Optimal Constituent Mix Ratio for Improved Fresh Properties of Cementitious and Alkali-Activated Porous Concretes

OPTIMAL CONSTITUENT MIX RATIO FOR IMPROVED FRESH PROPERTIES OF CEMENTITIOUS AND ALKALI-ACTIVATED POROUS CONCRETES

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Abstract

This study focuses on the ideal mix of constituents (aggregate, binder, liquid phase, and admixtures) for porous concrete (PC) with optimal fresh properties to be used in pervious road pavements. Ordinary Portland cement (CEM-I) and alkali-activated blast furnace slag (AA-BFS) were used as binders. This experimental investigation focused on finding the mix-proportion which can best produce a consistent fresh mixture in which the mortar attaches strongly to the coarse aggregates. CEM-I and AA-BFS mortars and concretes were designed to meet the consistency criteria for PC mixtures and then tested to assess their volumetric and mechanical properties. The effect of mix composition on the consistency of fresh mixtures was adjudged through statistical analyses. In the case of AA-BFS mixtures, latex admixture (LA) and a polycarboxylate-ether-based superplasticizer (SP) both helped to achieve a higher level of consistency, while the addition of a viscosity modifying admixture was necessary for CEM-I PC mixtures only. In terms of hardened properties, AA-BFS mortars exhibited slightly higher strengths than CEM-I ones independently of curing time. Although neither LA nor SP increased strength values at the mortar scale, in PC mixtures the use of LA proved fundamental in the production of AA-BFS concrete with adequate strength values. This study recognizes that the optimization method as per the consistency assessment of fresh mixtures can be applied to PC with both cementitious and AA-BFS binders.

Keywords

Porous concrete; geopolymer mortars; alkali-activation; blast furnace slag; mix-design; consistency.

Introduction

The use of porous concrete (PC) in urban pavements is gaining in popularity for a number of reasons. In contrast with ordinary impervious road pavements, PC pavements (i) provide a stormwater runoff retention capacity to counteract flooding (Scholz and Grabowiecki 2007), (ii) reduce peak flows and extend the duration of outflows (Abbott and Comino-Mateos 2003), (iii) facilitate the replenishment of local groundwater sources (Ahiablame et al. 2012), (iv) contrast the heat-islands effect (Ferguson 2005), and (v) reduce traffic noise by adsorbing sound energy through the porous surface (Tian et al. 2014). Furthermore, some studies have demonstrated that PC pavements can reduce the concentration of pollutants in filtering runoff (Legret et al. 1996; Dierkes et al. 1999; Pagotto et al. 2000; Gilbert and Clausen 2006; Bassani et al. 2017). PC consists mainly of coarse aggregates bounded by a cementitious binder which may include admixtures to enhance internal cohesion (Ghafoori and Dutta 1995a; Huang et al. 2010). The voids content, in the 15-35% range, is obtained by adopting an open-graded particle size distribution with little or no sand (American Concrete Institute 2010).

Despite pavements made from PC being considered more sustainable than traditional impervious pavements (Dietz 2007; Fassman and Blackbourn 2010), their use is limited to residential streets, pedestrian paths, bikeways, and parking lots (Field et al. 1982; Ferguson 2005). In fact, due to their pervious nature, PC pavements exhibit lower flexural and compressive strength compared to conventional rigid ones (Joshaghani et al. 2015; Güneyisi et al. 2016). Some authors suggested improving the mechanical properties of PC mixtures by adding functional admixtures and fibers (Chandrappa and Biligiri 2016a; Bhutta et al. 2012; Kim et al. 2016). For instance, latex polymer was regarded as a valid admixture to improve the bond between cement paste and aggregates (Kevern et al. 2005; Wu et al. 2011; Bhutta et al. 2013; Shu et al. 2011).

Furthermore, to make PC more sustainable, attempts to avoid the use of ordinary Portland cement (OPC) were carried out (Jang et al. 2015). Binders obtained from the alkaline activation of industrial by-products are regarded as a promising solution due to their environmental benefits (Komnitsas 2011; Davidovits 2005) and excellent mechanical properties (Wang et al. 1995; Rashad 2013). In fact, a number of studies have proved that both alkali-activated (AA) fly-ash (FA) and blast furnace slag (BFS) can be employed as alternative binders for PC manufacturing (Tho-in et al. 2012; Sata et al. 2013; Jo et al. 2015; Zaetang et al. 2015; Arioz et al. 2020; Sun et al. 2018; Chen et al. 2020; Bassani et al. 2019a).

Problem statement

Over the years, a number of alternative mix-proportioning methods such as ACI-211 (American Concrete Institute 2009) have been proposed for the production of dense OPC concrete for rigid pavement applications (Richardson 2005). The

Shilstone (1990), 8-18 gradation (Burnham et al. 2006), and Strategic Highway Research Program SHRP (Roy et al. 1993) methods were all based on the optimal combination of aggregate sizes needed to guarantee workability of the fresh mixture and adequate mechanical strength values. According to the U.S. National Ready Mixed Concrete Association, increased density and improved performance can be achieved with the aggregate gradation 8-22 mm (Obla et al. 2007a; Obla et al. 2007b). More recently, with the adoption of performance-based specifications for rigid pavements (Hoerner et al. 2000), durability has been introduced as a factor in mixture optimization procedures (Obla et al. 2016a; Obla et al. 2016b; American Concrete Institute 2014)

In the case of PC, the essential aim of the proportioning procedure is to reach an adequate level of porosity for water infiltration, while maintaining a minimum level of mechanical strength (National Ready Mixed Concrete Association 2020). PC mixtures containing OPC are conventionally prepared in the following ranges: 270-415 kg/m^3 of cement, 1190-1480 kg/m^3 of coarse aggregate, a limited amount of or no fine aggregate, 0.27-0.34 water/cement (w/c) mass ratio, and a 4.0-4.5 aggregate-binder mass ratio (a/b) (American Concrete Institute 2010). The main objective in the mix-design is to establish the right amount of fresh binder that can uniformly coat coarse aggregates and ensure that the voids remain interconnected with each other (Chandrappa and Biligiri 2016a; Chindaprasirt et al. 2008; Sonebi et al. 2016). In fact, Chandrappa and Biligiri (2016b) attributed the strength properties of PC to the thin cement coating around the aggregates. Despite maintaining the suggested proportion between constituents, the use of different binder, aggregate, and admixtures may affect the behavior of fresh mixtures, thus leading to a variation in density which, in turn, may result in inadequate hardened properties (Pereira da Costa et al. 2021). For these reasons, the properties of fresh PC mixtures must be investigated. Some studies pointed out that the conventional slump test does not provide adequate information in this regard. (Kevern et al. 2011; Ghafoori and Dutta 1995b; Kevern et al. 2009; Obla 2010; Chopra et al. 2007). Tennis et al. (2004) suggested that the optimal constituent mix ratio is achieved when the fresh cement paste fully covers the aggregate but does not flow away. This condition can be visually assessed during the mixing stage by taking a small amount of fresh paste mixture in your hand and confirming that it does not crumble, lose voids between grains and/or stick to your hand when you tighten your grip around the paste. If the fresh mixture is too wet and easy to compact, the voids are filled with cement paste compromising its porous nature. Vice versa, when the fresh mixture is too dry and not workable, the cementitious paste will not bond sufficiently well with the coarse particles and the hardened PC will be weak and fragile.

The mixture optimization procedure of Tennis et al. (2004) was intended to provide an empirical and practical approach to PC mix-design. It requires a “trial and error” learning procedure that may require a significant number of tests before arriving at the best solution, especially when several variables have to be managed. As a result, statistical

support is necessary to univocally understand the effect of each variable (constituents and related mix proportions) on the properties of fresh PC mixtures.

Furthermore, the mix-design approach proposed by Tennis et al. (2004) was tested for PC made up with OPC only, while no specific indications are available for investigating the consistency of fresh PC mixtures containing AA binders. In this case, the greater viscosity (with respect to water) of the alkaline liquid in the mixture can affect the fresh properties (Bassani et al. 2019b). Differences in the characteristics of fresh mixtures can also be attributed to the AA reactions which differ from the hydration processes of cement (Thomas et al. 2016). The primary C-S-H gel in AA materials which forms immediately when activated with waterglass tends to quickly harden the paste, thus leading to a loss of workability (Puertas et al. 2018). A further source of uncertainty in the fresh behavior of AA materials is due to the nature of the alkaline activator which strongly affects the rheology of fresh products (Alonso et al. 2017; Pacheco-Torgal et al. 2011; Palacios et al. 2019). Furthermore, admixtures used with OPC may behave differently with AA materials, thus compromising the fresh behavior of PC mixtures (Nematollahi and Sanjayan 2014; Palacios and Puertas 2004). In light of these differences, it would be useful to extend the use of the consistency assessment of Tennis et al. (2004) to the optimization of PC made with AA binders.

