USING GLASS WASTE FOR PRODUCING LOW CO_2 CEMENTITIOUS MATERIAL AS A CONTRIBUTION TO CIRCULAR ECONOMY

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Promoting the circular economy is one of the main tools to achieve carbon neutrality by 2050. The culture of using residues in cementitious materials, mainly in concrete, is already established, favouring circularity. Fly ash is commonly used in blended cement or concrete production as supplementary cementing material. However, waste glass is not as commonly used as a cement substitute. In this context, this research contributes to the knowledge about the use of waste glass as partial cement replacement, developing an experimental work. Glass bottles were transformed into glass powder using two different grinding processes. They were produced glass powders with different colours and fineness. These powders were used to produce mortars with 25% of glass powder replacing cement. Mortars containing fly ash were also produced. Their compressive strengths were evaluated over time. Results concluded that white, green, and brown glass powders are acceptable to be used as cement replacements. The results also identify glass powder as a potential substitute for fly ash.

Keywords: *Glass powder; Fly ash; Cementitious materials; Circular economy; Low CO_2.*

1. Introduction

The incorporation of waste and industrial by-products into concrete has been one of the alternatives to reduce the world consumption of cement and, consequently, to make it a more eco-friendly material [1]. As an industrial energy consumer, the cement industry ranks third globally, while also being the second-largest emitter of industrial CO_2 [2]. The European Union (EU) has been fighting climate change through policies with an important impact. One of the most important measures is to achieve carbon neutrality by 2050, meaning the economy must reach net-zero greenhouse gases emissions (GHG). In this context, cement production is highlighted. It had an annual increase in direct intensity CO_2 equal to 1.8% in the recent five years period (between 2015 and 2020). Nevertheless, to meet the carbon neutrality target by 2050, it is indispensable to experience an annual decrease of 3% until 2030 [2].

Apart from the reduction in the clinker-to-cement ratio through greater utilization of blended cement, the reduction in cement consumption through the use of supplementary cementing materials (SCM) in partial replacement of the cement is an efficient and current strategy to achieve the main EU targets. Fly ash (FA) is one of the most used SCM in concrete over the world. The presence of amorphous alumina and silica in FA, as well as the pozzolanic properties demonstrated by FA, are highlighted characteristics. Through a chemical reaction between the silicon dioxide found in FA and calcium hydroxide, which results from cement hydration, additional calcium silicate hydrate structures are created. These structures are particularly effective in reducing concrete porosity and, by extension, the transport of aggressive agents. Considering that the EU's measures to achieve carbon neutrality by 2050 include the closure of thermoelectric plants, it is important to consider a substitute material for fly ash.

Concrete can incorporate various other waste or recycled materials with supplemental cementing properties, and the utilization of such materials becomes an increasingly appealing option when confronted with environmental problems pertaining to their disposal. Glass powder represents an exemplary material in this category [3]. Glass waste has been studied as aggregate and as a partial replacement for cement in concrete. Their role in the concrete mixture is closely related to their particle size. Incorporating glass waste as an aggregate in concrete mixtures is a way to help address the issue of waste elimination and minimize the usage of mineral aggregate in concrete production [4]. Simultaneously, there has been a growing interest in utilizing waste glass as an alternative material to cement, given its non-degradable nature and the predominant composition of soda-lime glass [5]. The utilization of glass waste as cement replacement in the concrete mixture has been studied worldwide. The mechanical properties and alkali-silica reactivity are the primary concerns about concrete containing glass waste. While the alkali-silica reactivity is strongly related to the diameter of particles, the mechanical properties are related to several factors [4].

Various authors have shown that the reduction in glass waste particles increases the pozzolanic activity of this material, improving the durability and mechanical properties of concrete or mortars [6–10]. Shao et al. [6] reported that glass powder could exhibit pozzolanic activity if finely

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ground to less than 38 mm. Recently, Idir et al. [11] and Pereira de Oliveira et al. [12] demonstrated that the reactivity of glass powder is closely related to the particle size, fixing 75 µm as the maximum particle size, considered as the upper limit of pozzolanic reactivity for glass. Mohammadreza Mirzahosseini and Kyle A. Riding [13] studied different types of glass particle sizes to understand the effects of particle size on the reactivity of glassy SCM. Ground glass ions with a size of 0-25 µm contain a larger specific surface area than other sizes, here is a stronger tendency for this effect to dissolve into a porous solution that needs to take place prior to the reaction of the glass this effect has a greater propensity to dissolve into porous solution that must occur before the glass can react, possibly another explanation for the higher reactivity of 0-25 µm particles. It is concluded then, that the specific surface area is an important factor in glass reactivity.

