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CREATING SUSTAINABLE ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC) UTILIZING RECYCLED GLASS

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Abstract

Sustainable construction materials and trash reuse are effective ecological remedial solutions. Concrete is widely used in construction and structural applications. Ultra-high-performance concrete (UHPC) is a popular concrete innovation with high mechanical properties. However, Portland cement is used in large quantities, making UHPC expensive and limiting its use in structural engineering. Significant CO_2 emissions and natural resource depletion occur. To make UHPC more environmentally friendly and affordable, substitute PC in concrete mixture with several additives. This study uses Ground Granulated Blast Furnace Slag (GGBS) and waste glass (WG) at 0%, 10%, and 20% cement replacement to create an eco-friendly and cost-effective UHPC. To accomplish this, 3 cylinders per mix were made and separated. Experimental tests include slump, UPV, compaction factor, and mechanical characteristics. GGBS and WG improved concrete mix workability, according to the findings. For best workability and mechanical properties, replace 10% of cement with WG and GGBS in concrete. Using 10% material additives as cement replacement decreased concrete compressive and tensile strength.

Keywords:

Waste Glass;
Ultra-high-Performance concrete;
Ground Granulated Blast Furnace Slag;
Eco-friendly concrete.

1 Introduction

Construction materials sustainability and the reuse of waste have become requirements for ecological issues. Concrete is dramatically and widely utilized in the construction industry and for structural engineering, and it is an important material in numerous kinds of buildings. It includes several substances that link together to offer required strength and achieve good performance in compressive resistance [1]. One of the common types of concrete that has become a trend over the recent years is known as “Ultra-High-Performance Concrete”, characterized by very high mechanical properties and significant durability and can be considered a novel kind of construction material [2,3].

The UHPC composition includes high-density Portland cement (PC), steel fibers, aggregates, a high-range water reducer, and a lower amount of water [4]. UHPC is executed by increasing the content of PC density to the maximum attainable level. Consequently, huge PC volumes are usually utilized to generate dense PC content; UHPC mixes PC amounts ranging from 900 to 1100 kg/m^3 [5], approximately two to three times higher than traditional concrete. The significant PC content in UHPC leads to an increase in the cost, restricting its employment in structural engineering. Moreover, high PC volumes result in a significant CO_2 emission. Huge quantities of resources and energy are utilized, resulting in an increase in the potential ecological consequences of UHPC all over the world [6-9].

Therefore, to make the construction industry more sustainable and enhance its economic viability, it is advised to alter the PC in preparations of concrete with different additives and to replace various natural aggregate resources with recycled aggregates. The waste utilization that results from construction and demolition (CDW) as a PC substitution or natural aggregate substitution is favorable to achieve this objective [10]. Glass waste, which is used in popular things, is one of the CDWs whose utilization has recently been extended. It results in a dramatic increase in the waste derived from cities, and the quantity of glass waste has increased significantly in the last decades [11] recycle glass waste is applying it in PC compositions. A significant amount of waste glass can be recycled in the construction industry by replacing PC or aggregates with recycled waste glass. It can reduce the ecological impact by recycling an otherwise useless element and reducing CO_2emissions resulting from PC production [12]. Glass contains a great fracture of silica to be utilized on behalf of fine aggregate [13]. This reduces the glass waste that contaminates landfills and can reduce the quantity of sand demanded for construction, leading to lower installation costs [14].

Broken glass that has a size smaller than 75 microns can also be used as a PC replacement in applications where pozzolanic characteristics are favorable. It has additionally been observed that glass will begin to display pozzolanic behaviors if the diameter is less than 150 microns; moreover, the pozzolanic performance will improve if the diameter of the particle is minimized to smaller than 35 microns, resulting in better findings than 150-micron-sized particles [15].

According to the outcomes of different studies, waste can be efficiently utilized as a linking component in concrete, while also improving the concrete's mechanical properties and enhancing its durability [13]. Several academic studies have been conducted to evaluate the impact of using waste glass as a PC alternative.

