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A Review of the Louisiana Department of Transportation's Structural Concrete Specifications in Response to House Resolution No. 309

by

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The Louisiana Department of Transportation and Development (DOTD) reviewed its materials specifications, particularly those pertaining to the surface resistivity of structural concrete. A comprehensive literature review was conducted on concrete durability, which found consensus on the fact that the ability to control concrete's permeability is essential to producing durable concrete. In addition, several test methods used to measure permeability or concrete's susceptibility to chloride ion penetration were reviewed for potential adoption in Louisiana's specifications for roads and bridges. Based on the literature search, surface resistivity remained consistently regarded as one of the most reliable and efficient methods to characterize concrete's chloride ion penetrability rating. Indeed, its reproducibility, ease of use, and rapid test time make it a highly desirable test method to adopt for the acceptance of structural concrete. A review on the bid pricing history of structural concrete since DOTD's implementation of the surface resistivity requirement determined that the cost differences are a

minimal 4 percent increase, with no reported delays. Lastly, a preliminary life-cycle cost assessment of a bridge deck assessed the expected long-term benefits from the adoption of the surface resistivity requirement. The results showed that when the produced concrete exceeds the surface resistivity requirement, the expected service life increases significantly and therefore reduces the frequency of major maintenance and repairs leading to a savings to the Department of 86 percent.

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Abstract

The Louisiana Department of Transportation and Development (DOTD) reviewed its materials specifications, particularly those pertaining to the surface resistivity of structural concrete. A comprehensive literature review was conducted on concrete durability, which found consensus on the fact that the ability to control concrete's permeability is essential to producing durable concrete. In addition, several test methods used to measure permeability or concrete's susceptibility to chloride ion penetration were reviewed for potential adoption in Louisiana's specifications for roads and bridges. Based on the literature search, surface resistivity remained consistently regarded as one of the most reliable and efficient methods to characterize concrete's chloride ion penetrability rating. Indeed, its reproducibility, ease of use, and rapid test time make it a highly desirable test method to adopt for the acceptance of structural concrete. A review on the bid pricing history of structural concrete since DOTD's implementation of the surface resistivity requirement determined that the cost differences are a minimal 4 percent increase, with no reported delays. Lastly, a preliminary life-cycle cost assessment of a bridge deck assessed the expected long-term benefits from the adoption of the surface resistivity requirement. The results showed that when the produced concrete exceeds the surface resistivity requirement, the expected service life increases significantly and therefore reduces the frequency of major maintenance and repairs, leading to a savings to the Department of 86 percent.

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Introduction

The latest infrastructure report card from the American Society of Civil Engineers (ASCE) has determined that the U.S. civil infrastructure is poorly maintained with insufficient funds to improve roadways and bridges throughout the nation, earning a D+ grade. From the nation's bridge infrastructure, more than one-fourth of all bridges are over 50 years old, the average design-life of a bridge. In addition, 38 percent of the nation's 616,087 bridges need repairs, of which 47,000 have been rated as structurally deficient by the Federal Highway Administration (FHWA). These compromised bridges are crossed by America's drivers 178 million times a day [1]. The state of Louisiana ranks second in the nation for the number of structurally deficient bridges based on bridge deck area [2].

The leading cause of premature degradation of bridges has been attributed to corrosion. The National Association of Corrosion Engineers (NACE) estimates that the annual direct cost of corrosion for highway bridges is estimated to be $13.6 billion. As infrastructure continues to deteriorate, the cost of maintenance and repair increase accordingly, where the backlog of rehabilitation projects for the nation's bridges has been estimated at $123 to $171 billion [1, 2]. As such, there is a pressing need to design and construct more durable civil infrastructure. With concrete structures in particular, this can be achieved by giving special attention to concrete's transport properties. It is well recognized that concrete's durability is controlled by permeability or diffusivity, which measure the ability of ions and fluids to move through the material.

When considering permeability in concrete, the properties of portland cement concrete (PCC) relating to chloride ion penetration are of particular concern to owners, designers, and materials engineers. The penetration of chloride ions can negatively affect the durability of PCC pavements and structures by (a) corroding the steel reinforcement, (b) affecting the chemical/electrical balance within concrete, and (c) inducing premature deterioration in concrete [3]. Thus, it is imperative to develop concrete that strongly resists chloride penetration to extend the service life of PCC pavements or bridge structures. In order to effectively measure chloride permeability, electrical test methods have been developed to provide a rapid indication of concrete's resistance to the chloride penetration including the ASTM C1202/AASHTO T 277 rapid chloride permeability test (RCPT), the AASHTO T 358 surface resistivity test, and the AASHTO TP 119/ASTM C1760 bulk resistivity test [4, 5, 6, 7, 8]. These test methods have been developed by correlating the electrical conductance of concrete with long-term chloride ponding exposures such as those described in AASHTO T 259 or ASTM C1556 [9, 10].

As a state highway agency (SHA), DOTD aims to develop concrete materials specifications that can deliver higher performance and longevity. Surface resistivity measurements have been required by DOTD specifically for structural concrete applications since 2013, and the 2016 edition of DOTD's Standard Specifications for Roads and Bridges includes a surface resistivity requirement as a pay item [11]. Besides Louisiana, Florida and Kansas require surface resistivity results for certain classes of structural concrete mixture design approvals [12, 13]. In addition, at least 12 other departments of transportation (DOTs) are in the process of adopting similar requirements for the acceptance of mixture designs.

Literature Review

Concrete, the most widely used construction material in the world, is a non-homogenous, composite material made from a mixture of portland cement, sand, water, and coarse aggregate (usually consisting of crushed limestone or gravel). The hydrated cement paste that binds the aggregates together consists of four principal solid phases: calcium silica hydrate, calcium hydroxide, calcium sulfoaluminates hydrates, and unhydrated clinker grains. However, hydrated cement paste is considered a porous material as it can contain several types of voids. Air voids are commonly found in a cement paste due to small amounts of entrapped air, and their sizes typically range from 50 to 200 microns. Capillary voids represent the space not filled by the solid components of the hydrated cement paste, and their sizes usually range from 10 nanometers to 1 micron [14]. It is through these voids where concrete is susceptible to the ingress and movement of water and harmful ions from the environment that can damage concrete's durability.

