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The Novelty of Using Glass Powder and Lime Powder for Producing UHPSCC

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Abstract: In recent years, UHP self-compacted concrete is an innovative category of concrete that has attached a lot of attention because of its higher durability and compressive strength than conventional concrete. So, to overcome the cost of preparation of UHPC and preservation of high-strength deformation and rheological characteristic of self-compacting concrete when replacing a part of expensive cement with three types of production waste. In addition, the problem of reducing environmental pollution is solved. In this study. recycled glass (GP) and lime (LP) powder were used as substitution materials in the manufacture of the UHPSCC. The flowability of UHPSCC was measured by slump flow, T_{50}, V-funnel tests as an indication for the capability of filling and J-ring tests as an indication for the capability of passing. Furthermore, durability and mechanical properties were investigated. The elevated temperature effect was investigated on several UHPCSCC samples with glass (GP) and lime (LP) powder. The test results showed that the incorporation of GP and LP partially replaced cement improved the flowability of UHPSCC. The compressive, tensile, and flexural strength were enhanced by using GP till 20% replacement of cement also, the compression strength values were highly improved by using LP replacement of cement at different ages for (hot and normal curing). The highly compressive strength values for UHPSCC mixes with a 20% replacement ratio of GP and LP as cement replacement materials were 119.0 and 128.8 MPa under hot curing regimes and increased by 6.25% and 9.62%, respectively, than that of similar mixes under normal curing regimes at 90 days. The highly splitting and flexural strength values for UHPSCC 7 mix with 20% replacement level of LP and UHPSCC 9 mix with 20% replacement level of LP and GP were reported at 11.80 and 17.85 MPa which increased by 24.20% and 58.60%, respectively, compared to the control mix.

Keywords: UHPSCC; glass powder; lime powder; recycling

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1. Introduction

UHPC is a new development in concrete innovation. This type of concrete is described by its high durability and compressive strength [1]. UHPC is generally distinguished by great Portland cement quantities, fine aggregates, quartz powder, and silica fume (SF) with reinforcement of steel fibers, providinga good flowability and extremely small water-binder ratio, as well as a great superplasticizer dosage [2]. The minimum compressive strength of 120 N/mm^2 and the larger limit of high-strength concrete are used to describe this category of advanced cement-based products [3]. These UHPC properties are the consequence of enhancing uniformity and removing the coarse- aggregate by using very fine powder with proper packing density, enhancing the microstructure, and mixed fibers [4]. Presently, UHPC is used in precast and prestressed concrete elements, such as lightweight bridges specially abutments and decks, concrete repairs, precast walls, marine platforms, and other architectural applications [5].

Structural elements of buildings made of high-strength concrete are usually densely sections reinforced. The small spacing between steel bars may lead to defects after casting concrete. If this high-strength concrete is self-compacting, the problem of concrete nesting is disappeared and the production of a high-strength concrete building with dense reinforcement would be easy, and the cost of laborers and compacting machines would be reduced because it fills completely the form work easily under its own weight without any defects [6].

Ultra-high-performance concrete (UHPC) can resist high-strength impacts and offers improved mechanical and durability properties compared with ordinary concrete, [7]. Yajun Lv et al. [8], studied the possibility of using hematite powder to partially replace natural river sand at different replacement ratios and its effect on the properties of ultra-high-performance concrete. Experimental results show that the addition of hematite slightly decreased the work performance and compressive strength of UHPC, but substantially increased its flexural and impact strength and showed satisfactory high-temperature performance.

The definition of SCC itself means that the fresh mixture of concrete illustrates an adequate capacity of flowing, passing, and filling under the own weight to be applied to the structural construction with hard congestion from steel reinforcement distribution and formwork with complicated shape without any durable impacts related to segregation, blocking, and bleeding [9]. The higher cement for producing UHPSCC had side affected on the ambiance with the emission of CO_2 gases, which may engage in the greenhouse [10]. To achieve sustainable concrete, cement maybe partially replaced with SF, GGBFS, FA, and RHA. This can reduce pollution by reducing cement content and consequently, reduce the amount of CO_2 released. Furthermore, the cost of used cement in UHPSCC would be reduced by using mineral admixture. Soutsos et al. [11] approved that GGBFS could be used as a cement replacement for up to 36% without a decrease in f_c.

More than one million tons of glass waste are produced worldwide every year. When the glass converts waste, it is disposed of by means of unsustainable places as it does not decompose in the atmosphere [12]. So, the glass can be used in principle as a partial cement substitute if it is finely ground to powder for being amorphous and including moderately huge silicon amount, glass would be an excellent pozzolanic material for concrete manufacturing [13]. Ali et al. [14], and Sharifi [15] studied the impact of using recycled glass waste, such as a fine aggregate on the properties of self-compacted hardened and fresh concrete. They approved that recycled glass aggregate has a positive impact on the SCC fresh properties, but it had an adverse effect on the SCC hardened properties. Some investigators approved the utilization of glass powder in the production of UHPC. Shi Cong Kou [16] presented an experimental study for using glass powder and fly ash as cement substitution and silica-sand, correspondingly in producing UHPFRC. The results proved that fly ash, and decreased the workability of UHPFRC, and using glass powder improved the UHPFRC mechanical properties. Limestone is an appreciated source produced during the stone-crushing process. Limestone powder is used to reduce the CO_2 concrete effect in the Portland cement manufacturing to produce the final cement of Portland limestone [17]. Other common researchers used limestone powders as a metallic admixture for workability improvement [18]. Bentz et al. [19] studied the effect of lime powder addition on early-age parameters such as setting time and heat of hydration, as well as compressive strength development. The inclusion of 10% very fine lime powder by volume as a substitute for cement resulted in a shorter setting time. The aim of this study is the preservation of high-strength, deformation, and rheological characteristics of self-compacting concrete when replacing a part of expensive cement with three types of production waste. In addition, the problem of reducing environmental pollution is solved. The study turned out to be quite extensive and detailed. Various types of analysis of the obtained new ultra-high-strength self-compacting concrete were carried out. Current research methods have been applied, and a number of important results have been obtained. The main target of this study is to develop recycled glass powder and lime powder as cement replacement materials for producing UHPSCC mixture. An experimental study of flowability, durability, and mechanical properties of different UHPSCC mixes and the results of these tests had been discussed.

2. Materials Used

2.1. Cement and Silica Fume

Ordinary Portland cement, CEM I-52.5N which follows EN 197/1, and the silica fume used with a spherical particles size from 0.1 μm to 1 μm and a specific surface area of 17,500 cm^2/g, which complies with IS:15388-2003 and ASTM C1240-03a. The cement and silica fume chemical and mechanical properties are given in Table 1.

Table 1. Chemical composition and physical properties of used fine materials.

Chemical Composition %				
	Cement	**Silica FUMES**	**Glass Powder**	**Lime Powder**
SiO_2	21.5	95	77.68	-
Al_2O_3	5.5	0.88	0.16	-
Fe_2O_3	3.34	1.94	0.32	-
CaO	63.4	0.4	6.89	-
MgO	0.7	0.91	2.9	-
Na_2O	0.15	-	11.2	-
K_2O	0.51	0.2	0.01	-
SO_3	2.4	0.32	-	-
LOI	2.2	-	0.44	-
TiO_2	-	-	0.04	-
Calcite	-	-	-	100
		Physical properties		
Specific Gravity	3.14	2.2	2.52	2.70
Fineness (m^2/kg)	355	17,500	13,050	-
Setting time (min.)	Initial 75			
	Final 322			
Compressive strength (N/mm^2)	2-days 27.3			
	28-days 51.6			

2.2. Aggregates

Natural quartz sand with a modulus of fineness of 2.56 and specific density of 2.60 complies with ASTM C33. Furthermore, quartz powders with specific gravity equal to 2.72 and a mean diameter of 0.803 μm. Figure 1 shows the quartz sand and powder distribution of particles.

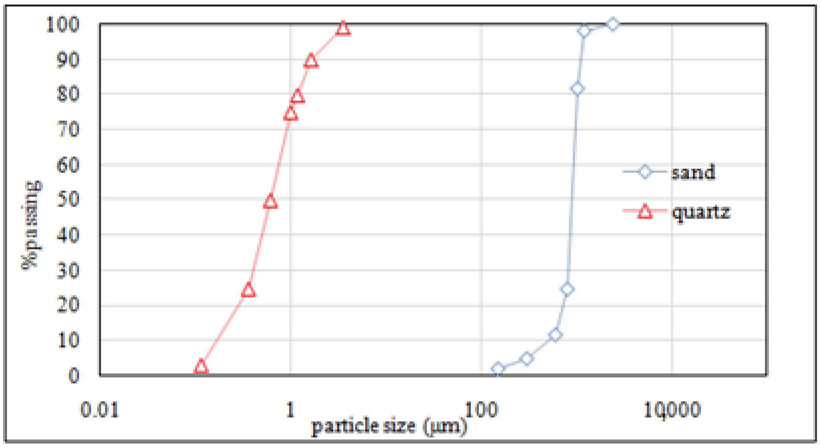


Figure 1. Quartz sand and powder distribution of particles.

2.3. Recycled Glass Powder

As a cement substitute material, glass powder was employed with BET 13,050 cm^2/gm. The specific gravity of used glass powder is 2.52. Figures 2 and 3 present the XRD and SEM for the used glass type.

