Use of a natural pozzolan for improving concrete properties

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ABSTRACT: In recent years, more optimized, high-performance Portland cements and combinations of Portland cements with pozzolanic materials have been used for concrete structures in severe chloride containing environment. In recent years, it was also shown that the filler effect is more important than its pozzolanic effect. Thus, the fineness of the pozzolan is very important for the modification of aggregate-cement interface zone in high performance concretes. To provide more information about a natural pozzolan on the resistance of concrete against chloride penetration, an experimental program was carried out, where pure Portland cement was partially replaced by the natural pozzolan at various amounts. To increase the filler effect, thus, obtain better concrete properties, the pozzolan was ground to two different finenesses. To compare the effectiveness of this pozzolan, mixtures with a finely ground blast furnace slag was also prepared. In the experimental study, strength of the mixtures were obtained at different ages. The resistances of the concretes against chloride penetration were determined using different methods. The rapid chloride penetration test according to ASTM C1202, an immersion test and a wetting-drying test using a chloride solution were performed. Electrical resistivities of the mixtures were also recorded. The results obtained were used as input parameters in a multi-objective optimization method where the strength of concretes were maximized but rapid chloride permeability and cost were minimized.

1 INTRODUCTION

Concrete is the world's most widely used construction material. Being the largest user of natural resources, concrete production has a serious effect on environment. Large amounts of greenhouse gases are released during this production and it is estimated that the cement production releases about 7% of the CO₂ production worldwide. A step in decreasing the energy consumption and greenhouse emissions caused by the concrete production can be to reduce the Portland cement usage by incorporating supplementary cementing materials in concrete. By replacing part of cement with these materials, cement consumption can be reduced and also at the same time, fresh and hardened concrete properties can be improved. Utilization of pozzolanic materials is an effective method for obtaining high performance concrete with good long-term durability. Extensive experience has shown that it is not the disintegration of the concrete itself but rather the electrochemical corrosion of embedded steel which poses the most critical and greatest threat to the durability and long-term performance of concrete structures in severe environments.

Since a number of different cementitious materials and reactive fillers are now being applied for concrete production, the concrete properties are more and more being controlled by the various combinations of such materials. In addition, the concrete properties are also more and more being controlled by the use of various types of processed concrete aggregates, new concrete
admixtures and sophisticated production equipment. As a result, the old and very simple terms “water/cement ratio” and “water/binder ratio” for characterizing and specifying concrete quality have successively lost their meaning. In particular, this is true for concrete durability such as the resistance of concrete against chloride penetration.

The main objective of the work presented herein is to provide more information about the effect of a natural pozzolan on the properties of concrete. In the experimental study, concrete mixtures containing a natural pozzolan were prepared. The pozzolan was ground to two different finenesses. For comparison, mixtures with a finely ground blast furnace slag were also produced. The details of the mixtures and the test performed are given below.

2 EXPERIMENTAL

2.1 Materials

Same ordinary portland cement (PC 42.5), natural pozzolan ground to two different finenesses, and a finely ground blast furnace slag were used in the concretes. The 7- and 28-day compressive strengths of the standard RILEM Cembureau cement mortars were 44.2 and 55.7 MPa, respectively. The natural pozzolan used in this study was brought from Sile, which is located approximately 100 km west of Istanbul. The blast furnace slag was obtained from Karabuk production plant located in the northwest coast region of Black Sea in Turkey. The Blaine surface areas (B.S.A.) of the natural pozzolan were 440 m²/kg and 660 m²/kg obtained by grinding. The ground blast furnace slag used in this study also Blaine surface area of 550 m²/kg. The natural pozzolan and blast furnace slag were ground in a laboratory ball mill. The specific gravity of the natural pozzolan and blast furnace slag were 2.55 gr/cm³ and 2.92 gr/cm³, respectively.