Concrete Durability

The American Concrete Institute defines the durability of PCC as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration [15]. These deterioration processes can be categorized as either physical or chemical. While water is undoubtedly a crucial component in the production of concrete, it can also cause physical degradation such as freeze-thaw damage, and act as a vehicle for the transport of harmful ions that cause chemical degradation in hardened concrete. In fact, exposure to acidic water or environmental conditions can break concrete's state of equilibrium and destabilize its cementitious products [14].

Concrete's ability to resist chemical or physical processes of degradation depends on its transport properties (i.e., its ability to limit fluid or ion penetration), which can be measured through permeability, absorption, or diffusivity [16]. Permeability is defined as the ease at which a fluid flows into and through the concrete matrix under a pressure differential. A high water permeability means the concrete is more vulnerable to acid attack, undesired expansive chemical reactions within concrete, and corrosion of the reinforcing steel. Absorption refers to the uptake of a fluid in concrete through capillary action. Thus, a higher absorption is indicative of concrete's susceptibility to water penetration. Lastly, diffusivity is defined as the rate of diffusion, which measures the rate at which a particular substance (e.g., ions, atoms, or molecules) is transferred from an area of high concentration to an area of low concentration. In particular, many practitioners are concerned with the rate of chloride diffusion into concrete (hereby referred as chloride ion penetration) due to its effect on durability. In addition to the steel reinforcement's corrosion, there is also the potential of calcium oxychloride ($Ca(OCl)_2$) attack caused by chlorides in deicing salts, leading to premature joint deterioration and ultimately failure [17]. In this section, the factors that affect permeability and the methods to quantify permeability in concrete are discussed.

Factors Affecting Permeability

Effect of Water-to-Cementitious Materials Ratios

The most significant factor affecting permeability is the water-cementitious materials (w/cm) ratio. Lower w/cm ratios decrease permeability, as long as the concrete mixture is consolidated properly. This is because the cement hydration reaction only consumes a certain amount of water from the total mixing water used. Once concrete is exposed to environmental conditions below 100 percent relative humidity, a considerable amount of the remaining free water evaporates as the concrete dries and creates void spaces that form capillary pores. When less evaporable water is present within the mixture after drying, the capillary porosity and pore size distribution decreases and therefore a lower water permeability is attained [14].

Effect of Cementitious Materials

The choice of cementitious materials will affect the permeability of the resulting concrete as certain combinations will produce a denser and thus less permeable paste structure. Supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume have been reported to reduce the water penetration in concrete when properly designed. These materials are used for partial cement replacements, and typically feature pozzolanic properties, which are highly desirable. A pozzolan is a silicate or aluminate-based material that reacts with the calcium hydroxide (the most soluble hydration product in the cement paste) to form additional cementitious materials with stronger binding properties.

Therefore, the reduction in permeability by using SCMs can be attributed to a number of reasons, such as their pozzolanic activity (that leads to stronger and thinner interfacial transition zone (ITZ)), pore refinement (decreased pore sizes and reduced pore connectivity), filler effect (densification of matrix), and possible increase of nucleation sites for precipitation of hydration products (as seen in case of fine particles of pozzolan). More finely ground and processed SCMs exhibit improved properties as compared to unground and unprocessed SCMs. This is because the unground and unprocessed SCMs may have higher porosity, contain bigger particles, and may contain impurities such as fibers [18, 19, 20].

Effect of Aggregates

By volume, coarse and fine aggregates make up the largest components by volume of PCC. Depending on the type and composition of aggregates (including mineralogy), they can be inert or react with the cement in the presence of moisture, leading to the undesired formation of expansive products (i.e., alkali-aggregate reactions) that lead to the deterioration of concrete. In addition, aggregate exposed to the outside environment (in exposed aggregate concrete (EAC)) can negatively affect the surface microstructure of concrete, resulting in decreased durability [21].

Dense aggregates are generally inert and they disconnect the pore spaces and thus increase the path of liquid movement in concrete. As a result, water permeability of concrete decreases [22]. On the other hand, porous aggregates increase the water permeability of concrete [23, 19, 24]. This is because such porous aggregates enhance the bulk pore connectivity in concrete. A notable exception includes lightweight aggregates typically made of expanded shale, clay, or slate. Despite having higher absorption, lightweight aggregates can help reduce the bulk water permeability of concrete due to the combination of improved ITZ between the aggregate-mortar matrix and a more unified microstructure compared with concretes with normal weight aggregates [25].

Mehta and Monteiro noted that the role of water-to-cementitious materials ratio is important with respect to ITZ properties [14]. Depending upon the aggregate characteristics (limestone versus gravel), it is possible to have differences in the size of the ITZ. It is a well-known fact that the ITZ for concrete containing limestone coarse aggregate is significantly smaller than the ITZ for concrete containing gravel coarse aggregate. Increasing the ITZ will lead to a more permeable concrete [14].

Measuring Transport Properties – Fluids

Previously, practitioners and designers were mostly concerned with the strength characteristics of concrete, as it was deemed as the single most important parameter concerning concrete construction. However, as infrastructure continues to deteriorate over time, significant attention has also been given to concrete's permeability or resistance to chloride ion penetration. The mechanisms by which chloride ions or harmful agents usually penetrate concrete are through either capillary absorption or diffusion.

Capillary absorption is the main transport mechanism for water in concrete materials. It describes the movement of water through concrete's pore structure, driven by moisture gradients. Typically, this mechanism would not transport chlorides or harmful agents by itself to the level of the steel reinforcement unless a highly porous, poor-quality concrete was used or a shallow concrete cover was used to protect the steel reinforcement [26]. However, it is a useful property to measure as it determines an unsaturated concrete's susceptibility to water penetration in the absence of a pressure head, given that hydraulic heads are rarely maintained on highway structures [27]. Two main test methods are used to assess concrete's water absorption properties: namely the water sorptivity test and the water absorption by boil test.