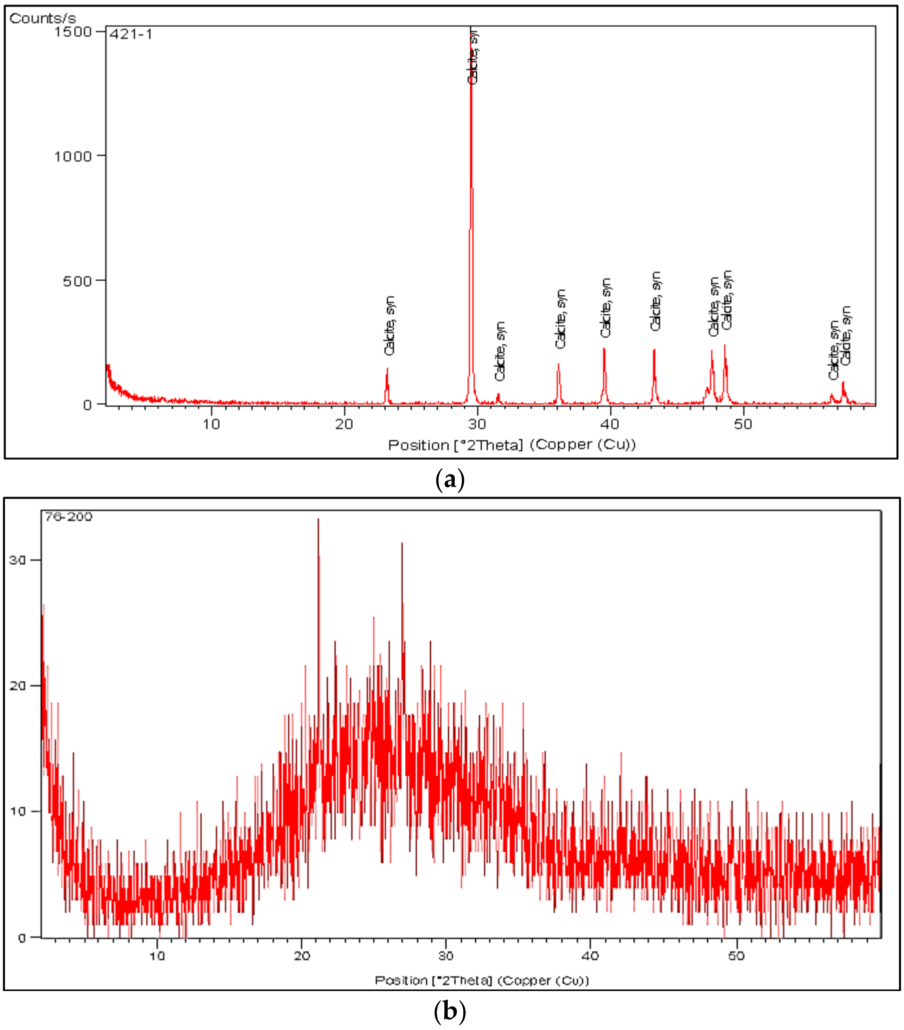
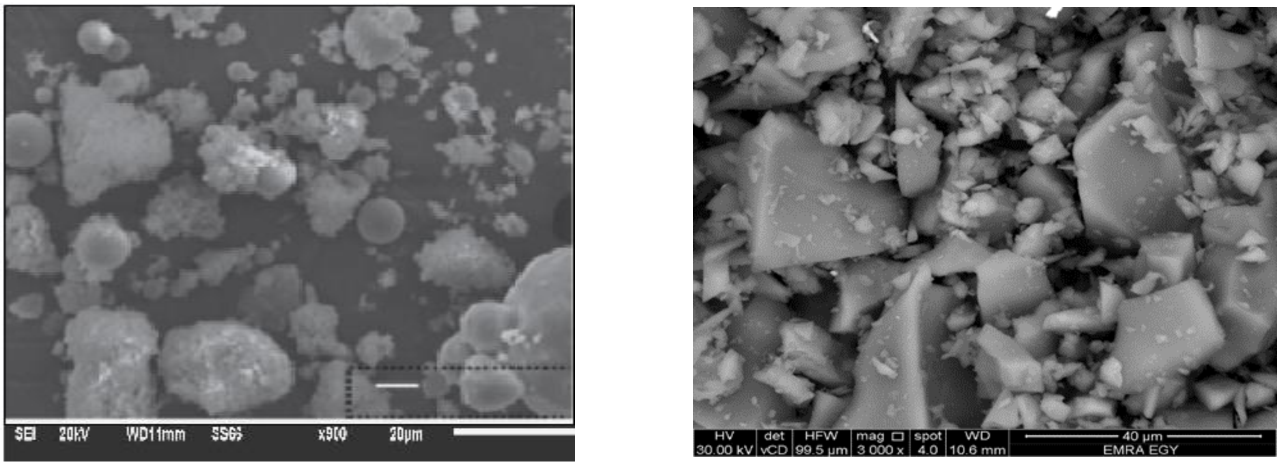


Figure 2. Lime and glass powder X-ray diffraction patterns. (**a**) Lime powder. (**b**) Glass powder.



(**a**) (**b**)

Figure 3. Photomicrographs of Lime and Glass powder under SEM. (**a**) Lime powder. (**b**) Glass powder.

2.4. Lime Powder

As a cement substitute material, lime powder was employed with a diameter of 0.912 µm and specific gravity of 2.7. Table 1 shows the lime powder chemical and physical properties, Figures 2 and 3 present the XRD and SEM for the used lime powder.

2.5. Chemical Admixture

High range water reducing admixtures were necessary for UHPSCC due to the low water/binder ratio. A polycarboxylates superplasticizer with a density of 1085 kg/m^3 was used to achieve the appropriate consistency of self-compacted-concrete.

3. Experimental Study

3.1. Mixture Proportion

A total of 9 mixes were used to produce UHPSCC. The control mix without GP or LP powder; four mixes (UHPSCC 2 to UHPSCC 5) using varying amounts of GP as partial cement substitute (Series I) (from 10% to 40%) as a percentage of cement replacement, and three mixes (UHPSCC 6, UHPSCC 7, and UHPSCC 8) using varying amounts of LP as partial cement substitute (Series II). The last mix UHPSCC 9 presents the combination of 20% of GP and 20% of LP as cement replacement and the polypropylene fiber with a weight of 900 Kg/m^3. The QS, QP, SF, w/b, and HRWRA were maintained constant in all mixes. The nine concrete mixes were designed with W/B 0.18 and %Solid HRWRA of 4.9%, as shown in Table 2.

Table 2. Concrete mixture properties (in kg/m^3).

Series No	Mix-ID	Cement (C)	Silica Fume (SF)	Sand (QS)	Water/ BINDER (w/b)	Glass Powder (GP)	Lime Powder (LP)	Quartz Powder (QS)	Super Plasticizer (HRWRA)	Polypropylene Fiber (PP)
	Control	900	220	1105	0.18	0	0	170	55	0
Series I	UHPSCC 2	810	220	1105	0.18	90	0	170	55	0
	UHPSCC 3	720	220	1105	0.18	180	0	170	55	0
	UHPSCC 4	630	220	1105	0.18	270	0	170	55	0
	UHPSCC 5	540	220	1105	0.18	360	0	170	55	0
Series II	UHPSCC 6	810	220	1105	0.18	0	90	170	55	0
	UHPSCC7	720	220	1105	0.18	0	180	170	55	0
	UHPSCC 8	630	220	1105	0.18	0	270	170	55	0
	UHPSCC 9	540	220	1105	0.18	180	180	170	55	900

3.2. Methods for Preparing Specimens and Testing

To obtain a homogenous mixture and minimize particle agglomeration, all concrete mixes were mechanically batched with a capacity of 10 L. All powder components were combined for 10 min before adding the water and HRWRA. Over the course of 5 min, half of the HRWRA diluted in half of the mixing water was progressively added. During an additional 5 min of mixing, the remaining water and HRWRA were progressively added. Finally, as shown in Figure 4, the fresh, hardened, and durability characteristics of the self-compacted UHPSCC mixes were measured.

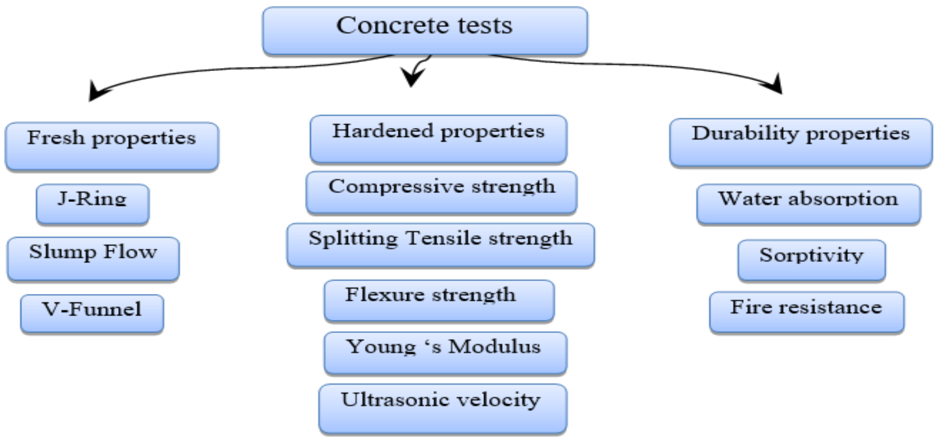


Figure 4. Fresh, hardened, and durability properties.

3.3. Experimental Tests

3.3.1. Slump Test

The slump test was developed to assess the flowability of the UHPSCC mixtures in the absence of any impediment. For the test, a typical slump cone was employed, and the concrete was carefully poured into the cone without compaction. The mean diameter of concrete after raising the standard slump cone is used to calculate the slump flow value.

3.3.2. J-Ring Test

EN 12350-12 was used to conduct the J-ring test. The cone was filled with approximately 7 L of concrete that had not been externally compacted. The heights from the concrete surface to the top of the J-ring within and outside the ring in two directions at right angles were measured when the mold was lifted vertically, and the concrete stopped flowing. Equation (1) was used to compute the final result, the J-ring blocking step *BJ* (also known as the step height).

$$BJ\ (\text{mm}) = \frac{\Delta h_{x1} + \Delta h_{x2} + \Delta h_{y1} + \Delta h_{y2}}{4} - \Delta h_0 \quad (1)$$

3.3.3. V-Funnel Test

EN12350-9 was followed in the construction of the V-funnel. The V-funnel time is the time required for an exact volume of UHPSCC to pass through a narrow opening and provides an indication of the filling ability of UHPSCC provided that blocking and/or flowability are not lower; the flow time of the V-funnel test is related to the plastic viscosity to some extent.

3.3.4. Compressive and Splitting Strength Test

The compressive and splitting strength tests were carried out using a compressive testing machine of 3000 kN capacity. The compressive test specimens are cubic with a length of 100 mm, and the splitting test specimens are cylinders with dimensions 100 × 200 mm. The tests were performed to measure the compressive strength of concrete at different ages of 7, 28, 56, and 91 days using normal curing at 20 °C and hotwater curing at 55 °C according to BS 1881. However, the splitting strength test was performed at 90 ages.

