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ENHANCING MECHANICAL BEHAVIOUR AND DURABILITY OF HIGH PERFORMANCE CONCRETE WITH SILICA FUME, GROUND BLAST FURNACE SLAG, AND MARBLE POWDER

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ABSTRACT:

This study investigates the impact of waste additives on the behaviour of high-performance concrete and its environmental implications, with a specific focus on resource conservation. The research objectives were realised through the preparation of high-performance concrete specimens incorporating industrial waste materials and marble powder as partial replacements for cement and fine aggregates, respectively. Silica fume and ground blast furnace slag were introduced as substitutes for 8% of the cement's weight. Powdered marble was volumetrically substituted at levels of 5%, 10%, and 15% of the fine aggregates. The physical and mechanical properties of both fresh and cured concrete specimens were evaluated at different ages, encompassing parameters such as density, compressive strength, impulse velocity, water absorption, and durability. The findings demonstrated that high-performance concrete formulated with silica fume and ground blast furnace slag exhibited superior properties compared to compositions relying exclusively on Portland cement. Furthermore, the inclusion of marble powder as an alternative building material constituent in high-performance concrete resulted in increased efficiency and improved resistance against chemical acid attacks. Significantly, this approach contributes to reduce aggregate demands, environmental preservation, and the production of environmentally sustainable concrete.

1. INTRODUCTION

In the global environmental context, environmental concerns have taken a prominent position within scientific discourse, particularly in relation to issues surrounding pollution and waste management. Within the domain of civil engineering, concrete stands as one of the most used materials in construction. However, the escalating demand for aggregates, a fundamental constituent of concrete, continues to rise annually, contributing to the depletion of aggregates quarries. This trend has compelled researchers to explore new sources of raw materials (Huang et al., Youssef et al., 2020). Hence, there exists a compelling need to optimize the usage of conventional materials and, more significantly, alternative materials, specifically waste and industrial by-products, in the formulation of high-performance concrete (HPC). The main objective is to limit the impact of the industry on the environment in terms of preservation of natural resources and limitation of pollution (Jalal et al., 2020). The revival of HPCs has witnessed a notable upsurge in recent years and holds promise for the future.

Nevertheless, this practice encounters certain constraints, as waste and industrial products deviate from the characteristics of standard materials. Consequently, incorporating them with conventional materials requires the development of HPC formulations that account for their distinct attributes.

Currently, the construction sector is the largest emitter of greenhouse gases (GHGs). Portland cement (PC) constitutes one of the vital ingredients of concrete that contributes majorly to GHG emissions. Literature indicates that an annual amount of PC amounting to 4000 million tons is currently produced and is expected to increase to approximately 6000 million tons by 2060 (Samimi et al., 2017). These statistics indicate the need for viable alternatives to meet high concrete demands with lower energy requirements and lower CO2 emissions (Taji et al., 2019, Tang et al., 2019). The use of industrial wastes and products in concrete constitutes one of the scientific and feasible remedies proposed to mitigate the above, not only addressing the increasing demand for concrete, but also will also minimize the impending environmental risk.

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In the construction sector, industrial wastes and by-products, such as silica fume and ground blast furnace slag, have been successfully used as supplementary materials for partial replacements for cement to mitigate the environmental impacts associated with its production and use in concrete (Vieira et al., 2020). The land filling of these industrial wastes poses serious environmental risks, but their use as a partial replacement for cement not only reduces the consumption of natural resources used in cement production, but also provides a better alternative to land filling these wastes (Tang et al., 2020). The presence of silica fume in concrete reduces the influence of the weak interfacial zone by strengthening the cement paste-aggregate bond resulting in a less porous and more homogeneous microstructure in the interfacial zone (Siddique, 2011, Koksal et al., 2008). The benefits obtained from using SF include significant improvement in compressive strength and improved durability when added in optimal amounts (Sanjuan et al., 2015). (Dilbas et al., 2014) demonstrated that replacing cement with 5% SF improves the performance of recycled aggregate concrete and increases the water absorption of natural and recycled aggregate concrete. (Gupta et al., 2016) concluded that the water penetration depth decreases by about 12% for 25% rubber fibre concrete with the replacement of 10% cement with SF, due to good adhesion between the fibers and the cementitious matrix. (Gesoglu and Guneyisi, 2007) found that silica fume decreases chloride penetration depth and improves compressive strength of rubberized concrete. (AbdeAleem and Hassan, 2018) added that the use of silica fume allows for increasing the recycled tire rubber rate in concrete while achieving enhanced mechanical properties and acceptable fresh properties.

Ground blast furnace slag (GBFS) is a mineral admixture with numerous qualities at this level, and its chemical composition is similar to that of Portland cement (PC). Globally, there are about 530 million tons, of which only 65% is used by the construction sector (Sharma, 2016). (Mhaya et al., 2020) observed that the incorporation of 20% of granulated blast furnace slag reduces the workability and increases mechanical properties of rubberized concrete.