2.2 Mixtures

Concrete mixtures having the same water/binder ratio of 0.45 were produced in the experimental study. The ordinary Portland cement was partially replaced by the natural pozzolan in which the partial replacement ratios were 15%, 30% and 50%. These replacements were made for both finenesses of the pozzolan. Two mixtures containing 50% and 70% blast furnace slag were also produced. In addition, a control mixture containing only ordinary Portland cement as binder was also prepared. Thus, nine different mixtures were obtained. In all mixtures, partial replacement of cement by natural pozzolan or slag was on one to one weight basis. Limestone type coarse aggregate was used in all concretes. The aggregate grading, water-binder ratio, and the maximum particle size of aggregate were kept constant in all mixtures. The grading curve of concrete aggregate was chosen between ISO A32-B32 and closer to B32. Natural sand, crushed limestone sand, crushed limestone No. I and II were used in the concretes. A superplasticizer was used to maintain approximately the same slump of 15 ± 1 cm.

The concrete mixtures were designated as follows: C00, P4-15, P4-30, P4-50, P6-15, P6-30, P6-50, S50 and S70. C00 is the reference concrete containing only Portland cement. The mixture codes P4 and P6 denote fineness of the natural pozzolan. P4 indicates the natural pozzolan having a Blaine surface area of 440 m²/kg and P6 indicates 660 m²/kg. The first two digits after P4 or P6 show the partial replacement amount of cement by the pozzolan. For example P4-30 represents the concrete containing 30% natural pozzolan that has a Blaine surface area of 440 m²/kg. B50 and B70 indicate the mixtures containing 50% and 70% blast furnace slag, respectively.

All mixtures were prepared in a laboratory mixer with vertical rotation axis by forced mixing. Details of the mixtures are shown in Table 1. All the specimens were demolded after 24 h and stored in a water tank saturated with lime at 20 °C until the testing day.
Table 1. Mix proportions and some properties of the fresh concretes

<table>
<thead>
<tr>
<th>Mixture Code</th>
<th>C00</th>
<th>P4-15</th>
<th>P4-30</th>
<th>P4-50</th>
<th>P6-15</th>
<th>P6-30</th>
<th>P6-50</th>
<th>S50</th>
<th>S70</th>
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<td>Cement, kg/m³</td>
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<td>Natural pozzolan, kg/m³ (BSA: 440 m²/kg)</td>
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<td>123</td>
<td>206</td>
<td>0</td>
<td>0</td>
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<td>62</td>
<td>123</td>
<td>206</td>
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<td>Blast furnace slag, kg/m³</td>
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<td>185</td>
<td>185</td>
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<td>Water/binder</td>
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<td>0.45</td>
<td>0.45</td>
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<td>Slump (mm)</td>
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2.3 Testing Procedures

Compressive strength of the concretes were obtained at 7, 28 and 90 days. Three cylinders of 100 mm diameter and 200 mm height were used for each testing age. Electrical resistivities of the specimens were also measured by the two-electrode method using external steel plates (Sengul and Gjorv, 2008). The tests were carried out on saturated surface dry specimens. The resistance of concrete against chloride penetration was obtained by using three different methods. The first test was the rapid chloride ion permeability test according to ASTM C1202 (2010). The test was performed only at the age of 28 days. The second type of testing performed for determining the resistance against chloride penetration was an immersion test in which, 28 day old concrete samples were immersed in a 3% chloride solution for 75 days. For this test, the specimen preparation and immersion procedures in NT Build 443 were followed. At the end of the immersion period, specimens were split into two and a silver nitrate solution was sprayed onto the split surfaces to determine the chloride penetration depth. The third testing was a spraying (wetting – drying) test in which 3% chloride solution was sprayed onto the concrete samples for 4 hours followed by 4 hours of drying obtained by blowing air onto the specimens using a fan. The drying was performed at 20°C. A specially designed spraying chamber was used for this exposure. Before testing, as in the immersion test, specimens were coated on all the surfaces except one, so that chloride penetration takes place only in one surface. 28 day old specimens were used for this test and wetting – drying cycles continued for 50 days. Thus, in total 150 cycles of spraying – drying were performed. ASTM C1202 test and resistivity test were performed on all the mixtures but the immersion test and spraying test was performed on the reference mixture and the mixtures containing natural pozzolan.
3 RESULTS AND DISCUSSION