3.3.5. Elasticity Modulus Test

The static elasticity modulus of the UHPSCC was determined using cylinder specimens with dimensions 150 × 300 mm as stated by ASTM C 469-02.

3.3.6. Flexural Strength Test

Prism samples of 100 × 100 × 500 mm were used in measuring the flexural strength according to ASTM C78. A universal testing machine of capacity 1000 KN was used for each mix, three prisms were tested. The flexural strength is expressed as the rupture modulus (*R*) using Equation (2).

$$R\ (\mathrm{MPa}) = \frac{PL}{bd^2} \tag{2}$$

where, *P*: flexure load in (Newton), *L*: length of prism between two supports in mm, *b*: width of prism section in mm, and *d*: depth of prism section in mm.

3.4. Durability Properties Tests

The superiority and durability of concrete were influenced by supplementary materials and inadequate compaction at later ages. Various tests such as water absorption, sorptivity test, and effect of elevated temperature on UHPSCC mixes were carried out as follow.

3.4.1. Water Absorption Test

This test was performed on concrete samples according to BS1881: Part 122. The specimen dimensions for this test were 100 mm size cube samples were prepared. Cubes were then dried at 105 °C in the oven for 24 h and after cubes gained constant weight (*W*1) they were submerged in water. To verify the weight of water gain and calculate the water percentage, cubes were removed from the water and excess water was removed with a cloth, and weight was taken (*W*2) at 0.5, 1-, 24-, 72-, and 168-h intervals and the water absorption calculated by Equation (3).

$$Water\ Absorption = \frac{W2 - W1}{W1} \times 100 \tag{3}$$

3.4.2. Water–Sorptivity Test

This test was performed to determine the rate of sorptivity through the surface of the concrete. The specimens were dried in an oven at 100 °C until they reached a consistent weight. They were placed on a support device at the bottom of the pan with a water level of 2 mm just above the top of the support device, and water take-up was assessed using weight pick-up tests using ASTM C1585-11.

3.5. Effect of Elevated Temperature on UHPC

In this work, an effort was made to analyze the performance of simple UHPSCC at increased temperatures. After being exposed to high temperatures, UHPSCC undergoes physical and chemical changes. In general, the assessment of a fire-damaged structure begins with visual observation of color change, crack growth, and concrete spalling [20]. So, the performance of UHPSCC produced with varying percentages of GP and LP powders at increased temperatures of 100 °C, 150 °C, and 200 °C is examined using an electric furnace. The period at elevated temperature is taken as 30 min for all temperature levels and the rate of heating was 3 C/min. The micro-structural investigation was made on UHPSCC samples exposed to different temperature levels. Physical parameters, such as color change and crack development at different elevated temperatures were recorded by SEM image with EDX.

4. Findings and Discussion

4.1. UHPC Fresh Properties

According to EFNARC criteria, the periods of T_{50} required for the UHPSCC mixes to attain a slump flow diameter of 50 cm were all within 3 average slump around 615 ± 10 mm diameter, as indicated in Table 3. According to the slump flow test findings, the slump flow diameter rose somewhat with increasing GP content. This tendency can be 4 s, which is acceptable according to EFNARC rules [21]. The minimal water absorption of glass powder and its smooth surface were attributed to all UHPSCC mixtures. In addition, as the GP and LP content increases, so does the slump flow time. The prolonged slump flow durations might be attributed to the greater surface area of GP and LP in comparison to cement surface area, which enhanced the viscosity of the paste.

Table 3. UHPSCC fresh properties.

MIX ID	SLUMP FLOW (MM)	T_{50} (SEC)	V-FUNNEL (SEC)	J-RING (MM)
Control	590	2.7	15	8
UHPSCC 2	600	2.8	13	9
UHPSCC 3	605	3.0	10	9
UHPSCC 4	608	3.1	8.5	10
UHPSCC 5	613	3.5	8.0	10
UHPSCC 6	620	2.1	9.0	7
UHPSCC 7	623	2.7	8.2	8
UHPSCC 8	625	3.1	7.5	8
UHPSCC 9	606	4.0	11	9

Table 3 shows how to reduce V-funnel timings by increasing the ratio of GP and LP. The EFNARC recommendations [21] (Table 3) recommend that the V-funnel time of SCC be between 6 and 12 s. Except for the control mix, which had a high V-funnel time, all UHPSCC mixes were approved as SCC mixes. The flat surface of the glass powder improved flowability, allowing the concrete to flow down easier and faster. The V-funnel results have been agreed upon, Sharifi (2013) [15].

4.2. UHPC Hardened PROPERTIES

4.2.1. Compressive Strength

Figure 5 shows the compressive strength values of all UHPSCC mixes at different ages under hot and standard curing, whereas Figure 5a,c shows the compressive strength values of UHPSCC mixes with varying levels of glass powder at different ages and under different curing circumstances (NC and HC). The substitution of cement with 10% and 20% GP resulted in better compressive strength values at NC and HC conditions at (56 and 90 ages) compared to the control mix. The compressive strength for the control mix at 90 days is 107.5 and 111.5 Mpa at NC and HC, respectively, while the values of compressive strength for UHPSCC 2 (10% GP) and UHPC 3 (20% GP) were 109.1 and 112 Mpa at 90-day for NC and 116.8 and 119 Mpa at HC, respectively, where values of compressive strength for UHPSCC 3 increase by 4.1% and 6.7% at 90 days for NC and HC which is considered better UHPC mix with glass replacement compared to control mix. The replacement of cement with 10% to 40% for mixes (UHPSCC 2 to UHPSCC 5), respectively, had lower compressive strength compared with the reference at early ages.

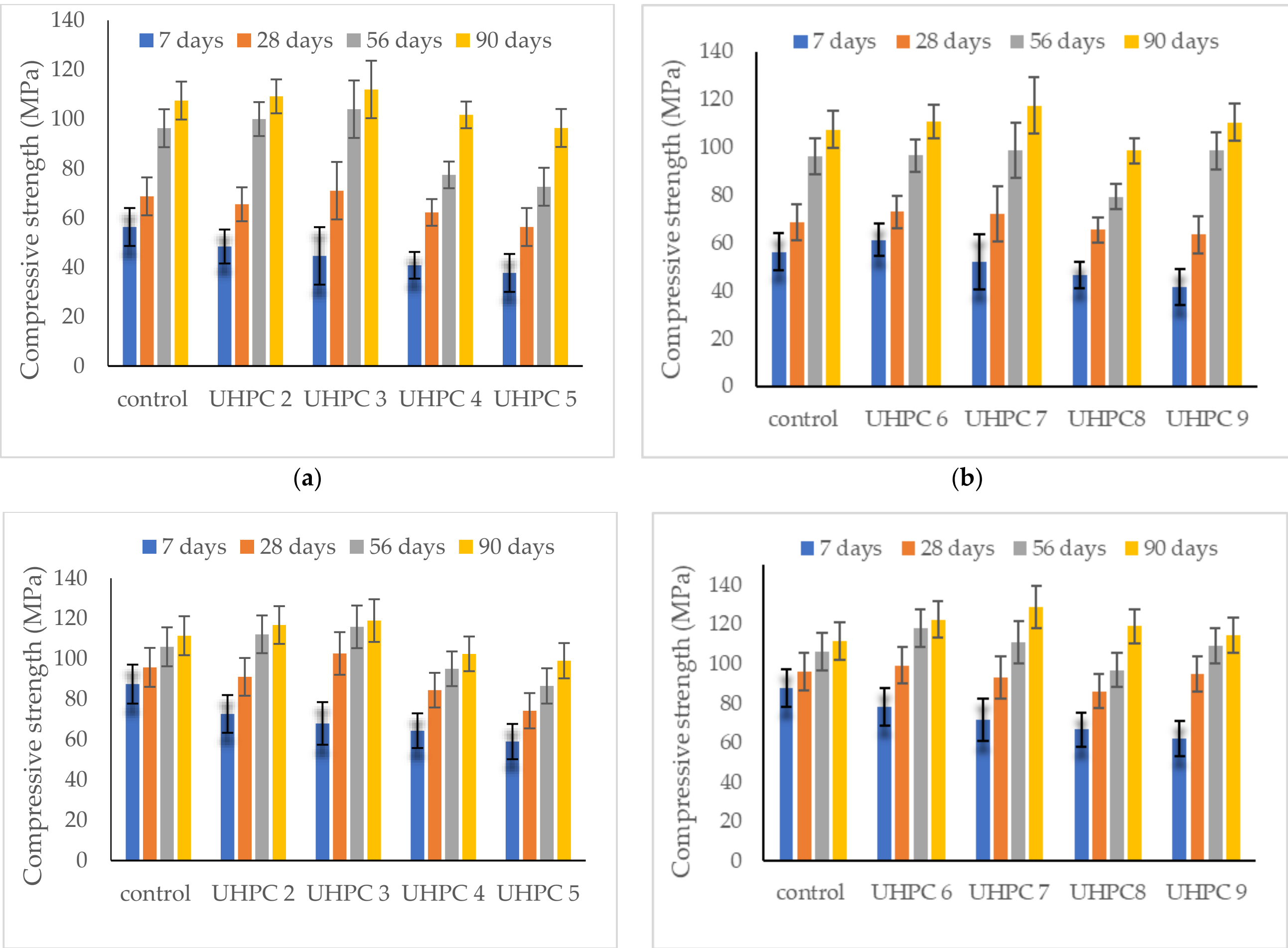


Figure 5. Compressive strengths of UHPC at 7,28,56, and 90 days.; (**a**) glass powder (N-curing), (**b**) lime powder (N-curing), (**c**) glass powder (H-curing), (**d**) lime powder (H-curing).

Also, Figure 5c showed the effect of hot curing on the compressive strength was clear by improving it for UHPC mixes with glass powder. It showed that the compressive strength for UHPSCC 3 (with 20% GP) at hot curing increased by 6.25% to the same mix at normal curing at 90 days. Figure 5 showed that UHPC mixes under hot curing have a lower standard deviation than that exposed to normal curing. This revealed the positive effect of accelerating curing for UHPC mixes and good trend for different curing ages.

