EXPERIMENTAL EVALUATION OF THE DURABILITY OF CORK CONCRETE

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ABSTRACT

Concrete elements used on the exterior of buildings are subjected to cycles of moisture and dryness with changing seasons and different weather conditions. In cold climates, this cyclical action on the concrete may have a considerable influence on its durability because of the aggressive freeze-thaw phenomenon.

More compact types of concrete are more sensitive to the freeze-thaw effect, since the expansion of frozen water within it creates great internal stresses. One way to assure higher durability is to introduce a controlled number of voids inside the concrete, to reduce these stresses. Some international standards for concrete, in particular European standard EN 206, prescribe the use of chemicals that produce air bubbles within the concrete.

The performance of an alternative method to provide concrete elements with the desired durability has been tested. The introduction of cork granules in concrete admixtures creates soft spots within the concrete, emulating the effect of air bubbles produced by chemical agents.

Laboratory tests were performed to compare the performance of different types of concrete when subjected to accelerated aging by freeze-thaw cycles. Standard concrete, cork concrete and concrete containing air-entraining chemicals were tested and the results are given in this paper.

Keywords: concrete, cork, durability, thaw, freeze, experimental
INTRODUCTION

Concrete structural design intends to provide concrete structures with enough mechanical strength to endure the expected mechanical loads. This design consists not only of defining the geometrical characteristics of the structural element but also of selecting materials with mechanical and physical characteristics compatible with the expected performance of the element to be built.

Mechanical loads are not the only demands made on concrete during its working life. Concrete elements surfaces are subjected to the influence of different climatic and chemical attacks, such as temperature variation, humidity, chloride, which lead to the deterioration of the structure, thus conditioning its durability.

One event that accelerates the deterioration process of concrete elements is the occurrence of freeze-thaw cycles. This phenomenon is related to the combined action of temperature and humidity, and is characteristic of cold regions. Since concrete is a porous medium, it will absorb water in the presence of humidity. If the temperature drops below 0ºC the absorbed water will freeze inside the concrete. The water will expand, generating internal stresses within the concrete, which will lead to fissures. The repetition of cyclic freeze-thaw will cause a progressive deterioration of the concrete, with two types of damage: superficial damaged, known as “scaling”, and internal structural damage.

The use of concrete in cold regions, and the need to ensure an acceptable durability for this material under freeze-thaw has motivated several research groups to study this phenomenon and try to find ways to increase concrete durability under low temperature cycles. Numerous research papers on this subject have been published recently.

The processes that govern the deterioration of concrete and other porous materials under freeze-thaw effect have already been described (see for instance [1], [2] and [3]). Kaufmann [4] studied the deformation and degradation mechanisms associated with freeze-thaw using indirect methods (acoustic emission, calorimetry and expansion evaluation). He proposed a model for the classification and quantification of sequential degradation of concrete.

In some parts of the world, chemical products (such as sodium chloride) are used to prevent the formation of ice on road surfaces. But these products all too often help to speed up the degradation provoked by the freeze-thawing. Wang et al. [5] studied the influence of different defrosting products and exposure conditions of the concrete surface on its deterioration. Their research included freeze-thawing and wet-drying events, and their effect in the loss of mass, scaling and loss of compressive strength.

The study allowed the conclusion that the calcium chloride solutions were most aggressive. A 6-level scale was proposed to classify the hardened concrete according to its surface degradation, evaluated the through visual inspection. The durability of concrete subjected to saline and non-saline environments, and its relation to the water/cement ratio and air percentage of concrete also was studied by Pentalla [6].

Different research has indicated that the degradation due to freeze-thawing may be related to the porosity of concrete and pore geometry. Basheer et al. [7] tested concrete batches with different porous structures, produced by different water-cement ratios in the admixture. Several polymers used to treat of concrete surfaces were also tested. The depth of surface treatment and the humidity of the concrete surface prior to the treatment were some of the variables studied. The results indicated that surface treatment may improve the mechanical resistance of porous concrete to freeze-thawing.

Cwirzen et al. [8] studied the interface between cement and aggregate in high-strength concrete. Various concrete batches, with low water-binder ratio were tested.
The micro-structure of the concrete was analyzed, and the results showed that the degradation mechanisms initiate in this interface.

Several other studies on the durability of special concrete types have also been carried out.

