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Feasibility and Advantages of Accepting Concrete Other Than 28 Days

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13. Abstract

The objective of this synthesis was to investigate the feasibility and advantages of accepting concrete at testing ages other than the standard 28 days. Earlier testing ages are possible with maturity and later testing ages are more representative of durability. Evaluating properties such as maturity and resistivity at testing ages other than 28 days for acceptance could be more representative of performance, help balance the risks and responsibilities associated with concreting, reduce variability in materials and construction practices, and extend the service life of pavements and structures.

Accepting concrete using maturity testing at early ages would greatly improve efficiently in concrete construction and reduce costs and times. The industry appears to be supportive of using maturity and it is becoming standard practice in Louisiana. In addition, several promising technologies are being investigated to determine their merit in providing an estimation of compressive strength non-destructively. If these methods prove their merit, the Department has the potential to test nearly every single cubic yard of concrete placed, increasing quality.

Resistivity measurements are known to increase with time, especially with supplementary cementitious materials (SCM) mixtures that produce highly durable concrete. Resistivity measurements also provide a cost and time reduction in testing. Testing at a later age would be beneficial to contractors, since they would meet the requirements much more easily. Moving surface resistivity testing to 56 days would ensure that the quality of concrete is meeting specifications. The Department, through the Louisiana Transportation Research Center (LTRC), is partnering with others to evaluate technology that would allow in-situ testing of resistivity in a non-destructive fashion. This would eliminate the production of cylinders, field curing, transporting and storing of specimens leading to a significant cost and time savings to the Department.

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Implementation Statement

The research presented in this report can be used to determine if changes to quality assurance specifications are warranted without compromising the quality of the concrete produced for the Louisiana Department of Transportation and Development.

Introduction

Although the technology and the materials used for developing concrete mixtures have advanced in recent decades, quality assurance programs for state transportation agencies have not always been readily adapted to reflect these changes. Today the concrete industry includes a more widespread use of additives and chemical admixtures, more aggressive chemicals and deicing salts, higher traffic loadings, and a changing climate that is resulting in more extreme environments. There are also technological advances in construction practices, such as an increase in accelerated construction resulting in greater use of high early strength concrete and high-performance concrete. The cement used in these modern mixtures is also becoming increasingly finer, producing concrete that hydrates and develops strength more quickly. A conventional concrete mixture, consisting of ordinary portland cement (OPC), will generally develop the majority of its compressive strength 28 days after placement. Therefore, the industry's reference standard for design codes and project specifications are based on this testing age. For example, section 19.2.1.3 of ACI 318-19 states that design strength ($f'c$) is based on 28-day test results, and sections 6.4.1.1 and 6.6.1.1 of ASTM C94 state that the specified age at test shall be 28 days for strength requirements, unless otherwise specified [1].

State transportation agencies generally specify and accept concrete based on its compressive strength (psi) for structural requirements. The testing of standard cylinders (ASTM C39) is relatively convenient and is less variable when performed correctly (Kosmatka and Wilson, 2016) [2]. The required average strength (f'_{cr}) of a mixture must be greater than the specified or design strength ($f'c$) in order to account for variations in materials, production, curing, and testing (McCormac and Brown, 2014). Other properties can be statistically deduced from compressive strength testing data [3]. For example, mixture-specific empirical correlations for flexural strength (ASTM C78) can be calculated using compressive strength or split tensile testing (ASTM C496) [4] [5]. The formula for relating stiffness to compressive strength of conventional concrete is $E = 57{,}000 \times \sqrt{f'c}$ (ACI 2014). Compressive and flexural strength have become standard measures of performance with common testing ages at 7, 28, 56, and 90 days.

Acceptance based on 28-day strength development provides consistency and standardization. However, it may not be effective for all mixture designs; it may not adapt effectively to variations in production, and strength itself is often limited in correlation with durability-related issues. Since field concrete often simply needs to attain a required average strength for acceptance, most contractors are now meeting this requirement much earlier than 28 days. Mixtures, such as those used for mass concrete, are generally proportioned to provide design strength at a testing age greater than 28 days (ACI 211). Some concrete structures in aggressive environments are designed to have thick sections and high cement fineness (ACI 207, ACI 224), thus achieving strength in advance of the 28-day standard. In-place strength testing can be determined with drilled cores or sawed beams (ASTM C42), but this practice is destructive to the concrete and typically used for forensics testing.