Water Sorptivity Test (ASTM C1585)

ASTM C1585 describes a standardized procedure to measure the rate of absorption (sorptivity) of water by hydraulic cement concretes [28]. This is achieved by measuring the increase in the mass of a concrete specimen resulting from absorption of water over a period of time (8 days). The concrete sample is conditioned in a controlled environment at a standard relative humidity to induce a consistent moisture condition in the capillary pore system. The initial absorption (within the first few hours) and the secondary absorption (over several days) are both of interest since the rate of absorption at the concrete surface differs from the rate of absorption from the interior. In unsaturated concrete, the rate of ingress of water or other liquids is largely controlled by absorption due to capillary rise. To facilitate the interpretation of the test results, only one surface of the concrete specimen is exposed and immersed in water [28].

Water Absorption by Boil Test (ASTM C642)

The water absorption by boil test measures the density, absorption, and voids in hardened concrete [29]. This test method differs from the previously mentioned water sorptivity test as it aims to determine the effective porosity of concrete and not its rate of capillary suction. Compared to other test methods for permeability, the boil test is simple to perform and does not require any specialized equipment. The test estimates the volume of permeable pore space in a hardened concrete specimen by determining the hardened concrete's density in different states (i.e., oven-dry, saturated, saturated-boiled) [30]. A higher volume of permeable pore space indicates less durable concrete. Thus, a limit on the volume of permeable pore space can be specified depending on the application. For example, for portland cement concrete pavements, a volume of permeable pores less than or equal to 12 percent is desirable for long-term durability [30]. However, this test method tends to underestimate the total porosity, and thus the results from the boil test need to be interpreted accordingly [31].

Water Penetration (EN 12390-8)

This test procedure is covered under the European standard BS EN: 12390-8, "Testing hardened concrete—Part 8: depth of penetration of water under pressure" [32]. Unlike the previous test methods, this procedure aims to measure the transport properties of concrete under hydrostatic pressure. The test method requires cylindrical specimens to be oven-dried 221°F (105°C) until reaching a constant mass. The specimens are then coated with epoxy on the circular side to prevent water penetration from the side during the test. A pressure of 72 ± 7 psi (500 ± 50 kPa) is subsequently applied to the specimens at a pressure head of 300 ft. (92.5 m). The pressure is maintained for 72 hours, after which the specimens are split in half and the maximum depth of water penetration is measured. The test setup, along with the tested and split concrete samples (with water depths marked with black lines), is shown in Figure 1.

Figure 1. Water permeability test set up to EN 12390-8 and tested concrete samples marked with water fronts to indicate depth of penetrated water [33]

Measuring Transport Properties – Ions

The main transport mechanism by which ions penetrate concrete is through diffusion, which is the principal pathway in which chlorides can infiltrate concrete to the level of the steel reinforcement. The rate of diffusion is controlled by the physical characteristics of the capillary pore structure, as well as the pore solution's ionic strength, which is usually expressed as a diffusion coefficient based on the types of ions present. It is important to note that a portion of the chloride ions react with the cementitious matrix by either becoming chemically or physically bound, which can produce deleterious reactions (such as calcium oxychloride attack) but also slow down the rate of diffusion [27]. Three major test methods are used to characterize the transport properties of chloride ions in concrete: the salt ponding test, the rapid chloride permeability test, and electrical resistivity.

Salt Ponding Test (AASHTO T 259)

This test method measures concrete's resistance to chloride ion penetration after subjecting the specimens to continuous ponding with a 3 percent sodium chloride solution [9]. AASHTO T 259 exposes concrete directly to an environment with a high concentration of chloride ions up to 90 days, to measure the absorbed chloride ion content throughout the depth of the concrete specimen. A chloride profile is subsequently developed, illustrating the average and maximum absorbed chloride ion values calculated at certain depth intervals. However, it is important to note that this test method's duration may not be applicable to high-quality concretes, as the 90-day exposure period may not be enough to develop a chloride profile due to its limited penetration. In such circumstances, it is recommended that the test duration is extended up to 180 days to address this problem [34, 35]. It is also worth mentioning that the long testing duration makes it impractical for an SHA to require concrete materials that limit chloride ion penetration based on the described test method.

Bulk Diffusion (ASTM C1556)

This test method is used to determine the apparent chloride diffusion coefficient for hardened cementitious mixtures [10]. The apparent chloride diffusion coefficient is a parameter that describes chloride transport in concrete. It is calculated from the acid-soluble chloride profile data obtained from saturated specimens exposed to chloride solutions (165g/L for at least 35 days extendable up to 90 days or longer for high performing concretes), albeit without a correction for chloride binding. Chloride binding refers to the loss of chloride ions during a chemical reaction with the surrounding cementitious products. Despite its lack of chloride binding correction, this test method provides a useful indication of concrete's susceptibility to chloride ion penetration. Similar to AASHTO T 259, however, the test method's main drawback is that a relatively long testing period is required to complete this test, which can make it impractical for routine quality control/quality assurance purposes [9].

Rapid Chloride Permeability Test (AASHTO T 277/ASTM C1202)

The rapid chloride permeability test (RCPT) is a standardized test method to determine an electrical indication of concrete's ability to resist chloride ion penetration that has been widely accepted for assessing the durability of concrete [5, 4]. This test method uses the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions, and its results are applicable to concretes that have been correlated to the long-term chloride ponding procedures such as those described in AASHTO T 259 [9]. The chloride ion penetrability rating is thus based on the charged passed (in Coulombs), as shown in Table 1.