Concerning the mechanical performance, the glass powder concrete has shown satisfactory results in the laboratory and in field exposure. Nassar et al. [14] carried out a study on the field and laboratory-tested performance of concrete manufactured with a 20% cement replacement of powder waste glass over an extended period. The outcomes of the field glass waste concrete tests have shown a significant improvement in compressive strength in comparison to the standard concrete at 300 days of concrete age. At the same time, the outcomes of laboratory tests showed an increase in the glass waste concrete performance when compared to standard one. This increase is equal to 43% and 28% in compressive and flexural strength (90 days), respectively.

Concerning glass waste concrete durability, most of the research is focused on alkali-silica reactions (ASR). The significant alkali content present in the glass is apprehension regarding its utilization in concrete. However, research have demonstrated that finely ground glass helps to do not induce ASR [15,16]. Matos and Coutinho [17] studied the durability of grounded waste glass in mortar as a partial cement replacement. They carried out an extensive experimental program including ASR, chloride, and carbonation tests, concluding that the durability results were enhanced with the presence of glass powder.

Despite the tendency of satisfactory mechanical resistance and durability of concretes containing waste glass powder, the comparison to concretes containing FA needs to be clarified considering all the influencing parameters. The pozzolanicity of the glass powder and FA for comparison was evaluated by [3] using a strength activity index over time obtaining promising results.

This research aims to contribute to the development of cementitious materials with low CO_2 emissions and a significant contribution to the circular economy. The advancement of knowledge concerning the application of glass waste as a partial alternative to cement holds great importance in the present discussion. In this sense, the impact of using glass powder on the mechanical strength of mortars, as well as the pozzolanic activity index of these powders, were investigated. The grinding methods for obtaining glass powder and the different glass colours used to obtain the powder were considered. The results will help clarify the potential use of glass powder in cementitious matrices, as a cement and fly ash partial substitute. Furthermore, these results may assist in valorising the waste in question, promoting glass recycling, with gains at social, environmental, and economic levels.

2.Experimental procedure

The experimental steps used can be described systematically as follows:

- Acquisition of glass powder to be used as a partial substitute for cement and characterization of materials used in the composition of the studied mortars.
- Preparation of representative samples for different scenarios to be evaluated in this work, namely: the influence of glass grinding method on the compressive strength of cementitious materials; the influence of different glass powder colours on the compressive strength of cementitious materials; the potential use of this material as a partial substitute for cement; the potential use of this material as an alternative to the shortage of FA in countries where there is no longer energy production through thermoelectric plants.
- Conducting the compressive strength test to assess the load-bearing capacity of the studied specimens.
- Determination of the pozzolanic activity associated with the different situations studied.

2.1.Materials

Cement CEM I 42.5R, FA, and glass powder were used as a binder to produce mortar specimens. Fly ash was obtained from the burning coal in Portuguese thermoelectric plants. Glass bottles (soda-lime glass) were chosen to produce the glass powder used in this research. Since only 49% of glass bottles and jars were collected for recycling in Portugal in 2020 [18], there is a growth potential for recycling this material. Natural silica sand, with a maximum diameter of 500 µm and density of 2.62 g/cm^3, and tap water was used for all mixtures production.

2.1.1.Glass powder obtaining process

The glass bottles were provided by local partners such as restaurants and wine companies. Considering the equipments commonly available in the laboratories, a preliminary study was carried out

Fig. 1 - Main steps of the process used to obtain glass powder.

to define the most efficient process to transform glass bottles into glass powder. The main steps of the final process are summarized below (Fig. 1):

a. Pre-treatment: select and clean bottles, removing stickers and washing them
b. Dry selected bottles: stove (FED 720 E3.1, BINDER GmbH, Germany) at 100 ±5^{0}C for 1 hour
c. Ground of the dried bottles resulting in glass powder
d. Segregation of glass powder using the sieve 75 µm to separate the usable fraction (passed through the sieve) from the residue (retained on the sieve)

The glass powder was grounded to obtain a finer grain size distribution, closer to the FA, which in turn was found to be close to that of cement. At this stage, it is important to know that previous studies highlighted the importance to study the alkali-silica reaction (ASR) in cementitious materials containing glass waste [19]. Considering that an important influence is exerted by particle diameter on the expansion induced by ASR [20,21], the sieve of 75 µm was chosen. The glass powder with a particle size less than 75 µm can suppress the ASR due to its pozzolanic properties (Jani & Hogland, 2014; Serpa et al., 2013).