Persson [9] studied the internal and surface degradation of self-compacting concrete, comparing its performance with standard concrete with a water-cement ratio of 0.39 and air content of 6%. Self-compacting concrete exhibited a significant increase on the internal strength, when compares with standard concrete. No important differences were noticed on the superficial degradation.

Kazberuk et al. [10] studied the scaling on bituminous modified concretes. They proposed a visual criterion to classify scaling. They concluded that bituminous modified concrete loses mass due to freeze-thaw cycles, in a 3% NaCl environment.

Zaharieva et al. [11] studied recycled aggregates concrete’s the resistance to freeze-thaw. These researchers concluded that this type of concrete is unsuitable for structures subjected to freeze-thaw cycles.

Past research data indicates that concrete’s resistance to freeze-thaw may be improved by introducing small air bubbles into fresh concrete via the addition of chemicals (air entraining products) to the concrete admixture. This improvement is recognized by the CEN (European Committee for Standardization) [12], which recommends the introduction of air bubbles representing at least 4% by volume of concrete required for good freeze-thaw durability.

A research project currently underway in the University of Coimbra, in Portugal, is designed to evaluate the possibility of using cork granulate, an industrial by-product, as a lightweight aggregate in concrete production. Previous results made it possible to quantify the influence of the cork granulate on the mechanical strength (Branco et al. [13]) and thermal conductivity (Simões et al. [14]) of concrete. Cork granulate is a soft, porous material. Taking into account the previous experimental work and the physical characteristics of this material, the research team set out to see if cork granulates improves the concrete’s performance under freeze-thaw cycles, thus becoming a technical alternative to air entraining chemicals.

Laboratory tests followed the procedure suggested by prENV 12390-9 (2003) [15]. Three different types of concrete were compared: a standard concrete, concrete containing an air-entraining chemical, and cork concrete. This paper describes the work performed, and presents the results and conclusions obtained from this study.

**EXPERIMENTAL WORK**

Previous work by the authors [13, 14] has shown that cork granulate can be used to produce structural concrete with better thermal behavior than standard concrete.

The work now described intends to establish whether the inclusion of cork granulate in concrete improves its performance under freeze-thaw cycles, making it an alternative to chemical air-entraining products. Different types of concrete were evaluated and compared. Laboratory tests were carried out. Concrete specimens were subjected to freeze-thaw cycles. The degradation of the specimens was assessed periodically by visual inspection and mass loss measurements. After 56 freeze-thaw cycles, the specimens were subjected to a compressive test, and their mechanical strength compared with that of reference specimens stored at room temperature.

**DEFINITION OF CONCRETE ADMIXURES**

Three types of concrete were studied: a standard concrete (BR), used as reference; a concrete containing an air-entraining product (BAER) and concrete with lightweight
expanded cork granulate (BE).
The aggregates (river sand and coarse limestone) and cement used to produce all test specimens were taken from the same batch. All types of concrete were produced using the same base composition.
The cork concrete (BE) composition was obtained by replacing a percentage of sand with an equivalent volume of cork granulates with a similar particle size distribution. A sufficient amount of cork was added so that the concrete contained a cork volume of 4%, equivalent to the 4% volume of air bubbles present in the air-entrained concrete (BAER). Table 1 lists the composition of all the concretes tested. In this Table, \( f_{cm,28} \) and \( f_{cm,84} \) are the average compressive strength of the concrete, evaluated in 150mm cube specimens [15], at 28 and 84 days, respectively, and \( f_{cm,84,ft} \) is the average compressive strength after the freeze-thaw cycles testing.

<table>
<thead>
<tr>
<th>Component</th>
<th>BR</th>
<th>BAER</th>
<th>BE</th>
</tr>
</thead>
<tbody>
<tr>
<td>River sand (kg/m³)</td>
<td>457</td>
<td>457</td>
<td>366</td>
</tr>
<tr>
<td>Coarse aggregate (kg/m³)</td>
<td>1372</td>
<td>1372</td>
<td>1372</td>
</tr>
<tr>
<td>Portland Cement (kg/m³)</td>
<td>380</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>190</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>Sika AER (l/m³)</td>
<td>-</td>
<td>0.36</td>
<td>-</td>
</tr>
<tr>
<td>Cork granulate (05/1) (kg/m³)</td>
<td>-</td>
<td>-</td>
<td>7.37</td>
</tr>
<tr>
<td>Cork granulate (1/2) (kg/m³)</td>
<td>-</td>
<td>-</td>
<td>2.13</td>
</tr>
<tr>
<td>W/C</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>( f_{cm,28} ) (MPa)</td>
<td>33.1</td>
<td>24.1</td>
<td>33.3</td>
</tr>
<tr>
<td>( f_{cm,84} ) (MPa)</td>
<td>38.2</td>
<td>27.9</td>
<td>37.7</td>
</tr>
<tr>
<td>( f_{cm,84,ft} ) (MPa)</td>
<td>27.7</td>
<td>23.6</td>
<td>26.7</td>
</tr>
</tbody>
</table>

