IN SEARCH OF RELIABLE IN-SITU TEST METHODS FOR DEVELOPMENT OF PERFORMANCE-BASED SPECIFICATIONS FOR CONCRETE IN HIGHWAY STRUCTURES

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Abstract: In order to minimise the impact on the natural environment, the move from prescriptive to performance-based specifications for concrete materials and construction has become a critical issue in highway bridge design and construction Many agencies are using or developing end-result specifications to promote innovation in construction of highway structures. The Ontario Ministry of Transportation (MTO) has been moving away from prescriptive specifications since the mid 1980's starting with introduction of end-result based specifications for compressive strength. Today, MTO uses payment adjustment formulas for quality indicators measured on hardened concrete that include: compressive strength, air void system parameters and, for high performance concrete, rapid chloride permeability.

However, the move to true performance-based specifications is impeded by the limited range of test methods available today and by the lack of verifiable links between test results obtained at the time of construction and the actual service life of the concrete structure. The paper describes attempts to evaluate, under realistic field conditions, the applicability of existing non-destructive test methods such as permeability to water, air penetrability, and electrical resistivity.

Introduction

Land, water, materials and significant amounts of non-renewable energy are consumed in the construction and maintenance of the infrastructure. It has a profound effect on the sustainability of the natural environment, therefore the quality and longevity of the infrastructure is an important factor in maintaining a healthy relationship between natural and built environment.

Performance-based specifications for concrete highway construction will promote technological innovation leading to sustainable concrete structures, and help to achieve longer service life and lower the costs of maintenance and repairs.

As described in [1], performance-based specifications define the desired level of engineering properties that are the predictors of performance and are appropriate for use as part of a construction acceptance process. Testing of the 'end-result' properties of concrete in a non-destructive manner requires reliable in-situ test methods; this paper reviews and summarizes the current status of development and use of non-destructive, in-situ test methods for determination of concrete quality as related to long-term durability.

From prescriptive to performance-based specifications, MTO perspective

The responsibility for achieving the desired level of concrete properties related to durability has to be shared by the concrete supplier (design and prequalification of concrete mixes) and concrete contractor (proper placement and curing techniques).

The MTO acceptance of 'as constructed' concrete should be determined based on in-situ testing, using limits verified as related to a desired level of concrete performance.

Currently, the quality indicators used by the ministry to accept or reject concrete are the compressive strength, air void system parameters, and for the high performance concrete (HPC), the concrete's ability to resist chloride ion penetration. As the ministry recognizes that it is impossible to reproduce reliably the characteristics of 'as constructed' concrete in cast specimens, two out of three quality indicators – the air void system and the resistance to chloride ion penetration - are tested on cores removed from the structure. The compressive strength, however, is still tested on cast cylinders.

Compressive strength has been traditionally considered a primary indicator of concrete quality and durability. When tested on cast cylinders, it is not a precise quantitative indicator of in-place concrete strength. It does not reflect how the binder hydration process is influenced by the size and geometry of the concrete element, nor is it indicative of the effect of the construction procedures, specifically handling, consolidation and curing of concrete. Compressive strength tested on cores removed from a structure gives a better approximation of 'as constructed' strength of concrete, however, the core removal process can inflict microcracking and weaken the internal concrete structure in the core and affect the integrity of the structure. According to Ontario Provincial Standard Specification OPSS.Prov.1350, April 2007, compressive strength of concrete in MTO work is tested at 28-days of concrete age on standard test cylinders cast, cured and transported according to CSA A23.2-3C.

The Ministry requires the provision of an acceptable air void system in the hardened concrete. A properly sized and distributed air void system is intended to act as a reservoir for the expanding volume of water when it freezes in concrete (approximately 9 percent volume expansion upon freezing). In a properly structured air void system, freezing water expands and moves from the capillary pores into the air voids, then in the 'thaw' part of the cycle, water returns from the air voids to the capillary pores, thus leaving the cement matrix unharmed. Cores (100 mm diameter and 200 mm long) for evaluation of the air void system parameters are removed from the structure and tested according to ASTM C457. To compensate for the heterogeneity of concrete and to reduce the variability of test results, the total concrete area tested has to be maximized; therefore the air void system parameters are calculated from the measurements taken across the 200 mm core length. To further improve the precision of the test method, the ministry specifies the minimum length of the total traverse and the number of points as twice the length and number specified by ASTM C457. Also, the magnification range specified by the ministry is narrower (100X-125X) than specified by ASTM (50X to 125X). Spacing factor and air content are critical parameters of the air-void system.

