and 40% replacement showed a decreasing trend which is due to the presence of magnesium ions. In previous observations, it has been established that magnesium ions can potentially substitute a portion of the calcium ions in calcium silicate hydrate gels, or alternatively, create magnesium silicate hydrate gels(Azimi et al., 2016). The effect of dolomite in compressive strength and density is graphically illustrated in Figure 8. Adding dolomite makes the compression strength better because it has a higher surface area to mass ratio than GGBFS. This makes the packing density higher, which makes the strength higher. But when there is more dolomite (more than 20%), the MgCO3 content went up, which kept the gel from reacting. This made the UHPGPC mixes more uneven, which slowed down the development of the compression strength values and made the microstructure partly weak.

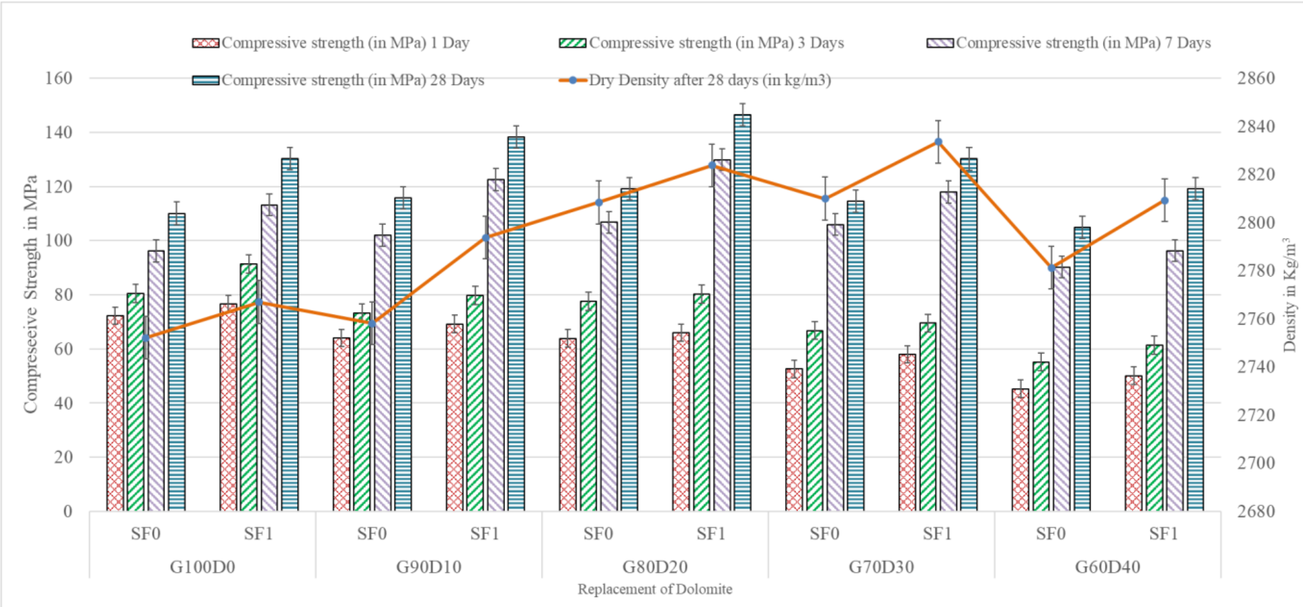


Figure 8. Effect of dolomite in the compressive strength of UHPGC

From the Phase-I results, it was evident that the copper slag utilization up to 100% in fine aggregates gave best results compared to naturally occurring aggregates. Hence, the other mechanical properties like split tensile strength, flexural strength and physical properties like water absorption and porosity were experimented using copper slag as aggregates.

4.3. Splitting tensile strength

4.3.1. Effect of dolomite

Splitting tensile strength is an indirect way of determining the tensile strength of concrete. From Table 7, it is evident that the split tensile strength of the UHPGC increases as the dolomite content increases. This may due to the higher reactivity of the calcium compounds and dense mix formation. The dense geopolymer gel creates a strong bond with granule of aggregates which makes a homogenous mix. On increasing the dolomite content over 20%, the unreactive compounds which acts as inert materials in forming CSH gel weaken the binding nature of the mix composition.