Since concrete strength governs major properties, strength is used to indicate quality and performance for acceptance criteria. This practice is largely based on the assumption that sufficient strength will ensure durability. Strength alone may not be comprehensive enough for characterizing durability or in determining the suitability of concrete for a specific application. Some contractors use strength as a rapid index for potential durability or an indicator for other properties, yet with the modernization of the concrete industry, these correlations are becoming less adequate [6]. Other properties such as air content and permeability have significant impacts on concrete performance and durability. Different methods for achieving strength may also not be applicable or effective in achieving certain measurements of potential durability. The interactions between strength and durability properties, such as moisture transport, internal stresses from chemical reactions, and temperature and mechanical stresses, are now considered in advanced performance modelling and service life prediction of concrete structures [7].

Evaluating concrete strength prior to 28 days is not only important for safety and compensation, but it can be useful for scheduling decisions pertaining to critical construction operations, such as forms and falsework removal; post tensioning of precast tendons; termination of cold weather protection; opening to traffic; and structural loading.

Another consideration for concrete durability is the increased use of supplemental cementitious materials (SCMs). The use of mineral cementitious additives is becoming more prevalent throughout the United States and portland cement is supplemented or partially replaced by SCMs in at least 60% of modern concrete mixes [8]. The Louisiana Department of Transportation and Development (DOTD) now allows up to 70 percent substitution of cement by weight for ternary mixtures using combinations of fly ash and steel slag [9]. Hydration for these mixtures tends to occur over longer periods of time. Thus, the durability benefits to concrete using SCMs is more comprehensively observed in late-age concrete.

Evaluating certain critical properties at testing ages other than 28 days for acceptance could be more representative of the performance and durability of modern concrete mixtures. These benefits can help balance the risks and responsibilities associated with concrete construction and extend the service life of pavements and structures. This synthesis will evaluate performance-based concrete standards and specifications in order to determine the most effective acceptance criteria for the Louisiana Department of Transportation and Development and ensure that the concrete being produced for state projects most accurately represents its design and intended use.

Objective

The objective of this research was to investigate the feasibility and advantages of accepting concrete at testing ages other than the standard 28 days.

Scope

The research investigated concrete acceptance criteria at testing ages other than 28 days by evaluating strength and durability performance standards and specifications. Specifically, acceptance at ages other than 28-days were evaluated against the 2016 DOTD Standard Specifications for Roads and Bridges.

Literature Review

Concrete is a highly heterogeneous and complex material widely used in the construction of transportation infrastructure for its strength and durability. Despite concrete pavements only making up about 11% of state roadways in Louisiana, 38 percent of the state interstate system is comprised of concrete. This roadway network includes about 13,000 bridges, which represents the state with the 23rd highest number of bridges in the United States, and 80 percent of these bridges have concrete decking. In addition, there are approximately 19.5 million square yards of bridge deck area throughout the state, which represents the 4th highest in the nation, and 91 percent of that area is concrete decking (Table 1). Concrete is also prevalent throughout the transportation infrastructure itself, including all precast and cast-in-place concrete used for bridges, airports, hydraulic structures, foundations, water resources systems, conduits, and minor structures.

Table 1. Concrete usage by DOTD

Concrete Pavement[1]					
State Roadways (lane miles)	**Total State Roadways (lane miles)**	**Percentage of Total (%)**	**State Interstate (lane miles)**	**Total State Interstate (lane miles)**	**Percentage of Total (%)**
4,172	38,852	10.7	1,313	3,467	37.9
Concrete Decking[2]					
State Bridges	**Total State Bridges**	**Percentage of Total (%)**	**State Deck Area**	**Total State Deck Area**	**Percentage of Total (%)**
10,381	12,915	80.4	17,753,212	19,599,533	90.6

*FHWA and DOTD 2019 data.

[1] Concrete Pavement includes jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), continuously reinforced concrete pavement (CRCP), unbonded jointed concrete overlay on PCC pavement, bonded PCC overlay on PCC pavement, and other (includes “whitetopping”).

[2] Concrete Decking includes cast-in-place (CIP) and precast panel.

There have been increased efforts by the federal government and state transportation agencies to evaluate concrete using performance-based standards and specifications, which provide guidance for producing concrete resistant to deterioration in order to avoid premature deterioration [10] [11] [12]. Performance evaluation can also help ensure that the as-built concrete satisfies design and project requirements. The Federal Highway Administration (FHWA) requires each state department of transportation (DOT) to develop an FHWA approved quality assurance program for projects on the National Highway System (NHS). Evaluation of concrete performance is based on properties relating to strength and durability since these tend to be the most influential when developing and implementing quality assurance (QA) programs [8].

