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Technical Evaluation of Block Masonry with Pozzolanic Additions

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Abstract: Tests are carried out on various specimens of concrete block masonry, replacing Portland cement with pozzolans available in the region of Antofagasta, Chile (fly ash, volcanic ash and desert dust). To characterize the strength of the masonry, individual blocks, prisms and small walls, made of concrete with different binder combinations cement-pozzolan are tested; the obtained resistances are compared with standard mixture (100% cement). The results indicate that it is feasible to replace a percentage of Portland cement with pozzolans, obtaining very similar resistance, contributing to the reduction of construction costs and also, contributing to the environment by reducing cement demand and thereby reducing emissions of greenhouse gases that are generated in the calcination of the raw material. It is also pretension to enhance the importance of the masonry of concrete blocks in the construction of low-cost housing (economic and ecological).

Key words: masonry; concrete blocks; pozzolanic cement; green construction

1. Introduction

Given the lack of clays in northern Chile, masonry block construction for medium and low-rise housing is a very popular option due to its low cost compared to reinforced concrete (Roldán, 2003). In turn, the manufacture of concrete blocks with partial replacement of cement by pozzolan is an option that has economic advantages because pozzolans are available at a lower cost than cement; it has technological advantages because good mechanical strength values and better durability conditions are available (Metha and Monteiro, 2006; Malhotra and Metha, 1996). It should be noted that it also has environmental sustainability benefits because by reducing the demand for cement, CO2 emissions to the atmosphere are reduced (O'Rourke et al, 2009). Previous research using pozzolanic materials in the Antofagasta region (Roldán et al., 2013; Roldán and Pavéz, 2011; Roldán and Robles, 2014) has shown that volcanic ash (natural pozzolan) has good cementitious properties, but slightly lower reactivity than fly ash produced in a thermoelectric plant; in turn, the pozzolanic reactivity of desert dust is lower than that of volcanic ash.

For this reason, the application of new Portland Cement/Pozzolan type binders (Metha and Monteiro, 2006) is sought, reflecting the pozzolanic reactivity detected in previous studies carried out in the Antofagasta region, mentioned above. Therefore, it is proposed to develop masonry units of microvibrated blocks with the following binder combinations (by weight): Cement/Flying Ash = 60/40, Cement/Volcanic Ash 70/30, Cement/Desert Dust = 80/20 and also 100% Cement in the binder, the results of which will serve as a comparison or control; also estimating the cost indexes associated with each product obtained.

2. Material Characterization

2.1 Cement characteristics

OPC high-strength Portland cement is used, without pozzolanic additions. Table 1 shows its mineralogical composition obtained from x-ray fluorescence (xRF) tests.

2.2 Pozzolans characteristics

2.2.1 Fly ash

Fine dust originating from coal combustion at the thermoelectric plant in the city of Tocopilla, Chile. The results of xRF chemical analysis are presented in Table 1.

2.2.2 Volcanic ash

Fine dust resulting from volcanic eruptions after expelling incandescent ash into the atmosphere, which upon decanting forms deposits in various places; many of them at great distances from their source of origin and which have remained there since the Miocene (Breitkreuz et al, 2014). The volcanic ash used comes from a natural deposit located in the vicinity of Ruta 5 Norte, 1,304km away from the Antofagasta region, Chile. The results of xRF chemical analysis are presented in Table 1.

2.2.3 Desert dust

It is a natural, loose, dispersed, finely pulverized, ocher-colored material that gives the characteristic color to the desert of northern Chile; it is colloquially called chuca, chusca or chuzca. It is found in natural deposits, arranged in superficial soil thicknesses of 10 to 30 cm. It is a powdery material formed by mixtures of diverse components: soils of volcanic origin, clay, gypsum, fragments of pulverized rock and diverse materials typical of the desert, which have been exposed for long years to solar radiation. The material used comes from free access deposits located near 1,385 km north of Route 5 North, Antofagasta region, Chile. The characteristic particle size distribution of natural materials used under ASTM mesh #100 is an average size of 47.1 µm, with 90% at 130.1 µm, 50% at 20.6 µm, and 10% at 1.4 µm. It has a true density of 2.23 g/cm^3. The results of the xRF chemical analysis are presented in Table 1, which were obtained at the Applied Geochemistry Laboratory of the Universidad Católica del Norte.

