Evaluation of Pervious Concrete Mixtures with Partial Replacement of Cement for Glass or Ceramic Waste

COLLECTION:
SUSTAINABLE CONCRETE

ARTICLE

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ABSTRACT

Due to its composition, pervious concrete allows water to pass through its structure, helping to solve infiltration and surface runoff problems. Cement is one of its components and its production is highly contaminating because it emits between 8 to 9% of CO_2 in addition to SO_x and NO_x. Hence, it is necessary to reduce the amount incorporated in the mixes. In this research, pervious concrete mixtures were made with 10 and 20% pozzolanic cement replaced by glass and ceramic wastes separately. Each mixture was evaluated for compressive strength at 7 and 28 days and permeability at 28 days. It was shown that the compressive strength of the mixtures with ceramic decreases as the replacement percentage increases, but, as the age of the test increases, the difference with respect to the control mixture is smaller. The mixes with glass show a decrease in compressive strength at 7 days, however, at 28 days they are similar to the control mix. The permeability of the mixtures of both wastes is adequate because it is between the ranges indicated in the literature and even close to the superior limit.

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1. INTRODUCTION

Urban growth has increased considerably in recent years and is expected to continue to increase in the next 30 years (Angel et al., 2011). Urbanization increases drainage and stormwater management problems due to land use change and impacts on the hydrological cycle (Trapote Jaume, 2016). To minimize this negative effect, pervious concrete pavements are used, which consist of a concrete with no or minimal presence of fine aggregates that creates a network of interconnected voids that allow water to infiltrate through its structure (American Concrete Institute, 2010) as shown in Figure 1.

Pervious concrete, like traditional concretes and mortars, includes cement among its components and the production of this material is highly contaminating, contributing to around 8 to 9% of global CO_2 emissions and between 2 to 3% of the energy used (Monteiro et al., 2017). It also emits SO_x and NO_x which are the cause of acid rain and smog (Potgieter, 2012). In addition, global cement demand has increased considerably, from 1.0 billion tons in 1990 to approximately 4.1 billion tons in 2016 (Armstrong, 2017; FICEM, 2020) is projected to reach a consume 5.0 billion tons by 2050 (Lehne & Preston, 2018). Therefore, it is necessary to reduce the amount of cement in the mixes to contribute to a reduction of the carbon footprint.

Figure 1 Pervious concrete.

There are several materials that can replace cement in concrete mixes and one of the best alternatives are some types of waste, because it comprises materials that are not destined for another use and contribute to the management and reuse of residues, which is a problem nowadays. The accumulation of waste generated by human activity has major consequences, causing health problems, transportation costs, pollution, environmental impact and waste of material resources that could have been reused or recycled (Columbié-Lamorú et al., 2020). In 2016, around 21.2 million tons of waste were generated in Chile. It is estimated that about 76% of the non-hazardous waste generated is disposed of mainly in landfills and dumps and 24% is valorized, so it is urgent to promote the transition to a circular economy that allows minimizing waste and properly using our resources (MMA, 2018).

Some of the wastes that have been incorporated into the concrete mixtures as cement replacement are ceramic and glass recycled. Ceramic belongs to construction and demolition waste and this type of waste is the largest waste worldwide (López Ruiz et al., 2020). In the EU, around one third comes from construction and demolition activities (European Commission, 2011). On the other side, glass is one of the wastes that needs the longest time to decompose, so wasting its reuse implies high pollution associated with the extraction, processing, production, distribution and commercialization stages (Columbié-Lamorú et al., 2020). Glass belongs to municipal solid waste and around 70% of municipal solid waste produced worldwide go into dumpsites and landfills (Sharma & Jain, 2020). In the case of Chile, the glass recycling rate corresponds to 31.1% (ANIR, 2019). Therefore, due to the low recycling rate, it is necessary to reduce the amount of waste going to landfills by promoting the use and recycling of waste.