In the rapid chloride permeability test (Standard Test Method ASTM C 1202), the concrete's ability to resist chloride ion migration under an electrical field applied across the specimen is tested. Cores (100 mm diameter and a minimum of 125 mm long) are removed from the structure, and two 50 mm long test specimens are cut after discarding a 10 mm thick slice from the top of the core. The electrical charge passed through the specimen, which has one end immersed in sodium chloride solution and the other in sodium hydroxide solution, is related to the resistance to chloride ion penetration. Ministry specifications require that the average value of electrical charge from two specimens cut from one core is reported as the test result.

The Ministry requires the air void system and the rapid chloride permeability testing to be done by prequalified operators; a round of correlation program designed for prequalification and certification of the private industry operators is carried out by the ministry every year.

The structure and connectivity of the paste pore system is directly related to its penetrability by liquid and gaseous media. Penetrability to gases and/or liquids is the single most important property related to durability.

The vulnerability of the structural element to the aggressive action of the environment depends on the quality of a relatively thin surface layer protecting the reinforcement and the core of the structural element against temperature and moisture cycles, chloride ingress, abrasion, and other effects of the structure environment. In many literature sources, this near-surface layer of concrete is synonymous with the concrete cover to the reinforcing steel; the term “covercrete” has been coined and used to define it.

The quality of the near-surface region of concrete is influenced by the quality of the concrete mix and construction procedures, particularly curing. The microstructure of the covercrete can be very different from the microstructure of the bulk concrete. Loss of moisture through the surface, aggregate to paste ratio affected by segregation, microcracking due to temperature and moisture fluctuations are only some of the adverse effects making the covercrete vulnerable to environmental attack. Therefore, it is critical to test the near-surface layer of concrete in order to truly evaluate the potential long-term durability of concrete.

In-situ determination of the penetrability

Many attempts have been made to develop and evaluate test methods for use in-situ evaluation of penetrability of near-surface concrete. The state-of-the-art report of RILEM Committee 189-NEC, published in 2007 [2)], reviews and summarizes in-situ test methods for determination of concrete penetrability. Still, for a proper interpretation of the test results and for the test methods to be fully functional in conditions different than that of a controlled laboratory environment, boundary conditions and correction factors for the age of concrete, ambient temperature and moisture conditions, concrete moisture content and temperature when tested, have to be build into the specifications.

The task of correlating the properties of concrete measured in-situ and early in the life cycle of the structure is extremely challenging. It requires a long-term commitment to carry out durability-related testing and evaluation.

Review of existing in-situ test methods for concrete penetrability

Three mechanisms are the basis for in-situ determination of concrete penetrability. They are:

- Permeation: transport of liquids or gases caused by pressure head
- Capillary suction: transport of liquids by capillary forces (sorptivity)
- Ion migration: transport of ions in pore solution with an electrical field as the driving force

Depending on the penetrating medium used: gas, water, or ions in solution moving under a driving force (electrical field), test methods are grouped in [2)] as follows:

- Test methods to measure gas permeability
- Test methods to measure water permeability or sorptivity
- Test methods to measure ion migration

Gas permeability: There are currently nine test methods, all but one developed in Europe. Out of nine, five are commercially available but only one method has been standardized (Torrent air permeability method, standardized in Switzerland as Norme Suisse SN 505 262/1:2003). Five test methods are intrusive and require drilling a small cavity in the concrete, four are non-intrusive, tested directly on concrete surface. Five test methods test gas permeability in overpressure, i.e., positive pressure is created over the test area, and the rate of pressure decay is measured. Four tests are done in underpressure, i.e., negative pressure is created over the test area, and the increase in pressure is measured. None of the test methods specifies any preconditioning of the test surface area; one method includes the measurement of the concrete resistivity for compensation of the moisture content in concrete. The repeatability of the in-situ test methods has been determined by the coefficient of variation from a reasonably uniform lot of concrete at 30 to 40 percent.

Water permeability or sorptivity: There are currently five test methods, all but one developed in Europe. Out of five, four are commercially available but only one has been standardized (Initial Surface Absorption Test, under British Standard 1881, Part 208). Out of five test methods, three are intrusive and two are non-intrusive. Intrusive test methods require drilled cavities, which are filled with water. Non-intrusive tests are done directly on the concrete surface. The level of pressure exerted by water on the test surface differentiates whether sorptivity, or water permeability is measured.

