MATERIALS TECHNOLOGY LABORATORY

R&D Consortium on De-Icing Salt Scaling Resistance of Concrete Incorporating Supplementary Cementing Materials

MTL 2004-15 (TR-R)

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October 2004

CANMET

DE-ICING SALT SCALING RESISTANCE OF CONCRETE INCORPORATING SUPPLEMENTARY CEMENTING MATERIALS

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EXECUTIVE SUMMARY

Numerous laboratory test data have indicated that concretes incorporating more than about 20% fly ash or slag often perform unsatisfactorily when exposed to freezing and thawing cycles in the presence of de-icing salts. On the other hand, there are several reported cases of concrete structures incorporating significant amounts of these SCMs that have performed well when exposed to de-icing salts in the field. So far, there is no clear explanation for this discrepancy. Concretes incorporating fly ash and slag may require slight changes to conventional concrete placing, finishing and curing practices to insure proper durability when exposed to de-icing salts; however, such changes are not well established. The objectives of this project are as follows:

- Compare the field and laboratory de-icing salt scaling resistance of concretes incorporating different proportions of fly ash, slag and ternary blends (with silica fume).
- Determine the effect of various key parameters such as concrete mixture design, finishing operations, and curing on the de-icing salt scaling resistance of such concretes in both laboratory and field exposures;
- Explain the somewhat lower deicing salt scaling resistance of concrete incorporating SCMs;
- Suggest procedures, modified concrete mixture proportioning or other field practices that will improve the de-icing salt scaling resistance of concrete incorporating fly ash, slag or ternary blends;
- Provide tools to better interpret the results of the current tests, and suggest new or modified laboratory testing procedures that will better simulate the field performance of concrete incorporating SCMs exposed to de-icing salts.

The present phase of the project consisted in placing sidewalks sections using selected concrete mixtures and different finishing and curing practices by a contractor specialized in this type of work. For each of the sidewalk sections representing the different variables investigated, large slabs (1.2m x1.2m) were cast from which specimens were cored and tested in the laboratory for determining their basic mechanical properties and de-icing salt scaling resistance. The casting and finishing of the large slabs were done by the same crew used for the sidewalk sections. The scaling test on the cored specimens was done according to standard procedures and to modified procedures. Also, during the casting of the sidewalk, using concrete from the same batch, specimens were cast on site according to the standard laboratory test procedures. These "laboratory-type" specimens were subjected to the same tests as the "cored" specimens, and their resistance to de-icing salt scaling were compared to that of the sidewalk sections subjected to natural exposure conditions in the field.

In order to evaluate the effect of the time of casting (and maturity of the concrete) on scaling

resistance, selected sidewalk sections were cast in the Spring and in the Fall of 2002.

Based on the results of this study, the following conclusions can be drawn:

General Conclusions

The objectives of the present study were to develop procedures or field practices that could insure an adequate field performance when exposed to de-icing salts of concrete incorporating SCMs and also to develop more realistic test procedures for properly evaluating the performance of such type of concrete when exposed to de-icing salts. The lab results have shown that the use of curing compound, especially during the fall, increased significantly the scaling resistance of the concrete incorporating SCMs. The results also show that the specimens of the concrete incorporating SCMs (except those using ternary fly ash-SF cement) scaled significantly less when tested according to BNQ NQ 2621-900 (Standard-test of the province of Quebec, Canada for evaluating de-icing salt scaling resistance) standard procedure in comparison to those tested according to ASTM C 672. The visual evaluation of the sidewalks after two winters (~20 freeze-thaw cycles) appeared to be more in line with the results of the specimens tested according to BNQ procedure.

Specific Conclusions

For sidewalks cast in Spring 2002:

- The use of fly ash decreased the scaling resistance of the concrete tested according to ASTM, but it did not significantly affect the scaling resistance of the concrete tested according to BNQ standard.
- Probably due to the high air content of the 25% slag concrete mixture, this mixture performed better than the control concrete in terms of deicing salt scaling resistance. The use of 35% slag decreased the scaling resistance of the concrete tested according to ASTM but it did not when tested according to BNQ.
- The finishing after the bleeding has stopped did not improve the scaling resistance of the concrete mixtures investigated. However, it should be noted that all concrete mixtures investigated did not show any bleeding when tested according to ASTM C 232. The finishing after bleeding was done approximately 40 min after the wooden trowel was applied.
- In general, the samples with field-type finishing (usual field practice made by professional finishers) scaled more than those using lab-type finishing (finished according to ASTM procedure).
- For both the lab-type (slabs) and field-type (cores) specimens tested at 28 days, the use of curing compound increased the scaling resistance of the fly ash concrete mixtures but decreased that of the slag concrete mixtures. When tested at 180 days, the use of curing compound enhanced significantly the scaling resistance of all the concrete mixtures.
- In general, the use of sand or geotextile at the bottom of the molds (to provide some drainage) used for the scaling test did not significantly improve the scaling resistance of the concrete made with SCMs when tested according to ASTM standard.
- All concrete samples (control, 25 and 35% fly ash, and 35% slag) tested at CANMET laboratory following the BNQ procedure showed high resistance to de-icing salt scaling. The inter-lab study has shown that the reproducibility of the BNQ test was acceptable for the control and the slag concrete mixtures. However, for the fly ash concrete mixtures, the reproducibility was

relatively poor i.e. specimens from 2 labs (out of seven labs) showed significantly more scaling than those tested in five other labs.

- The increase in concrete maturity in the field increased the scaling resistance of the concrete significantly, except for that made with ternary fly ash-SF cement (TerC^3). It seems that the relatively lower air content of that specific concrete affected its performance in an unexpected manner.
- The visual evaluation of the sidewalks after two winters (~20 cycles of freezing and thawing) confirmed the severity of the ASTM C 672 procedure and the adequateness of the BNQ procedure to better evaluate the performance of concrete made with SCMs to the de-icing salt scaling resistance.

<u>For Sidewalks Cast in the Fall 2002:</u>

- The use of fly ash decreased the scaling resistance of the concrete tested according to ASTM, but it did not when tested according to BNQ standard.
- The use of cement TerC^3 decreased the scaling resistance of the concrete tested according to both ASTM and BNQ test procedures.
- In general, the samples with field-type finishing (usual field practice made by professional finishers) scaled marginally more than those using lab-type finishing (according to ASTM C 672).
- For a curing compound regime, the field conditioning seems to decrease the scaling resistance of concrete compared to the lab conditioning (mainly due to the low temperature in the field). Whereas, for a wet curing regime, the lab conditioning seems to decrease the scaling resistance of concrete compared to the field conditioning, especially for concrete made with SCM.
- The use of curing compound enhanced significantly the scaling resistance of the concrete mixtures incorporating SCMs.
- The use of geotextile at the bottom of the molds used for the scaling test did not improve the scaling resistance of the concrete made with SCMs when tested according to BNQ standard.
- The inter-lab study has shown that the reproducibility of the BNQ test was acceptable for the control concrete, but was not for the fly ash concrete and the concrete made with cement TerC^3.
- The field evaluation shows that the control concrete and the concrete made with 25% fly ash performed well after one winter (~10 freeze-thaw cycles) whereas, the concrete made with cement TerC^3 showed some scaling. This conformed that the ASTM C 672 procedure is presently inadequate to evaluate the performance of concrete made with SCMs to the de-icing salt scaling resistance. It appears that the BNQ test is yielding more realistic results.

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INTRODUCTION

The current state of knowledge indicates that the mechanical properties and durability performance of concrete incorporating supplementary cementing materials (SCMs) as partial replacement for portland cement are generally comparable to superior to those of conventional ordinary portland cement concrete (opc).

However, one durability aspect of concretes incorporating fly ash or slag still remains highly controversial. Indeed, numerous laboratory test data have indicated that concretes incorporating more than about 20% fly ash or slag often perform unsatisfactorily when exposed to freezing and thawing cycles in the presence of de-icing salts (1-7). On the other hand, there are several reported cases of concrete structures incorporating significant amounts of these SCMs that have performed well when exposed to de-icing salts in the field (7-9). So far, there is no clear explanation for this discrepancy. It is believed that a porous surface layer that is present in almost all laboratory concretes, which is weaker than the bulk concrete in de-icing salt scaling, appears to be thicker for concretes incorporating SCMs, and therefore more susceptible to scaling than the conventional concrete (opc); this phenomenon apparently is not observed in concretes cast in the field, and partly explains the better scaling durability observed in field concretes (10). Also, there is consensus among researchers that the conditions of standardized laboratory testing in use at present are more severe than those actually occurring in the field, thus resulting in more scaling in the laboratory testing. Concretes incorporating fly ash and slag may require slight changes to conventional concrete placing, finishing and curing practices to ensure proper durability when exposed to de-icing salts; however, such changes are not well established.

Based on the above controversial laboratory test data regarding the poor de-icing salt scaling resistance of concrete incorporating SCMs, most specifications from government agencies (municipalities, provincial departments of transportation) in Canada often have strict limits on the proportion (usually 20% or less) of fly ash and slag that can be used in concrete exposed to de-icing salts. Contractors in certain regions of Canada have gone to the extent of completely banning the use of fly ash or slag in concretes exposed to de-icing salts because of bad experience with that type of concrete in the field. In fact, the general belief about the poor performance of concretes incorporating fly ash or slag based on de-icing salt scaling test data, and the strict limits of the specifications have a very negative impact on people's perception of the overall performance of such concretes, even for applications where resistance to de-icing salt scaling is not an issue. This creates barriers for the use of large amounts of SCMs in concrete, and at times even for the use of small amounts.

Convincing the different specifying agencies to increase the use of fly ash or slag in concretes exposed to de-icing salts will require the demonstration of good field performances, and explanations for the observed poor performance in the laboratory test. The development of any procedures or field practices that could ensure an adequate field performance when exposed to de-icing salts of concrete incorporating SCMs is also essential in order to avoid any failure that would cause severe damage to the reputation of this type of concrete. The development of more realistic test procedures is also necessary to properly evaluate the performance of materials to be used in concrete exposed to de-icing salts.

It is the global objective of this project to develop the necessary technical data that will increase the confidence in the use of fly ash or slag in concrete exposed to de-icing salts.

SCOPE

The present phase of the project consisted of placing sidewalk sections using selected concrete mixtures (made in ready-mixed concrete plants) and different finishing and curing practices. For each of the sidewalk sections representing the different variables investigated, large slabs (1.2m x1.2m) were cast on site from which specimens were cored and tested in the laboratory for determining their basic mechanical properties and de-icing salt scaling resistance. The casting and finishing of the sidewalk sections and of the large slabs were done by the same crew of professionals. The scaling test on the cored specimens was done according to standard procedures and to modified procedures. Also, during the casting of the sidewalk, using concrete from the same batch, specimens were cast on site according to the standard laboratory test procedures. These "laboratory-type" specimens were subjected to the same tests as the "core" specimens, and their resistance to de-icing salt scaling were compared and will be compared to that of the sidewalk sections subjected to natural exposure conditions in the field.

In order to evaluate the effect of the time of casting (and maturity of the concrete) on scaling resistance, selected sidewalk sections were cast in the spring and in the fall of 2002. This report is divided into two parts, Part I dealing with the sidewalk sections cast in the spring, and Part II dealing with those cast in the fall 2002.

PART I: SIDEWALK SECTIONS CAST IN THE SPRING 2002

Part I consisted in placing sidewalks sections using seven concrete mixtures and applying four finishing and curing practices. The concrete mixtures consisted of a control concrete and concrete mixtures incorporating 25 and 35% fly ash, 25 and 35% slag, a ternary blended cement based on fly ash and silica fume and a ternary blended cement based on slag and silica fume. The finishing and curing practices consisted of two practices commonly used in Montreal, Canada, one using a curing compound and one using a wet burlap as a curing mode; the third practice consisted of using a second type of curing compound and the fourth practice consisted of delaying the final finishing till the bleed water evaporated completely. The parameters investigated were as follows:

- Effect of the use and percentage of fly ash;
- Effect of the use and percentage of slag;
- Effect of the use of ternary blends (fly ash B silica fume; slag B silica fume);
- Time of finishing (early finish, after bleeding is finished);
- Lab-test conditioning and exposure versus field conditioning and exposure;
- Moist curing versus curing compound;
- Effect of the type of curing compound;
- Effect of mold (a layer of geotextile or wet sand at the bottom of the mold to allow some drainage);

- Inter-lab comparison (seven labs participated in the study).

Concreting of the sidewalk sections, and specimens was done at the end of May, in the city of Verdun, Montreal, Canada, during a sunny and hot day in which the ambient temperature reached 32°C at noon.

Materials

Cementous materials

The materials used in Part I of the study consisted of one ASTM Class F fly ash, one Grade 100 Ground Granulated Blast Furnace Slag (GGBS), two CSA Type 10 (ASTM type I) cements (designated as A and B; cement A used for control and fly ash concrete mixtures, and cement B used for slag concrete mixtures), one silica fume blended cement (HSF, ~8% silica fume), and two ternary blended cements ($TerC^3$ incorporating ~20% fly ash and ~5% silica fume, and TerCem incorporating ~20% slag and ~5% silica fume). The physical properties and chemical composition of these materials are given in Table 1.

Chemical admixtures

For air entraining admixtures (AEA), fatty acid based AEA was used for the control and the concrete mixtures incorporating fly ash, while synthetic resin type AEA was used for the concrete mixtures incorporating slag. For the water reducers, mid-range water reducer was used for the control concrete, hydrocarboxilie acid-based was used for the concrete mixtures incorporating fly ash and carbohydrated and glucose was used for the concrete mixtures incorporating slag. Meadows 12/15 (designated as curing compound 1) considered as a high range curing compound and Planicure 65 (designated as curing compound 2) considered as a mid-range curing compound were also used.

Aggregates (coarse and fine)

The coarse (5 to 20 mm in size), and fine aggregates selected for this study were those commonly used at the batching plant(s) selected from the region of Montreal. The coarse aggregates used for the control and fly ash concretes were crushed limestone, and those used for slag concretes were crushed igneous rock (trap rock).

Concrete Making and Preparation of Test Specimens

Concrete mixtures

The concrete mixtures were designed to meet the requirements of the Canadian Standard Association CSA A23.1, C2 Class of exposure concrete: 32 MPa minimum, 0.45 maximum water-to-cementititous materials ratio (W/cm), and 5 to 8% air content. The control concrete and the concrete mixtures incorporating fly ash were made by St-Lawrence Cement/Demix, while those incorporating slag were made by Lafarge.

- Control mixture without fly ash and slag (typical conventional sidewalk concrete mixture design used by the City of Montreal which incorporates ~2% of silica fume) made with a w/cm of 0.45, and designated as V1.
- Mixture incorporating 35% fly ash (FA) made with a w/cm of 0.41, designated as V2.

- Mixture incorporating 35% slag made with a w/cm of 0.42, designated as V3.
- Mixture incorporating 25% FA made with a w/cm of 0.41, designated as V4.
- Mixture incorporating 25% slag made with a w/cm of 0.41, designated as V5.
- Mixture incorporating a commercially available ternary fly ash-SF cement ($TerC^3$) made with a w/cm of 0.42, designated as V6.
- Mixture incorporating a commercially available ternary slag-SF cement (TerCem) made with a w/cm of 0.45, designated as V7.

The concrete mixture proportioning is given in Table 2. The control mixture V1 was made using 25% of blended silica fume cement HSF and 75% of Portland cement A. The control mixture (V1) and the mixtures incorporating fly ash (V2 and V4) were made at a different plant from those incorporating slag; both plants located in the greater Montreal area.

<u>Casting, finishing and curing of field sections</u>

Sidewalk sections

The sidewalk sections made with each of the above concrete mixture were divided into a number of sub-sections. Each sub-section, of 2.8 x 3.7 m in size, was cast, finished and cured using one of the procedures described below, and illustrated in Fig. 1,2.

A. Manual placing, followed by finishing with a bull float, wooden trowel for fine tuning, finishing of the edges, wait till bleeding water disappeared then final finishing with trowel, followed shortly (i.e. generally within 15 to 30 min) by the application of the curing compound 1
B. Manual placing, followed by finishing with a bull float, wooden trowel for fine tuning and final finishing, finishing of the edges, and followed shortly by the application of the curing compound 1. T his is common practice in the field, i.e. no real waiting period between the various operations.
C. Same as B, except that the curing compound 2 was used.
D. Manual placing, followed by finishing with a bull float, wooden trowel for fine tuning and final finishing, finishing of the edges; cover with wet burlap and plastic sheets as soon as possible and cure for two days.

The above four procedures were used for the concrete mixtures V1 to V3, whereas, only procedures B and D were used for the concrete mixtures V4 to V7.

1.2x1.2-m large slab specimens

A total of twenty 1.2 x 1.2m large slabs were cast at the site i.e. one large slab for each type of concrete and each finishing/curing operation used for 0that type of concrete. The finishing/curing operations were similar to those used for the sidewalks and were done by the same professional finishers.

<u>Test specimens cored from the large slab specimens</u>

Figure 2 shows the samples cored from the slabs. Two to three 100 mm cores were collected and tested for compressive strength at 3 and 180 days. Two ~250 mm cores were taken from each large slab at 2 days and transferred to the laboratory to be cured and tested according to ASTM C 672 test procedure. Among these, the specimens cored from the large slabs cured with wet burlap were stored in a moist-curing room at 23 °C for 12 days and then subjected to 14 days of drying; the cores with the curing compound were cured for 12 days in the laboratory air, the surface of the cores was gently brushed to remove the curing compound before starting the 14-day drying period.

At 91 days, four ~250 mm cores were cored from selected large slabs of concrete mixtures V1 to V4. Two cores were tested according to ASTM C 672 procedure, and two according to BNQ NQ 2621-900 (De-icing test standard of the province of Quebec, Canada) standard procedure. The specimens with curing compound at the surface were first brushed, then all the specimens were subjected to a drying period of 14 days at the lab-air conditions. The cores tested according to ASTM procedure were then immediately subjected to the freezing and thawing cycles in the presence of the de-icing solution. Those tested according to BNQ procedure were first re-saturated with the solution at the surface for one week prior to the starting of the freezing and thawing cycles. The differences between the ASTM C 672 and BNQ NQ 2621-900 test procedures are discussed below.

The remaining of the large slabs were kept outdoors exposed to natural environmental conditions, until the freezing and thawing periods began (Mid-November). Four 100 mm cores were then collected and tested for compressive strength at ~180 days, and for the determination of the air-void parameters. Two ~250 mm cores were also taken from each large slab and transferred to the laboratory where they were immediately subjected to the freezing-thawing cycles (according to ASTM C 672) with no drying period. The surface of the cores with curing compound was brushed prior to testing.

Lab-type specimens

For each of the concrete mixtures, the specimens listed below were cast and cured following the ASTM standard procedures except that the specimens were kept in their molds for the first 48 hours and then transferred to the laboratory to be subjected to the selected curing procedure:

- Four slabs using the standard moulds i.e. two using the moist curing mode (designated as MC), and two using the curing compound1 (designated as CC1). These slabs were subjected to identical storage conditions as the 250-mm cores (cored at 2 days) described before.
- Four slabs using modified moulds, i.e. two with a 40 mm layer of sand (designated as S) and two with a 7 mm layer of geotextile (designated as G) at the bottom of the moulds to provide some drainage. The sand used was wet with an absorption of 3%, and the geotextile used was a polypropylene type with a specific surface of 900 g/m^2.
- Twelve 100 x 200 mm cylinders for the determination of the compressive strength.

For the concrete mixtures V1 to V4, fourteen extra slabs were cast to be used for the inter-lab study (two for each of the seven labs involved in this study) and were cast cured and tested following the BNQ NQ 2621-900 standard procedure. The BNQ standard differs from the ASTM C 672 in the following points:

- The BNQ standard does not require brushing after the bleeding, i.e. the slabs are simply covered with a plastic sheet immediately after finishing with a wooden trowel;
- The BNQ standard requires a moist curing period of thirteen days (in this case it was 12 days) followed by a fourteen days period of drying and seven days period of re-saturation of the surface with a solution of 3% NaCl;
- The scaling residues are collected and weighed after 7, 21, 35 and 56 cycles of freezing and

thawing, and the cycles continue during the weekends as well. In the province of Quebec most laboratories performing the test use automated freeze-thaw cabinets programmed to operate 7 days a week.

Testing of the sidewalk sections and of the lab specimens

Properties of fresh concrete

The slump, air content and the bleeding were determined following the ASTM standards (ASTM C 143, C 231, and C 232, respectively). Forced bleeding was also determined by means of an apparatus that consists of putting a sample of fresh concrete in a cylinder, 90 x 120 mm in size and to exert a pressure of 0.35 MPa on the concrete to collect the water resulting from the pressure (1). The total bleeding water and the time taken for the bleeding to stop were then recorded.

Compressive strength

For each concrete mixture, the compressive strength was determined on two cylinders at 3, 14, 28, 91 and ~180 days, and also on two to three cores at 3 and ~180 days. The test was carried out according to ASTM C39.

Air-void parameters

Two specimens (100 mm cores) were taken from each large slab for the determination of the air-void parameters following the ASTM C 457 test procedure. The top surface of the cores was the finished surface, and thus needed to be ground to be suitable for microscopical observation. Therefore, the air-void parameters were determined at the closest layer to the surface of the slabs that could have been practically investigated, but not at the surface of the slabs.

De-Icing salt scaling resistance

The sidewalk sections will be monitored visually to determine the scaling resistance of the concrete mixtures. Six thermistor wires were embedded in the control concrete mixture V1 (sub-section using the casting/curing procedure B), at a depth of 20 and 32 mm, to determine the number of freezing and thawing cycles the concretes were subjected to.

For the cores and slabs, the scaling resistance was determined according to ASTM C 672, except for the specimens tested according to BNQ standard. The former test was started after an initial moist curing of the specimens for 12 days (the first 2 days the specimens were kept in the moulds), followed by 14 days drying in laboratory air. The top surfaces of the specimens were exposed to 50 cycles of freezing and thawing in the presence of a 3% NaCl solution. For the BNQ test, the specimens were moist cured for 12 days, air cured in the lab for 14 days, and re-saturated with 3% NaCl solution for 7 days. The top surfaces of the specimens were then exposed to 56 cycles of freezing and thawing in the presence of 3% NaCl solution.

At the end of each 5 cycles (for ASTM procedure) and after 7, 21 and 35 cycles (for BNQ procedure), the surface of the specimens was flushed off thoroughly, the scaling residue was collected, dried and weighed, and the specimens were ponded with a fresh sodium chloride solution. At the end of the test, the surface of the specimens was rated visually following the ASTM C 672 rating.

Results and Discussion

Properties of fresh concrete

The unit weight, slump, air content, temperature, bleeding and forced bleeding water of the concrete mixtures are presented in Table 3. The results show that the unit weight of the concrete mixtures ranged from 2270 to 2325 kg/m^3. The slump of the concrete mixtures ranged from 70 to 100 mm which is in the range of the slump required for the concrete used in sidewalks. The air content of the concrete mixtures ranged from 5.4 to 7.2%, the concrete mixtures made with slag (except that made with cement TerCem, ternary slag-SF cement) had higher air content than those made with fly ash.

The temperature of the fresh concrete ranged from 21 to 26°C, the temperature was higher for the concrete mixtures cast in the mid-day and lower for those cast in the morning (10 AM) and in late afternoon (4:00 PM). The ambient temperature reached 32°C at noon.

The bleeding water tested according to ASTM C 232 was negligible for all the concrete mixtures investigated. However, the forced bleeding water ranged from 23 to 71 ml and was generally high for the concrete made with fly ash. The highest value of the forced bleeding was for the concrete incorporating 25% fly ash and the lowest value was for the concrete made with cement TerCem (ternary slag-SF cement). The total bleeding water divided by the time that took the bleeding to finish i.e. the bleeding rate, indicates the easiness of water extraction from the concrete. The results show that the highest bleeding rate was that of the concrete made with 35% fly ash and the lowest rate was that of the concrete made with the ternary slag-SF cement.

Compressive strength

The compressive strength of the concrete mixtures tested on cylinders and on specimens cored from the large slabs are given in Tables 4 and 5, respectively.

Table 4 shows that the 3, 14, 28 and 91-d compressive strength of the concrete mixtures determined on moist cured cylinders ranged from 18.3 to 27.8, 24.8 to 42.6, 28.3 to 46.7 and from 36.6 to 53.9 MPa, respectively. The lowest values were obtained for the concrete incorporating 25% fly ash and the highest values were for the concrete made with the ternary slag-SF cement. It should be noted, however, that the concrete made with cement TerCem was initially made with a w/cm of 0.41, the concrete delivered had a slump of 70 mm. The large slabs and the lab-specimens were cast first, the concrete was, then supposed to be poured into the sidewalks, but the slump of the concrete at that moment decreased to less than 60 mm, the contractor refused to cast the sidewalks with such slump . A determined quantity of water was then added to the concrete into the truck to increase its slump to 70 mm and its w/cm to 0.45. The compressive strength values reported in Table 4 and 5 are those of the initial concrete that has a w/cm of 0.41, which partly explained the highest values recorded for that concrete.

The 28-d compressive strength values show that the concrete mixtures incorporating 25 and 35% of fly ash did not meet the CSA requirement of the concrete used in sidewalks, which is a minimum 28-d compressive strength of 32 MPa. However, the results show that the 91-d compressive strength of these concrete mixtures met the above strength requirement, the concrete incorporating 35% fly ash developed even higher compressive strength than that of the control concrete. This suggests that the above requirement could be adjusted for concrete incorporating supplementary cementitious materials such as fly ash, which develops higher strength at later ages. This requirement could be specified at later age rather than at 28 days (i.e. 56 days for example). It is however interesting to note that the concrete made with 35% fly ash developed higher compressive strength values at all ages than that made with 25% fly ash although both concrete mixtures had similar w/cm, similar air content and similar total weight of cementitious materials.

