Effects on the properties of cementitious composites using waste glass powder (WGP) as a partial replacement for cement: a systematic review

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Abstract

The use of waste glass powder (WGP) as a supplementary cementitious material (SCM) rich in pozzolan as a partial replacement for cement has been a viable alternative, from the environmental and economic point of view, to solve problems caused by the high consumption of cement worldwide. Therefore, the objective of this study was to evaluate the effects of the use of WGP, when used as a partial cement substitute, in some properties of cementitious composites (pastes, mortars and concretes), in the fresh and hardened state. Through a systematic literature review, 23 experimental research articles obtained from the world-renowned Science Direct database were analyzed. The results obtained from this review indicate improvements in some properties of cementitious composites with WGP, such as increased compressive strength at advanced ages, increased thermal neutron shielding capacity, reduced penetration of sulfate *and chloride ions, mitigation of alkali-silica reaction, reduced thermal conductivity, improved mechanical and chemical properties, including the formation of a new crystalline phase (devitrite) when exposed to high temperatures, reductions in air entrapment, water absorption and porosity. Regarding workability, there was no consensus, however, regardless of the substitution content, all composites were within the slump limits. Therefore, it can be concluded that the use of WGP in cementitious materials produces beneficial effects on some properties of cementitious composites.*

Keywords: properties; glass; cement; WGP; SCM;

1. Introduction

The use of supplementary cementitious materials (SCMs) rich in pozzolans as partial substitutes for cement has been a viable alternative, from an environmental and economic point of view, to solve problems caused by high cement consumption worldwide. The cement industry is responsible for approximately 7% of global CO_2 emissions (IEA, 2018), for every kg of cement produced there is the emission of about 0.8 kg of CO_2 or 821 kg CO_2/t cement (Kajaste & Hurme, 2016) arising from the consumption of fuel, calcination and electricity in the cement manufacturing process.

The use of SCMs, therefore, favors environmental sustainability, because by replacing part of the volume of cement there is a reduction in CO2 emissions (smaller carbon footprint), besides allowing a better destination for solid waste, industrial or urban, by recycling them through insertion in cement matrix composites. The costs related to the purchase of SCMs, generally, are also lower than the cost of cement.

These pozzolanic-rich materials, known as pozzolanics, are siliceous or silicoaluminous materials that, by themselves, have little or no binder activity, but which, when finely divided and in the presence of water, react with calcium hydroxide at room temperature to form compounds with binder properties (ASTM C125 - 10a, 2010; NBR 12653, 2015). Glass is a material that has high silica content in the amorphous state (no crystalline peaks in XRD analysis), therefore it is considered a pozzolanic material. Several studies have demonstrated the role of waste glass powder (WGP), when finely ground, in improving the mechanical properties and durability of cementitious composites.

For WGP to be considered a natural pozzolan the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ must represent 70% or more of its chemical composition (ASTM C618-19, 2019; NBR 12653, 2015). Glass can be divided into several main families, depending on the field of application: soda-lime, borosilicate, aluminosilicate, lead glass, silica glass, zirconia glass, bioglass, fluorinated glass, vitroceramic, chalcogenide, and metallic, according to Barton (2005) apud Nahi *et al.* (2020).

Therefore, the objective of this paper is to evaluate the effects of WGP, when used as a partial replacement to cement, in some properties of cementitious composites (pastes, mortars and concretes), in the fresh and hardened state, through a systematic review of the literature.

2. Methodology

This article is a systematic review of the literature on experimental studies that evaluate the main properties of some cementitious materials when added to their dosages (formulations) glass waste powder as a partial replacement for cement. For the development of this work, researches available in the Science Direct database were analyzed.

For this, four descriptors were used during the search and selection of articles: "Glass" and "Concrete" and "Mortar" and "Supplementary Cementitious Materials" or "SCM". The articles used as reference were selected according to the theme presented, with the publication period between the year 2017 and (July) 2021, which are related to the general objective of this review.

During the initial search phase of the articles, using the chosen descriptors, a total of 1,087 results were found. However, respecting the inclusion and exclusion criteria, only 23 articles of the experimental research type were selected, by reading the titles and a detailed analysis of their abstracts, according to the chosen inclusion and exclusion criteria.

The inclusion criteria were: (1) complete studies with full availability (2) scientific research articles depicting the following cementitious materials with partial replacement of cement by glass waste: pastes, mortars and concrete. In contrast, the exclusion criteria were: (1) studies that did not contain in their title the descriptor "Glass" associated with any of the other descriptors, (2) review articles, (3) articles that do not present clear methodologies, (4) articles that study binary, ternary or quaternary mixtures combined with glass waste.

3. Results

During the initial phase of searching the articles, using the chosen descriptors, a total of 1,087 results were found. However, respecting the inclusion and exclusion criteria, 23 experimental research articles were selected. The list of authors studied is shown in table 1.