Table 1. Chloride ion penetrability rating based on the RCPT results [4]

Chloride Ion Penetrability	Charge Passed (Coulombs)
High	> 4,000
Moderate	2,000 – 4,000
Low	1,000 – 2,000
Very Low	100 – 1,000
Negligible	< 100

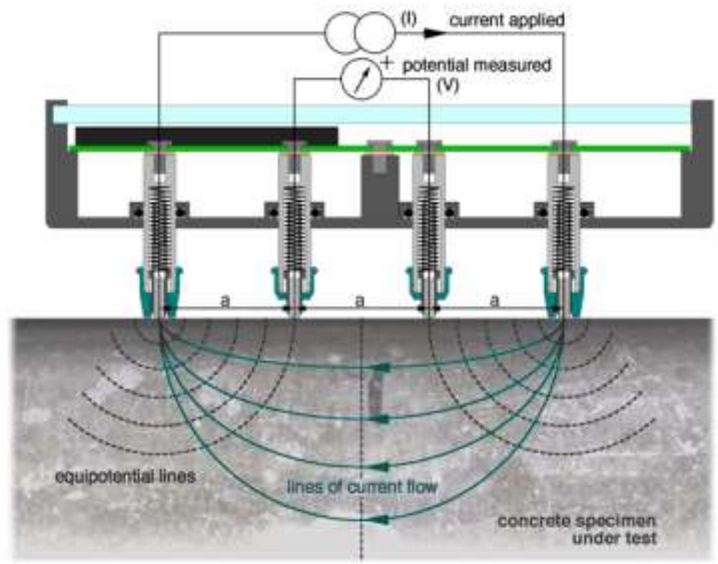
Although RCPT is a widely accepted test method, it also has notable shortcomings that are worth mentioning. The test method in itself is an indirect measurement of chloride ion penetrability since it is an electrical test. While ion diffusion depends on the microstructure and chemical binding capacity of the cementitious matrix, electrical conductivity measurements depend on concrete's microstructure and the pore solution chemistry. Thus, it is important to note that this test method is not applicable for concretes that contain certain corrosion inhibitor admixtures added directly into the fresh concrete mixture. This is due to the fact that some corrosion inhibitors such as calcium nitrite can increase the pore solution's conductivity, and thereby produce misleading results.

While RCPT drastically reduces the testing time from the ponding tests (which can last up to one year), it is still considered slow and time-consuming, destructive, prone to errors caused by sample heating, and fails to adequately capture some features associated with supplementary cementitious materials (SCMs). However, SHAs have extensively utilized this test, and have correlated test results to local field performance. As such, the ASTM C1202 test results have been applied by SHAs to other areas of concrete permeability by considering that a slower transport of chloride ions can also slow down or mitigate the ingress of other water-borne aggressive agents.

Surface Resistivity (AASHTO T 358)

AASHTO T 358, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration, is the standard test method for determining surface resistivity (measured in kΩ-cm or kΩ-m) as an indication of resistance to chloride ion penetration, using a Wenner array probe [6]. The test method requires a current to be applied across the outside two probes while measuring the resistance (potential) with the inside two probes [36]. This procedure is illustrated in Figure 2.

Figure 2. Schematic of the surface resistivity meter [36]



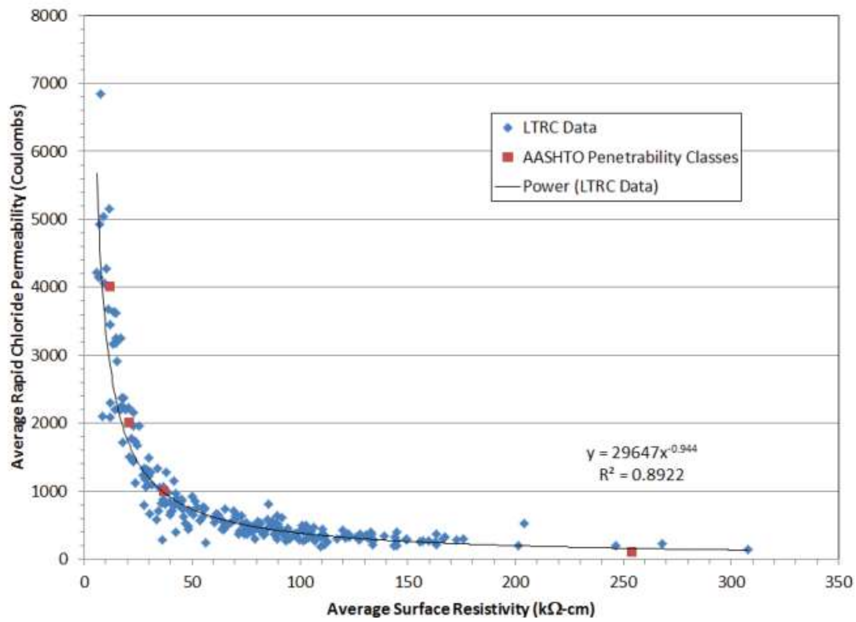
The test is rather simple and easily repeatable as indicated by Icenogle and Rupnow with a reported single operator and multi laboratory coefficient of variation of a single test results to be 2.2 percent and 3.9 percent, respectively [37]. The surface resistivity measurements are then compared with Table 2 to obtain the concrete sample's chloride ion penetrability. It is important to note that the sample dimensions, ambient temperature, as well as the Wenner probe's tip spacing can influence the results. For this reason, these variables must be consistently verified to ensure that the test results can be characterized by Table 2. Otherwise, correction factors need to be applied.

Table 2. Chloride ion penetration rating for the surface resistivity test method [6]

Chloride Ion Penetrability	Surface Resistivity Test	
	4" x 8" Cylinder (kΩ-cm)	6" x 12" Cylinder (kΩ-cm)
High	< 12	< 9.5
Moderate	12 – 21	9.5 – 16.5
Low	21 – 37	16.5 – 29
Very Low	37 -254	29 – 199
Negligible	> 254	> 199

Electrical resistivity measurements have the potential to provide a performance-based evaluation of hardened concrete. Past and recent efforts have correlated surface resistivity to chloride ion penetrability, as shown in Figure 3 [38, 39, 40, 41, 42]. In addition, Jenkins completed a study for the Kansas Department of Transportation (KDOT) and noted that the surface resistivity test method correlates well to ASTM C1202, confirming previous study findings [43].