Figure 5b,d show the compressive strength values of UHPSCC mixes with varying levels of lime powder substitution at various ages and curing circumstances (NC and HC). The substitution of cement with 20% LP for mix UHPSCC 7 resulted in greater compressive strength values at NC and HC conditions at (56 and 90 ages) equivalent to the control mix. The compressive strength values of UHPSCC 7 (20 percent LP) were 117.5 and 128.8 MPa at 90 days for NC and HC, respectively, as compared to the control mix, which exhibited compressive strength values of 107.5 and 111.5 MPa at 90 days for NC and HC, respectively. Which increased by 9.3% and 15.5% at 90 days for NC and HC, respectively.

Due to the pozzolanic interaction of the GP with the hydrate cement product, which occurred at a later age, the UHPSCC mixes with GP replacement ratios give superior mechanical characteristics at both 56 and 90 days of NC, as well as HC, compared to the control. Particularly, the development of CH is a result of the hydraulic reaction between cement and water, which reacts with glass powder to generate new C–S–H to fill the pores structure in concrete. As a result, at a later age of NC or with accelerated HC, the mechanical characteristics of the concrete are greatly enhanced [10].

The UHPSCC 7 mix with a 20% LP replacement ratio has a higher compressive strength than the control mix by 9.3 percent and 15.5 percent at 90 days for NC and HC, respectively, and it also has a higher compressive strength than the UHPSCC 9 mix with a 20% LP and GP content combined by 6 percent and 11.2 percent at NC and HC, respectively due to the consumption of calcium hydroxide, which is created by hydration products with low cement concentration following replacement.

Furthermore, the increasing of LP content provides enhancement of the compressive strength up to 20% of the replacement level of cement. This is contrasted with Nguyen, 2018 [22] who experienced the highest amount of slag substitution using dolomite powder was 30% at 7 and 28 days to produce higher compressive strength but Wang, C [23] agreed with those results which stated that the optimum cement substitute of LP is 20% to produce UHPSCC at different ages. Additional studies [24] reveal that LP has a large dispersion and good compaction filler impact on the hydration precipitation of Ca $(OH)_2$ and C–S–H gel in binder content systems and plays a key role in crystallization.

4.2.2. Splitting and Flexural Strength

Figure 6 shows the results of the split tensile tests performed on the cylinders. The results show that UHPSCC mixes with glass powder content up to 20% have a significant increase in tensile strength when compared to control mixes. When compared to the control mix, the UHPSCC 3 mix (20 percent GP) enhanced tensile and flexural strengths by 14.7%, 26.7%, and 26.7%, respectively. In addition, when compared to the control mix, the UHPSCC 7 mix (20 percent LP) enhanced tensile and flexural strengths by 24.2 percent, 49.2 percent, and 24.2 percent, respectively. Glass powder presence increases splitting strength owing to its strong pozzolanic reactivity and filler effect, which decreases the volume of weak calcium hydroxide and substitutes it with C–S–H, which has greater strength. With 16.78 MPa when lime powder appears to have the best effect on flexural strength enhancement. GP is increased by 20%.

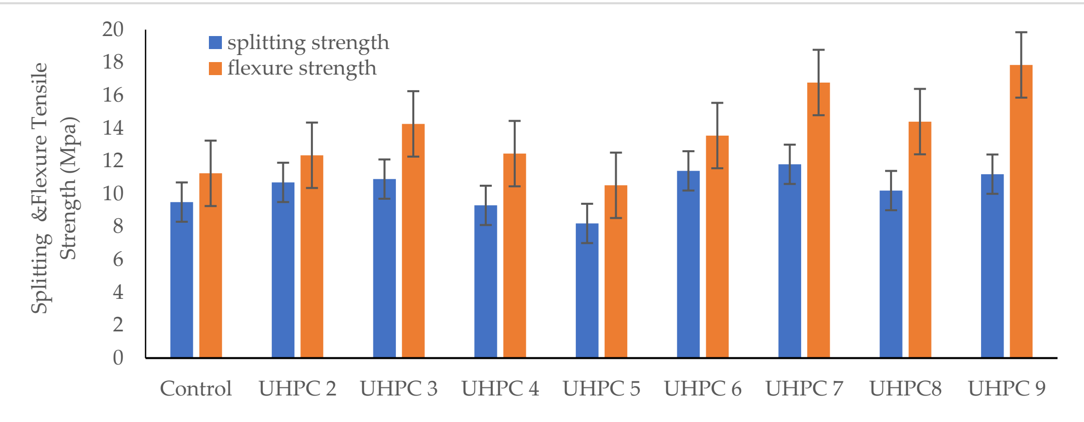


Figure 6. Flexural and splitting strengths after 90 days for glass and lime powder replacement ratios.

The strength tends to diminish as the number of doses increases. In addition, the flexural strength of the UHPC 9 mix was 17.85 Mpa, which was greater than all other UHPSCC mixes. This is owing to the inclusion of polypropylene fiber content in this mix, which acts as a crack stopper in the underloading of concrete, resulting in an increase in ductility and toughness, as well as enhanced flexural strength. Dili and Santhanam, 2004 [25], found that the flexural strength of both fibers reinforced and plain UHSC and HPC specimens were stronger for specimens treated in hot water at a temperature of 90 °C (194 °F) compared to specimens cured under normal circumstances.

4.2.3. Elasticity Modulus

Figure 7 represents the UHPSCC mixes elasticity modulus. It is observed that the modulus of elasticity is ranged from (35–47) Gpa. This is inconsistent with Richard and Cheyrezy's who reported values for Young's modulus of (50–60) Gpa [4]. From Figure 7, it is noticed that the elasticity modulus increased with increasing substitute level of cement by GP and LP up till reached 20% then with more dosage, this value is decreased. The increase in compressive strength can be attributable to the pozzolanic reactivity for producing dense newly C–S–H and consumption of CH. The modulus of elasticity for mixes UHPSCC 7 (20% LP) and mixes UHPSCC 3 (20% LP) was recorded at 43.75, and 46.4 Gpa, which are considered higher values compared to the control mix to be recorded at 39.6 Gpa.

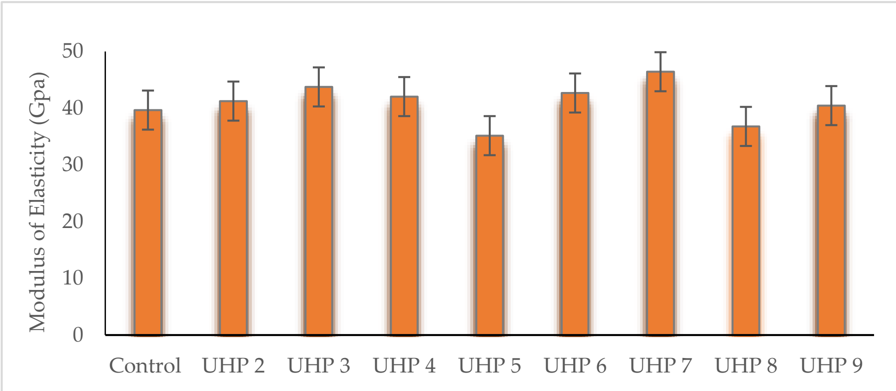


Figure 7. Modulus of elasticity after 90 days for glass and lime powder replacement ratios.

4.2.4. Ultrasonic Pulse Velocity

The ultrasonic pulse velocity device is a non-destructive method of determining the internal homogeneity of concrete. For all UHPC mixes, we can conduct from this test the effect of utilization of glass and lime powder as filler effect for UHPC mixes. The UPV method followed the same path as compressive strength, with the UPV increasing as the compressive strength increased. The velocity of UPV depends on the density and the quantity of voids which obstructed the waves of ultrasonic. So, it can transverse easily into solid but the transition of it into voids difficulty. Figure 8 represents the values of ultrasonic pulse velocities for all UHPSCC mixes at 90 days. The UPV ranges from 4.03 to 5.07 Km/s. This variance is attributed to the structure's degree of densification and percent of internal vacancies. In the UHPSCC 7 mix, which contains 20 percent LP, the maximum pulse velocity value of 5.07 Km/s was attained and increased by 21.8% compared to the control mix with a value of 4.16 Km/s. However, for the UHPSCC 3 mix with 20 percent GP, the maximum pulse velocity value of 4.24 Km/s was attained and decreased by 16.3% compared to the UHPSCC 7 mix. This is an indication of better homogeneity for using the optimum percentage of 20% LP in UHPSCC 7 mix corresponding to all mixes. Furthermore, the increase of replacement by LP content leads to increasing the UPV values up to 20%.

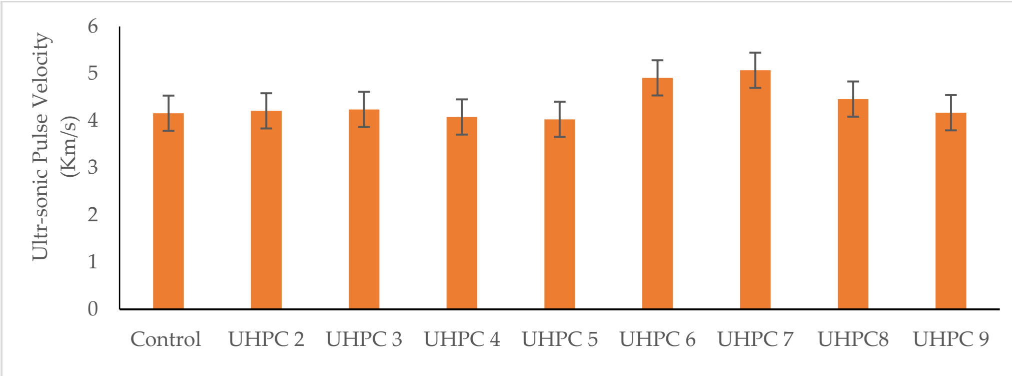


Figure 8. Ultrasonic pulse velocity after 90 days for glass and lime powder replacement ratios.