Table 1. List of authors

Authors	**Cementitious material**	**% Cement replacement**	**Glass particle (mean diameter d50)**
Du, Yang, Ge, Wang and Liu (2021)	paste	0%, 5%, 10%, 15%, 20% e 25%	10 μm
Higuchi, Marques, Ribas and Vasconcelos (2021)	paste and mortar	0%, 10%, 15%, 20% e 25% (pasta) e 0%, 5%, 10%, 15%, 20% e 25% (argamassa)	7 μm
Ibrahim (2021)	concrete	0%, 5%, 10%, 15%, 20% e 25%	<75 μm
Jochem, Casagrande, Onghero, Venâncio and Gleize (2021)	paste	0%, 10 e 20%	20 μm, 14 μm e 12 μm
Kim and Yang (2021)	paste and mortar	0%, 10% e 20%	13,07 μm
Pitarchi *et al.* (2021)	paste e mortar	0%, 15%, 25%, 35% e 50%	20,3 μm e 22,6 μm
Yang, Usman and Hanif (2021)	concrete	0%, 10 e 20%	10,98 μm e 37,01 μm
Yang, Lu and Poo (2021)	paste	0%, 10%, 20% e 30%	30,5 μm e 114,7 μm
Moradllo *et al.* (2020)	paste and mortar	0%, 5%, 10%, 15%, 20%, 25% e 30%	13 μm
Nahi, Leklou, Khelidj, Oudjit and Zenati (2020)	paste and mortar	0%, 10%, 25%, 35% e 60%	17,68 μm
Wang *et al.* (2020)	paste	0% e 20%	0,5–5 μm
He, Zhan, Du, Liu and Yuan (2019)	concrete	0%, 10%, 20% e 30%	10 - 20 μm

Hilton *et al.* (2019)	concrete	20%	7,7 µm e 7,3 µm
Li, Ling, Yu, Wu and Chen (2019)	paste and mortar	30%	1) Maior: 0,6–2,36 mm, 2) Médios: 75–600 µm 3) Menor: <75 µm
Liu, Florea and Brouwers (2019)	paste and mortar	0%, 10% e 30% até 60%	10,97 µm
Meesak and Sujjavanich (2019)	mortar	20%, 25%, 30%, 40% e 50%	< 300 µm
Tayeh, Saffar, Aadi and Almeshal (2019)	mortar	0%, 10%, 20% e 30%.	<400 µm e <200 µm
Ibrahim and Meawad (2018)	mortar	20%	1,6 - 5 µm
Lee, Hanif, Usman, Sim and Oh (2018)	concrete	20%	14,7 µm
Rodier and Savastano (2018)	mortar	10% e 20%	12,28 µm
Du and Tan (2017)	paste and concrete	15%, 30%, 45% e 60%	<10 µm
Islam, Rahman and Kazi (2017)	mortar and concrete	0%, 10%, 15%, 20% e 25%	<75 µm
Harbec, Zidol, Tagnit-Hamou and Gitzhofer (2017)	mortar and concrete	10%	0,03 µm - 0,2 µm

Source: Elaborated by the authors (2021).

As observed in table 1, all researches used very small WGP particles. This can be explained due to the high pozzolanic activity potential of WGP as a complementary cementitious material, however, WGP needs to be finely ground to be activated effectively as a result of the increased specific surface area of the particles, according to Wang *et al.* (2020). An optimal solution to valorize waste glass is to grind it to a fineness at the micrometric level (µm) slightly higher than that of cement (Harbec *et al.*, 2017).

Fine particles (below 150 µm) of glass generally have benefits for cement-based materials due to pozzolanic activity, while coarser particles are detrimental due to alkali-silica reaction (Jochem *et al.*, 2021). Some studies correlate increased pozzolanic activity with decreased expansions caused by alkali-silica reaction (ASR) when WGP particles are ground below the size of cement particles (>10 µm) (Higuchi *et al.*, 2021).

4. Discussions

4.1 Workability

The measurement of workability is a way to verify the consistency of cementitious composites in the fresh state (not hardened). In concrete, according to the American standard ASTM C143 (2010), the slump test is used, which aims to provide the user with a procedure to determine the slump of hydraulic-plastic cement concrete and thus monitor the consistency of the concrete not hardened. Slump generally increases proportionally with the water content of a given concrete mixture and is therefore inversely related to concrete strength. Concrete with slumps less than 15 mm may not be adequately plastic and concrete with slumps greater than about 230 mm may not be adequately cohesive for this test to be meaningful. In mortars and pastes the slump flow test or flow test are used.

4.1.1 Concrete

Yang, Usman and Hanif (2021) in an experiment on concrete with two types of glass powder of different diameters (10.98 μm and 37.01 μm) found that the coarser particles of GPW tend to hinder the flow of concrete, thus reducing the slump values. The concrete with 10% cement replacement by GPW and particles of 10.98 μm obtained 222 mm slump, however the concrete with 10% cement replacement by GPW and particles of 37.01 μm obtained only 179 mm slump. Moreover, as the percentage of GPW replacement increased in each concrete tested, the slump decreased.

In contrast, Ibrahim (2021) found that the slump of all concrete mixtures tested in his experiment increases as the concentration of WGP increases, attributing this performance to the smooth surface and low water absorption of WGP, which increases the fluidity of the mixtures. Moreover, all mixtures showed slump equal to or greater than 65 mm and showed no segregation. The slump values obtained were 65 mm, 75 mm, 86 mm, 93 mm and 102 mm for samples composed of 0%, 5%, 10%, 15% and 20% of WGP, respectively.

4.2.2 Mortar

Islam *et al.* (2017) found a small increase in mortar flow as the replacement of cement with WGP increased, ranging from 132 mm to 135 mm, attributing these results to glass being a cleaner material by nature. Liu *et al.* (2019) obtained similar results to this in tests done on high-strength mortars with the addition of superplasticizer (SP). The high-strength sample mix with 60% recycled glass waste exhibited a 15.3% higher fluidity at 245 mm of slump, when compared to the plain samples (0% GWP) which showed no significant change in fluidity or even a slight decrease when high-volume recycled glass was incorporated.