Figure 3. Relationship between surface resistivity and rapid chloride permeability at all ages for all samples tested [38]



Several factors affect electrical resistivity test results. AASHTO T 358 and Florida Department of Transportation's (FDOT's) test procedures (FM 5-578) indicate that calcium nitrite, lime water curing, and the temperature during testing are all significant factors [44]. In addition, studies have found that sample geometry, aggregate size, moisture conditions, and probe spacing can also influence the electrical response [40]. Kessler et al. confirmed that curing conditions and the surface moisture affect the results as well as the alignment of the meter while Morris et al. noted the effects of aggregate type as well as size. In addition to calcium nitrite and aggregate type and size, Rupnow et al. also found that concrete age affects rapid chloride permeability significantly after conducting a ruggedness study [41, 42, 45].

Ramezanianpour et al. reported a good correlation between water penetration measured by EN 12390-8 and SR measured using the four-point Wenner array probe technique [46]. These correlations are shown in Figure 4 and Figure 5.

Figure 4. Relationship between EN 12390-8 water penetration and SR for plain mixtures (top) and for mixtures containing metakaolin (bottom) [46]

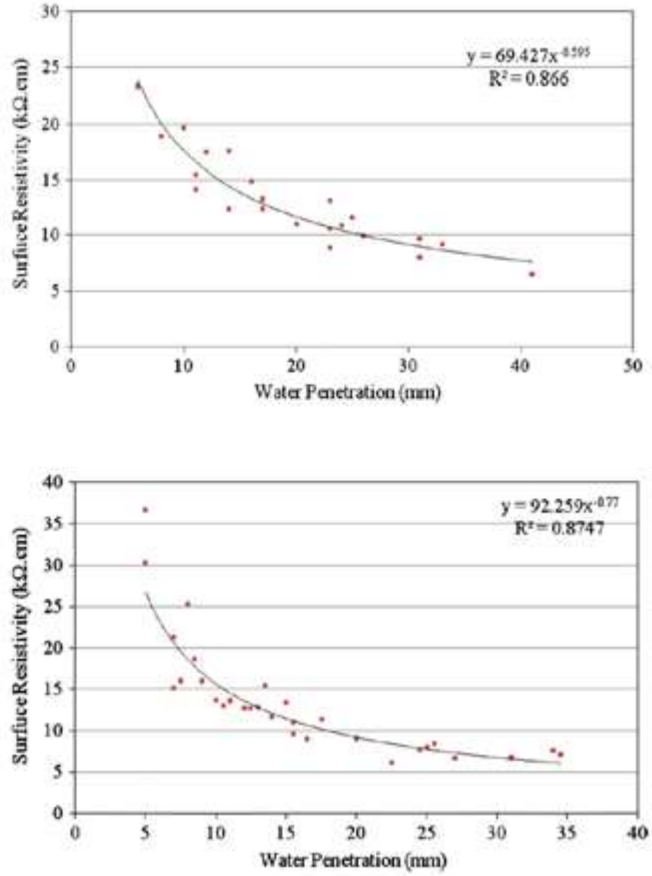
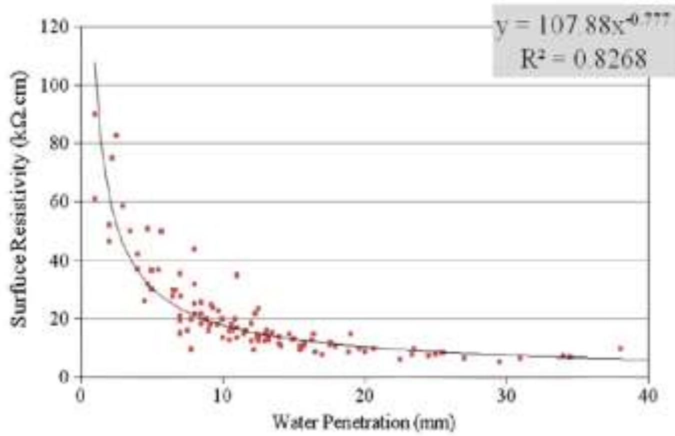


Figure 5. Relationship between EN 12390-8 water penetration and SR for all mixtures [46]



It was observed that a good correlation between EN 12390-8 water penetration and SR was obtained with the same type of cementitious materials (with R^2 = 0.866 and 0.875), and the correlation coefficient reduced (to R^2 = 0.827) when samples with different cementitious materials were used. The probable reason behind this is that the SR test depends on both microstructure and pore solution of concretes, while the water penetration test depends only on microstructure [46]. In the concrete samples with different cementitious materials, the chemical compounds of pore solution are changed and various level of conductivities for pore solution are achieved. Therefore, the resistivity of concrete samples changes and the correlation between the results of SR and water penetration is reduced. However, in samples made with the same cementitious materials and as a result of the similar chemical compounds of pore solution, the results of both tests are more sensitive to microstructure of concretes and a good correlation between the results can be achieved [46].

Bulk Resistivity (AASHTO TP 119)

AASHTO TP 119, Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in Uniaxial Resistance Test, is a method used to determine the bulk electrical conductivity of concrete. To perform the test, a current is applied through the interconnected pores and voids through the sample and the resistance to the current is measured. Ghosh et al. demonstrated that the bulk resistivity of concrete correlates well with surface resistivity measurements [47]. The advantages of using bulk electrical conductivity over surface resistivity include potential shorter testing time and the ability to test the entire concrete cylinder [7].

Electrical Resistivity Specifications

Currently, Florida and Kansas require surface resistivity test results for certain classes of structural concrete mixture design approvals, while Louisiana utilizes surface resistivity as a pay item for structural concrete [12, 13, 11]. In addition, at least 12 other state departments of transportation (DOTs) are in the process of adopting surface resistivity requirements for the acceptance of mixture design approvals.

