IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 50, No. 5, October, 2026, pp. 485-491
Journal homepage: http://iieta.org/journals/acsm

Experimental Study of the Properties of High-Performance Concrete Incorporating Recycled Glass Powder and Metal Fibers

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https://doi.org/10.18280/acsm.500507

Received: 15 June 2026
Revised: 21 July 2026
Accepted: 17 August 2026
Available online: 31 October 2026

Keywords:
cement, glass waste powder, high-performance concrete, metal fibers, mechanical performance, substitution

ABSTRACT

This research investigated the use of glass waste powder (GWP) in high-performance concrete (HPC) as a partial replacement for cement at proportions of 15% and 20%. In addition, the HPC mixtures were reinforced with metal fibers (MF) at dosages of 1% and 2%, with the aim of improving their mechanical performance, particularly their compressive strength and flexural tensile strength. The influence of each additive, as well as their combined effects, on the physical and mechanical performance of HPC was evaluated using experimental tests of density, slump, ultrasonic pulse velocity (UPV), compressive strength, and flexural tensile strength at 3 and 28 days. The experimental findings were compared with those of a reference HPC formulated without GWP or MF. The results showed that the incorporation of GWP at the studied rates did not improve the mechanical performance of the HPC. At 28 days, the incorporation of 20% GWP led to a 30.54% reduction in compressive strength compared with the reference concrete. In contrast, the addition of 1% MF increased compressive strength by 18.84%, while 2% MF resulted in a 24.66% improvement in flexural tensile strength. However, increasing the fiber content was accompanied by a decrease in workability. For the combined formulations, the beneficial effect of the fibers on flexural tensile strength was less pronounced. Overall, the combined use of GWP and MF appears to be a promising approach for the valorization of glass waste and the targeted improvement of certain HPC properties, provided that the incorporation ratios are appropriately optimized.

1. INTRODUCTION

One of the main areas of research in the field of cementitious materials nowadays is the creation of more environmentally friendly high-performance concrete (HPC). Due to its potential advantages for the mechanical and environmental behavior of concrete, the use of recycled glass powder as a partial replacement for cement and the addition of metal fibers (MF) have drawn more attention among the options under investigation. Glass powder, characterized by its high content of amorphous silica, exhibits pozzolanic activity, which can consume the calcium hydroxide produced throughout the hydration process of cement and generate additional calcium silicate hydrate (C-S-H) hydrates, resulting in a denser microstructure and reduced porosity [1-4]. Various studies have demonstrated that substituting a moderate proportion of cement with glass powder can improve concrete durability, chloride penetration resistance, and compressive strength [5-10]. In addition, MF are essential for preventing cracking and improving post-peak behavior through crack bridging, thus improving the concrete's tensile and flexural strengths, toughness, and ductility [11-14]. Research on fiber-reinforced composite materials has shown that combining MF with densified cementitious matrices can improve stress redistribution and reduce microcrack propagation [15-17]. Furthermore, several studies have investigated the combined use of glass powder and MF in cementitious materials and reported favorable effects on certain mechanical properties, cracking resistance, and durability [7, 8, 17, 18]. However, the effects of this combination depend on the characteristics of the constituent materials, the dosages used, and the properties considered. Therefore, the influence of different combinations of glass powder and MF in HPC, particularly with regard to the trade-offs between workability, compressive strength, and flexural tensile strength, warrants further investigation.

In this context, the present study aims to evaluate the individual and combined effects of glass waste powder (GWP), used at replacement rates of 15% and 20%, and MF, incorporated at dosages of 1% and 2%, on the physico-mechanical properties of HPC. These proportions were selected to investigate the effects of moderate cement replacement with GWP and increasing metal fiber content while maintaining an acceptable balance between mechanical performance and workability. The analysis focuses on density,

workability, ultrasonic pulse velocity (UPV), compressive strength, and flexural tensile strength at 3 and 28 days. The objective is to assess the influence of the different dosage combinations and determine the trade-offs between workability and mechanical performance.

