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"Massive volume fly-ash concrete: A more sustainable material with fly ash replacing cement and aggregates"

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ABSTRACT

Fly ash (FA) has been widely used to improve concrete sustainability for many years; however, the amount of FA has been limited by the relatively low cement contents in concrete. In this study, massive volume fly-ash concrete was developed that maximizes the use of FA in concrete through its use as both a cement and aggregate replacement. Concrete containing as much as 728 kg of FA per cubic meter was produced with a compressive strength greater than 30 MPa, a low permeability measured in terms of chloride ion permeability (2300C at 56 d) and electrical resistivity (60 Ω-m at 56 d), and a decreased environmental impact.

1. Introduction

Fly ash (FA) is a by-product of the combustion of pulverized coal in thermal power plants. It has been widely used to attain sustainability in the cement and concrete industry for many years [1–4]. In addition to its environmental benefits [5–7], the proven technical benefits of using FA to replace cement in concrete include improvement in workability, reduction of bleeding, reduction in the temperature rise in hardening concrete, reduction of drying shrinkage, reduction of reinforcement corrosion in reinforced concrete [3,8,9], and overall improvement in durability [10–13]. From the direct cost perspective, using FA reduces costs in concrete production and in FA disposal [14]. Additionally, a more durable concrete also results in long-term costs savings over the lifecycle [15]. Despite the reported benefits of using FA in concrete, the use of FA in the industry is only approximately 25% of the FA world production [16–20].

In Chile, energy from coal-based thermal power plants represents approximately one-third of the total energy production [21]. However, the FA obtained is treated as waste and disposed of in landfills. The Chilean cement industry has traditionally used natural pozzolans to produce blended cements and to assess cement sustainability over the years. Today, higher costs in quarrying and transportation make FA more attractive for use in the production of blended cements.

Maximizing the use of FA in concrete as a cementitious material was proposed in the past, when high-volume fly-ash (HVFA) concrete was formally introduced by Malhotra at CANMET [3]. As stated by Malhotra and Mehta [22], HVFA concrete uses a minimum of 50% replacement of cement by FA as a supplementary cementitious material (SCM) and has a low cement and water content and a low water-to-binder ratio (w/b). However, the quality and composition of FA, the slow development of strength and stiffness, the longer setting time, and practical issues related to construction methods have been an obstacle to its vast use in practice [15,22,23]. Recent research concerning HVFA concrete has proposed solutions to these issues, resulting in cement replacements by FA as high as 80% by mass. Possible solutions include the selection of better materials [22,24,25], chemical admixtures [15,26], fine limestone powder to accelerate the strength development and regulate setting [23,27,28], or internal curing [29,30]. Regardless of the efforts and successes in maximizing the use of FA as a cement replacement, its use remains chiefly limited to the cement volume

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in concrete, which usually represents approximately 15% of the total volume of concrete (assuming concrete volume composition is 70% aggregate and 30% paste, and 50% of paste volume is cement).

Another use of FA in concrete is to produce lightweight aggregates (LWA), which is another potential solution to address FA disposal and concrete sustainability. The benefits of using LWA in concrete were reported by Ries and Holm [31]. FA-LWA benefit concrete in the same manner, while offering the environmental benefits of the use of FA. Different production methods have been used for FA-LWA, which vary in the amount of energy used during the process and affect the physical and mechanical properties of the FA-LWA. Videla and Martinez [32] produced FA-LWA using a cold-bonding pelletization process and outdoor exposure hardening. Their study showed the best results for FA-LWA produced with 5% by mass of cement as the initial binder material, considering the physical and mechanical properties of the aggregates and economic and practical criteria. The cold-bonding technique addresses sustainability issues by using the least amount of energy compared with other solutions (sintering, autoclaving, and steam curing). More recent research on cold-bonding FA-aggregate (CBFA aggregate) has focused on understanding the production of aggregates and its effects on the durability of the concrete [33–38].

Thus far, the use of FA in concrete has been addressed separately in cement paste, using FA as SCM, or as aggregates, which limit the quantity of FA to be used in concrete. This study aims to develop a Massive Volume Fly-Ash (MVFA) concrete that maximizes the use of FA in the concrete as cement replacement and CBFA aggregate, which increases the total volume of FA consumed in concrete to a new ceiling of 65%–85% by volume of concrete. This approach can result in synergies between the high volumes of FA in the paste and in the aggregate.

The effect of the addition of FA (as a cement or aggregate replacement) is first assessed separately based on the compressive strength of cement pastes containing FA as a cement replacement (SCM), and the compressive strength and modulus of elasticity of concrete with CBFA aggregates. Then, the combined effect of the FA addition is assessed based on the mechanical properties (compressive strength and modulus of elasticity), and physical properties (unit weight, electrical resistivity and chloride ion permeability), of concrete containing FA as both a cement replacement and an aggregate replacement.

2. Experimental program

2.1. Materials

ASTM Type I ordinary Portland cement (OPC) and blended cement available in Chile (BC) were used in this study for control mixtures. BC is the most commonly used cement in Chile, and its composition is similar to ASTM Type IP cement, with an estimated content of natural pozzolans of 40% by mass ($\approx$45% by volume).