Table 5 presents the compressive strength of the concrete mixtures determined on cores. The results show that in general, the type of curing had no significant effect on the compressive strength, except, possibly, for some concrete mixtures for which the wet curing increased the compressive strength by 10 to 15% (V3 at 3 days, V2, V4, and V6 at 180 days).

The results given in Table 4 show that the 3-d compressive strength determined on cores were similar to those determined on cylinders, except for the concrete mixture incorporating 25% fly ash, for which the results on cores were higher than those tested on cylinders, and the control concrete for which the results on cylinders were higher than those tested on cores. At 180 days, with the exception of the control mixture V1, and the concrete made with cement TerCem V7, the compressive strengths measured on cores were slightly higher than the strengths obtained on cylinders.

According to ASTM C 42, there is no universal relationship between the compressive strength of a core and the corresponding compressive strength of standard-cured molded specimens. However, it is generally expected to obtain lower strength values with cores than with moist cured specimens. This is due to the fact that moist cured specimens have more chance to cure and to develop strength. Also, unlike a moulded cylinder, in a core some coarse aggregate particles are cut in the drilling process and are therefore, not wholly bonded to the cement paste matrix resulting in a lower value of compressive strength when tested (12). ACI 318-99 and ACI 301-99 say that concrete shall be considered adequate "as specified" when the average of three cores is equal to at least 85% of the compressive strength determined on moist cured specimens. In the present project, for some reasons, the majority of cores tested higher than the corresponding laboratory moist cured cylinders.

Air-Void Parameters

The air-void parameters of the concrete mixtures are presented in Table 6. The air content and spacing factor of the control concrete ranged from 4.6 to 4.9%, and from 200 to 230 µm; those of the fly ash concrete mixtures ranged from 3.9 to 5.2%, and from 160 to 200 µm; those of the slag concrete mixtures ranged from 4.6 to 6.7, and from 140 to 200 µm, and those of ternary blends ranged from 3.6 to 5.1 and from 140 to 180 µm, respectively.

The results show that in general, the air content of the hardened concrete is lower than that of the fresh concrete. All the concrete mixtures exhibited an average air content below 5%, except that of the concrete mixture incorporating 25% slag (V5), that shows an average air content of 6%. It is generally agreed that air-entrained concrete should have a spacing factor value of not exceeding 200 µm for satisfactory resistance to freezing and thawing cycling. Table 6 shows that with the exception of the control concrete, all the concrete mixtures had a spacing factor below 200 µm. However, it is possible that the spacing factors at the surface of the slabs (the most critical part in terms of scaling) show different values than those presented in Table 6. The values presented in

Table 6 represent the air-void parameters of the closest layer to the surface of the slabs that could have been practically investigated following the ASTM C 457 procedure.

<u>De-icing Salt Scaling Resistance</u>
The results on the de-icing salt scaling resistance of the concrete mixtures are presented in Table 7 to 10, and in Fig. 3 to 16.

Effect of the use and percentage of fly ash (Figs. 3, 4)
The results show that in general, concretes incorporating fly ash showed more scaling, and the scaling increased with increasing fly ash content, which is in line with some published data (1-7).

None of the fly ash concrete specimens tested according to ASTM C 672 met the requirement of MTO (Ministry of Transportation of Ontario, Canada) that specifies a maximum of 0.8 kg/m^2 of scaling residue after 50 cycles of freezing and thawing in the presence of deicing salt (Fig. 3).According to Thomas (8), the specimens that show mass losses of the order of 0.8 kg/m^2 generally exhibit ASTM visual ratings in the range of 4 to 5 considered as moderate to severe scaling.

ASTM C 672 stipulates that in order to compare the scaling resistance of different concrete mixtures, the specimens should have similar compressive strength at the beginning of the drying period. Table 4 shows that the control concrete developed a compressive strength of 31.6 MPa at 14-d (date of the beginning of the drying period), while the 35% and 25% fly ash concrete mixtures developed a compressive strength of only 26.1 and 24.8 MPa at 14-d, respectively. These results suggest that the poor performance of the fly ash concrete mixtures compared to that of the control concrete could be somewhat related to the lower strength of the former mixtures. However, the results on concrete made with 35% slag, cement TerC^3 and cement TerCem, as discussed below, show poor performance in terms of scaling resistance despite having developed higher 14-d compressive strength than the control concrete. These results confirm that the scaling resistance of concrete is not directly related to the mechanical properties of the bulk concrete but most likely to the microstructural characteristics of the surface layer of concrete (which is different when incorporating fly ash or slag compared to conventional portland cement concrete).

On the other hand, the results in Fig. 4 show that the fly ash concretes performed similarly to the control concrete in terms of scaling resistance when tested according to BNQ standard. The results show that fly ash concretes did meet the requirement of MTQ (Ministry of Transportation of Quebec, Canada) that specifies a maximum of 0.5 kg/m^2 of scaling residue after 56 cycles of freezing and thawing in the presence of deicing salt (Table 8). When using the ASTM procedure, the scaling residue recorded at the end of test for the concrete mixtures made with 35% and 25% of fly ash were 2.8 and 3.4 kg/m^2, respectively, while those numbers were reduced to 0.45 and 0.29 kg/m^2, respectively, when using the BNQ procedure (Table 8, column 1).

This discrepancy could be due to the difference that exists between the two test procedures. As mentioned before, the BNQ procedure does not require brushing the surface after the bleeding water disappears, and it requires a re-saturation period of one week with the salt solution prior to the first freezing cycle. During finishing, if brushing is done too early or much later after the bleed water has disappeared, it may damage the surface and specifically the air void network / microstructural characteristics at the surface of the slabs, and in turn adversely affect the scaling resistance of the slab. In fact, it was pointed out in the literature that the final finishing is considered as a shortcoming of the ASTM C 672 test method as this could cause operator variability due to differing interpretations as to the end of bleeding (8). The results obtained with the BNQ procedure suggest that leaving the surface layer untouched (i.e. no brushing) could possibly improve the resistance to scaling in the test. In addition to the above, the 7-day re-saturation period of the slabs with the solution might also create ions-equilibrium between the concentration of the solution at the surface and that in the voids formed in the first layers of the slab, thus reducing the osmotic pressure within this surface layer of the concrete specimen, leading to reduced scaling. The osmotic pressure is one of the main factors causing scaling (13).

It is, however, interesting to notice in Table 8 that despite the low weight of scaling residues of the fly ash concrete specimens tested according to BNQ, the visual rating of these mixtures ranged from 2 to 3 (ASTM rating) which is considered as slight to moderate scaling. Some specimens did not show any scaling of the paste but only popouts, possibly related to the presence of a very small fraction of frost-susceptible particles in the coarse aggregate. In fact, the authors understand that during spring and summer, considered as high seasons for construction in Canada, small fractions of undesirable particles get occasionally mixed with the coarse aggregates, due to the high demand of aggregates.

Effect of the use and percentage of slag (Figs. 5, 6)
For testing performed in accordance with ASTM C 627,the results illustrated in Fig. 5 show that, in general, the concrete mixture incorporating 25% slag performed better than the control concrete in terms of scaling resistance. However, the increase of the slag content in the concrete from 25 to 35% resulted in reduction in scaling resistance of the concrete. Most of the concrete specimens (slabs or cores) incorporating 35% slag exhibit moderate to severe scaling, and none of the specimens actually met the MTO requirement, while most of the specimens incorporating 25% slag showed light scaling, and produced scaling residues either slightly over or slightly below the MTO limit.

The specimens tested according to the BNQ procedure scaled significantly less than those tested according to ASTM method (Fig. 6) and this is in line with the results obtained with fly ash concrete mixtures (Fig. 4). The slag concrete mixtures appeared to perform better than the fly ash concrete mixtures, and this is partially due to the fact that the slag concrete mixtures had higher air content and enhanced air-void parameters than the fly ash mixtures.

Effect of the use of ternary blends (Fig.7)
When tested in accordance with ASTM C 672, the concrete mixtures made with both ternary blended cements performed poorly in terms of scaling resistance. The results of the tests performance in this study have shown that the concrete made with ternary fly ash-SF cement scaled more than the concrete made with ternary slag-SF cement. However, cautions are to be made to draw any conclusions on the relative performance of these cements when used in concrete exposed to freezing and thawing cycles in the presence of de-icing salts. The results dealing with fly ash and slag concrete mixtures have shown poor performance when tested according to ASTM but acceptable performance when tested according to BNQ. The concrete mixtures made with ternary blends were not tested according to BNQ procedure in this part of the study.

Time of finishing (Fig. 8)
Although, no bleed water was noticed on the large slabs of the three concrete mixtures investigated (i.e. V1, V2 and V3), the finishers waited for 33, 38 and 42 minutes to perform the final finishing on the control concrete, the concrete made with 35% fly ash and that made with 35% slag, respectively. The results show that the de-icing salt scaling resistance of the control concrete and the concrete mixture made with 35% of fly ash was not affected by the time of final finishing, whereas, for the concrete mixture made with 35% of slag, the above mentioned delay in the final finishing appears to have contributed in decreasing the scaling residue almost by half, though the scaling residue was still above the MTO limit (Fig. 8). Published data have also shown that delayed finishing improves the scaling resistance of slag concrete (7). Additional testing is needed to determine if this behavior is specific to slag concretes.

Lab-finishing versus field-finishing of test specimens (Figs 9, 10)
Fig. 9 shows the results of the lab-slabs cast and moist cured according to ASTM C 672 ("MC" in Table 7) and those of the specimens cored from the large slabs cast and covered with a wet burlap for 2 days ("Procedure D" in Table 7). Fig. 10 shows the results of the lab-slabs cast and cured with the curing compound according to ASTM C 672 ("CC1" in Table 7) and those of the specimens cored from the large slabs for which the same type of curing compound was applied immediately after the final finishing ("Procedure B" in Table 7). These results show that, in general, the field-finished specimens (cores) scaled similar to, or slightly more than the corresponding lab-finished slabs.

The difference seems to be more pronounced for the 35% fly ash concretes for both curing regimes (i.e. moist cured - Fig. 9, and curing compound - Fig. 10), and for the control mixture in the moist curing regime (Fig. 9). With the exception of the 35% fly ash concrete, the difference in scaling between the lab- and field-finished specimens was not that pronounced for the specimens with curing compounds (Fig. 9). The above results show that the somewhat excessive severity of the ASTM procedure is not specific to the finishing prescribed in that procedure; in fact, with the actual field finishing, the specimens sometimes scaled more.

Moist curing versus curing compound (Figs. 11, 12)
Table 7 shows that, with the exception of the control concrete tested on lab-slabs, curing of the test specimens using moist cure or with curing compound did not result in significant differences in visual ratings of the test specimens after 50 cycles following ASTM C 672 procedure; however, more pronounced differences were observed from the results of scaling residues. The results show that for some reasons, the curing compound reduced the scaling residue of fly ash concretes, but increased that of the control and slag concretes. However, the results on specimens tested at 180 days (as discussed below) show that the curing compound reduced the scaling residue of all concretes (Table 10). Published data have also shown that the curing compound significantly increases the scaling resistance of fly ash concrete, the curing compound possibly lowers the degree of microcracking and thus increases the scaling resistance (1, 5, 14-16).

Effect of the type of curing compound (Fig. 13)
The results show that the type of curing compound did not significantly affect the scaling resistance of concrete.

Effect of mould (Fig. 14)
The results show that the use of the modified molds (geotextile and wet sand at the bottom of the molds) to drain water to the bottom of the slabs significantly decreased the scaling resistance of the control concrete but marginally increased the scaling resistance of the other concrete mixtures. It should be noted that all the concrete investigated have shown negligible bleeding.

Therefore, it generally appears that the use of geotextile or wet sand at the bottom of the moulds to decrease the bleeding water at the surface of the slabs that adversely affect the scaling resistance of the concrete did not significantly enhance the scaling resistance of the concrete with negligible bleeding. On the contrary, it did significantly decrease the scaling resistance of the control concrete, which was not expected.

Inter-lab comparison (Fig. 15)
Seven laboratories participated in evaluating the scaling resistance of the control concrete (V1), the concrete mixture incorporating 25% fly ash (V4), 35% fly ash (V2) and 35% slag (V3) following the BNQ test procedure. The specimens tested by all the laboratories were made in similar moulds and were cast and finished by the same operator. The specimens were distributed to the participants at the age of 24 h; they were demoulded at the age of 48 hours and then subjected to the curing mode prescribed by BNQ procedure as described earlier. The MTQ, based on the BNQ test procedure, requires a scaling residue limit of 0.5kg/m^2 after 56 cycles of freezing and thawing in the presence of 3% NaCl solution. Although studies have shown that the MTO limit (0.8kg/m^2 after 50 cycles following the ASTM procedure) corresponds to moderate/severe scaling (8), no data correlating the MTQ limit to the visual scaling rating have been published. Thus, this limit value should be taken with more cautions before rejecting any concrete mixture.

The results given in Table 8 and illustrated in Fig. 15 show that, except for lab 3 that shows the 35% fly ash concrete failing to meet the MTQ requirement, and lab 7 that shows both fly ash concrete mixtures not meeting the MTQ requirement, all the concrete investigated by the other labs involved in the study met the MTQ requirement. These results show that two different test procedures / regimes, i.e. ASTM and BNQ, can classify very differently (i.e. pass or fail) the scaling resistance of concrete incorporating up to 35% fly ash or slag.

It should be noted that for lab 7, the results for fly ash concrete mixtures represented the average of two values with one meeting the requirement and the other not. Also, the visual rating (according to ASTM C 672) of the investigated concretes, as reported by Lab No.1, ranged from 1 to 3 despite the low weight of the scaling residue. As mentioned before, this could be due to a fraction of frost susceptible coarse aggregates that affected the visual ratings and the average results when these aggregates are present more at the surface of one specimen than in the other. It takes very few of such aggregate particles to make a significant difference in the results.

Table 8 shows that the reproducibility of the BNQ test was acceptable for the control concrete and the concrete incorporating 35% slag, but was not for the fly ash concrete mixtures. In fact, the average scaling residue (of the seven labs) of the control and the slag concretes was 0.29 kg/m^2 and 0.22 kg/m^2, with a standard deviation of 0.11 kg/m^2 and 0.12 kg/m^2 and a coefficient of variation of 38% and 55%, respectively. For the concrete mixture incorporating 35% and 25% fly ash, the average scaling residue was 0.34 kg/m^2 and 0.33 kg/m^2 with a standard variation of 0.61 kg/m^2 and 0.41 kg/m^2 and a coefficient of variation of 179% and 124%, respectively.

ASTM vs BNQ (Table 9)
Specimens were cored at 91 days from the large slabs of the four concrete mixtures involved in the interlab study (control concrete, concrete incorporating 35% fly ash, 25% fly ash and 35% slag) to compare the scaling resistance of these concrete determined according to ASTM procedure to that determined according to BNQ procedure in order to confirm the above findings. The results show that for similar concrete mixture, the scaling residue determined according to the ASTM procedure was similar to that determined according to BNQ procedure. The control concrete and the 35% fly ash concrete specimens showed no scaling or very slight scaling. The 35% slag concrete specimens showed moderate scaling, although the amount of scaling residues was fairly low. This is again due to a fraction of frost susceptible coarse aggregates that was accidently included in this concrete mixture. On the other hand, the 25% fly ash concrete specimens showed very slight scaling, but the scaling residues were above the MTQ and MTO limits, suggesting these limits should be used with more cautions, especially when dealing with concrete including SCMs.

The fact that at 91 days, the scaling resistance determined according to ASTM procedure was similar to that determined according to BNQ procedure for each of the concrete investigated is most likely due to the maturity of the concrete as discussed in the following section.

Effect of maturity (Fig. 16)
Two additional specimens were cored from each of the large slabs just before the beginning of the freezing and thawing cycles in the field (at 180 days) to evaluate the scaling resistance of the concrete cast in sidewalks at this age. When brought to the laboratory, none of the specimens were subjected to the drying period as specified in the standard. The specimens with the curing compound at the surface were brushed and then all the specimens were subjected to the freezing and thawing cycles in the presence of the de-icing salt solution. The objective of this part of the study was to determine the effect of maturity on the scaling resistance of the concrete and also to verify if the standard lab-test conditioning of 28 days is valid in determining the scaling resistance of a concrete cast for example in the spring and would have got the time to mature for several months before the beginning of freeze/thaw cycles.

Table 10 and fig. 16 compare the amounts of scaling residues produced for the core specimens when tested at the ages of 28 and 180 days. In all but one case, the concrete specimens that failed the scaling test at 28 days, actually passed the test at 180 days. A longer period of conditioning in the field under natural environmental conditions (wetting and drying) resulted in an increased maturity of the concrete. When testing the mature concretes in scaling, this resulted in a significant increase of the scaling resistance of all the concrete mixtures. The testing was conducted according to the ASTM regime. Published data have shown that, surprisingly, the longer the moist curing in the lab (from 28 days to 91 days), the lower the scaling resistance of the concrete incorporating fly ash; the data also show that the shorter the drying period prior to the beginning of the cycles, the higher the scaling resistance of such concrete (5, 16). Therefore, this suggests that the improved performance of the core specimens from 28 to 180 days can either be related to the longer curing period in the field or to the absence of the drying period in the lab or a combination of both. However, the results presented in the previous section (BNQ vs. ASTM, Table 9, samples tested at 91 days) show that even when the cores were subjected to the drying period, the scaling resistance of these cores was significantly higher than that of the corresponding cores tested at 28 days. This strongly suggests that the reason for the better performance of the cores tested at 180 days is the longer maturing period in the field under natural wetting and drying conditions, which unfortunately cannot be simulated by a longer moist curing period in the lab.

The results also show that at 180 days, the cores cured using the curing compound (A, B and C in Table 10) performed significantly better than those wet cured for the first 48 hours (D in Table 10), especially for the concrete incorporating 25% fly ash. This was not the case for the cores tested at 28 days (especially for slag concrete mixtures). Probably, the wet curing for only 48 hours was not enough to ensure proper curing, and to improve the microstructure at the surface of the slabs as it did with the curing compound. The relatively poor performance of the wet cured specimens of the concrete made with 25% fly ash and that made with cement TerCem, and the poor performance of the concrete mixture made with cement TerC^3 (ternary fly ash-SF cement) even with a long conditioning period is possibly due to the air-void parameters at the surface of these slabs.

Field evaluation

Fig. 17 shows the temperature recorded at a depth of 20 mm from the top surface of the sidewalks from May 2002 to April 2003. According to Neville (17), normal concrete freezes at about -5°C due to impurities in water and the capillary pressure in concrete. Concrete will thaw at 0°C, provided that this temperature is maintained or exceeded long enough (few hours) to thaw concrete completely. Based on these assumptions, the sidewalks were subjected to at least ten freezing and thawing cycles per year during the first two years. Figs. 18 to 24 show that all sidewalks performed fairly well after being subjected to ~20 cycles of freezing and thawing, along with the application of a deicer that is used in the city of Verdun, i.e. usually a mix of 70% sand and 30% salt (NaCl).

The field evaluation shows that concrete incorporating fly ash and slag (up to 35%), and ternary blended cement TerCem have performed satisfactorily after 20 cycles of freezing and thawing combined with the application of the deicer. Sidewalk sections made with cement TerC^3 have shown slight scaling compared to the other sidewalks. If the other sidewalk sections can be visually rated as 0, the sidewalk sections made with cement TerC^3 would be rated from 0 to 2. The visual survey of the sidewalk sections also shows that the time of finishing, the mode of curing (moist curing vs curing compound) and the type of curing compound did not have a significant effect on the scaling resistance of concrete. However, some sidewalk sections have shown few popouts, especially the moist cured sidewalks using 25% fly ash and 25% slag. As mentioned with the lab-results, this could be due to a fraction of frost susceptible coarse aggregates.

The results also confirmed the severity of the ASTM C 672 test; Table 11 shows the cumulative scaling residues of the lab-slabs after 20 cycles following the ASTM and the BNQ procedures. The table shows that all the fly ash concrete mixtures performed poorly when tested in accordance with ASTM C 672, while, as mentioned above, these mixtures performed relatively well in the field. This is in line with published data in which the performance of more than 20 highway structures incorporating fly ash concrete, which had undergone freezing and thawing in the presence of deicing salts for more than 20 winters, was evaluated; the results of that study have shown that all these structures showed no scaling due to deicing salt application, whereas, all fly ash concrete samples taken from field placements and tested using the ASTM C 672 in the laboratory showed poor performance (8). The author of the survey concludes that the ASTM de-icing salt scaling test is not appropriate for the evaluation of the scaling resistance of fly ash concrete.

The results of the field performance survey seem to be more in line with the results obtained on the specimens that were exposed to natural conditioning, cored at 180 days and tested in the laboratory following the ASTM C 672 procedure (Table 12). However, as mentioned before, it is difficult to simulate the field conditioning in the laboratory. The results of the field performance survey seem also to agree with the results obtained on the specimens tested according to BNQ procedure (Table 11). This test seems to better simulate the field performance of concrete mixtures incorporating SCMs and subjected to freezing and thawing cycles in the presence of de-icing salt solution. However, it should be mentioned that the concrete investigated were made with a w/cm of around 0.40, and did not exhibit any bleeding. Research is still needed to confirm the above observations for concrete with higher w/cm and noticeable bleed water values.

Concluding Remarks to Part I

Based on the results of this part of the study, the following conclusions can be drawn:

- The concrete mixtures incorporating fly ash investigated in this study have shown a realtively poor resistance to scaling when tested in accordance with ASTM C 672; however these mixtures generally performed satisfactorily when tested in accordance with BNQ standard.
- Probably due to the high air content of the 25% slag concrete mixture, this mixture performed better than the control concrete in terms of deicing salt scaling resistance. The concrete mixture incorporating 35% slag performed poorly in terms of scaling resistance when tested according to ASTM standard, but satisfactorily when tested according to BNQ standard.
- The delay to the final finishing to allow for the bleeding water to disappear did not improve the scaling resistance of the concrete mixtures investigated. This is most probably due to the fact that the bleeding of the concretes investigated was negligible.
- In general, the samples with field-type finishing (usual field practice made by professional finishers) scaled more than those using lab-type finishing (finished according to ASTM procedure).
- For both the lab-type (slabs) and field-type (cores) specimens tested at 28 days, the use of curing compound increased the scaling resistance of the fly ash concrete mixtures but decreased that of the slag concrete mixtures. When tested at 180 days, the use of curing compound enhanced significantly the scaling resistance of all concrete mixtures.
- In general, the use of sand or geotextile at the bottom of the moulds (to provide some drainage) used for the scaling test did not significantly improve the scaling resistance of the concrete made with SCMs when tested according to ASTM standard. This is again due to the fact that these mixtures had negligible bleeding.
- The inter-lab study has shown that the reproducibility of the BNQ test was acceptable for the control and the slag concrete mixtures. However, for the fly ash concrete mixtures, the reproducibility was relatively poor i.e. specimens from 2 labs (out of seven labs) failed to pass the test.
- The increase in concrete maturity in the field increased the scaling resistance of the concrete significantly, except for that made with ternary fly ash-SF cement. The relatively lower air

content in that concrete may have played a greater role than anticipated.
- The visual evaluation of the sidewalks after two winters (~20 cycles of freezing and thawing) confirmed the severity of the ASTM C 672 procedure and the adequateness of the BNQ procedure to better evaluate the deicing salt scaling resistance of concrete made with SCMs.

PART II: SIDEWALK SECTIONS CAST IN THE FALL 2002

The objective of this part of the study was to determine the effect of maturity on the scaling resistance of the concrete i.e. performance of sidewalks cast in the spring vs that of sidewalks cast in the fall. A number of concrete mixtures tested in the spring 2002 were then repeated in the fall 2002. Since the results of Part I of this study have shown that the time of finishing, the type of curing compound and the modified moulds did not significantly affect the scaling resistance of the concrete, these parameters were not tested in Part II of the study.

Part II consisted in placing sidewalk sections using three concrete mixtures and applying two curing practices. The concrete mixtures were similar to those used in Part I and consisted of a control concrete, a concrete mixture incorporating 25 % fly ash, and a concrete mixture made with ternary blended cement based on fly ash and silica fume. The curing practices consisted of using curing compound and wet burlap as a curing mode. The parameters investigated were as follows:

- Effect of the use of fly ash (FA).
- Effect of the use of ternary fly ash – silica fume (SF) cement;
- Lab-test conditioning and exposure versus field conditioning and exposure;
- Moist curing versus curing compound;
- Effect of mould, but tested according to BNQ procedure (a layer of geotextile was added at the bottom of the mould);
- Inter-lab comparison (six labs participated in the study).

Concreting of sidewalk sections and specimens was done at the end of October in the city of Verdun, Montreal (Canada), during a sunny but cold day in which the ambient temperature was about 12°C at noon but dropped down to -2°C at night.

Materials

The materials used in this second Part were similar to those used in Part I of the present study i.e. cementitious materials, chemical admixtures and aggregates. The physical properties and chemical compositions of the cementitious materials are presented in Table 1.

Concrete Making and Preparation of Test Specimens

Concrete mixtures

The concrete mixtures were designed to meet the requirements of the Canadian Standard Association CSA A23.1, C2 Class of exposure concrete: 32 MPa minimum, 0.45 maximum water-to-cementititous materials ratio (W/cm), and 5 to 8% air content. All the concrete mixtures were made by St. Lawrence Cement/Demix.

- Control mixture without fly ash or slag (typical conventional sidewalk concrete mixture design used by the City of Montreal which incorporates ~2% of silica fume) made with a w/cm of 0.44, designated as VF1.
- Mixture incorporating 25% FA made with a w/cm of 0.40, designated as VF2.
- Mixture incorporating a commercially available ternary FA-SF cement made with a w/cm of 0.42, designated as VF3.

The concrete mixture proportioning is given in Table 13. The control mixture VF1 was made using 25% of blended silica fume cement HSF and 75% of Portland cement.

<u>Casting, finishing and curing of field sections</u>

Sidewalk sections

The sidewalk sections made with each of the above concrete mixture were divided into a number of sub-sections. Each sub-section, 1.5 x 3.7 m in size, was cast, finished and cured using one of the procedures described below, and illustrated in figure 25.