2. MATERIALS AND METHODS

2.1 Materials

The purpose of this experiment is to assess how MF and GWP affect the behavior of HPC. The two materials are presented in Figure 1. To evaluate the effects of these additives on concrete properties, a series of mixtures was prepared, including a reference concrete and mixtures incorporating GWP as a partial cement replacement at rates of 15% and 20%, combined with metal fiber dosages of 1% and 2%.

The combined incorporation of GWP and MF was further examined, with particular attention to their influence on the fresh-state and hardened-state properties of concrete. Prior to mixing, the constituent materials were thoroughly characterized to determine their main physical, chemical, and mechanical properties.

For each mixture and testing age, three specimens were prepared and tested for the mechanical properties. The reported values correspond to the average results obtained from the three tested specimens.



Figure 1. Visual appearance of the materials used: (a) glass waste powder (GWP) after grinding and sieving; (b) hooked corrugated steel fibers (MEDAFAC type)

The cement used was CPJ-CEM II/A 42.5 Portland composite cement, supplied by the Hadjar Soud cement plant in Azzaba, Algeria. It consists primarily of Portland clinker, mineral additions, and gypsum. Its principal physical and mechanical properties are presented in Table 1.

Table 1. Physical and mechanical properties of cement

Property	Value
Start setting (min)	102
End of setting (min)	216
Hot expansion (mm)	2
Cold expansion (mm)	1
Compressive strength at 2 days (MPa)	15.40
Compressive strength at 7 days (MPa)	30.40
Compressive strength at 28 days (MPa)	44.00
Blaine specific surface area (cm²/g)	3200

The GWP was obtained from glass waste subjected to successive crushing, grinding, and sieving operations until a grain size of below 80 µm was achieved. The results of the physicochemical characterization showed that the powder consisted mainly of silica (SiO_2 = 56.85%), indicating a significant pozzolanic potential when used in finely ground form. Its high specific surface area (3,936 cm²/g) enhances the filling effect and contributes to improved compactness of the cementitious matrix. Its density (2.46 g/cm³), which falls below that of cement, may also affect the density of mixtures incorporating this additive. However, its relatively high Na_2O content (15.17%), characteristic of soda-lime glass, requires particular attention because of the possibility of an alkali-silica reaction (ASR). Since ASR expansion and long-term durability were not experimentally investigated in the present study, no definitive conclusion can be drawn regarding the ASR resistance of the developed mixtures. Nevertheless, its chemical composition demonstrates the potential of GWP to serve as a mineral additive and partially substitute cement in concrete, while its long-term durability and ASR behavior require further investigation.

The MF used in this work were corrugated, drawn MF of the MEDAFAC type. Their geometry, characterized by a corrugated surface that promotes mechanical anchorage within the cementitious matrix, improves stress transfer after cracking and thus contributes to enhanced toughness, ductility, and post-cracking behavior of the concrete.

Table 2. Physicochemical characteristics of aggregates

Physical Properties				
	Sand 0/4	**Gravel 3/8**	**Gravel 8/15**	**Gravel 15/25**
Absolute density (g/cm³)	2.74	2.63	2.70	2.75
Apparent density (g/cm³)	2.60	2.59	2.63	2.65
Saturated density (g/cm³)	2.65	2.60	2.66	2.69
Absorption (%)	2.00	0.66	1.00	1.33
Sand equivalent (%)	65	—	—	—
Fineness modulus	2.84	—	—	—
Fine content (%)	20	2.62	2.00	5.36
Micro-Deval (%)	—	—	16.40	—
Los Angeles (%)	—	—	23.16	—
Flattening coefficient	—	—	1.45	5