Table 7. Splitting Tensile strength and Flexural strength of UHPGC mixes

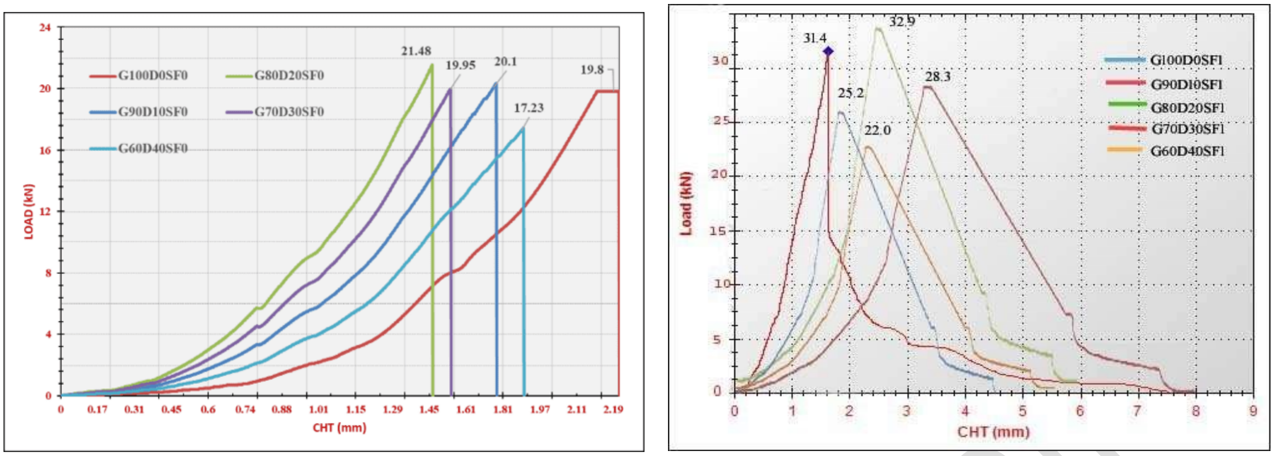
S.No.	Mix ID	Splitting Tensile strength (MPa)	Flexural strength (MPa)
1	G100D0SF0	8.15	9.9
2	G100D0SF1	9.49	12.6
3	G90D10SF0	8.54	10.05
4	G90D10SF1	11.21	14.15
5	G80D20SF0	9.20	10.74
6	G80D20SF1	12.36	16.45
7	G70D30SF0	9.36	9.98
8	G70D30SF1	11.85	15.7
9	G60D40SF0	8.95	8.62
10	G60D40SF1	10.19	11

4.3.2. Effect of steel fiber

The resistance to brittle failure of UHPGC was enhanced by the incorporation of steel fiber to attain ultra-high strength in concrete (Guo and Yang, 2020). The split tensile strength is enhanced by the incorporation of steel fiber, and the specimen is prevented from splitting by the crimped steel fibers. It was clear that the UHPGC samples without fibers shows a brittle failure developed from a single crack, whereas in UHPGC samples with steel fibers failed from multiple distributed cracks by proving the enhancement of ductility to the concrete.

4.4. Flexural strength

The results of the tests conducted on the flexural strength of UHPGC with and without steel fibers indicate that the presence of steel fiber significantly increases the post-crack straining of the material. The flexural strength obtained from the maximum flexural load shows that the as the dolomite content increases the flexural strength increases up to 20%. Then the strength decreases due to the high value of unreacted calcium and magnesium content. The ultimate flexural load vs Cross Head Travel (CHT) of the UHPGC with varying dolomite content is graphically illustrated in Figure 9a and 9b.



a) (b)

Figure 9. a) Flexural load of the UHPGC without fibers (b) Flexural load of UHPGC with fiber

4.4.1. Effect of Steel fiber

The inclusion of steel fiber in UHPGC is intended to enhance its ductile property in bending. The UPGC is known for its brittle nature. It can be noted in Figure 9a and 9b that the post failure slope is gradually decreasing in the UHPGC specimen with steel fibers but there was a sudden brittle failure in specimen without fibers. The introduction of crimped steel fibers improves the concrete's ductile behavior, which in turn improves its flexural strength (Bhutta et al., 2017; Liu et al., 2020b; Lao et al., 2022). It is evident from the crack formation that specimen without fiber failed suddenly after first crack. But the UHPGC with fibers sustained the load through stretching of crimped fibers. The pattern of crack formed also is a non-linear crack showed the resistance developed against flexure.