Study objective

This experimental study investigates the optimization of PC mixtures with both traditional and alkali-activated binders through the consistency assessment proposed by Tennis et al. (2004). To meet this objective, OPC classified as CEM-I 32.5R and alkali-activated ground granulated BFS were employed to produce PC mixtures for consistency assessment and mechanical tests. The consistency assessment sought to determine the optimal constituent mix proportion for a fresh mixture of stable consistency in which the mortar surrounds and covers the coarser aggregates without flowing through the pores. The effects of several mix variables (i.e., mass ratios of liquid phase to binder, coarse aggregate to binder, sand to coarse aggregate) were evaluated through the regression and ANOVA analyses. The addition of latex, viscosity modifier, and superplasticizer admixtures to the PC mixtures was also evaluated.

According to the optimal constituent mix ratio, specimens of mortars were prepared at room temperature, cured for 2, 7, and 28 days, and tested to evaluate the effects of both superplasticizer and latex admixtures on their compressive strength properties. In the meantime, prismatic and cylindrical specimens of PC mixtures were prepared and subjected to flexural and compression tests at the same curing times.

Materials and Methods

Materials

Binders

Dry samples of cement type I (CEM-I 32.5 R) according to EN-197 (European Committee for Standardization 2011) and BFS powders were subjected to X-ray fluorescence (XRF) analysis to determine their elemental composition, as reported in Table 1. XRF analysis shows that, as expected, CEM-I is predominantly composed of calcium oxide (67.6%) together with lower amounts of Al_2O_3 and SiO_2. The main constituents of BFS are CaO (38.9%), SiO_2 (31.0%) and Al_2O_3 (9.2%) together with small percentages of magnesium oxide, which were not detected in CEM-I. Fig. 1-a exhibits the particle size distribution of cement and BFS raw powders; it shows that CEM-I has a slightly higher percentage of finer particles than BFS.

The AA of BFS was obtained by adding an alkaline solution (AS) to the dry powder. It acts as both a chemical activator and liquid phase for providing workability to PCs. The AS, 80wt.% of sodium silicate (Na_2SiO_3) and 20wt.% of sodium hydroxide (NaOH), was prepared in two stages. First, the NaOH, in the form of solid flakes, was dissolved in distilled water to form an aqueous solution at 50% concentration (25 M), then liquid Na_2SiO_3, characterized by a SiO_2/Na_2O mass ratio of 3.4 (i.e., SiO_2 = 28.1%, Na_2O = 8.4%, H_2O = 63.5%) and a pH value of 11.6, was added. The AS was magnetically stirred and left to cool down to room temperature before use.

Aggregate

A calcareous natural aggregate (crushed limestone) in the 4-16 mm size fraction was used as a coarse aggregate in PC production, while natural river sand passing at a 2 mm sieve was employed as fine aggregate in the preparation of mortars and PCs. Fig. 1-b illustrates the particle size distribution of sand and coarse aggregates used in the investigation according to EN 933-1 (European Committee for Standardization 2012). Referring to EN 1097-6 (European Committee for Standardization 2013) and EN 1097-2 (European Committee for Standardization 2010), a particle density of 2773 kg/m^3, water absorption of 0.9% and a Los Angeles index of 26% were recorded for the coarse aggregate.

Admixtures

A latex admixture (LA) based on the dispersion of a synthetic styrene-butadiene elastomer in water was added during the preparation of mortars and PCs to enhance the adhesion between aggregates and binders and to improve the consistency of the fresh mixtures. The LA, with the appearance of a white liquid, has a density of 1.02 g/cm^3, a pH of 8, and a dry solid content of 36%. A viscosity modifying admixture (VMA) was added during the mixing of PC containing CEM-I to avoid segregation and bleeding phenomena in the fresh mixture (Aïtcin and Flatt 2016; Bhutta et al. 2012). It is in the

form of a whitish powder and has a density of 0.6 g/cm^3. To improve the workability of fresh mixtures, a polycarboxylate-ether-based superplasticizer (SP) was added to all the mortars and PCs, apart from mortars containing CEM-I.

Trial proportions of constituents

The mix ratio for the PC constituent materials (binder, coarse aggregates, sand, liquid phase, and admixtures) satisfied the consistency requirements for fresh mixtures suggested by Tennis et al. (2004).

Fig. 2 illustrates four fresh PC mixtures with different levels of consistency that have been classified here as (a) "poor", (b) "nearly good", (c) "good", or (d) "excellent". With the "poor" consistency the binding mortar adheres to the aggregate particles but does not have sufficient plasticity to remain cohesive and to hold the particles together. Fig. 2-a shows that part of the mortar remains on the glove after the mixture is tightened by hand. Moreover, the paste assumes a dull aspect due to the scarcity of binder in the fresh mixture (Ferguson 2005). With the "nearly good" consistency, the mortars are more plastic and better able, albeit partially, to stick to the particles; however, part of the mortar is still left on the gloves. In this condition, the mortar is too liquid and drains through the pores between aggregates. Frequently, this happens for an excessive quantity of free liquid phase, as depicted in Fig. 2-b. The "good" consistency is when the full mixture achieves a plastic state, with the mortar attaching itself to the coarse aggregate despite not appearing fluid-like. However, as depicted in Fig. 2-c, part of the mortar still remains on the glove. Finally, the "excellent" consistency occurs when the mortar fully binds to the coarse grains and maintains the shape formed after the hand tightening action; furthermore, the mortar does not wet the glove as clearly depicted in Fig. 2-d. Field experiences indicate that the best consistency is when the mixture achieves "a shiny film giving a metallic gleam" (Ferguson 2005).

In this study, the first attempts at defining mix proportions were based on literature (Huang et al. 2010; Arhin and Madhi 2014; Chandrappa and Biligiri 2016b) with consideration given to six different factors when evaluating the consistency of fresh PC mixtures: the liquid phase to binder (l/b, i.e. water for CEM-I and AS for BFS), the coarse aggregate to binder (a/b), the sand to coarse aggregate (s/a), the LA to binder (LA/b), the VMA to binder (VMA/b), and the SP to binder (SP/b) mass ratios. Several mixtures with consistency levels ranging from "poor" to "excellent" were prepared and tested according to the procedure presented here. The attempts were based on decisions made following a "trial and error" learning mode, i.e., based on evidence of the consistency evolution after a specific parameter variation. The mix ratios of constituent materials were determined at relatively wide intervals to cover the range of possible values from literature.

To assess the impact of the mix-design factors (l/b, a/b, s/a, LA/b, VMA/b, and SP/b ratio) on the mixture consistency, a multiple linear regression analysis coupled with an analysis of variance (ANOVA) was carried out. Before

starting this analysis, visual judgements on the consistency of trial mixtures were firstly converted into a numeric scale (from 1 = poor, to 4 = excellent), and then associated with the experimental variables.

Specimen preparation and testing

Mortars

Mortars were prepared with a binder (CEM-I and BFS), the liquid phase (water or AS), sand, and finally the admixtures. Prismatic mortar specimens of 80×20×20 mm were prepared by placing the constituent materials into a mechanical mixer according to the procedure reported in EN 196-1 (European Committee for Standardization 2016). In line with sustainable road construction procedures, no thermal treatments were considered in the laboratory study. Krizan and Zivanovic (2002) testified to high strength development with AA-BFS mortars cured at 20°C and relative humidity (RH) equal to 90%.

Fresh mixtures were then cast into prismatic molds which had been treated beforehand with a form release agent to facilitate demolding operations. After casting, molds were placed on the jolting apparatus and subjected to 60 blows to remove residual air from the mixtures. After 24 hours of curing at room temperature (25 °C) and RH of 90%, the specimens were demolded and subjected to further curing until the testing stage. CEM-I mortar samples were cured in water at room temperature, while AA-BFS mixtures remained in a humidity chamber at room temperature and RH = 90%. Maximum compressive ($\sigma_{c,max}$) stress values were assessed in accordance with EN 196-1 (European Committee for Standardization 2016) after 2, 7, and 28 days. Since flexural data displayed the same trend as that observed with compressive data, only the latter are presented and analyzed from this point. Before starting with the test, the mass and size dimensions (length, height, and thickness) of all specimens were measured to calculate the density (γ_{mortar}) at testing time.

Porous concretes

The PCs were mixed in a concrete mixer for 2 minutes and cast into cylindrical and prismatic molds depending on the testing configuration. Cylindrical specimens of 200 mm in height and 100 mm in diameter were arranged in four layers for compression tests, with each specimen subjected to 20 blows of a steel rod (Fig. 3-a) to ensure compaction. The top layer was also levelled by a 5 kg steel cylinder to create a smoothened surface and ensure uniform contact with the loading plate of the testing machine. The flexural strength values (of the PCs) were measured on 100×100×500 mm prismatic specimens assorted into 4 layers and compacted with 50 blows of a steel rod uniformly distributed over the surface (Fig. 3-b). The fourth layer was also levelled superficially by using the 5 kg steel cylinder.

After 24 hours of curing at room temperature in a humidity-controlled environment (RH = 90%) both cylindrical and prismatic specimens were demolded and the curing stage continued for the duration of the testing time selected (2, 7,

and 28 days). Compression tests were performed using a 500-kN testing machine which applied a constant displacement of 0.50 mm/min and a preload of 500 N to the cylindrical specimens. The flexural strength was measured in the 4-point configuration (bottom span equal to 300 mm and top span equal to 150 mm) by applying a constant strain rate of 0.25 mm/min with the 50-kN electro-pneumatic testing machine.