FAs from two different sources in Chile were used in this study: one was a Class C fly ash (FA-C) from a power plant with spray dry scrubbers, which uses lime slurry to remove SO_2 from the flue-gas, resulting in relatively high sulfate content in the ash. The other was a Class F fly ash (FA-F) from a power plant using an electrostatic precipitator to collect the ash after the combustion of the coal. The chemical composition and physical properties of the cements and fly ashes are listed in Table 1. The particle size distributions, as measured by laser diffraction, of the OPC, BC and both FAs are presented in Fig. 1.

Normal-weight siliceous aggregates (NWA) were used to produce the concrete. The coarse aggregate had a fineness modulus of 7.53, specific gravity of 2.67, and absorption of 1.7%. The fine aggregate had a fineness modulus of 3.30, a specific gravity of 2.68, and absorption of 3.3%. Combined aggregate was 40% fine and 60% coarse aggregate by mass.

2.2. Mixture proportions and experimental methods

The experimental methods consisted of a sequential three-stage experimental approach studying the FA in cement pastes as a cement replacement (Stage 1), CBFA aggregates (Stage 2), and in concrete mixtures as a cement replacement and as CBFA aggregate (Stage 3).

2.2.1. Stage 1: Effect of replacement level and type of FA in cement pastes

The first stage focused on the assessment of the effect of both the replacement level and the type of FA on the compressive strength of pastes using 40%, 60% and 80% FA replacement by volume of cement, maintaining the w/b by mass constant at 0.42. The mixture proportions of the pastes are listed in Table 2. Eight mixtures were considered in this stage, six of them with OPC and varying FA type and content, and two control pastes using 100% OPC or 100% BC. The mixture ID indicates the percentage of cement replaced by volume in the cement paste and identifies the FA used in the mix (-C or -F). In the six FA pastes, the cement used was OPC.

The cement pastes were prepared in a mechanical mixer, and 50-mm cube specimens were cast to determine the compressive strength at different ages (three specimens per age). Fresh samples were covered with plastic sheets to prevent evaporation. At the age of 24 h, the specimens were demolded and placed in vacuum-sealed plastic bags in a moist room, (95 $\pm$ 3) % RH and (23 $\pm$ 2) °C, until the age of testing.

2.2.2. Stage 2: Manufacture and assessment of cold-bonded fly-ash aggregates

The second stage focused on the manufacture and characterization of the CBFA aggregates. CBFA aggregates of both FA-C and FA-F were manufactured using a pelletizer disc of 1.5-m in diameter and 0.25-m in depth. The parameters used for the pelletizer disc (an angle of inclination of 57° and speed of 21 rpm) were based on the parameters recommended by Martinez [39]. A photograph and a schematic drawing of the disc are presented in Fig. 2.

The CBFA aggregates were produced at room temperature using 5% by mass of OPC as the binder material, as reported by Videla and Martinez [32]. A dry pre-mix of OPC and FA was performed until a homogenous mixture was obtained. A dry pre-mixture of approximately 6 kg was placed in the pelletizer disc each time for pelletization. Water was sprayed until the formation of pellets. The total amount of water sprayed on the mixture was approximately 28% by total mass for FA-C and approximately 24% by total mass for FA-F, as determined visually by the consistency of the CBFA pellets. Immediately after pelletization, fresh aggregates were stored at 58 °C in an oven for accelerated curing for 28 d to increase the strength gain in the CBFA aggregates to be used in Stage 3.

The physical characterization of the CBFA aggregates included measurements of specific gravity and water absorption. The mechanical potential of the CBFA aggregates as coarse aggregates in concrete was assessed using the methodology proposed by Moreno et al. [40]. This methodology assesses the effect of using a porous coarse aggregate by comparing the unit weight, compressive strength, and modulus of elasticity of a concrete containing 40% by volume of the aggregate (phase under study) embedded in 60% of mortar (reference phase) with those properties obtained using only the mortar. The proportions of the mixtures to assess the mechanical potential of the CBFA aggregates are listed in Table 3. In addition to the mortar, three different mixtures were prepared to evaluate the effect of the FA source and CBFA aggregate size on the

Table 1
Chemical composition and physical properties of materials used in this study.

Material	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	Na_2O	SO_3	Specific gravity	Loss on ignition (%)
OPC	20.39	6.01	3.15	0.75	63.25	1.30	0.15	2.35	3.12	1.72
BC	28.30	2.80	2.19	0.40	54.10	1.18	0.54	0.74	2.90	9.23
FA-C	33.10	11.60	6.53	0.80	28.50	1.66	1.39	7.69	2.37	7.08
FA-F	55.80	21.00	8.31	1.07	5.87	2.70	1.54	0.44	2.39	1.01

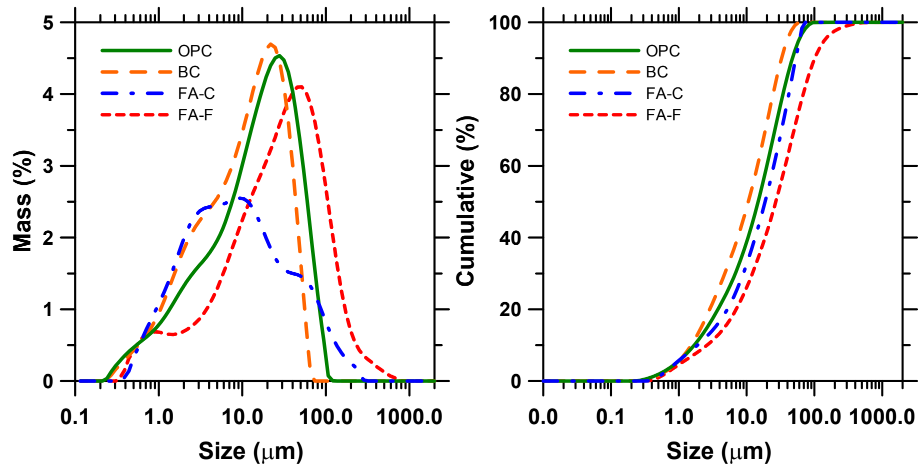

Fig. 1. Particle size distribution of ordinary Portland cement (OPC), blended cement (BC), and different fly ashes (FA) used in this study, as measured by laser diffraction. The tests were performed at the National Institute of Standards and Technology.