4.5. Water Absorption and Porosity

The samples were weighed before and after immersion in water. The percentages of water absorption and porosity are shown in Table 8. From Figure 10, it is evident that the water absorption and porosity increases as dolomite content increases up to 20%. Then the properties getting decreased on increasing the dolomite content. As a result of the high packing density and the substitution of GGBS with dolomite up to 20%, the intermolecular space was reduced significantly (Vaganov et al., 2017). But the increase of dolomite increases the $MgCO_3$ content in the geopolymer matrix which leads to the inferior effects. The occurrence of white patches is observed in the cube specimens with 30% and 40% dolomite content. This may due to the unreacted $CaCO_3$ and $MgCO_3$ components.

Table 8. Water absorption and porosity of UHPGC

Sample ID	Water Absorption (%)	Porosity (%)
G100D0SF0	0.35	3.45
G100D0SF1	0.32	3.44
G90D10SF0	0.34	3.41
G90D10SF1	0.33	3.43
G80D20SF0	0.33	3.36
G80D20SF1	0.34	3.46
G70D30SF0	0.33	3.37
G70D30SF1	0.35	3.48
G60D40SF0	0.35	3.40
G60D40SF1	0.34	3.43

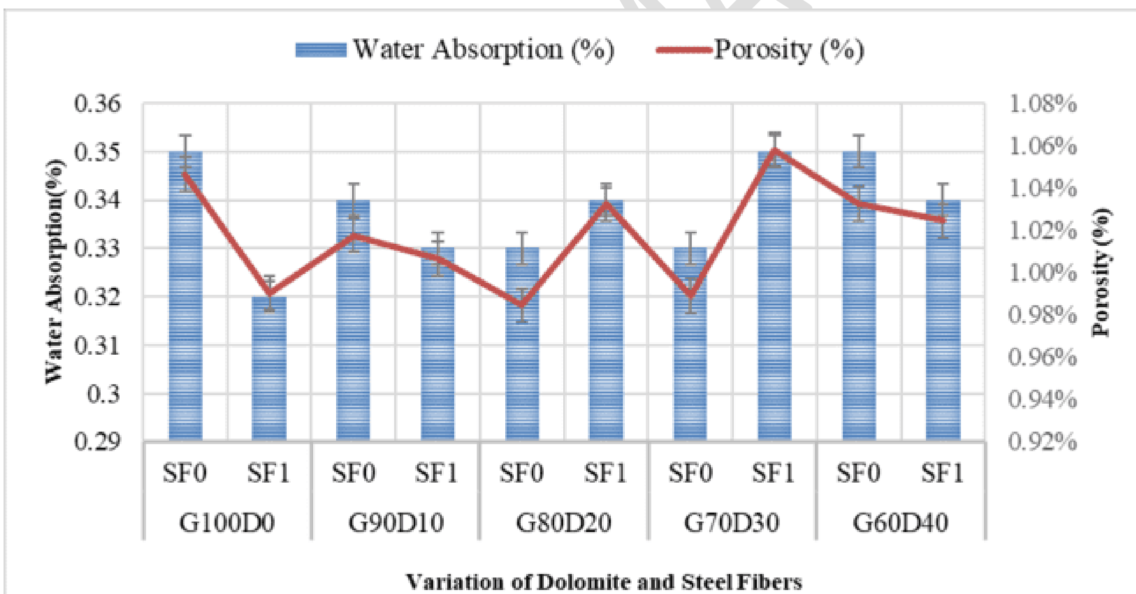
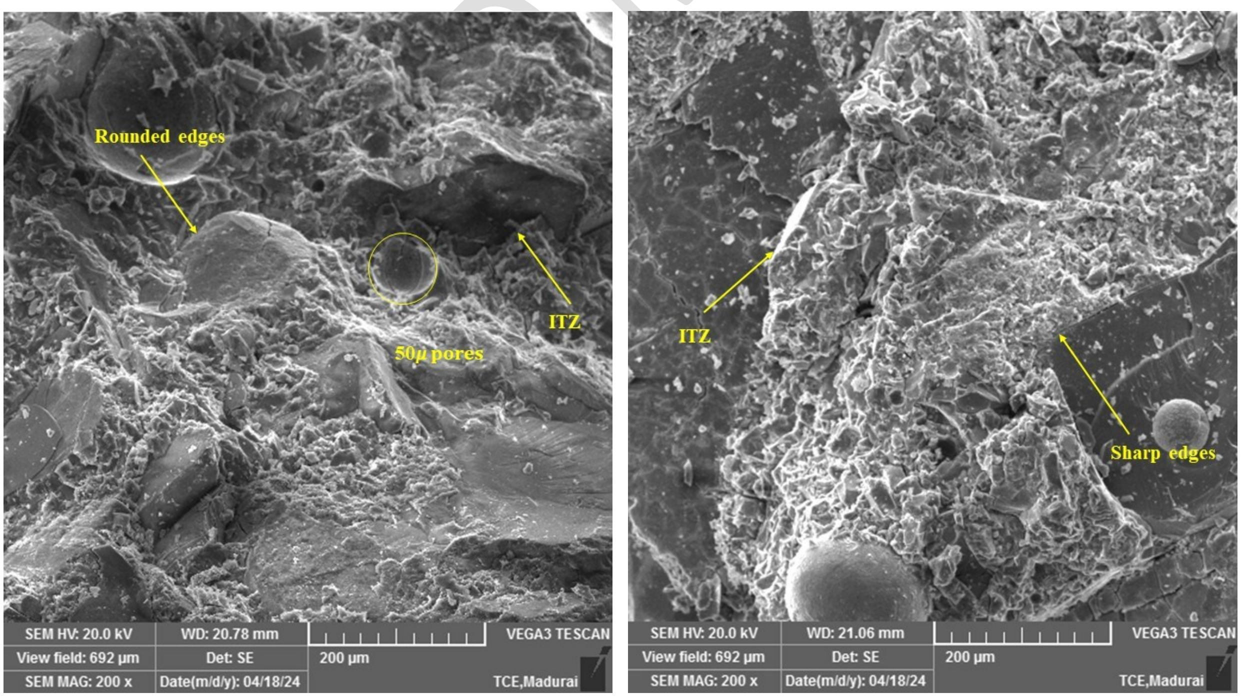