A study by [16] indicated that despite utilizing waste glass with a grain size of 40 μm reduces the compressive strength, adding 20% of waste glass as an alternative to PC weight can improve the mechanical properties. [17] illustrated that compressive resistance after 28 days and 300 days was reduced by 40% and 42%, respectively, when PC was replaced with powdered waste glass at a 30% grade. [18] revealed that using waste glass with a particle size lower than 15 μm as a substitution for PC led to a decrease in 28-day compressive resistance. [19] referred that specimen replacing waste glass at 10 μm, 20 μm, and 40 μm exhibited a resistance of 55.5 MPa, 66.6 MPa, and 51.5 MPa, respectively, which means that the pozzolanic behavior was improved by utilizing fine waste glass. [20] illustrated similar outcomes, where increasing the period of GW milling greatly enhanced the 7-day and 28-day compressive strength. Another possible selection for waste glass (GW) use in PC products is natural aggregate replacement [21]. In correlation to mechanical properties, [22] detected that when using the following percentages of waste glass: 20%, 50%, or 100%, it led to higher values of compressive and flexural strengths. On the other hand, using 100% of waste glass resulted in a lower value compressive strength after 28 days. [23] showed that increasing the fine waste glass quantity utilized instead of aggregate has a significantly adverse influence on the mechanical properties.

2 Experimental Program

2.1 Materials Used

Portland cement (PC) C25/30 was utilized in this experimental work. UHPC mixes are characterized by a great amount of PC (1000 kg/m^3). The features of PC are illustrated in Table 1.

Table 1: Cement Properties Adopted in this Research

Chemical and physical properties of cement	
SiO2 [%]	19.37
Al2O3 [%]	4.96
Fe2O3 [%]	3.02
CaO [%]	61.95
Mgo [%]	3.36
SO3 [%]	2.01
Na2o [%]	0.79
Loss on ignition [%]	2.24

Specific gravity	3.09
Specific surface area [cm^2/gr]	3823
C_3S	67
C_2S	12
C_3A	7
C4AF	12
Loss on Ignition [%]	2.4
Insoluble residue [%]	0.8
Clinker mineralogical composition	
C_3S [%]	42
C_2S [%]	31
C_3A [%]	2.7
C4AF [%]	10.24

Silica fume (SF) was utilized to meet close to ASTM C1240 standards. In addition, SF with dimensions ranging from (0.1 – 1) μm is crucial to produce UHPC [24]. The GW used in this research was gathered. The glass bottles were thoroughly cleaned with tap water to eliminate any debris on the surface and any pollutants. Then, waste glass was crushed into very small pieces using a jaw crusher that conforms to the ASTM C 33 standard. Waste plastic was passed through 4.75 mm sieves to be sorted. Figure 1 shows the glass waste milled that was used in this research. In this study, crushed granular GW was utilized as a sand replacement. This contributes to preserving natural resources and minimizing contamination. When used as a fine aggregate, the crushed GW protects concrete from the detrimental effects of chloride. The GW was crushed using a hammer before being placed in a Los Angeles abrasion mill and rolled to form glass grains (G) varying in dimensions from (0.150 - 4.75) mm, which was utilized as a sand replacement

(a) Glass Waste (GW) (b) Ground Mill (c) Crushed Glass (size >> 4.75 mm)

(d) Crushed Glass (size >> 4.75 mm) (e) Crushed Glass (size > 4.75 mm) (f) Glass Particles

(g) Milled Glass (size << 4.75 mm) (h) Milled Glass (size <<< 4.75 mm) (i) (GP) as a substitute for PC (size < 75 μm)

Fig. 1: Different stages for glass waste milling. (a) Glass waste (GW); (b) ground mill; (c) crushed glass (size >> 4.75 mm); (d) crushed glass (size >> 4.75 mm); (e) crushed glass (size > 4.75 mm); (f) glass particles (G) used as fine aggregate (size < 4.75 mm); (g) milled Glass (size << 4.75 mm); (h) milled glass (size <<< 4.75 mm); and (i) glass powder (GP) used as a substitute for PC (size < 75 μm).