For Nahi *et al.* (2020), there is no variation in the flowability of mortar made with 10% and 25% WGP compared to the reference mortar (0% GWP) in vibrated or non-vibrated form. However, a slight decrease in flow is noted with the mortar made with 35% and 60% replacement in the vibrated form, unlike the non-vibrated form, which remains the same as the reference mortar.

4.2.3 Paste

For Jochem *et al.* (2021), pastes prepared with waste glass showed little influence on workability compared to the reference paste (0% WGP). Moreover, no trend could be evidenced, since the spread on the table of pastes made with 20% GPW milled for 48h increased by 1.8% or reduced to 5.4% in pastes made with 10% GPW milled for 6h compared to the sample without WGP, which obtained 328 mm of spread on the table.

Wang *et al.* (2020) observed in a study that the control sample (0% WGP) has a flowability of 135 mm, however, it increases to 140 mm when WGP (of size 5 to 20 μm) is incorporated into the cement. Attributing this fact to the non-hydrophilic and smooth texture of the WGP particles, although the WGP has an angular shape. Compared to the WGP sample with a size of 5 to 20 μm, the mixture with WGP milled for 20 minutes (which drastically reduced the particle size, making it more regular) exhibits a 10.7% higher fluidity at 155 mm. For samples with WGP milled for 60 or 120 minutes, the slump reduced to 150 and 147 mm. Therefore, if the wet grinding time of WGP is no longer than 120 min, the workability of

WGP modified cement pastes are better than the control.

Jochem *et al.* (2021) and Wang *et al.* (2020) are emphatic that the workability of samples with GPW can be influenced by the high specific surface area and the angular shapes of the glass particles. The increase in workability was attributed to the smooth surface of the finely ground glass grains and the impermeable characteristic of glass that results in higher free water content in the mixture. While the reduction in spreading can be explained by the reduction in trapped air content and irregular shape of coarser glass particles, which hinders particle lubrication, and the improved packing caused by the glass waste acting as filler.

4.2 Air entrapment, water absorption and porosity

4.2.1 Concrete

For Yang, Usman, and Hanif (2021), the values of air content in the samples of concrete specimens represented minimum change of up to 3% with the use of GPW. The sample with 20% GPW and an average diameter of 10.98 μm showed the highest air content (2.53%), which favors better performance in freeze-thaw cycles in concrete. This is because the water within the concrete tends to expand in volume, and the air voids within the matrix accommodate the swelling and expansion, thus relieving internal stress (which can result in cracking and fragmentation).

The results of Ibrahim's (2021) studies indicate a decreasing rate in the water absorption of samples made of 5%, 10%, 15%, and 20% WGP compared to the control concrete (0% WGP) are 5.56%, 11.11%, 20.37%, and 27.78%, respectively. This result was already expected because the water absorption rate of glass is almost zero. In addition, the influence of filling tiny ground WGP particles results in enhanced particle packing, resulting in a denser and therefore less permeable microstructure with fewer voids in the concrete.

Du and Tan (2017) observed an average water penetration depth of 31.8 mm for the reference concrete mix. However, in comparison, all mixtures with various WGP substitutions showed very reduced penetration depths, about 75% lower. At the same time, it is interesting to note that there was no further improvement when the glass powder exceeded 15%. The water permeability of concrete depends on porosity, pore size distribution and pore connectivity. It is concluded that high-volume WGP in concrete effectively hindered the penetration of water at long (and potentially of harmful agents in the water, such as chloride and sulfate).

4.2.2 Paste

In the experiments of Jochem *et al.* (2021) using pastes, the reference series (without GPW) showed 0.8% of trapped air. The cement pastes prepared with cement replacement by 10 and 20% GPW ground for 6 h showed less air entrapment compared to the REF series, 0.67% and 0.47% (respectively). This can be explained by the size of the frosted glass that may have acted as filler, being able to fill part of the pores of the matrix and causing a reduction in the porosity of the specimens. Using waste glass samples ground for 24 and 48 hours resulted in an increase of 216 to 309% of trapped air compared to the reference series. In other words, the longer the grinding time of the waste glass, would result in cementitious pastes with higher trapped air contents. However, the values of trapped air found in the samples can be considered a low value and within acceptable standards, since all values are below 2.5%.

Li *et al.* (2019) observed that pastes with WGP or other SCMs had water absorption ranging from 12.2% to 17.8%. Specifically, the paste with medium sized WGP had a water absorption of 12.0%, similar to the absorption of the control paste. However, increasing or decreasing the particle size of the GPs increased the water absorption of the cement pastes. The water absorption of pastes with larger or smaller WGP sizes was about 17.5%, probably attributed to the relatively large voids caused by the WGPs when they were too fine or too coarse.

4.2.2 Mortar

Rodier and Savastano (2018) found after 56 days of testing that the mortar with 10% WGP showed an 18% decrease in absorbed water compared to the control (mortar without mineral addition). This behavior is due to the decrease in mortar porosity. The mortar with 20% WGP presents a water absorption value similar to the control mixture.