Table 2
Mixture proportions of the cement pastes used in this study, Stage 1.

Mixture ID	Cement (kg/m^3)	Fly ash (%)	Fly ash (kg/m^3)	Water (kg/m^3)
OPC	1359.7	0	0.0	571.1
BC	1307.5	0	0.0	549.1
40-C	865.7	40	431.5	544.8
60-C	595.4	60	667.7	530.4
80-C	307.4	80	919.2	515.2
40-F	864.4	40	434.5	545.5
60-F	594.0	60	671.7	531.6
80-F	306.4	80	924.0	516.7

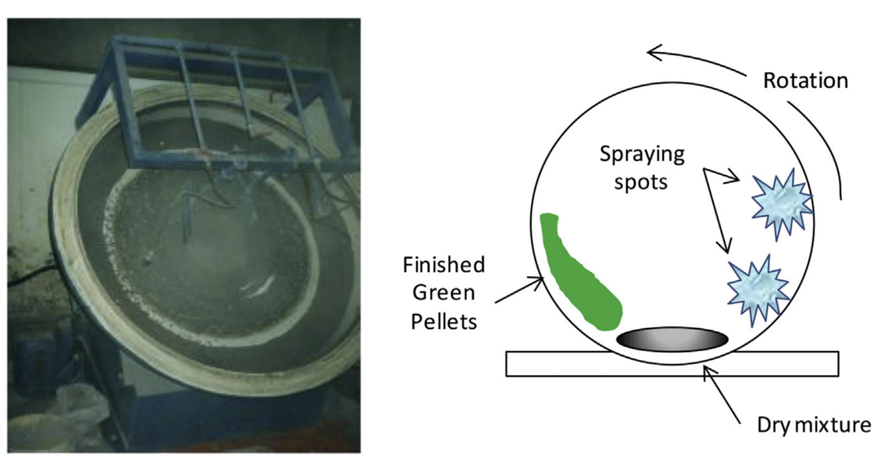

Fig. 2. Photograph (left) and schematic drawing (right) of the pelletizer disc used in this study.

mechanical potential. The mixture ID indicates the FA source and the maximum size aggregate (MSA) used in the mixture. The water content was varied to maintain a constant w/b by mass of 0.48 in the mixtures, replicating the work performed by Moreno et al. [40]. The CBFA aggregates were pre-wetted for 72 h before mixing and added to the mixer in a saturated-surface-dry (SSD) condition.

Table 3
Mixture proportions of mixtures used in Stage 2. CBFA aggregates and NWA in SSD condition.

Mixture	OPC	CBFA aggregate	Normal-weight fine aggregate	Water	MSA
ID	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(mm)
Mortar	623.0	0.0	1245.0	299.0	4.75
FA-C-12.5	373.8	726.2	747.0	179.4	12.50
FA-C-25.0	373.8	710.1	747.0	179.4	25.00
FA-F-25.0	373.8	735.0	747.0	179.4	25.00

2.2.3. Stage 3: Mechanical performance and physical properties of the concrete mixtures

The third stage focused on the assessment of the MVFA concrete. The mixture proportions of the concrete mixtures for this stage are listed in Table 4. Six mixtures were considered in three groups: the first group, "Control", consisted of OPC and BC concretes with normal-weight coarse and fine siliceous aggregates. The second group, HVFA concrete (HV), consisted of either FA-C or FA-F as the SCM and normal-weight coarse and fine siliceous aggregates. The third group, MVFA concrete (MV), consisted of either FA-C or FA-F as SCM and CBFA coarse aggregates, and normal-weight fine siliceous aggregates. The mixture ID indicates which FA (-C or -F) was used in the mixture. Normal-weight coarse aggregate replacement by CBFA aggregate was performed on a volume basis. Both the HV and MV mixtures contained 60% by volume FA in the cement paste. In the MV group, the grading of the normal-weight coarse aggregate was matched by that of the CBFA aggregates. The cement paste represented a constant 34% of the concrete volume in all the mixtures, and the coarse-to-fine aggregate volume ratio was approximately 1.0. CBFA aggregates were used in pre-wetted condition at the moment of mixing; the pre-wetting consisted in 72 h of immersion, so most of the accessible porosity was filled with water. In fact, 175 and 117 kg/m3 of water were held within the FA-C and FA-F aggregates, respectively at the moment of mixing. Since the water held within the aggregate is not available during mixing, it does not modify the w/b; however, it can migrate from aggregate to paste as relative humidity of the paste decreases. This phenomenon is known as "internal curing" and has been proven to be an effective way to enhance hydration for low w/b mixtures with SCM that require longer curing periods [41]. The water content was varied to maintain a constant w/b by mass of 0.42. All the mixtures were prepared with a 66% aggregate volume.