3 Research Methodology

3.1 Mix Design

The purpose of this research is to achieve low-cost Ultra-High Performance Concrete (UHPC) suitable for special applications such as underground structures, shelters, high-rise structures, and bridges, with a major focus on minimizing ecological pollution by reducing cement usage during concrete production. To prepare economically feasible UHPC, two experimental techniques were utilized and compared. The first technique involved substituting up to 20% of the binder with Ground Granulated Blast Furnace Slag (GGBS), whereas the second technique involved replacing up to 20% of the binder with waste glass (WG). Tensile resistance and UHPC ductility in concrete structures can be improved by using 13-mm steel fibers with a 0.22-mm diameter. The UHPC mix had a 1:1 fine aggregate-to-binder ratio and a 0.27 water-to-cement W/C ratio. A 2% steel fiber ratio improved the suggested UHPC's tensile and ductility.

Cement, micro silica, limestone powder, GGBS, waste glass, sand, steel fiber, superplasticizer, and water were accurately weighed after determining the constituent amounts for concrete mixtures. Clean and oil concrete cylinder specimens made on steel and wooden formworks.

After adding fine aggregates, the remaining ingredients were added. Add water and superplasticizer (SP) slowly after blending dry ingredients for 2 minutes. 3–4 minutes were needed to stir the mixture homogeneously. Table 2 provides detailed data on the required components for mix design, which are essential to ensure the quality and performance of UHPC in this study.

Table 2: The materials density utilized in the UHPC mix design.

Mix ID	[kg/m^3]								
	C	MS	LP	GGBS	WG	S	SF	SP	W
S1	600	40	160	0	0	800	157	10	220
S2	540	36	144	80	0	800	157	10	220
S3	480	32	128	160	0	800	157	10	220
S4	540	36	144	0	80	800	157	10	220
S5	480	32	128	0	160	800	157	10	220

C: cement, MS: micro silica, LP: limestone powder, GGBS: Ground granulated blast furnace slag, WG: waste glass, S: sand, SF: steel fiber, SP: super plasticizer, W: water.

3.2 Experimental Tests Used

The experimental program in this research will include tests to evaluate both mechanical and freshness characteristics. The tests will be conducted according to several standards as follows: slump test (ASTM C143), compaction factor test (BS EN 12350-4:2009), density (ASTM C138 testing concrete cylinders under compression at 7 days, 28 days, and 90 days (ASTM C39)), ultrasonic pulse velocity (UPV) test (ASTM C597), and tension test (ASTM C496).

3.2.1 Slump Test

This test is conducted according to the (ASTM C-143) specifications. It adopts a cone with a diameter of 200 mm, while its top has a diameter of 100 mm and a height of 300 mm. The concrete is placed in the cone in three layers and compacted using a steel rod, with 25 strokes for each concrete layer. Once the concrete is filled and its surface is levelled in the cone, the cone is removed without inducing vibration. The shape of the concrete after removal is evaluated to determine its workability.

3.2.2 Compaction Factor

It operates on the concept of identifying the level of compaction attained by a standard quantity of work applied by allowing the concrete to drop through a standard height. This test is more desirable and advantageous for concrete with low workability. It is more accurate than the cone test for concretes with low workability. The compaction factor test is standardized by (BS EN 12350-4). A lower value indicates that the workability of concrete is extremely low, while a higher value indicates high workability of concrete.

3.2.3 UPV Test

The pulse velocity technique is a traditional method to investigate the quality of in-situ concrete. The basic concept to assess concrete's workability is that higher velocities are achieved when the quality of concrete, according to density, homogeneity, and uniformity, is good. In cases of poorer quality, lower velocities are obtained when concrete contains fractures, voids, or defects, resulting in lower speeds. The ultrasonic pulse is generated using the energy converter that is fixed in contact with one surface of the concrete specimen. The pulse velocity (V) is calculated using the following equation:

$$V = L/T \tag{1}$$

Where:
T: transit time of the pulse
L: path length in concrete.