The use of ground granulated blast furnace slag (GGBFS) as a binder ingredient in concrete preparation can also result in significant cost savings (Wang and Lee, 2010). For over a century, GGBFS has been the primary supplementary cementing material used in the construction industry. Both cementitious and pozzolanic characteristics can be found in GGBFS material. Various research studies have been conducted on the impact of GGBFS on the performance of various types of concrete and mortars (Dunakar and Saho, 2013, Dhir and Tang, 2009, Abbass and Sinth, 2021, Du and Tan, 2013). The substitution of cement decreases the release of harmful gas and the use of unnecessary electricity (Naik, 2008). In addition to its cost effectiveness and environmental friendliness, GGBFS exhibits strength and durability characteristics equivalent to cement. (Ganesh and Murthy, 2019) have shown that a replacement beyond 20% of cement with GGBFS significantly reduces, and according to another study, the compressive and tensile strength of concrete increased up to 20% when replaced with GGBLS, but further addition of GGBFS reduces them due to lack of fluidity, causing an increase in the permeability of the concrete (Ahmad et al., 2021) and reduces the resistance to chemical attack (Ramezanianpour, 2011). The micro-filling effects of GGBFS cause the voids between the concrete ingredients to be filled leading to a more compact mass, which ultimately increases the density of the concrete (Ahmad et al., 2021). (Thomas, 1999) discovered that concrete incorporating glassy blast furnace slag exhibits increased resistance to chloride penetration compared to conventional concrete. (Srikanth et al., 2022) demonstrated that replacing the ordinary Portland cement (OPC) with 30% ground granulated blast furnace slag (GGBFS) results in 60% and 70% higher compressive strength and produces less porosity, less permeability and less sorptivity in HPC.

The depletion of natural deposits and the challenges associated with opening new quarries necessitate alternative sources of supply. (Vardhan et al., 2019) observed that marble waste constitutes about 20-30% of the total production of the marble industry. In Algeria (Hebhoub et al., 2011) observed that 70% of marble is wasted during the extraction, processing and polishing stages. This waste poses significant environmental problems, leading to soil fertility and morphology (Zhang et al., 2020), as well as presenting disposal challenges (Choudhary et al., 2020), air pollution and clogging of waterways (Varaharajam, 2020).

The valorisation of marble waste (MW) in concrete technology represents a viable and effective solution to bridge the deficit between production and consumption, promote environmental protection, and contribute to sustainable development. Highlighting potential utilization of marble sand (MS) in concrete manufacturing constitutes a primary research direction towards the development of robust, durable, and environmentally friendly concrete. Several researchers have investigated the incorporation of marble waste in both aggregate and powder forms within concrete technology (Djebien et al., 2015). (Ergum, 2011) observed that the incorporation of 5% MW leads to a 12% improvement in concrete compressive strength. This strength enhancement has been observed by other researchers as well (Boughamsa et al., 2020, Corinaldesi et al., 2019, Hebhoub et al., 2011, Verdhan et al., 2019). The enhancement of mechanical properties of concrete containing marble waste is attributed to the generation of carbo-aluminates in the presence of MW, which possesses binding capacity (Chawla et al., 2018, Ergun, 2011). (Aliabdo et al., 2014) showed that the use of MW significantly enhances concrete's tensile strength. (Vardhan et al., 2019) pointed out that due to its filling effect, MW is better suited as a fine aggregate substitution than being used as a cement substitution. (Ince et al., 2020) utilized MW as a partial substitution of fine aggregates in concrete and reported that its use of MW improves resistance against sulphate attack and freeze-thaw resistances of concrete. (Bourzik et al., 2023) investigated the use of waste marble powder (WMP) as a partial replacement of sand in concrete, the results indicate that the increase in waste marble powder rations leads to an increase in the compressive strength of concrete with an optimal percentage of 15%. Therefore, they concluded that mixtures containing less than 15% WMP enhanced mechanical properties compared to conventional mixtures. This implies that WMP can serve as a substitute for sand in concrete. Furthermore, the employment of WMP offers a practical source of raw materials for the construction industry, while also providing an environmentally friendly solution for the disposal of WMP in order to preserve the natural aggregate reserves.

(Chandramouli, 2022) observed that the combined partial replacement of cement with 7.5% SF and fine aggregate with 15% marble powder significantly improves concrete's compressive and tensile strength by 20% and 24% respectively. (Karakurt and Dumangoz, 2022) discovered that utilizing 10% marble dust (MD) and 30% granulated blast furnace slag (GBFS) in place of fine aggregate in the composition of self-compacting concrete (SCC) can impact the mechanical

properties and durability of SCC. Using MD and GBFS in SCC production will not only enhance concrete's performance but also create new opportunities for utilizing waste materials that might otherwise pose environmental challenges. Moreover, incorporating these industrial wastes instead of fine aggregates will contribute to the consumption of higher amounts of MD and GBFS in SCC mixtures compared to their use as supplementary cementitious materials. (Shinde et al., 2022) investigated the concrete's strength by replacing cement with GGBFS, and fine aggregates were substituted with marble dust powder (MDP) using appropriate proportions, they found that this replacement can produce durable, stronger, and economical concrete, suitable for the manufacture of pavers and other concrete elements.