In the experiments of Nahi *et al.* (2020), the mortar made with 60% glass powder presented larger pores due to the dilution effect. However, between 28 days and 90 days, all mortars with glass powder show slight increases in water porosity.

Rodier and Savastano (2018) and Nahi *et. al* (2020) attributed the good performance of mortars at advanced curing ages to the increased CSH (calcium silicate hydrate) gel in the cementitious matrix that was produced in the additional pozzolanic reaction caused by WGP use. The additional CSH produced fills the capillary pores leading to microstructure refinement (smaller pores), thus reducing the total volume of permeable voids and absorbed water.

4.3 Shielding protection

According to Kim and Yang (2021), boron composite materials have been recommended as a supplementary cementitious material for increasing the neutron shielding capacity of concrete. Boron oxides in WGP from liquid crystal display (LCD) can act as a suppressor of thermal neutrons, capturing them, producing an enhanced neutron shielding capability. In addition, there are no alkalis in the residual LCD glass (known as alkali-free glass), so there is no ASR reaction in concrete partially replaced with residual LCD glass.

These authors in a research found that the thermal neutron shielding rate of mortar is increased with increasing LCD replacement. By replacing 10% and 20% of the residual LCD glass powder with cement, the thermal neutron shielding capacity was increased to 89.51% and 93.91%, respectively. This enhanced performance for mortars incorporating WGP originating from LCD glass may be due to the presence of boron oxides in the cementitious matrix. In fact, it is known that the use of boron-containing binders, such as borosilicate glass, can effectively improve thermal neutron shielding performance. Due to the higher B_2O_3 content, the thermal neutron shielding performance for the mortar replaced by the 20% residual glass was up to about 1.23 times higher than that for the mortars without WGP.

For Moradllo *et al.* (2020), the influence of WGP on the neutron attenuation coefficient was clearly observed. As the replacement level of increased, the neutron attenuation coefficient increased by 10 to 40% depending on the WGP replacement level and curing time. This indicates that the cement mortar with WGP showed higher neutron attenuation than the plain cement mortar. In addition, it is interesting to note that some samples showed a plateau in the improvement of the attenuation coefficient after replacing 25% WGP. This can be attributed to a lower amount of chemically bound water at higher substitution levels (30% sample compared to the 25% sample), as water serves as an excellent fast neutron moderator due to its high neutron absorbing cross section. A lower amount of chemically bound water corresponds to a reduction in hydration and pozzolanic reaction due to the dilution effect, which offsets the impact of the additional WGP content on the attenuation coefficient.

4.4 Sulfate Attack/Chloride Penetration

The pozzolanic reaction promoted by the use of WGP, by allowing the additional formation of CSH gel in cementitious composites, can reduce the penetration of sulfate or chloride ions through the densification of the microstructure, due to the refinement of the pores (Harbec *et al.*, 2017).

As stated in ASTM C1202-05 (2005), one of the ways to analyze chloride penetration is through the RCPT test (rapid chloride permeability test) or the chloride diffusion and migration test. RCPT values are classified as high (> 4000 Coulombs), moderate (2000 - 4000 Coulombs, low (1000 - 2000 Coulombs) and very low (< 1000 Coulombs). Sulfate penetration is verified by immersion in magnesium sulfate or sodium sulfate solutions, observing the erosion or expansion of the specimens, and analyzing the compressive strength.

4.4.1 Mortar

Tayeh *et al.* (2019) conducted an experiment in which he sought to evaluate the compressive strength of mortars with WGP subjected to different concentrations of $MgSO_4$ solution (5%, 10% and 20%) for 10, 30 and 60 days. For the 5% concentration of $MgSO_4$ for 60 days of external exposure, the compressive strength of the mortar decreased by approximately 12.59 times, 9.04 times, 8.89 times and 8.36 times for 0%, 10%, 20% and 30% WGP, respectively. Meanwhile, for the 20% concentration of $MgSO_4$, the compressive strength of the GP mortar decreased by approximately 28.1 times for the control mixture (0% WGP), 18.7 times for 10% WGP, 20.3 times for 20% WGP, and 18.8 times for 30% GP. This result showed that using WGP can be advantageous for the compressive strength of mortars to $MgSO_4$ attack.

Harbec *et al.* (2017) analyzing sulfate attack in mortars at 14, 28, 91, 182, 270 and 365 days of immersion in Na_2SO_4 solution for reference mortars with 10% GF (glass fume) and 10% SF (silica fume) concluded that all mixtures develop expansion below 0.05%, suggesting good resistance to sulfate attack.

4.4.2 Concrete

Yang, Usman, and Hanif (2021) found that WGP from LCD glass significantly improved the sulfate attack resistance of concrete, regardless of particle size and percentage of replacement of glass powders. The 20% WGP replacement of particle sizes 30.5 μm and 114.7 μm showed better performance, especially the specimens with 30.5 μm particles, due to their finer gradation and better reactivity. Concrete specimens immersed in magnesium sulfate solutions showed greater erosion of the hardened material compared to their counterparts immersed in sodium sulfate solution, which was evidenced by both weight loss measurements and visual inspection of concrete specimens after being subjected to sulfate attack by the respective solutions. Therefore, the magnesium sulfate solution has a more aggressive and damaging effect on concrete deterioration. However, it is evident that WGP apparently improved the resistance to sulfate attack, showing less worn surfaces of the specimens when compared to the specimens without WGP, which indicate its better performance.

