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EFFECTIVENESS OF A NATURAL POZZOLAN FROM SOUTHERN SASKATCHEWAN FOR CEMENT REPLACEMENT IN CONCRETE

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Abstract: Pozzolans are a category of supplementary cementitious materials that can be used as a partial replacement of portland cement in concrete. Aside from their environmental benefits, some pozzolans have been found to increase the strength, reduce the permeability, and thereby increase the durability of concrete. In this study, a natural pozzolanic material from deposits in Southern Saskatchewan was evaluated for its effectiveness as a partial replacement of portland cement in the production of concrete. Specimens with replacement amounts of 10%, 20% and 30% by weight of cement were prepared and tested to measure compressive strength and permeability, along with a reference mix without pozzolan for comparison. The effect of sieving out particle sizes greater than 74 μm was investigated. The results showed that 10% and 20% replacement amounts slowed down the strength development, but produced long-term compressive strengths at greater than six months that did not differ significantly from that of the reference mix, except when pozzolan particle sizes were not limited to less than 74 μm at the 20% replacement amount. The permeability of samples produced with the 10% replacement amount was significantly lower than that of the reference mix, and was also significantly lower when pozzolan particle sizes were limited to less than 74 μm. The natural pozzolan is therefore considered to be an effective cement replacement material.

1 INTRODUCTION

1.1 Background

Natural pozzolans are naturally occurring materials that contain reactive silica and/or alumina. They may be found in volcanic deposits, clays, shales and diatomaceous earth. When mixed with portland cement, the silica in the pozzolans reacts with the calcium hydroxide that is produced by the cement hydration reactions to produce more calcium silicate hydrate (CSH). As a result, the pozzolanic reaction reduces the amount of calcium hydroxide in the hardened cement paste and increases the amount of CSH, producing a more refined pore structure that may reduce the permeability and increase the long-term strength of the concrete.

The use of natural pozzolans for the production of concrete dates back several millennia to Greek and Roman times. More recently, within the last century, the benefits of natural pozzolans have become more apparent, and they have been used extensively as a partial replacement for portland cement in many large projects throughout North America (ACI 232, 2012). Among the many documented advantages are the lower heat production, improved workability, improved sulphate resistance, control of expansion due to alkali-silica reaction (ASR), lower permeability, and higher strengths at later ages (Gibbons 1997, Joshi and Lohita 1997, Ramezanianpour 2014). In addition, the use of natural pozzolans has environmental benefits since it reduces the energy use and CO_2 production associated with the manufacture of portland cement. The effectiveness of a given natural pozzolan, however, is highly dependent on its unique characteristics and must be evaluated.

The amount of pozzolan required to produce a desired effect depends on the reactivity of the particular pozzolan. Low reactive pozzolans can be used in replacement amounts (by mass) varying from 15 to 35%, whereas high reactive ones are used in lower amounts varying from 5 to 15%, depending on the amount of cement in the concrete mix (Al-Chaar et al. 2011). In order for the pozzolanic reaction to proceed, it is also necessary for pozzolan particles to be relatively small, ideally of a similar size to that of the portland cement. Therefore, natural pozzolanic materials often require grinding, and some also require heat treatment (calcination) to be effective. The quantity of natural pozzolans used in the concrete depends on the application and on the specifications of that particular work.

Southern Saskatchewan is home to a large number of volcanic deposits that are potential sources of natural pozzolans, as documented by Crawford (1951). The effectiveness of these materials for use as a replacement for portland cement has yet to be determined; however, they could have economic value if they are found to be a suitable replacement.

1.2 Objectives and Scope

The primary objective of this investigation was to determine the usefulness of a natural pozzolan from one of the deposits in southern Saskatchewan as a supplementary cementitious material for partial replacement of portland cement in concrete. In particular, the study was undertaken to determine whether concrete produced with up to 30% pozzolan replacement by mass could develop compressive strengths equal to or greater than that of a control group without the pozzolan, and reduce the permeability. Tests were conducted over a one-year period on samples containing the pozzolan in two different forms (as crushed and passing a #200 sieve) to determine the effect of particle size.