The concrete mixtures were prepared in a vertical axis mechanical mixer. Fresh samples were covered with plastic sheets to prevent evaporation. After 24 h, the samples were demolded and cured in a lime water curing tank until testing. Nine 10 cm × 20 cm cylinder specimens per mixture were cast to determine the compressive strength and static modulus of elasticity at different ages. Additionally, one 10 cm × 20 cm cylinder specimen per mixture was cast for the rapid chloride penetration test (RCPT), per ASTM C1202, conducted after 56 d. Four 10 × 10 × 30 cm prism specimens per mixture were cast to evaluate the dynamic modulus of elasticity, per ASTM C215, at different ages. The same prims specimens were used to measure the electrical resistivity, based on the work performed by Spragg et al. [42]. This test consisted of passing a current through two poles separated by a concrete specimen and recording the electrical resistance to that flow measured using an analog resistance meter (Fig. 3). The electrical resistivity (ρ, in Ω m) is calculated using the relation hrms $\rho = R*S/l$, where R is the measured resistance (in Ω), S is the transversal section (in m^2), and l is the length (in m) of the tested medium (concrete specimen).

3. Results and DISCUSSION

3.1. Stage 1: Effect of replacement level and type of FA in cement pastes

The compressive strength gain after 3 d, 7 d, 28 d and 90 d for each mixture is reported in Fig. 4.

The compressive strength of the 40-F paste was similar to that of the OPC paste at any age, while that of the 60-F paste was very similar to the BC paste at early ages (3 d and 7 d) and higher at 28 d and 90 d. The compressive strength of the 80-F paste was lower than that of the BC paste at any age; its strength reached 22 MPa at 28 d and 35 MPa at 90 d.

Between 7 d and 28 d, the FA-C pastes exhibited a similar strength gain (1.18–1.20 MPa/d) for all three replacement levels. In

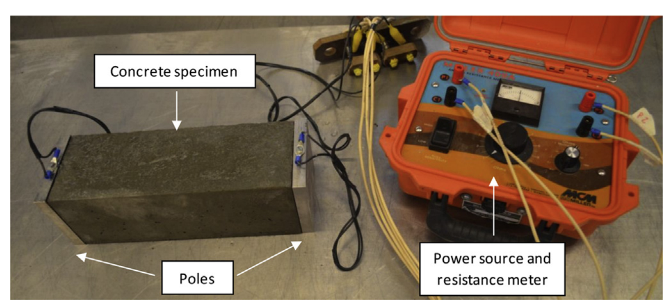

Fig. 3. Electrical resistivity test setup with a prismatic specimen.

Table 4
Mixture proportions of concretes used in this study, Stage 3. CBFA aggregates and NWA in SSD condition.

Mixture	Cement	Fly ash	Normal-weight coarse aggregate	Normal-weight fine aggregate	CBFA Aggregates	Water
ID	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
OPC	462.3	0.0	1057.3	707.5	0.0	194.2
BC	444.5	0.0	1057.3	707.5	0.0	186.7
HV-C	202.4	227.0	1057.3	707.5	0.0	180.4
HV-F	201.9	228.4	1057.3	707.5	0.0	180.7
MV-C	202.4	227.0	0.0	707.5	732.6	180.4
MV-F	201.9	228.4	0.0	707.5	704.9	180.7

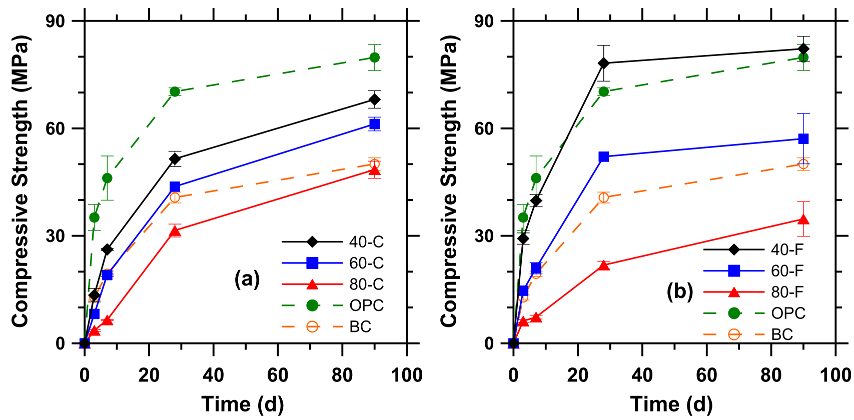

Fig. 4. Compressive strength gain in cement pastes for (a) FA-C cement pastes and (b) FA-F cement pastes, both compared with OPC and BC pastes. The error bars represent one standard deviation from the average of three specimens. The compressive strength of the 40-C paste was between that of OPC and BC pastes at any age, while that of the 60-C paste was very similar to BC paste until 28 d, and showing a compressive strength a 23% larger at 90 d, possibly due to greater pozzolanic activity than that of the pozzolans used in BC. Paste 80-C exhibited a lower compressive strength than the OPC and BC pastes at any age, reaching 32 MPa after 28 d and 49 MPa after 90 d.

contrast, the strength gain in the FA-F pastes varied widely (0.69–1.83 MPa/d) with the replacement level.

Between 28 d and 90 d, the OPC paste exhibited a strength gain similar to that of the BC paste but lower than that of all three FA-C pastes (0.27 MPa/d to 0.29 MPa/d) and the 80-F paste (0.21 MPa/d). For the 40-F and 60-F pastes, the strength gains were the lowest (0.07 MPa/d and 0.08 MPa/d, respectively), among the assessed pastes between 28 d and 90 d.

