EFFECT OF FLY ASH ON DURABILITY OF LIGHTWEIGHT CONCRETE

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ABSTRACT
Lightweight concrete is widely used in civil engineering construction mainly because its low density and thermal conductivity, consequently yielding lower dead load, faster construction and other advantages. Workability, mechanical properties, durability, and other features of lightweight concrete were widely investigated by many researchers. Results of previous studies have shown that stability of the ternary lightweight concrete, based on using high fly ash volume, under the environmental temperature and humidity conditions of the hot and humid Mediterranean climate was confirmed. This result is essential for practical application of such concrete. The current paper presents results of a recently carried out experiments, focused on investigating durability of ternary lightweight concrete using cyclic crystallization tests. The experimental results, obtained in the frame of this study, demonstrate that formation of high volume solid cement-fly ash matrix creates a lightweight concrete structure with a minimum porosity. It is shown that partial replacement of the lightweight aggregate (for example, bottom ash) by fly ash reduces the water content in the concrete mixture due to spherical shape and glassy surface of the fly ash particles. It is also evident from the experimental results that a dense transition zone between cement-fly ash matrix and porous aggregate prevents formation of water layers, revealed on the aggregates surface.

INTRODUCTION
The enhanced durability of normal weight concrete, containing high volume fly ash, is well known and was reported in the literature 1-3. The following positive properties of such concretes were noted: enhanced resistance to repeated freezing and thawing cycles, higher resistance to reinforcement corrosion, better resistance to alkali-silica expansion and other kinds of aggressive environmental effects. The advantages seem to result from improved water-tightness of concrete containing high-volume fly ash. However, the concrete strength decreases along its lifetime period, and micro-cracks are easily formed. Therefore increasing the concrete durability is one of the most important problems in civil engineering that are intensively investigated. Penetration of water and aggressive solutions to porous concrete structure results in cracks formation, corrosion of concrete and reinforcing steel that finally yield to failure of structural elements or even constructions’ collapse 4.

In the ternary lightweight concretes, the fly ash and other pozzolanic materials seem to contribute to forming with cement a solid cementitious paste, compensating the low strength of bottom ash or other porous aggregates5, 6. It is known that the properties of concrete depend rather on defects than on overall average parameters, and the final features of a complex composite like concrete, although approachable by materials science and modeling, are often a hardly predictable and surprising effect of many factors on the material's microstructure. Without wishing to relate the invention to any particular theory, it seems that the role of fly ash (or other materials with cementitious properties) in increasing the durability of the investigated ternary concretes can be understood much better with the following considerations:
- the main objective for using fly ash is formation of solid cement-fly ash matrix that has a sufficient volume for creating a lightweight concrete structure with a required strength.

- in the case of normal weight concrete increasing the total cement and fly ash volume instead of replacing a part of cement by fly ash is possible. Partial replacement of the bottom ash or other porous aggregates by fly ash causes lowering the water content in the concrete mixture because the fly ash particles have spherical shapes and glassy surfaces. The cement-fly ash paste adhesion to the rough surface of highly porous bottom ash is strong due to the mechanical factor in the adhesion of the porous aggregates.

The most used standard method for determining the resistance of concrete (including the lightweight one) to varying environment humidity and temperature conditions is a freeze-thaw cyclic test\(^7,8\). For example, it was shown\(^9\) that the increment in fly ash content in concrete significantly decreases the effect of freeze-thaw cycles. Strength loss of concrete without fly ash was found to be around 15%, whereas for fly ash concrete with FA/(C+FA) = 0.3 it is just about 5%.

For the Mediterranean climate conditions, characterized by a very hot summer with temperature extremes (especially in desert regions) and a very wet winter with prolonged rains the freeze-thaw cyclic test method is not suitable for concrete evaluation. Therefore a proper method for concrete failure or shaking loose evaluation, conforming to the above-mentioned climate conditions, is required.