2 EXPERIMENTAL METHODS

2.1 Materials

The mix proportions used for this study are listed in Table 1. The proportions correspond to a basic mix that might be used for an application requiring a higher quality normal strength concrete, such as for a bridge deck. As can be seen, a relatively low w/cm ratio of 0.34 was used. Type GU (general use) hydraulic cement obtained from Lafarge Canada was used. The fine aggregates consisted of natural sand with most particles smaller than 5 mm, while coarse aggregates had a maximum particle size of 20 mm. All aggregates were prepared to a saturated surface dry (SSD) condition prior to mixing. Tap water was used to prepare the mixes.

Table 1. Mix proportions

Material	Quantity (kg/m^3)
Gravel	1074
Sand	706
Cement + Pozzolan	439
Water	151
Superplasticizer	3.12 – 3.73
Air entrainment	0.17

The natural pozzolan was procured from southern Saskatchewan and provided by Pozzeco Corporation. It was used in two forms; the first form was prepared by crushing the raw material in a ball mill, while the second form was passed through a # 200 sieve after crushing and prior to use. Thus, the maximum particle size after sieving was 74 μm. In addition to a control batch containing only portland cement, three different pozzolan replacement amounts were investigated: 10, 20, and 30% cement replacement by weight.

The superplasticizer (Supercizer 5, Fritz-Pak) and air entrainment admixture (Air Plus, Fritz-Pak) were both added directly to the mix in powdered form. Some trials were performed that showed that adding the admixtures directly in powdered form or dissolved in water did not produce any difference in the workability of the mix. The amount of superplasticizer was varied slightly from one mix to the next to maintain similar slumps among the different materials used.

2.2 Specimen Preparation

After the aggregates had been prepared to a saturated surface dry (SSD) condition, the dry materials were poured into the mechanical mixer one by one, beginning with coarse aggregates, then sand, cement and pozzolan. This was followed by the addition of water, super plasticizer and air entrainment. Mixing was carried out for approximately 5 to 10 minutes, depending on the consistency of the paste, and continued until a homogeneous mix was obtained.

Slump was measured to check workability following standard procedures (ASTM Standard C143 2004). As shown in Table 2, measured slumps ranged from 80 to 98 mm for all batches, confirming that consistency of workability was achieved for all batches. The same amount of superplasticizer was adequate to achieve the desired workability for all except the 30% pozzolan batches, for which the higher amount listed in Table 1 was required. Immediately after the slump test, the mix was poured into the molds in three layers, and standard rodding procedures were followed. After 24 hours, the samples were de-molded and submerged in a lime saturated water bath for curing. The specimens remained in the water bath until testing.

Table 2. Measured slump for all batches (mm)

Pozzolan amount	As crushed	Passing #200 sieve
0%	80	80
10%	90	95
20%	85	90
30%	92	98

Cylindrical specimens having dimensions of 200 mm long by 100 mm in diameter were prepared for compression tests. For permeability tests, cylindrical specimens having dimensions of 100 mm long by 50 mm in diameter were prepared, from which disks of appropriate thickness were later cut, as described below.

2.3 Tests Methods

2.3.1 Compressive Strength

Compressive strength tests were performed at 7, 28, 56, 112, 182 and 364 days following ASTM Standard C 39 (1996). Five samples were tested at each age, except that 15 samples were tested at 56 days and 364 days for more statistically reliable results at those ages. The samples were left to cure in the water bath until they were ready for testing.

2.3.2 Permeability

The saturated permeability of samples was measured at ages ranging between 440 and 480 days. A centrifuge technique was used, following procedures similar to those described in ASTM Standard D6527 (2008). The centrifuge (J6-Hc Centrifuge-Beckman Coulter) consisted of a rotor attached to six swing buckets with their corresponding soil sample holders. When the centrifuge begins to spin, the buckets swing out horizontally, forcing the water to pass through the samples. Specially designed concrete sample holders were prepared that fit into the soil sample holders (see Figure 1). Details of the sample holders, as well as the procedures for permeability testing, are described by Ramadani (2013). The centrifuge can be run at angular velocities ranging from 50 to 6000 RPM, but a velocity of 3000 RPM was used for the set of tests described here.

After the appropriate curing time, the concrete samples were cut into disks 50 mm in diameter and 15 mm thick. Each sample was saturated under water for 24 hours before being sealed in the sample holder with marine epoxy to prevent leakage of water around the sides of the sample. The samples were then completely immersed with the samples holders in water for 72 hours in order to ensure complete saturation. Thereafter, the samples were taken out of the water and the sample holder was filled with water to the top and placed in the centrifuge for testing. After every four hours, the height of the water was recorded and the water loss was used to calculate permeability. Six samples were tested for each material. At the time of writing, results were not available for the 30% batches.