Sorptivity is tested under a pressure of 100 or 200 mm head of water, equivalent to 1 or 2 kPa. Water permeability is tested at much higher pressure, up to 600 kPa for commercially available test methods. Only one test method (not available commercially) specifies preconditioning of the test area by application of vacuum followed by presaturation with water to create uniform moisture conditions. Other test methods specify the measurement of relative humidity in the cavity; the measurement can proceed if the relative humidity measured in the test cavility is at not higher than 90%. The within-specimen repeatability for water sorptivity/permeability cannot be determined due to the nature of the penetrating medium; water interacts with cementitious microstructure and changes it permanently. The repeatability of the in-situ test methods has been determined by the coefficient of variation from a reasonably uniform lot of concrete at 25 to 40 percent.

Ion migration: Two different test techniques are used: resistivity (measurement of electrical conductivity of the concrete pore solution, with dissolved ions naturally present in concrete) and the migration of ions externally introduced into the pore solution under electrical field. The characteristics of the electrical field is different; for resistivity measurement the voltage applied is at 10V or lower, for externally introduced ion migration the voltage applied is in the range of 60 to 80 V.

Two methods for testing resistivity are commercially available, and both are non-intrusive. One has been standardized as the adaptation of a standard test method for the measurement of soil resistivity (ASTM G57). The test methods use different types of probes, one uses a four-electrode probe, and the other one uses a disc probe. No preconditioning or any determination of the near-surface moisture content in concrete is specified for field testing of resistivity. For electrical resistivity measurement, the repeatability, as expressed by the coefficient of variation has been reported in the range of 20 percent for laboratory conditions, and 30 percent for field conditions.

Out of two test methods for testing of migration of externally introduced ions under electrical field, one is available commercially, the other one is not. Both are non-intrusive. The Whiting test method is based on the concept of a reversed chloride ion removal technique. Instead of driving the chloride ions out from the concrete, chlorides are migrating into the concrete from solution in contact with the concrete surface by reversing the polarity between the concrete reinforcement and the external electrode (copper mesh). The PERMIT test method is based on the concept of the ion migration through the concrete surface in the test chamber consisting of two concentric cylinders, the inner filled with sodium chloride solution, the outer containing deionised water. There are certain similarities between this method and the laboratory test method ASTM C1202 " Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration", mainly the potential difference of 60 V applied to enforce the ion movement. The preconditioning of the test surface, specified for the Whiting test requires the 1-hour vacuum treatment preceding an 18-hour saturation with the limewater at 60°C. There is no preconditioning procedure specified for the PERMIT test method. The repeatability of the test methods has not been determined. The major drawback of both test methods is the deposition of chloride ions in concrete.

MTO evaluation of in-situ test methods for concrete penetrability

In-situ test methods for determination of air and water penetrability, and intrinsic ion migration by resistivity measurement were selected for evaluation under realistic field conditions to assess their potential for use in performance-based specifications.

Prequalification criteria were: commercial availability, non-invasiveness, short duration of test, and ease of use.

Water sorptivity: Modifications of the Initial Surface Absorption Test (ISAT) standardized in the UK under BS 1881, carried out by the former MTO Research and Development Branch in co-operation with the University of Toronto, lead to design of a non-invasive test methods, with the apparatus attached by vacuum to horizontal and vertical concrete surfaces. Test procedure and interpretation of the test results were modified, as well. Initially, the possibility to apply this test for comparative evaluation of the effectiveness of concrete sealers was investigated. Laboratory trials, to determine if the test could be used to evaluate the sorptivity of concrete specimens made with different concrete mixes, followed. Extensive testing has been carried out in the field (Fig.1) to test the sorptivity of 30 MPa and 50 MPa concrete in deck slabs and barrier walls of new bridge structures. A series of tests was carried out at the same location to evaluate changes in sorptivity for concrete at different ages.

Fig.1 In-situ testing of water sorptivity, high-performance concrete barrier wall

Analysis of the results showed that testing done under controlled laboratory conditions on slab specimens had the potential to differentiate between sorptivities for mixes with different w/c ratio (0.60; 0.45 and 0.30), at different ages. At the same time the effect of the quality of the concrete surface (formed versus hand-finished) on sorptivity values was observed.