3.2.4 Compression and Tension Tests

To study the effect of (WG) and GGBS on the mechanical properties of UHPC, a proposed mix design was implemented. Three concrete cylinders with dimensions (10 x 20 cm) were cast for each concrete mix. Before testing, each specimen underwent density measurement recording to assess the influence of each material on the concrete's density. Figure 2 illustrates the testing of mechanical properties of the cylinder specimens.

(a) (b)

Fig. 2: Mechanical properties testing.

4 Results and Discussion

4.1 Slump

Table 3 illustrates slump values corresponding to various percentages of WG and GGBS. S1 represents control concrete mix without additions, while S2 and S3 represent concrete mixes with 10% and 20% GGBS addition, respectively. Similarly, S4 and S5 represent concrete mixes with 10% and 20% WG addition.

Figure 3 shows that both WG and GGBS could increase workability in concrete mixes. Concrete mixes S2 and S3 achieved slump values of 153mm and 175 mm respectively, with enhancements in workability of 8% and 11% respectively, compared to control mix S1. Concrete mixes S4 and S5 achieved slump values of 147 mm and 150 mm respectively, with enhancements in workability of 5% and 7% respectively, compared to control mix S1. These findings are consistent with [25]. This is attributed to the fact that glass absorbs less water than fine aggregate, thereby increasing the free water content in the mix. Additionally, GGBS can fill up the pores and microcracks in concrete, making it less permeable to water and other materials, consequently enhancing its workability. Moreover, it can be noted that GGBS increases concrete workability more than WG.

Table 3: Workability Slump According to Different Additive Ratios

Mix ID	GGBS	WG	Workability Slump (mm)
S5	0	160	150
S4	0	80	147
S3	160	0	157
S2	80	0	153
S1	0	0	140

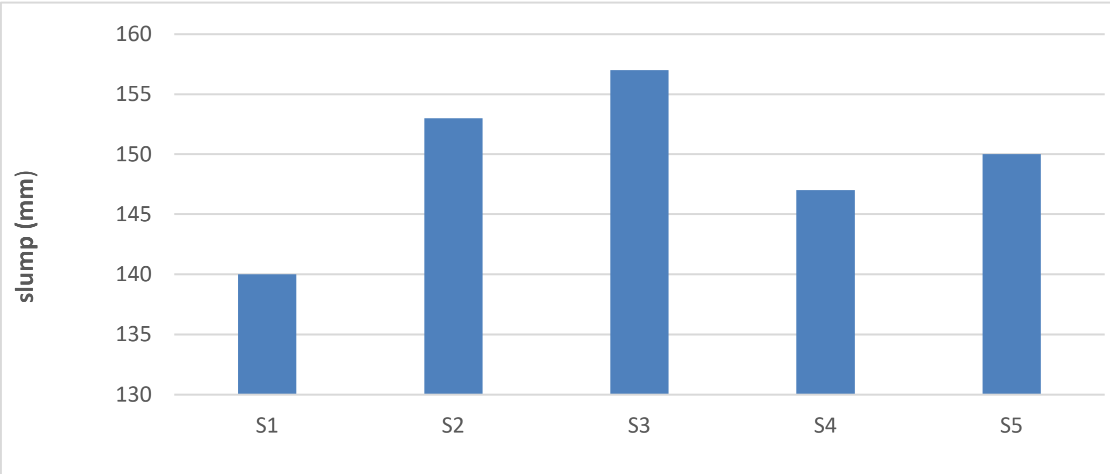

Fig. 3: Slump values of all the mixes.

4.2 Compaction Factor

Table 4 and Figure 4 demonstrate that both WG and GGBS could increase the compaction factor values and consequently workability in concrete. The addition of GGBS or WG in concrete mixes enhances workability due to the smooth surface area of WG and GGBS additives compared to the control concrete mix. The hydrophobic nature of waste glass and GGBS results in a dramatic reduction in the permeability of the concrete mix.