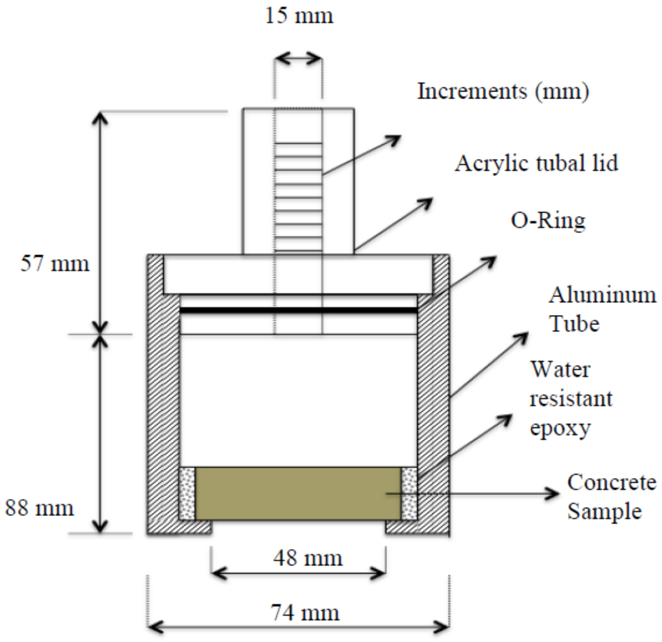

Figure 1. Schematic section through a concrete sample holder (after Ramadani 2013)

3 RESULTS AND DISCUSSION

3.1 Compressive Strength

The compressive strengths of samples tested to date are listed in Table 3. Also listed in the table is the coefficient of variation, which gives an indication of the variability of measured compressive strength. A graphical presentation of the results is provided in Figure 2.

Table 3. Mean compressive strength of each group of specimens at all test ages (MPa)

Pozzolan amount[1] & type[2]	7 days	28 days	56 days	112 days	184 days	364 days
0%	38.6 *(2.0)*[3]	50.3 *(2.6)*[4]	46.9 *(6.1)*	47.0 *(15.5)*[4]	51.1 *(9.6)*[4]	54.6 *(8.2)*
10% (ac)	35.9 *(5.4)*	40.0 *(9.3)*	44.1 *(4.4)*	45.9 *(4.9)*	49.4 *(4.4)*	54.2 *(5.6)*
10% (-200)	38.2 *(6.9)*	39.7 *(5.9)*	47.4 *(6.4)*	48.9 *(8.3)*	48.5 *(6.5)*	55.2 *(5.1)*[4]
20% (ac)	30.1 *(8.0)*	34.1 *(2.5)*[4]	35.1 *(6.6)*	38.8 *(10.7)*	39.3 *(4.8)*	44.8 *(9.4)*
20% (-200)	33.7 *(7.6)*	37.4 *(4.4)*	42.9 *(6.3)*	46.0 *(8.9)*[4]	43.0 *(22.1)*	52.1 *(9.7)*
30% (ac)	32.0 *(19.4)*	39.2 *(1.0)*[4]	36.4 *(8.9)*[4]	39.8 *(16.2)*		
30% (-200)	35.0 *(4.7)*	38.9 *(6.2)*	39.3 *(7.7)*	46.2 *(6.8)*		

1. Percentage of total cementitious materials by weight
2. ac = as crushed; -200 = passing #200 sieve
3. The italicized values shown in parentheses are the coefficients of variation in percent
4. Indicates that an outlier was removed, or one of the tests failed, or both