Chemical Composition %				
SO_4^{2-}	$CaCO_3$	Cl^-	MB	SO_3
—	82.40	0.24	0.90	—

Both fine and coarse aggregates used in the present work were subjected to physical and mechanical characterization, including particle size analysis, density, water absorption, fineness modulus, sand equivalent, Los Angeles and Micro-Deval coefficients, and the flakiness coefficient. The results obtained for the sand showed a high calcium carbonate content ($CaCO_3$ = 82.40%), indicating that it was primarily limestone. The low chloride (Cl^- = 0.24%) and organic matter (OM = 0.90%) contents were compatible with its use in concrete production. Furthermore, the sulfate (SO_4^{2-}) and SO_3 contents were present only in trace amounts, thereby limiting the risk of harmful reactions that could affect the durability of the material. These results confirmed the good chemical quality of the sand used. Table 2 provides an overview of the aggregates' properties.

In order to maintain a reduced water-to-binder ratio and guarantee sufficient concrete workability, a superplasticizer,

POLYFLOW SR 3600, based on modified polycarboxylic ether, was added to the mixtures. The physicochemical characteristics of this admixture exhibit a brown appearance liquid with a density of 1.05 ± 0.02 g/cm³, which is consistent with the typical characteristics of superplasticizers in this category. Its pH, ranging from 5.5 to 6.0, is not expected to adversely affect concrete performance. Its low chloride content (<0.1%) is advantageous in terms of reducing the risk of reinforcement corrosion, while its dry matter content (22 ± 1%) indicates a sufficient concentration of active components to ensure effective water reduction and improved workability.

Finally, the water used to prepare the mixtures and conduct the experimental tests was obtained from the LHC laboratory in Skikda, Algeria. The physicochemical analysis indicated a pH of 7.34, characterizing the water as nearly neutral and suitable for concrete production. The chloride (60.35 mg/L) and sulfate (54.08 mg/L) contents were relatively low and are not expected to significantly affect hydration reactions or concrete durability. The measured temperature (13.2 °C) was compatible with normal mixing conditions. However, the presence of suspended solids at a concentration of 912 mg/L requires appropriate control to prevent potential alterations in concrete performance. Overall, the water exhibited characteristics compatible with its use in the preparation of the mixtures studied.

The particle size distribution curves for sand and the different gravels used in the concrete mix design are shown in Figure 2. As can be observed, each aggregate fraction exhibits a particle size distribution appropriate for its respective size class, ensuring good complementarity among the different particle sizes.

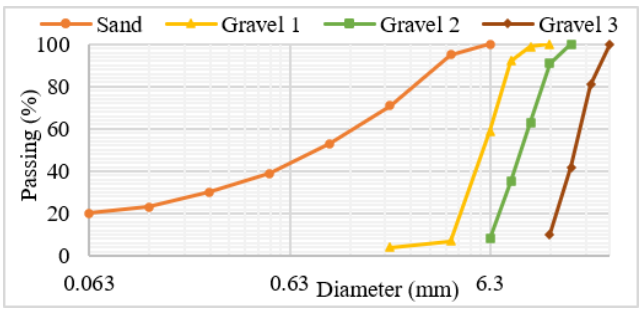


Figure 2. Aggregates' particle size distribution

The gradual evolution of the combined particle size distribution indicates good continuity between the different aggregate fractions, which promotes efficient particle packing and contributes to reducing the void content within the aggregate matrix. Consequently, the resulting granular skeleton is expected to provide improved compactness and workability of the fresh concrete, while also contributing to better mechanical performance in the hardened state. Numerous studies have demonstrated that the performance of concrete is strongly influenced by aggregate particle size distribution. According to Subash et al. [19], a continuous particle size distribution promotes better particle packing, reduces voids, and contributes to improved mechanical properties. Furthermore, optimizing aggregate grain size distribution has been shown by Li et al. [20] to increase packing density, improve mixture compactness, and ultimately improve concrete performance in both the fresh and hardened states.

2.2 Experimental program

As part of this experimental program, nine HPC mixtures were developed to investigate the impact of adding MF (MF) and partially substituting GWP for cement on concrete performance. A reference concrete, designated HPC(R), was prepared without GWP or MF. Additionally, two mixes were created that contained MF solely at dosages of 1% (HPC1) and 2% (HPC2). At 15% (HPC15) and 20% (HPC20) levels, GWP was introduced as a partial substitute for cement.