2. SIGINIFICANT RESEARCH

Concrete stands as the most widely used construction material worldwide. Recent years have witnessed a significant milestone in the evolution of concrete with the emergence of HPCs, in which cement and sand serve as essential ingredients, collectively accounting for more than 50% of its volume. This contributes to CO2 emissions and leads to the depletion of natural resources. The incorporation of waste materials in HPC formulation is now regarded as a prospective and effective solution that works to reduce the consumption of raw materials, ameliorate waste accumulation and promote environmental conservation. To accomplish these objectives, HCP mixtures were formulated in this study, marking the first instance of utilizing: powdered marble (PM), powdered marble (PM) combined with the silica fume (SF), and powdered marble (PM) combined with ground blast furnace slag (GBFS). It is important to note that PM partially replaces sand, while SF and the GBFS partially replaces cement in HPC. The influence of these waste additions in HPC mixtures demonstrated significant enhancements in both fresh and hardened properties, culminating in the production of environmentally conscious concrete that is both environmentally friendly and economically efficient.

3. MATERIALS, MIX DESIGN AND TESTS

3.1. Materials

The different materials used included:
-Cement CEM I 42.5 with an absolute density of 3.08 g/cm3 and the Blaine specific surface of 3896 cm2/g. The chemical composition of cement is presented in Table 1.

Properties	Value
Initial setting time (min)	77
Final setting time (min)	182
Specific gravity (g/cm3)	3.135
Blaine fineness (cm2/g)	3157
Shrinkage for 28 days (µm/m)	791
Compressive strength at 2 days (MPa)	26.97
Compressive strength at 14 days (MPa)	44.02
Compressive strength at 28 days (MPa)	58.15
Flexural strength at 2 days (MPa)	5.13
Flexural strength at 7 days (MPa)	7.44
Flexural strength at 28 days (MPa)	9.11
C4AF (%)	10.05
C3A (%)	8.23
C3S (%)	58.56
C_2S (%)	13.74

Table 1. Physical and mechanical properties of PC

- Marble powder (PM) is derived from the marble quarry in the Skikda region of Algeria. Its properties are given in Table 2.

Properties	MP
Colour	White
Specific gravity (g/cm3)	2.74
Absorption (%)	0.41
Compressive strength (dry state) (MPa)	9.68
Wear strength (g/cm2)	1.85
Impact strength (kg/cm2)	41
Blaine fineness (cm2/g)	2856
CaCo3 (%)	97.05
CaO (%)	54.07
Al2O3 (%)	0.41
Fe2O3 (%)	0.25
SiO2 (%)	1.13
MgO (%)	2.85
Na2O (%)	0.17
K2O (%)	0.06
Cl- (%)	0.03
SO3 (%)	0.00

Table 2. Properties of MP

- Silica fume (SF) and ground blast furnace slag (GBFS) were used as mineral additions with cement. The properties of additions used are detailed in table 3.

Properties	SF	GBFS
Colour	Dark grey	Light beige
Particle size (µm)	<1	<80
Specific gravity	2.25	3.05
Bulk density (Kg/m3)	652	933
Surface area (m2/Kg)	23 002	852
Finess modulus (m2/Kg)	20 005	803
CaO	1.48	40.13
Al2O3	1.04	7.63
Fe2O3	1.03	1.45
SiO2	97	42.05
MgO	1.06	5.38
Na2O	0.63	0.15
K2O3	0.78	0.41
SO3	0.12	0.16
Loss in ignition	1.78	0.10

Table 3. Properties of SF and GBFS

-Two types of gravel (G1 and G2) were employed, featuring a maximum nominal size of 15 mm and 8 mm respectively. Additionally, Crushed sand (CS) with maximal normal size of 4 mm was used in this study. The properties of aggregates used are presented in table 4. The particle size distributions of aggregates used are shown in Fig.1.

Properties	G1	G2	CS
Specific gravity	2.65	2.70	2.68
Sand equivalent (%)	69.07	-	-
Fineness modulus	3.09	-	-
Blue of Methylene value	0.53	-	-
Micro-Deval (%)	-	18.3	17.10
Los Angeles (%)		28.3	29.15

Table 4. Properties of aggregates

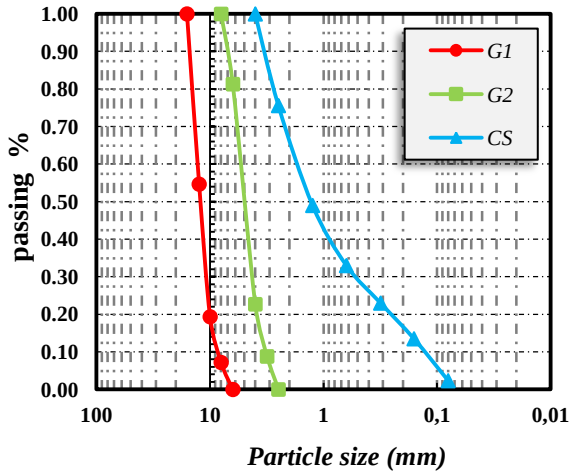


Figure 1. Particles size distribution of aggregates

-The superplasticizer (SP) utilized was Master Glenium SKY 3080, formulated on a poly carboxylic ether basis, exhibiting a brown colour, density of 1.09, and a pH of 7.

- Tap water for mixing.