Table 1. Chemical composition of cementitious materials used from xRF tests

Compound, %	Cement OPC	Fly ash	Volcanic ash	Desert dust
SiO_2	15.1	54.8	63.6	46.7
Al_2O_3	4.4	21.2	12.7	12.8
Fe_2O_3	3.4	7.5	2.8	3.8
CaO	67.6	3.9	5.2	8.6
MgO	0.6	2.7	3.1	4.5
K_2O	0.8	2.0	3.7	2.1
Na_2O	0.4	1.4	3.3	3.6
SO_3	3.5	0.3	1.1	3.8
Ppc	3.5	3.3	3.7	5.4
Otros	0.7	2.4	0.3	7.2
H_2O	0.0	0.5	0.5	1.5
Note: Ppc: loss on ignition; Other: miscellaneous compounds (Sr, Ni, Cu, Zr, Cr, Zn, V, Rb, Cl, I, Ba, Mo, Se)				

2.2.4 Aggregates, sand and gravel used

In order to produce concrete admixtures for building blocks and processing joint mortar, aggregates from the region were used, and their characteristics and properties are shown in Table 2.

Table 2. Granulometry and properties of aggregates

Mesh sieves		% passing	
Mesh N°	Aperture, mm	Sand	Gravel
1/2"	12.5	100	99
3/8"	10.0	100	92
#4	5.0	100	29
#8	2.5	90	2
#16	1.250	70	1
#30	0.630	46	1
#50	0.315	27	1
#100	0.160	16	1
Actual density, kg/m^3		2,580	2,626
Density ap. loose, kg/m^3		1,570	1,595
Density ap. compact, kg/m^3		1,720	1,845
Absorption, %		0.74	0.80
Note: [a]NCh1239 (2009), NCh1117 (2010), [b]NCh1116 (2008)			

2.3 Manufacture of concrete blocks

In order to have controlled conditions in the manufacture of blocks, we proceed to develop the complete manufacturing cycle in the laboratory, designing and manufacturing a metal mold, as shown in Figure 1, with which we proceed to manufacture concrete blocks with different binder combinations. For each combination, the necessary quantity of blocks is produced to test specimens of individual blocks, prisms and walls (5 specimens of each type).

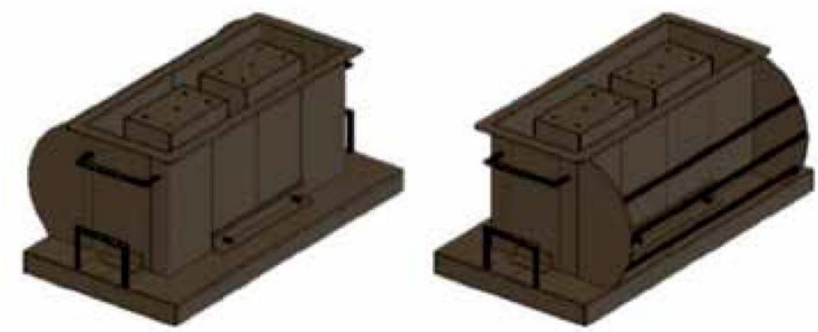

Figure 1. Metal mold for block making, three-dimensional view.

The metal mold used is made up of three removable parts: a rectangular perimeter wall, responsible for the outer flat faces, defining the dimensions of the block according to: width-length-height = 14-39-19 cm; a double central truncated pyramidal piece, which allows generating the block's hollows; and finally, the metal base that allows joining and stiffening the whole molding system.

The concrete is produced in a 150 lt capacity concrete mixer and the blocks are produced manually; the compaction of the mixture is carried out with the aid of a vibrating platform with an electric motor and an eccentric mass shaft. Once the mixture is compacted, the mold is turned over to leave the blocks on the floor of the curing room where they are kept at room temperature between 23 and 25°C and relative humidity between 90 and 100% until the test age.

