Effect of finishing practices on surface structure and salt-scaling resistance of concrete

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Abstract
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Keywords
salt scaling, Surface hardness, Bleeding, Slag cement, Spacing factor

Disciplines
Civil and Environmental Engineering

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Accepted Manuscript

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PII: S0958-9465(18)30437-2
DOI: https://doi.org/10.1016/j.cemconcomp.2019.103345
Article Number: 103345
Reference: CECO 103345

To appear in: Cement and Concrete Composites

Received Date: 29 April 2018
Revised Date: 5 April 2019
Accepted Date: 3 June 2019


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Effect of finishing practices on surface structure and salt-scaling resistance of concrete

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Abstract

The impact of three different finishing times on the surface layer properties of concrete containing different contents of slag cement replacement was evaluated, as well as the relationship between finishing, abrasion resistance of surface layer, and salt-scaling resistance. In addition, a novel method for monitoring the bleeding period of fresh concrete was investigated. Based on the results obtained in this study, choice of finishing time can influence salt scaling resistance by affecting abrasion resistance of concrete mixtures. It was found that lower resistance of slag cement concrete to salt scaling is not necessarily due to a weaker surface layer. While slag replacement reduced the mixtures’ scaling resistance, up to 40\% of slag replacement improved mechanical properties, including surface abrasion resistance.

Keywords: salt scaling, surface hardness, bleeding, slag cement, spacing factor.

1. Introduction

A great deal of research regarding salt scaling has been focused on the effect of mixture proportions [1–4], types of deicing salts [5–8], and the mechanism of salt scaling [9–11], while less attention has been given to the impact of workmanship [12,13]. Inadequate finishing, the operation of creating a concrete surface with a desired texture and smoothness, not only affects surface properties, but also accelerates the ingress of aggressive elements like deicing salt into
the concrete [12–14]. The term “inadequate finishing” can be described as not giving sufficient attention to the impact of finishing efforts, timing, and tools. For example, excessive finishing effort can compromise the near-surface air-void system [15,16], which is crucial for freeze-thaw resistance of concrete. Alternatively, early finishing may cause water to be trapped below the surface, building in a weak layer.

Increasing the dosage of supplementary cementitious materials (SCMs) such as slag cement or fly ash, has sometimes led to misleading test results obtained from salt-scaling test methods [17–19] that do not correlate well with field data [18,20,21]. This observation is based on laboratory salt-scaling tests carried out in accordance with MTO LS-412 [22], ASTM 672 [23], and BNQ [24]. Some researchers have attributed this discrepancy to the slow hydration and an insufficient curing regime for concrete containing SCMs [25,26]. Taylor, et. al, [12] proposed that the apparent poor performance of concretes containing SCMs in ASTM C672 salt-scaling tests [12] might be due to differences in timing of finishing. They studied the effect of variable finishing time on three different mixes: plain cement concrete, 50% slag cement concrete, and 25% fly ash concrete, and found that sensitivity of finishing time was a function of mixture composition.

Despite the obvious importance of the surface layer with respect to concrete durability, there has been little research aimed specifically at characterizing surface structure and the factors that influence it [27]. Evidence suggests that surface hardness, itself highly dependent on finishing and curing practices, is among the most important factors affecting the scaling resistance of concrete. Glinicki and Zielinski [28] investigated scaling resistance of concrete containing circulating fluidized bed combustion (CFBC) fly ash and confirmed the significance of concrete surface hardness on salt frost-scaling resistance. Similar results were obtained by Tremblay, et al., [29]. The effects of finishing, however, were dismissed in both of these studies. Sadegzadeh,
et. al., [30] studied the effect of different finishing techniques, including hand finishing, power finishing, and repeated power finishing, on the abrasion resistance of concrete, with results indicating substantially different microstructural characteristics of surface layer. Their study included only portland cement and did not consider timing.

Bleeding can also be an important defect when studying salt scaling resistance of concrete [12,13,31–33], and while several methods have been proposed to measure concrete bleeding, none is considered completely satisfactory [34]. If the rate of evaporation is higher than the rate of bleeding, no water accumulation can be observed on the top surface of the concrete [35], making monitoring the bleeding duration difficult or impossible.