The ground step (c) was carried out in two stages. First, it was used the Los Angeles machine (A075N, MATEST, Italy), Fig. 1 (step c), rotate at 32 rpm, with 20 cast iron balls, mass equal to 8.74 kg, for 10 hours. The residue passed through the sieve 75 µm was collected, step (d), and called glass powder 1 (GP1). Second, all material provided by Los Angeles machine (after ten hours) was put into a porcelain ball mill, rotate at 30 rpm, with 10 ceramic balls, mass equal to 0.11 kg, for 0.5 hours.The residue passed through the sieve 75 µm was collected, step (d), and called glass powder 2 (GP2).

The complete process (a to d) was made separately for the different colours of glass bottles. Green, white, and brown glass bottles were used to produce three types of glass powder: green glass powder (GGP), white glass powder (WGP), and brown glass powder (BGP).

2.1.2.Characterization of binders

A cement CEM I 42.5R, FA and different glass powders were used to produce mortar specimens. Their chemical compositions are presented in Table 1. The chemical compositions of glass powders are similar mainly to Na_2O and SiO_2 quantities, but there are some slight differences namely in the content of CaO, Al_2O_3 and Fe_2O_3.

Since the fineness is strongly related to the pozzolanic activity [6], it is also important to understand the behaviour of the studied glass powders. The specific surfaces (SS) of binders were determined according to NP EN 196-6 [23] and they are shown in Table 2, as well as their density (**δ**).

Due to the small size of the particles, the particle size distributions of binders were determined by laser diffraction particle size analyser equipment (Malvern, Mastersizer 3000, United Kingdom). This equipment measures the size of the particles and their size distribution through laser diffraction, after placing an amount sample in a liquid environment. The particle size distributions of binders are shown in Fig. 2.

Table 1

Chemical composition of cement, fly ash and, different glass powders (GGP, WGP, and BGP).

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	Fe_2O_3	Cr_2O_3	SO_3	P_2O_5	TiO_2	IR	LOI
CEM I 42.5R	0.77	2.06	5.12	20.74	0.85	61.28	3.16	-	3.24	-	-	3.38	2.97
CV	1.52	1.55	22.70	53.70	3.46	1.25	12.70	-	0.79	0.25	1.60	-	6.20
BGP	12.00	-	2.00	66.00	0.80	13.60	5.60	-	-	-	-	-	-
WGP	11.50	0.30	1.10	68.70	-	15.10	3.30	-	-	-	-	-	-
GGP	13.40	1.00	2.30	69.20	0.90	11.80	1.30	0.10	-	-	-	-	-

Table 2

- Specific surface of cement, FA, and, different glass powders (GGP, WGP, and BGP).

	Cement	FA	BGP1	BGP2	WGP1	WGP2	GGP1	GGP2
SS (m^2/kg)	599.4	740.2	398.4	448.4	211.6	261.2	283.0	440.7
δ (kg/m^3)	3100	2360	2510	2520	2540	2560	2530	2460

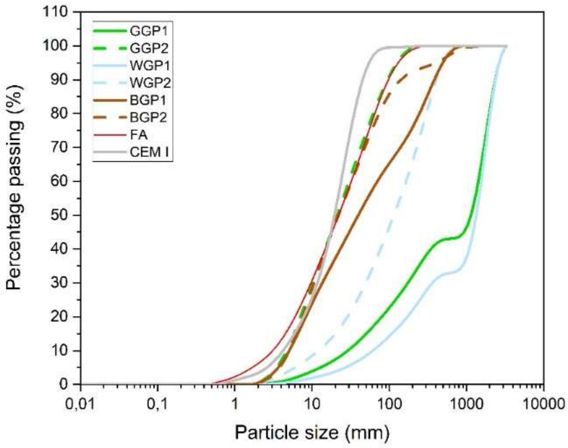

Fig. 2 - Particle size distribution of cement, FA, and different glass powders (GGP, WGP, and BGP).