Hilton *et al.* (2019), through RCPT testing, observed that the control mix without WGP had the highest chloride permeability at 28 and 56 days; however, it still achieved the "Low" permeability designation. Both concretes with CRT-MRF type glass mixes achieved the "Very Low" chloride penetrability designation according to ASTM C1202-05 (2005), and the chloride penetrability resistance increased with increasing age of the concrete mixes. The results show that the mortar bar length in all concrete mixtures tested changed by less than 0.024% in 56 days. After one year, the 5% CRT-MRF and 15% CRT-MRF mixtures, both with 20% WGP, exhibited considerably better resistance to sulfate attack when compared to the control mixture without WGP, did not negatively affect the performance of fresh, hardened concrete or long-term durability.

According to Lee *et al.* (2018), concretes with 20% WGP exhibited a 'Moderate' level of chloride penetrability. The samples of the concretes with even finer particles, known as waste glass sludge (WGS), and 20% WGP achieved the best performance among all other samples, being rated at 'very low grade'. This is attributed not only to the pore filling effect caused by the fine WGS particles, but also to the pozzolanic reaction, which is a long-term reaction effect of aging. At 56 days of aging, all specimens showed a 'Negligible' grade, which is mainly due to the slower hydration rate after 56 days of age.

Du and Tan (2017) conduct chloride diffusion and migration tests to investigate the chloride penetration resistance after 56 days of immersion. The reference concrete (0% WGP) showed the highest chloride content at each depth, indicating that it has the lowest resistance. The diffusion coefficient decreases significantly with the incorporation of WGP into the cement, regardless of the replacement level. A 90% reduction in diffusion coefficient was recorded for 30% glass powder concrete. The reduced chloride diffusivity in glass powder concrete is due to the more compact microstructures in the interfacial transition zone (ITZ) of the aggregate-cement paste and the reduced pore size and connectivity as a result of the pozzolanic reaction. This could help prolong the service life of reinforced concrete structures under chloride attack.

Harbec *et al.* (2017), analyzing the resistance to chloride attack, noticed that while the reference concrete (without the addition of pozzolanic nanoparticles or so-called "glass fume (GF)") exhibited moderate and low penetration at 28 and 91 days, respectively, the introduction of amorphous silica-based fine particles, glass fume (GF) and silica fume (SF), into the concrete reduced the RCPT values. Although concrete with 10% SF showed very low RCPT at both ages (28 and 91 days), concrete with 10% GF indicated low and very low RCPT at 28 and 91 days respectively.

4.5 Compressive strength

4.5.1 Increased strength at advanced ages (14, 28 days or 90 days)

The use of WGP produces changes in the compressive strength of cementitious composites at different curing ages and at different WGP contents. Most of the researchers noted that at early ages of strength development (3 and 7 days of curing, for example) the control cementitious composites (0% WGP) exhibited a higher compressive strength relative to the composites with different WGP contents. Some of the researchers attributed this decrease in strength of the cementitious composites with WGP to the dilution effect of the cement-WGP binary system (Kim & Yang, 2021; Rodier & Savastano, 2018) and the fact the glass residue takes longer to react and form hydrated products (Jochem et al., 2021). This dilution effect (caused by the partial replacement of cement with WGP) leads to a decrease in cement content, decreasing the amount of hydration products at an early age (Rodier & Savastano, 2018).

However, according to most researchers, at advanced curing ages (14, 28, and 90 days), cementitious composites with WGP obtained better performance with an increment in compressive strength compared to the control mixture. This can be attributed to the cementitious matrix incorporating WGP with siliceous compounds to form a denser microstructure with higher pozzolanic activity, reacting with CH to produce more CSH gel (Kim and Yang, 2021; Jochem *et al.*, 2021), consequently decreasing porosity (Rodier & Savastano, 2018) due to the reduction of trapped air content in the cement-based matrix (Jochem *et al.*, 2021).

The results of Yang, Usman, and Hanif (2021) at early ages of strength development indicated that the control concrete (0% WGP) exhibited the highest strength, however, at 28 days of age the concrete with 20% glass waste replacement with finer particles (10.98 μm) indicated 3% and 5% higher strength than the control concrete specimens and the specimens with 20% coarser particle WGP (37.01 μm), respectively.

Ibrahim (2021) found that using 5% WGP in concrete increases the compressive strength at 28 days of curing, however, after this proportion, the strength decreases compared to the reference mix (0% WGP). The increase value at 5% proportion was 7.51% and the decrease was 3.48%, 6.98% and 21.65% at 10%, 15% and 20% proportions, respectively.

The results of He *et al.* (2019) show that the use of WGP reduces the compressive strengths of concrete from 7 to 28 days of curing and the higher the WGP replacement content the strengths achieved by the concrete are also lower. However, the compressive strengths of specimens containing 10% and 20% GP exceed those of the control specimen at 90 days. The author concludes that the ideal content of GP to replace the cement is 20% due to the maximum strength achieved at later ages.

Regarding mortar strength Moradllo *et al.* (2020), using a glass powder from borosilicate glass, noticed an 8% increase in compressive strength at 28 days in mortars with 10% WGP. In general, the samples with WGP ranging from 5% to 25% replacement showed similar or higher compressive strength results at all ages when compared to the reference sample. The only exception was at the 30% replacement, which showed a reduction in compressive strength at 28 days of 15%.