In this study, an experimental investigation was undertaken to evaluate the effect of the time of finishing on surface properties and scaling resistance of concrete samples containing various binary systems, i.e., 0%, 20%, 40%, and 60% slag cement. The surface properties were tested using abrasion resistance test method. In addition, a novel method for monitoring the bleeding of fresh concrete was investigated.

2. Experimental program

2.1. Materials and mixing
Type I portland cement and slag cement (ground granulated blast furnace slag) were combined into four different binary systems. Table 1 presents the chemical and physical characteristics of the cementitious materials utilized. Polycarboxylate-based high-range water reducing admixture (HRWRA) and vinsol-based air entraining admixture were employed. The dosage rates of the HRWR and AEA were adjusted to secure initial slump and air content values of 50 ± 10 mm and 2–9 %, respectively. Continuously graded crushed limestone aggregate with 19-mm nominal maximum size (NMS) was used. The coarse aggregate had a bulk specific gravity of 2.68 and an
absorption value of 0.81%. Well-graded limestone sand with a fineness modulus of 2.97, an
absorption value of 1.5%, and a specific gravity of 2.62. was used.

Four concrete mixtures were prepared with a fixed w/cm of 0.48 and various binary
combinations of slag cement (0%, 20%, 40%, and 60%). Because cementitious materials have
different solid densities, all mixtures were designed using volume-based replacement to maintain
a constant volume of solid particles; the mixture proportions of the concrete mixtures are given
in Table 2.

The mixing sequence consisted of introducing AEA diluted in 1/3 of the mixing water into the
crude aggregate and mixing until foam began to form (in an unpublished practice by the authors,
in was found that this method may be advantageous in regard to the stabilization of the bubbles,
and will not affect the final effective air content of the mixture) followed by homogenizing the
sand and coarse aggregate for 30 sec before introducing the cementitious materials along with
the remaining water. The concrete was mixed for 3 min and kept at rest for 3 min before
remixing for 3 additional minutes.

2.2. Finishing and testing program

2.2.1. Finishing

Three sets of samples were prepared for each mix and different finishing techniques were applied
to each set. The times for conducting the finishing were as follows:

(a) Immediately after casting.

(b) After the bleeding slowed down or stopped.

(c) At the initial setting time.

A wooden trowel was used for fine tuning and final finishing that included moving the trowel
from top to the bottom and bottom to the top of the span, edge to edge, for three to five repetition
depending on the ease and time of the finishing. The same operator finished all the slabs under instruction to apply the same amount of effort in all cases.

2.2.2. Testing procedures

Initial setting time of the mixtures was assessed using penetration resistance test based on ASTM C403 [36] and ultrasonic pulse velocity measurements [37]. Results were later confirmed using a calorimeter test [38]. Calorimetry measures the heat fluctuation during a chemical reaction such as cement hydration and which can be used to assess hydration-related properties, such as setting, based on the obtained temperature-time curve. In the thermal profile obtained from calorimetry test, it is recommended to use 20% and 50% fraction thermal setting times as initial and final setting times, respectively [39,40].

The amount and duration of bleeding water was measured based on ASTM C232 [41], and a novel method was also developed to monitor the bleeding duration of the mixtures. For that purpose, a specimen identical to that described by the standard was used, and the ambient temperature \( T_a \) and that of the concrete \( T_c \) (5 in. inside the sample) were assessed using thermometers. The surface temperature gradient \( T_s \) was monitored using a FLIR T650sc infrared camera. Ambient temperature was maintained at 27± 1°C during the testing period, which was higher than \( T_a \) and \( T_c \), and allowed for evaporative cooling of the surface while the concrete was bleeding. However, when the bleeding stopped, the natural cooling system was no more valid, and the surface started absorbing energy from the environment (higher temperature) through convection. This can be a solid sign of the fact that bleeding is stopped, and was confirmed with the results showing that the time when \( T_c \) and \( T_s \) became equal, implying no more evaporation of bleed water from the surface, is about the time that bleeding has slowed down or stopped.
It should be noted that the infrared camera has been commonly used in concrete industry as a nondestructive testing tool to detect any deficiency such as crack or leakage in a concrete structure [42]. It also has been used as a temperature controlling tool during a concrete placement [43], but to the best knowledge of the authors, neither infrared camera nor any other tools have been used before to monitor the timing of bleeding through the temperature gradient between solid concrete, concrete surface, and ambient.