Critical Properties

Concrete standards and specifications identify properties that are not only critical to safety and longevity, but to constructability, serviceability, and economic liability [13] [14] [1] [9]. While fresh and hardened end results specifications may contradict each other, performance requirements may impose mutually exclusive demands. For example:

- A lower water to cementitious materials ratio (w/cm) may reduce permeability, but at the same time increase the risk of random shrinkage cracking;
- Increasing cement content may be required to achieve high early strength, but using such cement may exacerbate shrinkage and could negatively affect durability properties; and
- Increasing water content will help a contractor achieve workability, but if not properly compensated for, may reduce strength or increase segregation, bleeding, and permeability.

While hydrating, chemical and physical changes can occur externally at exposed surfaces and within the concrete. The effects of these changes on the densification of the microstructure ultimately dictate critical properties.

Strength

Concrete strength is a critical property with regard to safety as it represents the ability to resist stresses and the ability to carry design loads without failure. The development of strength is critical in the first few days and plays a prominent role in the late-age performance and service life. During construction, changes in environmental conditions, variations in materials, consolidation, and curing conditions affect strength at a specified age and strength development with age.

Durability

For decades now, state transportation agencies have increasingly included durability in design and quality assurance through the evaluation of permeability. Durability is now considered in mechanistic-empirical (ME) design methodologies and service life prediction. Durability is contextual and encompasses various properties that help the concrete withstand exposure conditions and resist deterioration. These properties can either contribute to or indicate the potential of durability.

Durable concrete can effectively resist the penetration of harmful agents and damage from distress mechanisms such as freeze-thaw damage, physical salt attack, aggressive chemical attack, alkali aggregate reactivity (AAR), sulfate attack, corrosion of embedded reinforcement and materials, and abrasion. The changing climate is causing more severe exposure conditions, such as higher humidity, higher rainfall, as well as more drastic freeze-thaw and wetting-drying cycles. The rate of deterioration depends on concentration of aggressive fluids and ions, duration of exposure, chemical resistance of the concrete, and permeability.

Pore size distribution and pore connectivity have more of an effect on permeability than porosity, since air bubbles are usually disconnected. Permeable concrete will be less resistant to the penetration and facilitated transport of harmful agents, such as chlorides (CL^-), carbon dioxide (CO_2), oxygen (O), sulfates (SO_4), and alkalis. CO_2 enters concrete mostly from surrounding water or ambient air in a process known as carbonation, which reduces the pH of the pore solution. Sulfates can infiltrate the cement paste and negatively react with products of C_3A, depositing salts, which crystallize, expand, and cause pressure leading to cracking [15]. Alkalis in the pore solution can facilitate the negative effects of expansive aggregates such as those that contribute to alkali-aggregate reactivity (AAR).

Test Methods

Compressive Strength

ASTM C39 is the most common method for determining compressive strength of concrete specimens. Concrete compressive strength is dependent upon the age tested, curing temperatures, curing moisture condition, and the water to cementitious materials ratio. Compressive strength is commonly specified at 28 days of age for acceptance. In the case of high early strength concrete, strength may be specified as early as 4 hours, 8 hours, 24 hours, or 3 or 7 days.

Maturity

Concrete maturity indicates the extent to which the degree of hydration has occurred in a mixture by accounting for the effects of time and temperature, and relating these to strength development. This correlation is based on the direct correlation between strength and strength development to the quantity of heat generated and developed from hydration. Maturity can be used: (1) to estimate the in-place strength and other mechanical properties of field concrete over a wide range of conditions; (2) to estimate the strength of laboratory specimens cured under non-standard temperature conditions; and (3) to project later-age strength. The maturity method (ASTM C1074) establishes a strength-maturity relationship of a given concrete mixture in the laboratory. This empirical relationship based on the assumption that specimens of the same mixture design will attain equal strength values if they attain equal values of the maturity index, regardless of time or temperature conditions. Maturity is represented by a numerical index that is calculated using the concrete's early-age thermal history, which consists of measuring temperature using embedded sensor technology from the time of placement to the time of desired strength estimation. This value can be expressed in terms of a temperature-time factor or of the equivalent age at a specified temperature.

Surface Resistivity

Surface resistivity indicates the resistance of concrete to the transport of harmful agents, specifically the penetration of chloride ions. Resistivity is an important factor in assessing potential durability as it provides an indirect measurement of permeability. AASHTO T358 is an electrical test method that determines the electrical resistivity of water-saturated concrete or how well the concrete can withstand the transfer of ions in an electric field.