A. Manual placing, followed by finishing with a bull float, wooden trowel for fine tuning and final finishing, finishing of the edges, and followed shortly by the application of the curing compound 1. This is common practice in the field, i.e. no real waiting period between the various operations.
B. Manual placing, followed by finishing with a bull float, wooden trowel for fine tuning and final finishing, finishing of the edges; cover with wet burlap and plastic sheets as soon as possible and cure for two days.

1.2x0.9 m large slab Specimens

A total of six 1.2 x 0.9 m large slabs were cast at the site i.e. one large slab for each type of concrete and each finishing/curing operation used for that type of concrete. The finishing/curing operations were similar to those used for the sidewalks and were done by the same finishers.

<u>Test specimens cored from the large slab specimens</u>

Figure 26 shows the samples cored from the slabs. Two to three 100-mm diameter cores were collected and tested for compressive strength at 3 days. Two ~250-mm diameter cores were taken from each large slab at 2 days and transferred to the laboratory to be cured and tested according to ASTM C 672 test procedure. Among these, the specimens cored from the large slabs cured with wet burlap were stored in a moist-curing room at 23 °C for 12 days and then subjected to 14 days of drying; the cores with the curing compound were kept for 12 days in the laboratory air, the surface of the cores was gently brushed to remove the curing compound before starting the 14-day drying period.

The remaining of the large slabs were kept outdoors exposed to natural environmental conditions, until the freezing and thawing periods began (Mid-November i.e. 28 days after casting). Two to three 100 mm cores were then collected and tested for compressive strength at 28 days. Two ~250 mm cores were also cored from each large slab and transferred to the laboratory where they were immediately subjected to the freezing-thawing cycles (according to ASTM C 672) with no drying period. The surface of the cores with curing compound was brushed prior to testing.

<u>Lab-type specimens</u>
For each of the concrete mixtures, the specimens listed below were cast and cured following the ASTM standard procedures except that the specimens were kept in their moulds for the first 48 hours and then transferred to the laboratory to be subjected to the selected curing procedure. Some specimens were cast, cured and tested according to BNQ standard procedure:

- Ten slabs using the standard moulds i.e. two using the moist curing mode (designated as MC), two using the curing compound 1 (designated as CC1), two without brushing (as it is normally required in ASTM C 672, after the bleeding has stopped), two with one week of re-saturation with the solution, and two slabs cast, cured and tested according to BNQ procedure. These slabs were subjected to identical storage conditions as the 250-mm cores cored at 2 days and described before.
- Two slabs using modified moulds, with 7 mm layer of geotextile at the bottom of the moulds cast, cured and tested following the BNQ procedure.
- Twelve extra slabs were added for the inter-lab study (two for each of the six labs involved in this study) and were cast, cured and tested following the BNQ standard.
- Twelve 100 x 200 mm cylinders for the determination of the compressive strength.
- Four 300 x 300 x 75 mm slabs for the determination of the abrasion resistance.

Testing of the sidewalk sections and of the lab specimens

<u>Properties of fresh concrete</u>
The slump, air content and the bleeding were determined following the appropriate ASTM standards. Forced bleeding was also determined by means of an apparatus that consists of putting a sample of fresh concrete in a cylinder of 90x120 mm and to exert a pressure of 0.35 MPa on the concrete to collect the water resulting from the pressure. The total bleeding water and the time taken for the bleeding to stop were then recorded.

<u>Compressive strength</u>
For each concrete mixture, the compressive strength was determined on two cylinders at 3, 14, 28, and 91 days, and also on two to three cores at 3 and 28 days. The test was carried out according to ASTM C39.

<u>Air-void parameters</u>
Two specimens (100 mm cores) were cored from each large slab for the determination of the air-void parameters following the ASTM C 457 test procedure.

<u>Abrasion Resistance</u>
For each mixture, the abrasion resistance of the concrete (ASTM C 779) was determined on two slabs each after 14 and 91 days of moist curing.

<u>De-Icing salt scaling resistance</u>
The sidewalk sections will be monitored visually to determine the scaling resistance of the concrete mixtures.

For the cores and slabs, the scaling resistance was determined according to ASTM C 672, except for the specimens tested according to BNQ standard. The former test was started after an initial moist curing of the specimens for 12 days (the first 2 days the specimens were kept in the molds), followed by 14 days drying in laboratory air. The top surface of the specimens were exposed to 50 cycles of freezing and thawing in the presence of a 3% NaCl solution. For the BNQ test, the specimens were moist cured for 12 days, air cured in the lab for 14 days, and re-saturated with 3% NaCl solution for 7 days. The top surfaces of the specimens were then exposed to 56 cycles of freezing and thawing in the presence of 3% NaCl solution.

Results and Discussion

Properties of fresh concrete

The unit weight, slump, air content, temperature, bleeding and forced bleeding water of the concrete mixtures are presented in Table 14. The results show that the unit weight of the concrete mixtures ranged from 2288 to 2321 kg/m^3. The slump of the concrete mixtures ranged from 80 to 90 mm which is in the range of the slump required for the concrete used in sidewalks. The air content of the concrete mixtures ranged from 5.5 to 6.2%.

The temperature of the fresh concrete was 18 to 19ºC, the average ambient temperature was around 8ºC.

The bleeding water tested according to ASTM C 232 was negligible for all the concrete mixtures investigated. However, the forced bleeding water ranged from 34 to 43 ml and was lower for the concrete made with cement TerC^3. Both the control and the 25% fly ash concrete mixtures had similar forced bleeding. The bleeding rate was also similar for these mixtures and lower for that made with cement TerC^3.

Compressive strength

The compressive strength of the concrete mixtures tested on cylinders and on specimens cored from the large slabs are given in Tables 15.

Table 15 shows that the 3, 14, 28 and 91-d compressive strength of the concrete mixtures ranged from 19.8 to 22.8, 30.7 to 37.6, 31.2 to 40.0 and from 41.8 to 45.4 MPa, respectively. The lowest values were those of the concrete made with 25% of fly ash. The control concrete and that made with TerC^3 developed similar compressive strength.

The 28-d compressive strength values show again that the concrete mixture made with 25% fly ash did not meet the requirements of the concrete used in sidewalks that requires a minimum 28-d compressive strength of 32 MPa. The results show once again that the 91-d compressive strength of the concrete made with 25% fly ash exceeded by far the 28-d strength requirement suggesting that the above requirement could be adjusted for concrete incorporating supplementary cementitious materials such as fly ash that develops higher strength at later ages.

Table 15 presents the 3 and 28-d compressive strength of the concrete mixtures determined on cores. The results show that the mode of curing had no significant effect on the compressive strength development. However, the results show that the compressive strength of the fly ash concrete mixtures determined on cores are significantly lower than those determined on cylinders. This is in line with published data that show that due to the lack of moist curing for the cores, and also due to the coring process that results in some coarse aggregate particles not wholly bonded to the cement paste matrix, tested cores generally show lower compressive strength than that of moist cured cylinders (12). According to ACI 318-99 and ACI 301-99, concrete shall be considered adequate "as specified" when the average of three cores is equal to at least 85% of the compressive strength determined on moist cured specimens. Table 15 shows that the 25% fly ash concrete and the concrete made with cement $TerC^3$ developed 3 and 28-d compressive strengths in the range of 80 to 85%, and 70 to 80% of those determined on moist cured cylinders, respectively. This is most likely due to the low ambient temperature that reached -2°C during the night of the day of casting. For the control concrete, the effect of the low temperature was negligible.

The results show that in general, during the fall the compressive strength of the fly ash concrete mixtures determined on cylinders cured in the laboratory overestimates the compressive strength of the same mixture cured in the field where lower temperatures slow down the process of strength development.

<u>Air-Void Parameters</u>
The air-void parameters of the concrete mixtures are presented in Table 16. The air content and spacing factor of the control concrete ranged from 5.5 to 5.8%, and from 190 to 200 μm, those of the 25% fly ash concrete ranged from 4.5 to 5.6%, and from 140 to 160 μm, and those of the concrete mixture made with cement $TerC^3$ ranged from 4.5 to 4.6, and from 190 to 200 μm, respectively. All the concrete mixtures had a spacing factor below 200 μm, which is considered satisfactory to provide appropriate resistance against freezing and thawing cycles. However, as mentioned in Part I of this document, it is possible that the spacing factors at the surface of the slabs have different values than those presented in Table 16 due to the finishing and curing operations.

<u>Abrasion Resistance</u>
Figures 27 and 28 present the results of the testing for abrasion resistance of the concrete at 14 and 91 days, respectively. The abrasion resistance of a concrete is generally related to its compressive strength, and since the control concrete and the concrete made with cement $TerC^3$ developed similar compressive strength that was higher than that of the 25% fly ash concrete, it was expected to have abrasion resistance following the same trend. The results show that the control concrete and the concrete made with cement $TerC^3$ developed indeed similar abrasion resistance both at 14 and at 91 days. However, for some reasons, the 25% fly ash concrete mixture developed higher abrasion resistance at 14 days but lower resistance at 91 days compared to that of the control concrete.

<u>De-Icing Salt Scaling Resistance</u>
The results on the de-icing salt scaling resistance of the concrete mixtures are presented in Tables 17 and 18 and in Fig. 29 to 31.

Effect of the use of fly ash (Fig. 29)
The results show that the concretes incorporating fly ash had a lower scaling resistance (i.e. higher scaling residues) than the control when tested according to the ASTM procedure ("MC" specimens). However, when the specimens were tested according to BNQ procedure, the fly ash concrete showed a much better scaling resistance. This is in line with the results presented in Part I of the study.

As mentioned before, the differences between the ASTM and BNQ procedure are the brushing after the bleeding has disappeared (for BNQ, there is no brushing), and the re-saturation with the solution of the surface of the slabs for one week (for ASTM, there is no re-saturation). In order to determine which of the two mentioned parameters affects the most the scaling resistance of the concrete, four slabs were tested, two slabs with no brushing (everything else was according to ASTM procedure) and two slabs with a re-saturation period of one week (everything else was according to ASTM procedure). The results in Table 17 show that for the fly ash concrete mixture, both parameters had a significant effect in enhancing the scaling resistance of the concrete.

Effect of the use of cement TerC³ (Fig. 30)
Fig. 30 shows that the concrete made with ternary blended cement performed poorly when tested according to ASTM C 672 ("MC" specimens). When the concrete specimens were tested according to BNQ, and also according to modified ASTM procedure (No brushing, and with re-saturation), the results show once again that the concrete made with ternary blended cement in this study has a poor resistance to scaling. The fact that the air content of the fresh and hardened concrete made with cement $TerC^3$ was slightly lower may partially explain the lower performance of this concrete.

Lab-test finishing and conditioning versus field finishing and conditioning (Fig. 31)
The results illustrated in Fig. 31 and given in Table 17 show that in general, the samples with field-type finishing (lab-cured cores, usual field practice made by professional finishers) scaled marginally more than those using lab-type finishing (lab-specimens finished according to ASTM procedure).

Table 17 and Fig. 31 show the results of scaling tests performed on cores cured in the lab and cores exposed to the field conditioning (lab-curing "A" and "B" vs field-conditioning "A" and "B"). For the cores using the curing compound (specimens "A"), the results show that the cores subjected to the lab curing performed better in the scaling test than those subjected to field conditioning; this is possibly due to the lower temperature in the field that may have affected the strength of the cores and consequently the scaling resistance. For the cores cured under wet burlap (specimens "B"), the results show the opposite i.e. the cores subjected to field conditioning (under lower temperature) performed better in the scaling test than those subjected to the lab curing. This clearly show that the lab-conditioning that consisted of 12 days of moist curing followed by 14 days of drying period had a detrimental effect on the scaling resistance of concrete made with fly ash, and cement $TerC^3$ (the cores with curing compound were not subjected to the moist curing period) . As mentioned in Part I, the field conditioning that consisted of natural wetting and drying conditions cannot be simulated by 13 days of moist curing and 14 days of drying period in the laboratory.

Moist curing versus curing compound (Fig. 31)
The results of Part I have shown that the use of curing compound marginally enhanced the scaling resistance of the fly ash concrete (especially at 28 days). In Part II, the results show that using curing compound increased significantly the scaling resistance of all the concrete mixtures (Table 17 and figure 31). For example, for the concrete made with cement $TerC^3$, the only specimens that showed low scaling residue were those cured with the curing compound, whether the specimens were lab-slabs, cores cured in the lab or subjected to field conditioning. This is possibly due to the

fact that the curing compound generally deceases the degree of microcracking due to the surface drying which increases the scaling resistance.

Effect of the mould
Table 17 shows that the use of the modified mould (with geotextile at the bottom) did not significantly affect the scaling resistance of all the concrete mixtures investigated. This is most likely due to the fact that the concrete investigated did not exhibit any bleeding.

Effect of operator
For each concrete mixture, four slabs were cured and tested at CANMET following the BNQ procedure. Two slabs were cast and finished by an operator from CANMET who did all the lab-slabs for which the results are presented in Table 17, and two slabs were cast and finished by an other operator who did all the specimens involved in the interlab study (results presented in Table 18, first column). The results show that the operator had a significant effect on the results of the concrete made with 25% fly ash and that made with cement $TerC^3$, but a marginal effect on those of the control concrete. For example, the scaling residue of the concrete specimens made with cement $TerC^3$, cast and finished by the operator from CANMET was 1.5 kg/m^2, and that of the companion specimens cast and finished by the other operator was 0.16 kg/m^2. This shows, that the BNQ test had poor reproducibility with the concrete made with 25% fly ash and cement $TerC^3$, but acceptable reproducibility with the control concrete.

Inter-lab comparison
Six laboratories participated in testing the scaling resistance of the three concrete mixtures investigated following the BNQ procedure. The specimens tested by all the laboratories used the same moulds and were cast and finished by the same operator. The specimens were distributed to the different labs at the age of 24 hours and were demoulded at the age of 48 hours and then followed the BNQ curing described earlier.

The results given in Table 18 show that the control concrete showed no scaling, and met the MTQ requirement (a limit of 0.5 kg/m^2 of scaling residue after 56 cycles) for all the labs involved in the study. For the concrete made with 25% fly ash, all the labs, except lab 3, showed that this concrete exhibited slight scaling and met the MTQ requirement. For the concrete made with cement $TerC^3$, three labs (1, 5 and 6) showed the concrete performing well, and three labs showed the results in excess of the MTQ requirement.

Table 18 shows that the reproducibility of the BNQ test was acceptable for the control concrete, but was not for the fly ash concrete and the concrete made with cement $TerC^3$, which is in line with the results of Part I. In fact, the average amount of scaling residues obtained by the five laboratories for the control concrete was 0.02 kg/m^2 with a standard deviation of 0.007 kg/m^2 and a coefficient of variation of 35%. For the concrete made with 25% fly ash, and that made with cement $TerC^3$, the average amount of scaling residues was 0.23 kg/m^2 and 0.80 kg/m^2 with standard deviations of 0.30 kg/m^2 and 0.75 kg/m^2 and coefficients of variation of 132% and 93%, respectively.

Field evaluation

As shown in Fig. 17, the sidewalks poured in the Fall 2002 (End of October) were also subjected to at least 20 cycles of freezing and thawing after two winters (assuming 10 cycles per year). Figs. 32 to 34 show that all the concretes performed fairly well, but scaled relatively more than those poured in the spring. This is probably due to differences in the maturity of the concrete, those poured in the spring were subjected to the first freeze/thaw cycles at the age of 180 days, whereas those poured in the fall were at the age of 28 days.

The figures show that all the wet cured sidewalks (control, 25% fly ash, and TerC^3) performed the same with a visual rating of 1, due to some exposed coarse aggregates. However, it is not clear whether this is due to the scaling or due to the abrasion resulting from the traffic of the sidewalks snow removal's equipment. For the sidewalks cured with the curing compound 1, the field evaluation shows that for some reasons, the sections made with TerC^3 scaled slightly more than those made with 25% fly ash, which scaled slightly more than the control sections.

Tables 19 and 20 show once again that the BNQ procedure simulates better the scaling resistance of the concrete incorporating SCMs compared to ASTM procedure.

Figs. 35 to 37 show also that the edges of the sidewalks made with all the investigated concrete mixtures were significantly damaged. The trucks that pass to clean the dirt left on the edges of the pavements using a spin sweeper exercises a significant abrasion action on the edges of the sidewalks. Since, the concrete mixtures were poured in late Fall and subjected to low curing temperature, these mixtures most likely did not develop enough abrasion resistance to sustain the above load. These results show that the use of 25% fly ash or cement TerC^3 could not help to improve the abrasion resistance of the concrete poured in late fall.

Concluding Remarks to Part II

Based on the results of this part of the study, the following conclusions can be drawn:

- The fly ash concrete investigated in this part of the study showed a poor scaling resistance when tested in the ASTM procedure; the mixture performed significantly better when tested in the BNQ test.
- The concrete made with cement TerC^3 cast in fall performed poorly when tested according to both ASTM and BNQ test procedures. Research is still needed to understand the reasons.
- In general, the samples with field-type finishing (usual field practice made by professional finishers) scaled marginally more than those using lab-type finishing (according to ASTM C 672).
- For a curing compound regime, the concrete specimens subjected to field conditioning showed lower scaling resistance than those subjected to the lab conditioning, whereas, for a wet curing regime, the concrete specimens subjected to field conditioning showed higher scaling resistance than those subjected to the lab conditioning, especially for concrete made with SCM.
- The use of curing compound enhanced significantly the scaling resistance of the concrete mixtures incorporating SCMs.
- The use of geotextile at the bottom of the moulds used for the scaling test did not improve the scaling resistance of the concrete made with SCMs when tested according to BNQ standard. This is most likely due to the negligible bleed water of the concrete investigated.

- The inter-lab study has shown that the reproducibility of the BNQ test was acceptable for the control concrete, but was not for the fly ash concrete and the concrete made with cement $TerC^3$.
- The field evaluation shows that the control concrete and the concrete made with 25% fly ash performed satisfactorily after two winter (~20 freeze-thaw cycles) whereas, the concrete made with cement $TerC^3$ showed some scaling. This confirmed that the ASTM C 672 procedure is presently inadequate to evaluate the performance of concrete made with SCMs to the de-icing salt scaling resistance. It appears that the BNQ test is yielding more realistic results.

CONCLUSIONS

The objectives of the present study were to develop procedures or field practices that could insure an adequate field performance when exposed to de-icing salts of concrete incorporating SCMs and also to develop more realistic test procedures for properly evaluating the performance of such type of concrete when exposed to de-icing salts. The lab results have shown that the use of curing compound, especially during the fall, increased significantly the scaling resistance of the concrete incorporating SCMs. The results also show that the specimens of the concrete incorporating SCMs (except those using ternary fly ash-SF cement) scaled significantly less when tested according to BNQ standard in comparison to those tested according to ASTM C 672. The visual evaluation of the sidewalks after two winters (~20 freeze-thaw cycles) appeared to be more in line with the results of the specimens tested according to BNQ procedure.

ACKNOWLEDGMENT

This investigation was funded by the partners of a R&D consortium on De-Icing Salt Scaling Resistance of Concrete Incorporating SCMs. These are, Blue Circle, Boral Material Technologies Inc., Lafarge Canada, St. Lawrence Cement, Ontario Power Generation OPG, Pozzolanic International Ltd., American Concrete Institute ACI, Cement Association of Canada CAC, CANMET Energy Technology Centre, CANMET Material Technology Laboratory MTL, EcoSmart, Transports Québec MTQ, and Public Works and Government Services Canada PWGSC. Grateful acknowledgment is made to those who help in the casting of the concrete and in the interlab study i.e. partners from private sector (St. Lawrence cement/Demix and Lafarge Canada), public sector (City of Verdun, City of Montreal, Transports Québec MTQ, and CANMET /MTL), and universities (Laval University, University of Sherbrooke and University of Toronto). Special thanks are made to V. Sivasundaram and P-C. Nkinamubanzi from CANMET/MTL for helpful discussions during the progress of the investigation, also Annibale Ferro and Raymond Chevrier from CANMET/MTL for performing various aspects of the laboratory investigations.

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Table 1 - Physical Properties and Chemical Composition of the Materials Used.

	CSA Type 10 (ASTM Type I)*	CSA Type 10 (ASTM Type I)**	Cement HSF	Ter C[3]	TerCem	Fly Ash	Slag
Physical Tests							
Fineness							
-passing 45Fm, %	-	90.5	91.0	-	-	-	91.4
-specific surface, Blaine, m^2/kg	389	399	501	532	-	-	563
Strength Activity Index, %							
-7-day	-	-	-	-	-	-	78.9
-28-day	-	-	-	-	-	-	109
Chemical Analyses, %							
Silicon dioxide (SiO_2)	20.2	19.9	27.5	32.6	27.0	51.3	39.1
Aluminum oxide (Al_2O_3)	4.2	4.7	3.6	8.5	5.9	25.0	9.8
Ferric oxide (Fe_2O_3)	3.4	2.2	3.8	5.8	2.1	15.7	0.4
Calcium oxide (CaO)	62.2	62.7	56.4	43.6	53.8	1.5	33.5
Magnesium oxide (MgO)	2.1	2.8	1.8	1.5	4.1	0.9	11.7
Sodium oxide (Na_2O)	0.2	0.9	-	0.3	0.3	0.4	-
Potassium oxide (K_2O)	1.0	-	-	1.4	0.9	2.9	-
Equivalent alkali	0.9	-	0.8	1.2	0.9	2.3	-
(Na_2O+0.658K_2O)	0.2	-	-	0.2	0.2	0.2	-
Phosphorous oxide (P_2O_5)	0.2	-	-	0.3	0.4	0.8	-
Titanium oxide (TiO_2)	3.7	3.4	3.4	3.7	4.0	0.3	-
Sulphur trioxide (SO_3)	2.7	2.2	2.0	2.0	1.6	0.9	0.7
Loss on ignition							
Bogue potential compound composition							
Tricalcium silicate C_3S	56.6	59.5	-				
Dicalcium silicate C_2S	15.1	12.1	-				
Tricalcium aluminate C_3A	5.3	8.7	3.0				
Tetracalcium aluminoferrite C_4AF	10.4	6.7	11.6				

*Cement used in fly ash and in control concrete mixtures
**Cement used in slag concrete mixtures

Table 2 - Proportions of Concrete Mixtures.

	Control	35% FA	35% Slag	25% FA	25% Slag	Ter C^3	TerCem
Mixture, (kg/m^3)	V1	V2	V3	V4	V5	V6	V7*
W/CM	0.45	0.41	0.42	0.41	0.41	0.42	0.45
Water	164	165	169	162	161	160	163
Cement Type 10 -A-	273	260	-	300	-	-	-
Cement Type 10 -B-	-	-	279	-	301	-	-
Cement HSF	90	-	-	-	-	-	-
Cement Ter C^3	-	-	-	-	-	380	-
Cement TerCem	-	-	-	-	-	-	366
Fly Ash	-	140	-	97	-	-	-
Slag	-	-	128	-	91	-	-
Total Cementitious Materials	363	400	407	397	392	380	366
Coarse Agg.	1003	1088	1074	1088	1090	1083	1075
Sand	795	672	720	672	733	691	754
Chemical Admixtures, (mL/m^3)							
A.E.A**	182	760	157	516	156	418	114
W.R.***	1090	920	1018	913	971	874	918

*The composition takes into account the water added to the concrete to increase the slump as discussed in the text.
**Air Entraining Admixture
***Water Reducer

Table 3 - Properties of the fresh concrete.

	Control (V1)	35% FA (V2)	35% Slag (V3)	25% FA (V4)	25% Slag (V5)	Ter C^3 (V6)	TerCem (V7)
W/CM	0.45	0.41	0.42	0.41	0.41	0.42	0.45
Unit Weight, kg/m^3	2325	2325	2280	2319	2270	2314	2295
Slump, mm	70	80	90	100	90	90	70
Air Content, %	5.8	5.5	6.8	5.4	7.2	5.6	5.5
Temperature, °C	21	24	24	26	26	24	24
Bleeding	neg.	neg.	neg.	neg.	neg.	neg.	neg.
Forced Bleeding, ml (length of time, min)	38 (20)	60 (25)	61 (35)	71 (35)	31 (15)	54 (30)	23 (25)
Bleeding rate, (ml/min)	1.9	2.4	1.7	2	2.1	1.8	0.9

Table 4 - Compressive Strength of Concrete Mixtures

	Control (V1)	35% FA (V2)	35% Slag (V3)	25% FA (V4)	25% Slag (V5)	Ter C^3 (V6)	TerCem* (V7)
3 d	25.9	19.4	26.7	18.3	23.5	21.5	27.8
3 d (cores)**	22.3	20.3	25.1	22.7	22.7	19.3	28
14 d	31.6	26.1	34.8	24.8	31.2	32	42.6
28 d	33.3	30.1	38	28.3	34.2	34	46.7
91 d	38.7	40.1	42	36.6	39	38.3	53.9
180 d	40.5	43.4	44	39.6	40.5	38.6	54
180 d (cores)**	39.3	45.7	46.6	46.1	43.9	43.4	53.4

* The results correspond to the concrete with w/cm of 0.41
** Average values of cores subjected to 2 or 4 different types of curing (see Table 5).

Table 5 - Compressive Strength of Concrete Mixtures (determined on cores).

	Control (V1)				35% FA (V2)				35% Slag (V3)				25% FA (V4)		25% Slag (V5)		Ter C^3 (V6)		TerCem** (V7)	
Type of finish*	A	B	C	D	A	B	C	D	A	B	C	D	B	D	B	D	B	D	B	D
3 d	22.8	22.1	22.5	21.9	20.2	19.7	21.4	19.8	24.9	24	24.3	27	22.7	22.7	22.8	22.5	18.5	20	28	27.9
180 d	40.2	38.5	39.1	39.2	45.1	44.4	46.2	47.1	47.2	47.8	44.8	46.5	44.7	47.5	44.3	43.4	40.1	46.6	52.6	54.2

Table 6 - Air-void Parameters of Concrete Mixtures (determined on cores).