Because the FA pastes with replacement levels of 60% or less had similar or higher compressive strengths than commercially available Chilean blended cement (BC), a replacement level of 60% was selected to be used in Stage 3 for the concrete mixtures.

3.2. Stage 2: Manufacture and assessment of cold-bonded fly-ash aggregates

Fig. 5 presents an image of fresh CBFA aggregates immediately after pelletization. The physical properties of the produced CBFA aggregates are listed in Table 5. The absorption and specific gravity of the CBFA aggregates were measured after 28 d, after the aggregates were submerged in water for 72 h Table 5 also includes previous results from LWAs [40] to show that the CBFA aggregates have similar absorption but a higher specific gravity compared with certain commercially available LWAs.

Moreno et al. [40] proposed a method to assess the potential of a LWA to be used as a coarse aggregate in concrete production. The method compares the compressive strength and modulus of elasticity of a reference matrix (mortar) and a concrete prepared with the mortar and the aggregate under evaluation and calculates two parameters, α and β, to assess the structural potential of the aggregate. Here, "α" indicates the strength deterioration produced

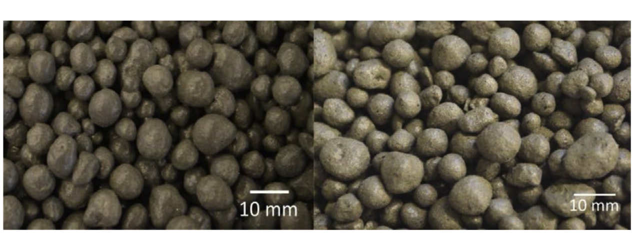

Fig. 5. Fresh CBFA aggregates after the pelletization process. The CBFA aggregates produced with FA-C are shown on the left, and those produced with FA-F are shown on the right.

by the aggregate and ranges from 0 to 3.84. A value of α equal to 0 represents an aggregate with the same compressive strength as the reference matrix, while a value of 3.84 represents an aggregate that is as weak as entrained air. The compressive strength of concrete is very sensitive to changes in α; for example, an α equal to 1.0 represents a loss of 60% in strength, while an α equal to 2.0 represents a loss of 84% in strength compared with the reference matrix, using 40% of the aggregate in the evaluation as performed by Moreno et al. [40]. The term β represents the apparent modulus of elasticity of the aggregate. For example, an aggregate with a value of β equal to 32.5 implies that the aggregate has a modulus of elasticity similar to that of the reference matrix and does not affect the modulus of elasticity of the concrete compared with the reference matrix. In contrast, an aggregate with a value of β equal to 14.0 reduces the modulus of elasticity of the concrete by 50% compared with the reference matrix. Any value of β greater than 32.5 indicates that the aggregate increases the modulus of elasticity compared with the reference matrix, using 40% of the aggregate in the evaluation as performed by Moreno et al. [40].

The mechanical performance of the aggregate can be grouped in three categories (see Fig. 6): group A, comprised of ExS-1 and all the CBFA aggregates, exhibits the best mechanical performance as a coarse aggregate in concrete because it does not impose a major loss of strength and results in a relatively high modulus of elasticity of the concrete. Group B, comprised of the two expanded clays, has a low-to-medium α and a low β-value, which gives the concrete a moderate loss of strength, but a relatively low modulus of elasticity. Group C, comprised of the expanded polystyrene, has low α and β values, yielding the weakest concrete with the lowest modulus of elasticity.

The mechanical performance (α and β values) obtained for the CBFA aggregates ranks between expanded clay and expanded slate. This result means that CBFA aggregates do not impose major strength deterioration in concrete while exhibiting a similar apparent modulus of elasticity as commercially available LWAs. The density of the CBFA aggregates (average density: 1800 kg/m^3) is higher than that of the LWAs (average density of mineral LWA: 1100 kg/m^3). These results indicate that CBFA aggregates can be used as coarse aggregates in concrete, and the mechanical performance will be similar to that of expanded slate. However, there is not a considerable reduction in the density of concrete with the use of these CBFA aggregates.

Because the β values of the CBFA aggregates produced with FA-C and FA-F are similar, it is expected that concrete produced with

Table 5
Physical properties of CBFA aggregates of FA-C and FA-F and LWA from Moreno et al. (2013).

	FA-C-12.5	FA-C-25.0	FA-F-25.0	ExC-2[b]	ExC-3[b]	ExS-1[c]	ExP-1[d]
Specific gravity[a]	1.87	1.85	1.78	0.95	1.49	1.44	0.002
Absorption (%)	23.5	23.9	16.6	20.7	32.8	5.5	–

[a] SSD condition.
[b] Expanded clay.
[c] Expanded slate.
[d] Expanded polystyrene.

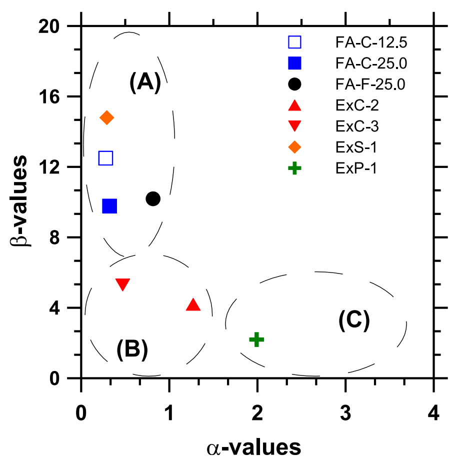

Fig. 6. Comparison of α and β values for commercial LWA (ExC-2, ExC-3, ExS-1, ExP-1) and CBFA aggregates (FA-C-12.5, FA-C-25.0, FA-F-25.0). The upper limit for α is 3.84, and the lower limit for β is 0, corresponding to air.

these components will also have similar moduli of elasticity. However, because the α values of FA-C are lower than those of FA-F, it is expected that concrete produced with FA-C would have a higher compressive strength.