Ceramic tiles waste has a potential pozzolanic reactivity (Mas et al., 2016; Pereira-De-Oliveira et al., 2012) and although no research has been found that incorporates this material in pervious concrete, it has been incorporated in mortar and traditional concrete mixes. Some of the investigations that have replaced cement with ceramics have obtained good results, increasing the compressive strength in mortars and concrete (Bhargav & Kansal, 2020; Najm & Ahmad, 2022; Poloju, 2022; Samadi et al., 2015). However, its incorporation has also been shown to decrease compressive strength (Kannan et al., 2017; Mas et al., 2016). It has been shown that mixtures with replacement of cement by ceramic can present lower resistance at early ages, but higher than a conventional mixture after 90 days, due to the effect of late pozzolanic reactions (Dieb & Kanaan, 2018; Li et al., 2020). In addition, pozzolanic activity is influenced by particle size, with 75 µm being considered appropriate for ceramics (Ay & Ünal, 2000; Chicaiza & Guerra, 2017; Pereira-De-Oliveira et al., 2012).

Glass waste has very high pozzolanic activity (Pereira-De-Oliveira et al., 2012), therefore it is also an alternative as a cement replacement. Waste glass has been successfully incorporated in pervious and traditional concrete. In pervious concretes, research is still scarce (Li et al., 2021; Pradeep et al., 2019; Talsania et al., 2015), but in traditional concretes it has been extensively studied (Du & Tan, 2014; Jiang et al., 2022; Kalakada et al., 2022; Li et al., 2022; Omran & Tagnit-Hamou, 2016; Tayeh et al., 2020). It has been shown that mixtures with replacement of cement by glass can present lower resistance at early ages, but higher than a conventional mixture after 90 days, due to the effect of late pozzolanic reactions (Islam et al., 2017; Li et al., 2022; Omran & Tagnit-Hamou, 2016). In addition, pozzolanic activity is influenced by particle size, with 75 µm being considered appropriate for glass (Pereira-De-Oliveira et al., 2012; Shi & Zheng, 2007; Vijayakumar et al., 2013).

The main objective of this research is to evaluate the incidence on mechanical and hydraulic properties of the partial substitution of cement by glass or ceramic waste in pervious concrete mixtures.

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. Water

The water used comes from the public water supply that complied with NCh 1498.

2.1.2. Cement

The cement used in all the mixtures was a typical cement used in construction in Chile, obtained by grinding clinker, pozzolana and gypsum together. It is classified as standard grade pozzolanic cement according to NCh 148, based on ASTM C150/C150M. Table 1 indicates the properties of the cement.

Table 1 Cement characteristics.

PROPERTIES		VALUE
Specific gravity (g/cm^3)		2.8
Autoclave expansion (%)		0.1
Initial setting (h:m)		2:40
Final setting (h:m)		3:40
Compressive strength (kg/cm^2)	7 days	320
	28 days	410

2.1.3. Aggregates

The aggregates used correspond to Biobío sand and 3/8" gravel, which are the typical aggregates for making concrete in the local market in Chile. The properties are indicated in Table 2 and the granulometric curves are shown in Figure 2.

Table 2 Properties of coarse and fine aggregate.

PROPERTIES	COARSE AGGREGATE	FINE AGGREGATE
Relative Density SSD (kg/m³)	2683	2729
Relative Density (kg/m³)	2643	2679
Apparent Relative Density (kg/m³)	2752	2814
Compacted Bulk Density (kg/m³)	1500	1638
Materials finer that #200 sieve (%)	0,49	0,74
Fineness Modulus	8,89	2,53
Water Absorption (%)	1,49	1,90