A series of field test results showed that the sorptivity test could differentiate between permeabilities of normal and the high performance concrete. At the same time, sets of test results for the same location (barrier wall or deck slab) had low repeatability, with a coefficient of variation of 30 percent. It has been concluded that, under field conditions, factors such as varying near-surface moisture content and concrete temperature, as well as quality of the surface finish quality, had significant effect on sorptivity and the variability of the measured values.

The test method was used by the MTO to comparatively evaluate the quality of the portion of a high performance concrete bridge deck surfaced by a bridge deck-finishing machine, with the outer edges finished by hand. The method was able to differentiate between the quality of the two finishes with the coefficient of variation not exceeding 20 percent [3)].

The standard laboratory test method which can be used as a reference for the in-situ sorptivity test method is ASTM C1585 “Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes”, originally adopted as an ASTM method in 2004. The test specimens are 50 mm thick discs, cut from 100 mm diameter moulded cylinders, or drilled cores. They are conditioned at 50 °C and 80%RH for 3 days with additional conditioning for at least 15 days in sealed containers to achieve an even moisture distribution within the specimen. The preconditioning procedure is designed to stabilize the internal relative humidity at 50-70%, the level claimed to be similar to relative humidity found near the surface in some field structures.

Gas permeability: The Torrent air permeability test method was selected for laboratory and field evaluation. The test equipment is commercially available, the method is non-invasive, and the test duration is short. The air pressure under the test chamber is reduced from the atmospheric pressure level (~1000mbar) to a few millibars and the rate at which the pressure increases to the value of 20 mbar (or the increase during 720 seconds, whichever comes first) is recorded. Based on the rate of pressure increase, the coefficient of air permeability of concrete is calculated.

A series of tests results were carried out under laboratory conditions on slab specimens with different water/cement ratios (0.60; 0.45 and 0.30), at different concrete ages. Analysis of test results showed that there was no clear relationship between air permeabilities and concrete of different w/c ratios. When tested in the field, test could not clearly differentiate between the permeabilities of normal and the high performance concrete. The air permeability tests had repeatability even lower than the sorptivity measurements, in the range of the coefficient of variation of 50 to 70 percent. Thus, it is possible that additional factors, other then those already listed with respect to sorptivity, may have had an effect on air permeability results.

As analysed in [4)] the mechanisms, which govern the movement of water and air in concrete are very different. Differences between gas and liquid permeability coefficients change from small, for highly permeable materials, to significant values, for materials of low permeability. The size and structure of the pore system has a significant impact on how the two media move in concrete. It is possible that the parameters of the Torrent test method (specifically the range of pressure increase) do not provide sufficient sensitivity for the measurement of low permeabilities.

The Torrent test method provided interesting results when used to comparatively evaluate the air permeability of formed concrete surface with different finishes [5)]. Sections of the same bridge barrier wall finished with and without a textile form liner were tested. Barrier walls cast with the normal 30 MPa concrete and the high performance 50 MPa concrete were selected for testing.
Figure 2 shows the test being done on a 50 MPa barrier wall, with a surface formed with a textile form liner (a portion surface formed without a liner is to the right; it has a much lighter colour).