Finally, four formulations combining the two parameters under investigation were prepared, namely HPC1-15, HPC1-20, HPC2-15, and HPC2-20, corresponding to combinations of 15% or 20% GWP with 1% or 2% MF, respectively. For all mixtures, the water content (134 kg/m³), superplasticizer content (1%), and aggregate proportions (42% sand, 7% G1, 21% G2, and 30% G3) were kept constant. The detailed compositions of the different concrete mixtures are listed in Table 3.

The concrete formulations were established based on the Dreux–Gorisse method, which allows the rational determination of constituent proportions based on the desired mechanical performance and workability. The method was adapted to include GWP as a partial cement substitute and MF as an additional component, while keeping the main parameters of the reference concrete unchanged.

To characterize the concrete in both its fresh and hardened states, several standardized experiments were conducted. One of the most popular techniques for evaluating the workability and consistency of fresh concrete is the Abrams slump test. In compliance with NF EN 12350-2, the procedure was performed with an Abrams cone. The mold was placed and fastened after the base plate had been slightly wetted. After that, the concrete was divided into three equal-height layers and compacted with 25 strokes using a tamping rod. Using the tamping rod, the top surface was leveled after filling. The concrete was then allowed to settle freely after the mold was gently raised vertically. The resulting slump was measured at the highest point of the concrete using a measuring device and recorded within one minute after demolding. The slump value was expressed in centimeters and rounded to the nearest centimeter.

In accordance with NF EN 12350-6, the density of the fresh concrete was determined by weighing a container of known volume filled with freshly compacted concrete. The filling and compaction procedure was similar to that used for preparing the cylindrical test specimens. The density was then calculated as the ratio of the mass of the compacted fresh concrete to the volume of the container.

Using hydraulic testing equipment, the compressive strength was measured on cylindrical test specimens measuring 16 × 32 cm in compliance with NF EN 12390-3.

Prismatic specimens measuring 7 × 7 × 28 cm were tested under three-point loading following NF EN 12390-5 to determine the flexural tensile strength and characterize the concrete's behavior under flexural stress.

The UPV test was conducted according to NF P 18-418. This non-destructive technique was used to assess the quality and homogeneity of the concrete by measuring the propagation velocity of ultrasonic waves. For the test, transmitting and receiving probes were placed at opposite ends of prismatic specimens measuring 7 × 7 × 28 cm. Higher pulse velocities generally indicate a denser and more homogeneous concrete matrix.

Table 3. Mix ratios of various concrete mixtures

Mixtures	W (kg)	C (kg)	GWP (kg)	SP (%)	S (%)	G1 (%)	G2 (%)	G3 (%)	SF (%)	W/C
HPC (R)	134	420	0	1	42	7	21	30	0	0.32
HPC1	134	420	0	1	42	7	21	30	1	0.32
HPC2	134	420	0	1	42	7	21	30	2	0.32
HPC15	134	357	63	1	42	7	21	30	0	0.37
HPC20	134	336	84	1	42	7	21	30	0	0.39
HPC1-15	134	357	63	1	42	7	21	30	1	0.37
HPC1-20	134	336	84	1	42	7	21	30	1	0.39
HPC2-15	134	357	63	1	42	7	21	30	2	0.37
HPC2-20	134	336	84	1	42	7	21	30	2	0.39

Note: W = water; C = cement; GWP = glass waste powder; SP = superplasticizer; S = sand; G = gravel; SF = silica fume; W/C = water-to-cement ratio; HPC = high-performance concrete.