Kim and Yang (2021), working with WGP from LCD glass in mortar realized that the control sample showed the highest strength at 7 days of curing, indicating 39.55 MPa, while the compressive strength for the mortars containing WGP ranged from 28.54 to 30.83 MPa (at 3 days) to 32.79 to 34.10 MPa (at 7 days), regardless of the proportion of replacement. However, the strength for all mortars at 28 days increased, ranging from 50.16 to 49.75 MPa for 10% and 20% WGP, respectively.

Rodier and Savastano (2018) found that at 3 days of curing, the compressive strengths of mortars with 10% and 20% WGP are lower than those of the control mortar (mortar without mineral additions). At 7 days, according to the standard deviation, all mortars show similar compressive strengths (about 28 MPa).

At 28 days, the mortars with 10% and 20% WGP showed an increase in compressive strength of 11 and 7%, respectively, compared to the control.

Hilton *et al.* (2019) studied WGP from discarded cathode ray tube (CRTs) waste and mixed container glass (MRF). The first mixture studied was composed of 5% CRT panel glass and 95% MRF glass with 20% WGP. The second mixture had a ratio of 15% CRT panel glass of and 85% with 20% WGP. The third mixture was the control mixture (0% WGP). It found that the compressive strength of the concrete mixes of WGP with 15% CRT-MRF is higher than the 5% CRT-MRF glass powder at all curing periods, plus all concrete mixes achieved the design compressive strength at 28 days. The compressive strength for both mixtures with WGP was lower than that of the reference concrete up to 56 days. However, the compressive strength of the mixtures with incorporated glass powder exceeded the compressive strength of the control concrete by one year.

Lee *et al.* (2018) noticed that at 7 and 28 days of age, the control concrete (0% WGP) showed higher strength, but at 90 days, the concrete with 20% WGS showed higher strength compared to the control concrete and the concrete with 20% WGP. The pattern of strength development indicates that WGS is superior to WGP in the long term when used as a partial cement replacement. The higher strength achieved for WGS indicates the increased pozzolanic reactivity leading to higher CSH formation.

Islam *et al.* (2017) obtained lower average compressive strengths compared to the control mortar (0% glass replacement) were obtained at 7, 14, 28 and 56 days of age. However, except for the 25% glass addition, all other mortars replaced with cement, the average compressive strength exceeded that of the control mortar at 90 days. At 90 days, the 10% WGP mortar gave the highest compressive strength among the mortars with glass addition, at 180 days, however, the 15% mortar was the highest performing and at 365 days the mortar with 20% glass waste obtained the maximum compressive strength, which is 8% higher than the control mortar without glass.

Harbec *et al.* (2017) investigating the use of very fine particulate glass smoke (GF) as a valuable and viable alternative to silica fume (SF) in high performance concrete (HPCs), observed that for concrete with 10% GF a rapid increase in its compressive strength occurred after 1 day of curing (38.6 MPa) compared to concrete with 10% SF (32.9 MPa). At 7 days, the 10% GF and 10% SF concretes indicated an average compressive strength of 54.5 and 52.0 MPa, respectively, while the reference concrete (with no GF or SF) obtained 49 MPa.

Jochem *et al.* (2021) noticed that at 28 and 90 days, the cement paste sample with the highest compressive strength was the 24 h and 10% WGP grindings, with 66.5 MPa at 28 days and 81.0 MPa at 90 days, with an increase in strength of 3.7 and 4.2%, respectively, compared to the reference concrete. Meanwhile, all other samples had lower strength than the reference paste.

4.5.2 Decrease in compressive strength at advanced ages

Although most research indicates an increase in compressive strength at advanced ages of curing in cementitious composites using WGP as a partial replacement for cement compared to the control mixture (0% WGP), there is still no consensus on the subject. Some studies have obtained contrary results, that is, there was a decrease in the strength of these composites compared to the control mixture. This decrease in the compressive strength of the cement paste with WGP can be explained by the dilution effect, due to reducing the cement content and increasing the effective water-cement ratio, so as to decrease the amount of formation of hydration products and ultimately reduce the compressive strength of the cement paste (Du and Tan, 2021; Nahi *et al.*, 2020)

Ibrahim (2018) found in an experimental study that all batches of glass mortars with 20% WGP exhibit lower compressive strength than the control (0% WGP) at all curing periods (7, 14, 28, and 90 days). In addition, they observed that the strength of mortars containing the soda-type WGP types is lower than that of the control by ± 2% after 90 days of curing, compared to 13% for those containing the colorless borosilicate type WGP. This indicated that the soda-lime glass powder types are promising pozzolanic materials and can replace cement in mortar without affecting the mechanical properties of the mortar.

The results of the studies by Higuchi *et al.* (2021) also indicate that mortars with 5%, 10%, 15%, 20%, and 25% WGP showed a reduction in compressive strength at 28 days of 14%, 18%, 9%, 18%, and 27%, respectively, compared to the control mortar. However, the mortar with 15% WGP showed the highest compressive strength.

Nahi *et al.* (2020) observed that at no curing age (7, 28, or 90 days), the compressive strength of mortars with WGP exceeded that of the reference mortar (0% WGP), however, as hydration days increased, the compressive strength increased regardless of the WGP replacement content. Furthermore, as cement replacement by WGP increased the compressive strength of the mortar decreased at all curing periods in this study (7, 28 and 90 days) relative to the reference mortar.