With this aim the effect of fly ash on the soundness of lightweight concrete under cyclic crystallization test can be tested. In order to evaluate the aggregate soundness the sulfates crystallization test (ASTM C88\(^10\), AASHTO T104\(^11\)), modified for testing concrete specimens is proposed to be used. The method is based on an application of alternative cycles of immersion of aggregates in saturated solutions of Na\(_2\)SO\(_4\) or MgSO\(_4\) at a temperature of 25±5\(^\circ\)C and drying at a temperature of 110±5\(^\circ\)C. Crystallization of sulfates causes pressure in concrete pores and capillaries. The method simulates the expansion of water when frozen and is used in several countries for this purpose. However, it is also accepted as a standard method for evaluating soundness of aggregates in India, characterized by a hot climate, (IS 383\(^12\)). An advantage of the method is that the testing procedure is as essentially stricter than the freeze-thaw cyclic test.

**RESEARCH AIM AND SCOPE**

As known, durability of lightweight concrete may be increased by combining cementitious material, comprising cement and materials with cementitious properties\(^13-15\). The present paper presents a method that enables to produce durable lightweight concrete, comprising: a matrix that includes the hardened paste of cementitious materials and a mixture of lightweight and normal weight aggregates that form the concrete structure. Such concrete combines low density with sufficiently high durability, making it very attractive for application in structures, subjected to severe environmental exposures.

In a preferred embodiment, the density of durable lightweight concrete, produced using the proposed method, should vary in the range between about 1400 and 2000 kg/m\(^3\), providing a combination of desirable concrete properties, such as low...
construction weight and required durability, as well as high thermal resistance in case of thermal insulating-structural concrete.

The lightweight concrete durability can be increased by means of varying the following parameters within certain range:
(a) relative volume of cementitious materials matrix and the total aggregates volume in concrete;
(b) relative volumes of cement and other materials with cementitious properties in the cementitious materials’ paste;
(c) relative volumes of lightweight and the normal weight aggregates in the total volume of aggregates.

Using cyclic crystallization test for evaluating concrete durability considers that the procedure does not allow distinguishing damage by sulfate crystallization from damage, caused by sulfate attack. However, character of macro-cracks in the concrete after a certain number of cycles can confirm the presence of a high pressure in pores of hardened cement-fly ash paste. Such cracks, resulting from an expansion of sulfate crystals, play a major role in the destruction of concrete. It allows using the crystallization method for an approximate evaluation of concrete exposure to cyclic humidity-temperature conditions with a simultaneous short-time action of sulfate attack.

EXPERIMENTS

Materials properties
Portland cement similar to ASTM C150\textsuperscript{16}, Type I, was used in all experiments. The cement physical properties were as follows:

- relative specific gravity – 3.1;
- Blain’s finesse – 370 m\textsuperscript{2}/kg;
- compressive strength of standard prism at 28 days – 41 MPa.

The samples of fly ash and bottom ash were taken from one of the local power stations. The ashes were produced by combusting a coal batch, supplied from one of the South African sources. The bottom ash was conveyed to the power station storehouse by hydraulic transport means. The wet sample of bottom ash was dried in the laboratory to a constant mass.

The fly ash met the requirements of ASTM C618\textsuperscript{17}, Class F. The sum of SiO\textsubscript{2} + Al\textsubscript{2}O\textsubscript{3} + Fe\textsubscript{2}O\textsubscript{3} was 81.57\% (the standard requirement is min. 70\%). The value of SO\textsubscript{3} was 2.98\% (the standard requirement is max. 5\%). The loss of ignition was approximately 3\% (the standard requirement is max. 6\%). The relative specific gravity of the fly ash was 2.1 and the Blain's finesse was 380 m\textsuperscript{2}/kg.

The percentage of bottom ash, passing the standard sieves were as follows:
- 10 mm – 100 \%
- 5 mm – 92 \%
- 2.36 mm – 78 \%
- 1.18 mm – 62 \%
- 600 µm – 45 \%
- 300 µm – 27 \%
- 150 µm – 12 \%.
Therefore, the bottom ash was used without any correction for grading. The physical properties of the bottom ash were as follows:
- relative specific gravity, 1.7;
- relative particle density (including pores), 1.35;
- porosity, 40.5 %;
- water absorption, 25.5 %;
- loose bulk density, 600 kg/m$^3$;
- volume of voids (interspaces between particles), 48 %.