3.3. Stage 3: Mechanical performance and physical properties of concrete mixtures

Stage 3 combines the results from stage 1 (FA used as cement replacement in pastes) and stage 2 (FA used for aggregate production) by producing and evaluating the following six concrete mixtures: two control concretes (with OPC or BC and normal weight natural aggregates), two HVFA concretes (with 60% FA replacement and normal weight siliceous aggregates) and two MVFA concretes (with 60% FA replacement, CBFA aggregate as the coarse aggregate, and normal weight siliceous fine aggregate).

Two different effects are studied separately in the concrete mixtures: FA replacement as a cementitious material and FA replacement as an aggregate. For the former, control mixtures were compared with HVFA mixtures (HV group). For the latter, MVFA mixtures (MV group) were compared with HV mixtures and an OPC control mixture.

3.3.1. Physical and transport properties

The average permeability of HV concretes measured in terms of chloride ion permeability at 56 d corresponded to the 40% of the permeability of OPC and to the 35% of the permeability of BC control mixtures (Table 6). Chloride ion permeability went from a Moderate to a Low category as per ASTM C1202. An electrical resistivity test (Fig. 7) reveals similar results, with HV mixtures exhibiting lower conductivity than the control mixtures. Both HVFA mixtures performed similar to BC for as long as 7 d and similar to OPC for as long as 14 d, which is consistent with the strength gain and the start of the pozzolanic reaction.

The reduction in the electrical conductivity of OPC concrete is the result of depercolation associated with hydration. Because hydration is relatively fast for OPC, concrete exhibits a relatively high electrical resistivity (relatively low permeability) early in time but does not improve significantly beyond that. In the HVFA mixtures, however, there are three factors that reduce the permeability: hydration of OPC, the filler effect of FA, and the pozzolanic reaction of FA. The OPC hydration effect is less pronounced at early ages because there is 60% less cement in the HVFA mixtures. However, the filler effect of FA in concrete somehow compensates for the lack of early hydration products. After 14 d, the HVFA mixtures improved their electrical resistivity significantly compared with the control mixtures: at 28 d, the HVFA mixtures had electrical resistivities that were approximately two times higher than those of the control mixtures and increased to 3.5-times at 90 d. This effect might be explained by the start of the pozzolanic reaction combined with the filler effect of FA. Based on these results, it is expected that the HVFA mixtures have higher durability than the control mixtures due to their lower permeability, regardless of the FA type used.

These test results should be taken just as a reference of the behavior of samples containing fly ash and fly ash aggregates, as the presence of porous aggregate and the lime water used for curing will alter the electrical conductivity of the samples. In addition, as all samples contain the same solution (lime water), correcting by the electrical conductivity of the solution is not needed for comparison purposes.

The permeabilities of the MVFA mixtures as measured with RCPT were higher than those of the HVFA mixtures (see Table 6). The replacement of normal aggregate by the CBFA aggregate increased the charge passed by approximately 80% for HV-C and by approximately 175% for HV-F. Overall, the MVFA mixtures still achieved similar or lower values than the control mixtures. The electrical resistivities of the HVFA mixtures developed faster than those of the MVFA mixtures (see Fig. 7). At 90 d, the electrical resistivity ratio between MVFA and HVFA was 60% for the FA-C mixtures and 34% for FA-F mixtures. This effect can be explained by the porosity of the CBFA aggregates compared with the NWA used in the HVFA mixtures.

At 90 d, the electrical resistivity in the HVFA and MVFA mixtures had not yet reached a plateau. MV-C and MV-F reached the same electrical resistivity of OPC ($\approx 60\ \Omega$ m) at 35 d and 56 d, respectively. Using CBFA aggregates to replace normal-weight siliceous coarse aggregates in concrete increased the permeability compared with HVFA systems. However, for ages of 56 d and longer, the MVFA mixtures performed similar or better compared with the OPC and BC mixtures.

3.3.2. Mechanical properties

As illustrated in Fig. 8, HV-C exhibited a compressive strength lower than that of OPC and greater than that of BC at any tested age. HV-F exhibited similar compressive strengths as BC at any tested age. These results are consistent with those obtained for the

Table 6
RCPT results for concrete samples at 56 d and chloride ion penetrability as per ASTM C1202. The standard deviation from the average of two specimens is less than 100C for each mixture.

Concrete mixture	Charge passed (C)	Chloride ion permeability
OPC	3110	Moderate
BC	3566	Moderate
HV-C	1287	Low
HV-F	1226	Low
MV-C	2303	Moderate
MV-F	3357	Moderate

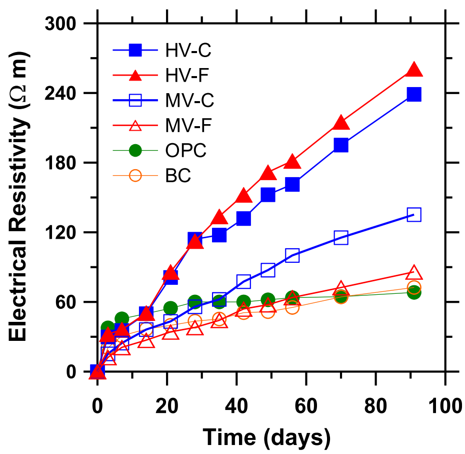

Fig. 7. Electrical resistivity as a function of time in concrete mixtures. The standard deviation from the average of four specimens is less than 10 Ω m for each mixture.