	Control (V1)				35% FA (V2)				35% Slag (V3)				25% FA (V4)		25% Slag (V5)		Ter C^3 (V6)		TerCem** (V7)	
Type of finish*	A	B	C	D	A	B	C	D	A	B	C	D	B	D	B	D	B	D	B	D
Air content, %	4.7	4.6	4.9	4.7	4.3	5.1	4.3	5.2	4.6	5.5	5.3	5.1	3.9	5	6.7	5.3	5.1	4.8	4.2	3.6
Spacing factor, µm	200	230	200	210	180	170	160	190	180	200	150	130	200	180	140	140	140	150	180	160

*A: Finishing after bleeding and curing compound 1.
B: Curing compound 1.
C: Curing compound 2.
D: Wet burlap curing.
** The results correspond to the concrete with w/cm of 0.41

Table 7 - Cumulative Scaling Residue (kg/m^2) and Visual Rating (vlues in bracket) after 50 cycles of freezing and thawing following ASTM C 672.

	Lab-Slabs*				Cores**			
	MC	G	S	CC1	A	B	C	D
V1-Cont	0.68 (1)	1.56*** (2-4)	2.03*** (3-5)	1.36 (3)	1.21 (3)	1.09 (3)	0.96 (3)	2.6 (4)
V2-35%FA	2.82 (5)	2.64 (5)	2.54 (5)	1.8 (5)	3.06 (5)	3.02 (4)	2.85 (5)	3.91 (5)
V3-35%Slag	0.95 (4)	0.87 (4)	0.49 (3)	1.24 (4)	0.97 (4)	1.78 (5)	1.74 (5)	1.25 (4)
V4-25%FA	3.38 (5)	2.52 (5)	1.8 (4)	1.2 (5)	-	1.09 (3)	-	2.93 (4)
V5-25%Slag	0.41 (3)	0.48 (2)	0.53 (3)	0.84 (3)	-	1.08 (4)	-	0.75 (3)
V6-TerC[3]	2.49 (5)	2.38 (5)	2.05 (5)	1.91 (5)	-	2.5 (5)	-	3.05 (5)
V7-Tercem	1.52 (4)	1.6 (4)	1.27 (4)	2.18 (5)	-	2.34 (5)	-	2.18 (5)

*MC: Moist curing
G: Geotextile
S: Sand
CC1: Curing compound 1

**A: finishing after the bleeding has disappeared + curing compound 1
B: Curing compound 1
C: Curing compound 2
D: Wet burlap

*** Average results of two samples that did not behave similarly

Table 8 - Cumulative Scaling Residue (kg/m^2) and Visual Rating (values in bracket) after 56 cycles of freezing and thawing following BNQ Standard Inter-lab Study.

	Lab. 1	Lab. 2	Lab. 3	Lab. 4	Lab. 5	Lab. 6	Lab. 7	Average	Sd** Cv***
V1- Control	0.18 (1)	0.32	0.37	0.31	0.1	0.34	0.41	**0.29**	**0.11** **38%**
V2- 35% FA	0.45 (2)	0.17	0.94	0.19	0.23	0.3	0.56*	**0.34**	**0.61** **179%**
V3- 35% Slag	0.19 (1)	0.46	0.13	0.17	0.11	0.23	0.24	**0.22**	**0.12** **55%**
V4- 25% FA	0.29 (3)	0.33	0.31	0.16	0.1	0.36	0.73*	**0.33**	**0.41** **124%**

* Average results of two samples that did not behave similarly.
** Standard deviation
***Coefficient of variation

Table 9 - Cumulative Scaling Residue and Visual Rating (values in bracket) of Cores exposed for 90 days to natural conditioning in the field and tested according to ASTM and BNQ Standards.

	Concrete mixtures			
	V1 – B* Control with curing compound	V2 – B* 35% FA with curing compound	V3 – D* 35% Slag with wet burlap	V4 – D* 25% FA with wet burlap
ASTM (50 cycles), kg/m^2	0.07 (0)	0.13 (1)	0.29 (3)	0.91 (1)
BNQ (56 cycles), kg/m^2	0.09 (0)	0.06 (0)	0.39 (3)	0.78 (1)

* B: Curing compound 1
D: Wet burlap

Table 10 - Cumulative Scaling Residue (kg/m^2) and Visual Rating of Cores exposed for 180 days to natural conditioning in the field and tested according to ASTM C 672 vs. cores cured and tested according to ASTM C 672.

Mixtures.	Type of finishing and curing*							
	A		B		C		D	
	28 days	180 days	28 days	180 days	28 days	180 days	28 days	180 days
V1 - Control	1.21 (3)	0.04 (1)	1.09 (3)	0.03 (0)	0.96 (3)	0.03 (0)	2.6 (4)	0.29 (0)
V2 - 35%FA	3.06 (5)	0.17 (3)	3.02 (4)	0.07 (2)	2.85 (5)	0.11 (1)	3.91 (5)	0.74 (3)
V3 - 35%Slag	0.97 (4)	0.03 (1)	1.78 (5)	0.05 (2)	1.74 (5)	0.21 (1)	1.25 (4)	0.25 (3)
V4 - 25%FA			1.09 (3)	0.06 (1)			2.93 (4)	1.24 (3)
V5 - 25%Slag			1.08 (4)	0.05 (1)			0.75 (3)	0.26 (2)
V6 - TerC^3			2.5 (5)	2.80 (5)			3.05 (5)	3.70 (5)
V7 - Tercem			2.34 (5)	0.60 (3)			2.18 (5)	1.22 (3)

*A: finishing after the bleeding has disappeared + curing compound 1
B: Curing compound 1
C: Curing compound 2
D: Wet burlap

Table 11 - Cumulative Scaling Residue (kg/m^2) and visual rating (values in bracket) of lab-slabs and sidewalk sections after 20 cycles of freezing and thawing.

	Lab-Slabs		Visual rating of sidewalk sections			
	ASTM (MC)	BNQ (21 cycles)	A	B	C	D
V1 - Control	0.33	0.08 (0)	0	0	0	0
V2 - 35%FA	1.41	0.20 (0)	0	0	0	0
V3 - 35%Slag	0.43	0.06 (0)	0	0	0	0
V4 - 25%FA	1.86	0.14 (0)		0		37986
V5 - 25%Slag	0.16			0		37986
V6 - TerC^3	1.6			37987		37987
V7 - TerCem	0.59			0		0

Table 12 - Cumulative Scaling Residue (kg/m^2) and visual rating (values in bracket) of cores and sidewalk sections after 20 cycles of freezing and thawing.

	A			B			C			D		
	Cores		Side -walks	Cores		Side -walks	Cores		Side -walks	Cores		Side -walks
	28 days	180 days		28 days	180 days		28 days	180 days		28 days	180 days	
V1 - Control	1.01	0.03	0	0.9	0.03	0	0.6	0	0	1.52	0.26	0
V2 - 35%FA	2.43	0.08	0	2.11	0.04	0	2.11	0.1	0	3.54	0.47	0
V3 - 35%Slag	0.54	0.02	0	1.32	0.03	0	1.35	0.17	0	0.65	0.15	0
V4 - 25%FA				0.87	0.05	0				1.78	0.88	37986
V5 - 25%Slag				0.68	0.02	0				0.39	0.18	37986
V6 - TerC^3				2.24	0.65	37987				2.21	2.22	37987
V7 - TerCem				1.96	0.26	0				1.1	0.68	0

A: Finishing after bleeding has disappeared + Curing compound 1
B: Curing compound 1
C: Curing compound 2
D: Wet burlap

Table 13 - Proportions of Concrete Mixtures.

Mix.	W/CM	Water, kg/m^3	Cement		Fly Ash, kg/m^3	Total Cementitious Materials, kg/m^3	Sand, kg/m^3	Coarse Aggreg .kg/m^3	A.E.A*, ml/m^3	W.R.**, ml/m^3
			Type	kg/m^3						
VF1- Control	0.44	162	I	275	-	368	793	989	177	1380
			HSF	93						
VF2- 25% FA	0.4	158	I	292	99	391	659	1080	430	899
VF3- Ter C^3	0.42	160	Ter C^3	378	-	378	643	1077	416	870

**Air Entraining Admixture
***Water Reducer (the one used for mixtures V2 and V3 was different from that used for mixture V1).

Table 14 - Properties of the Fresh Concrete.

Mix.	W/CM	Unit Weight, kg/m^3	Slump, mm	Air Content, %	Temperature, °C	Bleeding	Forced Bleeding		Bleeding rate, (ml/min)
							ml	length of time, min	
VF1- Control	0.44	2321	90	5.8	19	neg.	42	30	1.4
VF2- 25% FA	0.4	2288	90	6.2	19	neg.	43	30	1.4
VF3- Ter C^3	0.42	2306	80	5.5	18	neg.	34	30	1.1

Table 15 - Compressive Strength of the Concrete Mixtures.

Mix.	Cylinders				Cores					
	3-d	14-d	28-d	91-d	3-d			28-d		
					A*	B*	Avg.	A*	B*	Avg.
VF1	22.8	35.8	38.1	44.2	22.9	23.9	23.4	36.4	34.8	35.6
VF2	20.4	30.7	31.2	41.8	15.4	17.1	16.3	25.9	27.6	26.8
VF3	19.8	37.6	40	45.4	15.5	16.9	16.2	28.3	26.9	27.6

*A: Curing compound 1
B: Wet burlap

Table 16 - Air-Void Parameters of the Concrete Mixtures.

Mix.	W/CM	Air content, %		Spacing factor, µm	
		A*	B*	A*	B*
VF1- Control	0.44	5.5	5.8	200	190
VF2- 25% FA	0.40	5.6	4.5	140	160
VF3- Ter C^3	0.42	4.6	4.5	190	200

*A: Curing compound 1
B: Wet burlap

Table 17 - Cumulative Scaling Residues (kg/m^2) and visual rating (values in bracket).

Mix.	Lab-Slabs*						Cores**			
	MC	No Brushing	with re-saturation	CC1	BNQ	BNQ with Geot.	lab-curing		field-conditioning (28 days)	
							A	B	A	B
VF1	0.006 (0)	0.006 (0)	0.11 (1)	0.014 (0)	0.03 (0)	0.04 (1)	0.03 (1)	0.12 (0)	0.10 (0)	0.15 (0)
VF2	2.6 (5)	0.21 (2)	0.33 (2)	0.12 (2)	0.45*** (1-4)	0.65 (3)	0.19 (1)	2.1*** (3-5)	0.66 (2)	0.15 (1)
VF3	2.0 (4)	2.6 (5)	1.6 (4)	0.18 (2)	1.5 (3)	1.6 (3)	0.16 (3)	3.15 (5)	0.49 (2)	2.38 (5)

* MC: Moist curing
CC1: Curing compound 1
** A: Curing compound 1
B: Wet burlap
***Average results of two samples that did not behave similarly.

Table 18 - Cumulative Scaling Residue (kg/m^2) and Visual Rating after 56 cycles following BNQ Standard, Inter-lab Study.

	Lab. 1 CANMET	Lab. 2	Lab. 3	Lab. 4	Lab. 5	Lab. 6	Average	Sd* Cv**
VF1- Control	0.02 (0)	0.03 (1)	0.02 (0)	0.02 (0)	0.006	0.02	**0.02**	**0.007** **35%**
VF2- 25% FA	0.10 (1)	0.08 (1)	0.84 (4)	0.27 (3)	0.017	0.08	**0.23**	**0.30** **132%**
VF3- TerC^3	0.16 (2)	1.38 (4)	2.02 (4)	0.80 (4)	0.2	0.26	**0.8**	**0.75** **93%**

* Standard deviation
**Coefficient of variation

Table 19 - Cumulative Scaling Residue (kg/m^2) and visual rating of lab-slabs and sidewalk sections after 20 cycles.

	Lab-Slabs		Visual rating of sidewalk sections	
	ASTM (MC)	BNQ (21 cycles)	A**	B**
VF1 - Control	0	0.01	0	1
VF2 - 25%FA	1.32	0.32*	1	1
VF3 - TerC^3	1.51	0.81	37987	1

* Average results of two samples that did not behave similarly
** A: Curing compound 1; B: Wet burlap

Table 20 - Cumulative Scaling Residue (kg/m^2) and visual rating of cores and sidewalk sections after 20 cycles.

	A*			B*		
	Cores		Sidewalks	Cores		Sidewalks
	28 days (in the lab)	28 days (in the field)		28 days (in the lab)	28 days (in the field)	
V1 - Control	0.1	0.09	0	0.02	0.06	1
V2 - 25%FA	0.16	0.13	1	1.12	0.6	1
V3 - TerC^3	0.16	0.36	37987	2.13	1.39	1

* A: Curing compound 1; B: Wet burlap

Manual placing and bull float finishing

Final finishing with wooden trowel

Curing Compound

Wet burlap and plastic sheets

Large slab specimens

Lab-type specimens

Fig. 1 - Pictures of field operations and type of specimens.

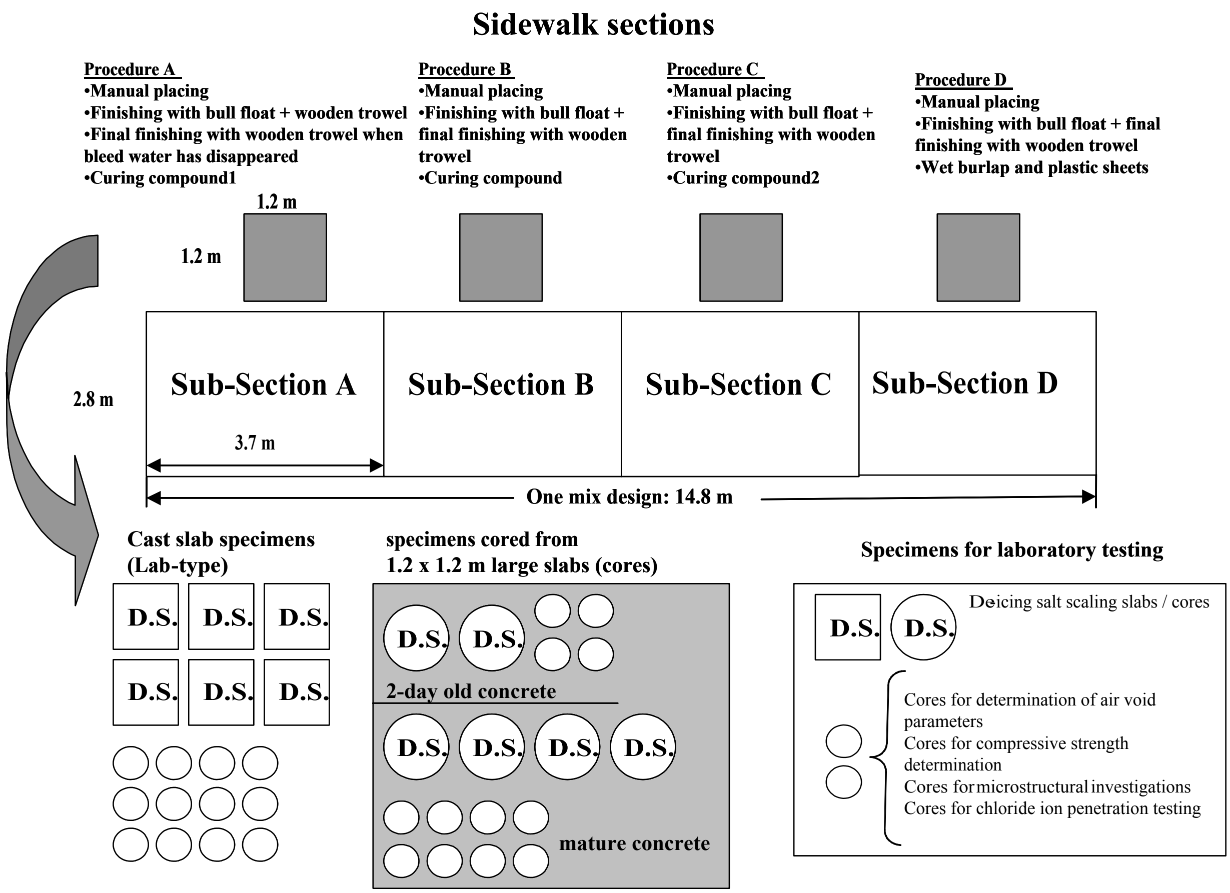


Fig. 2 - Concrete sidewalk sections - summary of field operations and specimens taken.

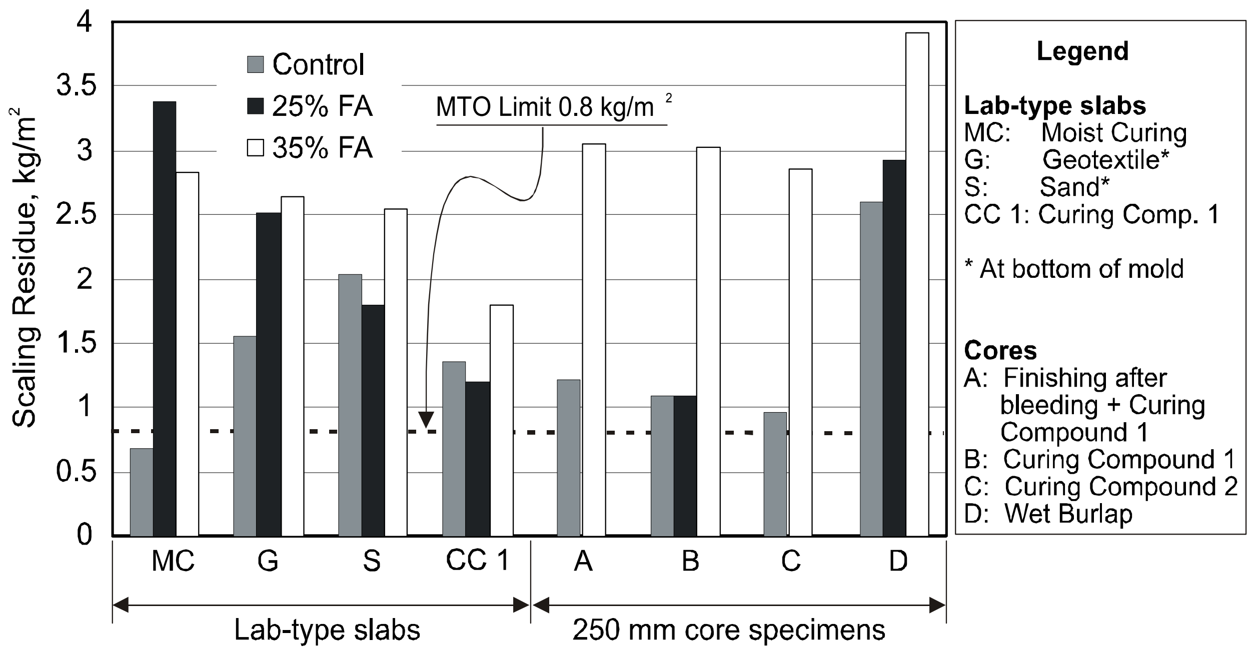


Fig. 3 - Effect of fly ash on the scaling resistance of concrete.
(test performed according to ASTM C 672 test procedure)

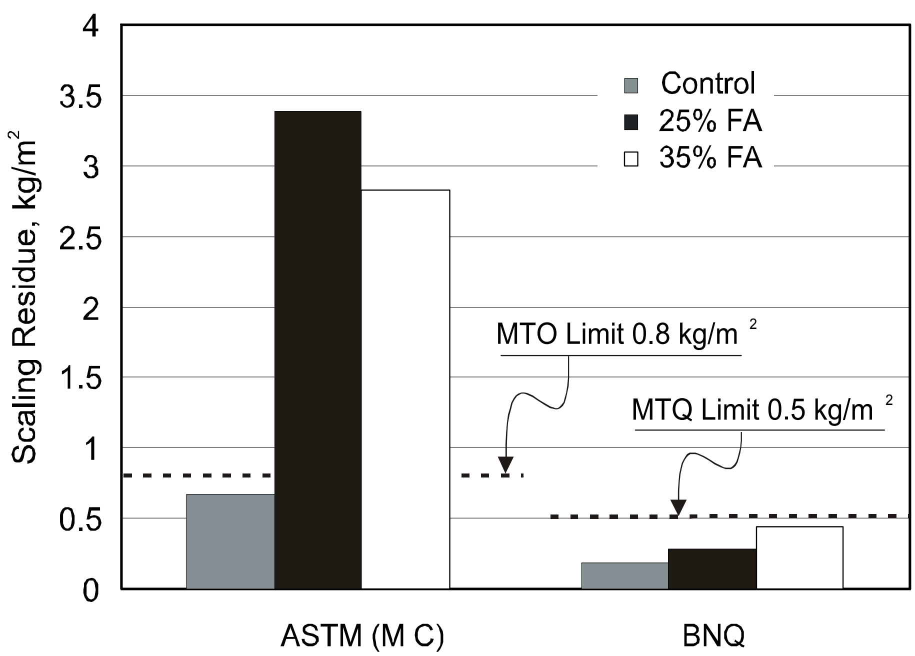


Fig. 4 - ASTM vs. BNQ test procedures, control and fly ash specimens.

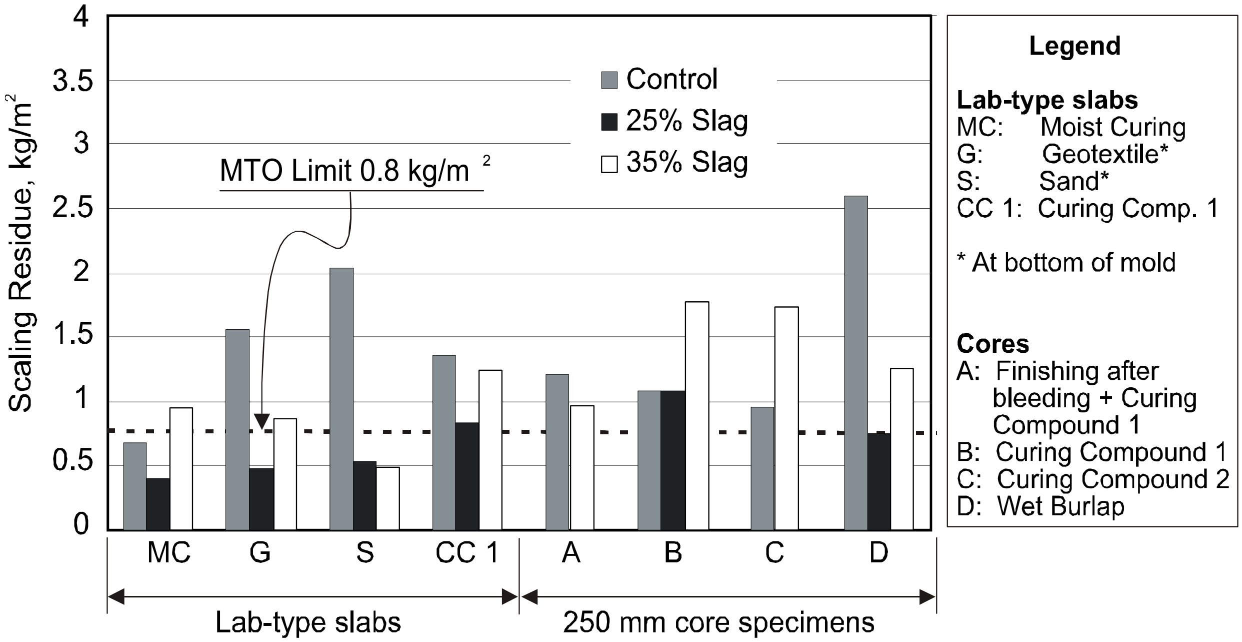


Fig. 5 - Effect of slag on the scaling resistance of concrete.
(test performed according to ASTM C 672 test procedure)

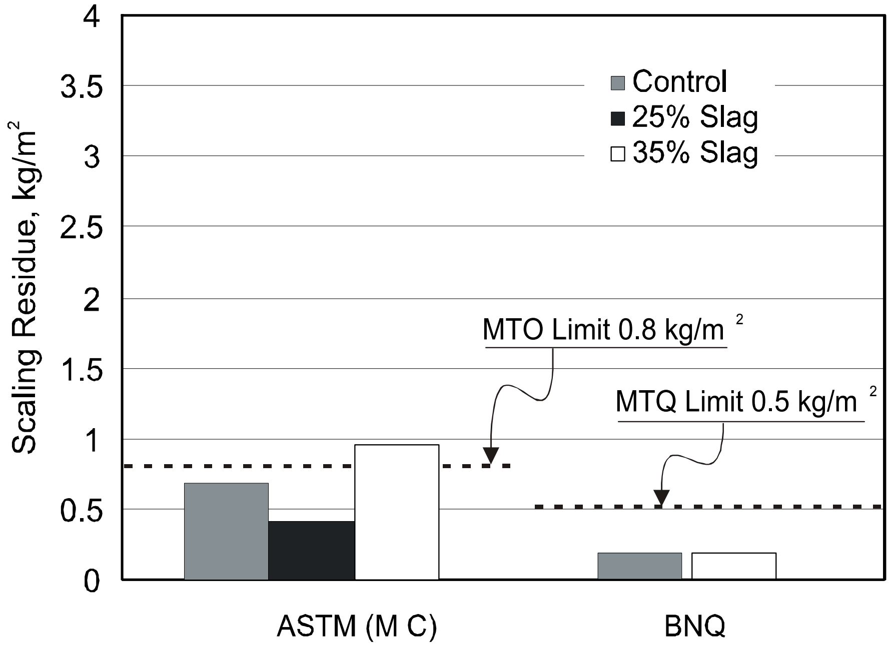


Fig. 6 - ASTM vs. BNQ test procedures, control and slag specimens.