4.3. Durability

4.3.1. Water Absorption

The UHPSCC water absorption percentages under different replacement ratios of cement by GP and LP are accessible in Figure 9. The results reveal that increasing the amount of GP and LP in the mix reduces water absorption compared to the control mix. The water absorption for the control specimen was 1.151% and the minimum values of water absorption were observed at 1.05% and 0.98% for both UHPC 4 (30% GP) and UHPC 8 (30% LP), respectively. So, the water absorption for UHPSCC 4, 8 mixes were decreased by 8.77% and 14.8% to the control mix. This decrease in water absorption might be attributable to improved aggregate paste matrix adherence and density with the addition of glass and lime powder. In addition, because of the nano-particle size used lime powder act as filler material and densified concrete. The increasing of lime powder content as cement replacement materials led to a decrease in the water absorption. This result contrasted with (Kanellopoulos, 2014) [26] who reported that the using recycled lime powder had an inverse effect on the water absorption, however, it has a lot of potential as a cement substitute filler.

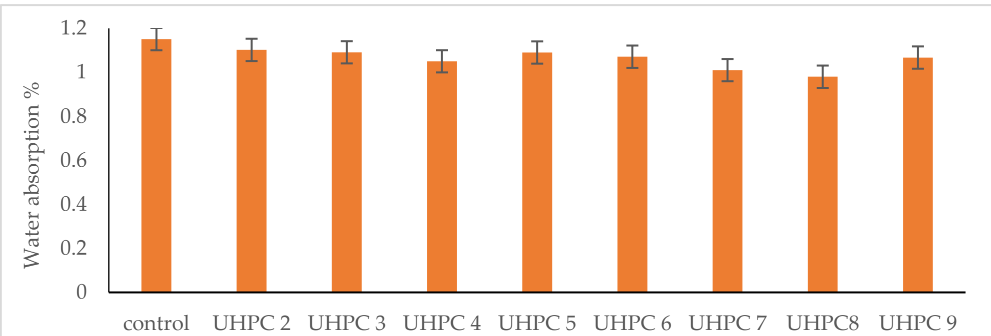


Figure 9. Water absorption values after 90 ages for glass powder replacement ratios.

4.3.2. Sorptivity

Sorptivity is used to assess the long-term durability of concrete. A UHPSCC concrete sample is partially submerged in a bottle containing with containing distilled water technique. The key attribute that absorbs water inside the concrete sample is capillary suction, which is primarily determined by the quantity and continuation of capillary pores. As a result, the mass of the concrete specimen grows and is recorded over time, allowing the sorptivity to be determined. Figure 10 shows the sorptivity test results for all UHPSCC mixtures, which varied from 6.5 to 4.1 gm/cm^2·s$^{-0.5}$. Obviously, all UHPC mixtures have such a smaller sorptivity than in the control. These were agreed with Mostafa, S. A., 2020 [27] who study the effect of nano glass on UHPC durability. The UHPSCC 4 (30%GP), and UHPSCC 9 (20%GP + 20% LP) mixes had the lower values of sorptivity with 4.1 and

4.2 gm/cm^2·s$^{-0.5}$ which decreased by 36.9 and 35.3% compared to the control mix. The high pozzolanic reaction is due to the exits of GP and SF to reduce the pores. In addition to small particles of LP (nanoparticles) due to its filler function, it plugs the pores.

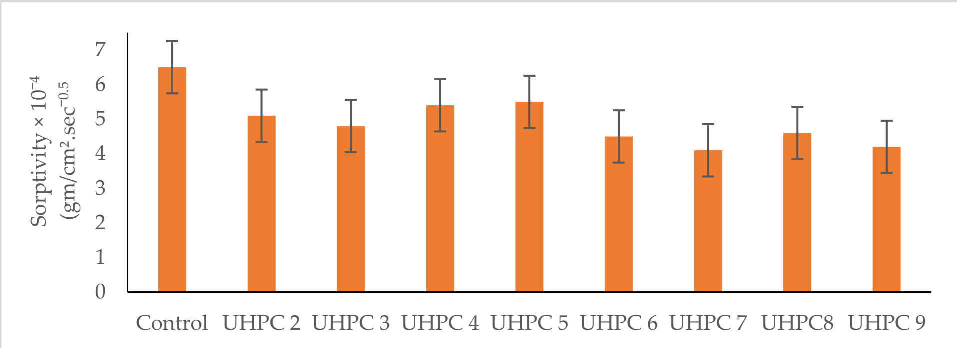


Figure 10. Sorptivity for glass and lime powder replacement ratios at 90 days.

4.3.3. Fire Resistance

UHPSCC concrete is characterized by dense microstructure and under high-temperature conditions, it may be more susceptible to explosive spalling. So, all UHPSCC mixes with glass and lime powder had exposure to the elevated temperature of 100, 150 and 200 °C or a 30-min retention period according to Hiremath, 2018 [28] who used the rate of heat was 5 °C/min, and the retention period of 30 min for heat the specimens up to 800 °C but. Table 4 and Figure 11a,b represents the values of compressive strength at elevated temperature for all UHPSCC mixes and it is noted that the compressive strength has increased for UHPSCC mixes from 22 °C to 200 °C. The percentages of increasing in strength ranged from (9.17% to 19.81%). The UHPSCC 5 mix had a higher percentage increasing strength with 19.81% and the UHPSCC 2 mix had a percentage increasing strength with 19.81%. Unreacted cement and silicafume fast hydrating produces huge volumes of hydrated products and accelerates the pozzolanic reactivity of GP and LP to produce more C–S–H. This is supported by (Hiremath, 2018) [28], who found that when UHPC is subjected to high temperatures, quartz powder participates in the hydration process, resulting in thick hydrated products. Explosive blasting was reported when UHPSCC mixtures were subjected to 250 °C. As a result, the residual strengths of UHPC reported in Table 4 are up to 200 °C, which contrasts with (Hiremath, 2018) [28] who reported that explosive blasting for specimens with various dosages of polypropylene fibers happened next to 400 °C.

Table 4. Compressive strength results under elevated temperatures.

Mixes ID	Compressive Strengths (Mpa) 22 °C	100 °C	150 °C	200 °C	Increasing in Strength (22–200 °C)	Average	STDV
Control	107.5	112.4	118.5	120.3	11.91	114.6	5.86
UHPSCC 2	109.1	113.5	115	119.1	9.17	114.2	4.13
UHPSCC 3	112	116.2	118	123.4	10.18	117.4	4.72
UHPSCC 4	101.7	107.8	112.7	118.1	16.13	110	6.99
UHPSCC 5	96.4	103.4	110.4	115.5	19.81	106.4	8.32
UHPSCC 6	110.7	114.4	119.7	125.3	13.19	117.5	6.36
UHPSCC 7	117.5	121.5	126.3	134.7	14.64	125	7.4
UHPSCC 8	98.5	105.2	112.4	117.5	19.29	108.4	8.31
UHPSCC 9	110.4	116.5	122.4	128.5	16.39	119.45	7.77

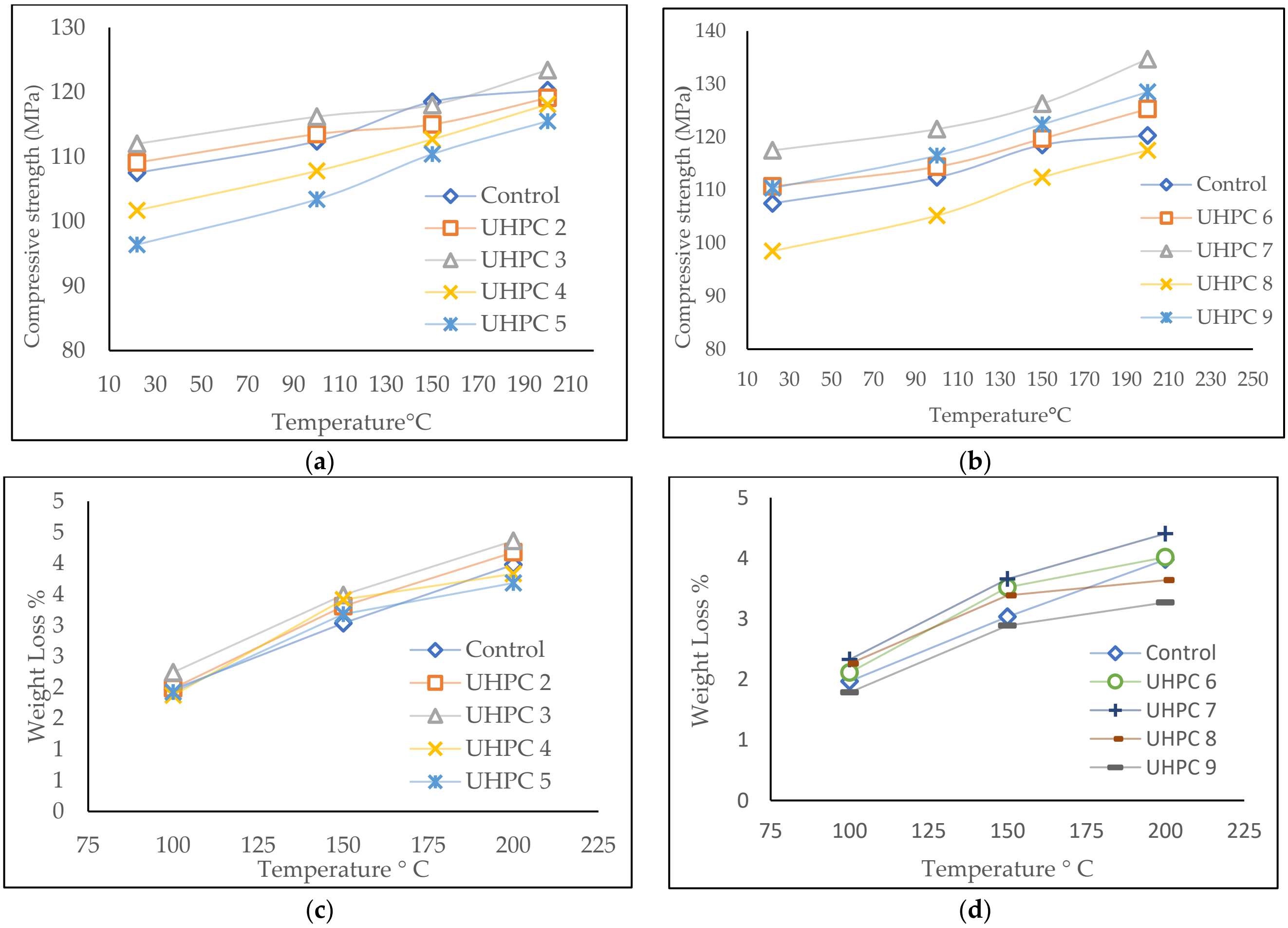


Figure 11. Compressive strengths and weight loss ratios under different temperatures of UHPC. (**a**,**c**) glass powder and (**b**,**d**) lime powder.