After casting, all specimens were covered with plastic sheeting for 24 hr, after which they were demolded and cured in accordance with ASTM C31 [44].

The abrasion resistance of the specimens was determined using a rotating-cutter drill press. The test was performed in accordance with ASTM C944 [45], with the specimen surface subjected to the rotating-cutter at 197 N for 2 minutes. All dust was removed, and each cylindrical sample was then weighed. The procedure was repeated for 2 more cycles on two specimens. The total mass loss was then averaged and reported.

Scaling resistance of concrete specimens was determined in accordance with the BNQ NQ 2621-900 [24] test method. This method requires use of rectangular prisms of size 300×200×82 mm or an equivalent surface area of 0.06 m². After 28 and 14 days of moist curing and air drying, respectively, 7 days of pre-saturation was carried in brine with a 3% NaCl concentration. The specimens were then subjected to freezing and thawing (F-T) cycles, each with freezing and thawing periods of 16 hr and 8 hr, respectively. F-T cycle testing was conducted for 45 days, and at every 5 cycles the surface of the specimens was washed with a deicing solution, and the residue was collected and dried in an oven at 110 °C for 24 hr. The total weight of the dried residue was measured and the average for the two specimens was reported.
A RapidAir 3000 automatic image analysis system compatible with ASTM C457 [46] was used to perform air-void analysis on the hardened mixtures. Square specimens of 100 × 100 mm$^2$ were cut perpendicular to the surface from the middle of the cylinders. Compressive strength testing was performed on 100 mm × 200 mm$^2$ concrete cylinders according to ASTM C39 [47]. Three cylinders, 28 days of age, were used for each test and the average compressive strength reported.

3. Results and discussions

Fig. 1 demonstrates calorimeter results showing specimen heat variation during the first 16 hours of hydration. As expected, incorporation of slag cement reduced the heat of hydration. In addition, the results of setting time measurement, based on Fig. 1, which agreed with the ultrasonic pulse velocity and penetration test results, as well as bleeding, air-void system, and compressive strength results, are tabulated in Table 3.

3.1. Bleeding

Fig. 2 illustrates the boundary conditions, relationship between bleeding duration and temperature variation, leading to evaporative cooling for different binary mixtures. Based on the results obtained in this study, this method can be used for effective monitoring of concrete bleeding duration. It can be observed that the time when surface temperature crosses the internal concrete temperature is about the time that concrete is no longer bleeding. This can be explained by the fact that evaporating bleed water cools the system. When bleeding stops the temperature at the surface rises. Although this method can aid field engineers with determining the correct time for finishing, it still needs to be fully developed considering factors such as changing weather conditions outside the lab. A limitation of this method also might be the high accuracy required of the infrared camera.
3.2. Effect of finishing

The results of salt-scaling tests for different binary systems are shown in Fig. 3. The results show that both the slag content and finishing have significant influence on salt-scaling resistance. It can generally be observed that mixtures finished after bleeding is stopped (finishing b) have superior performance compared to the other finishing practices, while the worst performance is achieved by samples that were finished early (finishing a). For example, with respect to the plain mixture, finishing after bleeding stopped reduced salt scaling from ~800 gr/m$^2$ to ~200 gr/m$^2$, compared to earlier finishing. Considering that all the samples continued to bleed for up to 100 minutes (Fig. 2), this can be attributed to the fact that early finishing results in trapped water under the finished surface, resulting in a weak surface layer. Such reasoning has been confirmed by Amini et. al [48] and Taylor and Amini [49] through a microscopic imaging.

When considering the mixtures made with 60% slag replacement, however, it can be observed that in contrast to other mixtures the worst performance was achieved by the sample that was finished at its initial setting time (finishing c), improving with earlier finishing. This is due to the slump loss of the 60% slag specimens that were no longer workable, and the mortar could not be brought to the surface (Fig. 4). Therefore, it is likely that the attempts to finish those samples damaged the surface to some extent, resulting in lower scaling resistance.