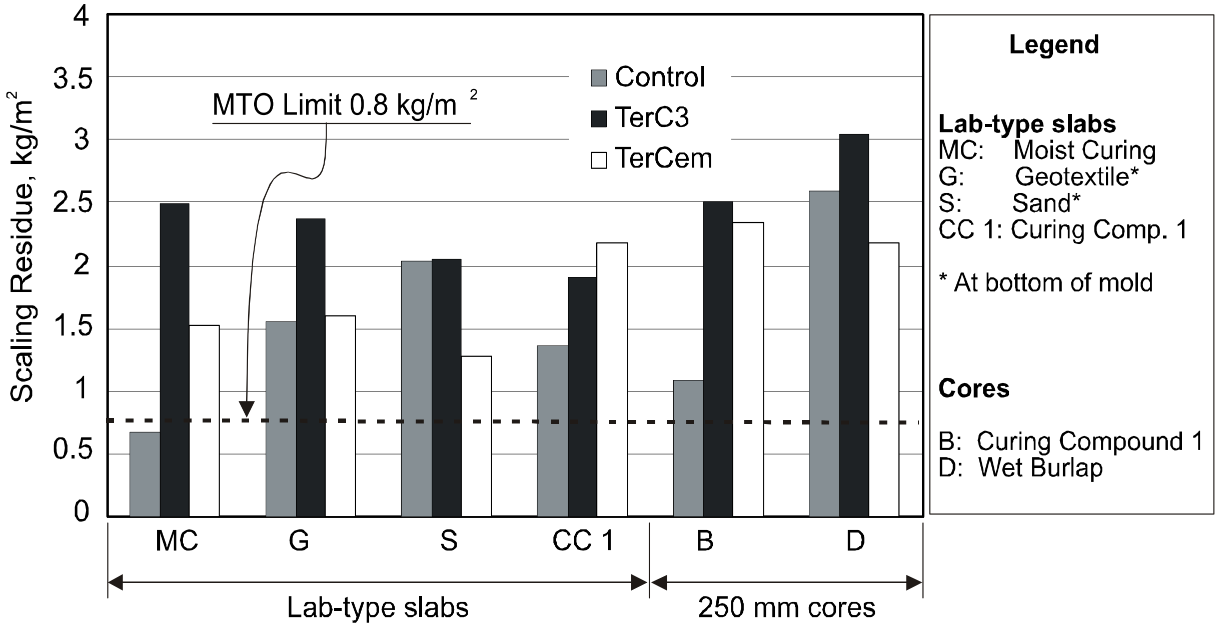


Fig. 7 - Effect of ternary blends on the scaling resistance of concrete.
(test performed according to ASTM C 672 test procedure)

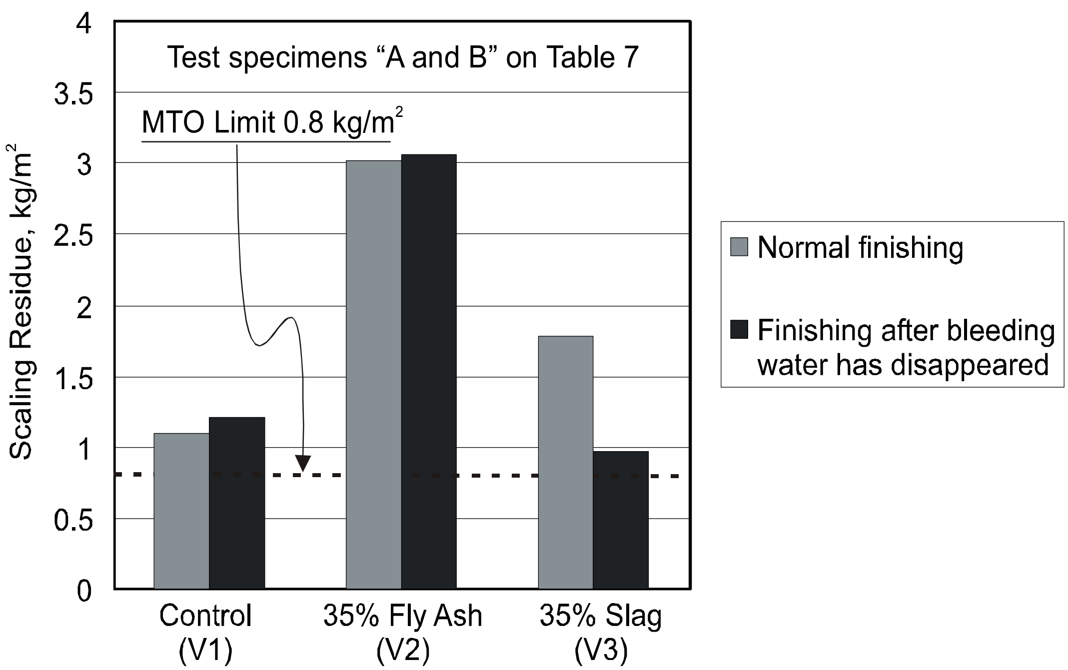


Fig. 8 - Effect of the time of finishing on the scaling resistance of concrete.

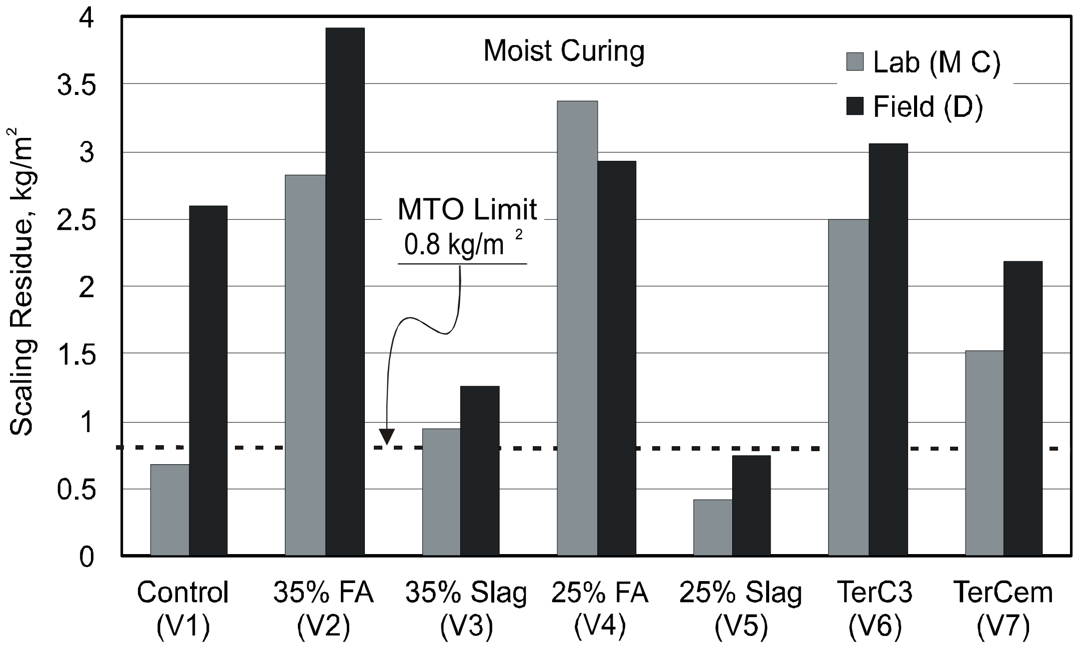


Fig. 9 - Laboratory finishing vs. field finishing for moist cured specimens.

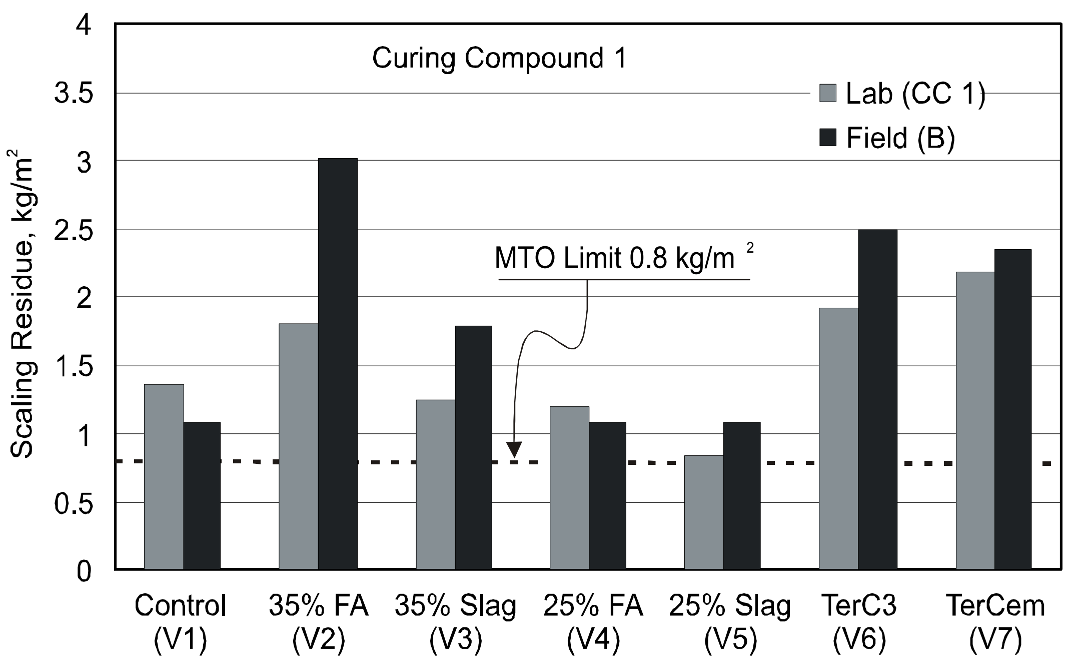


Fig. 10 - Laboratory finishing vs. field finishing for specimens using curing compound.

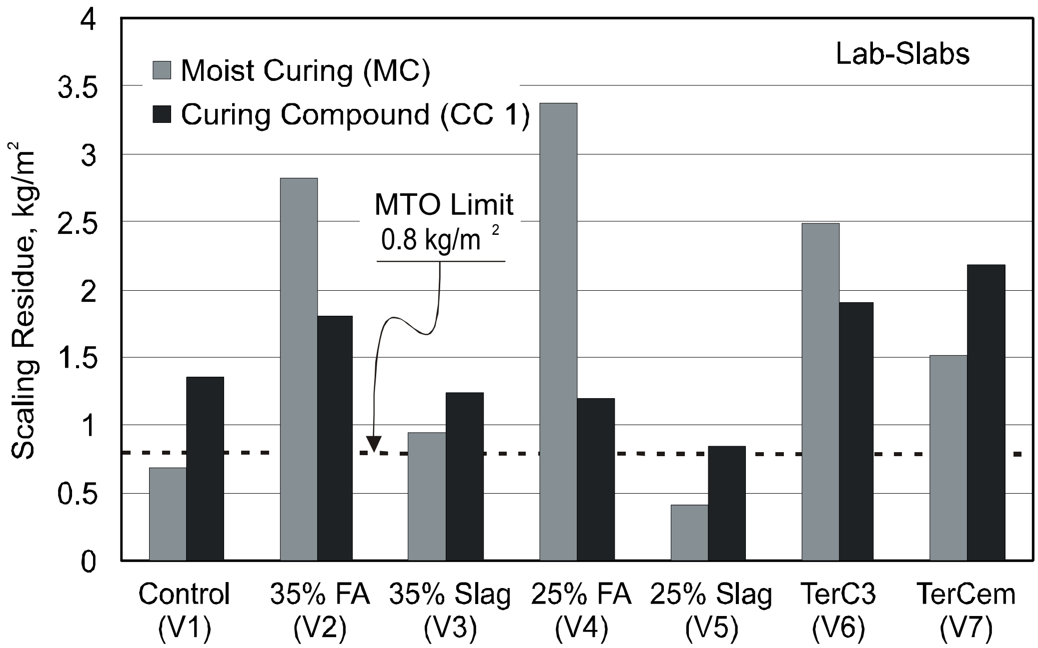


Fig. 11 - Moist curing vs. curing compound for lab-specimens.

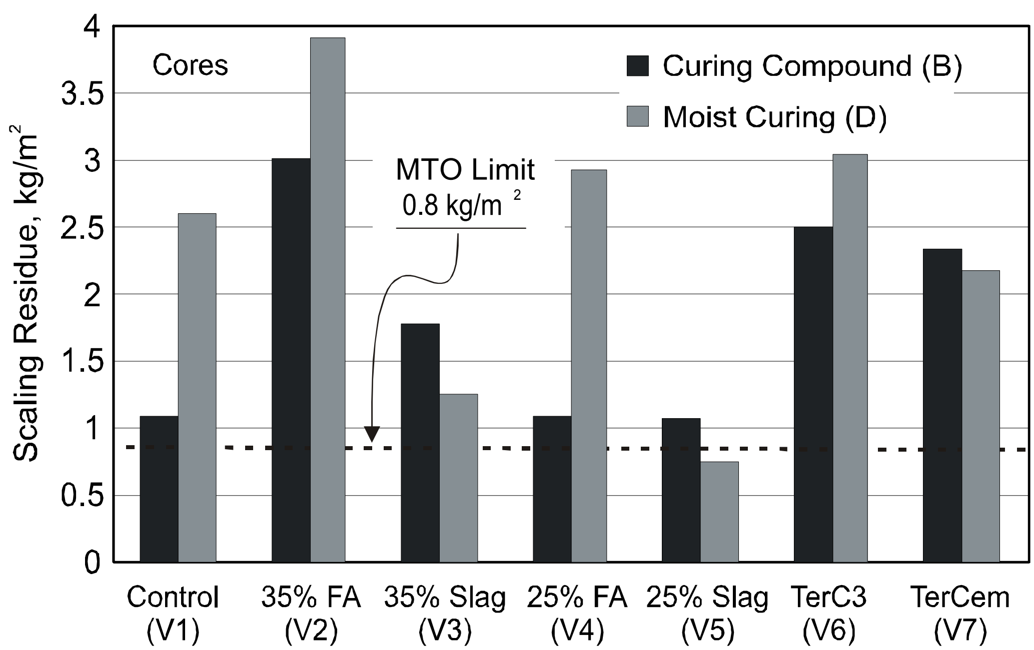


Fig. 12 - Moist curing vs. curing compound for cores.

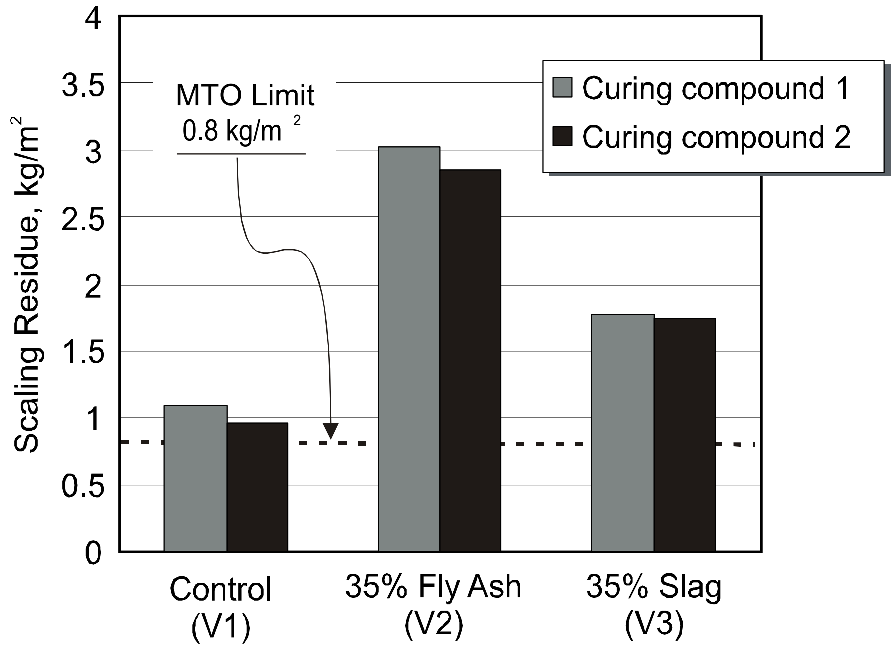


Fig. 13 - Effect of the type of curing compound.

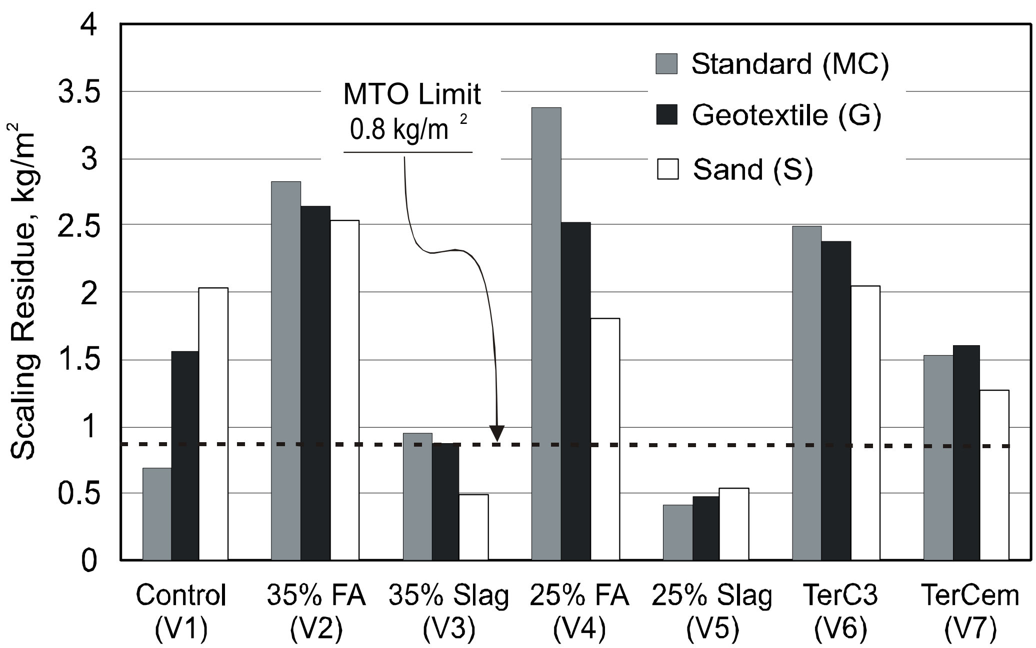


Fig. 14 - Effect of the type of mould.

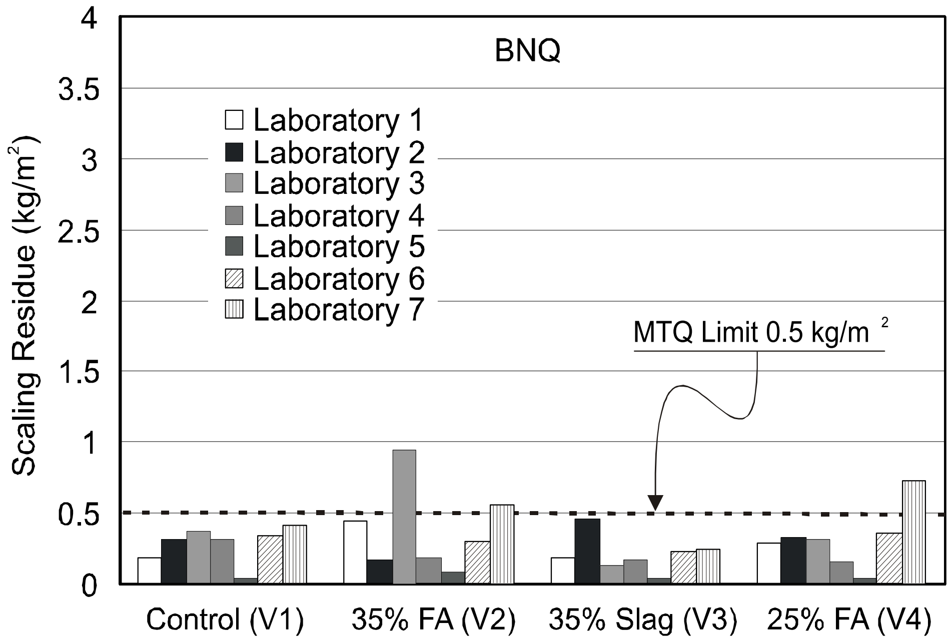


Fig. 15 - Inter-lab study (test performed according to BNQ test procedure).

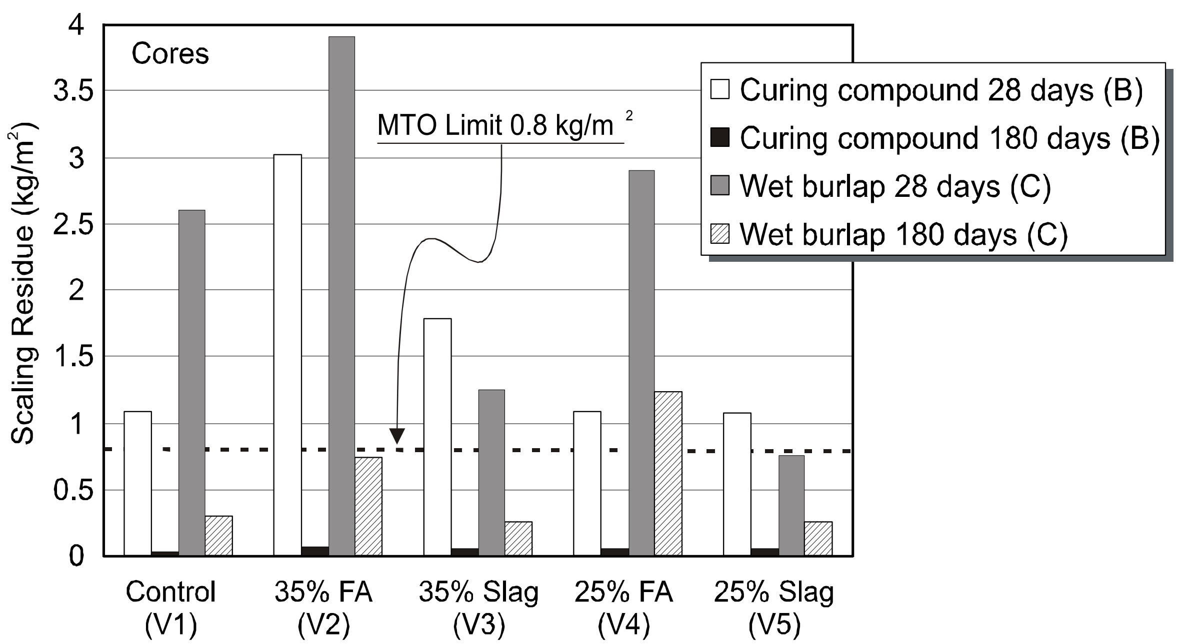


Fig. 16 - Effect of maturity.

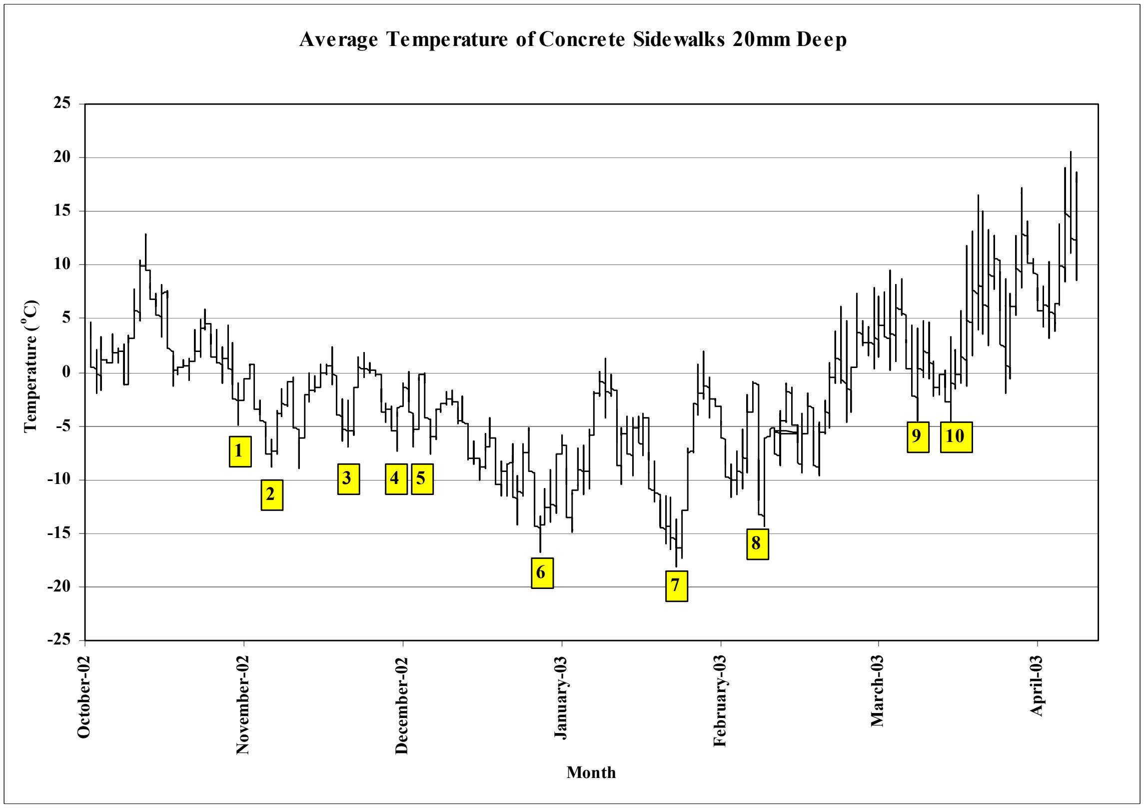
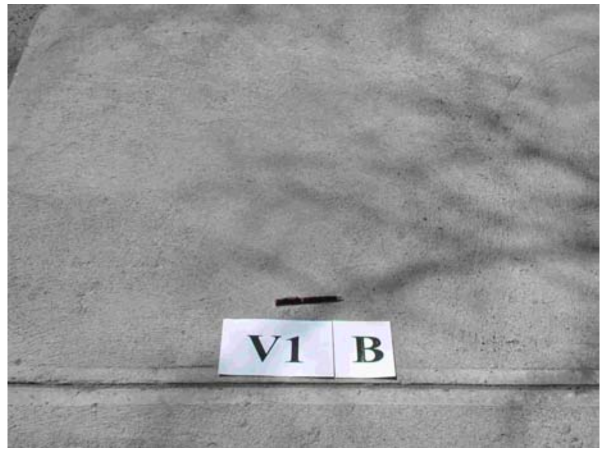
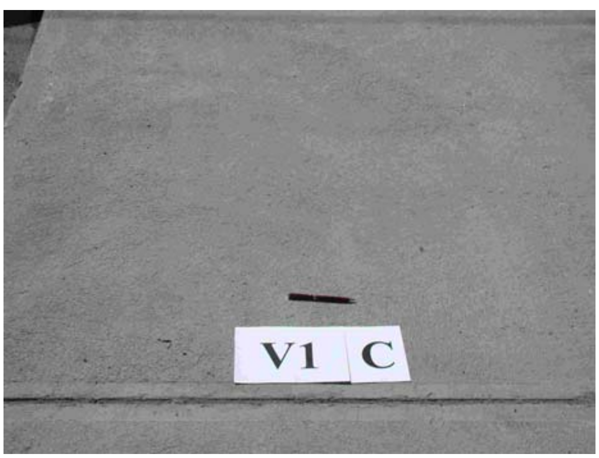


Fig. 17 - Temperature at 20 mm deep of the top surface of the sidewalks.