There is a side effect of temperature on the control mix, UHPSCC 3 and UHPSCC 7 under a temperature of 100 °C, 150 °C, and 200 °C. At 100 °C, there is no color change and no obvious fracture growth on the surface of UHPSCC. However, the UHPSCC mixes were exposed to temperatures of 150 °C and 200 °C revealed color change and some visible cracks on their surfaces. With regard to the UHPSCC mixes, there were a lot of cracks that appeared on the UHPSCC 3 (20% GP) and UHPSCC 7 (20% LP) mixes compared to cracks that appeared on the control mix under temperatures of 150 °C and 200 °C. This is attributed to the incorporation of GP and LP replaced by cement to add more C–S–H, so under elevated temperature, the vapor pressure increases inside the concrete leads to creating micro-cracks. At increasing temperatures, these little fractures developed to be big cracks.

The percentage of weight loss of all UHPSCC specimens, when exposed to high temperatures, is shown in Figure 11c,d. When the temperature rises, the proportion of weight loss for all UHPC specimens rises. The excess of GP content as cement replacement led to an increase in the percentage of weight loss at elevated temperatures up to 20% replacement. For example, at 200 °C, the UHPSCC 2 mix (10% GP) and UHPSCC 3 mix (20% GP) was recorded 4.18 % and 4.36% weight loss, respectively, while the UHPSCC 4 and UHPSCC 5 mixes were recorded 3.83% and 3.68%, respectively.

Furthermore, the UHPSCC 7 mix (20% LP) was recorded 4.41% weight loss to be considered higher weight loss value compared to the control mix which was recorded 3.98% weight loss at 200 °C. This is explained due to a dense microstructure for UHPSCC containing 20% replacement for GP than the control mix in addition to the amount of excess C–S–H resulting from pozzolanic reactivity and reducing the CH presence and enhancement of the artificial transition region between the matrix and aggregate. Despite raising the percentage of GP replacement to 30 and 40%, the percent weight reduction decreased. In comparison to GP, lime powder proved to be more effective in speeding up cement hydration and increasing pozzolanic reactivity with CH. In the case of lime powder concrete, the UHPSCC 7 mix has the biggest weight loss owing to an increase in C–S–H concentration, which is responsible for the concrete's binding capability, and it decomposes at increased temperatures between 100 °C and 250 °C.

4.4. Microstructure Analysis

The morphology and microstructure of the specimen and the chosen samples containing GP and LP were studied using SEM. Six UHPSCC were selected as samples to study their microstructure as the control mix at normal and hot curing, UHPSCC 3, UHPSCC 7, UHPSCC7 at elevated temperature (150 °C), and UHPC7 at elevated temperature (200 °C). Figures 12 and 13 reveal a thick microstructure with few micro-cracks in the control mix, and this increased density was also caused by the faster hydration process in the hot cured control mix with SEM Figure 14 compared with the normal cured control mix in Figure 12 but the spalling of UHPSCC mixes at a temperature of 250 °C. The previous results are contradicted with li, tan (2018) [29] who studied the effect of 250 ° C temperature for 4 h on UHPC mixes without fibers. He found that after heating at 250 °C for 4 h, micro-cracks can be noted in the concrete mix and the formation of micro-cracks together with the decomposition of hydration products increases the porosity of the matrix and increases in permeability at elevated temperature.

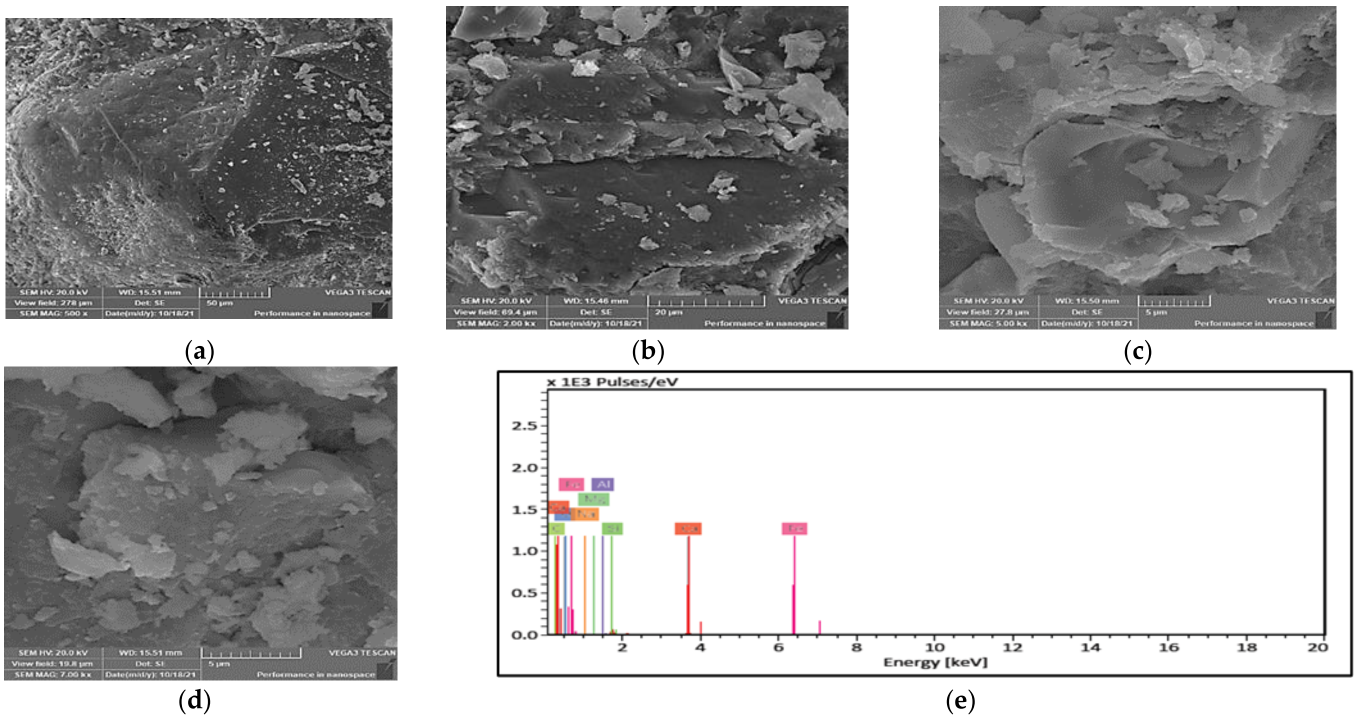


Figure 12. SEM with various magnification factors (**a**–**d**); (**e**) EDX for the control mix at 22 °C curing temperature.

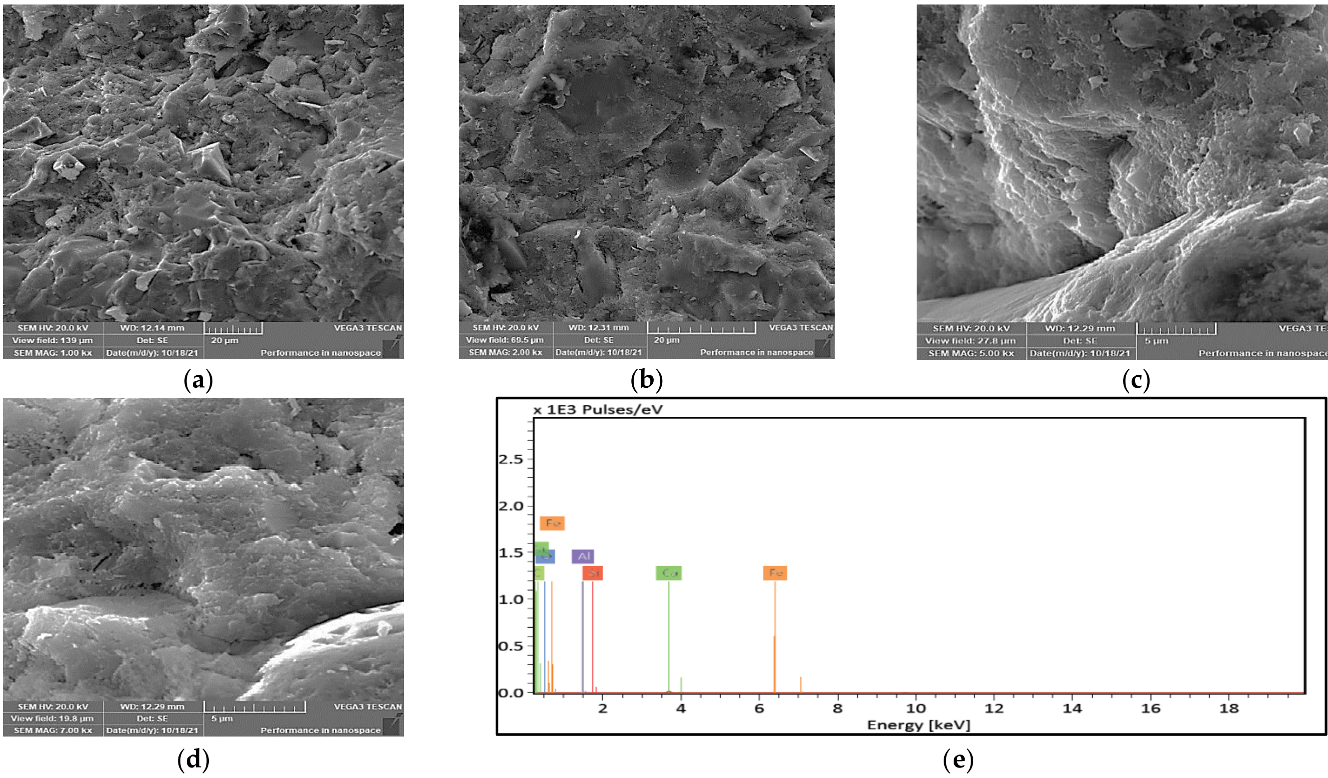


Figure 13. SEM with various magnification factors (**a**–**d**); (**e**) EDX for the control mix at hot curing temperature.