Laboratory tests to evaluate the freeze-thaw durability of the concrete were performed according to prENV 12390 – 9 [12]. The test procedures, the temperature cycle, and the frequency of the measurements taken were those indicated in the standard. The standard procedures were, however, modified; in particular, standard 150mm cube specimens were used, instead of the 100mm cubes specified in the standard procedure. This made it possible to compare the results after 56 freeze-thaw cycles with compressive tests made in standard conditions [15]. The metal containers described in the standard procedure were adapted to accommodate the new specimen dimensions. The free distance between test specimens and between their surfaces and the container, remained as prescribed in the standard document.

**SPEdIMEN PREPARATION AND LABORATORY TESTS**

Four test specimens of each type of concrete were produced. A thermal probe was inserted inside the specimen, to monitor and record the temperature along the freeze-thaw cycles.

After casting, the test specimens were kept at room temperature (20±2) °C for 24h. The surface of the specimens was protected with a polyethylene film, to reduce moisture loss due to evaporation. After 24h, the specimens were placed in a water tank, at (20±2) °C. They were removed from the water seven days after casting and stored for 20 days in a climatic chamber, at (20±2) °C and 95% relative humidity. At 27 days the specimens were removed from the climatic chamber and placed inside metal containers (Figure 1). The containers were then filled with distilled water to cover the specimens to a level (25±5) mm above their surface. After 24h the specimens were weighed to determine the 24h water absorption. The metal containers holding the water and the test specimens were put in a climatic chamber and the freeze-thaw cycles started.
The test specimens were subjected to cyclic freeze and thaw conditions inside the climatic chamber. The temperature rate was programmed and carefully monitored throughout the entire process. According to the standard [12], the specimen temperature should be kept within prescribed values at all times. Figure 2 illustrates the temperature recorded for one entire freeze-thaw cycle.

After certain prescribed series of cycles (7, 14, 28, 42, and 56 cycles), the specimens were removed from the climatic chamber in the thaw phase and they underwent the following procedure:

a) Visual inspection to detect the presence of fissures or other surface changes and to check the locations (surface of corners) of the mass losses;

b) Scrubbing of their surfaces to remove all loose material. The loose particles were collected and the liquid inside the container was filtered to determine the mass loss of each specimen;

c) The test specimens were wiped and weighed;

d) The specimens were returned to the containers, which were filled again with distilled water and placed in the climatic chamber. A new series of temperature cycles was initiated.

e) The loose particles collected from the filter and surface scrubbing were dried at (110 ± 10) °C and the dry mass was determined.

**EXPRESSION OF THE RESULTS**

Before the start of the freeze-thaw cycles, the amount of water absorbed by each specimen was determined. Water absorption is expressed as a percentage of the specimen mass, according to expression

\[ L = \frac{m_{28d} - m_{27d}}{m_{27d}} \cdot 100 \]  

(1)

where \( m_{27d} \) is the dry mass and \( m_{28d} \) is the saturated mass of the specimen.
The average mass loss of the concrete is determined by expression

\[
P = \frac{m_{s,n}}{m_0} \cdot 100\%
\]

where \(m_{s,n}\) is the mass of the dry specimens, determined before the beginning of the temperature cycles, and \(m_0\) is the total dry mass of loose material collected since the beginning of the test.

The average mass loss and the individual mass loss of each specimen are used to quantify the freeze-thaw durability of the concrete. After 56 freeze-thaw cycles the specimens were subjected to standard compressive tests [15]. Reference specimens, which were stored in a water tank at \((20 \pm 2)\) °C, were tested at the same age.