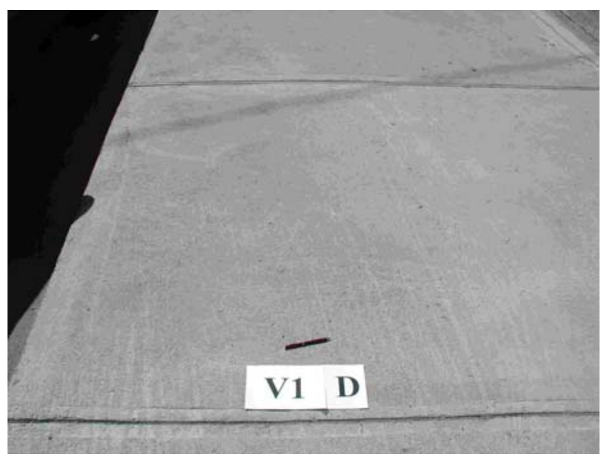
Procedure A: Finishing after bleeding and curing compound 1.



Procedure B: Immediate finishing and curing compound 1.

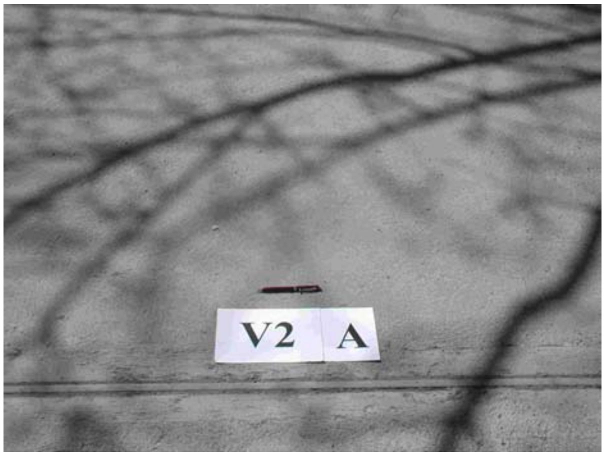


Procedure C: Immediate finishing and curing compound 2.

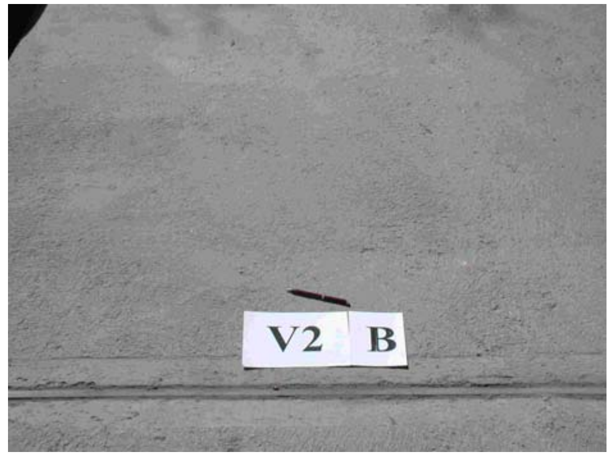


Procedure D: Immediate finishing and wet burlap curing.

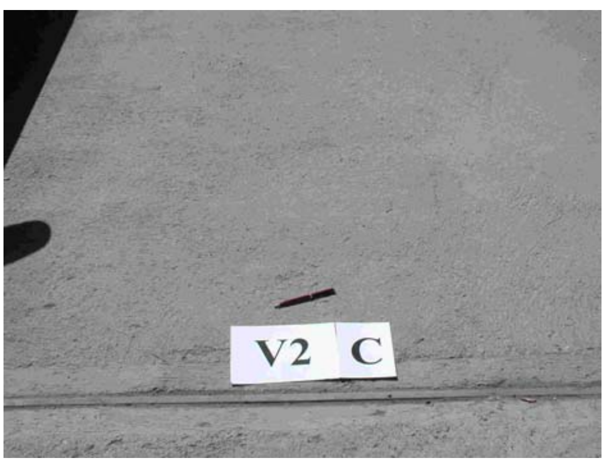
Fig. 18 - Sidewalks made with the control concrete after two winters (20 freeze-thaw cycles) spring 2002.



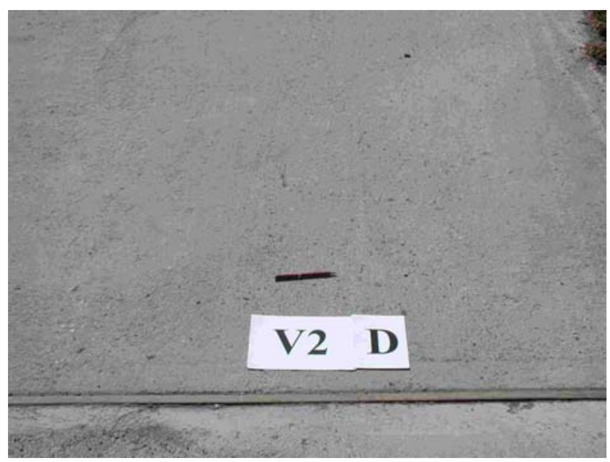
Procedure A: Finishing after bleeding and curing compound 1.



Procedure B: Immediate finishing and curing compound 1.

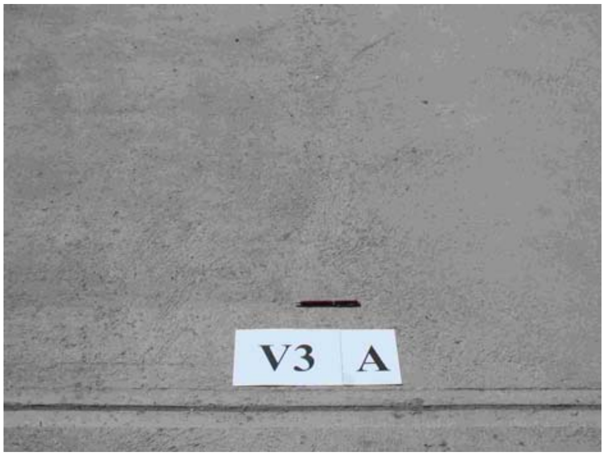


Procedure C: Immediate finishing and curing compound 2.

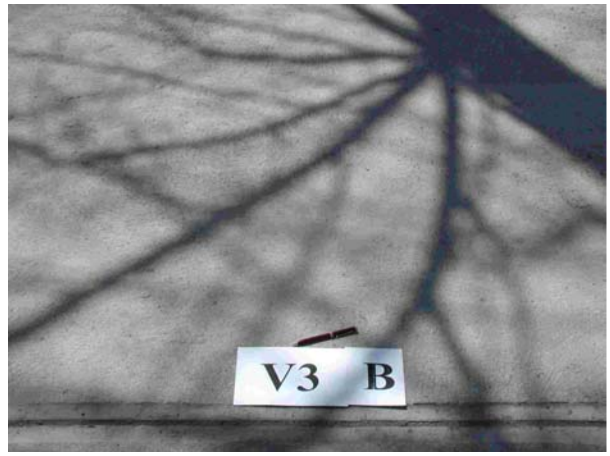


Procedure D: Immediate finishing and wet burlap curing.

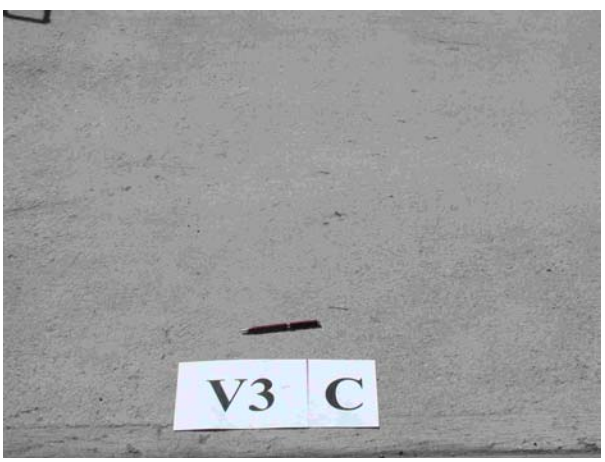
Fig 19 - Sidewalks made with 35% fly ash concrete after two winters (20 freeze-thaw cycles) spring 2002.



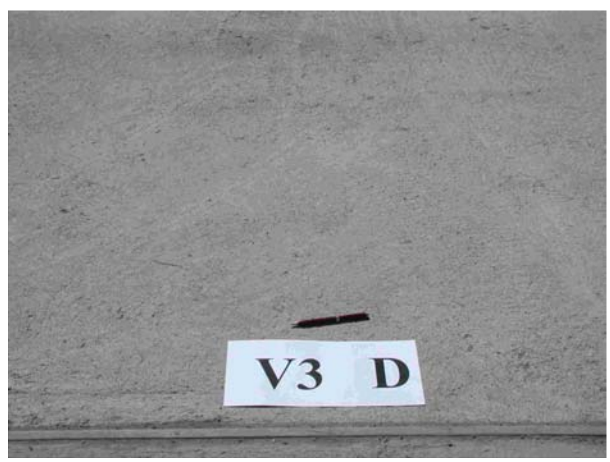
Procedure A: Finishing after bleeding and curing compound 1.



Procedure B: Immediate finishing and curing compound 1.

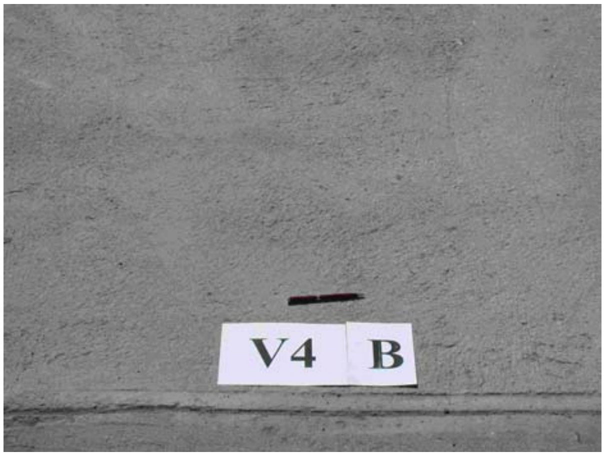


Procedure C: Immediate finishing and curing compound 2.

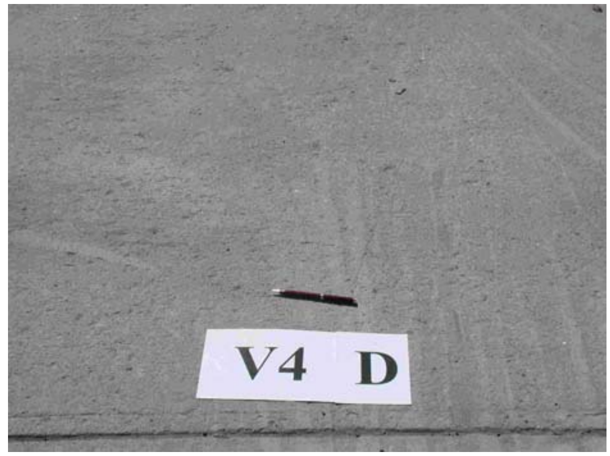


Procedure D: Immediate finishing and wet burlap curing.

Fig 20 - Sidewalks made with 35% slag concrete after two winters (20 freeze-thaw cycles) spring 2002.

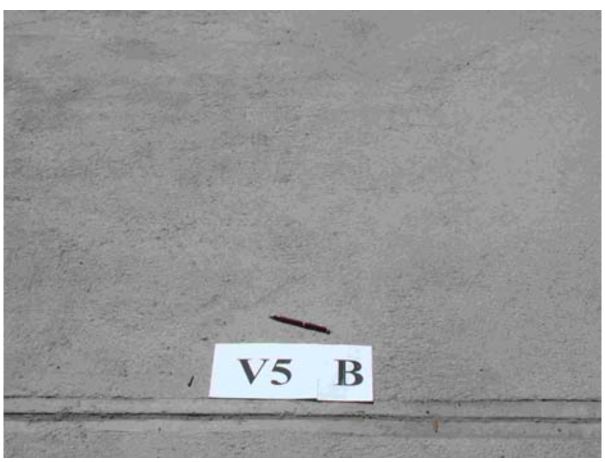


Procedure B: Immediate finishing and curing compound 1.

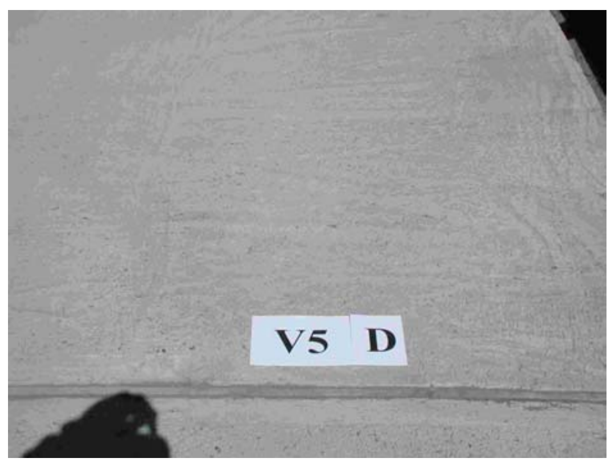


Procedure D: Immediate finishing and wet burlap curing.

Fig. 21 - Sidewalks made with 25% fly ash concrete after two winters (20 freeze-thaw cycles) spring 2002.

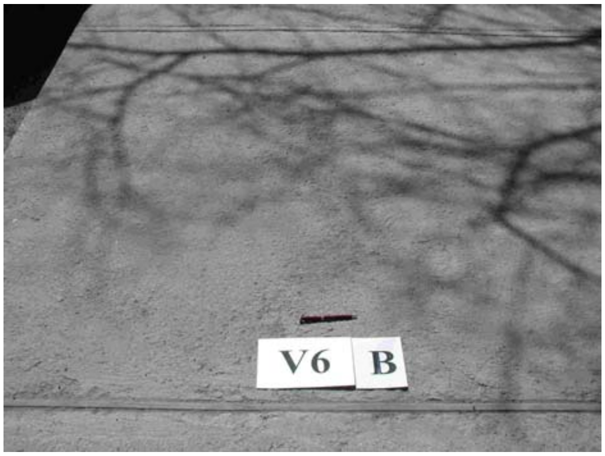


Procedure B: Immediate finishing and curing compound 1.

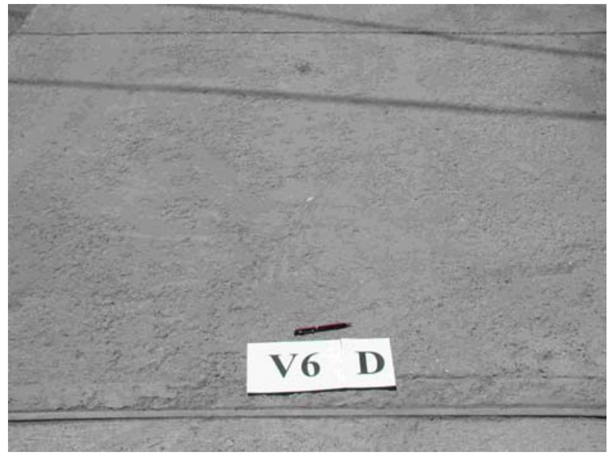


Procedure D: Immediate finishing and wet burlap curing.

Fig. 22 - Sidewalks made with 25% slag concrete after two winters (20 freeze-thaw cycles) spring 2002.

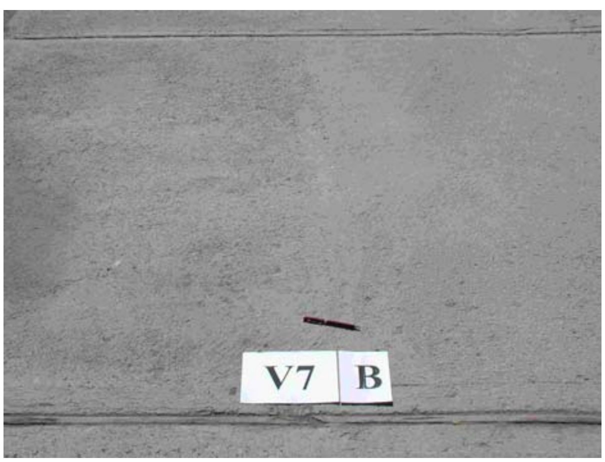


Procedure B: Immediate finishing and curing compound 1.

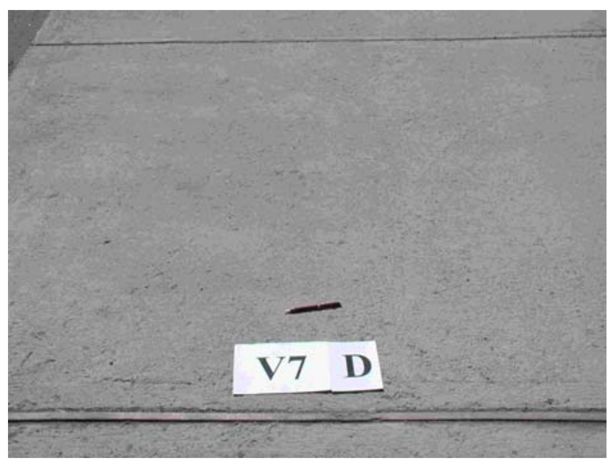


Procedure D: Immediate finishing and wet burlap curing.

Fig. 23 - Sidewalks made with the Terc3 concrete after two winters (20 freeze-thaw cycles) spring 2002.



Procedure B: Immediate finishing and curing compound 1.



Procedure D: Immediate finishing and wet burlap curing.

Fig. 24 - Sidewalks made with the TerCem concrete after two winters (20 freeze-thaw cycles) spring 2002.

Curing compound

Wet burlap and plastic sheets

Manual placing and bull float finish

Final finishing with wooden trowel

Large slab specimens

Fig. 25 - Pictures of field operations and type of specimens

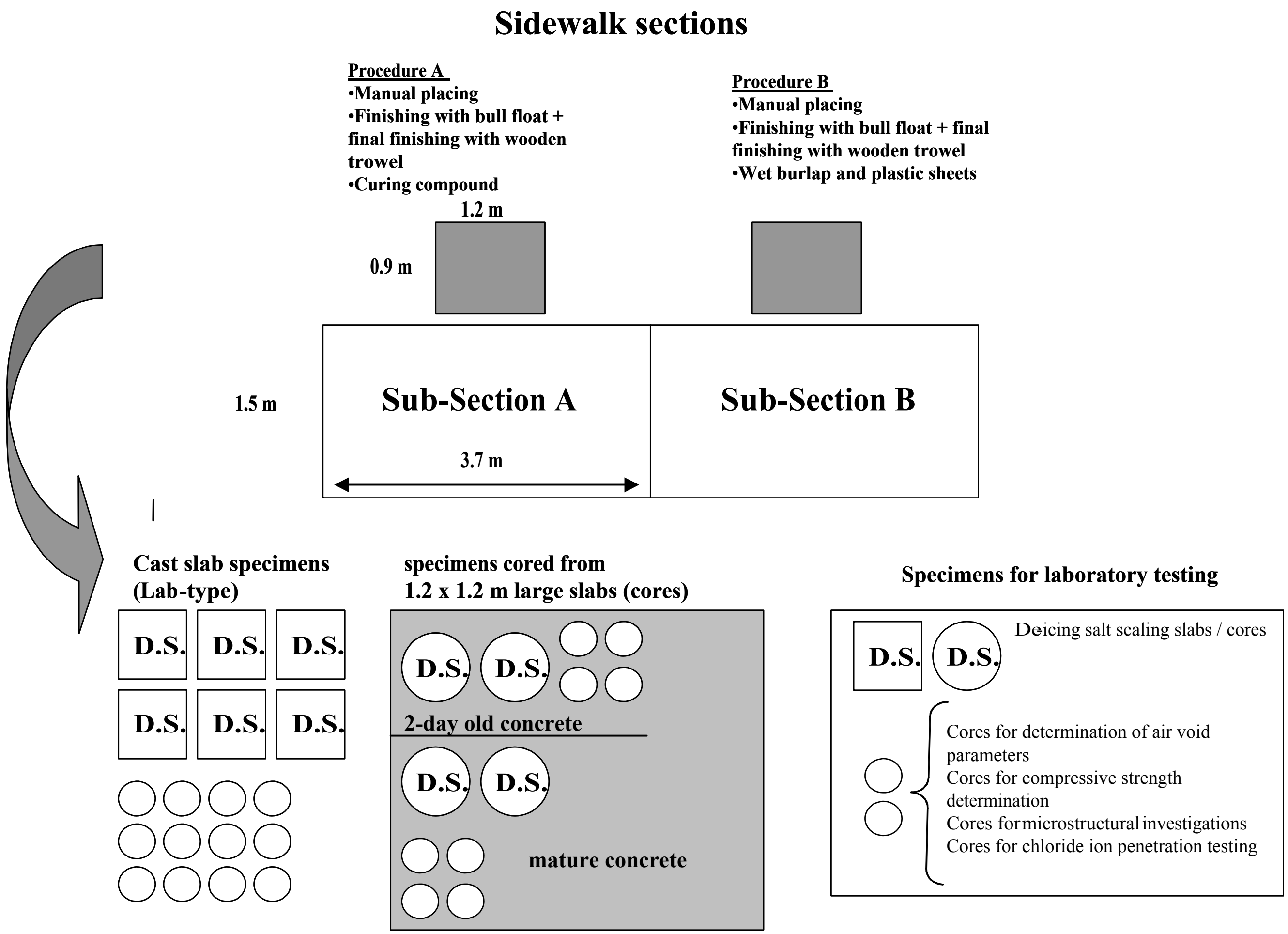


Fig. 26 - Concrete sidewalk sections - summary of field operations and specimens taken.

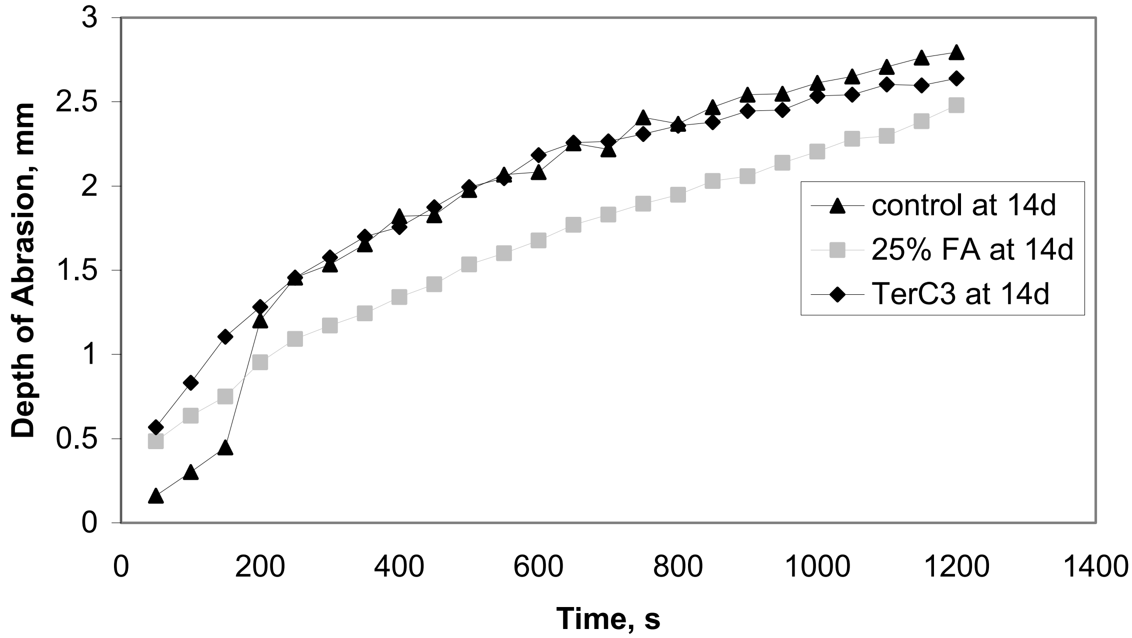


Fig. 27 - Depth of abrasion vs. duration of wearing of concrete at 14-d.

