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Assessing the impact of waste glass and metakaolin on the durability and mechanical strength properties of concrete

Raquel Barros Leal[1], Crislene Rodrigues da Silva Morais[1], Kallyana Da Silva Santos[1]

[1]Universidade Federal de Campina Grande, Unidade Acadêmica de Engenharia de Materiais. Campina Grande, PB, Brasil.
e-mail: raquel.barros@estudante.ufcg.edu.br, crislene.rodrigues@professor.ufcg.edu.br, kallyanasilva@gmail.com

ABSTRACT

In the face of environmental challenges stemming from the accumulation of waste glass and cement production, significant contributors to CO_2 emissions, this study explores sustainable construction alternatives by incorporating waste glass (WG) and metakaolin (MK) as partial cement substitutes. Experimental Various concrete mixes containing different percentages of WG and MK (10%, 20%, 30% for WG, and 15% for MK) were evaluated against a standard reference mix. Analyses focused on workability, compressive strength, water absorption, electrical resistivity, ultrasonic pulse velocity (UPV), and chloride ion penetration. The results showed that mixes with 20WG and 30WG enhanced fluidity by 16.67%. In the hardened state, mixes with 10WG and 15MK recorded compressive strength increases of 31.5% and 25.97% at 91 days, respectively. Further tests on electrical resistivity, UPV, and chloride ion penetration indicated that WG and MK contribute to a denser and less porous concrete microstructure, improving durability against chloride ingress. Additionally, water absorption did not increase proportionally with strength, suggesting that other factors beyond porosity influence strength. These findings support the use of glass waste and metakaolin in concrete production to promote more sustainable building practices and extend the lifespan of concrete structures.

Keywords: Sustainable Construction; Waste glass; Metakaolin; Compressive Strength; Durability of Concrete.

1. INTRODUCTION

Over the past few decades, the escalating demand for construction materials can be attributed to economic development, industrial growth, and a rapid population increase [1]. This surge has underscored the critical need to address the environmental impact of the cement production sector, particularly its role in greenhouse gas (GHG) emissions, with carbon dioxide making up the vast majority of these emissions [2]. Efforts to mitigate these effects have led to innovative proposals, including the partial substitution of cement in concrete structures with less environmentally detrimental materials, aimed at prolonging the lifespan of these structures while maintaining their structural and durability properties [3].

An increase in the disposal of waste glass is closely linked with the pace of industrialization and urban development. Each year, global glass production totals approximately 130 million tons, with about 100 million tons of this quantity ending up as waste [4]. The environmental challenges posed by the non-biodegradable nature of waste glass, which occupies significant landfill space indefinitely, are compounded by the scarcity of disposal sites and the growing costs associated with waste management [5].

Glass's primary component, silica or silicon dioxide (SiO_2), rendering it a pozzolanic material of interest for inclusion in the cement matrix [6]. This inclusion has significantly enhanced cementitious composites' mechanical properties and durability. The research conducted by KAMALI and GHAHREMANINEZHAD [7] demonstrated that replacing 5%, 10%, 15%, and 20% of cement with waste glass, featuring an average particle size of 8.4 µm, can significantly enhance the mechanical properties of concrete. Similarly, METHA and ASHISH [8] found that replacing up to 20% of cement with waste glass, with particle sizes ranging from 0 to 75 µm, could enhance the long-term mechanical properties of concrete, including compressive strength, tension, and flexure.

The analysis conducted by ALIABDO *et al.* [9] explored the mechanical effects of incorporating ground waste glass into concrete, noting improvements in both tensile and compressive strengths alongside a decrease in the void index and density of the samples. Additionally, KHAN *et al.* [10] emphasized the significance of waste glass's fineness for its pozzolanic reactivity, demonstrating that concrete mixes with waste glass showed

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superior mechanical properties compared to mixes without it, especially when the waste glass particle sizes were below 45 μm.

Investigations into the influence of waste glass particle size on concrete's mechanics and microstructures by ZHANG *et al.* [11] revealed that particle size distribution plays a crucial role in the performance of waste glass-based concrete. Furthermore, SHAO *et al.* [12] observed that substituting cement with glass particles of a specific granulometry could enhance mechanical properties due to pozzolanic reactions.

GUIGNONE *et al.* [3] found that using a combination of metakaolin and ground glass waste in proportions of 10% each can achieve the same compressive strength gains as using 10% metakaolin alone, but with reduced cement consumption.

EL-DIN *et al.* [13] studied the mechanical performance of concretes with metakaolin contents ranging from 0 to 50%. They found that even at high substitution levels, concretes could maintain satisfactory mechanical performance, with 15% metakaolin yielding the highest strength values.

While the individual use of glass waste and metakaolin has been extensively studied, their combined use in ternary mixes with cement is less explored. Studies suggest a potential synergistic effect when these materials are finely ground, which could enhance the technical performance of concrete at later ages.

This study aims to advance our understanding of the potential benefits of using powdered waste glass (WG) and metakaolin (MK) as partial substitutes for cement in concrete. Focusing on evaluating aspects such as workability, mechanical strength, and durability—including water absorption, void index, ultrasound, and resistance to chloride ions—this research endeavors to contribute to developing more sustainable and durable concrete mixes that respond to environmental and structural requirements.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in this study included Portland cement type CPII-F, coarse aggregate (crushed stone No. 1) from the crushing process of granitic rocks, siliceous sand, ground soda-lime clear waste glass (WG), and metakaolin (MK).

The glass was obtained in shard form. The waste glass was cleaned to remove impurities and air-dried for 24 hours. An eccentric parakeet-type ball mill with alumina balls and jars was used to grind the waste. The weight ratio of balls to material was 1:1, and the grinding time was 45 minutes. After grinding, the ground glass was sieved, collecting the material that passed through the #200 mesh.