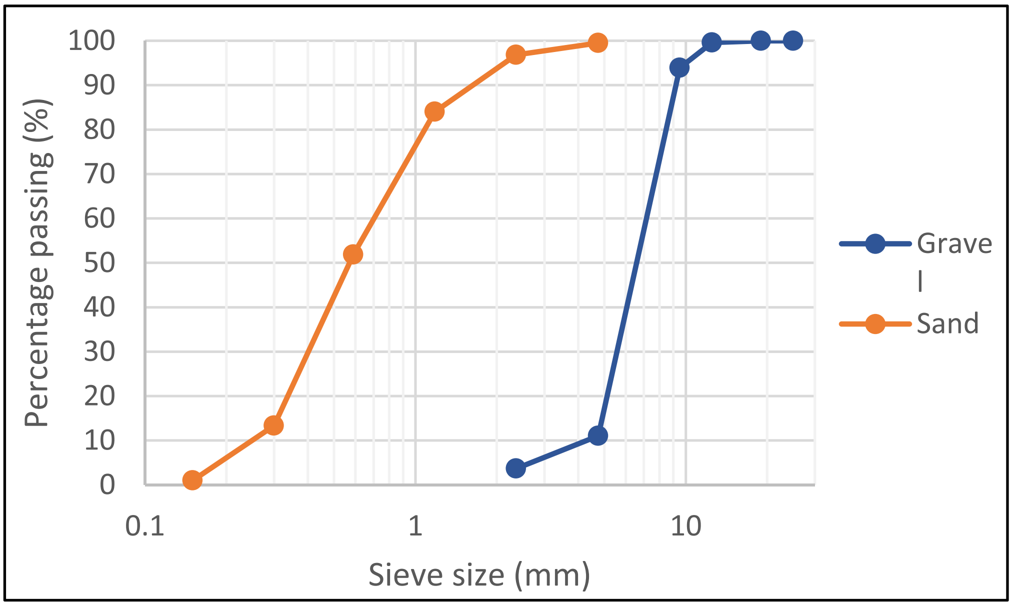

Figure 2 Granulometric distribution of aggregates.

2.1.4. Glass and ceramic waste

The waste glass used in this study are bottles collected without differentiating by color or type, which were labeled, washed, dried and ground in a ball mill. The waste ceramic used was ceramic floor or wall tile, dry pressed, glazed and with a water absorption of 7.5%, which, like the glass, were ground in a ball mill.

The pozzolanic materials are all those inorganic materials, which harden in water when mixed with calcium hydroxide or with materials that can release calcium hydroxide, such as Portland cement (Lea, 2019). Glass and ceramics are pozzolanic materials when finely ground. Therefore, both materials were ground and sieved to obtain particles of less than 75 µm, which is considered appropriate for replacing cement in concrete mixtures (Ay & Ünal, 2000; Pereira-De-Oliveira et al., 2012; Shi & Zheng, 2007; Viera & Chicaiza, 2018; Vijayakumar et al., 2013). The conditioned wastes are shown in Figure 3.

2.2. MIXTURE DETAILS

The pervious concrete mixtures were designed based on Nguyen et al. (2014) modified design method with modifications made by Oviedo et al. (2022), which mainly consist of modifying the k-factor to 1.1194 and increasing the amount of fine aggregate to 16.5%. A design porosity of 15% and a water-cement ratio of 0.35 were considered. Five different mixes were made, the control mix (PC-C), mix with 10% replacement of cement by ceramic waste (PC-10CW), mix with 20% replacement of cement by ceramic waste (PC-20CW), mix with 10% replacement of cement by glass waste (PC-10GW) and mix with 20% replacement of cement by glass waste (PC-20GW). The dosage for each mix is presented in Table 3.

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Figure 3 Conditioned wastes: **(a)** ceramic and **(b)** glass.

MIX	COARSE AGGREGATE (kg/m³)	SAND (kg/m³)	CEMENT (kg/m³)	WASTE CERAMIC (kg/m³)	WASTE GLASS (kg/m³)	WATER (kg/m³)
PC-C	1325.07	264.92	341.43	–	–	119.50
PC-10CW	1325.07	264.92	307.29	34.14	–	119.50
PC-20CW	1325.07	264.92	273.15	68.29	–	119.50
PC-10GW	1325.07	264.92	307.29	–	34.14	119.50
PC-20GW	1325.07	264.92	273.15	–	68.29	119.50

Table 3 Mix proportions of pervious concrete.