Regardless of finishing time, incorporation of slag cement resulted in higher salt scaling. For example, salt scaling of the mixtures made with 40% slag cement is twice that of mixtures made with 20% slag cement replacement. Similar results have been obtained by other researchers [12,50].

It has been suggested that the lower resistance of slag concrete to salt scaling, especially its fast scaling within the first few cycles, might be attributed to formation of a weak surface caused by
inadequate finishing [17,32]. However, the effect of finishing time on the abrasion resistance of the mixtures, shown in Fig. 5, reveals that regardless of finishing time, up to 40% of slag-cement replacement improved abrasion resistance, although at higher slag cement replacement, abrasion resistance of the specimens was significantly reduced; most likely because not all the cementitious materials participate in the pozzolanic reaction for the case of high slag cement replacement.

In case of the effect of finishing, it can be observed that for a given mixture the time of finishing can influence the abrasion resistance of the mixtures, i.e., with respect to the plain mixture, finishing after bleeding had stopped improved the abrasion resistance by up to 40%, compared to earlier finishing.

3.3. Relationship between different properties

In order to clarify the mechanism behind the relationship between finishing and salt scaling, Fig. 6 was developed demonstrating the ternary correlation of finishing, abrasion, and salt scaling for different binary systems. Although the figure shows initially no clear trend, comparisons for a given mixture help developing the following interpretations. For all the mixtures investigated in this study, time of finishing contributed to scaling performance of concrete by affecting the abrasion resistance of the surface layer. Slag cement replacement (up to 40%) improved the abrasion resistance, while the slag-cement specimens achieved the lowest salt scaling resistance. These results, therefore, confirm that testing the mechanical properties and salt scaling of mixtures containing slag as a cement replacement at 28 days or less can be misleading. Similar relationship between abrasion resistance and salt scaling is reported elsewhere [50].

Correlation between compressive strength and salt scaling of the concrete specimens is shown in Fig 7. Similar to the relationship between abrasion and salt scaling, it can be observed from the
figure that although slag cement improves compressive strength of the specimens, lower scaling resistance is obtained. Among other factors, greater scaling of slag-cement concrete, while exhibiting improved mechanical properties, has been attributed to carbonation of the surface layer of concrete. Stark and Ludwig [51], suggested that this can be due to re-crystallization of calcium carbonate at the surface layer in metastable forms (aragonite and vaterite) that are soluble in NaCl. In another study [52] they found that after de-icing salt reactions only a weakly crystallized calcite exists.

The relationship between spacing factor and salt scaling resistance of the concrete mixtures is presented in Fig. 8. It has been reported by many researchers that independent of concrete type, a spacing factors below 250–300 $\mu$m can guarantee a scaling resistance concrete [53–57]. However, it can be observed from the figure that although the spacing factor of the specimens is within the specified range ($<0.2 \text{ mm}$), many of the specimens exhibited severe salt scaling (Figs. 8 and 9). This agrees with recent findings in the literature [17,58,59] indicating that ensuring a spacing factor of less than 0.2 $\text{mm}$ does not necessarily ensure satisfactory scaling resistance of concrete.

Visual inspection of the mixtures is shown in Fig. 9. Based on these figures, Table 4 was developed in accordance with BNQ 2621-900 summarizing the visual salt scaling index (VSSI) of the specimens. Comparing the results of Fig. 9 and Table 4 confirms the previous findings of this paper and shows potential for allowing the use of mass loss approach as a less subjective and more informative way of evaluating salt-scaling performance of the specimens.

4. Conclusions

This study has investigated the effect of finishing time on surface structure and salt-scaling resistance of concrete samples made with different binary systems, as well as the relationship
between these parameters. Three different finishing times: immediately after fabrication, after bleeding stopped, and at initial setting time, were applied. In addition, a novel procedure was investigated for monitoring the bleeding time of fresh concrete. The general highlights of the study are as follows:

- Slag-cement replacement improved mechanical properties, while resulted in lower salt-scaling resistance. Therefore, salt scaling assessment based on mechanical properties of mixtures containing different slag-cement replacement levels at 28 days or less can be misleading.

- In general, based on the limited data obtained in this study, delaying finishing after bleeding is stopped was found to be the most beneficial practice, while the worst performance (abrasion and salt scaling) was attained with early finishing. In addition, finishing at the time of initial set improved the scaling resistance to some extent, compared to early finishing.