Metakaolin was manufactured through grinding and calcinating clay with a high kaolinite content, collected from the southern coast of Paraiba, subjected to 700ºC, and controlled burning in a special furnace.

Figure 1 compares the granulometric distribution of waste glass, cement, and metakaolin.

The chosen fine aggregate was natural quartz sand extracted from a river. The unit mass of the aggregate is 1.60 g/cm^3, as determined by ABNT NBR NM 45 [14]. The specific mass is 2.63 g/cm^3 and was determined following the parameters of ABNT NBR 52 [15]. Figure 2 presents the particle size distribution curve of the sand, following the determinations of ABNT NBR NM 23 [16] and ABNT NBT 7211 [17].

Crushed stone Nº. 1, used as coarse aggregate, had a fineness modulus of 6.9 and a specific gravity of 2.82 g/cm3. The X-ray fluorescence spectrometer (XRF) was used to determine the basic value of the chemical composition of cement, waste glass, and metakaolin. The chemical composition, particle size, specific gravity, and specific surface area are presented in Table 1.

The mineral composition of waste glass (WG), metakaolin (MK), and cement (CPII - F) was determined through X-ray diffraction (XRD), as illustrated in Figures 3a, 3b, and 3c, respectively.

2.2. Methods

2.2.1. Mix Proportioning

To explore the synergistic effect of WG and MK, we utilized varied substitutions of these materials in concrete. For this analysis, graphs, tables, and equations from Abrams, Lyse, and Molinari were used. Eight concrete mixes were prepared in a 1:3.5 ratio with a water-to-cement ratio (w/c) of 0.45, as detailed in Table 2.

A control mix labeled as "REF" was prepared as the reference standard without any cement substitution. Additionally, three mixes (10WG, 20WG, and 30WG) were formulated with cement mass substitutions by waste glass at proportions of 10%, 20%, and 30%, respectively. Another mix (15MK) was developed with exclusive

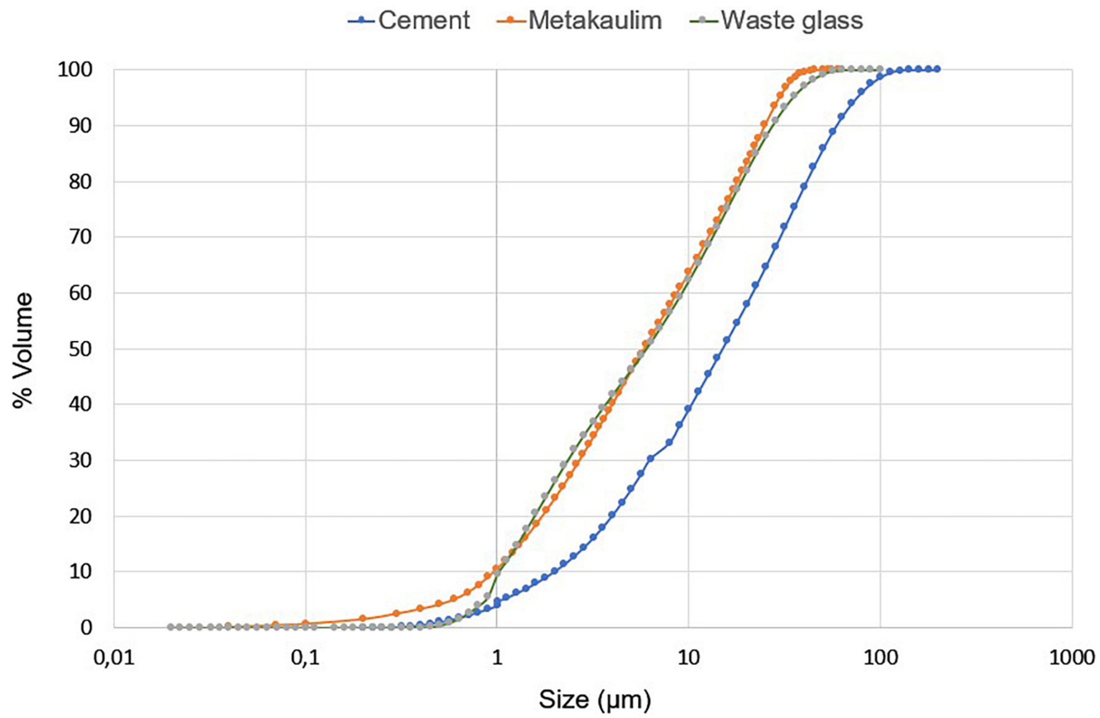

Figure 1: Particle size distribution of cement, metakaolin, and waste glass.