Comparing the curves shown in Fig. 2 is clear that the grinding method used to obtain GP2, namely the need for a secondary porcelain ball millage, is necessary since it led to particle size distribution closer to cement and FA, regardless of the type of glass powder. The Los Angeles machine used to obtain GP1 helps to reach D50 values between 41 and 1040 μm (Table 3). The use of Los Angeles machine followed by a porcelain ball mill to obtain GP2 reduced D50 to values between 22 and 110 μm (Table 3), closer to cement and FA values.

Table 3

Characteristic diameters of the materials.

	D10 (μm)	D50 (μm)	D90 (μm)
Cement	4.3	18	49
FA	3.1	22	100
BGP1	5	41	395
BGP2	5	22	150
WGP1	64	1040	1120
WGP2	12	110	395
GGP1	30	1015	1120
GGP2	4.9	22	100

As above-mentioned, to obtain the GP2 it is necessary to spend more time in the process and to use two different machines (Los Angeles and porcelain ball mill). Since how more processed the waste glass is, the less environmentally favourable it is, it is very important to know the more efficient process to reach a satisfactory mechanical behaviour.

2.2. Mixture proportions and specimens

In the current experimental program, two types of mortars were prepared: control (plain, without cement replacement) and blended (25% replacement of cement). It is important to notice that the 25% of cement replaced in mass (179.3 kg) occupied a certain volume (0.058 m^3) and the glass powders masses presented in Table 4 were calculated to occupy the same volume as cement. A water-to-binder ratio of 0.5 was used and kept constant for every mixture. The mixture proportions for all mortars studied are given in Table 4.

Since the glass powder obtention in the laboratory is a very slow process, it was used cubic moulds with an edge of 20 mm to reduce the amount of necessary material. After filling the moulds with the mixtures, they were enveloped with plastic film and in a controlled humidity environment for storage (18 ± 2 ºC, 93 ± 2% RH) for 48 h. Following that, the specimens were taken out of the moulds and then submerged in tap water saturated with lime for 7, 28 and 90 days.

2.3.Compressive strength evaluation

The partial replacement of cement by glass powder was evaluated considering its impact on the compressive strength test results. The compressive strength tests were carried out based on ASTM C 109 [24], using a compression machine (LR50K PLUS, LLOYD Instruments, AMETEK, USA), in the Construction Materials Laboratory at the University of Minho, Portugal. With the aim of assessing the progress of pozzolanic reactions, emphasis was placed on evaluating the compressive strength of the mixtures over time (7, 28 and 90 days). A set of seven cubic specimens were tested for each studied mixture and the average was reported as well as the standard deviations.

Table 4

Mortar mixture proportions (1 m^3).

	GP (%)	FA (%)	Cement (kg)	FA (kg)	GP (kg)	Sand (kg)	Water (kg)
Control	0	0	717.2	-	-	1075.4	358.2
FA	0	25	537.9	136.9	-	1075.4	358.2
B_GP1	25	0	537.9	-	145.4	1075.4	358.2
B_GP2	25	0	537.9	-	146.2	1075.4	358.2
W_GP1	25	0	537.9	-	147.3	1075.4	358.2
W_GP2	25	0	537.5	-	148.5	1075.4	358.2
G_GP1	25	0	539.5	-	146.7	1075.4	358.2
G_GP2	25	0	539.5	-	142.7	1075.4	358.2

2.4. Pozzolanic activity index

The pozzolanic activity index is used to determine whether the used pozzolanic material results in an acceptable level of strength development when used with hydraulic cement in cementitious materials. Considering the materials used in this work, the European standard for FA, NP EN 450-1 [25], was chosen to determine the activity index of glass powder and also FA. According to the cited specification, the activity index is the ratio between the compressive strength of standardized mortar specimens prepared with 75% cement and 25% of the pozzolanic addition (by mass), and the compressive strength of control mortar specimens prepared only with cement (Eq.1):

$$AI = \frac{A}{B} x100 \qquad (1)$$

AI - Activity index;
A - Compressive strength (MPa) of mortar with pozzolanic addition;
B - Compressive strength (MPa) of the control mortar.

3. Presentation and discussion of results

3.1. Influence of the grinding method on the glass powder resulting

Since more processed material is a less sustainable material, it is important to think about the grinding method to use in the laboratory. The ideal method leads to satisfactory performance of cementitious material. Considering that the expected performance is related to the utilization of the material, the chosen grinding method may vary for different situations. This study carried out two methods to obtain glass powder. First, it was used one grinding machine for 10 hours. Second, it was used two types of grinding machines and increased the time process to 10.5 hours.