The sample of unprocessed crushed sand (UCS) was taken from the local dolomite quarries. The grading of UCS met the specifications of ASTM C33, with the exception of a lower content of particles passing sieve 1.18 mm, and higher content of particles passing sieve 0.15 mm. The percentage of the particles passing sieves according to ASTM C33 were as follows:
- 9.5 mm – 100%;
- 4.75 mm – 92%;
- 2.36 mm – 62%;
- 1.18 mm – 41%;
- 0.6 mm 31%;
- 0.3 mm – 20%;
- 0.15 mm – 17%.

The physical properties of the UCS were as follows:
- relative specific gravity – 2.8;
- relative particle density (including pores) – 2.72;
- porosity – 3%;
- water absorption – 1.7%;
- loose bulk density – 1490 kg/m$^3$;
- volume of voids (interspaces between particles) – 45.2%.

**Experimental program**
Experiments, evaluating durability of the suggested lightweight concrete were performed using the fly ash as an additive to cement. The cement content complied with ASTM C330 (intended for the evaluation of aggregates for structural lightweight concrete) was 200 kg/m$^3$, 335 kg/m$^3$ and 400 kg/m$^3$. The content of UCS was constant (515 kg/m$^3$), in order to exclude influence of its varying on the concrete properties. Fly ash was used as a main varied component. The variation of fly ash content was in the range of 0, 0.3 and 0.5 from sum cement and FA content (FA/(C+FA)). The bottom ash content was in the range, according to the fly ash content. The water content was such that the concrete mixture consistency was constant (slump = 70 mm). The concrete mixtures compositions, used in experiments, are presented in Table 1.

The volume distribution of all concrete mixtures components (per 1 m$^3$ of the freshly mixed compacted concrete), is presented in Figure 1. Vertical straight-line segments between the solid lines characterize the volume of the concrete components for a given ratio of FA/(C+FA). Figure 1 shows also the volume of the cement-fly ash paste (dotted curve).

To evaluate the concrete durability, data on the volume of pores and capillaries, accessible for filling by water, is essential. This volume was determined separately for
the entire volume of concrete specimens, and for the volume of the hardened cement-fly ash paste in the specimens.

Table 1. Proportions of concrete mixtures used in experiments

<table>
<thead>
<tr>
<th>Component</th>
<th>Concrete mixture, No</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Cement, C, kg/m³</td>
<td>200</td>
</tr>
<tr>
<td>Fly ash, FA, kg/m³</td>
<td>-</td>
</tr>
<tr>
<td>Bottom ash, BA, kg/m³</td>
<td>730</td>
</tr>
<tr>
<td>UCS, kg/m³</td>
<td>515</td>
</tr>
<tr>
<td>Water, l/m³</td>
<td>320</td>
</tr>
<tr>
<td>Density of fresh concrete, kg/m³</td>
<td>1765</td>
</tr>
<tr>
<td>Density of hardened concrete, kg/m³</td>
<td>1485</td>
</tr>
<tr>
<td>28-days concrete strength, MPa</td>
<td>14</td>
</tr>
</tbody>
</table>

The volume of pores and capillaries in the hardened concrete was assumed to be equal to the volume of water evaporated by hardening, i.e. approximately equal to the mass of water in the fresh concrete less the mass of water, used for the cement/fly ash paste hydration. This mass was calculated as the difference between densities (Tables 1) of the fresh and hardened concretes (the latter were dried to the constant mass). The volume of pores and capillaries in the hardened cement or cement-fly ash paste was calculated as the difference between the volume of pores and capillaries in the concrete and that in the aggregate, accessible for filling by water. The latter volume was determined from the data on water absorption of bottom ash in the concrete mixture. In the present study it was 17.5%. The water absorption of the UCS is essentially lower and can be ignored. The results of determining the above-mentioned studied lightweight concrete characteristics are presented in Table 2. The volumes of pores and capillaries are expressed in percents of the concrete specimens and cement-fly ash paste volumes, accordingly.
Figure 1. Dependence of concrete mixture constituents volumes on the FA/(C+FA) ratio: a – for cement content 200 kg/m$^3$ (mixtures No 1, 2 and 3), b - for cement content 335 kg/m$^3$ (mixtures No 4, 5 and 6) and c - for cement content 400 kg/m$^3$ (mixtures No 7, 8 and 9).