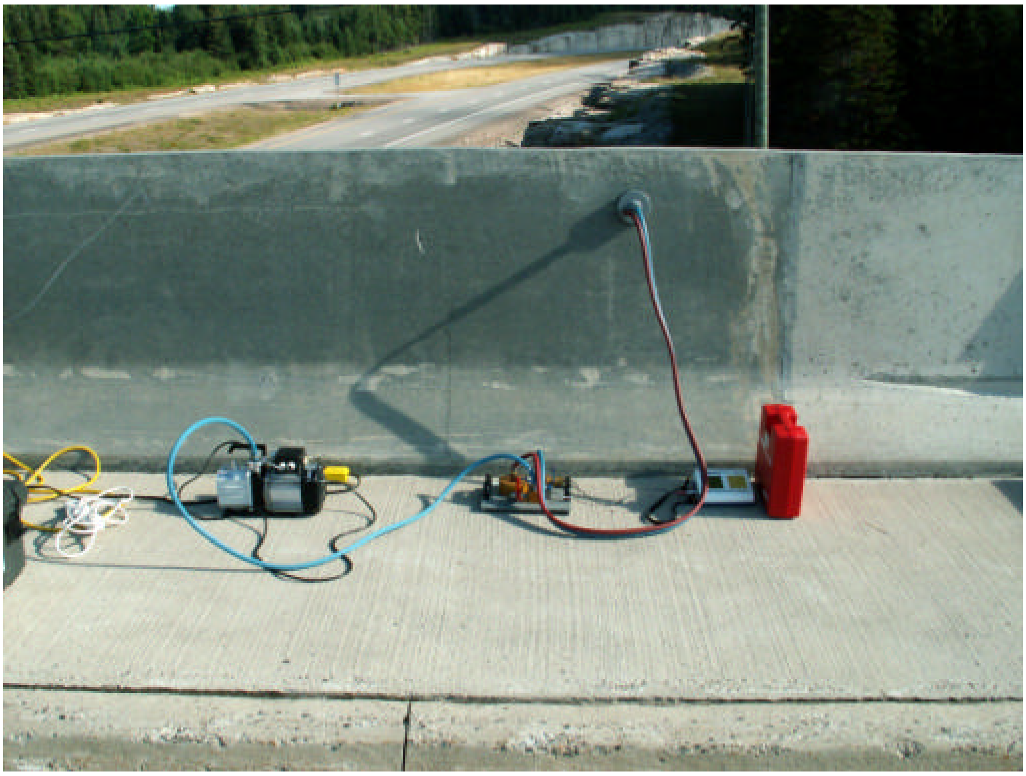

Fig. 2 Testing of Torrent air permeability, 50MPa concrete barrier wall

While the test did not measure different air permeability levels of the two types of surface finishes for the 50 MPa concrete, it showed a consistent difference in air permeability for the 30 MPa concrete. The surface of 30 MPa concrete formed with the liner had an air permeability 3 times lower than the surface of the same concrete formed without the liner. At the same time the air permeability of the surface of 30 MPa concrete formed with the liner was close to the permeability of the 50 MPa concrete surfaces. This leads to the conclusion that the surface of the 50 MPa concrete formed with or without the liner, had a pore system consistent with low air permeability, while the use of the form liner for the 30 MPa concrete lowered the permeability to air, thus improving the quality of the concrete surface.

Currently, there are no standard laboratory test methods for determination of air permeability of concrete, which could be used as reference for in-situ test methods. The CEMBUREAU test method, developed in France, has been frequently used as a non-standard laboratory test for air permeability of concrete. The optimized preconditioning procedure for this test, as described in [6)], involves determination of gas permeability for three different degrees, 0%, 30% and 70% of concrete saturation. The method recognizes different drying capacities related to strength classes of concrete, from ordinary to very high performance concrete (VHPC), spanning compressive strengths from 25 to 120 MPa. Drying curves have been established to select the duration of drying at 80±5°C for different concrete classes to achieve the desired level of concrete saturation.

Resistivity: Non-destructive, in-situ measurement of electrical resistivity of concrete was carried out using the Wenner technique. Several models of the Wenner resistivity probe are available commercially; the test is non-destructive and takes minutes to complete. In a four-electrode probe, four equally spaced contacts are made with the concrete surface, a small AC current is passed between the outermost two electrodes, and the resulting potential difference between the inner two electrodes is measured (Fig 3).