2.4 Dosage of concrete mixes used

Dosages are used according to the binder combination described above and according to the following proportions (by weight): water/binder ratio = 0.65 and gravel/sand ratio = 1.0.

Table 3. Dosage for 1 m^3 of concrete for the production of blocks

Materials		Concrete according to binder			
		100% OPC	60/40	70/30	80/20
Conglomerate	Cement, kg	277.0	166.2	193.9	221.6
	Fly ash, kg	–	110.8	–	–
	Volcanic ash, kg	–	–	83.1	–
	Desert dust, kg	–	–	–	55.4
Water, lt		180.0	180.0	180.0	180.0
Sand, kg		897.4	897.4	897.4	897.4
Gravel, kg		897.4	897.4	897.4	897.4

2.5 Preparation of test specimens

2.5.1 Preparation of tests of masonry block units

For the compression test, the upper and lower faces of the block are coated with plastic mortar composed of Portland cement and gypsum in equal parts, with a thickness of no more than 3 mm, in order to obtain parallelism between the two load surfaces, following the indications of the NCh1928 (1993) standard. A block prepared for testing is illustrated in Figure 2(a). The compressive strength of block units shall be expressed as the quotient between the compressive ultimate load and the cross-sectional area at load application. A series of five blocks shall be calculated on the basis of the total area of the unit, including voids (gross area), as indicated in NCh1928 (1993); the concept of gross area is kept in force for the calculation of prismatic resistance. In addition, in order to comply with the requirements of NCh182 (2008), another series of five blocks is prepared and tested, whose compressive strength is calculated on the basis of the average net area, which makes it possible to compare the strength results with the minimum average threshold requirement of 13 MPa indicated in NCh181 (2006).

(a) (b) (c)

Figure 2. Arrangement of concrete block masonry specimens in the test press:
(a) masonry unit, (b) masonry prism and (c) masonry wall.

2.5.2 Preparation for testing of masonry prisms

Five prisms were prepared, each consisting of three strands of blocks, connected together by a joint mortar made of the same gravel combination as the block concrete, with a thickness of about 10 millimeters. The prisms are tested with the upper and lower faces properly coated with gypsum-cement-water paste, at the age of 28 days after their production. A prism prepared for testing is illustrated in Figure 2(b). The compressive strength of prisms is expressed as the quotient between the breaking load and the gross area of the cross section, according to NCh1928 (1993).

2.5.3 Preparation for testing of masonry walls

Five square walls, each measuring 60 × 60 cm, are constructed, using rows of one and a half blocks horizontally and three rows vertically. These are joined by joint mortar of the same combination as the block concrete. After 28 days of their production, the walls are tested by applying compression load in the direction of one of the main diagonals, with the aid of metal heads that are adequately faced with gypsum-cement paste and supported on the vertices. A wall prepared for testing is showun in Figure 2(c). In this case, the mechanical resistance is expressed as shear resistance according to the quotient between the maximum breaking load and the area that compromises the length of the main diagonal and the thickness of the wall, without taking into account the hollow surface of the blocks, according to the procedure described in standard NCh2123 (1997).

2.5.4 Preparation for joint mortar testing

The joint mortar used for the construction of prisms and walls consists of the ratio sand/gravel/water = 8/2/1 (by weight); the dosage that will be kept fixed both for the prism test and for the wall test. The conglomerating material is understood as the joint addition of cement and pozzolan in the combinations described above. For quality control of the mortar, 40 × 40 × 160 mm Rilem specimens are made and tested in flexural and compressive tests, according to NCh158 (1967). The test is carried out after 28 days of curing submerged in water.

2.6 Determination of the characteristic compressive strength of masonry specimens

All values of characteristic strength of masonry specimens shall be expressed according to Annex A of NCh1928 (1993). To obtain the characteristic strength, an age of 28 days should be complied with and 5 specimens should be tested in their type, where the value is expressed by the following equation:

$$R_k = \overline{G} - 0.431(G_5 - G_1) \qquad (1)$$

where R_k is the characteristic strength corresponding to the type of specimen, $\overline{G}$ is the average strength of the five specimens tested and *G5*, *G1* correspond to the highest and lowest strength values obtained from the tests, respectively. Therefore, the following characteristic strengths are defined, depending on the type of specimen: a) characteristic strength of concrete block units f_p, b) characteristic strength of prisms or prismatic strength of concrete blocks *fm*' and c) characteristic shear strength or basic shear strength of concrete block walls T_m.