From Table 2, the glass powders studied are coarser than the cement and FA for all studied situations, regardless of the grinding method and glass colour. The WGP has the smallest SS while the BGP has the highest one. BGP2 has the SS closest to the SS of cement and FA, but is still 33 and 46% lower, respectively. Considering the used of the same machines (Los Angeles and ball mill), increasing the grinding time can help to reach a finer glass powder, closer to the cement and FA´s fineness. Using a more efficient machine is also an option.

Lui et al. [26] studied the effect of grinding time on the particle characteristics of glass powder using a ball mill with 48 rpm (almost 18 rpm higher than the machine used in this study). They grounded waste glass for 10, 30, 60, 90 and 120 min and the results suggest that the activity index of glass powder is positively correlated with grinding time, leading to the conclusion that the former increases as the latter is extended. However, according to the research, only 90 minutes are necessary to reach the optimal grinding time for glass powder in consideration of economic and technical benefits. The glass powder resulting in 90 minutes has characteristics similar to cement and FA used in this research (Table 5). The glass waste was smashed before grinding. It is possible that the smash step and the high efficiency of the grinding machine are the main cause for this great result. Concerning the environmental advantages, it is important to carry out a study about the impact of grinding machine efficiency on environmental gains.

3.2. Influence of the grinding method and glass colour on the compressive strength

Different grinding methods lead to glass powders with different characteristics, namely SS (Table 2) and particle size distribution (Table 3). Considering the influence of materials on the cementitious final materials' characteristics, the impact of the grinding method and glass colour on the compressive strength was evaluated over time, Fig. 3. The value of each bar corresponds to the average value for seven specimens.

The control mortar (plain, without cement replacement) behaviour is in accordance with the literature, showing a noticeable increase in compressive strength at 28 days [6]. The FA mortar' behaviour is also expected, reaching the highest compressive strength at 90 days, when the pozzolanic reactions are almost complete [27,28]. Regarding the glass powder mortars, there is an increase in compressive strength from 7 to 90 days, reaching the highest compressive strength at 90 days, similar to FA. This gain in compressive strength at 90 days is already verified in another research [6,13].

Regarding glass powder mortar results (Fig. 3), it is observed that the grinding method influences the compressive strength. At the

Table 5

Specific surface areas and equivalent particle size considering grinding time and efficiency of the grinding machine.

Material	Grinding time (hours)	SS (m^2/kg)	D10 (μm)	D50 (μm)	D90 (μm)
Cement	-	599.4	4.3	18	49
FA	-	740.2	3.1	22	100
BGP2	10.5 (30 rpm)	448.4	5	22	150
GGP2	10.5 (30 rpm)	440.7	4.9	22	100
GP [26]	1.5 (48 rpm)	817	1.45	10.64	62.17