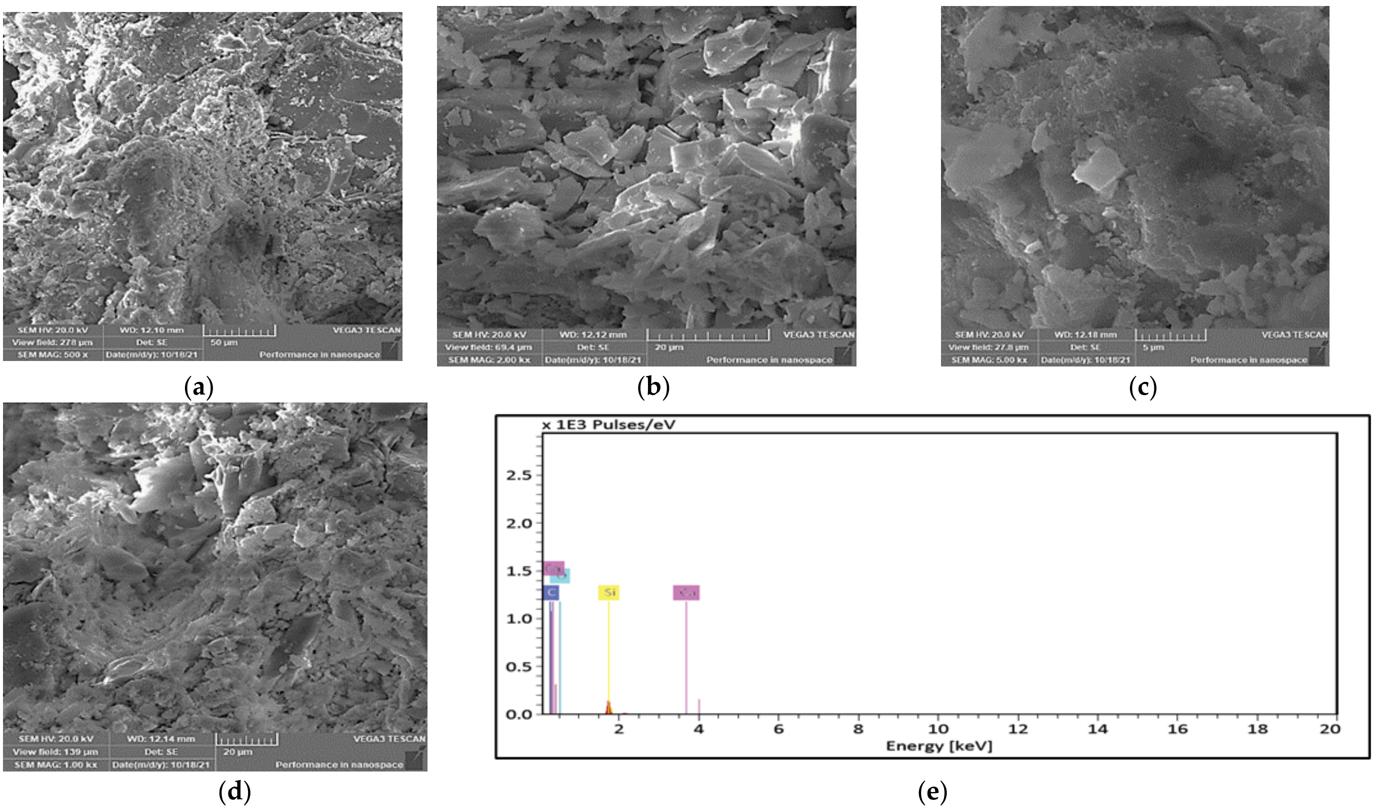


Figure 14. SEM with various magnification factors (**a**–**d**); (**e**) EDX for the mix UHPC 3 at normal curing temperatures.

Table 5 shows the EDX results of the selected UHPSCC mixes to calculate the percentage of Ca/Si which is an indication of C–S–H gel formed by the pozzolanic reactivity. Ca/Si for the hot cured control mix was recorded at 2.98 compared to Ca/Si for the normal cured control mix which was recorded at 1.52. This indicates a stronger pozzolanic reactivity, as well as a reduction in the size of C-H crystals and the production of new C–S–H, all of which contribute to increased strength. SEM figures for UHPSCC 3 mixes with 20%GP content and UHPC 7 mixes with 20% LP content were represented in Figures 14 and 15, respectively. These mixtures had a strong microstructure and a strong bond, with microfractures of a modest thickness surrounding the aggregates ITZ In addition to the use of fine materials such as silica fume and lime powder which had a chemical and physical effect to improve the microstructure and low water-binder ratio acting an important position to reduce the voids, consequently, increase the strength and permeability. From Table 5 the Ca/Si ratio for the UHPSCC 3 mix was recorded at 2.34 to be lower than the Ca/Si ratio for the UHPSCC 7 mix which was recorded at 3.05. This is a perfect indication for more C–S–H gel in the case of mixes with 20% LP than that containing 20% GP. This value of Ca/Si of glass powder mixes is considered lower than the values that Mostafa et al. (2020) [27] reported it to be 2.72. He used the nano glass powder as a low partially cement replacement for producing UHPC.

Table 5. EDX results in different UHPSCC mixes.

Elements	UHPSCC 1 Normal Curing	UHPSCC 1 Hot Curing	UHPSCC 3	UHPSCC 7	UHPSCC 7 (150 °C)	UHPSCC 7 (200 °C)
calcium	29.99	39.62	35.15	38.65	65.25	73.77
oxygen	38.88	34.80	35.49	32.47	21.78	16.74
silicon	19.76	13.28	15.03	12.64	6.25	5.67
Aluminum	1.92	3.15	2.15	4.95	1.79	0.57
Carbon	5.28	3.17	5.97	4.36	4.16	1.19
Iron	2.03	5.39	5.42	5.98	0.77	1.02
magnesium	0.78	0.59	0.88	0.95	-	-
Sodium	1.36	-	-	-	-	0.40
Niobium	-	-	-	-	-	-

Figures 16 and 17 show SEM figures for UHPSCC 7 mixes with 20% LP content exposure to 150 °C elevated temperature and UHPCSCC 7 mixes with 20% LP content exposure to 200 °C elevated temperature. SEM figures show the presence of micro-cracks propagation and formation of air voids especially in the UHPSCC 7 mix at 200 °C compared to a similar mix but with 150 °C. This is because the breakdown of C–S–H to improve the matrix's porosity adds to a mild rise in permeability at increased temperatures. These micro-cracks were seen in the matrix and at the aggregate-matrix contact, particularly at 200 °C in the UHPSCC 7 mix. This discovery contradicts the literature's findings that extremely tiny aggregate particles (less than 1 mm) induce minor bond breakdown at the aggregate-matrix contact [30].

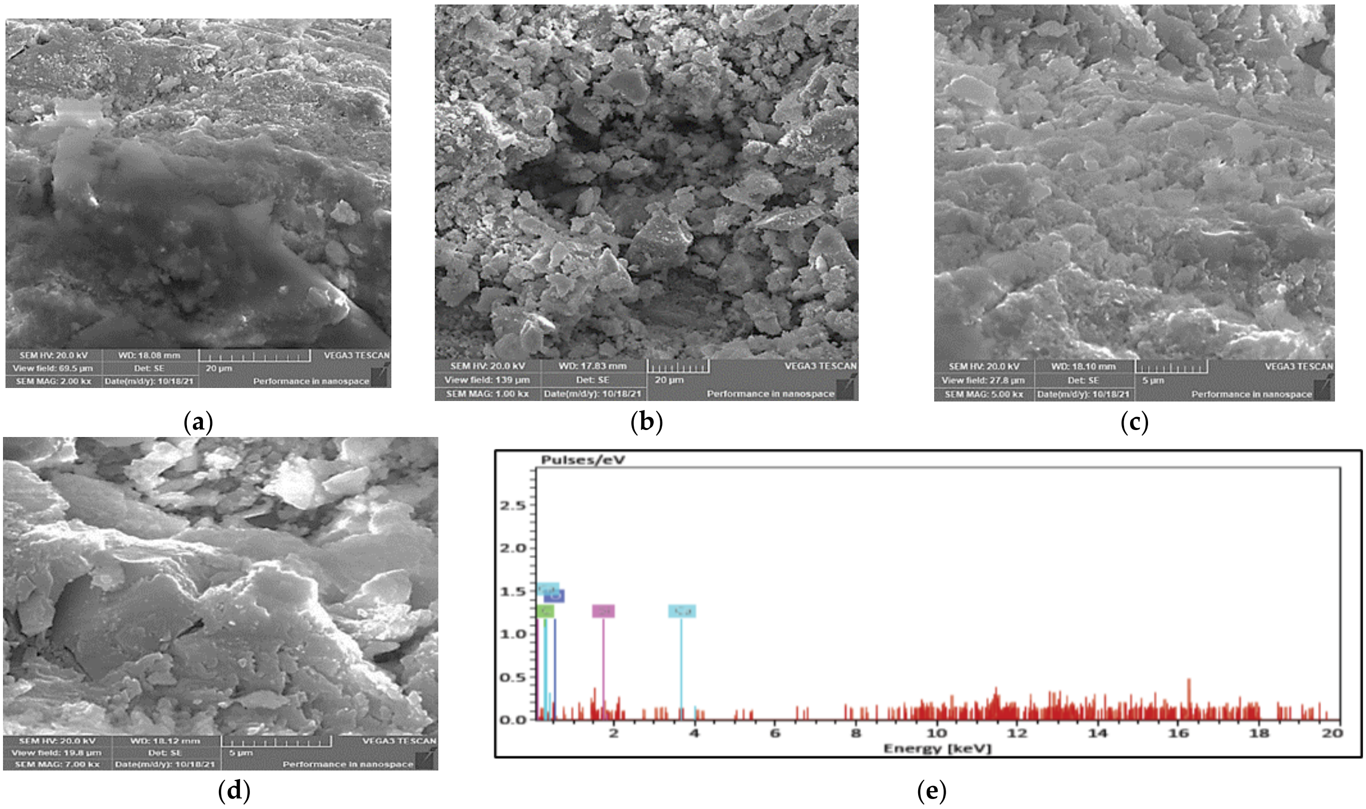


Figure 15. SEM with various magnification factors (**a**–**d**); (**e**) EDX for the mix UHPSCC 7 at normal curing temperature.