Corrosion in Reinforced Concrete

The corrosion of reinforcing steel is one of the main causes of structural degradation and failure of a concrete structure. The corrosion of steel reinforcement can be due to multiple processes including: chloride ingress, carbonation, or other changes in the local area of the embedded steel [48]. For corrosion to occur, there must be an anode, a cathode, and a continuous conductive medium. The anode and cathode are the locations on the reinforcement steel where the oxidation and reduction reactions occur, respectively.

Concrete's pore solution is a conductive medium that ionically connects the anode and the cathode [49]. However, its high alkalinity (usually with a pH greater than 12.5) can protect the steel reinforcement from corrosion. This is achieved by providing a "passive film," which consists of a thin corrosion film that forms on the steel's surface when oxygen is present. The passive film is in equilibrium with the surrounding environment and slows down the corrosion reactions. Once the chloride concentration at the surface of the rebar has reached a critical concentration, the passive layer breaks down and the corrosion reactions take place [15].

To estimate the service life of a reinforced concrete structure, the rate of chloride ingress becomes a key parameter, as it would control the corrosion initiation and propagation period. The initiation period is the time required for chloride ions to infiltrate into the concrete and reach a critical concentration at the surface of the embedded reinforcement, which could initiate corrosion. Once corrosion has been initiated, the rate of corrosion will determine how long the structure may remain in service. This period is known as the propagation period, which corresponds to the time it takes for the steel reinforcement to deteriorate until the structure fails [50]. For this reason, it is imperative to provide an adequate concrete cover thickness, as well as a high-quality concrete material with high resistance to chloride ion penetration.

DOTD's strategy to provide long-term durability and extended service life for structural concrete applications includes the following measures:

- Use high performance concrete with a high resistance to chloride ion penetration
- Use the most economical steel reinforcement material (black steel)
- Provide increased concrete cover exceeding the minimum AASHTO requirements
- Control crack widths by providing distribution reinforcement
- Specify water curing requirements to minimize concrete cracking

Objective

The objective of this report is to respond to the inquiries stated in House Resolution No. 309. Specifically, this report addresses the reliability of the surface resistivity test method, the cost-effectiveness of the method for developing concrete, construction time period requirements, and the expected long-term benefits resulting from the implementation of the surface resistivity specifications.

Scope

The scope of work includes a review of the concrete materials specification developed by DOTD. Specifically, the material requirements pertaining to the surface resistivity of structural concrete are examined. The effectiveness of the test method and the implication of requiring such a test method for the approval of structural concrete for transportation infrastructure is discussed.

Methodology

DOTD implemented the surface resistivity test method for acceptance of structural concrete in the 2016 edition of DOTD's Standard Specifications for Roads and Bridges. In response to the House Resolution No. 309, this document discusses the reliability of the test method for measuring resistivity, the cost-effectiveness of the method for developing concrete, construction time period requirements, and a life-cycle cost assessment as a result of the specification changes.

Reliability of the Test Method

An overview of the accepted test methods to measure concrete's durability properties is discussed herein. Within those test methods, emphasis was placed on electrical test methods as they are able to assess concrete's transport properties through the ionic movement within the cement paste. In addition, surface resistivity (a standardized test method by AASHTO and recently ASTM) was compared with other accepted test methods to measure concrete's resistance to chloride penetration in terms of the significance of test results, factors affecting test results, duration, and reproducibility based on bias and precision statements.

Cost-Effectiveness of the Method for Developing Concrete

Given the recent change in specifications requiring an end-result-based criteria through target surface resistivity values, the cost-effectiveness of making concrete that meets the current specifications was examined with respect to bid pricing data. A three-year dataset prior to the surface resistivity requirement and a three-year dataset after its implementation was evaluated to determine the effect of the test method on construction costs.

Construction Time Period Requirements

Construction practices and durations for structural concrete were examined before and after the surface resistivity specification was implemented. Therefore, historical data was reviewed and comparisons were made with projects of similar size and construction conditions to determine if any delays were caused by the new surface resistivity specification.

Life-Cycle Cost Assessment (LCCA)

A life-cycle cost assessment was conducted to determine the long-term economic impact of the new surface resistivity specification for concrete bridge decks, over an analysis period of 100 years. In this analysis, the total economic cost of a hypothetical concrete bridge project with a 44-ft. wide deck (accommodating two 12-ft. lanes and two 10-ft. shoulders), with a span length of 100-ft. and a deck thickness of 8 in. was evaluated. This was achieved by examining the initial construction costs, as well as the costs from major maintenance activities that DOTD employs to rehabilitate bridge decks. It is important to note that the analysis excludes the work zone user costs and minor rehabilitation activities such as joint sealing. In addition, the analysis considered typical mixture designs used in concrete bridge structures before and after the surface resistivity specification was required by DOTD. All design and construction activities were assumed to be the same for both scenarios.

The Net Present Value (NPV) represents the discounted monetary value of expected net benefits, and was calculated using the following formula:

$$NPV = Initial\ Cost + \sum_{k=1}^{N} Rehab\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] \quad (1)$$

Where,

i = discount rate, and n = the number of years into the future.

The cost estimates were expressed in constant dollars, which reflect dollars with the same or constant purchasing over time. A real discount rate was used to reflect the true time value of money with no inflation premium, and it was selected to be at 4 percent per FHWA's guidelines [51]. Major maintenance activities for reinforced concrete are scheduled based on the concrete's deck service life predictions. They are set to begin when the corrosion process from the steel reinforcement is in its initiation period. DOTD's bridge deck preservation program usually involves hydro demolition of the damaged surface layer, and the installation of a latex-modified concrete (LMC) overlay to extend the deck's service life for an additional 25 years. Based on the Department's historical bid pricing data, the average cost for hydro demolition is $47.73 per square ft.

of deck area consisting of 1 in. of thickness (referred as $47.73/SF-in). In addition, the costs to install a LMC overlay averages around $10 per square ft. of deck area consisting of 1 in. of thickness ($10/SF-in) for moderate volume quantities (155,000 SF-in).