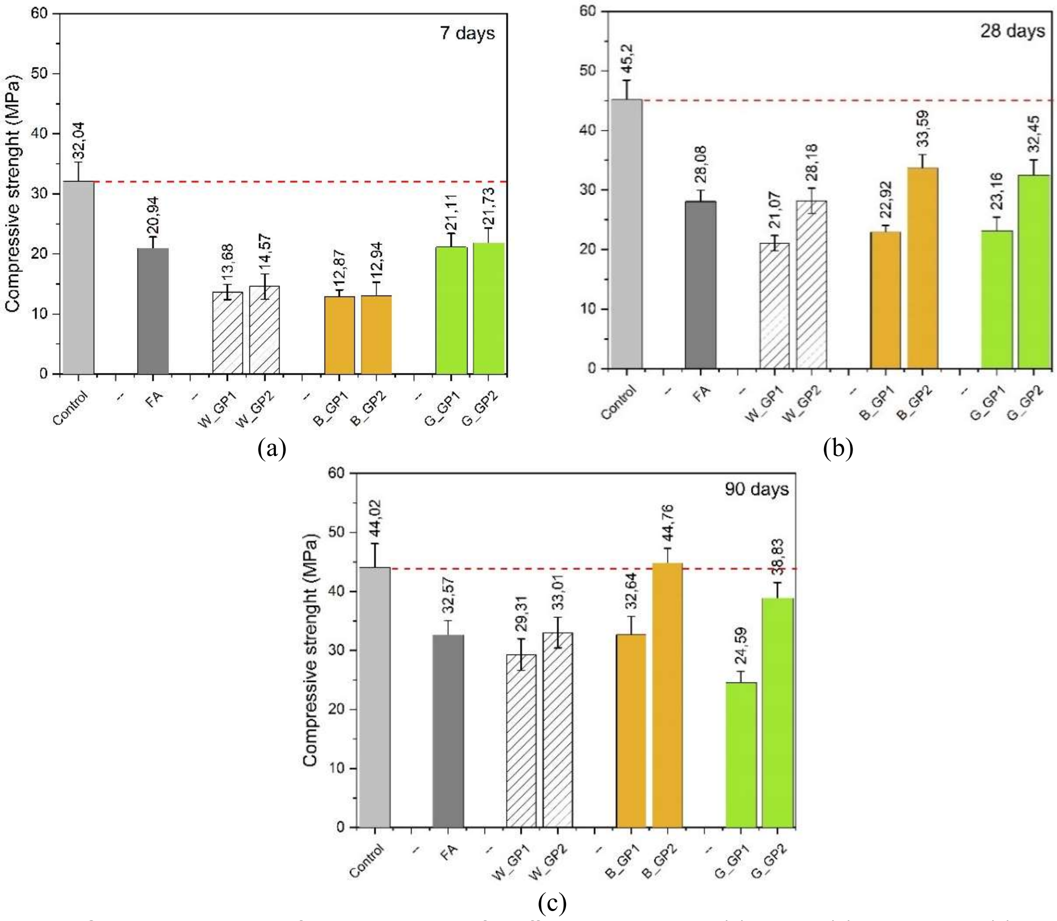

Fig. 3 – Compressive strength for mortars studied for different curing times: (a) 7 days; (b) 28 days; and (c) 90 days.

7 days of curing the values obtained are very similar between them and no significant influence of grinding method is verified (Fig. 3(a)). However, with time and the development of hydration and pozzolanic reactions, it is possible to observe an increase in the compressive strength of mortars using GP2 when compared to mortars made using GP1. At 28 days, this difference is more evident in BGP, reaching 31.76% (Fig. 3(b)). This tendency is consolidated at 90 days of curing, highlighting BGP and GGP mortars where the increase was 27.07 and 36.67%, respectively. The higher SS of GP2 when compared to GP1 (Table 2) can be related to higher compressive strengths, as seen in Fig. 3(c) at 90 days of age. Previous research shows that the compressive strength of mortar containing glass powder increases with increasing the glass powder SS, and the SS increases with increasing its grinding time [26]. Although WGP2 has the smallest specific surface than BGP2 and GGP2, it also reaches a satisfactory compressive strength at 90 days, 33.01 MPa, similar to the FA mortar result. It can be related to its particles size distribution which provides a better packing effect and, consequently, a denser microstructure.

Since FA is frequently used as a cement replacement, the comparison between glass powder and FA mortars plays an important role in this context. On one hand, the glass powder mortars made using GP1 reached compressive strength values similar to or less than FA mortar. Considering GGP1, for example, the decrease is 25%. On the other hand, the glass powder mortars made using GP2 reached very satisfactory compressive strength, higher than FA mortar values regardless of the colour of the glass bottle used to make the powder. There is an increase of 37% when comparing FA and BGP2 compressive strength results.

Considering the control plain mortar, a reduction is observed in the compressive strength for almost all mortars studied (FA and glass powder). However, the mortars containing GP2 are clearly more efficient than mortars containing GP1. The compressive strength reached by BGP2 is very close to the control mortar and GGP2 has a very slight decrease (around 10%). Replacements with percentages equal to or less than 20% have shown good results in compressive strength [29]. Islam et al. (Islam et al., 2017) used glass powder to produce mortars with replacement levels of 5, 10, 15, 20 and 25%. They obtained lower compressive strength results than the control mortar at 90 days only for mortars with 25% replacement. However, for replacements above 20%, the effect on compressive strength seems to be not consensual.

Regarding the glass powder colour, at 7 days of curing the GGP1 and GGP2 are highlighted as the highest compressive strength among the glass powder mortars. At 28 days of curing, there is

Table 6

Chemical requirements for pozzolanic materials.