2.3. SPECIMEN PREPARATION, COMPACTION AND CURING

The preparation, compaction and curing of the pervious concrete mixes were conducted according to the NCh 1017 standard, based on ASTM C31. Firstly, the coarse aggregate, sand and the cement were added to the mixer in that order and it was stirred for a minute to ensure that all aggregates are covered by cement. After that, water was added and the mixture was stirred for 5 minutes. In the case of mixtures with residues, these were incorporated in small quantities after the addition of water.

The cylindrical specimens were compacted with 25 rod blows in three layers of equal volume and 5 lateral blows to the mold for each layer of concrete. The specimens were left to curing for 48 hours at room temperature and covered with transparent polyethylene. Subsequently, the specimens were placed in a curing room that presents ideal conditions, with humidity above 90% and temperature between 17-23°C. The specimens were kept in the curing room until the test age of 7 and 28 days. Three 150 × 300 mm cylindrical samples were made for each test age. The samples are shown in Figure 4.

Figure 4 Samples of pervious concrete.

2.4. TESTING

2.4.1. Docility test

The docility test was realized before incorporating the mixture into the specimens and was performed according to NCh 1019, standard complemented by ASTM C 143.

2.4.2. Compressive strength

Compressive strength was evaluated according to NCh 1037, based on the ASTM C39, using cylindrical concrete specimens with a diameter of 15 cm and a height of 30 cm. Compressive strength test was performed at 7 and 28 days.

2.4.3. Permeability

The permeability measurement was performed with a falling head permeameter specified by the ACI (2010) at 28 days. A single cylindrical specimen was considered to perform this test and was repeated three times to determine the time it takes for the water to descend between known heights. The coefficient of permeability (k) is calculated according to Equation 1, where "a" is the cross-sectional area of the standpipe, "L" is the length of the sample, "A" is the cross-sectional area of the sample, "t" is the time that takes for water to reach from h_1 to h_2, where h_1 to h_2 are the initial and final water level, respectively.

$$k = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \tag{1}$$

3. RESULTS AND DISCUSSION

3.1. COMPRESSIVE STRENGTH FOR MIXES WITH CERAMIC WASTE

The results of compressive strengths at 7 and 28 days curing for mixtures with ceramic waste are shown in Figure 5 and the compressive strength development curves are presented in Figure 6.

It is observed that at 7 days the standard mix presents the highest compressive strength values, reaching 11.74 MPa. In addition, as the percentage of cement substitution by ceramic increases, the compressive strengths decrease by approximately 18 and 24% for 10 and 20% ceramic substitutions, respectively. At 28 days, the tendency is maintained that there is a decrease in the compressive strength as the percentage of cement substitution increases, observing decreases of approximately 10 and 13% for substitutions of 10 and 20% of ceramic. Although at 28 days the compressive strength is affected, the effect is less than that occurring at 7 days, since the difference with respect to the standard mix is smaller, which may show a greater development of compressive strength between 7 and 28 days. This can be observed in the compressive strength development curves presented in Figure 6. The results obtained for the ceramic mixtures are similar to those obtained by Kannan et al. (2017) and Mas et al. (2016).