Discussion of Results

Reliability of the Surface Resistivity Test Method

DOTD implemented the surface resistivity specification requirement in a bid to move from prescriptive specifications towards performance-based specifications for materials. Indeed, prescriptive specifications limit innovation (since SHAs require specific requirements for mixture proportioning), and it places the performance risk entirely on the owner. In contrast, performance-based specifications allow industry to design mixtures that address specific performance requirements, in which case minimizing chloride penetrability is a major concern. This shifts the responsibility for performance from the SHA to the contractor, and provides an opportunity for innovation.

Based on the literature review, it was determined that surface resistivity is the most suitable test method to be implemented by an SHA that measures the transport properties of concrete, specifically regarding the chloride ion penetrability. This is largely due to the fact that it correlates very well with RCPT test results, which used to be the most widely accepted test method by SHAs, at an increased precision.

The RCPT precision statement test states that the single operator coefficient of variation of a single test result has been found to be 12.3 percent. Therefore, the results of two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by more than 34 percent [4]. In contrast, the single-operator precision from the surface resistivity test method is reported to be significantly lower, at 4.3 percent. This means that two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by more than 12.1 percent of their averages [6].

With respect to multi-laboratory precision, the multi-laboratory coefficient of variation of a single test result from the RCPT has been found to be 18 percent. This means that two properly conducted tests in different laboratories on the same material should not differ by more than 51 percent [4]. On the other hand, the multi-laboratory coefficient of variation of a single test result is reportedly 11.5 percent for the surface resistivity method. Hence, the results of two properly conducted tests in different laboratories on the same material should not differ by more than 32.5 percent of their averages [6].

While there are shortcomings to the RCPT method with which surface resistivity has an excellent correlation, these shortcomings are only applicable to low-quality concretes (which should not be used for bridge decks in any case), or testing at high temperatures (which is not a concern when testing in a laboratory environment). In addition, misleading results have been reported when corrosion inhibitors such as calcium nitrite are directly admixed into the fresh concrete paste, yet this is seldom used in most structural concrete applications. If the situation merits the use of a corrosion inhibitor admixture such as calcium nitrite directly into the concrete mixture, the ACI recommends testing for the concrete mixture with and without the corrosion inhibitor admixture for reference [15].

The other test methods described in the literature take significantly longer periods of time to conduct, and are costlier or impractical to implement for quality assurance and acceptance of concrete mixtures. In addition, the Louisiana Transportation Research Center performed a cost-benefit analysis that showed that implementation of the surface resistivity method saved DOTD approximately $101,000 in personnel costs within the first year, dramatically decreasing the cost per lot tested from $224 using ASTM C1202 to $13 using surface resistivity. Similarly, the adoption of surface resistivity was estimated to save contractors about $1.5 million in quality control costs a year, dropping costs per sample from $506.00 using ASTM C1202 to $8.65 using surface resistivity [52].

Cost-Effectiveness of the Method for Developing Concrete

The authors reviewed bid tabulations for two three-year periods including the three years prior and after implementation of the surface resistivity test method. The results are shown in Table 3. Note that the Class AA(M) concrete bid item is the previous structural concrete bid item while the Class A1 is the bid item containing surface resistivity requirements.

The results showed that, for the deck and slab span Class A1 concrete, there was no increase. A 36 percent increase was found for the Class A1 bent cap and column concrete compared to the Class AA(M) concrete, while a 23 percent decrease was found for the A1 footing concrete compared to the Class AA(M) concrete. The calculated average percent difference was calculated to be about a 9.8 percent increase.

Table 3. Bid cost comparison for Class AA(M) and Class A1 structural concrete

Bid Item	Average Bid Cost per CUYD ($)	Percent Increase	Quantity (CUYD)	Weighted Average Cost ($)
Class AA(M) Concrete	1,100	N/A	179	N/A
Class A1 Concrete (Slab Span)	1,100	0%	494	543,400
Class A1 Concrete (Deck)	1,100	0%	633	696,300
Class A1 Concrete (Bent Cap)	1,500	+36%	188	282,000
Class A1 Concrete (Column)	1,500	+36%	54	81,000
Class A1 Concrete (Footing)	850	-23%	137	116,450
AVERAGE	1,142	+4.0%	301.2	$ 343,830

The weighted average was calculated by multiplying the average quantity by the average bid cost and then summing them up ($343,830) and dividing them by the average quantity (301.2 CUYD). The weighted average is equal to about a 4 percent increase in cost for the Class A1 compared to the Class AA(M) concrete.

The results presented here show that the cost increase is negligible at a weighted average of about 4 percent.

Construction Time Period Requirements

The authors reviewed contracts for a period of three years prior to the implementation of surface resistivity and compared them to contracts for the three years after the implementation of surface resistivity. The results show no significant change in construction time occurs on projects of comparable size. This included both calendar day projects and working day projects.

Life-Cycle Cost Assessment (LCCA)

Recommended bridge deck maintenance schedules for major repair involve a latex modified concrete (LMC) overlay after 50 years of the initial construction, which is expected to extend the deck’s service life by 25 years. Therefore, after 75 years of the initial construction, another LMC overlay is required to rehabilitate the bridge deck. These maintenance schedules are recommended based on the time of corrosion initiation of the steel reinforcement.

With concrete bridge decks that have a low chloride ion penetrability (as is required by the current specification), the expected time of initiation occurs at a longer period of time, and thus significantly longer service lives can be expected of these structures. This was determined by the authors after conducting multiple analyses using Life-365 software to predict the service life of the proposed bridge deck by taking into account the following factors: the water-cement ratio, type of cementitious materials used, climate and exposure conditions, and concrete cover depth. These inputs have a significant impact on concrete's durability, and were subsequently analyzed by the software to develop chloride diffusion coefficients used to predict the time to corrosion initiation and propagation of the steel reinforcement, and thus establish appropriate service life predictions.