Figure 10. Water absorption and porosity of UHPGC Samples

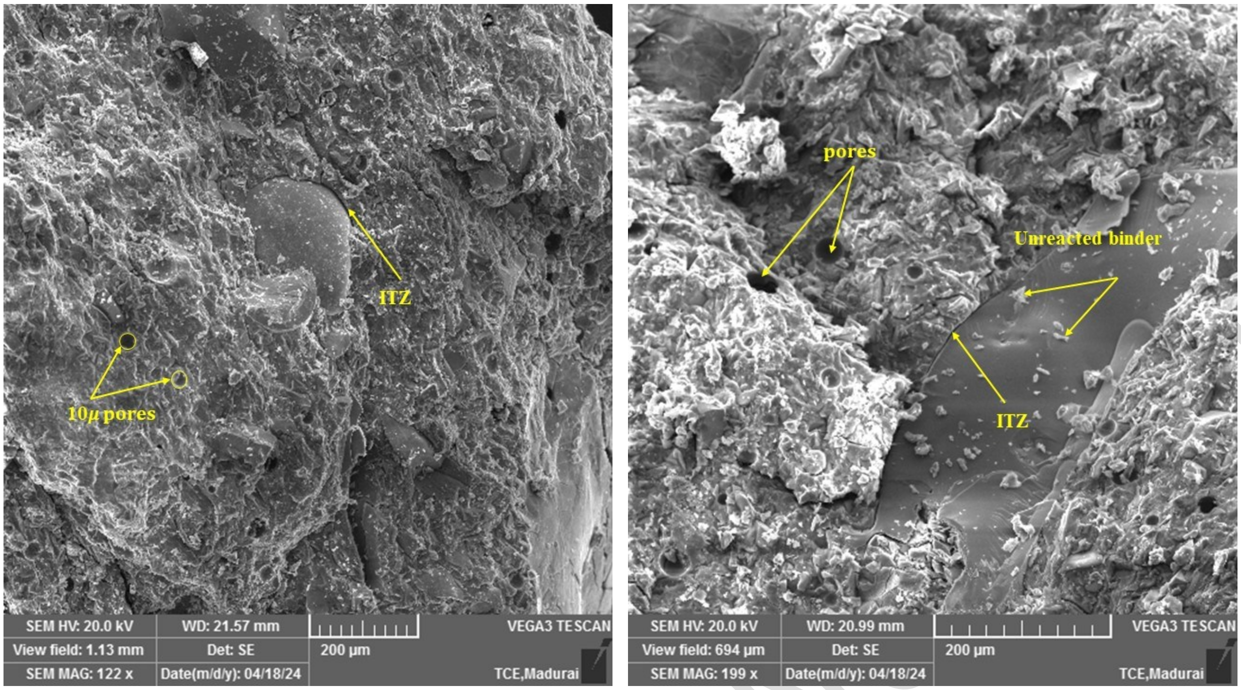
4.6. Micro properties

The microscopic images of UHPGC samples are presented in Figure 11 to 13. The fine aggregates under 1.18mm used shows a good result in achieving high packing density. The influence of copper slag in UHPGC shows a huge impact in the bonding between binding gel and filler materials. In Figure 11a, it can be seen that the irregular rounded edges of natural aggregates create a smoother bond with the gel material, whereas from Figure 11b it is clear that the copper slag with its irregular sharp edges creates a stronger bond with gel materials. The multi-faceted granule with sharp edges bounds a strong