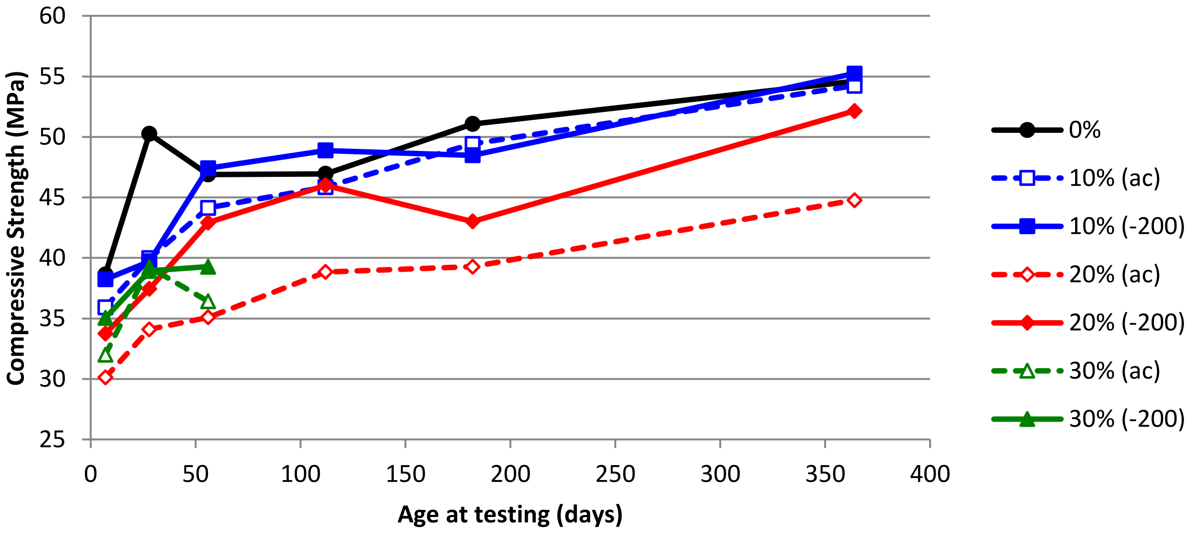

Figure 2. Variation of compression strength with age (ac = as crushed; -200 = passing #200 sieve)

Despite some apparent inconsistencies in the measured data (e.g., the high strength of the control mix at 28 days), some trends are observed. First, at earlier ages (up to 56 days), with two exceptions, the compressive strengths of all mixes differ significantly from that of the control mix. The two exceptions are the 10% pozzolan -200 samples at 7 and 56 days, which do not differ from the control group at a 90% level of confidence. At later ages (112 days and later), only the 20% as crushed batch differs significantly from the control group. Thus, replacing 10 or 20% of the cement with the natural pozzolan appears to slow the strength development, but does not have a significant effect on the compressive strengths developed in the long term (i.e., greater than six months), except if the maximum particle size is not controlled at the 20% replacement rate. It should be recalled that the data for 56 and 364 day compressive strengths are considered more reliable, since a larger number of samples were tested at these ages.

Comparing compressive strengths of the samples prepared with the pozzolan in as-crushed form and with particle sizes below 74 μm, a statistical analysis shows that at the 10% replacement rate, there is generally no difference between the two, while at the 20% replacement rate, the samples prepared with the pozzolan in as-crushed form is generally significantly lower than that prepared with particle sizes below 74 μm. Thus, limiting the maximum particle size to 74 μm is important to ensure that compressive strength is not compromised at the 20% replacement rate.

3.2 Permeability

The mean values for the coefficient of permeability of all samples tested to date are listed in Table 4 and presented graphically in Figure 3. Coefficients of variability are also listed in the table, and error bars in the graph correspond to one standard deviation from the mean.

Table 4. Mean coefficients of permeability

Pozzolan amount[1] & type	Coefficient of permeability (m/s)
0%	3.17 *(31)*[2]
10% (as crushed)	2.06 *(36)*
10% (passing #200 sieve)	1.45 *(1.2)*
20% (as crushed)	3.70 *(13)*
20% (passing #200 sieve)	2.83 *(39)*

1. Percentage of total cementitious materials by weight
2. The values shown in the parentheses are the coefficients of variation in percent