3.2. Mix design and tests

The Dreux-Gorisse method was used to determine the amounts of Gravel and Sand in the composition of control HPCs. For control HPCs based on SF or GBFS, 36 kg of PC was replaced by these mineral additions, as indicated in Table 5. Subsequently, percentages of 5%, 10% and 15% of MP introduced into the composition of the reference HPCs through volumetric replacement of Sand. The contents of PC, SF, GBFS, water and SP were maintained at consistent levels. The SP quantity used in this study was 1% of PC weight.

	G1 (kg/m^3)	G2 (kg/m^3)	CS (kg/m^3)	PC (kg/m^3)	SP (L/m^3)	Water (L/m^3)	MP (kg/m^3)	SF (kg/m^3)	GBFS (kg/m^3)
HPC	565	305	823	450	4,55	180	00	00	00
HPC+5MP	565	305	781,54	450	4,55	180	43,17	00	00
HPC+10MP	565	305	740,08	450	4,55	180	86,34	00	00
HPC+15MP	565	305	698,62	450	4,55	180	129,51	00	00
HPCSF	520,13	303,83	817,83	414	4,55	180	00	36	00
HPCSF+5MP	520,13	303,83	776,96	414	4,55	180	42,90	36	00
HPCSF+10MP	520,13	303,83	736,09	414	4,55	180	85,80	36	00
HPCSF+15MP	520,13	303,83	695,22	414	4,55	180	128,70	36	00
HPCGBFS	520,13	303,83	817,83	414	4,55	180	00	00	36
HPCGBFS+5MP	520,13	303,83	776,96	414	4,55	180	42,90	00	36
HPCGBFS+10MP	520,13	303,83	736,09	414	4,55	180	85,80	00	36
HPCGBFS+15MP	520,23	303,83	695,22	414	4,55	180	128,70	00	36

Table 5. HPC mixtures prepared

The tests carried out on the mixtures are:
- Density test in the fresh state according to standard NF EN 12350-6.

- The Compressive strength at the age of 7, 28 and 90 days measured on cubic specimens with dimensions of 15x15x15 cm^3

Kept in water and open air in accordance with standard NF EN 12504-4.

- Absorption by capillarity measured on prismatic test pieces with dimensions of 15x15x15 cm3 in accordance with standard NBN B 15-215.

- Chemical effect tests with solutions of 5% HCL on cubic specimens with dimensions of 10x10x10 cm3 preserved for 28 days in water then immersed in the solutions until the age of 56 days, 90 days and180 days according to standard ASTM C 267-96.

4. RESULTATS AND DISCUSSION

4.1. Fresh Density

The results of density tests of different concrete mixes are presented in Table 6.

M P (%)	Fresh Density		
	HPC+ %MP	HPCSF+ %MP	HPCGBFS+ %MP
0	2.37	2.35	2.36
5	2.41	2.38	2.39
10	2.51	2.46	2.49
15	2.57	2.52	2.55

Table 6. Fresh density values of HPC mixtures

Table 6 shows that the partial replacement of cement with GBFS and SF in HPC mixtures results in a reduction in density, attributable to the higher density of cement.

However, the increase in the rate of substitution rate with MP leads to a corresponding elevation in density, reaching up to 7,23 % for HPC combined with SF, 8,05 % for HPC combined with GBFS, and 8,44 % for HPC. This phenomenon is attributed to the higher density of MP in comparison to the other aggregates.

4.2. Compressive Strength

Table 7 indicates the effect of substitution rate on compressive strength of HPC mixtures. The replacement of cement by 8 % SF in HPC increases slightly the compressive strength at early and late age. These results are comparable with those obtained by (Chandramouli, 2022), it was due to the filler role of very fine particles of SF (Behnood and Ziari, 2008).

Age (Days)	MP (%)	Compressive Strength (MPa)		
		HPC + % MP	HPCSF + % MP	HPCGBFS + % MP
At 7 Days	0	33.19	33.42	40.36
	5	35.68	37.22	49.09
	10	38.14	39.74	51.20
	15	40.48	41.98	53.06
At 28	0	50.32	50.57	50.45
	5	54.05	55.57	56.98
	10	56.93	58.43	59.53
	15	59.53	60.48	62.41
At 90	0	56.86	57.44	57.48
	5	61.25	63.12	65.06
	10	64.44	66.44	67.5
	15	67.44	69.23	71.41

Table 7. Compressive strength values of HPC mixtures

As for the specimens containing GBFS, showed improvement at an early age by an increase of 22, 68%compared to the control sample due to the pozzolanic activity and the finesse of GBFS additive (Chaid, 2008).

The incorporation of 15% Marble Powder (MP) in HPC results in a substantial 21.96% increase in compressive strength at 7 days. This enhancement can be attributed to the presence of CaO in MP, which imparts high initial strength (Djebien et al., 2018). At 28 and 90 days, a noteworthy rise in compressive strength of 18.30% and 18.60%, respectively, is observed, primarily due to the elevated content of C2S, known for its contribution to long- term strength, in accordance with the findings of (Farinha et al., 2015).