2.7 Selectivity criteria of pozzolanic binder mixes for block making

It is proposed to use three different pozzolanic additives, in three different Portland cement replacements. In general, the parameter that most influences the decision of selectivity of the materials to be used is the result of the mechanical resistance obtained, however, the economic cost of its use also has an incidence in this decision. In this case, it is interesting to compare the combined contribution of each of the binder mixtures in order to obtain a good mechanical strength at the lowest economic cost. In this sense, it is proposed to evaluate each of these mixtures through the definition of the arbitrary parameter ~~K,~~ which represents the quotient value between the mechanical strength and the economic cost.

$$K = \frac{\text{Mechanical resistance}}{\text{Economic cost}} \qquad (2)$$

Using the parameter K, the most suitable mix is selected based on the highest value obtained through its evaluation, with the prismatic strength fm' (or the basic shear strength T_m) in the numerator and the economic cost of the binder in the denominator. To determine the economic cost of the binder, it is assumed that the benchmark economic cost of acquiring a unit weight of Portland cement (e.g., ton) is equivalent to 100%. The equivalent economic cost of pozzolanic materials can also be estimated for the same unit weight, associating it with the economic cost of stockpiling, loading and transportation to the consumption center and comparing it with the cost of cement, resulting in the following economic costs. Value 18% for fly ash, value 14% for volcanic ash and value 10% for desert dust. The pozzolanic materials tested have a lower acquisition cost than cement because in some cases they are industrial liabilities that are disposed of in landfills, such as fly ash. In other cases they are found in freely available natural deposits such as volcanic ash and desert dust. Thus, the economic cost of new pozzolanic binders is determined according to the following weighted calculation:

- Cost of fly ash binder 60/40:

$$60\% \text{ cement} + 40\% \text{ fly ash} = 0.60 \times 100\% + 0.40 \times 18\% = 67.2\%$$

- Cost of volcanic ash binder 70/30:

$$70\% \text{ cement} + 30\% \text{ volcanic ash} = 0.70 \times 100\% + 0.30 \times 14\% = 74.2\%$$

- Cost of desert dust binder 80/20:

$$80\% \text{ cement} + 20\% \text{ desert dust} = 0.80 \times 100\% + 0.20 \times 10\% = 82.0\%$$

In other words, with these replacements, it is possible to save between 33% and 18% of the cost of using 100% Portland cement conglomerate in the production of concrete for blocks, figures that describe an interesting economic saving. However, to achieve these savings, it is also important to have adequate mechanical strength. This is also what we intend to evaluate in this research.

2.8 Strength of concrete block masonry and mortar specimens

Table 4 shows the experimental results of maximum strength, minimum strength, average strength and characteristic strength obtained in series of concrete block masonry specimens made with different binder mixes and joint mortars. In the case of specimens of block units, series strengths are shown referring to the total gross area (length and width), without discounting voids; also, results of series strengths referring to the average net area, calculated according to the indications of the NCh182 (2008) standard.

Table 4. Strength of masonry specimens of concrete block masonry and joint mortar

Type of specimen	Properties	Concrete according to binder			
		100% OPC	60/40	70/30	80/20
Blocks, gross area	Gross area, m^2	0.0557	0.0555	0.0557	0.0551
	f_c maximum, MPa	17.30	14.48	13.64	14.29
	f_c minimum, MPa	16.00	12.16	13.14	12.89
	f_c average, MPa	16.68	13.62	13.37	13.44
	f_p, MPa	16.12	12.62	13.15	12.84
Blocks, net area	Net area, m^2	0.0329	0.0329	0.0331	0.0336
	f_c maximum, MPa	27.82	23.80	22.46	23.64
	f_c minimum, MPa	25.73	19.98	21.63	21.33
	f_c average, MPa	26.82	22.39	22.01	22.23
	f_p, MPa	25.92	20.74	21.65	21.23