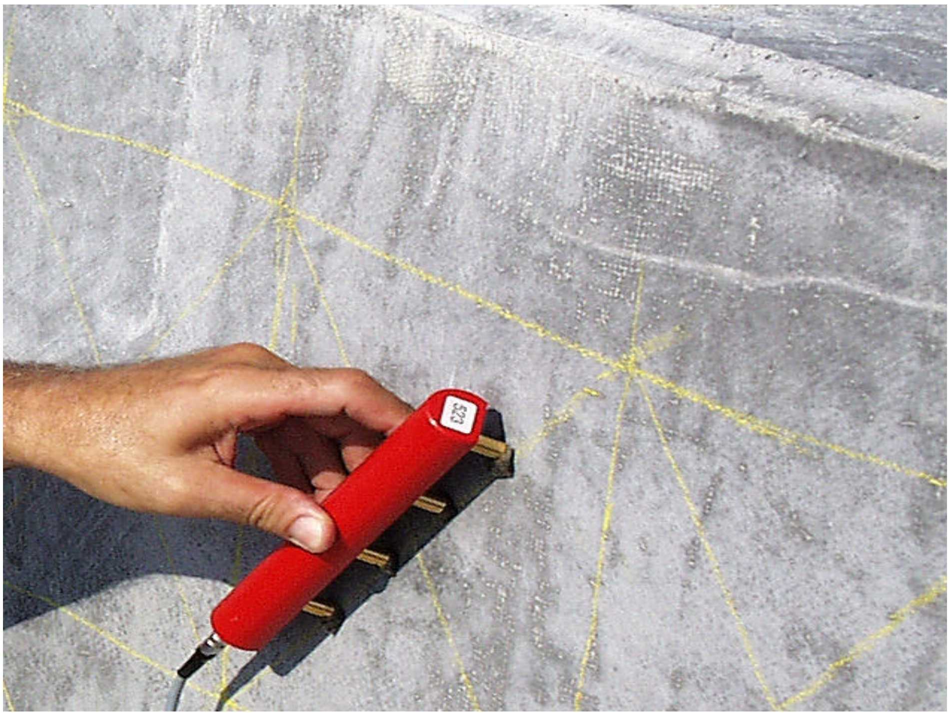

Fig. 3 Using a four-point Wenner probe to test in-situ resistivity

Resistivity is calculated as the proportion of the potential difference to the current flowing through concrete. In some commercially available instruments, the proportion of current flowing through the concrete to the nominal probe current can be measured. This index provides information about the reliability of the measurement; an accurate reading of concrete resistivity is expected when the ratio is at, or above, 90 percent.

The correlation between the resistivity measured using the Wenner probe and the laboratory test for the concrete's resistance to chloride ion penetration (ASTM C1202) was carried out during the ministry's evaluation of the in-situ resistivity test method. Resistivity, using the Wenner probe, was determined on 300x300x75 mm slabs, at the end of a 14-day moist curing period. As can be seen in Fig. 4, there is a good correlation between the Wenner probe resistivity and the laboratory test for the concrete's resistance to chloride ion penetration, which, in principle, measures the conductivity of concrete. The resistivity test can differentiate between mixes with different binder compositions at varying w/c ratios and is proportional to the total charge (in Coulombs) passed through the specimen using the ASTM C1202 test method.

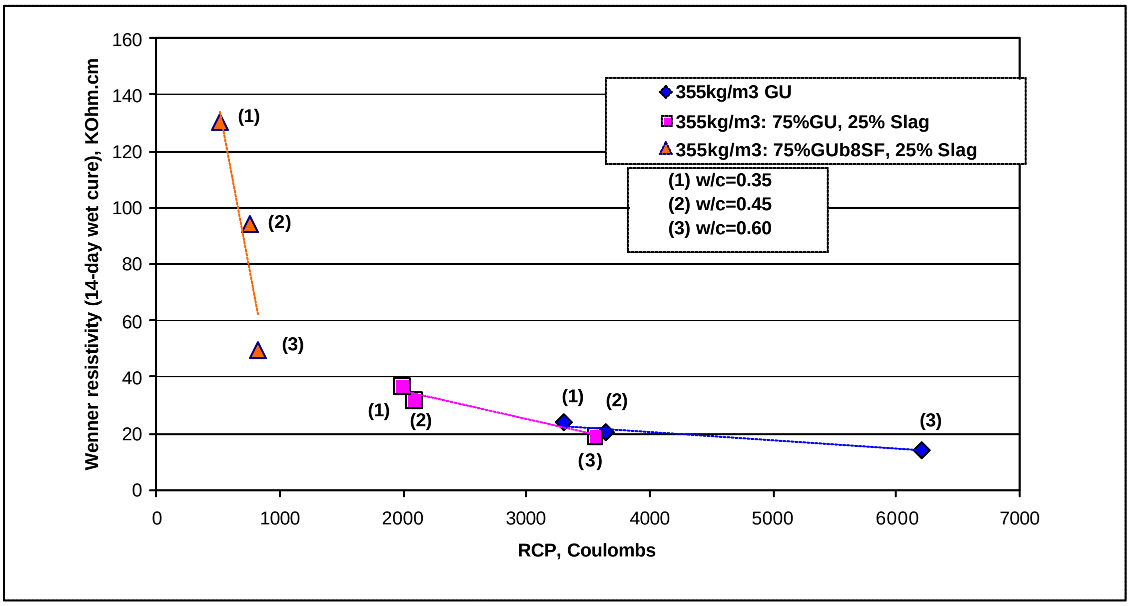

Fig. 4 Correlation between RCP (ASTM C1202) and the resistivity (Wenner probe)

Field testing of resistivity using the Wenner probe was carried out on 30 MPa and 50 MPa concrete structures, at varying concrete age, and on concrete surfaces with different finishes (formed, machine finished, hand finished). Resistivity test could clearly differentiate between normal and HPC, however the measurement was extremely sensitive to the near-surface moisture content in the tested concrete. Accurate readings were possible on the 30 MPa concrete, where the 90 percent current flow index was achieved most of the time. For the HPC, accurate measurements with the 90 percent current flow index were only possible shortly after construction. Later on, a pre-wetting (20 minutes or longer) of the concrete surface allowed for consistent readings for the 30 MPa, but was ineffective for the HPC.