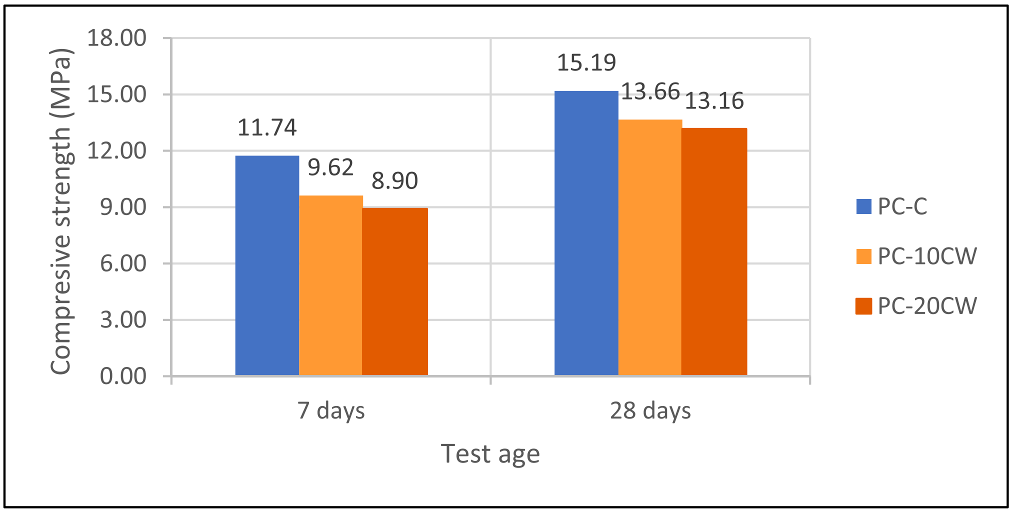

Figure 5 Compressive strength of ceramic waste mixes.

Between 7 and 28 days, the standard mix increased the compressive strength by approximately 29.5%, while the mixes with 10 and 20% of ceramic increased by approximately 42 and 48%, respectively. This is explained by the fact that the ceramic has a slower behavior than the cement, having low pozzolanic reactions at early ages and increasing considerably with increasing age. The strength development agrees with that obtained by other authors, such as Dieb & Kanaan (2018), Li et al. (2020) and Mas et al., (2016), who at 7 and 28 days present a reduction in compressive strength, however they note an increase as the test age increases, having strengths close to or higher than the standard mix at 90 days. This is why it can be inferred that the mixes with partial substitution of cement by ceramic waste could continue to develop their resistance as age increases and at 90 days present a resistance close to the standard.

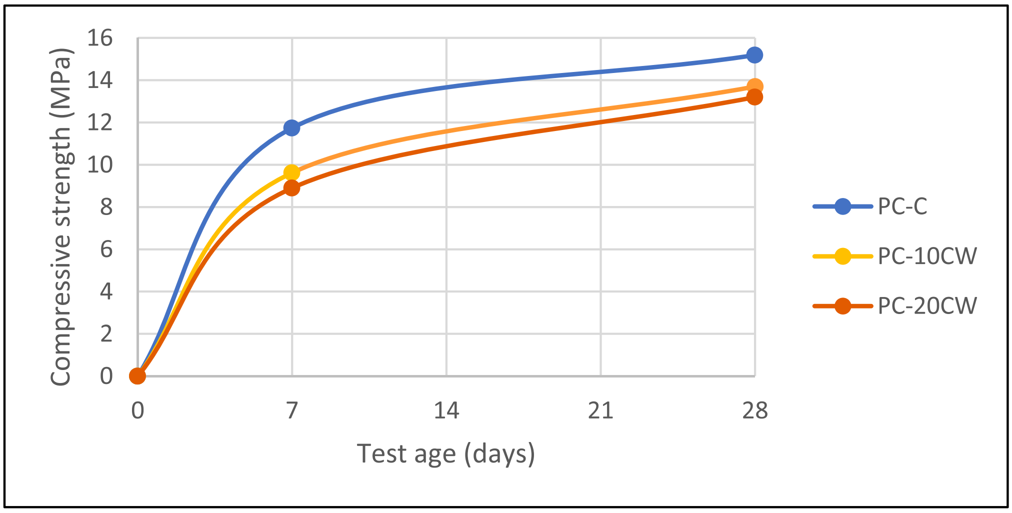

Figure 6 Development of the compressive strength of ceramic waste mixes.

3.2. COMPRESSIVE STRENGTH FOR MIXES WITH GLASS WASTE

The results of compressive strengths at 7 and 28 days curing for mixtures with glass waste are shown in Figure 7 and the compressive strength development curves are presented in Figure 8.