Analogously to mortars, both the mass and size of specimens were recorded before testing to define the density as the ratio between the mass and the volume ($\gamma_{g,p}$ for prismatic and $\gamma_{g,c}$ for cylindrical specimens). The porosity (v) of PC was then calculated as follows:

$$v_{g,p\ (or\ c)} = \left(1 - \frac{\gamma_{g,p\ (or\ c)}}{\gamma_{max}}\right) \cdot 100 \qquad (1)$$

where γ_{max} is the maximum density obtained with the pycnometer method according to EN 1097-6 (European Committee for Standardization 2013) on samples collected during the mixing stage, all of which were adequately crumbled and cured before testing. The γ_{max} of PC with AA-BFS and CEM-I was found to be equal to 2850 and 2890 kg/m^3 respectively.

In addition, the bulk density of cylindrical specimens $\gamma_{b,c}$ (cured 7 and 28 days) were determined using the automatic sealing method indicated in ASTM D6752 (ASTM International 2011). The mass values of the specimens were initially determined, then the specimens were placed in a plastic bag and the air was removed utilizing an automatic vacuum chamber, in which the bag was also sealed at the end of the process (Fig. 4). The mass of the plastic bag with the specimen inside was determined underwater, and $\gamma_{b,c}$ was calculated as per the eq. 2:

$$\gamma_{b,c} = \left(\frac{m_1}{\frac{m_{bag} - m_1 - m_2}{\gamma_w} - \frac{m_{bag}}{\gamma_{bag}}} \right) \qquad (2)$$

where m_1 is the mass of the specimen in air, m_2 is the mass of the sealed specimen underwater (it also includes the mass of the bag), m_{bag} is the mass of the plastic bag used for sealing the specimens, γ_{bag} is the density of the plastic and γ_w is the water density at the testing temperature. Similarly to eq. 1, the void content ($v_{r,c}$) was determined by taking both $\gamma_{b,c}$ and γ_{max} into account.

Results and analysis

Best constituent mix proportion

Table 2 and Table 3 include the results of the several attempts at PC mix proportioning carried out for CEM-I or AA-BFS binder, respectively. The mixtures in the two tables were coded with the letters A and B (A being with LA and B without), and with a progressive number to identify the attempt number.

The two tables list the numerical values of the constituent mix ratios and the corresponding visual judgement of the consistency obtained. It is worth noting that for both CEM-I and AA-BFS mixtures, small modifications of the constituent material mix ratio parameters (l/b, a/b, s/a, LA/b, VMA/b, and SP/b) resulted in significant variations in the consistency of mixtures. The effects of each mix factor were evaluated as per the regression and ANOVA analyses presented in the next section.

Effects of constituent mix ratio on fresh concrete consistency

Table 4 shows the Person's r correlation (with p-values) matrix between the mass proportions of constituents reported in Table 2 and Table 3; the upper figurative triangle of the matrix refers to CEM-I, while the lower triangle refers to AA-BFS mixtures. The correlations between the independent factors (i.e., mass proportions of constituents) and the mixture consistency values are reported in the part of the table with a grey background. The factors with the greatest influence on mixture consistency were l/b for AA-BFS and VMA/b for CEM-I. It is worth noting that VMA is correlated to consistency in the case of CEM-I mixtures ($r = 0.460$, p-value = 0.041), while it is not correlated to the consistency of AA-BFS ones ($r = -0.260$, p-value = 0.156). The latter is explained by the fact that the AS is more viscous than water, thus the contribution of small quantities of VMA proves negligible in comparison to that of the liquid content in the mixture (l/b: $r = 0.428$, p-value = 0.015). Although the mix ratio of constituents was varied randomly, the matrix revealed both positive and negative correlations between independent factors. Some of these correlations, i.e., VMA/b and SP/b vs. a/b for AA-BFS mixtures, and SP/b vs. VMA/b for both mixtures, even proved to be highly significant.

The analysis of variance (ANOVA) and the regression analysis reported in Table 5 and Table 6 respectively were carried out by converting the mixture consistency into numerical values as follows: 1 = poor, 2 = nearly good, 3 = good, and 4 = excellent. They reveal which factor have a significant effect on the mixture consistency. However, because of the significant correlations between constituent mix ratios highlighted by the correlation matrix, the condition of multicollinearity in the models was also evaluated.

In the case of CEM-I mixtures, as already highlighted in the correlation matrix (Table 4), only VMA/b was found to be significant, and no other constituent mix ratio had a similarly evident effect on the mixture consistency. Conversely, in the case of AA-BFS mixtures, the liquid-to-binder (l/b) and the three admixture proportions (LA/b, VMA/b, and SP/b)

all resulted significant. However, the ANOVA (Table 5) indicated that the addition of LA was not-very significant (F_1 = 6.5, p-value = 0.093). Regression coefficients (Table 6) suggested that an increase in the content of AS, LA and SP tends to improve the mixture consistency, while the higher the VMA the poorer the consistency judgment. This fact is well evidenced by the average marginal effect diagrams (related to the significant constituent mix ratio factors) of Fig. 5. As a result, the addition of VMA contrasted the effects of other factors on mixture consistency, so it was excluded from the AA-BFS in the subsequent steps of this research. The diagrams also indicate that the SP contributed to an increase in the consistency level of those mixtures lacking in liquid constituents.

Finally, multicollinearity between independent factors was checked as per the variance inflation factor (VIF). Results in Table 5 indicate that the VIF values were significantly lower than 10, and always lower than 2.5 (O'brien 2007), so multicollinearity was not considered to be problematic in the regression models.

Constituent mix proportions for mechanical assessment of mortars and mixtures

The constituent mix ratios for CEM-I and AA-BFS mortars and mixtures to be evaluated through mechanical tests were defined in accordance with the previous statistical analysis based on the results listed in Table 2 and Table 3.

Despite the addition of SP to cement mixtures having no apparent impact on the mixture consistency, several studies demonstrated that SP admixture improves the fresh and hardened properties of PCs (Bhutta et al. 2012; Yang and Jiang 2003; Lian and Zhuge 2010; Avinash et al. 2018; Muthaiyan and Thirumalai 2017). For this reason, a small quantity of PCE-SP was included in all PC mixtures.

Table 7 summarizes the constituent mix ratios adopted in the preparation of mortars and PCs. For the sake of clarity, mortars and PC mixtures were coded as indicated in the caption of Table 7. PC mixtures made up with AA-BFS required a greater amount of liquid phase to achieve the desired consistency due to the higher viscosity of the AS with respect to water. The optimal amount of LA for consistency purposes was equal to 7.0% of the binder mass, while the amount of SP was set equal to 1.0% of the binder mass.

At the mortar scale, six different sets of specimens, derived from combinations of the two binders (CEM-I, AA-BFS), the addition of LA, and the presence of SP (only in the case of AA-BFS), were prepared. A total of 90 specimens were prepared and tested (6 mortars × 5 replicates × 3 curing times). As for concretes, four different mixtures were designed by combining binders and admixtures. Considering two testing configurations, two replicates per test, and three different curing times, a total of 48 PC samples were prepared.

Hardened properties of mortars

Density of hardened specimens

The average density values determined for several mortar samples are shown in Fig. 6. Results suggest that AA-BFS mortars exhibit similar densities to CEM-I ones notwithstanding the significant differences in l/b (liquid to binder) ratios. The addition of SP or LA to AA-BFS mortars led to a similar reduction in the density of mixtures. The change in density due to the LA addition was found to be always significant (all p-values < 0.001) independently of the mortar type (AA-BFS, CEM-I). This behavior is consistent with that reported by Barluenga and Hernández-Olivares (2004), who attributed the reduction in mixture density to the lower density of LA with respect to other constituents. The coefficient of variation (i.e., the ratio between the average value and the standard deviation) of each mortar was between 0.7 and 2.1%, thus confirming the good reproducibility of the method adopted for sample preparation.

Compressive strength

The results in Fig. 7 show that the compressive strength values of mortars increased in line with curing time independently of the binder and LA. These results are in line with Krizan and Zivanovic (2002), whose AA-BFS mortars reached compressive strengths ranging from 65.0 to 80.0 MPa depending on the concentration of the AS after 28 days of curing at room temperature.

A remarkable increase in compressive strength when passing from 2 to 28 days of curing was observed in mixtures made up of AA-BFS without LA, with an increment of 85% and 51% for specimens with and without SP respectively. In contrast, mortars containing CEM-I showed a more limited increase in $\sigma_{c,max}$ from 2 to 28 days of curing than AA-BFS: +27% and +28% for MO-CEM and MO-CEM-LA mortars respectively. The addition of LA to both AA-BFS and CEM-I mortars caused a general lowering of compressive strengths independently of curing time. Considering the 7-day cured specimens of AA-BFS, the average value of $\sigma_{c,max}$ for the MO-BFS specimens was equal to 67.4 MPa, while $\sigma_{c,max}$ = 57.6 MPa was observed in the case of MO-BFS-LA. Mortars made up of CEM-I without LA exhibited compressive strength values which were on average 37% higher than those with LA for all the investigated curing periods.

The addition of the SP did not result in any significant strength development of AA-BFS mortars, apart from the 28-day cured mixture MO-BFS-SP (without LA), which reached a compressive strength of 91.5 MPa. This value is also the highest recorded in this experiment (the corresponding mortar MO-BFS exhibited a $\sigma_{c,max}$ = 78.4 MPa).