The same effect was noticed by Du and Tan (2021) when they added WGP to cement pastes: a reduction in compressive strength as the amount of WGP increased. Furthermore, with the addition of 25% WGP, the compressive strength of the cement paste decreased by 23% relative to the control mixture at 28 days of curing.

Liu *et al.* (2019) studying high strength mortars containing 0%, 10%, 30% and 60% WGP as cement replacement found compressive strengths of 44.9 MPa, 38.15 MPa, 33.6 MPa and 19.11 MPa, respectively, at early age (7 days of curing) and 115 MPa, 104.3 MPa, 106 MPa and 99.07 MPa, respectively, after 90 days of curing. At early age, the sample containing 60% recycled glass waste shows relatively low initial compressive strength at 7 days with 60.78 MPa compared to 92.47 MPa, 87.69 MPa and 89.69 MPa for samples incorporating 0%, 10% and 30% recycled glass waste. However, this indicates that the sample containing 60% recycled glass waste exhibits a higher rate of strength increase during the curing period (90 days) than other samples. They also observed a significant decrease in compressive strength with increasing amount of glass powder throughout the curing period.

Li *et al.* (2019) comparing the strength of mixtures with different particle sizes in cementitious pastes concluded that the paste with medium GPs showed 5% higher strength than that prepared with large and small GPs. This may be due to better size classification, resulting in denser pore structures in the matrix and higher density. However, compared to other SCMs, all GP pastes exhibited considerably low strength and similar strength development. This illustrates that GPs exhibit almost no pozzolanic properties under ambient curing, even at a size of less than 75mm. In addition, the large GPs acted mainly as the inert aggregate in the paste, which may create a weak interfacial bond between the glass surface and the hydration product.

4.7 Alkali-silica reaction (ASR)

The alkali-silica reaction (ASR) is a chemical reaction that can occur in cementitious composites in the hardened state between the alkalis (sodium or potassium oxides) present in the cement and the reactive silica contained in the aggregates of pastes, mortars or concrete. The reaction occurs when moisture is present, leading to the formation of an expansive silica gel, as the product of the reaction. This gel when expanding, increases internal stress, resulting in cracking that can lead to loss of structural integrity of the composites (Meesak & Sujjavanich, 2019; Ibrahim, 2018).

The increase in silica (Si) in mortar with WGP (silica-rich) may be related to the low expansions that these mortars exhibit. Studies show that expansions in mortars decreased as the ratio of Ca (calcium): Si (silica) decreased, that is, as the amount of cement being replaced increased, because the higher the WGP content the higher the silica content (Meesak & Sujjavanich, 2019; Higuchi *et al.*, 2021). According to the American standard ASTM C1260-14 (2014), which evaluates ASR in mortars, expansions greater than 0.2% are indicative of potentially deleterious expansion, while less than 0.1% are considered harmless.

4.7.1 Mortar

Meesak and Sujjavanich (2019) observed that mortar samples that used WGP as partial cement replacement showed improvement in ASR behavior, with a decrease in the average measured expansion in all samples. The results showed that the higher the partial replacement of cement by WGP, the more effective in reducing the expansions of ASR, as the amount of Si in all samples with WGP was higher than the control sample. The following relationship was obtained for the average expansions of the mortar bars with different amounts of WGP: WGP 50% < WGP 40% < WGP 30% < WGP 25% < WGP 20%.

Ibrahim (2018) realized that replacing Portland cement with 20% WGP of soda-lime glass types uncolored, green and brown significantly decreased the expansion up to 21 days, but at 28 days green and brown glass powder increased the expansion compared to the control sample. However, the ASR expansion values of all the selected glass types are less than the upper limit of expansion. In fact, the samples containing borosilicate glass type show higher expansion than those with soda-lime glass types compared to the same immersion time.

Harbec *et al.* (2017) found that, compared to the control mortar (0% WGP), introducing WGP into the binder reduced the expansion. During the first 14 days of monitoring, the 10% WGP mortar shows slightly lower expansion than the control, but falls in the moderately reactive aggregate range. At 14 days, the expansion of 10% WGP was 0.20%, while that of the control was 0.24%. From 10 to 35 days, the expansion of 10% WGP developed at a substantially lower rate than that of the control. At 35 days, 10% WGP expanded at 0.45% and the control expanded at 0.74%. The ASR was also reflected in the mass gain of the mortar bars. At 10 days, the control mortar and the mortar with 10% WGP gained 0.012% and 0.008% of their initial mass, respectively. From 10 to 35 days, the mass gain rate of 10% WGP decreased. At 35 days, 10% WGP gained 0.014% of its initial mass.

For Higuchi *et al.* (2021), in their study, it can be seen that the largest dimensional variations occurred in the control series and decreased with increasing percentage of WGP in the mixture during the test period. The samples with 20% partial replacement of cement by WGP showed reductions in dimensional variations of approximately 40% at 14 and 28 days compared to the control samples. Although the WGP studied cannot be considered harmless, because it presented expansions > 0.10% at 16 days, in this work the most effective replacement content to mitigate expansions caused by ASR reactions was 20% WGP, as partial replacement of cement.