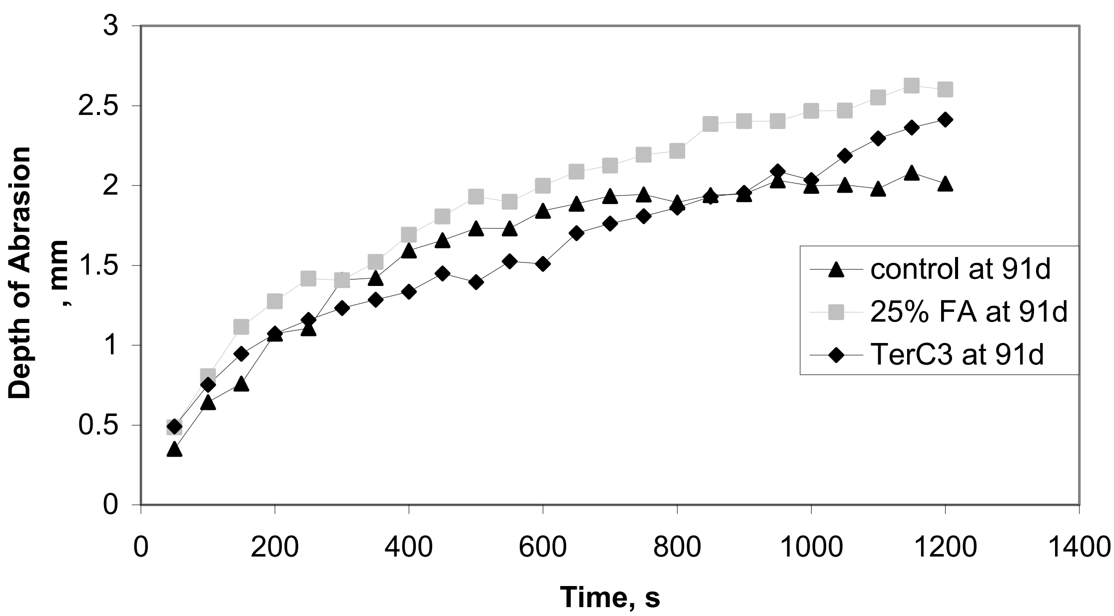


Fig. 28 - Depth of abrasion vs. duration of wearing of concrete at 91-d.

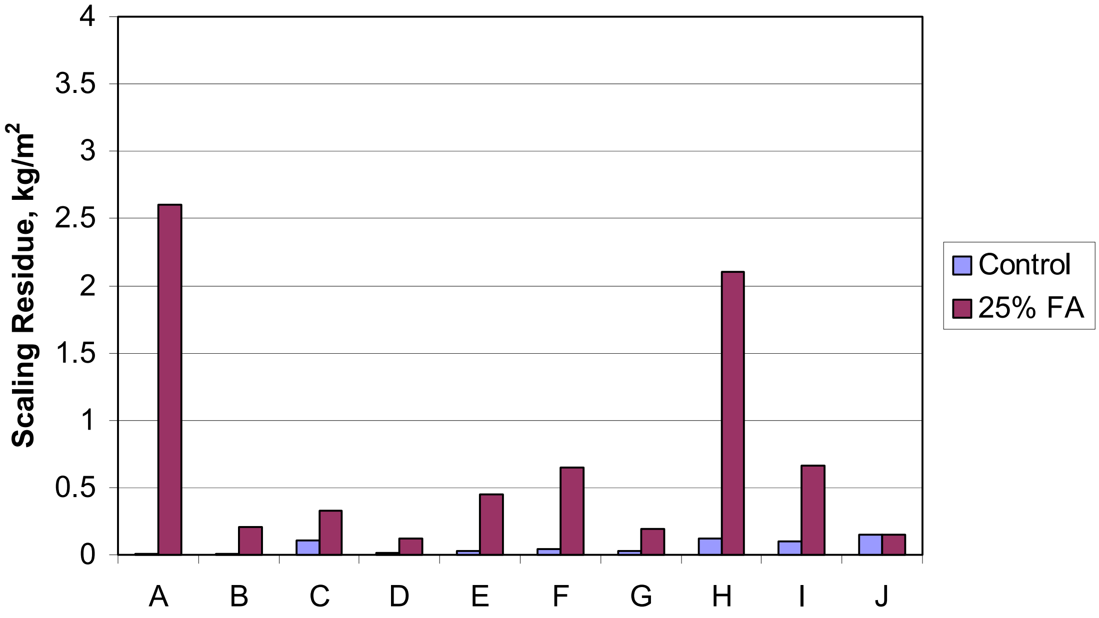


Fig. 29 - Effect of fly ash on the scaling resistance of concrete.

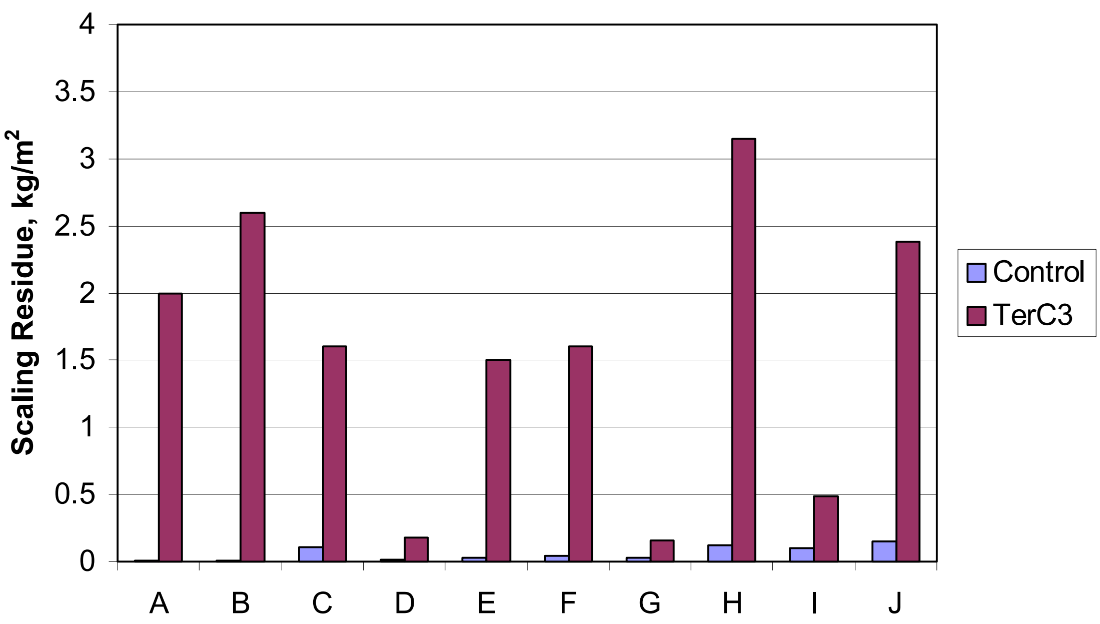


Fig. 30 - Effect of ternary blended cement on the scaling resistance of concrete.

A	B	C	D	E	F	G	H	I	J
ASTM	ASTM No Brush	ASTM re-saturat	ASTM curing compound (CC)	BNQ	BNQ geotextile	Cores CC cured in lab	Cores wet burlap cured in lab	Cores CC cured in field	Cores wet burlap cured in field

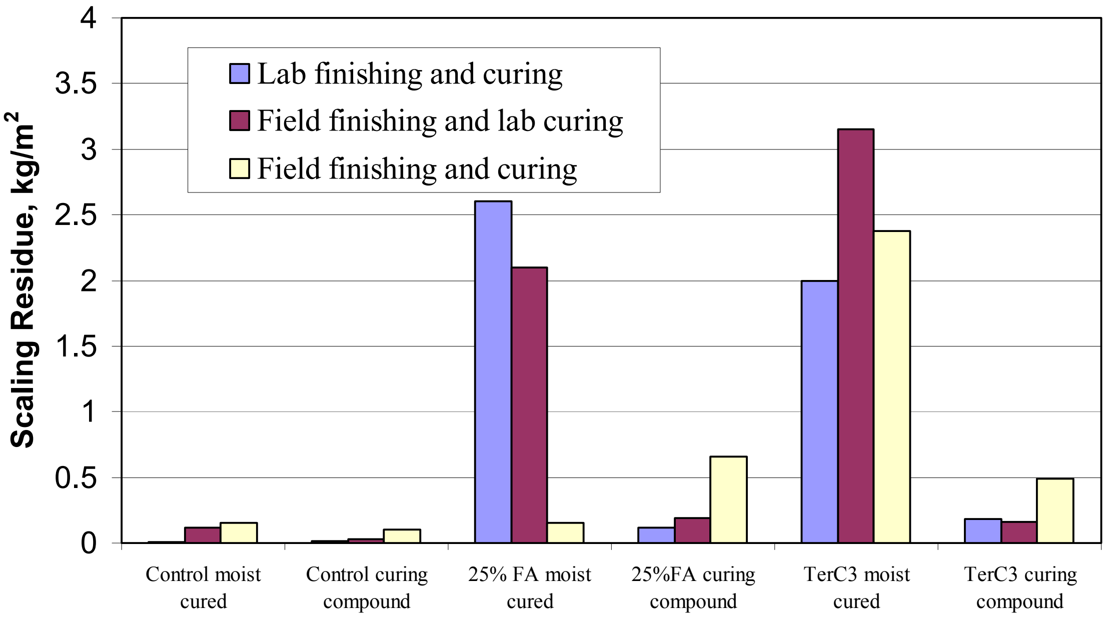
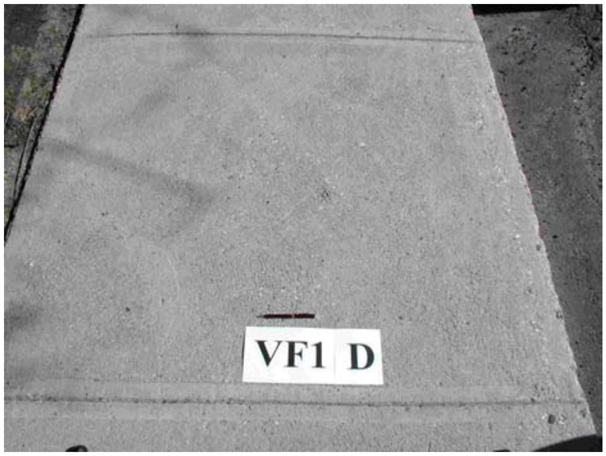


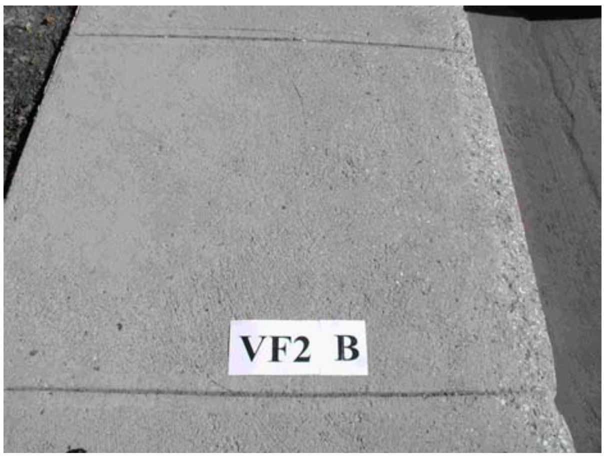
Fig. 31 - Lab conditioning and exposure vs. field exposure and conditioning.

Procedure B: Immediate finishing and curing compound 1.



Procedure D: Immediate finishing and wet burlap curing.

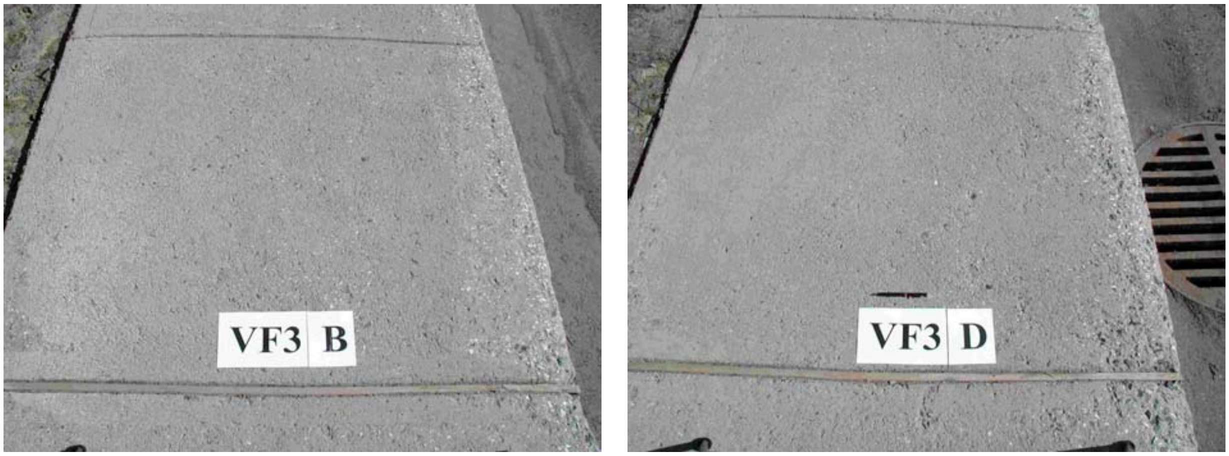
Fig. 32 - Sidewalks made with the control concrete after two winters (20 freeze-thaw cycles) fall 2002.



Procedure B: Immediate finishing and curing compound 1.

Procedure D: Immediate finishing and wet burlap curing.

Fig. 33 - Sidewalks made with 25% fly ash concrete after two winters (20 Freeze-thaw cycles) fall 2002.



Procedure B: Immediate finishing and curing compound 1.

Procedure D: Immediate finishing and wet burlap curing.

Fig. 34 - Sidewalks made with the Terc3 concrete after two winters (20 freeze-thaw cycles) fall 2002.

Procedure B: Immediate finishing and curing compound 1.

Procedure D: Immediate finishing and wet burlap curing.

Fig. 35 - Sidewalks edges made with control concrete after one winter (10 freeze-thaw cycles) fall 2002.

Procedure B: Immediate finishing and curing compound 1.

Procedure D: Immediate finishing and wet burlap curing.

Fig. 36 - Sidewalks edges made with 25% fly ash concrete after one winter (10 freeze-thaw cycles) fall 2002.

Procedure B: Immediate finishing and curing compound 1.

Procedure D: Immediate finishing and wet burlap curing.

Fig. 37 - Sidewalks edges made with the Terc3 concrete after one winter (10 freeze-thaw cycles) fall 2002.

Appendix A

Table 1: Cumulative Scaling Residue of concrete mixtures subjected to 50 freeze-thaw cycles following ASTM C 672 procedure, kg/m^2 (Spring 2002)

	Sample No.	Lab-Slabs*				Cores**			
		MC	G	S	CC1	A	B	C	D
V1-Cont	Sample 1	0.76	0.85	1.29	1.36	1.21	0.93	1.24	3.53
	Sample 2	0.59	2.29	2.76	1.36	1.21	1.26	0.68	1.67
V2-35%FA	Sample 1	2.69	2.94	2.95	1.82	3.22	3.23	3.19	5.26
	Sample 2	2.95	2.33	2.12	1.77	2.9	2.8	2.51	2.57
V3-35%Slag	Sample 1	1.13	0.77	0.51	1.4	0.99	1.68	1.77	1.22
	Sample 2	0.77	0.96	0.48	1.07	0.94	1.88	1.7	1.27
V4-25%FA	Sample 1	3.69	2.31	1.43	1.2	-	1.25	-	2.77
	Sample 2	3.07	2.73	2.17	1.39	-	0.92	-	3.08
V5-25%Slag	Sample 1	0.3	0.43	0.58	0.88	-	1.1	-	0.85
	Sample 2	0.52	0.52	0.47	0.8	-	1.07	-	0.65
V6-TerC^3	Sample 1	2.49	2.32	1.94	1.96	-	2.71	-	2.99
	Sample 2	2.48	2.44	2.15	1.86	-	2.28	-	3.11
V7-Tercem	Sample 1	1.6	1.26	1.51	2.2	-	2.34	-	2.16
	Sample 2	1.44	1.54	1.02	2.17	-	2.34	-	2.19

* MC: Moist curing
G: Geotextile
S: Sand
CC1: Curing compound 1

**A: finishing after the bleeding has disappeared + curing compound 1
B: Curing compound 1
C: Curing compound 2
D: Wet burlap

Table 2: Cumulative Scaling Residue of concrete mixtures subjected to 56 freeze-thaw cycles following BNQ Standard (Inter-lab Study), kg/m^2 (Spring 2002)

	Sample No.	Lab. 1	Lab. 2	Lab. 3	Lab. 4	Lab. 5	Lab. 6	Lab. 7
V1- Control	Sample 1	0.16	0.28	0.29	0.49	0.06	0.42	0.52
	Sample 2	0.2	0.37	0.44	0.12	0.13	0.27	0.29
V2- 35% FA	Sample 1	0.48	0.17	1.26	0.2	0.16	0.21	0.71
	Sample 2	0.41	0.17	0.62	0.17	0.3	0.4	0.41
V3- 35% Slag	Sample 1	0.17	0.48	0.13	0.07	0.11	0.21	0.18
	Sample 2	0.22	0.44	0.13	0.28	0.11	0.26	0.3
V4- 25% FA	Sample 1	0.34	0.39	0.29	0.15	0.11	0.28	0.44
	Sample 2	0.24	0.26	0.31	0.17	0.09	0.44	1.01

Table 3: Cumulative Scaling Residue of Cores exposed for 90 days to natural conditioning in the field and tested according to ASTM and BNQ Standards, kg/m^2 (Spring 2002)

	Sample No.	Concrete Mixtures			
		V1 - B* Control	V2 - B* 35% FA	V3 - D* 35% Slag	V4 - D* 25% FA
ASTM (50 cycles), kg/m^2	Sample 1	0.07	0.17	0.31	0.97
	Sample 2	0.07	0.09	0.26	0.86
BNQ (56 cycles), kg/m^2	Sample 1	0.03	0.05	0.37	0.72
	Sample 2	0.14	0.07	0.41	0.84

Table 4: Cumulative Scaling Residue of Cores exposed for 180 days to natural conditioning in the field and tested according to ASTM C 672, kg/m^2 (Spring 2002)

	Sample No.	A*	B*	C*	D*
V1 - Control	Sample 1	0.04	0.02	0.03	0.42
	Sample 2	0.04	0.04	0.03	0.16
V2 - 35%FA	Sample 1	0.16	0.07	0.08	0.74
	Sample 2	0.18	0.07	0.14	0.76
V3 - 35%Slag	Sample 1	0.04	0.04	0.3	0.23
	Sample 2	0.02	0.06	0.13	0.28
V4 - 25%FA	Sample 1		0.09		1.14
	Sample 2		0.04		1.38
V5 - 25%Slag	Sample 1		0.04		0.27
	Sample 2		0.05		0.25
V6 - $TerC^3$	Sample 1		2.79		3.62
	Sample 2		2.78		3.86
V7 - TerCem	Sample 1		0.59		1.42
	Sample 2		0.61		1.04

*A: finishing after the bleeding has disappeared + curing compound 1
B: Curing compound 1
C: Curing compound 2
D: Wet burlap

Table 5: Cumulative Scaling Residue of concrete mixtures subjected to 50 freeze-thaw cycles following ASTM C 672 procedure, kg/m^2 (Fall 2002)

Mix.	Sample No.	Lab-Slabs*						Cores**			
		MC	NB	RS	CC1	BNQ	BNQ with Geot.	lab-curing		field-conditioning (28 days)	
								A	B	A	B
VF1	Sample 1	0	0.01	0.18	0.02	0.04	0.06	0.16	0.04	0.15	0.13
	Sample 2	0.01	0	0.05	0.01	0.02	0.02	0.07	0.02	0.14	0.07
VF2	Sample 1	1.76	0.4	0.18	0.17	0.006	0.83	0.15	3.57	0.13	0.74
	Sample 2	3.39	0.02	0.49	0.07	0.68	0.48	0.23	0.54	0.17	0.58
VF3	Sample 1	2.14	3.03	1.64	0.12	1.65	1.25	0.28	3.17	0.64	2.28
	Sample 2	2.15	2.21	1.52	0.26	1.33	2.15	0.17	3.15	0.33	2.52

* MC: Moist curing
NB: samples were not brushed
RS: samples were saturated with the solution prior to be tested
CC1: Curing compound 1
** A: Curing compound 1
B: Wet burlap

Table 6: Cumulative Scaling Residue of concrete mixtures subjected to 56 freeze-thaw cycles following BNQ Standard (Inter-lab Study), kg/m^2 (Fall 2002)

	Sample No.	Lab. 1	Lab. 2	Lab. 3	Lab. 4	Lab. 5	Lab. 6
VF1-Control	Sample 1	0.04	0.03	0.02	0.03	0.008	
	Sample 2	0	0.03	0.01	0.01	0.003	
VF2- 25% FA	Sample 1	0.18	0.09	0.89	0.35	0.02	
	Sample 2	0.03	0.08	0.78	0.18	0.01	
VF3-$TerC^3$	Sample 1	0.18	1.53	2.04	0.71	0.14	
	Sample 2	0.15	1.22	2.01	0.88	0.26	

Appendix B

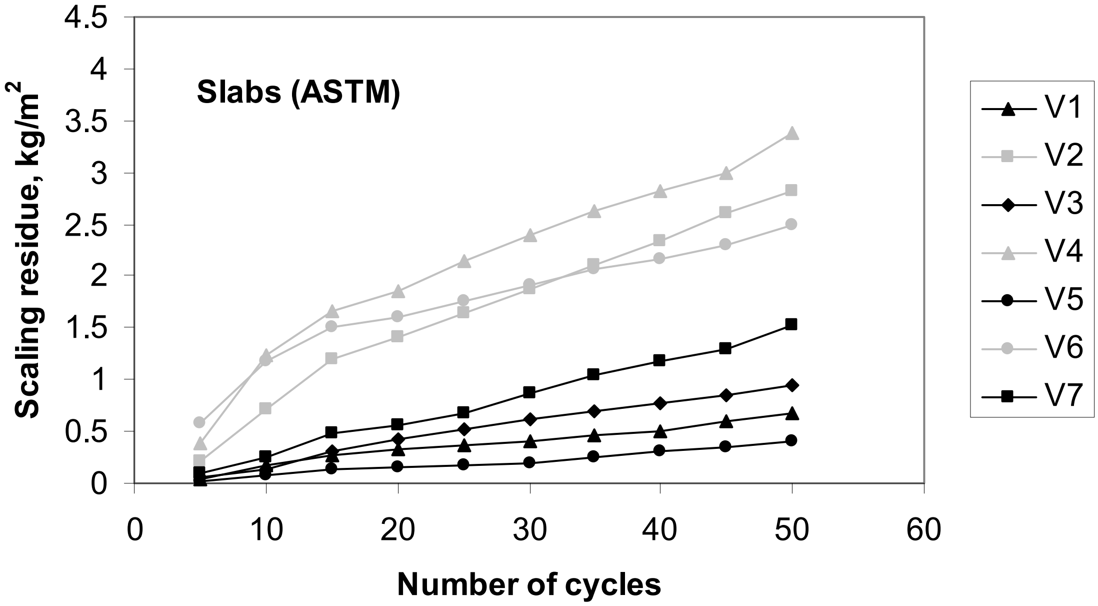


Fig. 1 Scaling residue vs. number of cycles of lab-specimens tested according

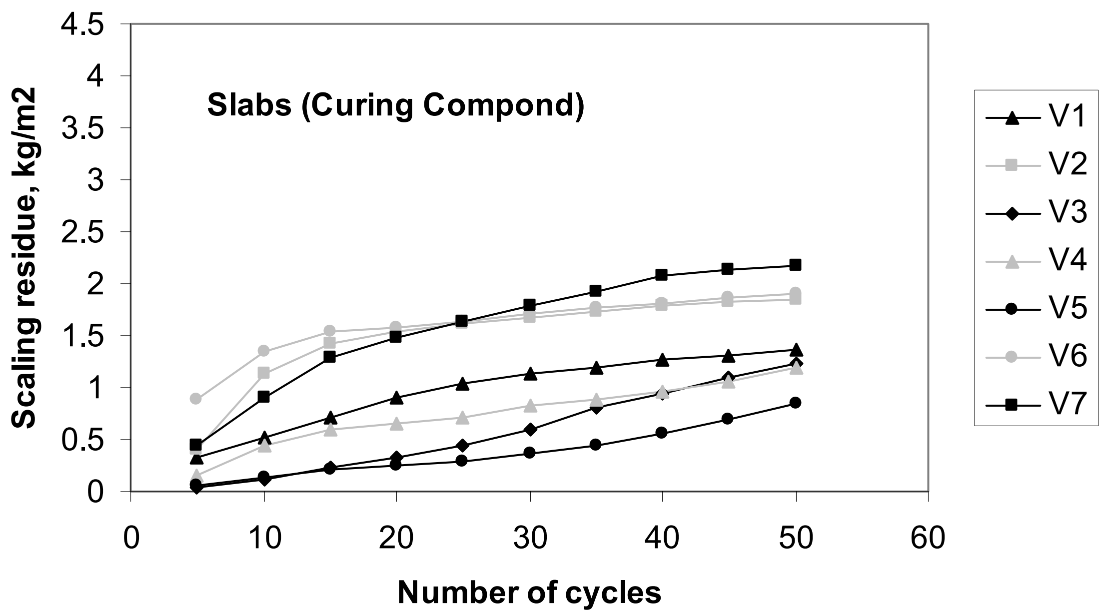


Fig. 2 Scaling residue vs. number of cycles of lab-specimens cured with curing compound 1 and tested according to ASTM C 672