AA-BFS mortars always displayed higher compressive strengths than CEM-I ones, demonstrating their potential as efficient binders for PCs with higher strength requirements. At the shortest curing time (2 days), MO-BFS-LA mixtures achieved 51.9 MPa, while for MO-CEM-LA specimens an average compressive strength of 44.5 MPa was recorded. Greater variations were observed for longer curing times: at the 7th day of curing, MO-BFS-LA mortars displayed an

average value of $\sigma_{c,max}$ equal to 57.6 MPa, while mortars with CEM-I (MO-CEM-LA) did not exceed 37.0 MPa; in the case of 28-day cured mortars, the average compressive strength recorded for MO-BFS-LA specimens was 71% higher than that obtained for MO-CEM-LA ones. These results are consistent with the experimental investigation carried out by Krizan and Zivanovic (2002), who confirmed that mortars containing AA-BFS (activated with sodium silicate only in a l/b ratio of 0.43) perform better than reference mortars containing OPC.

Hardened properties of porous concretes

Density and porosity

Table 8 lists the volumetric properties of prismatic and cylindrical PC samples. Both samples exhibited similar geometric density and related porosity values, thus confirming that their compaction led to similar internal void content values. As expected, the "real" void contents ($v_{r,c}$) of cylindrical specimens are lower than the corresponding geometric ones ($v_{g,c}$). This is due to the lower volume of specimens wrapped and vacuum sealed in plastic (in accordance with the ASTM D6792 sealing method - (ASTM International 2011) with respect to the geometric volume of the ideal cylindrical mold which surrounds the specimen. In fact, the volume defined as per the ASTM D6792 sealing method (ASTM International 2011) is reduced since the voids between the specimen and the ideal mold wall are not taken into account. The differences between $v_{g,c}$ and $v_{r,c}$ are around 2% and can be explained by the presence of surface irregularities with respect to the reference cylindrical volume.

In contrast to that observed at the mortar scale, the addition of LA to concrete mixtures caused only a slightly significant statistical increase in the density of CEM-I cylindrical (p-value = 0.018) and prismatic (p-value = 0.045) specimens. LA improves workability (Lewis and Lewis 1991) and reduces the flow resistance of the fresh mixture (Sun et al. 2019) at the mixing stage. This explains the reduction in volume of the voids between particles as evidenced by the small decrease in porosity values. While this effect was statistically significant in CEM-I samples as confirmed in literature (Huang et al. 2010; Shu et al. 2011; Aliabdo et al. 2018), it was not so in AA-BFS samples (all p-values > 0.05).

Mechanical strengths

Fig. 8-a and Fig. 8-b exhibit the results of flexural and compressive tests on PCs at different curing times. As expected, mechanical proprieties were enhanced with curing time. The value of $\sigma_{f,max}$ significantly increased passing from 2 to 28 days of curing in PC-BFS-LA-SP (+130%) and PC-CEM-SP mixtures (+139%), while this increment was limited to +51% and +56% in PC-BFS-SP and PC-CEM-LA-SP respectively.

The addition of LA caused a lowering of $\sigma_{f,max}$ in AA-BFS PCs at early stages, while LA produced a substantial increment in flexural strength after 28 days of curing. After 7 days, the average value of $\sigma_{f,max}$ was 1.9 and 1.3 MPa for

PC-BFS-SP and PC-BFS-LA-SP mixtures respectively, while after 28 days AA-BFS mixtures with LA reached 2.7 MPa in comparison to the 2.0 MPa value for mixtures without LA. Conversely, the $\sigma_{f,max}$ of CEM-I specimens was positively affected by the addition of LA for short curing times, albeit the effects after 28 days (of curing) were negligible.

In terms of compressive strength results (Fig. 8-b), the addition of LA led to a higher compressive strength value in both cases of AA-BFS and CEM-I PCs at the shortest curing age (2 days). Specifically, the $\sigma_{c,max}$ of specimens with AA-BFS increased from 5.2 to 7.1 MPa following the addition of LA , while for PCs with CEM-I, the addition of LA resulted in a strength gain of 60%. For longer curing times (7 and 28 days), the effect of LA was negligible in the case of concretes with CEM-I, while a significant improvement of 14% in strength was obtained in mixtures containing AA-BFS.

In the case of PCs made up with AA-BFS, it is worth noting that the mixtures experienced a significant increase in the $\sigma_{c,max}$ value when passing from 2 to 7 days of curing, while any further enhancements were negligible after 28 days. Independently of curing time and LA addition, PCs containing AA-BFS always exhibited higher compressive strengths than the corresponding mixtures with CEM-I. At 28 days, both CEM-I mixtures (PC-CEM-SP and PC-CEM-LA-SP) exhibited a compressive strength of 8.6 MPa, while AA-BFS samples achieved values of $\sigma_{c,max}$ equal to 11.6 and 12.3 MPa without and with LA respectively. It suggests that the AA-BFS binder provided greater compressive strength to the PC than CEM-I, confirming the potential of this material as a substitute for traditional OPC in pervious pavement applications.

In contrast, the benefits of AA-BFS with respect to CEM-I are less evident for flexural strength: in this case, it is not possible to identify a clear trend. Considering PCs without LA, PCs with AA-BFS showed higher $\sigma_{f,max}$ values than those with CEM-I at short curing times (2 and 7 days). Conversely, 28-day cured PC-CEM-SP mixtures displayed greater $\sigma_{f,max}$ (2.4 MPa) values than PC-BFS-SP (2.0 MPa). In PCs with LA, the benefits of using AA-BFS in place of CEM-I are only evident in specimens cured for 28 days. In this case, the flexural strength of the PC-BFS-LA-SP mixture is around 10% higher than the corresponding mixture containing cement (PC-CEM-LA-SP).

Discussion

Mortars

Effects of latex

The lower strength of mortars containing LA is ascribable to their lower density (Fig. 6). Wang and Wang (2010) stated that the density of a CEM-II 52.5 R mortar is reduced with an increase in the LA content, leading to a general decrease in strength. Mortars containing CEM-II 52.5 R were also investigated by Zhong and Chen (2002), who noticed a systematic reduction in compressive strengths in specimens containing LA compared to reference ones, independently of the type of LA added. Sumathy et al. (1997) observed a significant reduction (19%) in $\sigma_{c,max}$ in mortars with 10% of LA

with respect to a reference mortar. They attributed this effect to the low probability of the polymer permeating the matrix at a high concentration of binder. More recently, Ukrainczyk and Rogina (2013) pointed out that the compressive strength of mortars containing calcium aluminate cement decreased when the LA content was increased from 0% to 9% in the mixture. Lee et al. (2016) observed no benefits in terms of strength improvement when LA is added to geopolymer mortars containing FA and BFS, since the polymer decreased the pH of fresh mixtures and lowered the alkali-activation potential of raw powders.

Effects of PCE superplasticizer

At the mortar scale, SP was only added to mixtures containing AA-BFS, to evaluate its effect on hardened mortars. According to the results in Fig. 6, the addition of SP caused a reduction in the sample density independently of the presence of LA. Therefore, the mechanical strengths of mortars containing SP were always lower than those of the corresponding mixtures without SP, at least at an early stage of curing (2 and 7 days). It is reasonable to suppose that the PCE superplasticizer retarded the alkali-activation reactions leading to lower strength development.

Despite some studies supporting the benefits of adding SP to cementitious mortars (Tkaczewska 2014; Silva et al. 2019; Li and Kwan 2015; Huang et al. 2016), it is worth mentioning that its behavior in AA binders is usually different with respect to OPC, due to alkaline conditions and to interactions between this admixture and the AS (Palacios et al. 2009). Palacios and Puertas (2005) attributed the negligible role of polycarboxylate SP in AA-BFS mortars to carboxylate-group chains which tended to be adsorbed from BFS particles. Moreover, the author stated that lateral ether-based chains tend to break away, nullifying the steric hindrance effect that ether chains usually have on particles of OPC. Nematollahi and Sanjayan (2014) found that the addition of an SP to FA activated with NaOH and Na_2SiO_3 produced an increase in the workability (+42%) of fresh mixtures but a decrease in the strength (-29%) of hardened products in comparison to a FA-based geopolymer without SP. Similar behaviors were observed by Bakharev et al. (2000), who confirmed that the addition of an SP to AA-BFS concrete improved and prolonged workability, but led to a retardation in strength development.

Porous concretes

Effects of latex

The addition of LA provided benefits in terms of density increment and strength gain, especially in the case of the compressive strengths of PC with AA-BFS. Considering the results for the average density and void contents in Table 8, the inclusion of LA guaranteed an increase in density and a reduction in the void volume in the mixtures. As evidenced in the mix-design stage, the addition of LA favored the consistency of fresh mixtures and led to a denser structure with a

low quantity of voids. These results are in line with previous studies, which unequivocally indicated an increase in density and a reduction in the porosity of PCs when LA is included (Shu et al. 2011; Aliabdo et al. 2018).