For HPC combined with SF, a significant upsurge of 25.61%, 19.60%, and 20.52% is observed at 7, 28, and 90 days, respectively, upon adding 15% MP. This can be attributed to the presence of abundant C2S, resulting from the chemical reaction between the CaO in MP and the SiO2 in SF. In the case of HPCGBFS, a notable increase of 31.47%, 23.71%, and 24.23% at 7, 28, and 90 days, respectively, is witnessed when 15% of MP is utilized. This phenomenon can be ascribed to the heightened CaO content within the HPC blend. This elevated CaO content enhances cohesion and provides strong adhesion of aggregates both in the initial and later stages of the concrete's development. Additionally, the positive impact of void filling due to MP's presence is observed (Ulubeyli and Artir, 2016).

The pinnacle of compressive strength was attained with HPCGBFS, formulated with 15% MP across various maturation periods. This observation underscores the favorable influence resulting from the concurrent incorporation of GBFS and SM on the mechanical performance of the concrete.

4.3. Pulse Velocity

The outcomes of the ultrasonic pulse velocity determination tests conducted on all HPC mixtures at different ages are graphically presented in Fig.2. The results indicate the excellent quality of the distinct HPC mixtures as their pulse velocities surpass 4575 m/s (Solis-Carcano and Moreno, 2008). A marginal rise in pulse velocity is observable for HPCSF and HPCGBFS. This can be attributed to the robust adhesion between SF-cement paste and GBFS-cement paste, respectively, which consequently diminishes pore sizes within the concrete, thereby delaying sound propagation.

Ultrasonic pulse velocity exhibits an increment with the augmentation of MP content across all HPC mixtures and at various ages. At 7 days, as MP content escalates from 0 to 15%, pulse velocities span from 4983 m/s to 5223 m/s for HPC+MP%, from 4990 m/s to 5289 m/s for HPCSF+MP%, and from 5235 m/s to 5396 m/s for HPCGBFS+MP%, signifying respective increments of 4.82%, 5.99%, and 3.07%. This phenomenon is attributed to the elevated density of MP, which occupies voids in HPC, thereby reducing porosity (Boughamsa et al., 2020). At 28 and 90 days, the pulse velocity for MP-based HPC mixtures continues to gradually increase, albeit at a lower rate compared to the early ages, as depicted in Fig. 2.

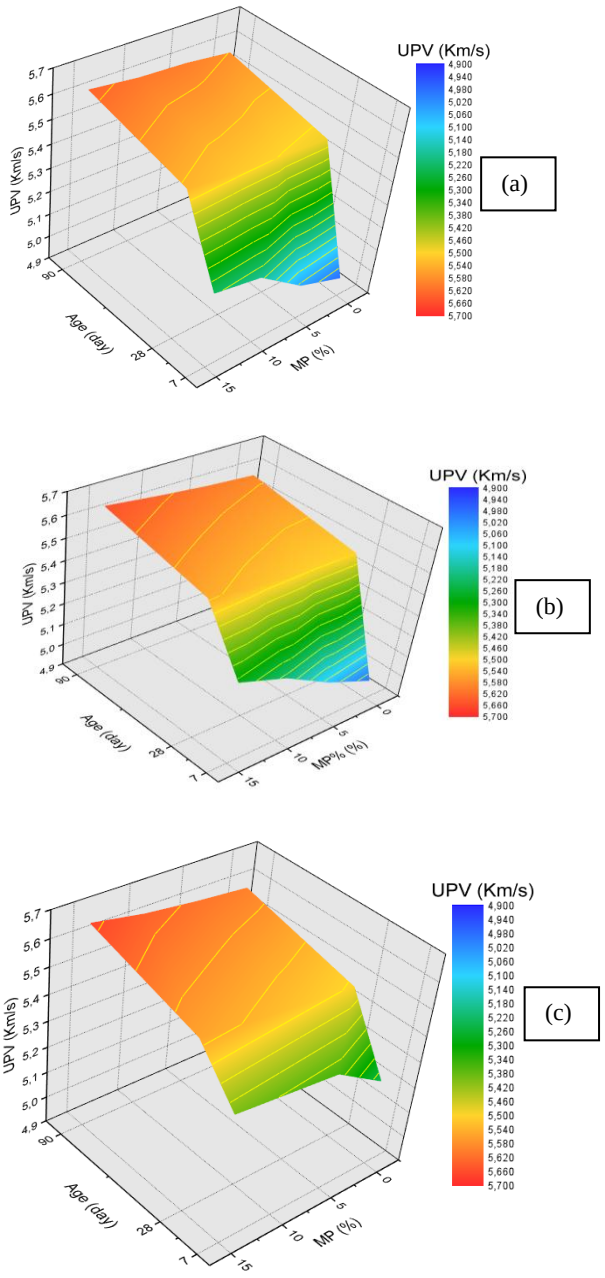
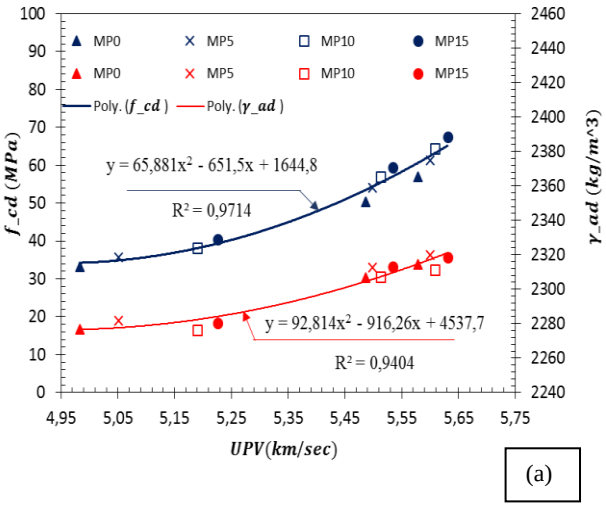