ID	ASTM 618/ NBR 12653		ASTM C1866					
	SUM (%) = SiO_2+ Al_2O_3 +Fe_2O_3	Req	SiO_2 (%)	Req	Al_2O_3 (%)	Req	Fe_2O_3 (%)	Req
		SUM ≥70%		SiO_2 ≥60%		Al_2O_3 ≤5%		Fe_2O_3 ≤1%
CV	89.10	OK	-		-		-	
BGP	73.60	OK	66.00	OK	2.00	OK	5.60	KO
WGP	73.10	OK	68.70	OK	1.10	OK	3.30	KO
GGP	72.80	OK	69.20	OK	2.30	OK	1.30	KO

*Req - Requirements

no significant difference in compressive strength for the different glass powder mortars. However, at 90 days the BGP1 and BGP2 are highlighted as the highest compressive strength among the glass powder mortars. Considering 90 days of curing, the mixtures made with GP2, regardless of the colour the of glass powder, showed satisfactory results when compared to control and FA mixtures. These results corroborate the results obtained by Ibrahin and Meawad [30] who concluded that uncoloured, green, and brown soda-lime glass types are acceptable for use as SCM, since the glass colour and its chemical compound has no effect on the mortar performance.

3.3.Pozzolanic activity

3.3.1. Chemical requirements

Minimum criteria have been established for considering some material as pozzolanic material. Some of these criteria are related to their chemical composition. According to ASTM C618 [31], a good pozzolanic material requires at least 70% sum of SiO_2, Al_2O_3 and Fe_2O_3. The same criteria is adopted by Brazilian Standard, NRB 12653 [32]. Regard specifically to glass powder, the ASTM C1866 [33] established minimum criteria for its utilization in cementitious materials. Table 6 shows the chemical requirements established in the above-mentioned standards and compares the results reached in this research. Considering ASTM C618 and NBR 12653, standards related to pozzolanic materials in general, the main chemical requirements have been satisfied. Concerning ASTM C1866M-20 there is a deviation in the Fe_2O_3 percentages, however, the main oxides related to the ASR are in accordance with the requirements. The deviation in the Fe_2O_3 percentages can be related to the colour of the glass. The ASTM C1866 [33] refers to the glass of the containers, i.e., glasses of various colours at the same time, whereas Table 6 refers to glasses with specific colours where Fe_2O_3 is used to colour the glass.

3.3.2. Activity index

The evaluation of the pozzolanic activity of waste glass powders may be conducted indirectly through the monitoring of the compression strength progression in mortars containing ones. Activity index at 28 and 90 days are calculated as prescribed by NP EN 450-1 [25] and they are shown in Fig. 4 (a) and (b) respectively. The FA mortar values are also shown. The red line in Fig. 4 displays the minimum recommended activity index that a pozzolanic material should have according to the NP EN 450-1 [25], while the blue line means the inferior threshold.

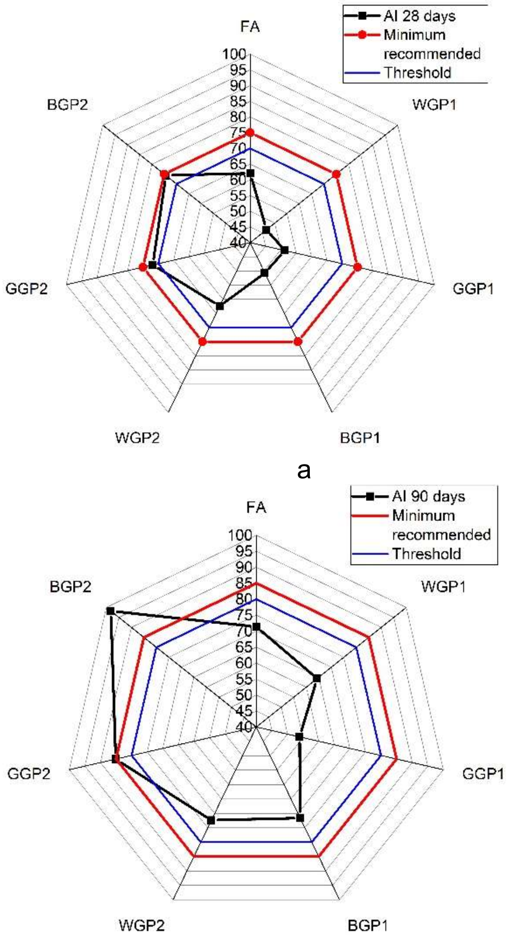

Fig. 4 – Activity index for mortars studied for different curing times: (a) 28 days; and (b) 90 days.