In terms of strength development (Fig. 8), the addition of LA boosted the $\sigma_{f,max}$ and $\sigma_{c,max}$ values of PCs containing CEM-I at very early stages of curing (2 days) only. For longer curing times (7 and 28 days), no benefits were noticed in PCs with CEM-I following the addition of LA. This is in partial contrast with other studies, which generally announced higher strength values in PCs with LA with respect to those without (Huang et al. 2010; Shu et al. 2011; Cheng et al. 2011; Kevern et al. 2011). Accordingly, two factors could explain the poor contribution of LA in PCs with CEM-I in comparison to literature: (i) the limited lowering of the liquid-to-binder ratio (l/b) from 0.35 to 0.32 and (ii) the low reduction in void content values in PCs with LA. According to literature, the addition of LA to PC mixtures contributes to a reduction in both l/b and void contents, factors which contribute to the significant increase in strength in mixtures with LA (Huang et al. 2010; Shu et al. 2011; Cheng et al. 2011; Kevern et al. 2011). Wang et al. (2006) attributed the increase in tensile strength recorded in PCs containing LA to the reduction in the 1/b ratio from 0.27 to 0.22.

In the case of PCs containing AA-BFS, the contribution of LA was always positive apart from the reduction in flexural strength at 2 and 7 curing days. The compressive strength of PC-BFS-LA-SP (with LA) was higher than PC-BFS-SP specimens (without LA) independently of the curing time. The addition of LA to AA-BFS PCs improved the adhesion between coarse aggregates and binder (Sprinkel 1993; Shaker et al. 1997; Beeldens et al. 1997), and increased the strength of contact areas between particles (Wu et al. 2011), thus leading to an overall improvement in final strength values. Concretes made up of AA-BFS and LA achieved flexural and compressive strengths which were 32% and 13% greater than the corresponding values obtained for mixtures without LA.

Strength

Table 9 lists the flexural test results after 28 days of curing available in literature for porous concretes with a similar void content (27÷31%) to the mixtures examined in this investigation. The results of this investigation are generally higher than in previous investigations (Joshaghani et al. 2015; Ibrahim et al. 2014; Cheng et al. 2011), especially in the case of CEM-I and AA-BFS mixtures with LA. Considering an average $\sigma_{f,max}$ value of 1.8 MPa from literature, PC-CEM-SP and PC-CEM-LA-SP mixtures exhibited flexural strength values which were 33% and 38% higher respectively. The superior flexural strength with respect to literature is also evident in the PC-BFS-LA-SP mixture, which reached 2.7 MPa. In this case, the combination of the AA-BFS with the added LA boosted the $\sigma_{f,max}$ of the PC by 50% when compared with other works (Joshaghani et al. 2015; Ibrahim et al. 2014; Cheng et al. 2011). The superior results obtained in this study with respect to those listed in Table 9 may be attributed to the differences in mixture composition and between the properties of constituent materials. For instance, Joshaghani et al. (2015) did not include LA and sands in investigated mixtures.

Moreover, the coarse aggregate used had a lower particle density (2670 kg/m^3) than that of the coarse aggregate employed in this investigation (2773 kg/m^3). Similarly, Ibrahim et al. (2014) did not use latex or sands, and the mixture density of their PC was significantly lower than the corresponding density of the mixture prepared in this study. In the case of Cheng et al. (2011), the lower flexural strength is attributed to the absence of sand and latex (Bu et al. 2017).

These results have a positive outcome from a practical point of view since flexural strength is a primary design input of rigid pavements and strongly affects their durability (Croney and Croney 1997; Lane 1998; Trost 2004). The use of AA-BFS for PC manufacturing could serve to extend the applications of this "green" technology to more trafficked roads. However, in this experimental study, the void content of PC specimens was always greater that 30%, with even higher flexural strength values achievable by reducing the void content.

A comparative analysis of the compressive strength results (Fig. 8-b) can be carried out by referring to the literature data (at 28-days of curing) summarized in Table 10. It is worth mentioning that Table 10 contains available results related to PC with comparable void content values, and the same aggregate and binder type as used in this investigation. It is known that PC with superior strengths have been developed (Yang and Jiang 2003; Zhong and Wille 2015; Bhutta et al. 2012; Güneyisi et al. 2016) but differences in mix constituents (binder, aggregate, admixtures) and volumetric properties (i.e., void content) were regarded as excessive for a proper and fair comparison. It is well-recognized that the void content of PC strongly affects their mechanical strengths (Aoki et al. 2012; Liu et al. 2018; Lian et al. 2011; Li et al. 2019).

The compressive strengths of PC containing CEM-I are higher than those obtained by Joshaghani et al. (2015), Ibrahim et al. (2014), and Cheng et al. (2011), but slightly lower than those in other studies (Lian et al. 2011; Park et al. 2005; Wu et al. 2011). This deficit in strength can be ascribed to the generally higher void contents of CEM-I PCs in this investigation ($v_{g,c}$ = 30.6% with LA, $v_{g,c}$ = 32.7% without LA) in comparison to values in literature (void content in the range 26÷29%).

The PC mixtures with AA-BFS used in this investigation exhibited compressive strength values comparable to the best results obtained in literature for PCs with CEM-I and the same void content (Lian et al. 2011; Park et al. 2005; Wu et al. 2011). Compressive strength results of AA-BFS PC recorded are in line with similar PC mixtures investigated by (Sun et al. (2018) and (Chen et al. (2020). The absence of LA led to a slightly lower compressive strength value ($\sigma_{c,max}$ = 10.8 MPa) with respect to literature (Sun et al. 2018; Chen et al. 2020).

Conclusions

This experimental investigation aimed at optimizing the fresh properties of porous concrete (PC) by using CEM-I and alkali-activated blast furnace slag (AA-BFS) as binders. The best constituent (binder, aggregates, liquid phase, and admixtures) mix ratios were determined by a trial-and-error process as suggested by Tennis et al. (2004).

A first set of conclusions relating to the effects of mix variables on the fresh properties of PC mixtures is as follows:

- the optimum constituent mix ratio for CEM-I mixtures was in line with recommendations from previous investigations documented in literature;
- due to the higher viscosity of the AS with respect to water, PCs with AA-BFS required a greater amount of liquid phase (alkaline solution, AS) to achieve the desired mixture consistency (AS equal to 46% of the mass of the BFS);
- mixtures with AA-BFS did not necessitate a viscosity modifier admixture (VMA) to achieve optimal adhesion between the mortar and the coarser aggregate; the AS used as a liquid in the activation of BFS is sufficiently viscous and is able to form a plastic mortar;
- for AA-BFS PC mixtures, the addition of latex admixture (LA) results in a l/b mass proportion reduction of 32%;
- a 1% mass of superplasticizer (SP) with respect to the BFS (binder) helps the mortar to achieve a higher consistency level without resorting to an excessive l/b mass ratio, thus reducing the amount of AS;
- a 5% mass of sand with respect to the coarse aggregate fraction helps the binding paste to reach the optimum consistency.

The statistical analysis carried out to evaluate the effects of mix-design variables on the consistency of fresh mixtures revealed that the fresh properties of CEM-I mixtures are affected by the quantity of VMA added rather than other mix constituents. The higher the VMA/b, the higher the mixture consistency. Despite the addition of SP producing a slight reduction in the consistency level, a small amount of it was used to improve the hardened properties of CEM-I PC mixtures as suggested by literature.

In AA-BFS PC mixtures, the statistical analysis evidenced that VMA, SP and LA have a significant effect on the properties of fresh mixtures, and that their addition should be carefully balanced to reach the desired consistency. In particular, the fresh consistency level decreases with an addition of VMA, while it increases when LA and SP are added. However, a balanced proportion of the liquid phase with SP and LA is sufficient to achieve the desired porous mixture consistency.

The key findings of hardened products (mortars and porous concretes) are as follows:

- mortars made up with AA-BFS exhibited higher strength values than those containing CEM-I, especially after longer curing times; AA-BFS mortars always exhibit average compressive strengths greater than 70.0 MPa after 28 curing days;
- in line with literature, the addition of LA (styrene-butadiene elastomer) to mortars did not result in stronger hardened products due to their lower density with respect to mortars prepared without LA;

- the inclusion of a polycarboxylate-ether-based SP in the AA-BFS mortars caused a slight reduction in strength at the early stages of curing (2 and 7 days), while no relevant effects were observed in 28-day cured specimens;
- the use of AA-BFS binder in PC guaranteed slightly superior compressive strength with respect to CEM-I, while in a flexural configuration, the relevant strengths of PC containing AA-BFS were only evident when LA was added;
- at the concrete scale, the addition of LA led to an increase in PC density and a reduction in the volume of voids in the mixtures; however, LA was a precursor for strength increases only in AA-BFS PC.

This research demonstrates that the optimization method proposed by Tennis et al. (2004) can also be applied to PC with an alternative binder obtained as per the AA of slag. However, the method needs the support of a robust statistical analysis to understand the effects of each mixture variable (constituent and related proportion) on the consistency level of fresh PC.

While the results of this study are very promising, the mixture strength could be further enhanced by using tougher aggregates and by reducing the void content value in the mixture. Future investigations will pursue this objective (increased strength), which is fundamental for optimizing the field performance of PC, thus facilitating their wider application to more heavily trafficked road pavements.

Data availability statement

All data, models, and code generated or used throughout the study appear in the submitted article.

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Table 1. Chemical composition of CEM-I and BFS as determined by XRF analysis.