adhesiveness towards the matrix. The Figure 16a and 16b are the micrographs of UHPGC with 20% and 40% dolomite respectively. The former shows a strong bond compared to 100% GGBS matrix which is shown in Figure 11b. From the Figure 12b, it is evident that the white unreacted compounds created in the matrix is due to higher quantity of dolomite in binder. This forms a weaker matrix and more ITZ with aggregates. Similarly, from the Figure 13a and 13b, the matrix containing 40% dolomite form a weak bonding with fibers whereas the 20% dolomite gel forms a clear bonding with the fibers which reduces the network of weak zones enhancing higher compressive and tensile strength.



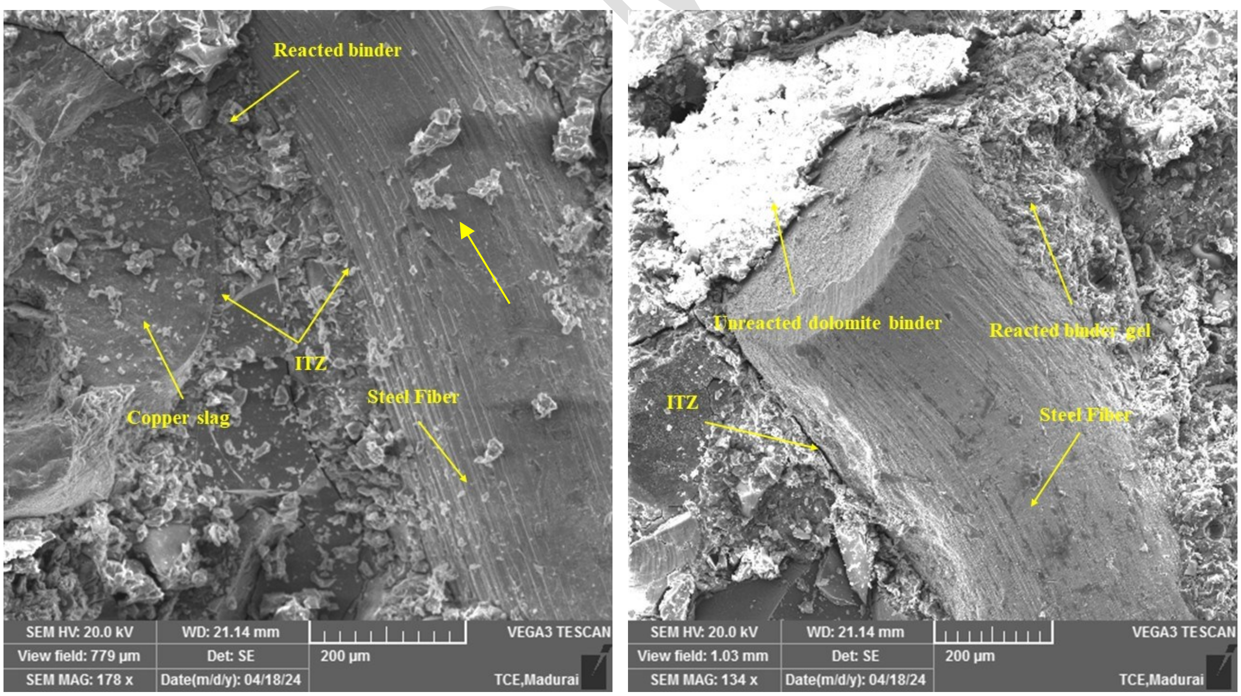
(a) (b)