Table 4: CF values According to Different Additive Ratios

Mix ID	GGBS	WG	Compaction factor, FC
S5	0	160	0.9813
S4	0	80	0.9792
S3	160	0	0.9862
S2	80	0	0.9834
S1	0	0	0.9743

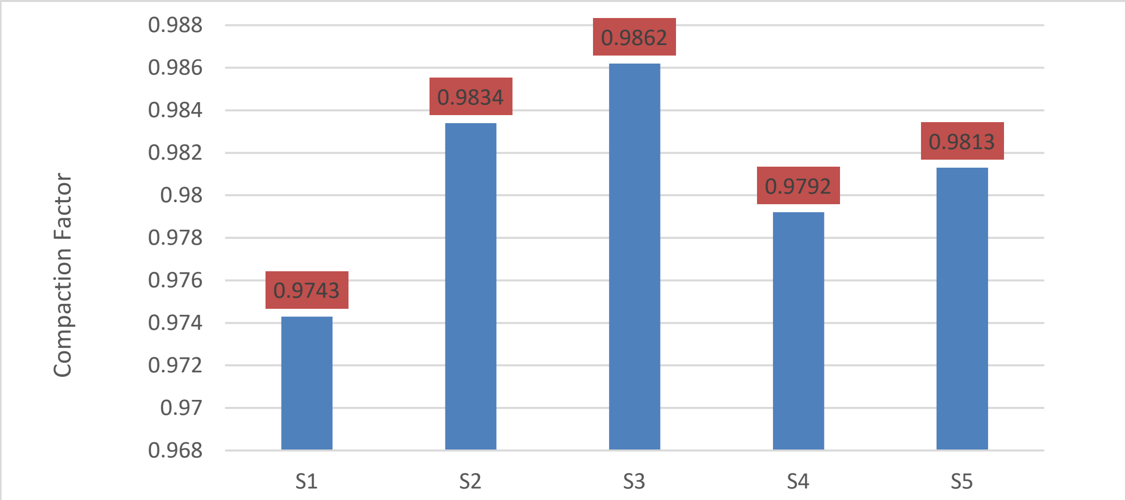

Fig. 4: Compaction Factor values of mixes suggested.

4.3 UPV Behavior

Figure 5 illustrates that the addition of both GGBS and WG contributed to an increase in UPV values compared to concrete mix S1 without additives. This is because of the enhanced reactions and the development of more Calcium Silicate Hydrate (C-S-H) gel as a result of the pozzolanic reaction between $Sio_2$and $\mathrm{Ca(OH)_2}$. This densification of the concrete matrix assists in reducing the time required for wave transmission. Additionally, it can be noted that while the addition of both GGBS and WG materials increases from (10-20) %, UPV values decrease. This reduction in UPV values with the increase in additive content could be due to the enhanced capacity of concrete to absorb additional energy.