- The investigated procedure for monitoring the bleeding time was found to be feasible, although more data needs to be collected and correlated with field experience to consider it definitive. The required accuracy of the infrared camera, rate of evaporation, and ambient temperature might be limitations.

**Future work**

Assessment of concrete bleeding duration is of interest to field engineers and future work may include conducting the proposed testing method in different weather conditions. In addition, more research is required to investigate the effect of slag-cement replacement on salt scaling resistance of concrete. A future activity may include the comparison of hydration products on different layers of concrete containing plain cement with those of slag-cement concrete, and the
reactions of these products with de-icing salt. In addition, the effect of finishing on the surface
quality may be evaluated by SEM on the cross-sectional of specimens. This may provide
supportive information and explanation on the phenomena.

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<table>
<thead>
<tr>
<th></th>
<th>Cement</th>
<th>Slag cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalis (Na₂O₃)</td>
<td>0.88</td>
<td>0.26</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>2.2</td>
<td>0.75</td>
</tr>
<tr>
<td>Insoluble residue</td>
<td>0.7</td>
<td>-</td>
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<tr>
<td>Free lime</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂</td>
<td>20.6</td>
<td>37.2</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.5</td>
<td>9.48</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.7</td>
<td>0.47</td>
</tr>
<tr>
<td>CaO</td>
<td>62.7</td>
<td>40.10</td>
</tr>
<tr>
<td>MgO</td>
<td>2.0</td>
<td>10.99</td>
</tr>
<tr>
<td>SO₃</td>
<td>3.6</td>
<td>1.11</td>
</tr>
<tr>
<td>Label</td>
<td>AEA (ml)</td>
<td>Slag (%)</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>S0</td>
<td>305</td>
<td>0</td>
</tr>
<tr>
<td>S20</td>
<td>240</td>
<td>20</td>
</tr>
<tr>
<td>S40</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>S60</td>
<td>200</td>
<td>60</td>
</tr>
</tbody>
</table>

**Table 2. Mixture compositions**
### Table 3. Concrete general properties

<table>
<thead>
<tr>
<th>Slag cement (%)</th>
<th>Initial set time (min)</th>
<th>Bleeding (ml)</th>
<th>Air content I (%)</th>
<th>Air content II (%)</th>
<th>Spacing factor (mm)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>320</td>
<td>12</td>
<td>9.00</td>
<td>9.47</td>
<td>0.131</td>
<td>34.85</td>
</tr>
<tr>
<td>20</td>
<td>370</td>
<td>17</td>
<td>7.50</td>
<td>6.95</td>
<td>0.136</td>
<td>35.49</td>
</tr>
<tr>
<td>40</td>
<td>445</td>
<td>27</td>
<td>9.25</td>
<td>9.66</td>
<td>0.089</td>
<td>36.68</td>
</tr>
<tr>
<td>60</td>
<td>435</td>
<td>15</td>
<td>6.50</td>
<td>6.93</td>
<td>0.156</td>
<td>39.23</td>
</tr>
</tbody>
</table>

Air content I: measured air content at concrete’s fresh state using a Type A meter (ASTM C231), Air content II: measured air content at concrete’s hardened state using RapidAir 3000 automatic image analysis system.
Table 4. Visual salt scaling index (VSSI) of concrete specimens in accordance with BNQ 2621-900

<table>
<thead>
<tr>
<th>Finishing</th>
<th>Slag Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>a</td>
<td>3</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
</tr>
</tbody>
</table>
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Fig. 2. Relationship between heat transfer and (accumulated) bleeding time of concrete mixtures

Fig. 3. Salt scaling of concrete specimens

Fig. 4. Example of surface finishes of samples made with 60% slag for different timings; (a) Immediately after casting, (b) after the bleeding slowed down or stopped, and (c) at the initial setting time.

Fig. 5. Abrasion test results for different binary systems

Fig. 6. Relationship between finishing, abrasion, and salt scaling resistance of the mixtures

Fig. 7. Relationship between compressive strength and salt scaling resistance of the mixtures

Fig. 8. Relationship between spacing factor and salt scaling resistance of the mixtures

Fig. 9. Visual inspection of specimens
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