Chemical compound	CEM-I (%)	BFS (%)
CaO	67.30	38.90
SiO_2	18.30	31.00
Al_2O_3	3.81	9.24
Fe_2O_3	4.97	1.07
SO_3	3.66	1.69
K_2O	1.21	0.37
SrO	0.04	0.08
MgO	-	6.50
TiO_2	-	0.84
MnO	-	0.36
ZrO_2	-	0.04
LOI (loss of ignition)	0.71	9.97

Table 2. Results of consistency analysis on PC mixtures containing CEM-I (l = liquid phase, i.e. water, b = binder, a = coarse aggregate, s = sand, LA = latex admixture, VMA = viscosity modifying admixture, SP = superplasticizer).

Mixture designation	l/b	a/b	s/a	LA/b	VMA/b	SP/b	Consistency
A-1	0.35	4.4	0.05	0.07	0.005	0.010	poor
A-2	0.35	4.4	0.06	0.07	0.005	0.010	poor
A-3	0.35	4.4	0.07	0.07	0.005	0.010	poor
A-4	0.35	4.4	0.08	0.07	0.005	0.010	nearly good
A-5	0.33	4.3	0.05	0.07	-	-	poor
A-6	0.33	4.3	0.06	0.07	-	-	poor
A-7	0.33	4.3	0.07	0.07	-	-	nearly good
A-8	0.33	4.3	0.07	0.07	0.005	0.010	poor
A-9	0.28	4.4	0.05	0.07	0.005	-	good
A-10	**0.32**	**4.4**	**0.05**	**0.07**	**0.005**	**0.010**	**excellent**
A-11	0.26	4.3	0.07	0.07	-	-	poor
B-1	0.35	4.4	0.05	-	0.005	0.010	good
B-2	0.35	4.3	0.07	-	0.009	0.009	good
B-3	**0.35**	**4.4**	**0.06**	**-**	**0.005**	**0.010**	**excellent**
B-4	0.35	4.4	0.07	-	0.005	0.010	poor
B-5	0.33	4.3	0.05	-	-	-	poor
B-6	0.33	4.3	0.05	-	-	0.010	poor
B-7	0.33	4.3	0.05	-	0.005	0.010	poor
B-8	0.33	4.3	0.06	-	0.005	0.010	good
B-9	0.33	4.3	0.07	-	0.005	0.010	nearly good

Table 3. Results of consistency analysis on PC mixtures containing AA-BFS (l = liquid phase, i.e. water, b = binder, a = coarse aggregate, s = sand, LA = latex admixture, VMA = viscosity modifying admixture, SP = superplasticizer).

Mixture designation	l/b	a/b	s/a	LA/b	VMA/b	SP/b	Consistency
A-1	0.32	4.4	0.05	0.07	0.005	0.010	poor
A-2	0.50	4.4	0.05	0.07	0.005	0.010	poor
A-3	0.47	4.2	0.05	0.07	0.005	0.010	good
A-4	0.42	4.2	0.05	0.07	-	0.010	nearly good
A-5	**0.46**	**4.2**	**0.05**	**0.07**	**-**	**0.010**	**excellent**
A-6	0.34	4.2	-	0.07	0.005	0.010	poor
A-7	0.42	4.2	-	0.07	0.005	0.010	poor
A-8	0.40	4.0	-	0.06	0.005	0.010	poor
A-9	0.34	4.2	0.05	0.08	0.005	0.010	poor
A-10	0.38	4.2	0.05	0.08	0.005	0.010	poor
A-11	0.42	4.2	0.05	0.08	0.005	0.010	good
A-12	0.42	4.4	0.05	0.07	0.000	-	good
A-13	0.35	5.0	0.05	0.08	0.006	0.010	poor
A-14	0.44	5.0	0.05	0.08	0.006	0.010	good
A-15	0.40	4.4	0.05	0.07	0.005	0.010	nearly good
A-16	0.44	4.4	0.05	0.07	0.005	0.010	good
A-17	0.37	5.0	0.05	0.08	0.006	0.020	poor
A-18	0.37	5.0	0.05	0.08	0.006	0.030	poor
A-19	0.37	5.0	0.05	0.08	0.006	0.040	nearly good
A-20	0.39	5.0	0.05	0.08	0.006	0.040	good
B-1	0.44	5.0	0.05	-	0.006	0.010	poor
B-2	0.46	5.0	0.05	-	0.006	0.010	poor
B-3	0.48	5.0	0.05	-	0.006	0.010	poor
B-4	0.48	5.0	0.05	-	0.006	0.020	nearly good
B-5	0.48	5.0	0.05	-	0.006	0.030	nearly good
B-6	0.48	5.0	0.05	-	0.011	0.030	good
B-7	0.39	5.0	0.05	-	0.006	0.040	poor
B-8	0.41	5.0	0.05	-	0.006	0.040	nearly good
B-9	0.41	5.0	0.05	-	0.011	0.040	poor
B-10	0.44	5.0	0.05	-	0.011	0.040	nearly good
B-11	0.44	5.0	0.05	-	0.011	0.060	good
B-12	**0.46**	**4.2**	**0.05**	**-**	**-**	**0.010**	**excellent**

Table 4. Correlation matrix between constituent mix ratio values (independent variables) and mixture consistency values (dependent variable). Significance of symbols: l = liquid phase, b = binder, a = coarse aggregate, s = sand, LA = latex admixture, VMA = viscosity modifying admixture, SP = superplasticizer. Level of significance in the correlation: * p < .05, ** p < .01, *** p < .001.

	CEM-I	Constituent mix ratio in the PC mixture						
AA-BFS		**l/b**	**a/b**	**s/a**	**LA/b**	**VMA/b**	**SP/b**	**Consistency**
l/b	Pearson's r	—	0.290	0.108	-0.290	0.395	0.605 **	0.009
	p-value	—	0.216	0.651	0.216	0.085	0.005	0.969
a/b	Pearson's r	0.124	—	-0.050	0.212	0.457 *	0.385	0.317
	p-value	0.499	—	0.846	0.369	0.043	0.094	0.173
s/a	Pearson's r	0.219	0.436 *	—	0.150	0.206	0.136	-0.089
	p-value	0.228	0.013	—	0.529	0.384	0.568	0.708
LA/b	Pearson's r	-0.510 **	-0.510 **	-0.180	—	-0.220	-0.363	-0.222
	p-value	0.003	0.003	0.319	—	0.345	0.116	0.346
VMA/b	Pearson's r	0.033	0.618 ***	0.061	-0.420 *	—	0.712 ***	0.460 *
	p-value	0.858	< .001	0.739	0.016	—	< .001	0.041
SP/b	Pearson's r	-0.020	0.635 ***	0.210	-0.450 *	0.666 ***	—	0.205
	p-value	0.933	< .001	0.248	0.011	< .001	—	0.385
Consistency	Pearson's r	0.428 *	-0.140	0.297	-0.010	-0.260	0.063	—
	p-value	0.015	0.451	0.098	0.957	0.156	0.734	—

Table 5. Analysis of variance (ANOVA) of constituent mix ratio affecting the mixture consistency. Significance of symbols: l = liquid phase, i.e. water, b = binder, a = coarse aggregate, s = sand, LA = latex admixture, VMA = viscosity modifying admixture, SP = superplasticizer. Level of significance in the ANOVA: * p < .05, ** p < .01, *** p < .001.

Mixtures	Analysis of Variance						Collinearity statistics
	Variable	Sum of Squares	df	Mean Square	F	p-value	VIF
CEM-I	VMA/b	4.50	1	4.50	4.47	0.050 *	2.03
	SP/b	0.68	1	0.68	0.68	0.422	2.03
	Residuals	17.10	17	1.01			
AA-BFS	l/b	8.16	1	8.156	12.63	0.001 ***	1.51
	LA/b	1.96	1	1.964	3.04	0.093	1.95
	VMA/b	4.2	1	4.196	6.5	0.017 *	1.87
	SP/b	4.88	1	4.884	7.56	0.011 *	2.01
	Residuals	17.44	27	0.646			

Table 6. Regression analysis of constituent mix ratio affecting the mixture consistency. Significance of symbols: l = liquid phase, i.e. water, b = binder, a = coarse aggregate, s = sand, LA = latex admixture, VMA = viscosity modifying admixture, SP = superplasticizer. Level of significance in the linear regression model: * p < .05, ** p < .01, *** p < .001.