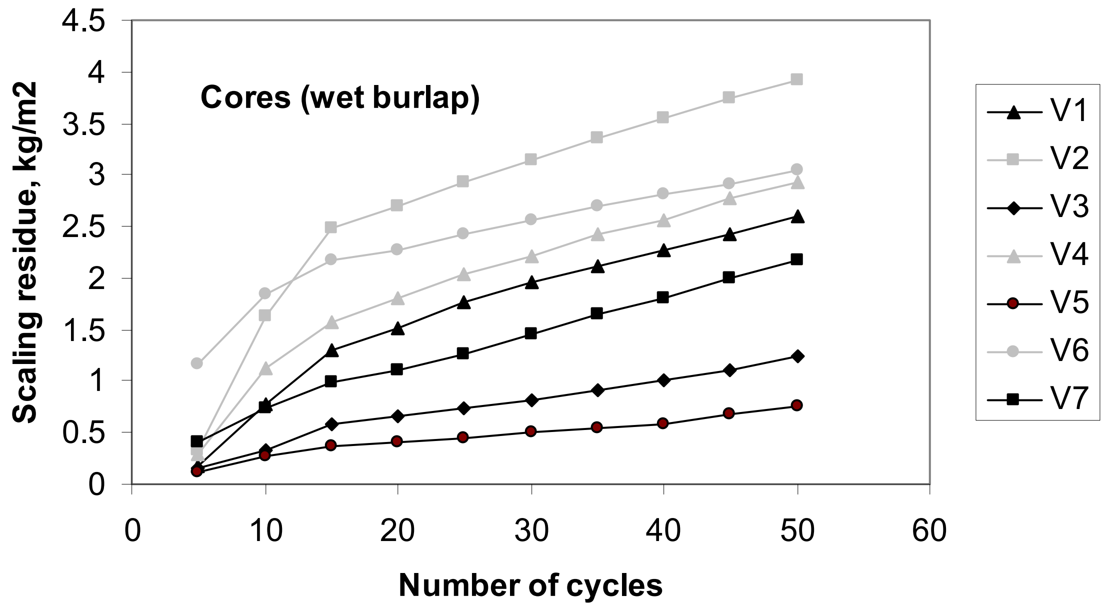


Fig. 3 Scaling residue vs. number of cycles of cores cured under wet burlap and tested according to ASTM C 672

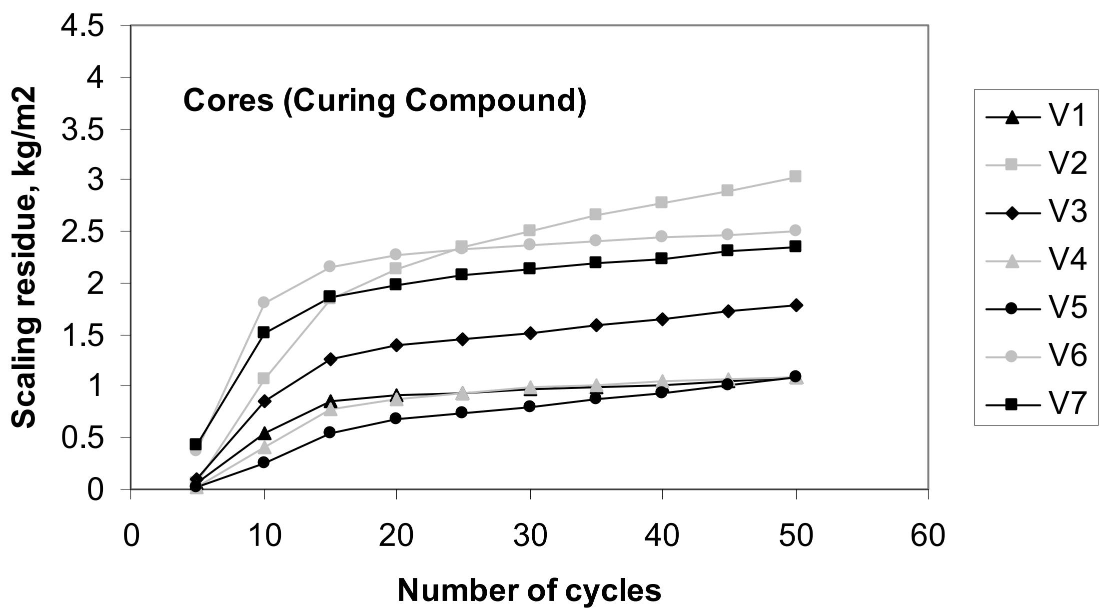


Fig. 4 Scaling residue vs. number of cycles of cores cured with curing compound 1 and tested according to ASTM C 672

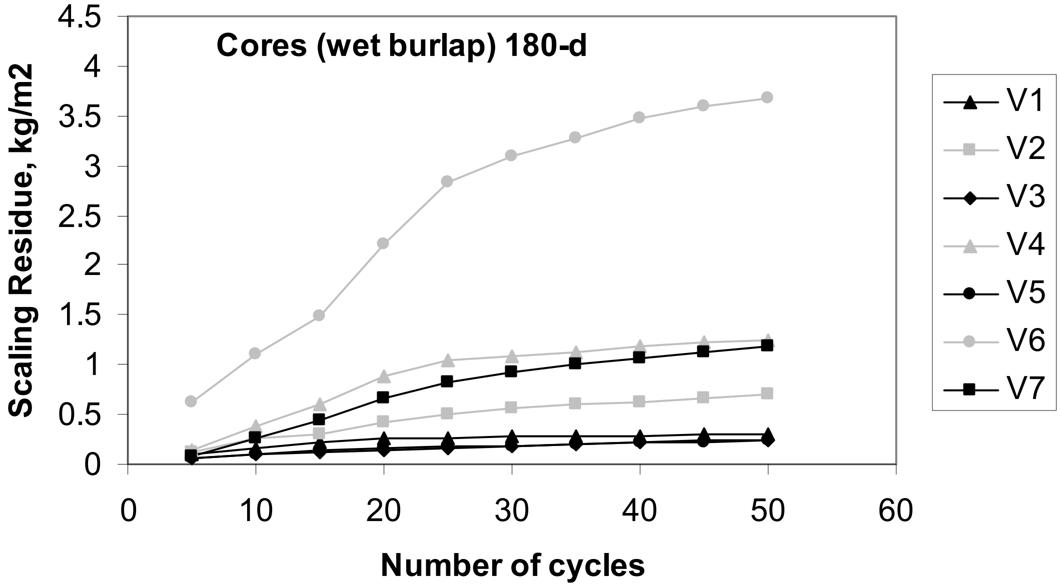


Fig. 5 Scaling residue vs. number of cycles of cores cured under wet burlap, left exposed to field conditioning for 180-d and tested according to ASTM C 672

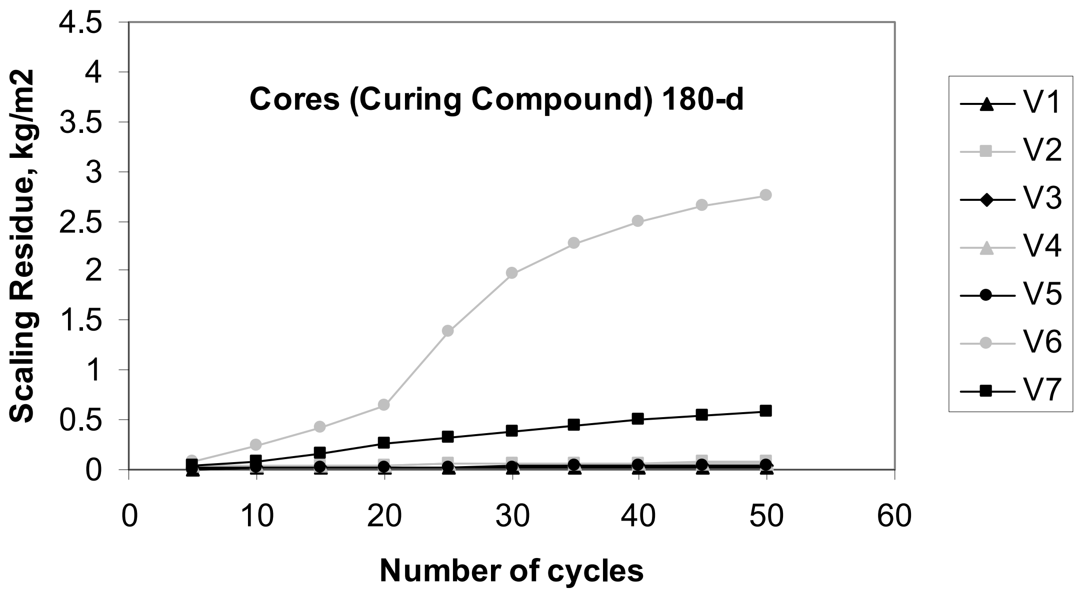


Fig. 6 Scaling residue vs. number of cycles of cores cured with curing compound 1, left exposed to field conditioning for 180-d and tested according to ASTM C 672

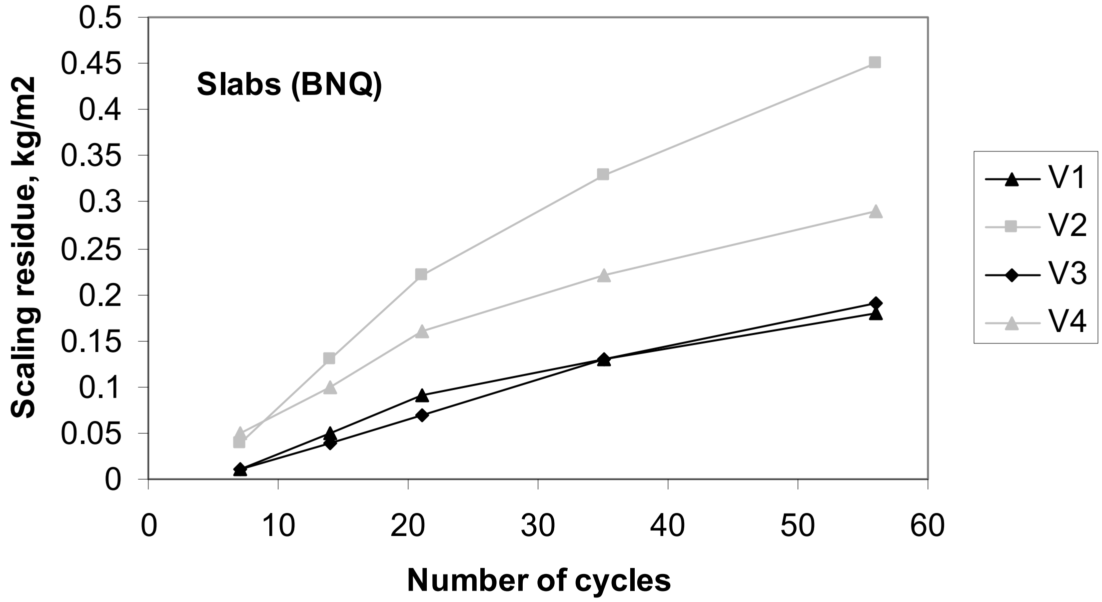


Fig. 7 Scaling residue vs. number of cycles of lab-specimens tested according to BNQ standard

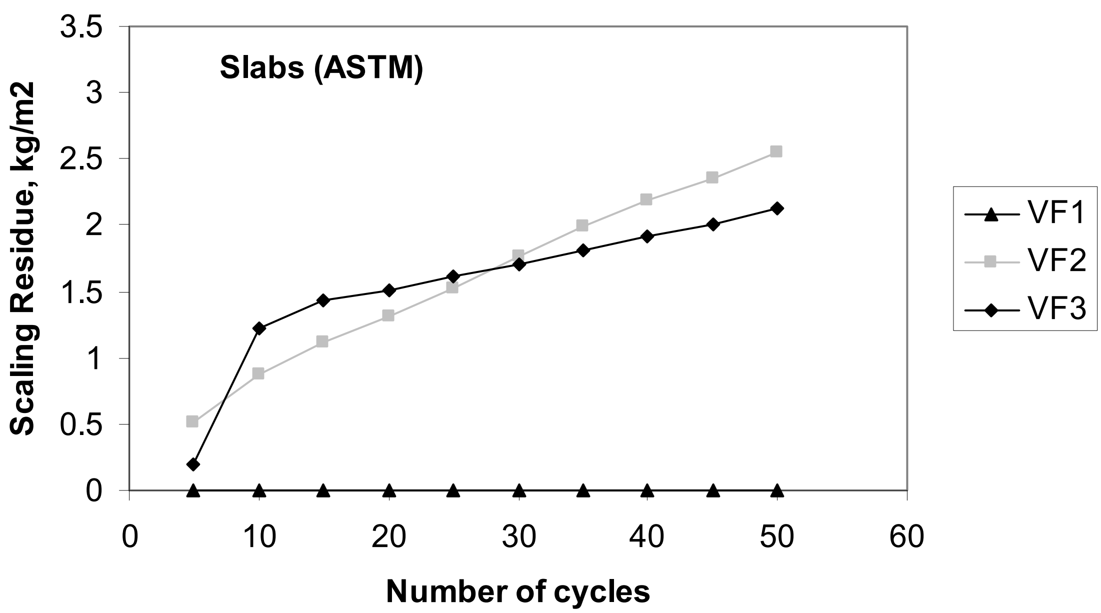


Fig. 8 Scaling residue vs. number of cycles of lab-specimens tested according to ASTM C 672

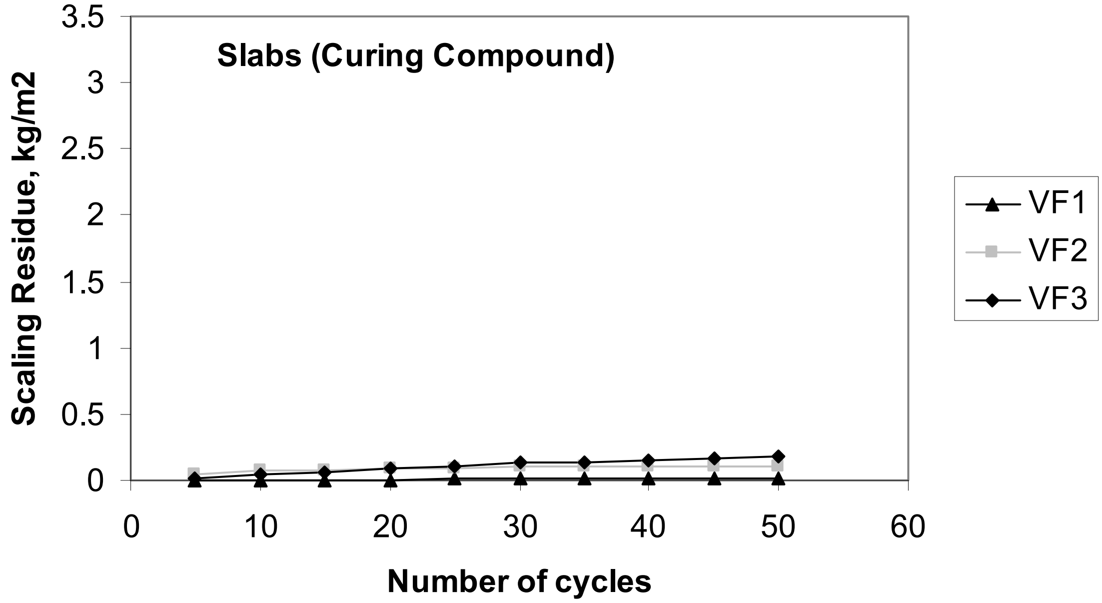


Fig. 9 Scaling residue vs. number of cycles of lab-specimens cured with curing compound 1 and tested according to ASTM C 672

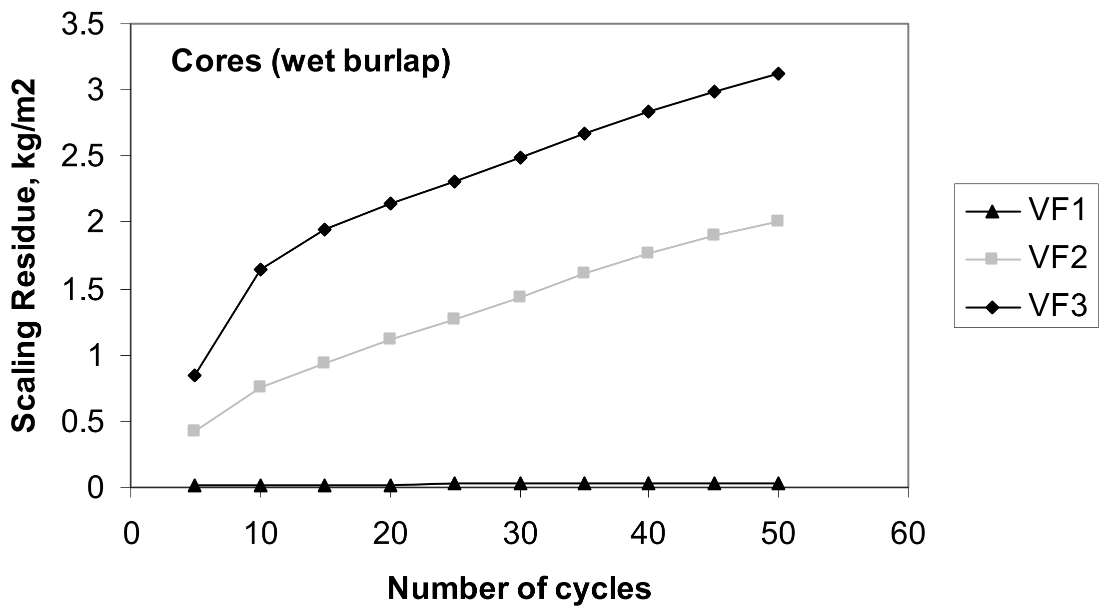


Fig. 10 Scaling residue vs. number of cycles of cores cured under wet burlap and tested according to ASTM C 672

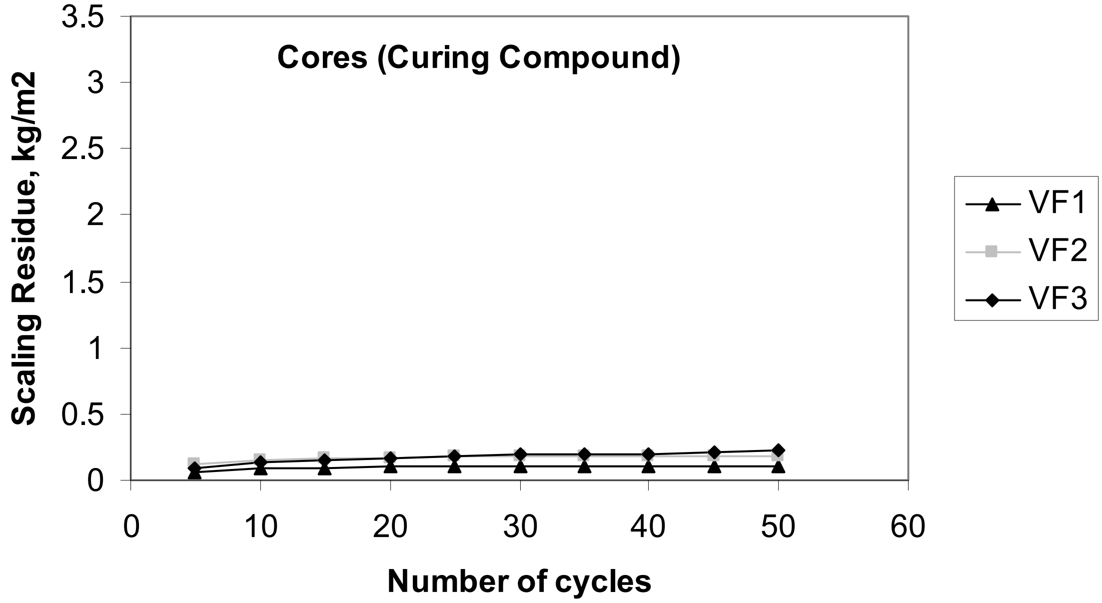


Fig. 11 Scaling residue vs. number of cycles of cores cured with curing compound 1 and tested according to ASTM C 672

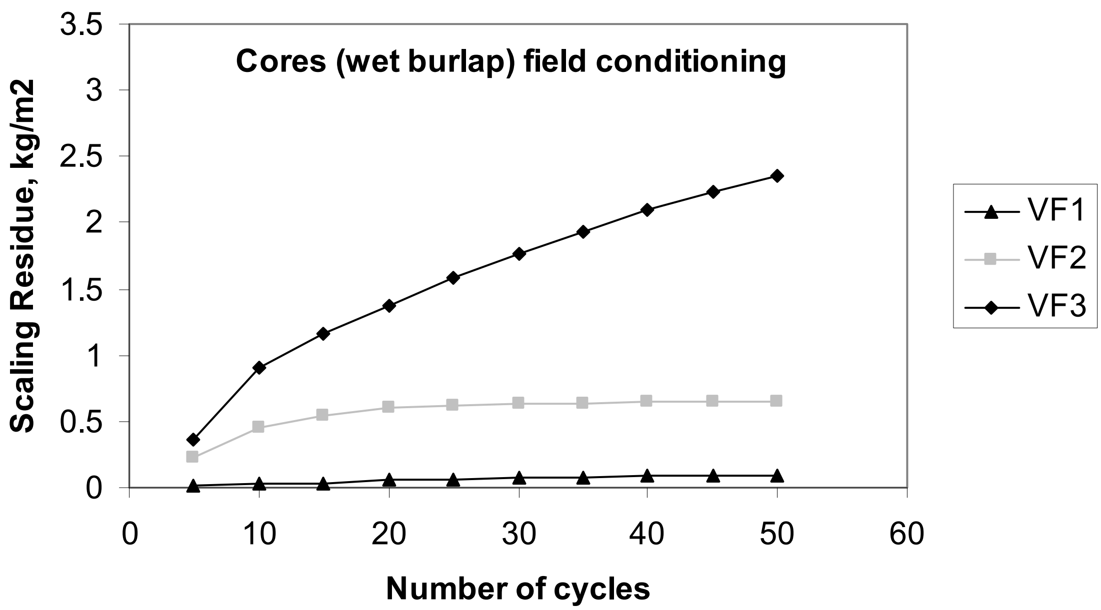


Fig. 12 Scaling residue vs. number of cycles of cores cured under wet burlap, left exposed to field conditioning for 28-d and tested according to ASTM C 672

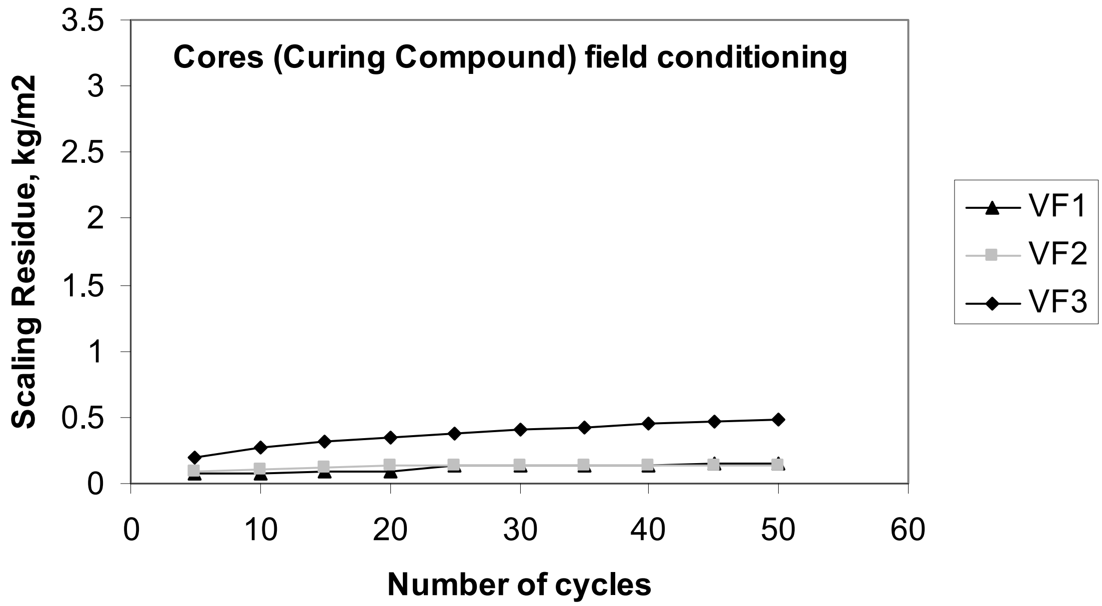


Fig. 13 Scaling residue vs. number of cycles of cores cured with curing compound 1, left exposed to field conditioning for 28-d and tested according to ASTM C 672

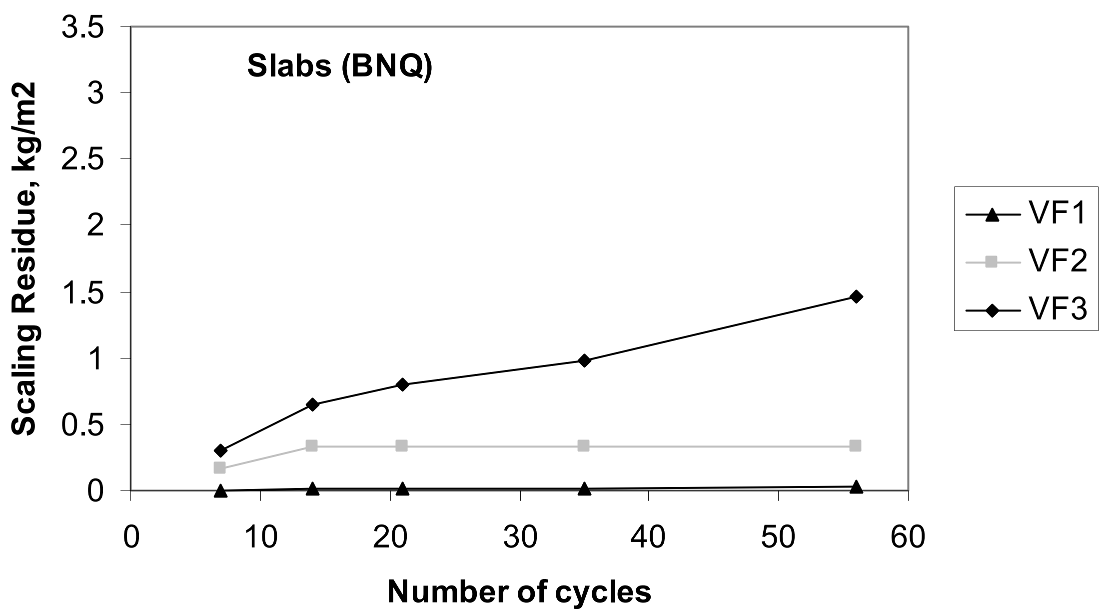


Fig. 14 Scaling residue vs. number of cycles of lab-specimens tested according to BNQ test procedure