The moisture content in concrete influences the electrical resistivity significantly: the resistivity can increase tenfold when the near-surface concrete moisture conditions change from fully saturated to dry. For a proper interpretation of the in-situ results, the near-surface moisture content has to be known and its effect accounted for by using correction factors, otherwise significant errors and misinterpretations in resistivity measurements may occur.

Currently, the only standard laboratory test method for determination of resistivity which can be used as a reference for the in-situ resistivity testing is the Florida DOT FM 5-578 (2004) “Florida Method of Tests for Concrete Resistivity as an Electrical Indicator of its Permeability”. The test method is limited to testing moist-cured concrete cylinders at 24±8 hours of concrete age. The work done at the University of South Florida [7)] to apply this test method for testing cores removed from a marine structure, showed that it took 30 days for a core kept in the moist room (100% RH) to reach the saturation required for stabilization of the resistivity measurement.

Summary and conclusions

A review, based on the most recent literature sources, shows that, in recent years, many in-situ test methods for determination of the concrete penetrability have been developed. Most of them are available commercially, and the test procedures are fast and easy to use in field conditions.

Three in-situ test methods were selected for laboratory and field evaluation by the ministry: the water sorptivity, the air permeability and the resistivity test methods. All test methods were non-invasive, easy to use in field conditions and allowing for sufficient number of tests to be carried out during a relatively short time allotted for testing on the construction site.

Based on the results of laboratory and field evaluation, the following conclusions can be drawn:

- When evaluated in laboratory, under controlled temperature and moisture conditions, the water sorptivity test method was able to measure a wide range of sorptivities for concretes made with varying water to cement ratios, at different concrete ages. The air permeability test, however, could not accurately differentiate between air permeabilities for the same variable concrete conditions. This situation can be explained by the difference between the mechanisms of water and air movement in concrete pores, but it is also possible that the parameters of the air permeability test method selected for evaluation did not provide sufficient sensitivity to measure low permeabilities. Resistivity test, carried out with the Wenner four-point probe on water-saturated specimens, was not only sensitive to varying water to cement ratios, but also to different binder compositions (partial replacement of cement with silica fume and slag). There was a good correlation between resistivity and the ASTM C1202 test for rapid determination of chloride ion permeability.

- Field evaluation of the selected in-situ test methods showed that the water sorptivity test could differentiate between permeabilities of normal and the HPC, while the air permeability test could not clearly differentiate between permeabilities of the two concretes. A high scatter of measured values was observed for water sorptivity and air permeability when tested under field conditions. The resistivity test could differentiate between resistivities of normal and the HPC, shortly after construction when the near-surface moisture content was high. The accuracy of the measurement was compromised when near-surface moisture content decreased to the level that could not facilitate the current flow at a value close to the nominal probe current. The near-surface moisture content, as well as temperature conditions, which cannot be controlled in the field, are the main reason for high variability of the test results.

- To ensure that the measurement process is in the state of statistical control, the measurement and adjustment for environmental variation has to be built into the test method. It is absolutely necessary to develop fast and reliable methodology for in-situ determination of the near-surface moisture content and temperature. Using this methodology, correction factors to normalize measured penetrability values need to be established.

- Building on the evaluation and in-house research completed so far, in-situ surface relative humidity test methods and electrical resistivity/conductivity test methods will be further investigated for potential of complementary use to determine the near-surface moisture content in concrete. Further testing using the MTO water sorptivity test method will be carried out to calibrate the sorptivity versus the near-surface moisture content.
  Other commercially available gas permeability test methods will be evaluated to test their sensitivity, specifically at the low end of the gas permeability range, for dense and very dense concretes.

- As part of the Ministry's Highway Infrastructure Innovation Funding Program proposals are solicited the proposals from universities and research organizations, for research projects to develop in-situ test methods for use in performance-based specifications.

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