Figure 2. UPV values of HPC mixtures at different ages for: (a) HPC+MP%; (b) HPCSF+MP%; (c) HPCGBFS+MP%

The correlation between compressive strength, pulse velocity, apparent density, and pulse velocity of all HPC mixtures at 7, 28, and 90 days is depicted in fig.3. A robust polynomial (multiple linear) relationship exists between compressive strength and pulse velocity, as evidenced in fig.3. The compressive strength can be estimated employing a 2nd degree polynomial equation ($\boldsymbol{fcd} = a\,\boldsymbol{UPV}^2 + b\,\boldsymbol{UPV} + c$) demonstrating a strong correlation coefficient (R^2) equal to 0,97, 0,96, and 0,88 for HPC+MP%, HPCSF+MP% and HPCGBFS+MP% respectively. A comparable pattern was discerned by (Belaribi et Mellas 2013) who utilized polypropylene fibers in concrete. This trend could arise from the likelihood that parameters exerting a substantial influence on concrete's compressive strength may similarly affect pulse velocity.

As evident from fig. 3 a strong polynomial relationship ($\boldsymbol{fcd} = a\,\boldsymbol{\gamma_{ad}}^2 + b\,\boldsymbol{\gamma_{ad}} + c$) is apparent between apparent density and pulse velocity across all concrete mixtures. These two parameters exhibit a noteworthy correlation, exemplified by respective R^2 values of 0,94 for HPC+MP%; 0,89 for HPCSF+SM% and 0,86 for HPCGBFS+SM%. This correspondence can be rationalized by the presence of fine constituents within the concrete that occupy voids. Additionally, the heightened solid density of MP, exceeding that of the fine aggregates (FA), contributes to this relationship. Moreover, the influence of MP content further reinforces this relationship. In essence, this underscores the predominant impact of MP content on both apparent density and pulse velocity.



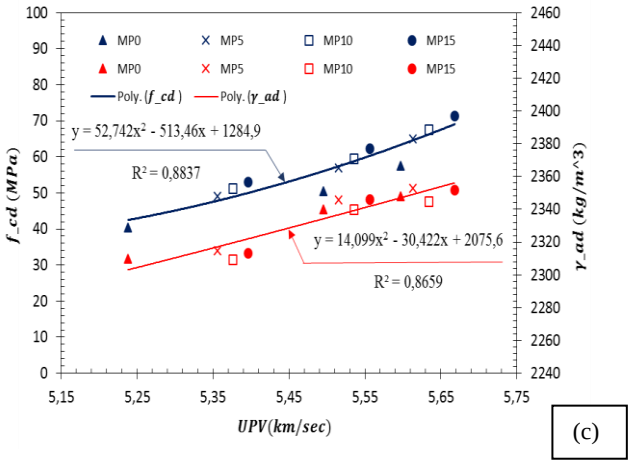
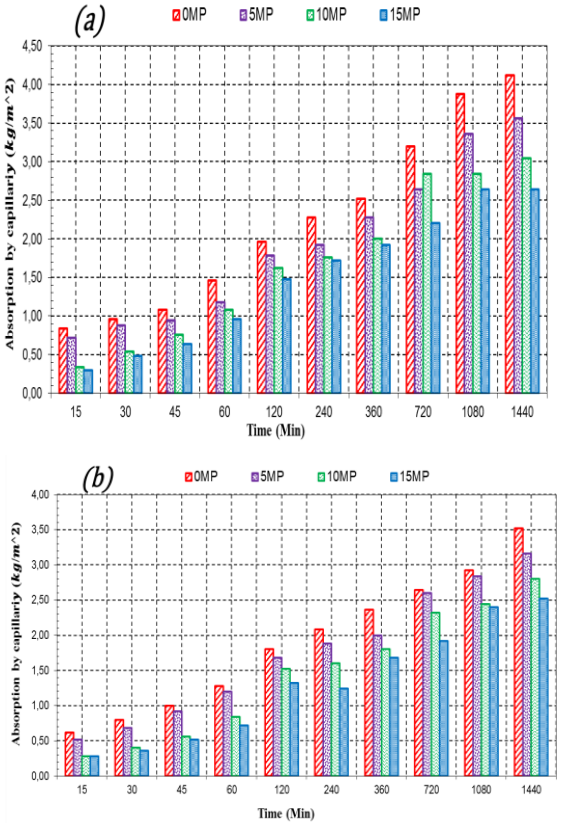


Figure 3. Relationship between compressive Strength and UPV, Apparent density and UPV of HPC mixtures at different ages for: (a) HPC+MP%; (b) HPCSF+MP%; (c) HPCGBFS+MP%

4.4. Water Absorption by Capillarity

As can be seen from fig. 4 the outcomes demonstrate that the incorporation of SF as a partial substitute for cement leads to a reduction in capillary water absorption by 14.56% at 24 hours, compared to the control concrete. This reduction can primarily be attributed to the micro-filling effect of SF, highlighting its favorable durability characteristic (Nadh et al., 2021). The introduction of GBFS in concrete results in a notable 28.15% decrease in capillary water absorption at 24 hours. This effect can be attributed to the pozzolanic reaction with secondary cementitious materials (CSH), enhancing the mortar's binding property. Furthermore, the micro-filling effect of GBFS contributes to a more compact mass, lowering permeability (Ahmad et al., 2022).