Mixtures	Linear regression model coefficient				
	Predictor	Estimate	SE	t	p-value
CEM-I	Intercept	1.279	0.42	3.01	0.008 **
	SP/b	-57.63	70.10	-0.82	0.422
	VMA/b	262.54	124.19	2.11	0.050 *
AA-BFS	Intercept	-3.87	1.86	-2.08	0.047 **
	l/b	13.3	3.74	3.55	0.001 ***
	LA/b	9.57	5.49	1.74	0.093
	VMA/b	-177.8	69.76	-2.55	0.017 *
	SP/b	38.61	14.04	2.75	0.011 *

Table 7. Summary of mass proportion (mass ratios) between constituents in mortars and PCs (l = liquid phase, b = binder, a = coarse aggregate, s = sand, LA = latex admixture, VMA = viscosity modifying admixture, SP = superplasticizer). The string XX-BBB-YY-ZZ indicates: (XX) identifies the scale of investigation (MO for mortars, PC for porous concrete mixtures), (BBB) discriminates the binder (CEM for OPC and BFS for AA-BFS), third (YY) and fourth (ZZ) parts are associated with the possible presence of admixtures (LA for latex admixture and SP for superplasticizer)

Scale	Binder (b)	LA	Code	LA/b	SP/b	VMA/b	l/b	a/b	s/a
Mortars	CEM-I	Yes	MO-CEM-LA	0.07	-	-	0.32	-	0.05
		No	MO-CEM	-	-	-	0.35	-	0.06
	AA-BFS	Yes	MO-BFS-LA-SP	0.07	0.010	-	0.46	-	0.05
		Yes	MO-BFS-LA	0.07	-	-	0.46	-	0.05
		No	MO-BFS-SP	-	0.010	-	0.46	-	0.05
		No	MO-BFS	-	-	-	0.46	-	0.05
PC Mixtures	CEM-I	Yes	PC-CEM-LA-SP	0.07	0.010	0.005	0.32	4.4	0.05
		No	PC-CEM-SP	-	0.010	0.005	0.35	4.4	0.06
	AA-BFS	Yes	PC-BFS-LA-SP	0.07	0.010	-	0.46	4.2	0.05
		No	PC-BFS-SP	-	0.010	-	0.46	4.2	0.05

Table 8. Physical and volumetric properties of prismatic and cylindrical specimens (symbols indicate: γ_g = mass/volume ratio, with volume calculation based on the mold geometry; γ_b = mass/volume ratio, with volume calculated according to ASTM D6792 sealing method; v_g = sample porosity; v_r = real porosity; subscripts p = prismatic; subscript c = cylindrical).

Binder	LA	Code	Parameter	Prismatic specimens		Cylindrical specimens			
				$\gamma_{g,p}$ kg/m^3	$v_{g,p}$ %	$\gamma_{g,c}$ kg/m^3	$v_{g,c}$ %	$\gamma_{b,c}$ kg/m^3	$v_{r,c}$ %
CEM-I	No	PC-CEM-SP	Mean	1915	33.7	1947	32.7	2010	30.4
			St. dev.	88	3.1	8	0.3	39	1.2
			# of data	6	6	6	6	4	4
	Yes	PC-CEM-LA-SP	Mean	2007	30.6	2007	30.6	2056	28.8
			St. dev.	23	0.8	21	0.7	22	0.7
			# of data	6	6	6	6	4	4
AA-BFS	No	PC-BFS-SP	Mean	1938	32.0	1941	31.9	2059	27.8
			St. dev.	92	3.2	70	2.5	2	0.1
			# of data	6	6	6	6	4	4
	Yes	PC-BFS-LA-SP	Mean	1967	31.0	1992	30.1	2047	27.4
			St. dev.	150	5.3	49	1.7	39	0.2
			# of data	6	6	6	6	4	4

Table 9. Flexural strength results after 28 days of curing from literature

Author	Material		Void content (%)	$\sigma_{f,max}$ (MPa)
	Binder	Aggregate		
Joshaghani et al. (2015)	CEM-I	Natural aggregate (9.5-12.5 mm)	30	1.8
Ibrahim et al. (2014)	CEM-I	Limestone (9.5-12.5 mm)	31	1.9
Cheng et al. (2011)	CEM-I	Natural aggregate (9.5-12.7 mm)	27	1.4
This study (PC-CEM-LA-SP)	CEM-I	Crushed limestone (4-16 mm)	31	2.5
This study (PC-BFS-LA-SP)	AA-BFS	Crushed limestone (4-16 mm)	31	2.7

Table 10. Compressive strength results after 28 days of curing from literature

Author	Material		Void content (%)	$\sigma_{c,max}$ (MPa)
	Binder	Aggregate		
Joshaghani et al. (2015)	CEM-I	Natural aggregate (9.5-12.5 mm)	30	6.3
Ibrahim et al. (2014)	CEM-I	Limestone (9.5-12.5 mm)	31	6.5
Cheng et al. (2011)	CEM-I	Natural aggregate (9.5-12.7 mm)	27	8.2
Lian et al. (2011)	CEM-I	Limestone (6.7-9.5 mm)	29	13.8
Park et al. (2005)	CEM-I	Natural aggregate (5-13 mm)	28	13.5
Wu et al. (2011)	CEM-I	Limestone (4.8-12.5 mm)	27	14.0
This study (PC-CEM-LA-SP)	CEM-I	Crushed limestone (4-16 mm)	31	8.6
Sun et al. (2018)	AA-BFS	Natural aggregate (8-16 mm)	32	11.3
Chen et al. (2020)	AA-BFS	Natural aggregate (4.8-9.5 mm)	30	12.7
This study (PC-BFS-LA-SP)	AA-BFS	Crushed limestone (4-16 mm)	30	12.3

Figure caption list

Fig. 1. (a) Particle size distribution of CEM-I and BFS obtained with the laser granulometry method. (b) Particle size distribution of sand and coarse aggregates.

Fig. 2. Consistency of fresh PC mixtures: (a) “poor”, (b) “nearly good”, (c) “good”, and (d) “excellent”.

Fig. 3. (a) Cylindrical specimens 200 mm in height and 100 mm in diameter for compression tests and (b) 100×100×500 mm prismatic specimens for flexural tests.

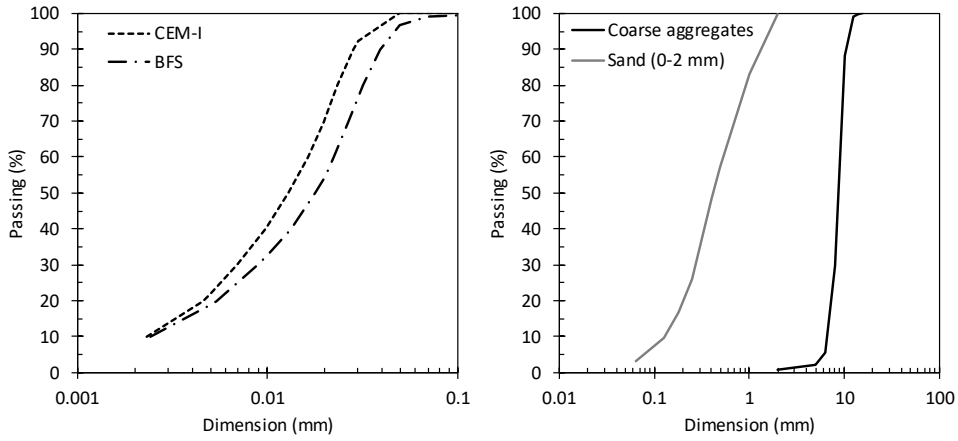
Fig. 4. Determination of bulk density according to the ASTM D6792 sealing method: (a) air removal operation, and (b) specimen sealed in a plastic bag.

Fig. 5. Marginal effects of significant variables in the AA-BFS (a - l/b, b - SP/b, c - LA/b, d - VMA/b) and CEM-I (e - SP/b, f - VMA/b) regression models (grey bands indicate the 95% of confidence interval). In the y axis (consistency), the numerical values correspond to: 1 = poor, 2 = nearly good, 3 = good, 4 = excellent.

Fig. 6. Results of average densities of CEM-I and AA-BFS mortars (error bars indicate one standard deviation)

Fig. 7. Compressive strength results for CEM-I and AA-BFS mortars at different curing times (error bars indicate one standard deviation).

Fig. 8. Results from the mechanical characterization of PCs: (a) flexural strength, (b) compressive strength



(a) (b)

Fig. 9. (a) Particle size distribution of CEM-I and BFS obtained with the laser granulometry method. (b) Particle size distribution of sand and coarse aggregates.

(a) (b) (c) (d)

Fig. 2. Consistency of fresh PC mixtures: (a) “poor”, (b) “nearly good”, (c) “good”, and (d) “excellent”.

(a) (b)

Fig. 3. (a) Cylindrical specimens 200 mm in height and 100 mm in diameter for compression tests and (b) 100×100×500 mm prismatic specimens for flexural tests.

(a) (b)

Fig. 4. Determination of bulk density according to the ASTM D6792 sealing method: (a) air removal operation, and (b) specimen sealed in a plastic bag.