3.1 Compressive Strength

Compressive strengths of the concretes are given in Figure 1. Strengths of the concretes containing 15% or 30% natural pozzolan were similar to that of the Portland cement concrete. For example, compared to the reference, the mixture containing 15% of the pozzolan with 440 m²/kg natural pozzolan had 3% lower strength at the age of 7 days and only 1% at 28 days. For the same replacement ratio, compressive strength of the one with 660 m²/kg had 10% higher strength at 28-days age. This difference increased to 22% at 90 days. For all the ages tested, the compressive strength of the concretes containing 50% natural pozzolan were lower compared to those of the reference concrete produced with Portland cement. Compressive strengths of the concretes containing blast furnace slag, however, were higher than the reference mixture. At the age of 28 days, the compressive strength of the mixture with 50% and 70% slag were approximately 25% and 11% higher, respectively. This difference was even more at 90 days. For the replacement ratio of 15%, the finer pozzolan (B.S.A.: 660 m²/kg) had significantly higher strength compared to coarser pozzolan (B.S.A.: 440 m²/kg). At the 30% replacement, however, the effect of fineness was not as high as expected and at the ages of 7 days and 28 days, the values obtained with the fine pozzolan (B.S.A.: 660 m²/kg) were approximately 5% lower than the reference mixture and 10% lower compared to the one with higher fineness. At 90 days, however, the finer pozzolan performed better and higher strengths were obtained.

![Cylinder compressive strength vs. Age](Image)

Figure 1. Compressive strengths of concretes.

3.2 Electrical Resistivity

Electrical resistivities of the concretes are shown in Figure 2. At the age of 7 days, mixtures containing natural pozzolans have lower electrical resistivities. For example, the resistivity of the mixture containing 30% pozzolan (B.S.A. 660 m²/kg) have 40% lower resistivity than the reference mixture. However, compared to the Portland cement concrete, mixtures containing blast furnace slag had higher resistivity values even at the age of 7 days. At 28 days and beyond, concretes containing natural pozzolans or slag performed much better and inclusion of these admixtures substantially increased the electrical resistivity. As seen in Figure 2, the electrical resistivities of the concretes produced with the slag cements were significantly higher than those of the other mixtures at all the ages tested. For example, at the age of 28 days, resistivity of the concrete containing 50% slag were approximately 2.7 times higher than the Portland cement concrete and 1.6 times than the one with 50% finely ground pozzolan. Electrical resistivity is a
material property and can be defined as the resistance of concrete to an electrical current. Electrical current is transported in the pore system of concrete and an increase in resistivity maybe an indication of a refined pore system. The ions in the pore solution may also be crucial for the transportation of electrical current in the samples.

![Figure 2. Electrical resistivity of concretes.](image)

### 3.3 Rapid Chloride Permeability

Figure 3 shows the effect of mineral admixtures on the rapid chloride permeability (RCP) of the concretes. The rapid chloride permeability of the concretes produced with the natural pozzolan or blast furnace slag were substantially lower than that of the Portland cement concrete. For example, the RCP of the concretes containing 30% natural pozzolan were approximately half of the value of normal concrete. Concretes containing blast furnace slag performed even better.

![Figure 3. Rapid chloride permeability concretes.](image)

As seen in the figure RCP of mixtures decreased with the pozzolan replacement ratio. This reduction is more significant in the mixtures containing the pozzolan of 440 m²/kg Blaine fineness. It seems that, except the replacement ratio of 15%, the fineness of the natural pozzolan did not affect the RCP of concretes (Figure 3). For 15% replacement, however, the reduction in RCP due to the pozzolan fineness was approximately 20%. RCP results are in good agreement with the resistivity values.
3.4 Chloride Penetration Depth after Immersion in Chloride Solution

Results of the immersion test are shown in Figure 4. Concrete produced by Portland cement had the highest chloride penetration depth while those of the ones containing natural pozzolan were substantially lower. As seen in the figure, the replacement ratio also affected the chloride penetration depth, but this effect is not significant. The effect of the fineness of the pozzolan was also not significant.