Type of specimen	Properties	Concrete according to binder			
		100% OPC	60/40	70/30	80/20
Prisms	f_c maximum, MPa	5.01	4.34	4.52	4.78
	f_c minimum, MPa	4.37	4.25	3.99	4.24
	f_c average, MPa	4.62	4.28	4.16	4.42
	f_c', MPa	4.34	4.25	3.93	4.19
Walls	T maximum, MPa	1.06	1.02	0.97	0.94
	T minimum, MPa	0.79	0.52	0.68	0.73
	T average, MPa	0.92	0.74	0.81	0.87
	T_m, MPa	0.80	0.52	0.69	0.78
Mortar	Flexion, MPa	7.8	5.7	6.9	7.0
	Compression, MPa	51.7	41.3	42.7	44.6

3. Analysis of Strength Results of block, Masonry Prisms and Masonry Walls

3.1 Analysis of block strength results

For the different binder combinations, the results of compressive strength of blocks referred to the gross area and net area do not show great variations among them, which would indicate that the mixtures and the manufacture of blocks were homogeneous. Neither are important differences observed between combinations of binders with pozzolanic additions, which proves the pozzolanic reactivity between the different cement replacement additions, coinciding with that reported by Roldán (2003). It should be noted that all the units tested significantly exceeded the strength requirements for block as a masonry unit. The Chilean masonry standards NCh1928 (1993) and NCh2123 (1997) indicate that the blocks must satisfy the requirements of class A specified in the old standard NCh181 (1965), 4.5 MPa referring to the gross area. However, this standard is no longer in force and has been replaced by NCh181 (2006), which specifies that the average of the units must exceed 13 MPa and the individual block must exceed 12 MPa, both values measured on the net area.

3.2 Analysis of strength results of masonry prisms

The results of the prism test, as shown in Table 4, also show that there are no great variations in results between the different binder combinations and that in general, although lower, the strengths are not exceed 10% less than the concrete with 100% cement binder, which is the reference or control mix. The NCh2123 (1997) standard indicates that the basic compressive strength of masonry fm' is determined from the test of five prisms coinciding with the expression (1), with which characteristic strength values have been calculated in this study. This standard also indicates that when fm' has not been determined by prism testing, and both the masonry units and the joint mortar meet the requirements of the standard, then f_m' can be determined from the unit strength value according to the following expression:

$$f_{m'} = 0.30 f_p \text{......(3)}$$

When applying expression (3) to the average value of unit resistance f_p, referred to the gross area, for all combinations with pozzolan; as well as for the series with fly ash and desert dust, we obtain a value of basic prism compressive strength that is 3.9% lower than the prismatic characteristic resistance value effectively measured through the test of five prisms. However, for the series with volcanic ash, we obtain a value that is 2.1% higher than the value measured through the test of five homologous prisms. This would validate what is specified by the NCh1928 (1993) standard in (3), since it indicates that such expression is adequate to assume it as f_m' value, which is a good criterion. However, this is not fulfilled for 100%

cement concrete, since the evaluation of (3) overestimates the basic compressive strength of the prism to assume it as f_m' value in the structural design processes. In fact, the evaluation of (3), provides a prism strength value 15.3% higher than the prism strength value measured through the five-prism test. This effect is most likely due to the early age hardening or stiffness produced by the hydration process of Portland cement compared to mixtures with pozzolanic additions; a stiffness condition that is lost with the slenderness of the prism.

3.3 Analysis of strength results of masonry walls

The standard NCh2123 (1997) indicates that the basic shear strength of masonry, T_m, is determined from the test of five walls coinciding with expression (1) above. This standard also indicates that when T_m has not been determined by means of wall tests, the basic shear strength indicator values specified in Table 1 of item 5.7.2 of this standard can be used. It indicates that in the case of block units with strength $f_p \geq 5.0$ MPa and mortar grade ≥ M10 (10 MPa), which would be the case of the present study, the indicative value of basic shear strength T_m will be 0.30 MPa.