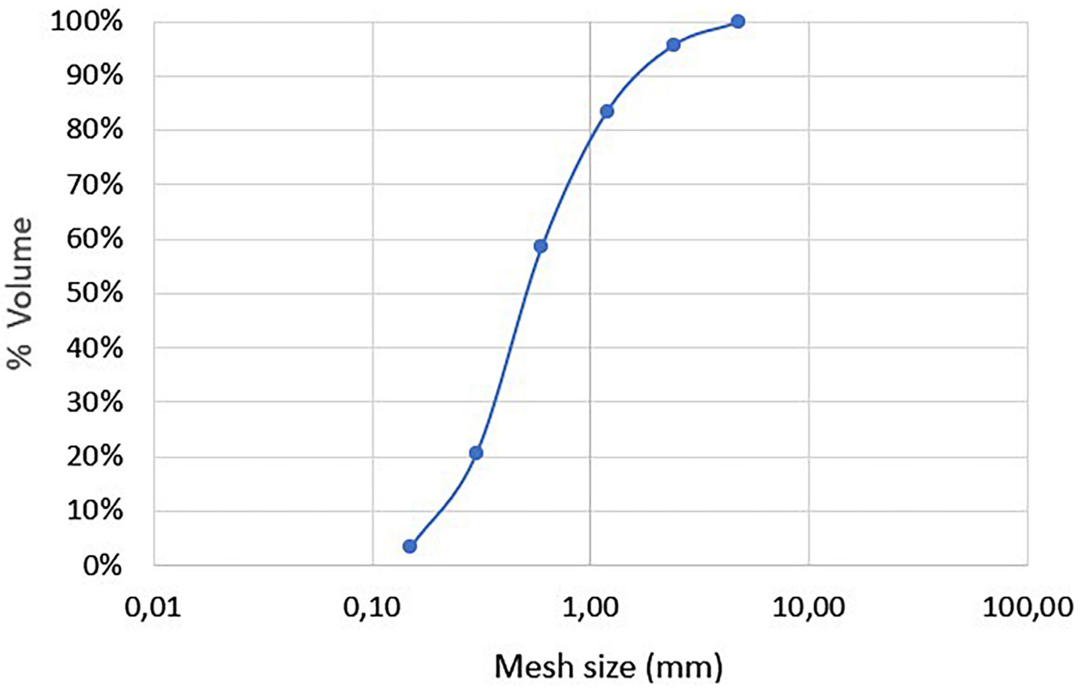

Figure 2: Particle size distribution of the sand.

cement substitution by metakaolin at a 15% proportion. Furthermore, three additional mixes (10WG15MK, 20WG15MK, and 30WG15MK) were prepared, where waste glass was substituted at proportions of 10%, 20%, and 30%, while metakaolin was replaced at a 15% proportion.

Table 1: Chemical composition, particle size, specific gravity, and specific surface area of waste glass (WG), metakaolin (MK), and cement (CPII-F).

COMPOSITION (% BY MASS)	WG	MK	CPII-F
Calcium oxide (CaO)	5,41	0,18	59,69
Silica (SiO_2)	54,20	48,83	19,96
Sulfur trioxide (SO_3)	0,13	0,15	7,29
Aluminum oxide (Al_2O_3)	3,89	44,98	4,92
Magnesium oxide (MgO)	–	2,21	4,12
Iron oxide (Fe_2O_3)	0,03	2,36	2,23
Potassium oxide (K_2O)	0,30	0,53	1,53
Titanium dioxide (TiO_2)	0,03	0,50	0,19
Barium oxide (BaO)	–	0,20	0,05
Sodium oxide (Na_2O)	35,99	–	–
Average particle size (µm)	8,30	12,25	18,01
D10 (µm)	1,02	0,96	1,98
Median particle size - D50 (µm)	5,97	5,81	13,82
D90 (µm)	27,17	24,76	38,20
Specific surface area (m^2/g)	0,36	20,90	0,37
Specific gravity (g/cm^3)	2,51	2,50	3,14

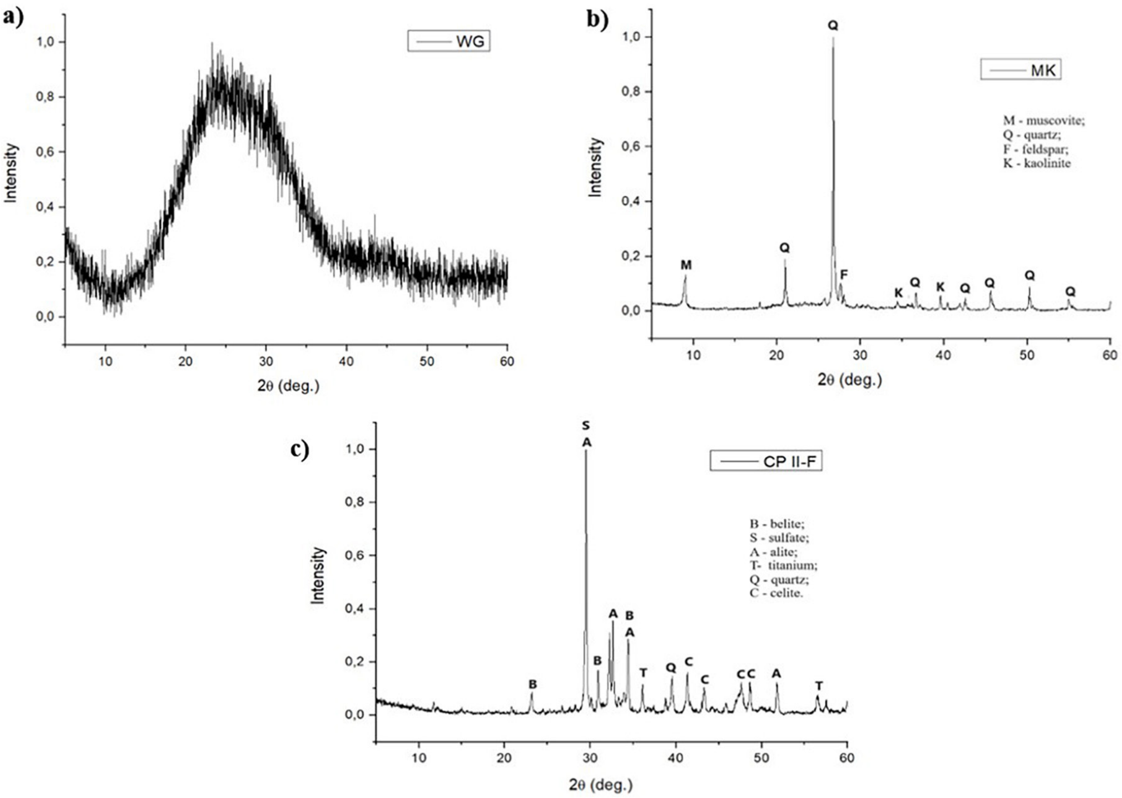

Figure 3: Diffractogram of a) Waste Glass (WG), b) Metakaolin (MK), and c) Cement CP II-F.