4.9 Exposure to high temperatures

The high temperature performance of cementitious matrix composites containing waste glass is a major concern for their use in construction applications. Rodier and Savastano (2018) observed that heat treatment of mortars containing 10 and 20% WGP at 700 °C leads to weight losses (about 10%), similar compared to the control mortar. In terms of strength loss, all mortars show high strength loss (up to 69% for control mortar). However, the mortars containing WGP present resistance loss of lower value than the control mortar, 61% and 60%, for 10% and 20% WGP respectively. This result is due to the higher content of hydrates such as CSH formed during the pozzolanic reaction between calcium hydroxide and amorphous silica present in WGP. According to this result, WGP can be used up to 20% by weight to improve the fire resistance of cementitious materials. Partial replacement of cement by 10% by weight of glass powder residue increases fire resistance and decreases sorptivity leading to improved durability of mortars at 28 days.

Yang, Lu and Poo (2021), aiming to investigate the mechanical and chemical properties of cement pastes with WGP after cooling to room temperature from elevated temperature exposures, found that after exposure of 800 °C, XRD and SEM results revealed that a new crystalline phase, devitrite ($Na_2Ca_3Si_6O_{16}$), was formed from the amorphous softened silica of glass powder in the cement paste with 30% WGP incorporated. The new crystalline phase together with the softened glass contributed to increase the compressive strength by filling the pores and micro-cracks of the cement pastes after being subjected to 800 °C exposure. Regarding the compressive strength of the paste with 30% glass powder exceeded the control group by 14%.

Liu *et al.* (2019), through thermogravimetric studies after 90 days of curing, found that all mortars show significant mass loss from 40 °C to 1000 °C due to physically bound water loss, chemically bound water loss, CSH gel decomposition, calcium hydroxide decomposition, and calcite decomposition. Therefore, the addition of recycled WGP results in decreased mass loss of high strength samples throughout the TG test. The remaining mass of the plain sample (0% WGP) after heating to 1000 °C is about 83.75%, which is the lowest compared to 84.08%, 85.26% and 87.59% for 10%, 30% and 60% recycled waste glass containing samples, respectively. The high strength samples exhibit lower mass loss than the normal strength samples during the test.

Li *et al.* (2019) observed that, similar to other SCMs, GPs can improve the residual compressive strength of pastes after exposure to a temperature of 300 °C, but decrease significantly when the temperature increases to 600 °C or 900 °C due to the decomposition of hydration products and the annealing effect of GPs. The cementitious paste with medium WGPs exhibited better strength than those with large WGPs and small WGPs due to their better packing density. It should be noted that the influence of GPs on strength is mainly governed by packing rather than pozzolanic effect.

4.10 Thermal conductivity

The thermal conductivity of cement-based materials is very important for their applications in civil construction, however, it is still little studied. For example, cement paste and concrete used in energy-saving construction should have a low thermal conductivity to achieve the goal of thermal comfort and energy savings. Whereas, the cement paste and concrete used in a geothermal well should have a high thermal conductivity to improve the heat exchange rate between the pump coolant and the surrounding medium (Du *et al.*, 2021).

Du *et al.* (2021) observed that the addition of WGP in the cement paste resulted in the reduction of thermal conductivity. For addition of 5% WGP, the reductions were 6.54% compared to pure cement paste (0% WGP). However, for addition of 25% WGP, the reductions were 24.05%. Thus, the use of WGP can be recommended for the production of cement paste with low thermal conductivity.

Du and Tan (2017) in another study found that the average amount of charges passing through the reference concrete is 3587 Coulombs. This value decreases continuously the higher the glass powder content. The explanation is that the electrical conductivity of concrete is governed not only by porosity and pore structures, but also by the pore solutions. For plain cement paste, the pore solution is filled with hydration products, including Na^+, K^+, Ca^{2+} and OH^-. With more cement replaced by glass powder, the amount of OH^- and Ca^{2+} would be reduced and at the same time, alkalis could also be incorporated into the formed CSH gels with low Ca/Si ratio. Therefore, both the improved microstructure and the reduced ion concentration in the pore solution result in reduced electrical conductivity.

5. Conclusion

- Workability:

Based on the literature, there are contradictory results about the influence of WGP as a cement substitute on the workability of cementitious materials, so there is no consensus on the subject. The workability may be influenced by several parameters related to WGP, such as the shape of the particles, their size, the non-absorbent nature of the glass, the smooth surface of the glass particles, and the amount of cement replacement. However, in all the cementitious composites studied and for all percentages of WGP replacement by cement, the workability was within the recommended standards.

- Reductions in air entrapment, water absorption and porosity

The use of pozzolans, such as WGP, improves particle packing in cementitious composites due to the filler effect. This leads to a more compact and less porous microstructure. Therefore, the values for air entrapment, water absorption and porosity are reduced.

- Increased compressive strength at advanced ages, increased neutron shielding capacity, and reduced penetration of sulfate and chloride ions

The cementitious matrix incorporating WGP with siliceous compounds forms a denser microstructure with higher pozzolanic activity, reacting with CH to produce more CSH gel.

- Alkali-silica reaction mitigation

The studies evaluated show that expansions in mortars decreased as the ratio of Ca (calcium): Si (silica) decreased.

- Exposure to high temperatures

Improvement was observed in mechanical and chemical properties of the cementitious composites, including the formation of new crystalline phase (devitrite), when on exposure to high temperatures.

- Thermal conductivity:

The effect of glass waste mineral addition on the thermal conductivity of cement-based materials is still something little studied, however, some studies observed that cementitious composites with WGP showed low thermal conductivity, which decreased the more the content of cement replacement by WGP increased.

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