Figure 11. SEM images of UHPGC specimens with (a) natural aggregates and (b) Copper slag



(a) (b)

Figure 12. SEM images of UHPGC specimens with (a) 20% dolomite and (b) 40% dolomite



(a) (b)

Figure 13. SEM images of fibers in UHPGC specimens with (a) 20% dolomite and (b) 40% dolomite

UHPGC with 20% dolomite exhibits a decrease in the occurrence of microvascular voids and micro cracks. Microstructural studies indicated that the UHGPC made with GGBS-dolomite exhibited a denser microstructure compared to the UHGPC made solely with GGBS.

5. Conclusion

The experimental findings clearly show that copper slag can be used as fine aggregate in UHPGC in place of natural crushed aggregates. From this experimental study, following conclusions have been made.

- The copper slag replacement can be made up to 100% in fine aggregate. The mixes having 100% copper slag is having maximum flow of 17.65% than the mixes having natural aggregates. The UHPGC samples with copper slag as fine aggregates is having 56.9% more compressive strength than the samples having natural aggregates.
- As the dolomite content increases, the percentage of flowability increases. The mixes having 40% dolomite replacement in GGBS is 23% more flowable than the mixes having 100% GGBS. As the previous studies concluded, the addition of steel fiber decreases the flowability of the UHPGC.
- When 20% of the dolomite content in the GGBS binder was substituted, the UHPGC mix showed the highest compressive strength. Even though the main objective of adding dolomite is to improve the workability, as an added advantage it improves the compressive strength up 20% of replacement.
- Regarding indirect tensile and flexural properties, the optimum dolomite content in GGBS based binder was found to be 20%. The increase in fresh and hardened density plays a vital role in the superior mechanical behavior. Porosity and water absorption in the UHPGC reduced when dolomite content raised up to 20% replacement in GGBS

- Microscopic tests show that replacing dolomite increased matrix-aggregate-steel fiber binding. The ITZ of the 80%GGBS/20%Dolomite matrix bonds well, enhancing mechanical and durability of the UHPGC composites. The study reveals that it is possible to produce the UHPC with geopolymer technology by utilizing industrial by products as major ingredients. This study has achieved a maximum compressive strength of 146.6 MPa and a maximum flexural strength of 32.9 MPa.

The study's limitations arise from the use of copper slag as a fine substance, which is discharged as land disposal in copper producing companies. The most difficult part of using copper slag is collecting and sorting the material. The GGBS-based geopolymer composites have a quick setting characteristic, requiring a fast casting process.

The results of this experimental investigation present good prospects for replacing natural sand with copper slag and utilizing geopolymer technology to create UHPC. This could contribute to the production of environmentally friendly building materials. This will create chances for the safe disposal of copper slag and drastically reduce UHPC's excessive production costs. Because of its high specific gravity, copper slag can be used in the high-performance concrete industry, which requires a larger consumption of natural resources.

Acknowledgments

The authors express their gratitude to the Thiagarajar College of Engineering (TCE) for supporting us to carry out this research work. Also, the financial support from TCE under Thiagarajar Research Fellowship scheme (File.no: TRF/Jan-2023/14) is gratefully acknowledged.

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