To investigate the impact of curing age on the mechanical strength of the concrete, four specimens (CPs) were fabricated and tested for each of the following curing ages: 7 days, 14 days, 28 days, and 91 days. The CPs were cured in a moist chamber, maintaining a relative humidity exceeding 95% and a constant temperature of

Table 2: Mix proportions of concrete mixtures.

CONCRETE	WG (%)	CEMENT (Kg/m^3)	SAND (Kg/m^3)	CRUSHED STONE (Kg/m^3)	MK (Kg/m^3)	WATER (Kg/m^3)
REF.	0	500	780	970	0	215
10WG	10	450	780	970	0	215
20WG	20	400	780	970	0	215
30WG	30	350	780	970	0	215
15MK	0	425	780	970	75	215
10WG15MK	10	375	780	970	75	215
20WG15MK	20	325	780	970	75	215
30WG15MK	30	275	780	970	75	215

23°C ± 2°C until the testing phase. A minimum strength of 25 MPa was adopted for concretes in environments with environmental aggressiveness class II in urban areas [18].

2.2.2. Performed Tests

2.2.2.1. Slump test

A class S100 slump was adopted, meaning a slump between 100 mm and 160 mm. The slump value was set at 100 ± 20 mm. This choice was based on the mixed design and consistency analysis to achieve adequate workability in preparing the specimens [19, 20]. To ensure proper workability for concrete with substitutions, a normal-setting liquid plasticizing additive was added, allowing the workability of various types of concrete manufactured based on sulfonated salts and carbohydrates in an aqueous medium.

2.2.2.2. Simple compression strength test

Compression strength is a fundamental parameter for comparison and remains the most used requirement in selecting cementitious materials. The specimens (CPs) were subjected to rupture after curing periods of 7, 14, 28, and 91 days, using a hydraulic press manufactured by ELE, with a capacity of 70 tons [21, 22]. Four CPs were prepared for each curing period, with the average of the results considered (the variation between individual forces and the average did not exceed 15%).

2.2.2.3. Water absorption, void index, and specific mass test

The concrete absorption test measures the amount of water the concrete can absorb [23]. This test is essential for evaluating the porosity and permeability of concrete, which, in turn, affects its durability and resistance to harmful agents such as water penetration and other deleterious agents.

2.2.2.4. Electrical resistivity

This testing method provides a means to obtain the electrical resistivity of concrete according to the standard AASHTO T 358-17 [24]. Three specimens measuring 10 × 20 cm for each mixture were prepared at 28 days and 91 days. The method involves a quick and straightforward measurement of resistivity, requiring only equipment calibration and electrode attachment to the lateral face of the specimen.

2.2.2.5. Ultrasonic wave propagation velocity

This testing method provides a means to obtain the wave propagation velocity in concrete according to the standard NBR 8802 [25]. It constitutes a non-destructive test that relies on the velocity of ultrasonic wave propagation (v), which depends on the emission and reception time of the wave by transducers along the specimen (height).

3. RESULTS AND DISCUSSION

3.1. Workability

Figure 4 illustrates the evolution of the consistency of the concretes during the production process, first without the incorporation of the superplasticizer additive and then after its addition.

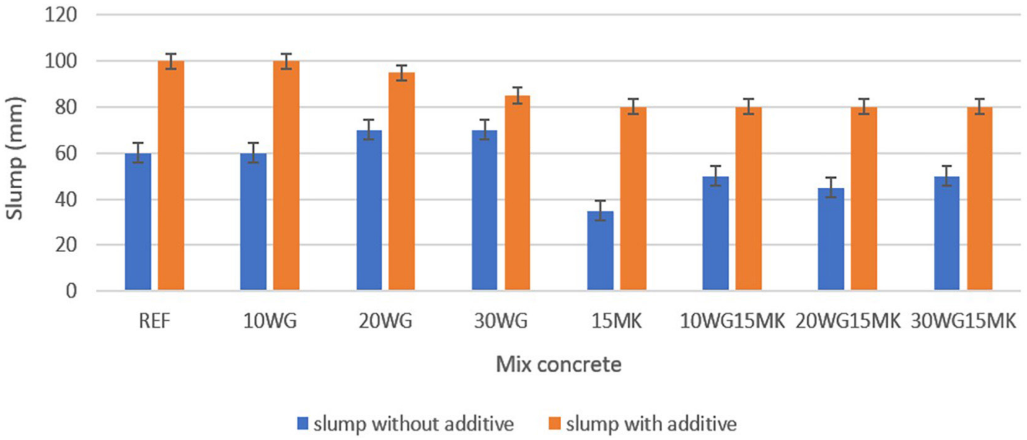

Figure 4: Slump values before and after adding the superplasticizer additive.

According to Figure 4, slump tests conducted without the presence of the superplasticizer did not reach the predefined value of 100 ± 20 mm. In general, this behavior may be partially due to the fact that the added particles replacing the cement particles have finer granulation, thereby requiring more water to saturate their surfaces; and partially due to the lower density of these additives [26].

In this initial stage, mixtures with 20% and 30% substitution by waste glass (WG) showed a 16.67% increase in fluidity compared to the reference concrete (REF). This improvement in fluidity can be attributed to the compact microstructure and smooth surface of glass, which contribute to reduced water absorption and friction [7].

Regarding mixtures with the addition of metakaolin, it is observed that these mixtures obtained the lowest slump values, increasing the demand for water and chemical admixture to maintain rheological properties. The lower slump value in concretes with metakaolin was caused by its high surface area, which does not react with other materials in the mixture, increasing the fine content. This observation is corroborated by the findings of GUIGNONE *et al.* [3] and ZEYBEC *et al.* [4].

MEDEIROS *et al.* [27], also observed this reduction in concretes containing additions of metakaolin, which increased the cohesion and reduced the fluidity of the concrete. This issue was mitigated by the appropriate dosing of fines and the superplasticizer additive.