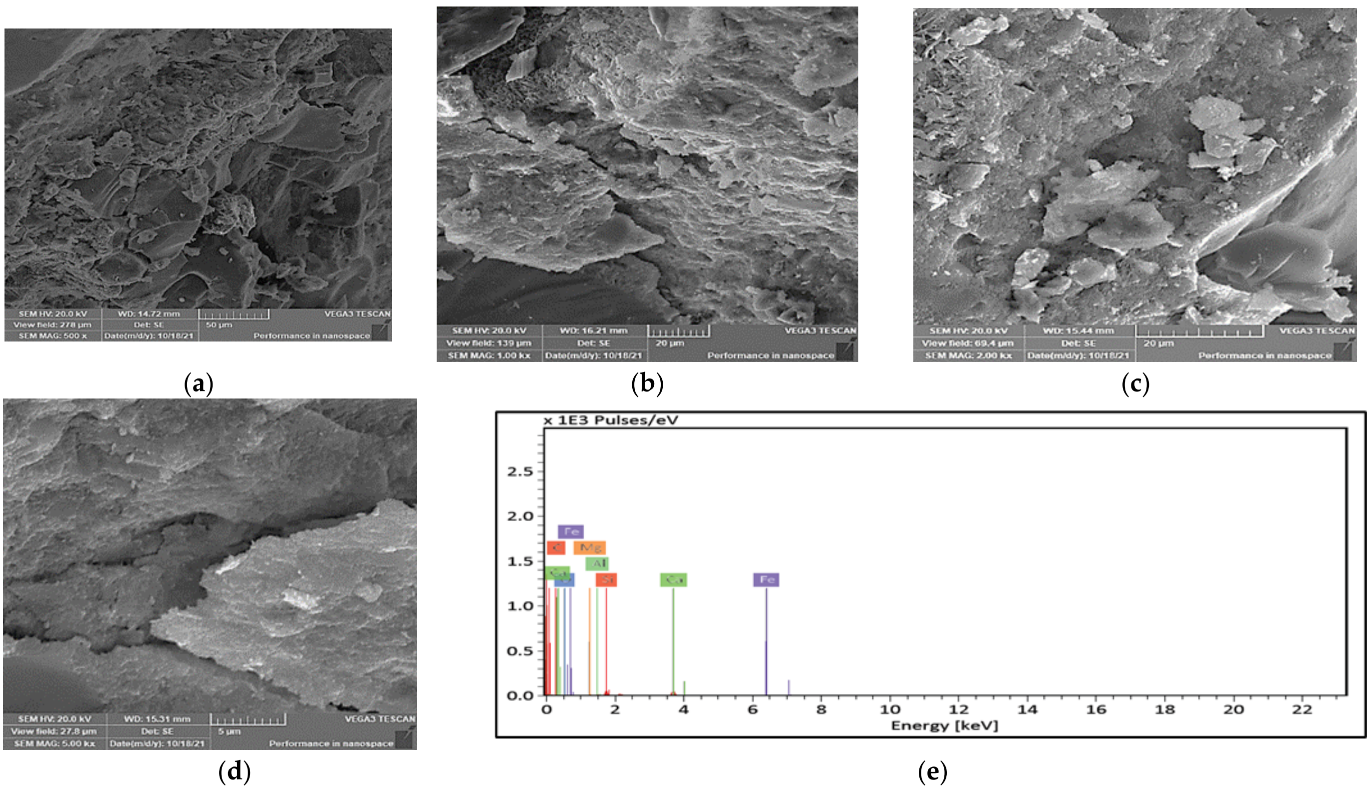


Figure 16. SEM with various magnification factors (**a**–**d**); (**e**) EDX for the mix UHPSCC 7 at (150 °C) temperature.

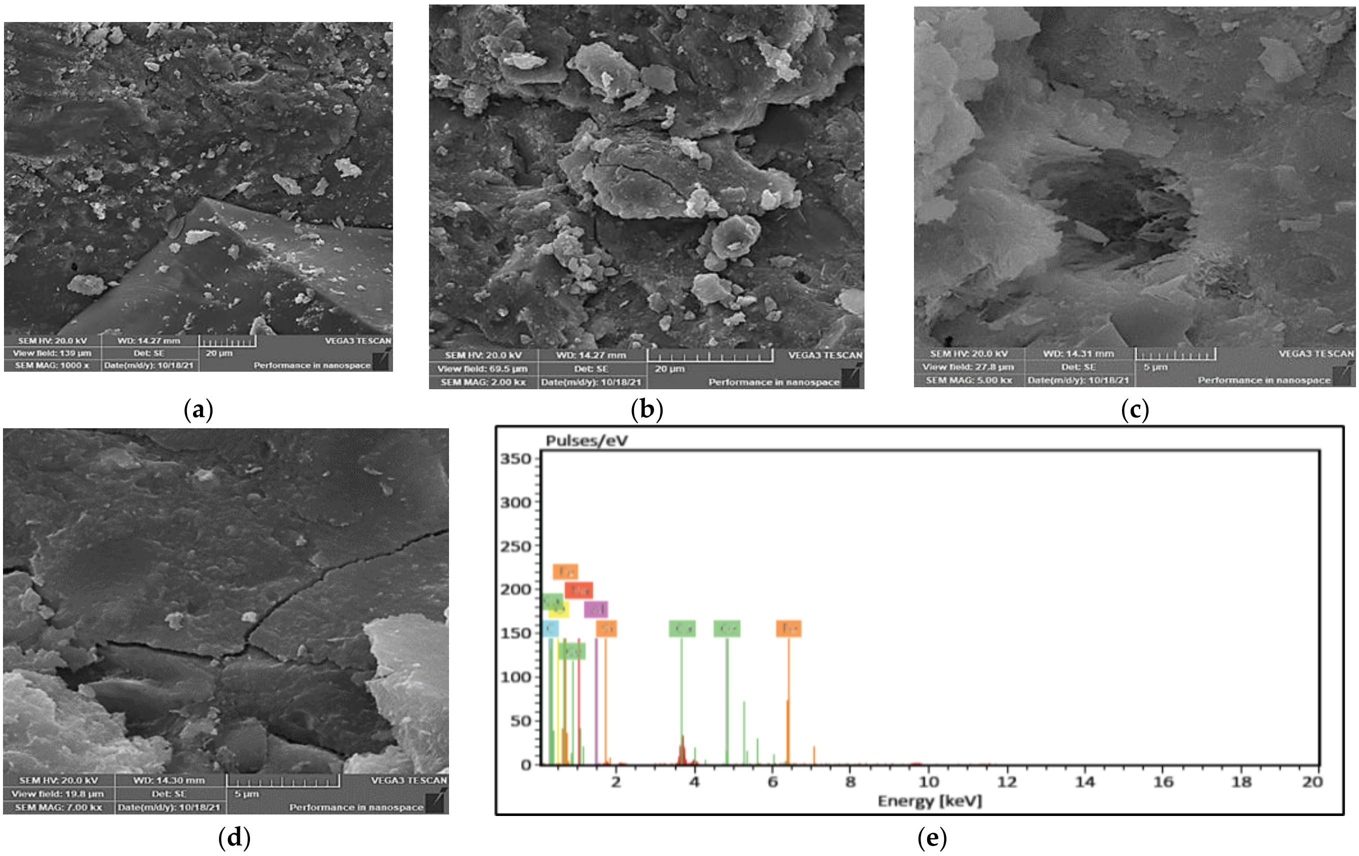


Figure 17. SEM with various magnification factors (**a**–**d**); (**e**) EDX for the mix UHPSCC 7 at (200 °C) temperature.

5. Conclusions

The concluding remarks can be summarized as follows:

1. UHPC can be achieved by a ternary system of glass powder, cement, silica fume, and lime powder.
2. Using glass and lime powder, the UHPSCC fresh behavior was improved. So, UHPC can be easily achieved to be SSC with glass and lime powder. All UHPSCC mixed with GP (except UHPSCC 2) showed good workability which complies with the guidelines of EFNARC.
3. The optimal cement substitute of glass powder was 20% with achieved compressive strength of 6.2% and 4.18% for hot and normal curing, respectively, at 90-days compared with control.
4. Due to the increase in the replacement level of cement by LP, the compressive strength is increased up to 20%. The UHPSCC 7 mix with 20% LP increases by 15.5% and 9.3% for hot and normal curing, respectively, at 90 days compared to the control mix.
5. The highest flexural and splitting strength was achieved at 20% LP by 49.2% and 24.2% increase in flexural and splitting, respectively, compared to the control mix while the combined mix with 20% GP and 20% LP and contain polypropylene fiber achieved increasing in flexural and splitting by 58.6% and 17.8%, respectively, compared to the control mix.
6. Using glass powder improves the elasticity modulus, where the increasing of GP content in the mix, led to increasing the modulus of elasticity up to 20% cement substitute when compared with control.
7. All UHPSCC mixes revealed a low permeability according to the lower values of Sorptivtiy compared to the control mix, since the UHPSCC 3 mix and UHPSCC 7 showed lower sorptivity decreased by 26.1% and 36.9% respectively.

8. The elevated temperature had a marked effect on UHPSCC which is distinguished by dense compact matrix to facilitate spalling. The increase in temperature led to increasing the compressive strength up to 200 °C then the spalling will form at 250 °C.
9. SEM images for normal temperature showed dense, thick sections with no porosity but SEM images at high temperature showed micro-cracks and increased porosity such as UHPSCC 7 mix at 150 °C and 200 °C.
10. In this paper, we have presented new experimental results of using local waste such as glass and lime powder as supplementary cementitious materials for producing UHPSCC and studying its fresh and mechanical properties. We have analyzed these results and have compared them with ones found in the literature. So, there are additional experimental research topics that should be considered for further study in order to allow deeper analysis of observed properties as follows:
    - Studying the durability of UHPC for glass and lime against acid–alkali attacks and resistance to sulfate.
    - Studying the structural behavior of using basalt fiber to improve the ductility of UHPC.
    - Studying of the structural behavior of reinforced UHPC elements such as columns, beams, and slabs.

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Symbols

UHPC	Ultra-high-performance concrete
SCC	Self-compacted concrete
GP	Glass powder
LP	Lime powder

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