![Figure 4. Chloride penetration depths obtained after immersing in chloride solution.](image)

3.5 Chloride Penetration Depth after Spraying with Chloride Solution

Figure 5 shows the chloride penetration depths in concretes after spraying with chloride solution and drying cycles. The reference concrete containing only Portland cement as the binder had the highest chloride penetration depth. Although the concretes including pozzolans had smaller chloride penetrations, the difference between the reference concrete and the ones with 15% pozzolan were small compared to immersion test results or RCP results. The chloride penetration depths reduced with increasing amounts of pozzolan. On the other hand, the chloride penetration depths obtained for both pozzolan finenesses were very close to each other.

![Figure 5. Chloride penetration depths obtained after 150 spraying – drying cycles.](image)
To optimize several responses, multicriteria optimization techniques were used in this study. A useful approach for the optimization of multiple responses simultaneously is to use desirability functions, which reflect the levels of each response in terms of minimum and maximum desirability. Details of the procedure, equations and conditions for the optimization are given elsewhere (Sengul et al. 2005). In this study, concrete compressive strength was maximized whereas chloride permeability and cost were minimized. A very simple approach was used to compare the cost of concrete mixtures. Assuming that the aggregate, water and admixture amounts were the same for all the mixtures, only the cement, natural pozzolan and slag were taken into account in the calculation of the cost of concretes. Cost analysis indicated that the ground pozzolan costs nearly the half of the cement and finely ground blast furnace slag has a cost of about 65% of the cement cost. Thus, the price of 1 kg cement was taken as a unit, where that of the pozzolan having B.S.A. of 440 m$^2$/kg was 0.45 unit, having B.S.A. of 440 m$^2$/kg was 0.55 unit, and the finely ground blast furnace slag as 0.65 unit. Based on these assumptions, the relative costs of the concrete mixtures were calculated according to the amounts of cement, natural pozzolan, and slag. In this study, three responses (compressive strength and rapid chloride permeability at 28 days, and cost) were used for the optimization procedure. Individual desirability functions for these responses were calculated and based on these values; an overall desirability function was obtained. Mixture having the highest overall desirability function is the most desirable (thus the optimum) mixture. Results of the optimization process showed that within the limits of this work, materials used and tests performed, the slag concrete containing 70% slag is the optimum mixture. For the concretes containing natural pozzolan, however, the mixture containing 30% pozzolan with B.S.A. of 440 m$^2$/kg is the optimum mixture. The multicriteria optimization technique can be extended by including more responses such as different ages or different properties that should be maximized or minimized.

5 CONCLUSIONS

The following conclusions could be drawn from the results obtained in this study:

1. For the natural pozzolan used in this study, the compressive strengths were not affected significantly up to 30% replacement, but for higher replacement ratios, important reductions in strength were recorded. The slag used, however, contributed to strength at all the ages tested.
2. Use of the natural pozzolan or slag increased the resistance of concrete against chloride penetration significantly. Their contribution is reflected on both resistivity and different chloride penetration tests.
3. Within the limits of this work, considering only the strength, chloride permeability and cost, 70% slag seems to be the optimum replacement amount among the mixtures in this study. The optimization performed can be extended to include other properties such as shrinkage and cracking, and thus, a more optimum mixture including other characteristics, can be obtained.
4. ASTM C1202 rapid chloride permeability test method is criticized that it may not always reflect the resistance of concrete against chloride penetration and several factors may affect the results obtained, however, by comparing to other methods in this study, it may be concluded that this method is effective for quality control and comparing different concretes.

References