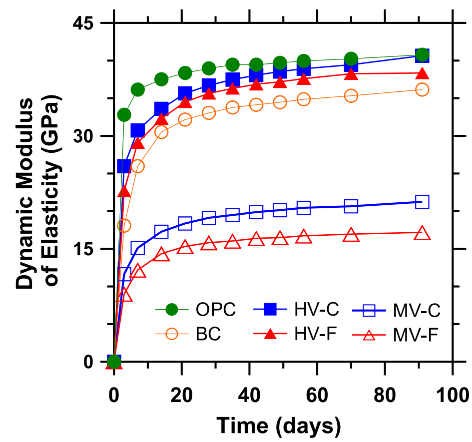

Fig. 9. Dynamic modulus of elasticity as a function of time. The standard deviation from the average of four specimens is less than 3 GPa for each mixture.

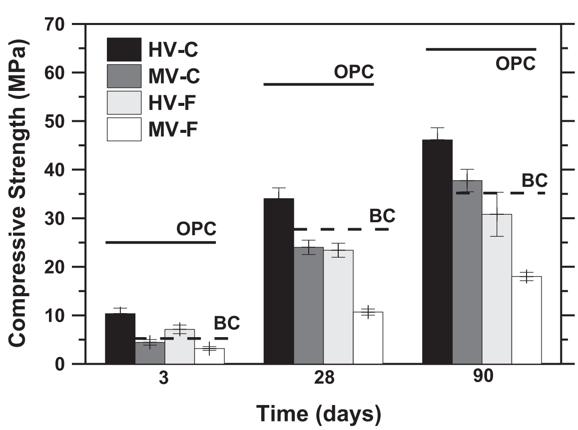

Fig. 8. Compressive strength as a function of time in concrete mixtures. The error bars represent one standard deviation from the average of three specimens. Fly-ash effect in cement paste assessment.

cement pastes in Stage 1. Pozzolanic reactions cause concrete mixtures to have slower strength gains compared with OPC, with decreasing differences with time. For instance, the strength ratio of HV-C to that of the OPC mixture increased from 40% at 3 d to as high as 70% at 90 d. Similar behavior can be observed in the HV-F mixtures, for which the strength ratio compared with that of the OPC mixtures increased from 30% at 3 d to as high as 50% at 90 d. The dynamic modulus of elasticity results indicate that stiffness development occurs similarly for all the mixtures (see Fig. 9). After 49 d, HV-C reached the same dynamic modulus of elasticity as the OPC mixture. The HV-C concrete exhibited a higher compressive strength and modulus of elasticity than the HV-F concrete, and both concretes exhibited greater mechanical performance than the BC mixture. The static modulus of elasticity was also measured before evaluating the compressive strength in concrete cylinders at 28 d and 91 d. The ratio of the static-to-dynamic modulus of elasticity was in the range 0.85 ± 0.1 for both testing ages and for all of the mixtures tested.

Regardless of the FA used, the mechanical performance of the HVFA mixtures was lower than that of the OPC mixture. However, compressive strengths greater than 25 MPa at 28 d and greater than 30 MPa at 90 d were achieved. The mechanical performance of HV-C was better than that of BC concrete, and HV-F performed similarly to BC concrete at any age. These results suggest that both fly ashes could be used as pozzolans to produce blended cements with a 60% fly-ash content by volume, obtaining results similar to the cements used commonly in Chile, but with lower contents of OPC.

A decrease in compressive strength between the HVFA and MVFA mixtures is observed for the same FA (Fig. 8). This decrease can be attributed to the use of the CBFA aggregates. The compressive strength of MV-F was 45% of that of HV-F at 3 d but reached 58% at 90 d. A similar tendency is observed for FA-C, where the compressive strength of MV-C was 43% of that of HV-C at 3 d and reached 82% after 90 d. This difference can be explained by the better mechanical performance of the CBFA aggregates used in the MV-C mixture compared with that of the aggregates used in the MV-F mixture, as anticipated by the results during Stage 2. Note that the strength differences between HV and MC concretes are relatively minor when considering that MV concretes used more than three times the amount of FA than the HV concretes.

The compressive strength of MV-F was 71% of that of MV-C at 3 d but decreased to only 48% at 90 d. Note that such a decrease in the difference with time was not observed for the HVFA mixtures, where the strength ratio between HV-F and HV-C was 69% at 3 d and 67% at 90 d. The ratio of the compressive strength of MV-C to OPC and MV-F to OPC increased from 18% at 3 d to 58% at 90 d and from 13% at 3 d to 28% at 90 d, respectively. Hence, the combined effect of using FA both as a cement replacement and as a CBFA coarse aggregate resulted in a loss in compressive strength between 42 and 72% with respect to high strength OPC concrete.