After adding the superplasticizer, all mixtures achieved adequate workability, albeit with no significant variations compared to the reference concrete. This fact is evident, as superplasticizers are designed to improve the workability and fluidity of concrete by dispersing primarily cement particles, thus reducing the amount of water required.

3.2. Compressive strength

All concrete compositions prepared with various combinations of WG and MK were tested for compressive strength at 7, 14, 28, and 91 days of curing. Figure 5 shows the results of the axial compression test of the concretes at ages.

According to the Figure 5, all concrete mixes showed increased compressive strength over time, which is expected as the concrete cures. However, the rate of strength gain varies among the different mixes. Mixes with waste glass (WG) show a trend of lower compressive strength compared to the reference mix, especially at early ages (7 and 14 days), as with the 20WG and 30WG mixes.

The initial reduction in compressive strength in concrete mixes with cement replaced by waste glass (WG) can be attributed to the slower pozzolanic reaction rate of WG compared to the hydration of traditional cement. This phenomenon is more pronounced in the early curing stages, where cement replacement with WG tends to decrease strength, especially when the replacement percentage is high [5, 7, 28].

It is observed that at 91 days, all mixed with exclusive substitution of waste glass (WG) – 10WG, 20WG, and 30WG – showed a significant increase in compressive strength, with values higher by 31.5%, 27.3%, and 11.7%, respectively, compared to the reference mix (REF). This increase in strength over time can be directly correlated with the chemical process inherent in the concrete matrix involving WG.

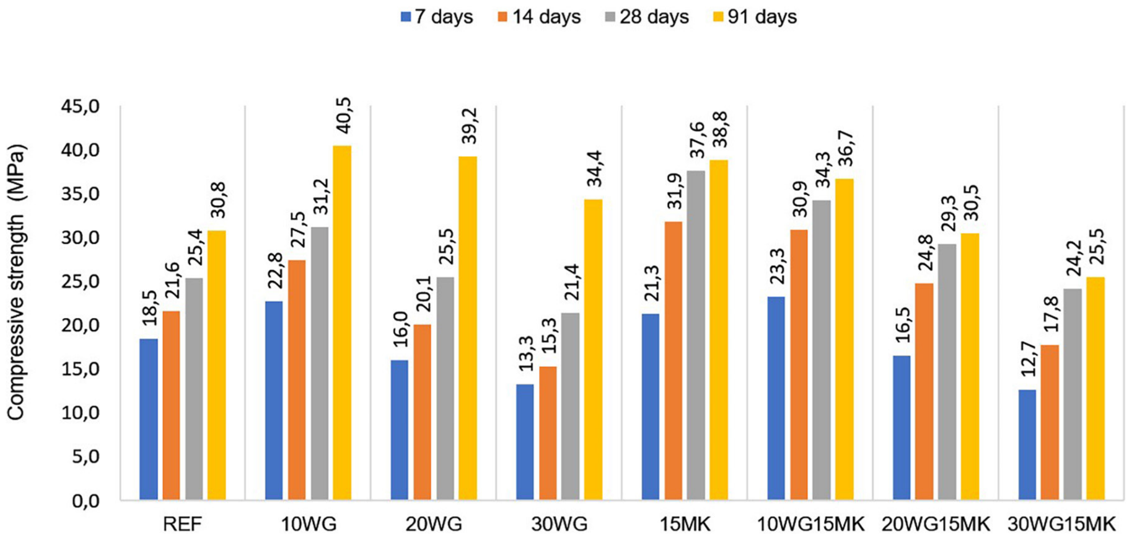

Figure 5: Compressive strength of concretes at 7, 14, 28, and 91 days of curing.

Prolonged curing facilitates the slow dissolution of the amorphous silica in WG in an alkaline environment, which subsequently reacts with calcium ions (Ca^{2+}) to form hydrated calcium silicate (C-S-H) gels [28]. This C-S-H gel formation process is gradual, reaching maturity only after 56 days, which explains the continuous gain in strength observed in the later stages of concrete curing.

Mixes combining WG and MK show significant results regarding compressive strength gain, which can be interpreted as a positive synergy between the two substitutes. MK and WG possess pozzolanic characteristics that further trigger the hydration reaction. This results in the formation of more C-S-H gel, which is responsible for increased strength and durability [29].

The study also observed that the presence of metakaolin (MK) improves the compressive strength of concrete at both early ages and over the long term. The strength gains at 7 and 28 days, based on the values presented in Figure 5, were 15% and 48%, respectively. Furthermore, MK contributes to reducing porosity, enhancing the homogeneity and density of the samples, which facilitates good distribution of C-S-H and C-A-H gels due to the greater surface area of the cement. These results are corroborated by the studies of NANDA *et al.* [1], SEKHAR *et al.* [29], and ZHANG and MALHOTRA [30].

3.4. Water absorption and permeability

Concrete specimens with different substitutions of MK and WG were investigated for absorption and porosity after a curing duration of 28 days, and it was found that all combinations of MK and WG, both combined and individually, resulted in lower water absorption compared to conventional concrete.

Water absorption and porosity are important indicators of the durability of hardened concrete. Reducing water absorption and porosity can significantly enhance concrete's long-term performance and lifespan in aggressive service environments. Reduced porosity also benefits the concrete's compressive and flexural strengths, as there is a fundamental inverse relationship between porosity and the strength of solids.

Table 3 presents the results of the water absorption test, void index, and specific mass of dry and immersed concrete test results at 28 days of age.

It is observed that the partial replacement of cement with ground glass leads to an increase in both the dry apparent density and the apparent density after concrete immersion. According to SEKHAR *et al.* [29], this can be attributed to the conversion of CH to C-S-H.

Regarding the concretes with the incorporation of metakaolin, a significant decrease in water absorption and void index is observed, especially when combined with waste glass. The metakaolin used in this study was finely ground, becoming even more reactive, influencing the cement hydration kinetics with both filler and chemical effects, where the reaction product is very efficient in filling the capillary spaces, improving permeability and strength.