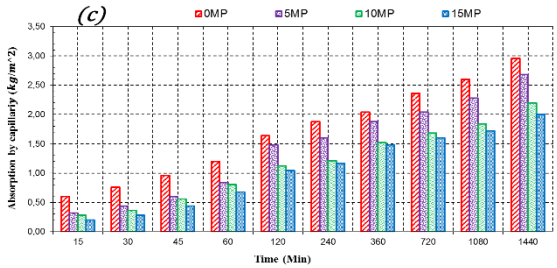


Figure 4. Water absorption by capillarity of HPC mixtures as function of time for: (a) HPC+MP%; (b) HPCSF+MP%; (c) HPCGBFS+MP%

Incorporating MP at levels ranging from 5% to 15% leads to a reduction in capillary water absorption by 13.59% to 35.92% for HPC+MP%, 10.22% to 28.413% for HPCSF+MP%, and 9.45% to 32.43% for HPCGBFS+MP% at 24 hours. This reduction signifies improved durability, in accordance with findings by (Topçu et al., 2008). This phenomenon can be attributed to several factors. Firstly, the presence of MP in the concrete improves the bond between cement paste and fine aggregates due to the angular and elongated geometry of the MP particles (Gameiro et al., 2014). Additionally, the grains of MP effectively fill the pores of HPC, leading to thinner capillary vessels. This phenomenon, along with the pozzolanic activity driven by the reaction between SiO2, Al2O3, and Ca(OH)2, results in the formation of additional phases like C-S-H (strangeness) and mono-sulfate, among others (Farhina et al., 2015, Silva et al., 2009, Vieira et al., 2016).

4.5. Chemical effect tests with hydrochloric acid

Age (Days)	MP (%)	Mass Loss (%)		
		HPC + % MP	HPCSF + % MP	HPCGBFS + % MP
At 56	0	3.11	2.38	1.87
	5	2.21	1.96	1.69
	10	1.91	1.73	1.54
	15	1.58	1.46	1.19
At 90	0	5.1	4.58	3.6
	5	3.6	3.42	2.91
	10	2.91	2.61	2.48
	15	2.67	2.32	2
At 180	0	6.11	5.91	5.68
	5	5.07	4.01	3.87
	10	4.22	3.75	3.62
	15	4.16	3.43	3.04

Table 8. Variation of mass loss versus the immersion period in HCL of HPC mixtures

Table.8 shows the variation of mass loss in function of time of all HPC mixtures immersed in the solution of 5% hydrochloric acid (HCL) at 56, 90 and 180 days. The obtained results reveal that, after 180 days of storage, there is an increase in mass loss of 6.11%, 5.91%, and 5.68% for HPC, HPCSF, and HPCGBFS, respectively. Notably, HPC formulations incorporating 8% GBFS and SF as partial cement replacements exhibit greater resistance to the effects of hydrochloric acid in comparison to the control concrete. This enhanced durability can be attributed to the micro-filling effect of GBFS and SF within the concrete aggregates, resulting in a denser concrete that reduces susceptibility to degradation caused by chloride attacks. (Ahmed et al., 2022) similarly observed this effect when utilizing GBFS as a cement substitute in concrete.

As the percentage of MP replacement increases from 0% to 15%, the mass loss decreases by 36.36%, 38.65%, and 49.20% for HPC; 44.44%, 49.34%, and 47.65% for HPCSF; and 46.48%, 41.96%, and 31.91% for HPCGBFS at 56 days, 90 days, and 180 days of storage, respectively. This decrease in mass loss can be attributed to the elevated CaO content in MP, which enhances initial strength. During the concrete mixtures' setting, accelerated reactions from numerous hydrates of portlandites (Ca(OH)2) and calcium silicate hydrate (C-S-H), thereby filling pores and providing stiffness to the matrix. This action impedes the absorption of hydrochloric acid by the concrete (Laoufi et al., 2016).

As seen in Table 9, the reduction in strength is notably more pronounced in the control concrete, with increasing strength loss observed over the immersion period for all formulations. Interestingly, at 180 days, the strength loss in mixtures incorporating SF and GBFS is notably lower at 33.42% and 27.9% respectively, in contrast to the control concrete (HPC) which experiences a strength loss exceeding 41%. This difference can be attributed to the pozzolanic reactivity and micro-filling effects of SF and GBFS, which effectively reduce the penetration of chlorides into the concrete (Kansal et al., 2021; Ahmad et al., 2022). With the inclusion of MP at proportions up to 15% in HPC mixtures, the strength loss diminishes by 16.20% for HPC, 18.95% for HPCSF, and 14.30% for HPCGBFS after 180 days of immersion. This trend aligns with findings by (Karkurt and Dumangoz, 2022). The presence of MP in HPC mixtures is instrumental in modifying the pore structure, contributing to these improvements in strength retention.