3. RESULTS AND DISCUSSION

3.1 Fresh properties

3.1.1 Workability

Figure 3 shows that the reference concrete (HPC(R)) has the highest slump value (4.0 cm), whereas the HPC2-20 mixture exhibits the lowest value (2.9 cm). This reduction in workability can be explained by the high fineness of the GWP, which increases the water demand of the mixture, as well as the presence of MF, which restricts the mobility of the fresh concrete. Despite this decrease, all mixtures exhibit slump values relatively close to those of the reference concrete, indicating satisfactory workability and compatibility with the placement requirements of the HPC studied.

The reduction in slump observed in mixtures containing GWP and MF corresponds with findings reported by previous researchers. According to Islam et al. [4], the addition of GWP reduces concrete workability due to its high fineness, which increases water demand. Similarly, Gholampour et al. [21] showed that the partial replacement of cement with glass-based additives generally leads to a reduction in the fluidity of fresh concrete. Furthermore, Poudel et al. [22] observed that incorporating MF limits the mobility of the cementitious mixture, consequently causing a gradual decrease in slump. The results obtained in the present study are therefore consistent with these previously reported trends.

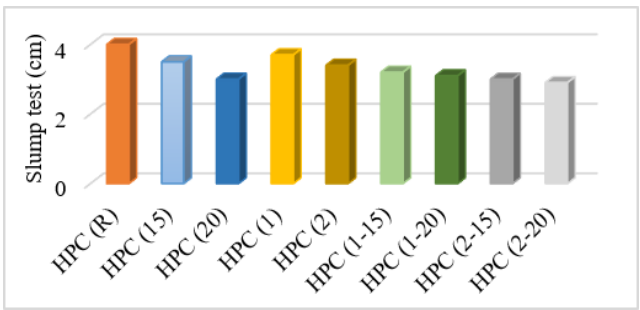


Figure 3. Slump variation for various high-performance concrete (HPC) combinations

3.1.2 Density

The fresh concrete density results listed in Figure 4 indicate variations depending on the cement replacement rate with GWP and the incorporation of MF. Overall, a slight decrease in density is observed for the mixtures incorporating these additives compared with the reference concrete. This trend can be explained by the difference in density between cement and glass powder, as well as the influence of the fibers on the compactness of the fresh mixture.

These observations are consistent with findings reported in the literature. Siddique [23] demonstrated that incorporating crushed glass materials into concrete can modify its density because of their slightly lower density and their influence on the granular structure. Similarly, Batayneh et al. [24] reported that the use of waste glass in concrete can slightly reduce density while maintaining satisfactory mechanical properties. Furthermore, Khaloo et al. [25] observed that the incorporation of steel fibers can affect the compactness of fresh concrete depending on the fiber dosage and their dispersion within the cementitious matrix.

The results obtained in the current investigation are generally consistent with the trends reported in the literature, while highlighting the combined influence of GWP and steel fibers on the density of fresh concrete.

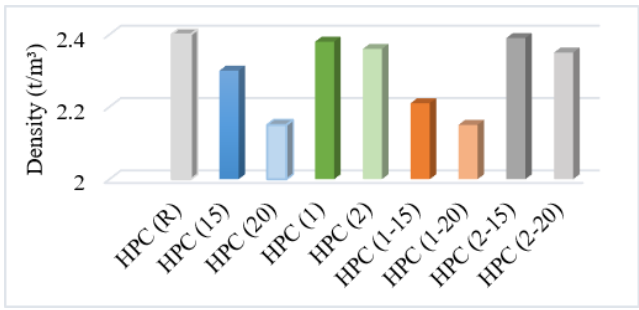


Figure 4. Fresh concrete density

3.2 Hardened properties

3.2.1 Compressive strength

Figure 5 illustrates the development of compressive strength, showing a progressive increase in all mixtures between 3 and 28 days as a result of ongoing hydration reactions. However, replacing cement with GWP leads to a gradual reduction in compressive strength compared with the reference concrete, with this decrease becoming more pronounced at a 20% replacement level. This decrease may be associated with the cement dilution effect and the relatively limited reactivity of ground glass at early ages. Conversely, the incorporation of MF enhances the mechanical properties of the concrete, as the fibers hinder microcrack propagation and facilitate more effective stress redistribution. Concrete mixtures incorporating both GWP and MF generally exhibit intermediate strength levels, with the fibers partially offsetting the strength loss associated with cement replacement. This trend agrees with the findings of Topçu and Canbaz [26], who observed a decline in compressive strength as the proportion