As shown in Figure 6, concretes with higher compressive strengths exhibited lower water absorption values than the reference concrete (REF). However, based on the results obtained, it cannot be stated that, in this study, absorption is directly correlated with the increase in strength.

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Table 3: Water absorption, void index, and specific mass.

CONCRETE	ABSORPTION (%)	VOID INDEX (%)	SPECIFIC MASS DRY (g/cm^3)	SPECIFIC MASS SATURATED (g/cm^3)
REF	3,16	11,29	2,44	2,52
10WG	2,98	10,60	2,69	2,77
20WG	3,02	10,35	2,70	2,78
30WG	2,26	8,15	2,73	2,79
15MK	2,95	10,21	2,86	2,95
10WG15MK	2,14	7,71	2,91	2,97
20WG15MK	2,03	7,27	2,88	2,94
30WG15MK	2,60	9,20	2,86	2,94

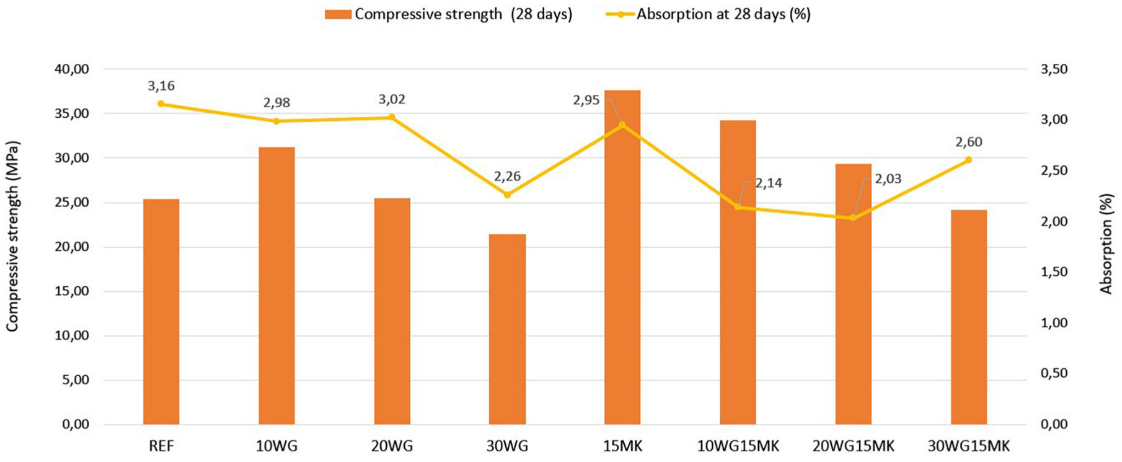

Figure 6: Relationship between water absorption and compressive strength in the concretes.

Adding metakaolin in all mixes seems to improve compressive strength over time and reduce water absorption, indicating a potential improvement in the durability of concrete.

Increasing the amount of waste glass tends to decrease compressive strength, but water absorption does not increase proportionally, suggesting that factors other than porosity may affect strength. An illustrative example is the 30WG concrete, which showed a significant reduction of 28% in water absorption, while it recorded a 16% decrease in strength at 28 days when compared to the REF concrete.

This phenomenon can be elucidated by the fact that, although glass presents two effects – the filler effect and the pozzolanic effect – when substituting an excessive percentage of cement with glass, there is a decrease in the concrete's compressive strength due to the insufficiency of calcium hydroxide to react with the glass. Thus, the production of C-S-H gel is reduced, suppressing the pozzolanic effect and leaving only the filler effect predominant; this phenomenon is called the "dilution effect" [31].

3.5. Electrical resistivity

In this stage of the study, the effect of the electrical resistivity of concretes at 28 days and 91 days of curing was evaluated. Electrical resistivity indicates the concrete's ability to resist the passage of electric currents, associated with the likelihood of corrosive processes.

Table 4 presents the average values of electrical resistivity (ER) along with the standard deviation (σ) and coefficient of variation (CV) of the results.

According to Table 4, the 30WG15MK mixture at 91 days exhibits a relatively low coefficient of variation (CV), which suggests good consistency among the samples. This may indicate that despite significant variation at 28 days, the pozzolanic reactivity associated with the metakaolin and glass stabilizes over time.

Table 4: Average values of Electrical Resistivity (ER).

CONCRETE	ER at 28 days (kΩ.cm)	σ	CV (%)	ER at 91 days (kΩ.cm)	σ	CV (%)
REF	18,82	1,3	6,91	23,13	0,98	4,24
10WG	20,58	1,48	7,19	37,43	1,15	3,07
20WG	20,14	0,89	4,42	39,45	3,42	8,67
30WG	49,25	2,49	5,06	67,10	1,25	1,86
15MK	29,57	1,13	3,82	59,15	2,47	4,18
10WG15MK	34,52	4,06	11,76	61,95	5,23	8,44
20WG15MK	94,15	3,96	4,21	134,3	2,02	1,50
30WG15MK	105,24	8,26	7,85	189,3	6,24	3,30