It is observed that at 7 days the standard mix presents the highest compressive strength values, reaching 11.74 MPa. In addition, as the percentage of cement substitution by glass increases, the compressive strengths decrease by approximately 6 and 20% for 10 and 20% glass substitutions, respectively. At 28 days, a change occurs with respect to what was obtained at 7 days, since the standard mixture presents a compressive strength of 15.19 MPa and is reached by the mixtures containing glass, obtaining 15.27 MPa and 15.44 MPa for 10 and 20% glass replacement, respectively, so that an increase of 0.5% is obtained for the mixture with 10% glass and 1.6% for the mixture with 20% glass. This results are in agreement with those obtained by other researches such as Kumar et al. (2014), Pradeep et al. (2019) and Talsania et al. (2015), with an optimum percentage of cement substitution by glass equal to 20%.

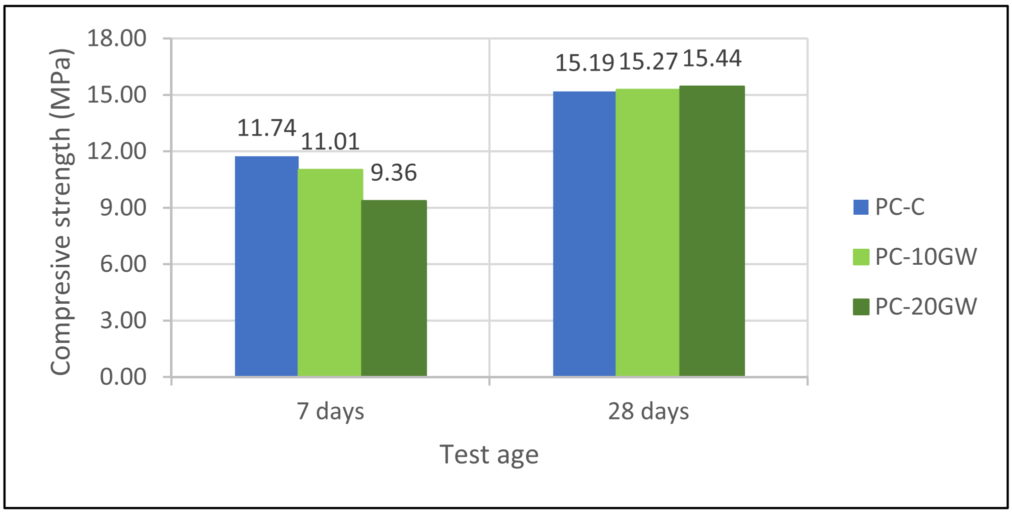

Figure 7 Compressive strength of glass waste mixes.

The mixes with glass waste in their composition show a higher compressive strength development than traditional pervious concrete between 7 and 28 days. This can be observed in the compressive strength development curves presented in Figure 8. Between 7 and 28 days, the standard mix increased the compressive strength by 30%, while the mixes with 10 and 20% glass increased approximately by 39 and 64.5%, respectively. This could be evidence of the influence of the late pozzolanic reactions generated by this type of material, reaching better strengths at higher ages, which is evidenced in the investigations of Islam et al. (2017) and Omran & Tagnit-Hamou (2016). Also, it is expected that the compressive strength will continue to increase and the highest strengths will be reached at ages above 90 days.