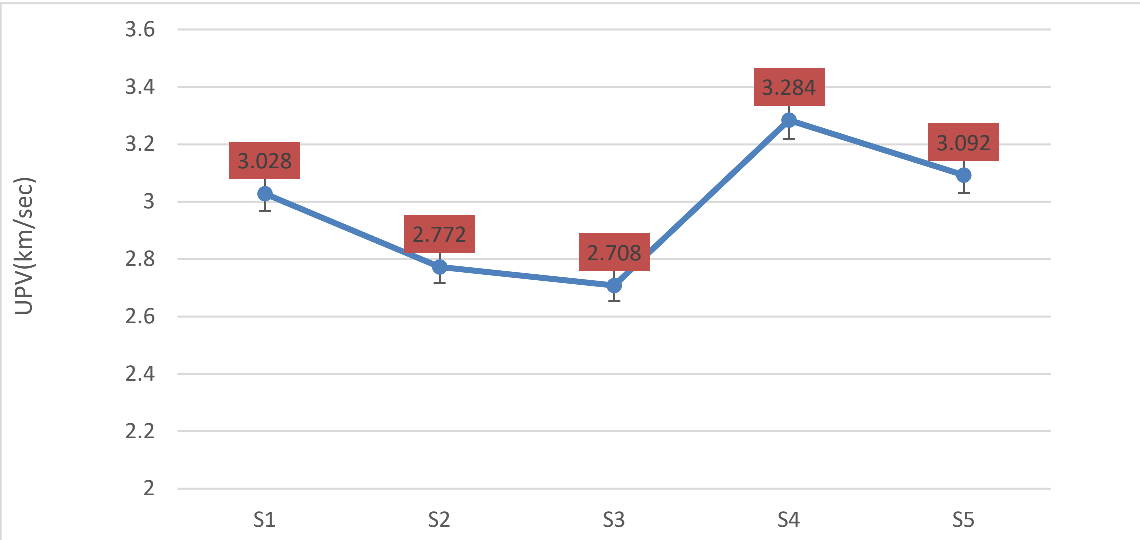

Fig. 5: UPV values of mixes.

4.4 Mechanical Properties

Figures 6, 7, and 8 illustrate outcomes regarding the influence of WG and GGBS as substitutes for cement on the mechanical resistance of UHPC. The reference concrete mix (S1) achieved a density of 2440 kg/m3, a tensile strength of 9.33 MPa, and a compressive strength of 102 MPa. Sample S2, which contains 10% GGBS as a cement substitute, showed a slight reduction in density to 2400 kg/m3 compared to the reference specimen S1. However, the compressive strength reduced to 95.9 MPa, while the tensile strength remained constant. This indicates that while GGBS contributes positively to the ecology by minimizing CO_2emissions, it can also lead to a decrease in the concrete's mechanical strength. Regarding Sample S3, which contains 20% GGBS as a cement substitute, it exhibited a similar behaviour, with a reduction in compressive strength to 92.4 MPa and a very slight reduction in tensile strength. The density stayed at 2400 kg/m^3. Sample S4, which contains 10% waste glass as cement, was denser than S1 at 2480 kg/m^3. Compressive strength increased to 105 MPa, while tensile strength increased. This shows that leftover glass can replace cement and improve concrete's mechanical properties. Sample S5, using 20% WG as a cement substitute, had a density similar to the reference specimen. However, compressive strength dropped to 102.1 MPa and tensile strength plummeted. This suggests that excessive waste glass content can reduce mechanical strength of UHPC.

However, UHPC can reach 120 MPa in compressive strength; the variation in compressive strength observed could be attributed to differences in the chemical composition of the additives used, which may vary by region. Such variations can lead to differences in the performance and results of the concrete specimens.

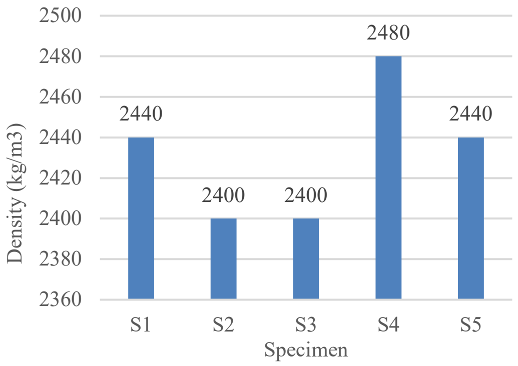

Fig. 6: Different UHPC density innovated.

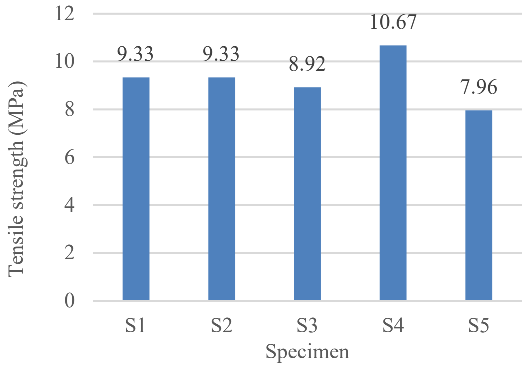

Fig. 7: Tensile strength for different UHPC innovated.