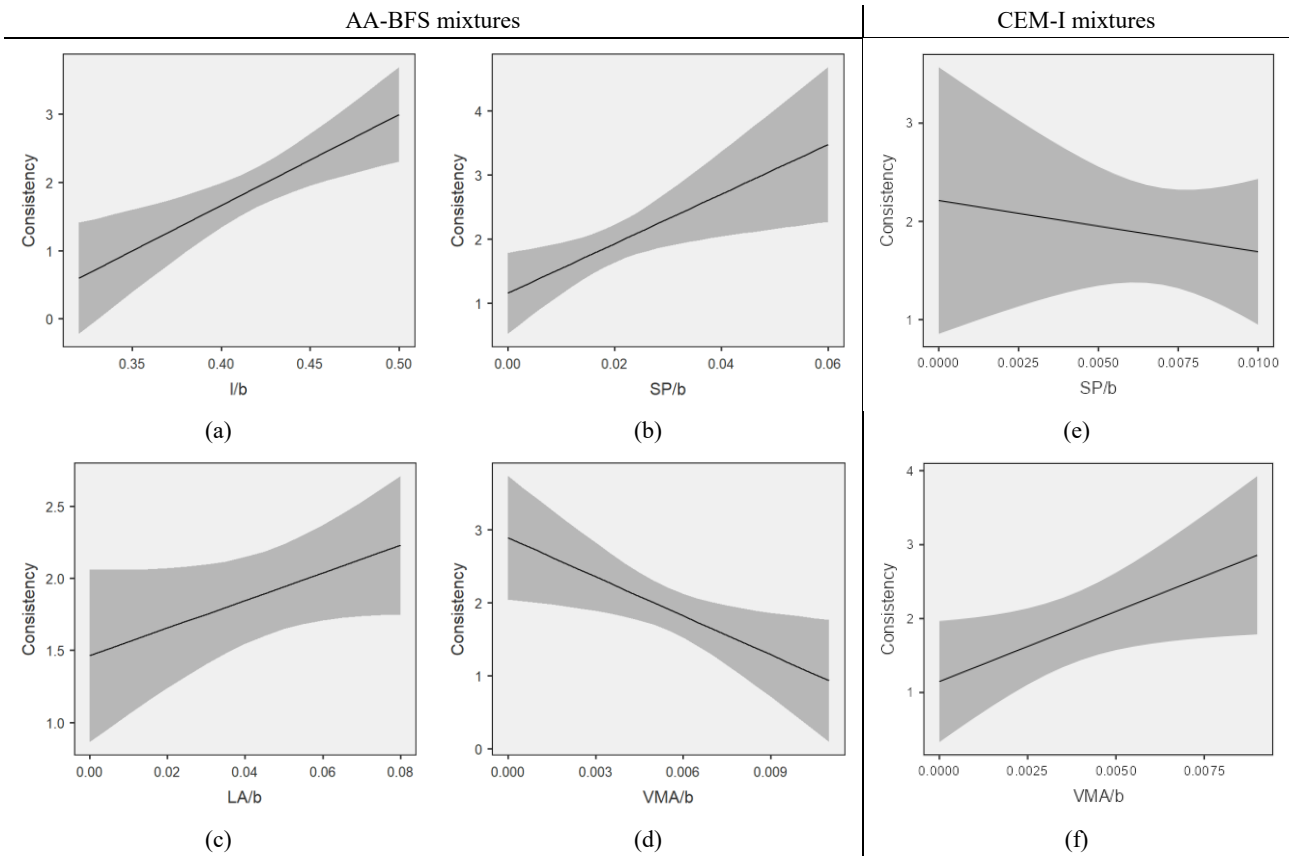


Fig. 5. Marginal effects of significant variables in the AA-BFS (a - l/b, b - SP/b, c - LA/b, d - VMA/b) and CEM-I (e - SP/b, f - VMA/b) regression models (grey bands indicate the 95% of confidence interval). In the y axis (consistency), the numerical values correspond to: 1 = poor, 2 = nearly good, 3 = good, 4 = excellent.

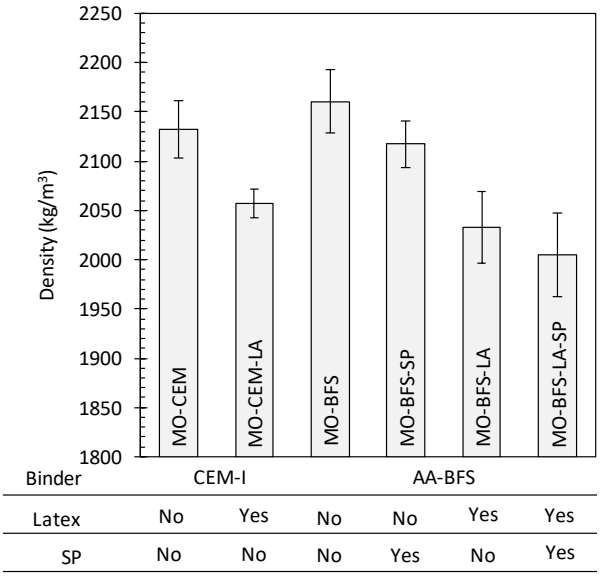


Fig. 6. Results of average densities of CEM-I and AA-BFS mortars (error bars indicate one standard deviation)

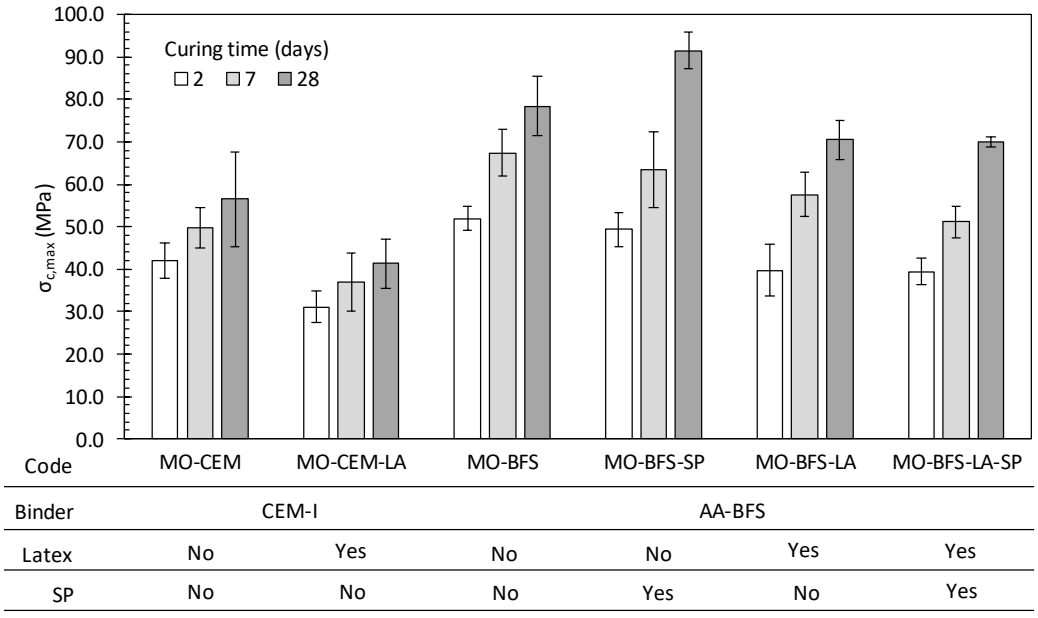


Fig. 7. Compressive strength results for CEM-I and AA-BFS mortars at different curing times (error bars indicate one standard deviation).

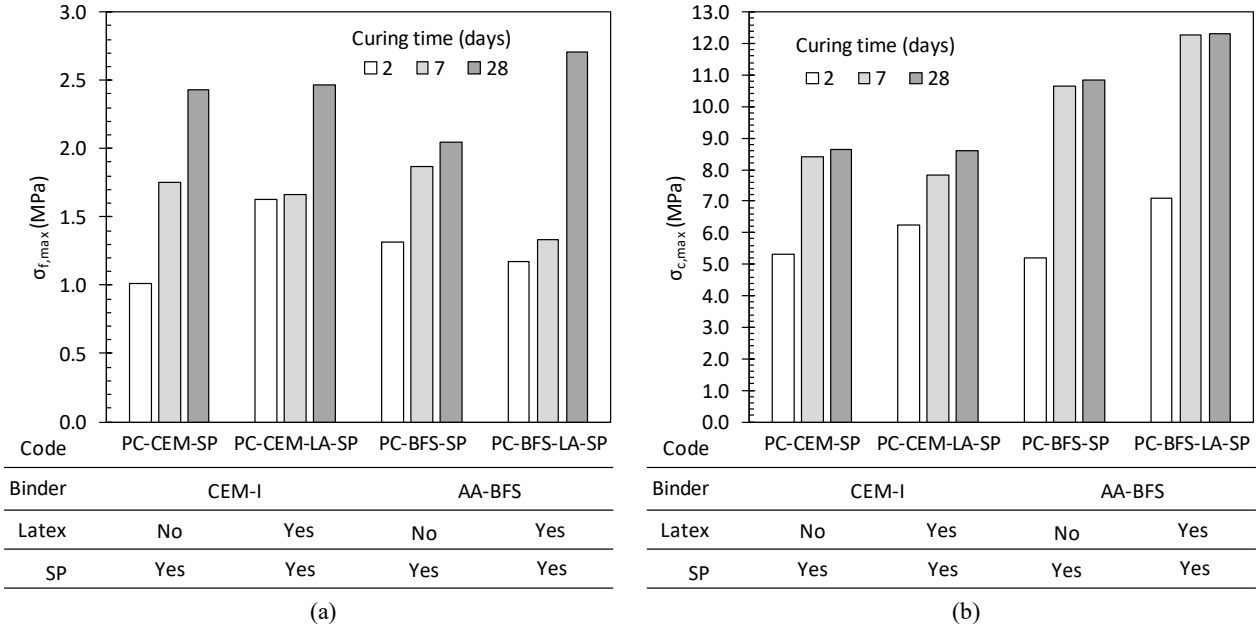


Fig. 8. Results from the mechanical characterization of PCs: (a) flexural strength, (b) compressive strength