From Table 4, it can be observed that the characteristic values of shear strength T_m obtained experimentally from the wall tests, in the most unfavorable case (binder with fly ash), are 73% higher than the value 0.30 MPa indicated by the standard (value without wall test). It is concluded that these mixtures with pozzolanic binders report very good shear strength of the masonry; for a highly seismic country like Chile, the shear strength T_m of the masonry serves as the quality reference.

4. Analysis of Results of Mechanical Resistance in Joint Mortar

The values of the compressive strength of joint mortar shown in Table 4 show the high values obtained in all conglomerate mixes, well above the requirements of the masonry standards, which indicate the use of joint mortar equal to or higher than M10 (10 MPa). Of all the results of compressive strength (at 28 days of age) exposed, those of 100% cement are higher than those of binders with pozzolanic additions, probably due to the fact that the reactivity of pozzolans at that age is not yet fully manifested in the mixture.

4.1 Selectivity analysis of pozzolanic binder mixes for the production of blocks.

Since all the binder mixes meet strength requirements related to masonry, the selection of the binder mix is made by comparison between them through the evaluation of the arbitrary parameter ~~K,~~ equation (2), which can be seen in Table 5.

Table 5. Binder mixes, evaluation of parameter ~~K~~

	Concrete according to binder			
Detail	100% OPC	60/40 Fly ash	70/30 Volcanic ash	80/20 Desert dust
Unit cost, %	100.0	18.0	14.0	10.0
Cost of binder mix, %	100.0	67.2	74.2	82.0
Prismatic resistance, MPa	4.34	4.25	3.93	4.19
Basic shear strength, MPa	0.80	0.52	0.69	0.78
~~K~~ for prismatic resistance	4.34	6.32	5.30	5.11
~~K~~ for basic shear strength	0.80	0.77	0.93	0.95

By means of the evaluation of parameter ~~K~~, Table 5 shows how convenient it is to use binder combinations with pozzolans and that in the case of similar strength, the greatest cost benefit will be produced by the binder combination that reduces the use of cement the most due to its high economic value. In this sense, if the important reference for a project is prismatic strength, the binder combination that results in the highest value of parameter ~~K~~ is the one that uses fly ash, with advantages over any other type of mix. However, if the important reference for a project is shear strength, then the best binder combination results with the use of desert dust as it provides a higher value of the K parameter. Both situations provide sufficient mechanical strength (in type) at the lowest economic cost.

5. Conclusions

The lower strengths shown by specimens using the combination of binder with pozzolan in comparison with specimens using 100% Portland cement are explained, because pozzolans have a slower reactivity than Portland cement, since they are activated by the action of calcium hydroxide produced during cement hydration (Malhotra and Metha, 1996). Furthermore, given that previous studies (Roldán et al., 2013) support the results of pozzolanic binders at 90 days, it is highly probable that as the age exceeds 28 days, these differences in strength will further decrease or exceed the strength of the 100% cement specimens, which would reaffirm the benefits of using this type of binder combinations in block masonry.

In general, the proposed objectives are met, since it is feasible to replace cement with pozzolanic materials in masonry blocks, as proven by both experimental results of mechanical resistance and the compliance with the standards in force in Chile. In addition, by reducing the demand for cement, it helps the sustainability of the environment by indirectly reducing the generation of CO_2. It should also be considered that the use of natural products such as volcanic ash and desert dust, as well as industrial waste such as fly ash, can reduce the economic cost.

Fly ash is currently considered an industrial liability that has no acquisition cost and perhaps the benefits of its use as a replacement for cement, as shown in studies such as this one, may eventually change this condition. On the other hand, both desert dust and volcanic ash are free economic goods, since one is available everywhere in the desert of northern Chile and the other is available in certain parts of the country and throughout the Andes Mountains. Therefore, the contribution they make to the preparation of cementitious mixtures cannot be underestimated since they would contribute to a greater increase in resistance than a similar reduction of the cement content in the mixture and to a non-negligible reduction in the economic cost of construction.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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