Fig. 9 shows that the dynamic modulus of elasticity developed similarly in the HVFA and MVFA mixtures, but reached different maximum values. The dynamic elastic modulus of the HVFA mixtures was approximately two times that of the MVFA mixtures (92% and 125% higher for FA-C and FA-F, respectively). The difference in the dynamic modulus of elasticity between the MVFA mixtures is attributed to the mechanical performance of each CBFA aggregate.

Regardless of the FA used and the differences in the mechanical performance of the CBFA aggregates produced, the compressive strengths of the MVFA concretes reached at least 10 MPa and as high as 24 MPa at 28 d and at least 18 MPa and as high as 38 MPa at 90 d. These results show the importance of the coarse aggregates in the mechanical performance of concrete, which represent 40% of the volume of the concrete in the assessed mixtures.

Considering the main objective of this study was to develop a concrete that maximizes the FA content, it is important to understand the results presented thus far through the proposed sustainability-driven approach. For this purpose, MVFA concrete is compared with mixtures using FA as a cement replacement (work by Hannesson et al. [43] and the HV mixtures of the present study) and mixtures using FA as an aggregate (works by Martinez 2002 [39], Gesoglu et al., 2007 [34], and Gesoglu et al., 2012 [38]). The comparison focuses on FA consumption and the compressive strength achieved at 28 d (Fig. 10). The use of FA in concrete was defined as the volume of FA per volume of concrete, expressed in m^3/m^3. The reference value is the FA used in MVFA concretes from this study (0.302 m^3 on average). FA use includes both FA present as a cement replacement and as an aggregate. When not reported, the specific gravity of FA was assumed to be 2.5, and the water used for pelletization was assumed to be 25% of the dry mass for calculations. Hannesson et al. [43] used self-consolidating concrete with a w/b of 0.35 and a mixture of an accelerator-superplasticizer-viscosity modifying chemical admixture. Martinez [39] varied the w/b from 0.35 to 0.51. Gesoglu et al. [34] used a high range water reducer (HRWR) admixture in all of their mixtures and prepared concretes with w/b ratios of 0.35 and 0.55. Gesoglu et al. [38] used a HRWR admixture and a w/b of 0.35.

The data from previous studies in Fig. 10 suggest a trend line between the FA content and compressive strength, where higher amounts of FA are associated with lower compressive strengths. However, the MVFA mixtures stand out from this trend, with much higher FA contents (50% approximately) than the other mixtures with similar compressive strength.

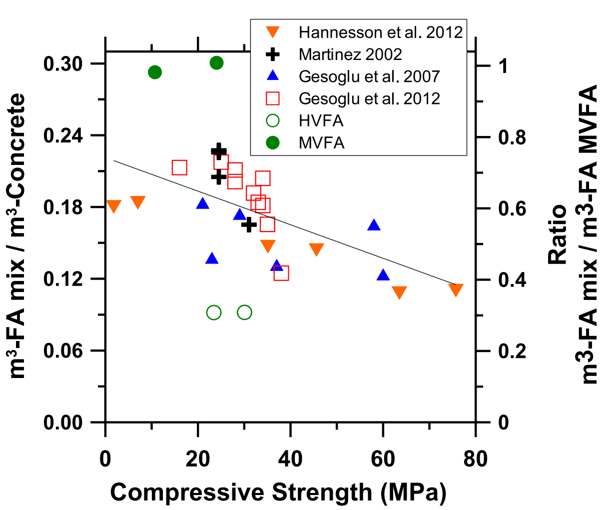

Fig. 10. Fly ash use as a function of compressive strength in HVFA, LWA and MVFA concretes.

When the approach for FA use in concrete is sustainability-driven rather than mechanical performance-driven, the use of FA is at least 30% more of the concrete's volume.

When compared with references, the compressive strength of MVFA concretes is relatively low. However, the strength reached at 28 d increased 57% for MV-C and 68% for MV-F at 90 d. Considering that 28 d is the standard age in specifications of concrete, future work should be conducted to address this issue, increasing the strength gain for MVFA concretes or considering to change the standard age of testing to later ages (i.e., 56 d or 90 d) when the project requirements allowed it (i.e., dump).

4. Conclusions

The novelty of this research is the use of FA as both a cement replacement and an aggregate replacement in concrete mixtures. The emphasis of this research was sustainability over mechanical performance, and the goal was to maximize FA consumption. This study assessed the mechanical performance of MVFA concrete mixtures and measured the physical and electrical resistance properties of these materials. The following conclusions can be drawn:

- The mechanical performance of CBFA aggregates was similar to that of certain commercially available LWAs (expanded slate and clays). CBFA aggregates can be used to successfully produce concrete with similar mechanical performance but superior environmental performance compared with normal-weight and lightweight aggregates.
- The permeability results for the concrete indicated that both HV and MV concretes are expected to have higher durability compared with conventional OPC concrete. However, the use of CBFA aggregates in MVFA concrete increased the permeability/conductivity compared with HVFA concretes.
- The combined use of FA as a replacement for cement and as an aggregate allowed the use of as much as 0.307 m^3 of FA per m^3 of concrete (at least a 33% increase compared with certain references and 200% increase compared with the HVFA concretes in this investigation). The produced MVFA concrete exhibited acceptable mechanical performance and superior environmental performance and durability.

One of the limitations of this study is the long-term durability issues related to sulfate attack that may arise due to the high content of sulphates in both FA-C and the CBFA aggregates produced with this FA. Further experimental research must be done to address this issue, and is considered to be tackled in the next stages of the ongoing study to use FA to replace both cement and aggregates in concrete.

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