**TEST RESULTS**

The specimens were placed in water for 24h prior to temperature cycle testing in order to quantify the water absorption. Table 2 presents the results obtained.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dry weight (g)</th>
<th>Saturated weight (g)</th>
<th>Weight increase (g)</th>
<th>Water absorption (%)</th>
<th>Average water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR – 1</td>
<td>7927.5</td>
<td>8004.4</td>
<td>76.9</td>
<td>0.97</td>
<td>0.98</td>
</tr>
<tr>
<td>BR – 2</td>
<td>7924.0</td>
<td>8000.2</td>
<td>76.2</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>BR – 3</td>
<td>7900.3</td>
<td>7994.2</td>
<td>93.9</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>BR – 4</td>
<td>7920.2</td>
<td>7984.1</td>
<td>63.9</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>BAER – 1</td>
<td>7461.3</td>
<td>7525.0</td>
<td>63.7</td>
<td>0.85</td>
<td>0.91</td>
</tr>
<tr>
<td>BAER – 2</td>
<td>7544.1</td>
<td>7622.7</td>
<td>78.6</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>BAER – 3</td>
<td>7465.1</td>
<td>7531.0</td>
<td>65.9</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>BAER – 4</td>
<td>7513.1</td>
<td>7576.6</td>
<td>63.5</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>BE – 1</td>
<td>7975.7</td>
<td>8045.3</td>
<td>69.6</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>BE – 2</td>
<td>7897.2</td>
<td>7971.6</td>
<td>74.4</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>BE – 3</td>
<td>8056.4</td>
<td>8126.4</td>
<td>70.0</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>BE – 4</td>
<td>7954.9</td>
<td>8022.9</td>
<td>68.0</td>
<td>0.85</td>
<td></td>
</tr>
</tbody>
</table>

Water absorption was similar for the three types of concrete, with a maximum of 0.98% observed in batch BR and a minimum of 0.88% in specimens BE.

The variation of the specimens mass was evaluated at different stages of the freeze-thaw cycles. Figure 2 illustrates the results obtained.

Results show that, despite the mass loss due to loose material, after 7 cycles, all concrete types tested exhibited a mass increase. Concrete BAER mass increased until 14 cycles were performed. The reason for this increase is the fact that the mass of water absorbed is higher to the mass loss due to scaling.

Above 14 cycles, all series tested revealed a mass loss which increased as the specimens underwent further temperature cycles. Higher mass loss occurs in concrete BR. Concrete BAER exhibits a mass loss clearly lower than the others.
Figure 2: Specimen mass variation over the freeze-thaw cycles: a) concrete BR; b) concrete BAER; c) concrete BE; d) average mass loss for all series.

At the same time as the specimens were weighed, the mass of detached material was also calculated. Figure 3 shows the dry mass of the loose material obtained at different times during the procedure.

The results show that series BR suffered higher deterioration, originating a higher amount of loose material (1.7%). This deterioration is particularly important after 7 freeze-thaw cycles. The deterioration rate for both BR and BE concretes increases with the number of cycles. After the seventh cycle, cork concrete BE had the lowest amount of loose residues (1.43%). After this point, the amount of detached material increased substantially although its deterioration level remained lower than that of concrete BR. The degradation rate of concrete BAER, however, did not increase. The amount of loose material increased almost linearly over the temperature cycles. The amount of lost material (0.42%) was substantially lower than that observed for the other concrete types. Visual inspections of the test specimens were carried out at different times during the freeze-thaw cycles to access the surface degradation of the specimens.

After 7 cycles the deterioration was not very obvious, except for the lower face of the specimens, which registered a small loss of material. After 14 cycles, the degradation of concrete BAER and BE was not very significant, with both losing the same amount of material. On the other hand, concrete BR exhibited some signs of surface
deterioration: more loose particles, especially on the lower face of the specimen and lateral edges. After 28 cycles, surface deterioration could be observed on both BR and BE concretes, although there was less degradation on the concrete specimens containing cork granulates. At this stage, no material detachment was visible on concrete BAER, which presented only slight surface degradation. Figure 4 shows the residues collected for all specimens after 28 cycles.