Age (Days)	MP (%)	Strength Loss (%)		
		HPC + % MP	HPCSF + % MP	HPCGBFS + % MP
At 56	0	18.15	14.08	11.01
	5	15.88	12.84	10.44
	10	14.6	11.26	9.14
	15	12.32	10.43	8.17
At 90	0	29.11	22.35	18.58
	5	26.02	20.88	15.55
	10	24.15	19.44	14.75
	15	24.07	17.25	13.79
At 180	0	41.22	33.42	27.9
	5	37.12	31.19	26.44
	10	36.27	30.5	25.68
	15	34.54	27.51	23.91

Table 9. Variation of strenght loss versus the immersion period in HCL of HPC mixtures

Figure 5 shows the relationship between the strength loss and mass loss at 56 days, 90days and 180 days of storage for all concrete mixtures exposed to chloride attack. The figure demonstrates a robust polynomial relationship between strength loss and mass loss across all HPC mixtures, characterized by favorable correlation coefficients: R^2 equal to 0,83 for HPC+MP% and 0,87 for HPCSF+MP% and HPCGBFS+MP%.

This strong correlation is likely a result of the substantial interdependence between strength and mass loss, influenced by shared parameters influencing both properties.

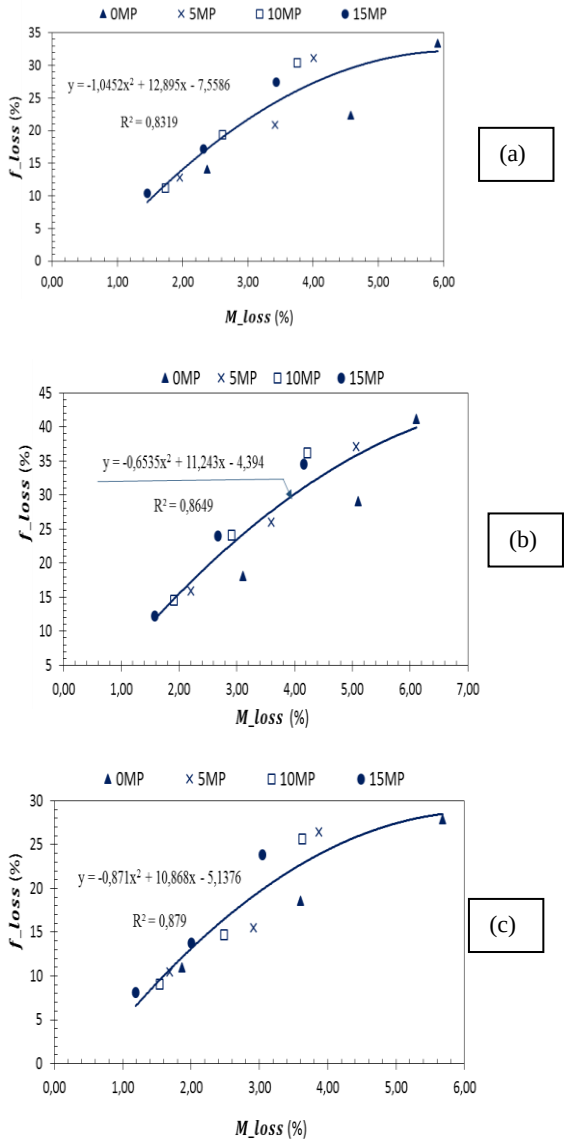


Figure 5. Relationship between strength loss and mass loss of HPC mixtures immersed in HCL for: (a) HPC+MP%; (b) HPCSF+MP%; (c) HPCGBFS+MP%

5. CONCLUSION

The objective of the research presented in this paper was to assess the impact of utilizing combined waste additions (SF, GBFS, and MP) on the physical, mechanical, and durability aspects of HPC. Based on the acquired experimental findings, the following conclusions can be drawn from this study:

- Both SF and GBFS additions contribute to a reduction in density.
- HPC mixtures combined with GBFS and MP exhibited superior compressive strength compared to other HPC mixes, with enhancement observed as the MP content increased from 0% to 15%.
- Strong correlations were observed between compressive strength, ultrasonic pulse velocity, and apparent density for all HPC mixes, with correlation coefficients surpassing 0.86.
- Water absorption decreased as the MP replacement level increased from 5% to 15% across all mixes. While SF inclusion led to a decline in water absorption, the reduction was more pronounced when GBFS was incorporated.
- HPC incorporating 15% marble powder and GBFS exhibited heightened resistance to hydrochloric acid.
- Durability assessments demonstrated that HPC produced with GBFS outperformed those with SF and without any additional materials.

In summary, the outcomes underscore the feasibility of employing singular or combined replacement of these waste materials (SF, GBFS, and MP) in high-performance concrete technology, leading to decreased cement consumption, reduced use of natural aggregates, and the creation of environmentally favorable green concrete. Furthermore, the combined utilization of GBFS and MP in high-performance concrete production exhibits notable mechanical strength and durability.

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