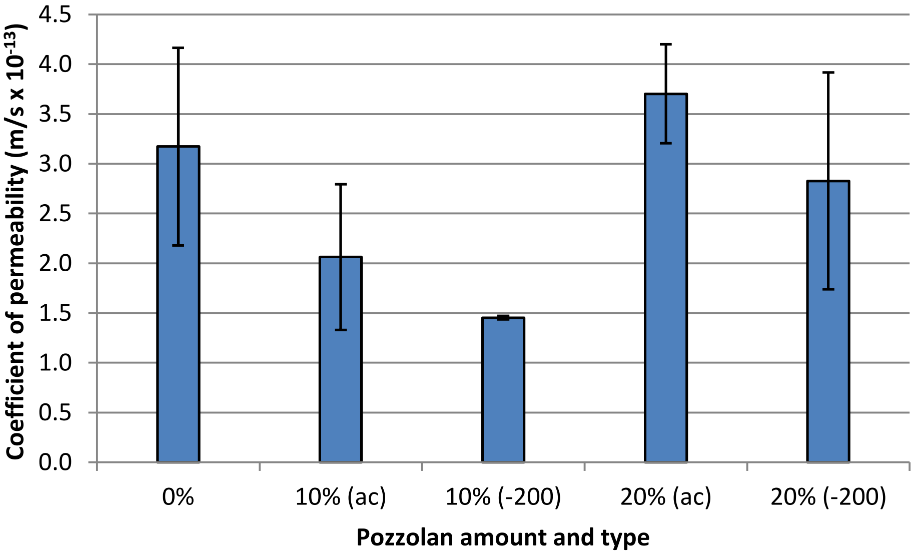

Figure 3. Coefficient of permeability, as measured between 440 and 480 days

The concrete used for this study was a relatively high quality mix, with a concomitantly low permeability. As a result, very little water passed through any of the samples over a 24 hour period, producing measured values for permeability lying close to the margin of error for the tests. Despite this, some differences are apparent among the samples. Both of the mixes prepared at the 10% pozzolan replacement rate had permeabilities that were significantly lower than that of the control mix at the 90% level of confidence. At this replacement rate, the reductions in permeability were 35% and 55% for the as-crushed and -200 mix, respectively. The two 10% mixes also differed significantly from each other, with the 10% -200 mix producing the lowest permeability of all the mixes studied, 30% lower than that of the 10% as-crushed mix. The permeability of samples prepared at the 20% replacement rate did not differ significantly from that of the control mix or from each other, although the mean value for the 20% -200 mix was 11% lower than that of the control mix, while that of the 20% as-crushed mix was 17% higher. The natural pozzolan therefore appears to be effective at reducing the permeability of the concrete, particularly at the 10% replacement rate and when the maximum particle size of the pozzolan is controlled. Future tests are planned to measure the effect of the pozzolan on permeability using a lower quality concrete.

4 CONCLUSIONS

Based on compression and permeability tests conducted using concrete samples prepared with 10% and 20% pozzolan replacement of cement by mass, in both as-crushed form and with a maximum size of 74 μm, the natural pozzolan from sources in southern Saskatchewan was found to be effective as a cement replacement. Replacing 10 or 20% of the cement with the natural pozzolan slowed the strength development, but did not have a significant effect on the compressive strengths developed in the long term (i.e., greater than six months), except when the maximum particle size was not controlled at the 20% replacement rate.

The permeability of all samples tested was relatively low, with measured values lying close to the margin of error for the tests, such that differences among the various groups of specimens were not as apparent as might have been the case if a concrete mix with a higher permeability had been used. Nonetheless, the tests showed that replacing 10% of the cement with the natural pozzolan significantly reduced the permeability, by 35% and 55% for the pozzolan in as-crushed form and with a maximum particle size of 74 μm, respectively. The 20% replacement rate did not result in a statistically significant difference in permeability relative to the control mix.

Considering the effect of the particle size of the natural pozzolan, very little difference was observed between the compressive strengths of samples prepared with as-crushed and sieved pozzolan at the 10% replacement rate, while at the 20% replacement rate, the samples prepared with the as-crushed pozzolan had compressive strengths that were generally significantly lower than that prepared with the pozzolan that had been sieved to a maximum particle size of 74 μm. Thus, not limiting the maximum particle size negatively impacted the compressive strength at the 20% pozzolan replacement rate. Samples prepared with particle sizes less than 74 μm had mean coefficients of permeability that were 30% and 24% lower than their companion specimens prepared with the as-crushed pozzolan, for the 10% and 20% replacement rates, respectively. However, the difference was only statistically significant at the 10% replacement rate. It would appear, therefore, that limiting the particle size of the natural pozzolan to below 74 μm has a positive effect on both compressive strength and permeability.

ACKNOWLEDGEMENTS

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