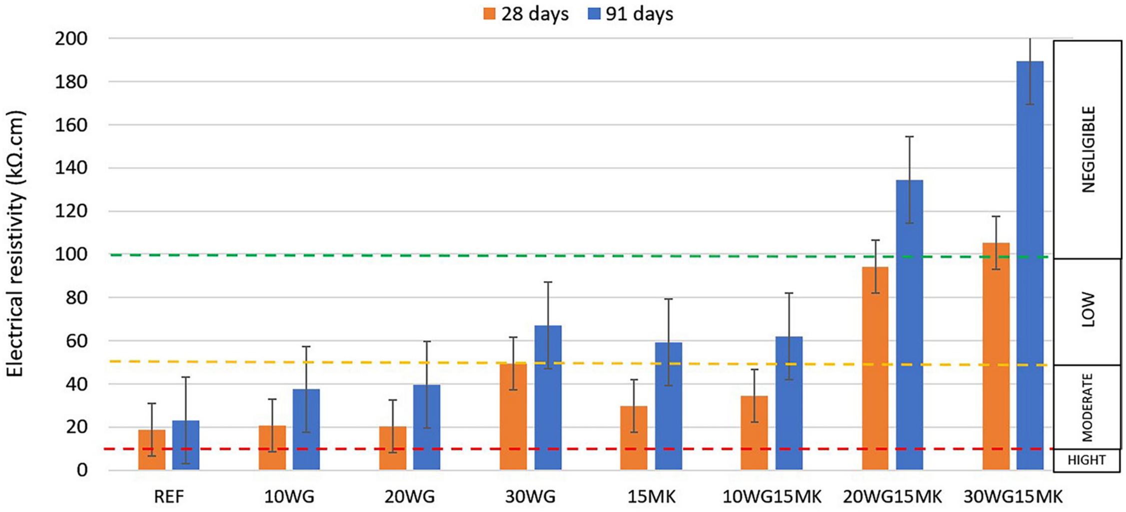

Figure 7: Profile of average electrical resistivity and corrosion ranges.

The reference mixture (REF) displays an increase in electrical resistivity (ER) from 28 to 91 days with a reduced coefficient of variation (CV), which is expected as the concrete continues to cure and resistivity increases. The consistency in the results suggests that the curing process was well controlled.

Figure 7 presents the profile of the average electrical resistivity of the reference concrete and concretes containing waste glass and metakaolin as substitutes for Portland cement. The dotted lines represent the corrosion risk ranges: high (< 10 kΩ.cm), moderate (10 to 50 kΩ.cm), low (50 to 100 kΩ.cm), and negligible (> 100 kΩ.cm), according to the European bulletin CE - COST 509 (1997).

This study observed significant enhancements in resistivity by incorporating waste glass and Metakaolin (MK) across all evaluated mixtures. Utilizing a substitution rate of 30%, this approach facilitates a shift in corrosion risk classification from moderate to low. Such improvements in resistivity align with the extent of cement replacement by glass and MK, as well as with the progression of curing time. This phenomenon could be attributed to the pore-filling action facilitated by the fine particles of waste glass, coupled with the generation of Calcium-Silicate-Hydrate (C-S-H) through the interaction between waste glass and cement hydration products, thereby yielding more resilient compounds [3, 7, 32].

Furthermore, the observed increase in resistivity points to a notable decrease in porosity and permeability within the cementitious composites, which have been modified by substituting traditional cement with waste glass and metakaolin. This trend suggests that the gradual incorporation of waste glass and metakaolin enhances the density of these composites and signifies a direct correlation with improved material properties. Electrical conductivity within the concrete is facilitated by the presence of continuous pores and microcracks, which are saturated with water and embedded within the matrix.

According to the AASHTO TP 95 [33] standard (Table 5), it is feasible to establish a classification of resistivity and chloride ion penetrability. In this way, it is possible to identify concretes with high resistivity and

Table 5: Classification of volumetric electrical resistivity values regarding chloride ion penetration.

ELECTRICAL RESISTIVITY (kΩ.cm)	CHLORIDE ION PENETRABILITY
<12	Hight
12–21	Moderate
21–37	Low
37–254	Very Low
>254	Negligible

Table 6: Test values (UPV) of the concrete mixes.

Concrete	UPV at 28 days (m/s)	σ	CV (%)	UPV at 91 days (m/s)	σ	CV (%)
REF	3146	35,21	0,99	3390	50,62	1,41
10WG	3610	51,20	1,42	4227	20,14	0,49
20WG	3606	40,02	1,11	4201	35,20	0,84
30WG	3582	48,24	1,35	3872	40,26	0,97
15MK	3895	18,51	0,48	4598	10,18	0,22
10WG15MK	3629	31,58	0,87	3703	27,09	0,72
20WG15MK	3575	54,20	1,52	3625	48,20	1,30
30WG15MK	3375	78,30	2,32	3509	28,74	0,79

low chloride ion penetrability, these characteristics being more notable in concretes with higher proportions of ground waste glass and in concretes that underwent substitution with metakaolin.

When correlating the AASHTO TP 95 standard [33] with the resistivity results displayed in Figure 7, it is observed that the REF, 10WG, 20WG, and certain 30WG mixtures exhibit values below 21 kΩ.cm at 28 days, indicating a "Moderate" to "Low" classification regarding chloride ion penetrability. However, at the 91-day mark, some of these mixtures transitioned into the "Low" to "Very Low" category, with this shift being particularly notable in mixtures comprising 30% waste glass.

Hence, it can be corroborated, consistent with prior research [3], that using waste glass as a cement substitute in concentrations of up to 30% yields enhanced resistance to chloride penetration, particularly during later stages of curing. This delayed impact on concrete microstructure enhancement may be attributed to either the pozzolanic effect or pore-filling mechanism, findings which are validated by the compressive strength, density, and void index analyses conducted in this study.

3.6. Ultrasonic wave propagation velocity

The ultrasonic test was carried out according to the standard NBR 8802 [25]. Three samples of each mixture were taken for each curing age, with ages selected at 28 and 91 days. Table 6 presents the average values of UPV (ultrasonic pulse velocity), along with the standard deviation and coefficient of variation of the results.

As demonstrated in previous sections, the concretes' electrical resistivity exhibited notable enhancements, particularly in compositions with higher levels of cement substitution by glass waste and metakaolin. These advancements in resistivity correlate with a decrease in porosity and an increase in the microstructural density of the concrete. Such densification is further validated by the outcomes from the Ultrasonic Wave Propagation Velocity assessments, underscoring the integral relationship between material density and ultrasonic response in enhanced concrete matrices.