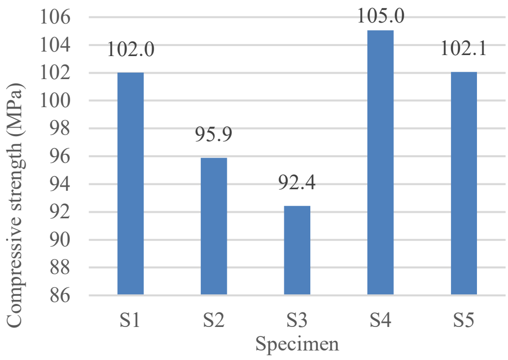

Fig. 8: Compressive strength for different UHPC innovated.

5 Conclusion

Eco-friendly Ultra-High-Performance Concrete (UHPC) integrated with material additives such as waste plastics and GGBS has been enhanced using different percentages of these additive materials (10-20%). A series of experimental tests was executed to investigate both the workability and mechanical properties of concrete. Based on the outcomes obtained in this study, the following conclusions can be drawn:

• Waste glass can effectively substitute for cement in UHPC and can enhance its mechanical characteristics. On the other hand, GGBS addition as a cement substitute can lead to a decrease in mechanical resistance. These outcomes can have dramatic implications for the improvement of eco-friendly and high-strength concrete.

• Waste glass and GGBS could improve workability in concrete mixes, wherein these additive materials contributed to reducing both slump values and the compaction factor while increasing their percentage.

• WG addition by percentage 10% contributed to increasing UPV values. This is because of the enhanced reactions and the development of more Calcium Silicate Hydrate (C-S-H) gel according to the pozzolanic reaction between SiO2 and Ca(OH)2. This densification of the concrete matrix assisted in reducing the period required for wave transmission. However, WG addition by percentage 20% contributed to reducing UPV values.

• While GGBS material addition increases from (10-20%), UPV values compressive strength and tensile strength decrease. This reduction in values with the increase in additive content can be due to the increased capacity of concrete to absorb additional energy. Increasing the percentage of glass waste by 10% in high-performance concrete may have contributed to improving the microstructure of the concrete, resulting in reduced gaps and improved bonding of the internal components. This improvement in structure makes the material denser and more uniform, allowing ultrasound waves to travel faster through the concrete, thus increasing the ultrasonic velocity value in addition to increase mechanical properties.

• However, when the percentage of glass waste increases to 20%, the opposite effect may occur. Increasing this percentage can lead to increased gaps or microcracks due to inhomogeneous distribution or aggregation of glass particles, which weakens the bonding between the components. These gaps and cracks impede the transmission of ultrasound waves and reduce their speed.

• In short, there is an optimum point for adding glass waste that improves the properties of concrete, but exceeding this point leads to negative results due to deterioration of the microstructure and increased gaps.

Limitations of the study:

Number and type of samples: The number of samples (five samples) may not be sufficient to provide accurate final conclusions about the effect of different additives. Adding more samples or using different types of concrete may help to enhance the results.

• Distribution of fibers and glass waste: The distribution of fibers and glass waste within the concrete may be inhomogeneous, leading to inaccurate effects on tensile and compressive strength.

• Environmental conditions: The environmental conditions in which the concrete was cast and tested may be specific and not precisely controlled, such as temperature and humidity, which may affect the results.

Future challenges:

• There is a need to study the long-term effect of these additives, such as concrete deterioration over time or its resistance to harsh environmental influences.

• Concrete mixing methods can be improved to ensure a homogeneous distribution of fibers and glass waste, which may improve the properties of the resulting material.

• The study can be expanded to include other proportions of additives (more or less than used) to better understand their effect on the properties of concrete.

• The effect of adding fibers and glass waste on other aspects of concrete, such as corrosion resistance or absorption, can be studied.

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