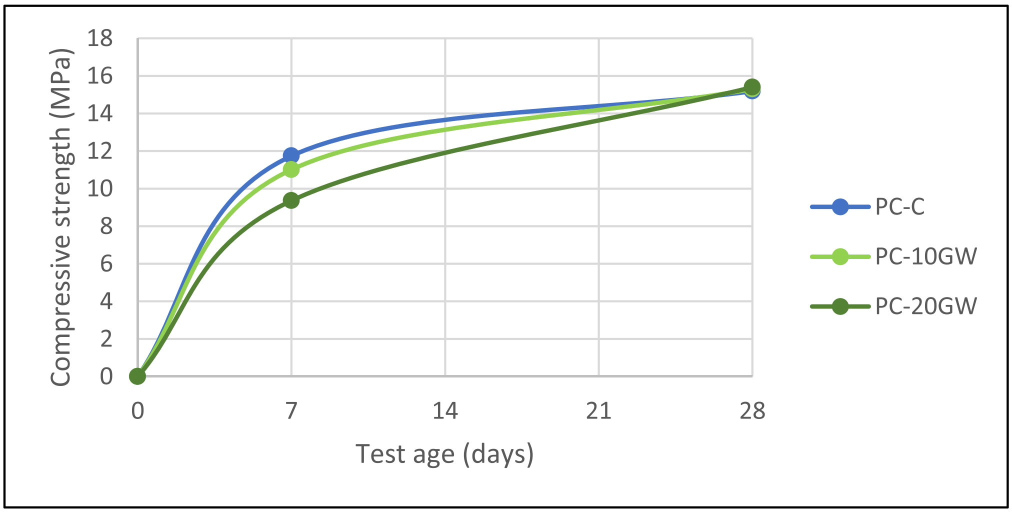

Figure 8 Development of the compressive strength of glass waste mixes.

3.3. PERMEABILITY FOR MIXES WITH CERAMIC WASTE

The results of permeability for mixtures with ceramic waste are shown in Figure 9. The standard mixture has a permeability of 0.97 cm/s, being exceeded by PC-20CW by 30% and being decreased by 3% by PC-10CW. The permeability of the mixes with ceramic are high, considering that the ranges in pervious concrete vary between 0.14 and 1.22 cm/s (ACI, 2010; Tennis et al., 2004). Therefore, it is observed that all the developed mixes allow the passage of water in a good way.

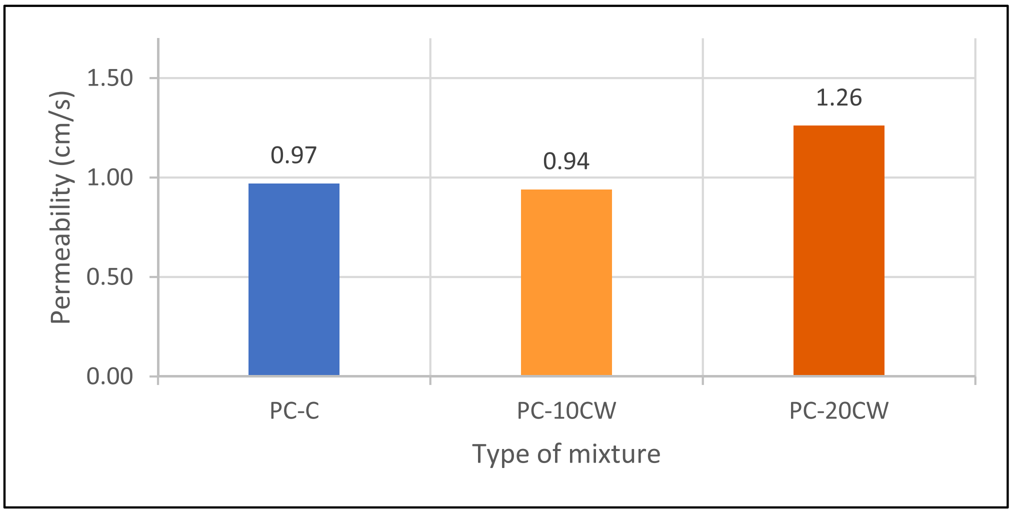

Figure 9 Permeability of ceramic waste mixes.

3.4. PERMEABILITY FOR MIXES WITH GLASS WASTE

The results of permeability for mixtures with glass waste are shown in Figure 10. The standard mixture has a permeability of 0.97 cm/s, being exceeded by PC-10GW by 5% and being decreased by 30% by PC-20GW. The permeability of the mixes with glass are high, considering that the ranges in pervious concrete vary between 0.14 and 1.22 cm/s (ACI, 2010; Tennis et al., 2004). Therefore, it is observed that all the developed mixes allow the passage of water in a good way.