Upon completion of the effort, the authors noted that the previous structural concrete classification, AA(M), produces an average 50-year service life depending on the concrete cover thickness and exposure conditions. In contrast, the proposed class A1 structural concrete with a resistivity value greater than 22 kΩ-cm (i.e., rated with a low chloride ion penetrability) at 28 days on average produces concrete with a service life between 100 to 120 years, depending on concrete cover thickness and exposure conditions. Thus, at a 100-year analysis period, the previous AA(M) concrete (referred as Alternative #1) may experience at least two major repair activities, while the proposed A1 concrete with a low chloride penetrability (referred as Alternative #2) would not experience any major repair activity, yielding substantial cost savings.

Since the initial costs for both types of concrete in bridge decks resulted in no cost differences, the maintenance and repair costs governed the economic impact. The first major maintenance activity typically requires hydro-blasting the current concrete deck surface to the steel layer, followed by the installation of a 2- to 4-in. LMC overlay, depending on traffic loading. For this analysis, a 2.5-in. overlay was assumed. The Department expects this preservation activity extend the bridge deck's service life for an additional 25 years. A cost of treatment of $10/SF-in was assumed for the materials costs of the LMC, and $47.73/SF-in was assumed for the hydro demolition costs, both of which were based on the Department's historical bidding data on moderate-sized projects. These estimates were applied towards the following examples, using a hypothetical bridge deck with the features described in Table 4.

Table 4. Bridge deck properties for LCC analysis

Property	Quantity	Unit
Area	4,400	SF
Length	100	ft.
Width	44	ft.
Thickness	8	in.
Concrete Cover Depth	2	in.
Hydro Demolition Pricing	$47.73	Per SF-in
Bridge Deck Thickness Removal	2	in.
LMC Pricing	$10	Per SF-in.
LMC Overlay Thickness	2.5	in.
Total Overlay Installation Cost	$120.46	Per SF

The initial cost of construction for the bridge deck using both AA(M) and A1 concrete, averaged at $1100 per cubic yard for each type, resulted in $119,506 per the bridge deck's dimensions. The cost to hydro-blast and install the LMC overlay was calculated at $530,024 for the sample bridge deck. Per Equation 1, this translates into an NPV of $74,581 at year 50 for the AA(M) concrete only. This major maintenance activity will be conducted again 25 years later, resulting in a NPV of $27,977 at year 75. Therefore, the cost advantage from Alternative #2 was of $102,558, or an 86 percent decrease in costs for the 100-year analysis period. The details for each alternative's NPV calculations are listed in Table 5.

Table 5. NPV calculation for each alternative using a 4 percent discount rate factor

Activity	Year	Alternative #1 [AA(M) Concrete]		Alternative #2 [A1 Concrete]	
		Cost	NPV	Cost	NPV
Initial Construction	0	$119,506	$119,506	$119,506	$119,506
Hydro Demolition and LMC Overlay	50	$530,024	$74,581	-	-

Activity	Year	Alternative #1 [AA(M) Concrete]		Alternative #2 [A1 Concrete]	
		Cost	NPV	Cost	NPV
Hydro Demolition and LMC Overlay	75	$530,024	$27,977	-	-
Total NPV		**-**	**$222,064**	**-**	**$119,506**

Changes to Current Specifications

The Department recently made several changes to specifications that include the use of surface resistivity. First, all structural concrete applications that require high early strength concrete have had the surface resistivity requirement removed. This is due to the very high degree of difficulty of meeting both the surface resistivity and high early strength requirements.

A note has been added to Table 901-3 noting that when a Class A1 concrete (structural) is substituted for a Class M (minor structure) concrete, the resistivity requirements are removed [11]. This is due to the Class M concrete not requiring surface resistivity for acceptance.

Additionally, the Department is considering changing how the penalties for failure to meet surface resistivity are applied. As new corrosion resistant reinforcement materials come onto the market for use, DOTD will re-evaluate the current long-life structural concrete strategy and perform a cost benefit analysis utilizing the new materials with a reduced demand for surface resistivity.

Conclusions

The purpose of this report was to review the DOTD materials specifications, focused particularly on the implementation of surface resistivity requirements for structural concrete. A comprehensive literature review was conducted on concrete durability, which unequivocally relates concrete's transport properties (measured through permeability, absorption, or diffusion) to its durability. The more susceptible concrete is to the penetration of aggressive fluids or ions, the more likely premature deterioration will take place. As such, it is imperative to measure the transport properties of concrete for quality control purposes.

Several test methods used to measure permeability, water absorption, or concrete's susceptibility to chloride ion penetration were reviewed for potential adoption in Louisiana's specifications for roads and bridges. Based on the literature search, surface resistivity remained consistently regarded as one of the most reliable and efficient methods to characterize concrete's chloride ion penetrability rating. Indeed, its reproducibility, ease of use, and rapid test time made it a highly desirable test method to adopt for the acceptance of structural concrete. In addition, DOTD and industry contractors benefited from the implementation of surface resistivity as a test method for quality control as it yielded significant cost savings per sample.

A review on the bid pricing history of structural concrete since DOTD's implementation of the surface resistivity requirement determined that the cost differences are no more than 4 percent greater, and with no reported delays. Lastly, a preliminary life-cycle cost assessment of a bridge deck evaluated the expected long-term benefits from the adoption of the surface resistivity requirement. The results showed that when the produced concrete exceeds the surface resistivity requirement, the expected service life increases significantly and therefore reduces the frequency of major maintenance and repairs, leading to 86 percent in cost savings to the Department.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
ARTBA	American Road and Transportation Builders Association
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
cm	centimeter(s)
DOTD	Louisiana Department of Transportation and Development
FHWA	Federal Highway Administration
ft.	foot (feet)
in.	inch(es)
ITZ	Interfacial transition zone
lb.	pound(s)
LCCA	Life-cycle cost assessment
LMC	Latex-modified concrete
LTRC	Louisiana Transportation Research Center
m	meter(s)
NACE	National Association of Corrosion Engineers
NPV	Net present value
psi	Pounds per square inch(es)
RCPT	Rapid chloride permeability test
SCM	Supplementary cementitious material(s)
SF	Square foot
SF-in	Square foot per inch of thickness
SHA	State highway agency
Ω	Ohm(s)

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