of recycled glass increased. Ismail and Al-Hashmi [27] also reported that high glass content can negatively affect the mechanical behavior of concrete. These findings are further supported by the recent study of Ikotun et al. [28], which reported that the incorporation of waste glass powder as a partial cement substitute affects the mechanical characteristics of concrete. Regarding steel fibers, Ikotun et al. [28] showed that their incorporation enhances the mechanical behavior of concrete by hindering crack formation and limiting crack growth. Similarly, Yoo and Banthia [12] illustrated the beneficial effect of steel fibers in enhancing the toughness and mechanical performance of HPC.

From a mechanistic point of view, the decrease in compressive strength with increasing GWP content can be attributed mainly to the cement dilution effect and the relatively slow kinetics of the pozzolanic reaction. Although the amorphous silica present in GWP can react with calcium hydroxide to form additional C-S-H, this reaction may not be sufficiently developed at the ages investigated to compensate for the reduction in cement content, particularly at the 20% replacement level [1, 3].

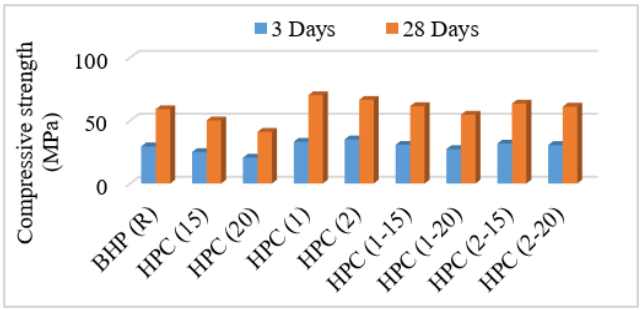


Figure 5. Variation of compressive strength of high-performance concrete (HPC) mixtures

3.2.2 Flexural tensile strength

As illustrated in Figure 6, the flexural tensile strength of the mixtures containing GWP falls slightly below that of the reference concrete, particularly at a 20% replacement level. Conversely, incorporating MF leads to a marked enhancement in flexural strength, with the greatest improvement observed at a fiber content of 2%, reaching a maximum value of 9.10 MPa after 28 days. For the combined mixtures, the fibers partially compensate for the strength loss caused by the incorporation of GWP, resulting in performance levels close to, and in some cases slightly exceeding, those of the control concrete.

These results are consistent with the findings of Zeybek et al. [29], who reported a decrease in flexural strength with increasing glass powder proportion. Islam et al. [4] also demonstrated that flexural strength may be affected during the initial curing period due to the slower reaction of ground glass. Conversely, Afroughsabet and Ozbakkaloglu [16] highlighted that steel fibers can enhance the flexural strength and toughness of concrete. Similarly, Khaloo et al. [25] confirmed that MF improves the ability of concrete to resist crack propagation under flexural loading. This behavior can be attributed primarily to the crack-bridging mechanism provided by the fibers. As they intersect developing cracks, the fibers transfer stresses across the cracked sections, thus restricting crack opening and delaying further crack propagation. Increasing the fiber dosage consequently improves the bridging capacity and post-cracking resistance, which helps explain the enhanced performance observed at a 2% fiber content [12, 30].