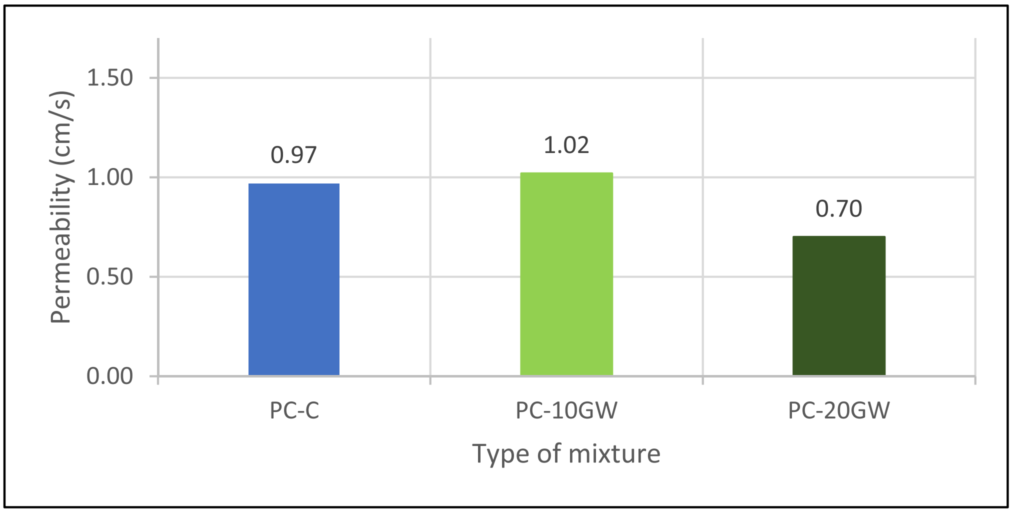

Figure 10 Permeability of glass waste mixes.

4. CONCLUSION

1. From the experimental study carried out on pervious concrete mixes with waste, it was found that the incorporation of ceramic waste as a partial replacement of cement generates a decrease in compressive strength with respect to the standard mix as the replacement percentage increases. However, as the test age increases, the difference is smaller. The permeability of the mixtures with ceramics is high, being close to the upper limit indicated in the literature.
2. The mixtures with waste glass show low compressive strength at 7 days, however, at 28 days, the mixes with glass achieve control mix compressive strength. The permeability of the mixes with glass is adequate, although it suffers a decrease of 30% with respect to the standard mix for a 20% substitution. Based on the above, it is feasible to partially replace cement with glass waste in pervious concrete mixes, either 10% or 20%, since both percentages do not generate negative alterations in the mixes and maintain their mechanical and hydraulic properties in adequate ranges.
3. It was noted that both mixtures with ceramic and glass incorporation show a better development of resistance at late ages. Between 7 and 28 days, the standard mix increased the compressive strength by 29.5%, while the mix with 20% ceramic increased it by 48% and the mix with 20% glass increased it by 64.5%. Therefore it is expected that after 28 days they will continue to increase resistance and reach the standard in the case of ceramic mixtures and surpass it to a greater extent in the case of mixtures with glass.
4. The results obtained do not completely coincide with those achieved by other studies due to several factors. In the case of ceramics, several studies achieved higher compressive strengths than the standard. One of the differences is in the use of Portland cement, which differs from that used in this research, which corresponds to pozzolanic cement, so the amount of waste incorporated is greater. In addition, there are no references to the use of ceramics in pervious concrete mixes, which generates another effect because these mixes are different from a traditional concrete. The case of glass is similar to that of ceramic, although there is research that incorporates glass as a replacement for cement in pervious concretes, the increases in compressive strength were not achieved as expected, because all the research uses Portland cement. However, the compressive strengths obtained in this research exceeded those obtained in the research reviewed.
5. The results obtained are very promising because it could be possible to have a pervious concrete that replaces cement with waste in order to reduce the carbon footprint associated to cement production, reuse waste and promote recycling and generate a material that is environmentally friendly by allowing water to pass through its structure, helping to control the problems of rainwater infiltration and flooding in cities.

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COMPETING INTERESTS

The author has no competing interests to declare.

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