According to Fig. 4, only BGP2 satisfy the minimum recommendation of NP EN 450-1 [25], AI ≥ 75% at 28 days and AI ≥ 85% at 90 days. Nevertheless, considering the threshold established by the same standard, AI ≥ 70% at 28 days and AI ≥ 80% at 90 days, GGP2 also present a satisfactory activity index. The colour of the glass powder seems to have no influence on the activity index, contrary to the grinding method, which clearly has. The better performance of GP2 instead of GP1 is significant and obvious looking for Fig. 4. This behaviour was also observed in the compressive strength results. As explained previously, it should be related to GP2 specific surface.

3.4.Utilization of glass powder as SCM

The use of glass powder as SCM can bring social, economic, and environmental gains. The transformation of waste glass from packaging into glass powder promotes a circular economy, while also helping in the reduction of CO_2 emissions and energy consumption associated with cement production. It can also promote the creation of a new production chain related to the collection of packaging, the transformation of packaging into powder, and its commercialization. All these new chains add value to glass waste and can drive an increase in recycling rates around the world. In this sense, the study of using glass powder as SCM is a current and relevant discussion. The publication of ASTM C1866 [33] has helped to push these studies forward by providing guidance on using glass powder as SCM, providing safety and legal security to the user.

The results achieved in this research point to the possibility of using glass powder as a SCM. This result corroborates the study developed by Ibrahin and Meawad [30]. The partial replacement of cement by glass powder at a percentage of 25% led to promising results in terms of compressive strength. In the worst scenario, at 28 days, the lowest result achieved was 21.07 MPa, while at 90 days it was 24.59 MPa. This performance is similar to FA mortar studied, representing only a 25% loss, both at 28 and 90 days. It is important to make it clear that the results achieved refer to mortars, which need to be reflected in studies related to concrete for this type of comparison to be valid. Additionally, the entire subject needs to be discussed from the perspective of durability.

The achieved results clearly demonstrate the influence of glass powder SS on compressive strength and activity index calculation. Only two of the finest powders (GP2), namely GGP2 and BGP2, reached the recommended activity index for pozzolanic materials according to NP EN 450 [25]. However, all studied mixtures showed satisfactory results for use, despite the reduction in compressive strength compared to reference values. It can mean that when not working as a pozzolan, glass powder can work as a microstructure enhancer through its filling effect.

In Europe, the closure of thermoelectric plants planned by 2050 promises to make FA a scarce material. Countries like Portugal are already suffering from a shortage of FA due to the closure of their coal-burning thermoelectric plants more than a year ago. In this context, the common and high use of FA worldwide will stop and making it necessary to find a substitute for it. Otherwise, we take the risk of taking a step backwards in the sustainability of the material most produced and used by man, concrete. Considering the valid and important comparison of results obtained for mixtures with glass powder with those obtained for mixtures with FA, it can be said that glass powder is a potential substitute for FA. According to the results presented, at 90 days, all mixtures produced with GP2 showed compressive strengths higher than those of FA.

4. Conclusions

Considering its significant impact on energy consumption and CO_2 emissions, the building sector has been looking actively for solutions that help to mitigate its impact on the environment. Also considering the relevance of the cement industry in this context, this research contributes to reducing the use of cement by expanding knowledge about the production of low CO_2 cementitious materials.

Experimental study was conducted to assess the feasibility of utilizing waste glass as a partial cement replacement, considering different grinding methods for obtaining glass powder and different glass colours. The potential use of glass powder in cementitious matrices, as a fly ash substitute, is also evaluated.

Concerning the ground methods, results show that the higher the ground time, the smaller the diameter of the glass particles. However, two main aspects need to be considered to reach more efficient decisions (considering costs and environment): the steps of the ground and the efficiency of the ground machine.

Results also concluded that white, green, and brown glass powders are acceptable to be used as cement replacements. Regardless of only BGP2 (brown) and GGP2 (green) satisfy the minimum recommendation of Portuguese standards in terms of pozzolanic activity, the compression strength results show satisfactory values (between 33 and 44 MPa at 90 days). Furthermore, the results also identify glass powder as a potential substitute for fly ash since the pozzolanic activity and compression strength values of cementitious materials with glass powder are very similar to fly ash values.

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Declaration of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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