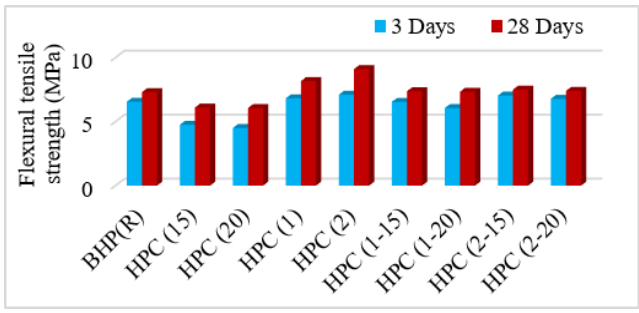


Figure 6. Variation of flexural tensile strength of high-performance concrete (HPC) mixtures



Figure 7. Variation of ultrasonic pulse velocity (UPV) of high-performance concrete (HPC) mixtures

3.2.3 Ultrasonic pulse velocity

As illustrated in Figure 7, the UPV generally increases between 3 and 28 days across all formulations, reflecting the gradual improvement in the density and homogeneity of the cementitious matrix as hydration progresses. Concretes incorporating GWP exhibit slightly lower velocities than the reference concrete at 28 days, whereas the addition of MF helps maintain relatively high velocities, indicating good internal quality of the material. The mixtures combining GWP and MF exhibit UPV values ranging from 5,530 to 5,675 m/s at 28 days, indicating a high degree of compactness. These findings are in line with the observations of Leporace-Guimil et al. [30], who demonstrated that the UPV of concrete incorporating recycled glass varies according to the replacement level and curing age. Wang et al. [31] and Benaicha et al. [32] demonstrated a strong correlation between UPV and the mechanical characteristics of fiber-reinforced concrete, while the incorporation of MF was found to cause only a slight change in wave propagation velocity. Furthermore, Nematzadeh et al. [33] confirmed that MF contributes to maintaining the internal integrity of concrete, as assessed by ultrasonic testing. Finally, Lencis et al. [34] highlighted that high ultrasonic pulse velocities are generally associated with better internal concrete quality, while noting that several parameters, including age, moisture content, and material composition, can affect the measured velocity.

4. CONCLUSIONS

The aim of this study was to investigate the performance of HPCs containing GWP as a partial substitution of cement and MF as reinforcement, with particular emphasis on their fresh

and hardened properties.

The analysis indicates that increasing the GWP content generally reduced the mechanical performance of the concrete. At 28 days, the incorporation of 20% GWP resulted in a 30.54% reduction in compressive strength compared with the reference concrete. In contrast, the addition of MF improved the mechanical performance. The highest compressive strength was obtained with 1% MF, reaching 70.15 MPa, corresponding to an 18.84% increase compared with the reference concrete. The highest flexural tensile strength was obtained with 2% MF, reaching 9.10 MPa, corresponding to a 24.66% increase.

For the hybrid mixtures, the beneficial effect of MF on flexural performance was less pronounced in the presence of GWP. The highest flexural tensile strength among the hybrid mixtures was obtained with 15% GWP and 2% MF, reaching 7.50 MPa, corresponding to a 2.74% increase compared with the reference concrete. The increase in fiber content also resulted in a reduction in workability, highlighting the need to optimize the fiber dosage.

Overall, the results indicate that 1% MF provides the most favorable performance in terms of compressive strength, whereas 2% MF is more beneficial for flexural tensile strength. The combined use of GWP and MF therefore requires careful optimization to balance mechanical performance, workability, and glass waste valorization. Further investigations, particularly on long-term durability and alkali-silica reaction, are recommended to assess the durability of these mixtures.

ACKNOWLEDGMENT

The authors gratefully acknowledge the individuals and organizations whose contributions supported the successful completion of this research project. Particular appreciation is extended to the technical staff for their valuable assistance with data collection, laboratory testing, and material preparation throughout the experimental program. The authors further acknowledge the researchers and colleagues whose constructive comments, fruitful discussions, and scientific guidance contributed to the quality of this work. Their cooperation, support, and encouragement throughout the research process are sincerely appreciated.

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NOMENCLATURE

HPC	high-performance concrete
GWP	glass waste powder
MF	metal fibers
UPV	ultrasonic pulse velocity
S	sand
W	water
C	cement
G	gravel
SP	superplasticizer