![Figure 4: Loose material collected after 28 freeze-thaw cycles: a) before drying; b) after drying process.](image)

After 42 freeze-thaw cycles, concrete types BE and BR registered a significant evolution in terms of deterioration. The cork concrete appears more affected, although the amount of loose material for this type of concrete is lower. Concrete BAER exhibited a mass loss similar to that observed after 28 cycles, but the specimens at this stage show a noticeable surface deterioration.

Figure 5 illustrates the appearance of test specimens after 56 freeze-thaw cycles. Concrete BAER exhibits minor degradation signs, with slight surface scaling. Specimens BR and BE exhibit higher degradation in all faces and edges, with loose cement and aggregates. According to Wang’s [6] visual classification, concrete BAER falls into class 1, while concrete BE and BR belong to class 5.

![Figure 5: Test specimens after 56 freeze-thaw cycles: a) BAER; b) BR; c) BE.](image)

This work also accessed the influence of freeze-thaw on the mechanical strength of the concrete. After 56 freeze-thaw cycles, the test specimens were subjected to a compressive test. Reference specimens, identical to those subjected to freeze-thaw, but which were kept in a climatic chamber, at (20±2) °C and 95% relative humidity, were also tested. Table 3 displays the results obtained.

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>f_{cm,28} (MPa)</th>
<th>f_{cm,84} (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAER</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>BR</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>BE</td>
<td>33</td>
<td>33</td>
</tr>
</tbody>
</table>

Three series of tests were performed: average compressive strength of concrete stored in the climatic chamber, at ages 28 and 84 days (f_{cm,28} and f_{cm,84}), respectively, and average compressive strength of specimens after 56 freeze-thaw cycles (f_{cm,84,ft}). The Table also compares the strength of concrete subjected to temperature cycles with the strength of reference specimens at 28 and 84 days.

At age 28 days, concrete types BR and BE registered 33MPa compressive strength. Concrete BAER had lower strength, about 24MPa. The presence of entrained air significantly lowers the mechanical strength of concrete. Tests show, as expected, an increase of strength with age, for all types of concrete tested. This increase was about 16% for concrete types BR and BAER, and 13% for cork concrete.
After 56 cycles, concrete BAER maintained 98% of its 28 days reference strength, while concrete BR and BE registered residual strengths of 83.7% and 80.1%, respectively. When compared with specimens with the same age (84 days) that were not subjected to freeze-thaw, BAER has a 15% strength loss, while losses for BR and BE are 28% and 29%, respectively. Figure 6 illustrates the results obtained.

**CONCLUSIONS**

The results obtained from the present work confirmed that, as stated in the technical bibliography, the introduction of air bubbles into concrete admixtures leads to significant enhancement in their performance in freeze-thaw cycles. In fact, concrete containing the air-entraining product revealed a lower degree of superficial degradation, with a little detachment of cement paste but no loss of aggregate material. This type of concrete suffered a fall in compressive strength of only 2% and 15% after 56 freeze-thaw cycles, compared with the strength exhibited by reference specimens aged 28 and 84 days, respectively. After being subjected to freeze-thaw cycles, standard concrete and concrete containing cork granulates exhibited a higher degree of scaling, with heavy detachment of aggregates and cement paste. The strength loss after the temperature cycles was found to be 28% to 29% for both types of concrete.

The results show that the introduction of cork granulates to replace river sand in the concrete admixture did not significantly improve the concrete performance under freeze-thaw conditions. Even though the behavior of cork concrete was similar to that of BAER up to 28 cycles, cork concrete experienced an accelerated deterioration from this stage forward. Above 28 cycles, BE performance approached that of the BR concrete. In terms of surface degradation, BE had an intermediate scaling level with the other types of concrete tested. The loss of its mechanical strength is similar to that observed in reference concrete BR.

This work leads to the conclusion that the addition of a 4% volume of cork granulate to concrete is not a valid alternative to a similar volume of air produced by an air-entraining chemical agent, to improve concrete durability when subjected to freeze-thaw cycles.

The results obtained up to 28 temperature cycles do, however, indicate that cork may improve the concrete performance under temperature cycles. During this initial phase
of the test, the surface degradation of cork concrete was similar to that of BAER concrete. This result may indicate that the amount of cork granulate may not have been enough to guarantee the desired performance. Supplementary tests, on concrete specimens containing higher amounts of cork granulate are recommended to quantify the influence of this parameter on freeze-thaw durability of concrete.

ACKNOWLEDGEMENTS

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