The crystallization test procedure that was used in the frame of the present study, complies with ASTM C88 (AASHTO T104), except specimens with a regular cubic shape. The tested specimen dimensions were 50 x 50 x 50 mm, corresponding to the maximum size of the aggregates, used for the standard test. The specimens were sawed out from the 100 x 100 x 100 mm concrete cubes. Twelve specimens were prepared from each concrete sample, and subjected to 5 sulfates crystallization cycles. The concrete specimens’ quality evaluation of and analysis of visible cracks formation was performed after each test cycle.

The Na$_2$SO$_4$ solution was prepared according to requirements of ASTM C88. In order to exclude an error due to reaction between the fresh sulfate solution and the
carbonate aggregate in concrete, a portion of UCS was previously placed in the sulfate solution.

Table 2. Properties of hardened lightweight concrete

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Concrete mixture, No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Volume of cement/fly ash paste, l/m³</td>
<td>257</td>
</tr>
<tr>
<td>Volume of pores and capillaries in concrete, %</td>
<td>59</td>
</tr>
<tr>
<td>Volume of pores and capillaries in cement-fly ash paste, %</td>
<td>28</td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS AND DISCUSSION

An increase in the volume of cement-fly ash paste as compared to concrete without fly ash was 10% for mixture No. 2, 28% for mixture No. 3, 26% for mixture No. 5, 53% for mixture No. 6, 20% for mixture No. 8, and 42% for mixture No. 9.

The improved properties included an increase of 3-14% and 18-57% of density and strength, respectively (Table 1). The above-mentioned increase of the cement-fly ash paste matrix volume and lowering its porosity resulted in an increase of density and in a decrease of water permeability.

Results of the cyclic crystallization test are presented in Fig. 2. As it follows from this figure, the tests confirm the effect of lowering the volume of pores and capillaries and accordingly the capillary water absorption on concrete durability. The cyclic crystallization test demonstrates that using an appropriate fly ash volume provides the possibility to control the damage, caused by the exposure of concrete to environment. The result of weight loss specimens are shown in Figure 3. It should be noted that concrete specimens, prepared using mixtures No 2, 3, 5, 6, 8 and 9, passed 5 cycles of cyclic crystallization test. Under these conditions the specimens without fly ash have completely destructed after 4-5 cycles.

Figure 2. Destruction of lightweight concrete specimens caused by 5 cycles of crystallization test
CONCLUSIONS

An experimental program, focused on investigating durability of ternary lightweight concrete using cyclic crystallization tests, was carried out. Nine concrete mixtures with different fly ash additive volume were used.

The experiments show a way for producing durable lightweight concrete with a matrix, including the hardened cementitious materials paste and a mixture of lightweight and normal weight aggregates. Such concrete has low density and sufficiently high durability, making it very attractive for application in structures, subjected to severe environmental exposures.

Durability of lightweight concrete, containing porous aggregates (or a blend of normal weight aggregates), can be significantly improved by incorporating a high volume of fly ash as an additive to cement. The main reasons for improving the durability of lightweight concrete in this case are:

a) increase of 10-53% in the cement-fly ash paste matrix volume (as compared to concrete without fly ash);
b) decrease of 9-32% in the volume of pores and capillaries of the cement-fly ash paste (as compared to the cement paste matrix);
c) decrease of 12-49% in the volume of pores and capillaries in concrete (as compared to that without fly ash).

The experiments have demonstrated that the above-mentioned factors, affecting the concrete proportion and structure, cause a significant decrease in the capillary water absorption of lightweight concrete. Accordingly, an essential increase of the lightweight concrete durability, demonstrated by higher soundness under the strict crystallization test is established due to high volume of fly ash additive.

The results, obtained in the frame of this research, have also shown that cyclic crystallization tests may be successfully used for determining the resistance of lightweight concrete to varying environment humidity and temperature conditions. Therefore the method can be recommended as a standard test for evaluating concrete durability in the Mediterranean region.
REFERENCES


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