It has been observed that all concrete mixes exhibited an increase in Ultrasonic Pulse Velocity (UPV) values at 28 and 91 days compared to the reference concrete (REF). This suggests that incorporating ground waste glass and metakaolin enhanced wave propagation velocity. Such an increase may be attributed to the pore-filling action of the waste glass, which augments the concrete's compactness. The highest coefficient of variation (CV) recorded was 2.32% for the 30WG15MK concrete at 28 days, indicating that the mean value in relation to the standard deviation did not exceed 10%, thus ensuring good representativeness of the values.

The concrete containing metakaolin (15MK) exhibited the highest ultrasonic pulse velocity (UPV) at 28 days (3895 m/s) and 91 days (4598 m/s). This implies that metakaolin, owing to its high reactivity and larger

Table 7: Quality Classification of Concrete Based on Ultrasonic Pulse Velocity (UPV).

ULTRASONIC PULSE VELOCITY (m/s)	CONCRETE QUALITY
>4500	Excellent
3500–4500	Good
3000–3500	Fair
2000–3000	Poor
<2000	Very poor

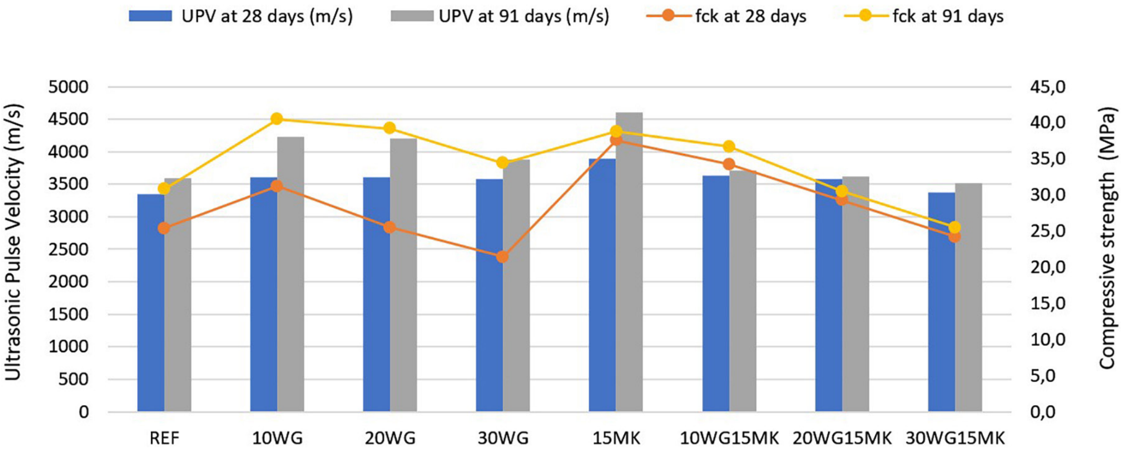

Figure 8: Compressive strength gains relative to ultrasonic pulse velocity (UPV).

specific surface area than waste glass particles, significantly improves the concrete's internal structure, such as density and homogeneity [1, 3, 34].

The ultrasonic pulse velocity (UPV) classification is an invaluable metric for assessing concrete quality, offering rapid insight into the material's longevity and durability prospects. UPV indicates the concrete's structural integrity and resilience to degradation over time.

As demonstrated in previous sections, the concretes' electrical resistivity exhibited notable enhancements, particularly in compositions with higher levels of cement substitution by glass waste and metakaolin. These advancements in resistivity correlate with a decrease in porosity and an increase in the microstructural density of the concrete. Such densification is further validated by the outcomes from the Ultrasonic Wave Propagation Velocity assessments, underscoring the integral relationship between material density and ultrasonic response in enhanced concrete matrices.

Table 7 delineates the quality classification of concrete based on ultrasonic pulse velocities as established by WHITEHURST [35]. At 28 days, only the REF and 30WG15MK concretes are deemed 'fair,' whereas other mixes achieve a 'good' rating. By 91 days, all concrete variants advance to 'good' or 'excellent' classifications, signifying materials characterized by markedly low porosity and significant potential for longevity. This superior rating implies a reduced susceptibility to the detrimental effects of chemical onslaughts and chloride ingress, suggesting enhanced durability and structural soundness [36, 37].

Figure 8 demonstrates that mixtures with higher compressive strength also exhibit greater ultrasonic pulse velocities, particularly at 91 days, when the concrete matrix is denser and more homogenous. For instance, the 10WG and 15MK mixes display remarkable compressive strength and high ultrasonic pulse velocity at 91 days, indicating excellent durability. In contrast, the REF mixture shows lower values in both metrics, suggesting an inferior quality compared to mixtures containing waste glass and metakaolin.

4. CONCLUSIONS

The present work evaluated the substitution of cement with two supplementary cementitious materials (Waste glass and Metakaolin) in conventional concretes. Based on the results, the following conclusions can be drawn:

- Partial substitution with WG improved concrete workability, while MK reduced consistency; both enhanced compressive strength, with notable increases up to 27.3% after 91 days of curing.
- Adding WG and MK decreased water absorption by up to 28% and enhanced concrete durability by reducing permeability.
- Chloride penetration resistance improved, with significant increases in electrical resistivity in mixes with high substitution of WG and MK.
- The environmental and economic benefits of reusing WG are significant, suggesting a positive impact on concrete's lifecycle and sustainability.
- Further research is recommended on varied substitution ratios and the long-term behavior of concrete under different environmental conditions.

For future investigations, it would be pertinent to explore the impact of varying proportions of cement replacement with other innovative pozzolanic materials and evaluate the long-term behavior of concrete under varied environmental conditions. Another promising area of research could focus on studying modified concretes' economic feasibility and life cycle analysis to more comprehensively assess these substitutions' environmental, social, and economic benefits. Further studies on optimizing the particle size distribution of substitute materials and the effect of specific chemical additives to further improve the properties of concrete could provide valuable insights for the construction industry in the search for more sustainable and high-performance materials.

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