In surface resistivity testing, concrete specimens are moist-cured for 28 days prior to testing unless specified otherwise. Accelerated moist curing is permitted and can provide an earlier indication of potential property development for concrete with slower hydrating SCMs. Factors known to affect electrical resistivity and chloride ion penetration include changes to the mixture design such as w/cm and air content, the use of SCMs, aggregate type, the presence of polymeric admixtures, and pore solution chemistry.

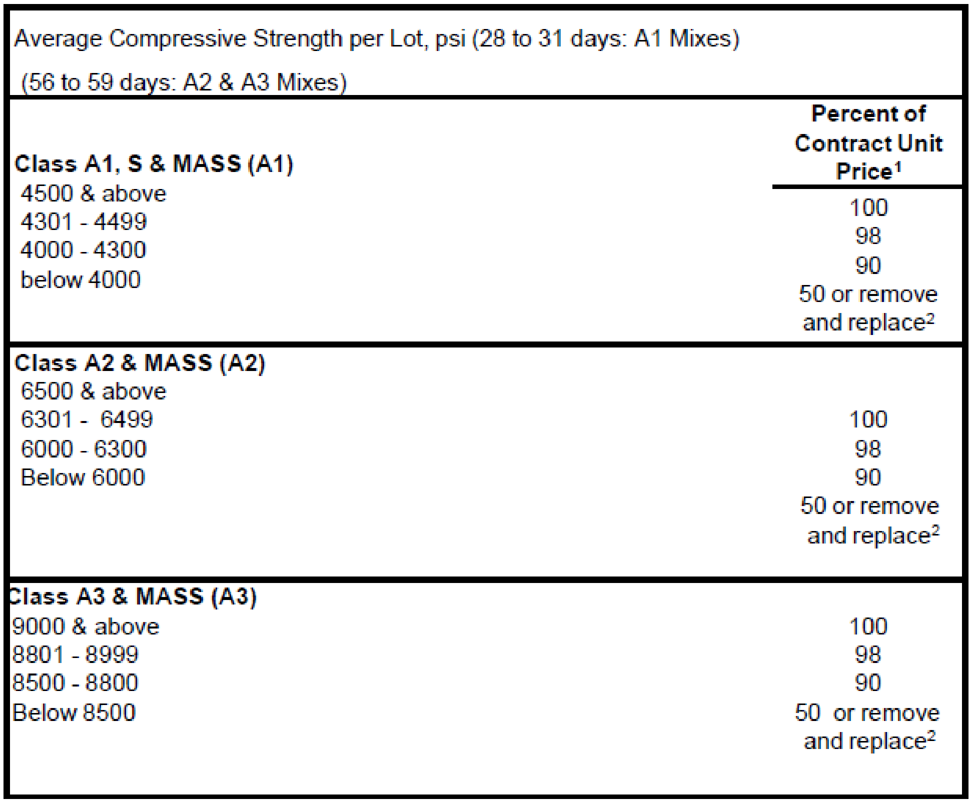
Factors known to cause errors in resistivity testing include geometry of the specimen, the testing temperature, the degree of saturation of the specimen, and storage conditions. DOTD has required surface resistivity testing for structural concrete applications since 2013, and the most recent Standard Specifications for Roads and Bridges in 2016 included a surface resistivity requirement for acceptance and payment schedule.

Like compressive strength, surface resistivity measurements will vary with the age tested. In general, surface resistivity values at 28 days of age will be half of measured values on the same specimens at ages of 56 and/or 90 days of age.

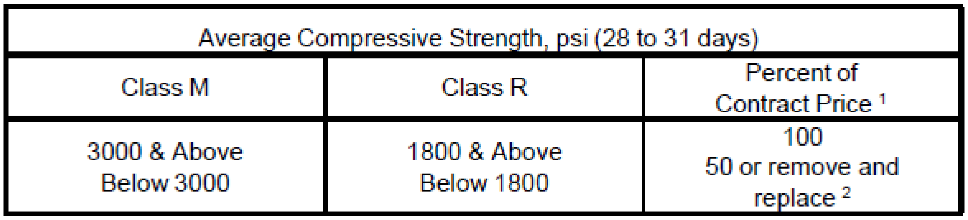
Discussion

Performance testing ages are determined in the contract documents or in accordance with Sections 601 and 901. DOTD accepts the performance of structural concrete based on compressive strength and surface resistivity at testing ages of 28 days or 56 days for higher strength requirements (i.e., mass concrete applications). DOTD accepts the performance of concrete pavement based on compressive strength of cores at 28 days or flexural strength when specified. DOTD also accepts on thickness and surface tolerance using the International roughness index (IRI). Table 2 shows the acceptance and payment schedules for case-in-place structural concrete. Table 3 shows the acceptance and payment schedules for concrete pavements.

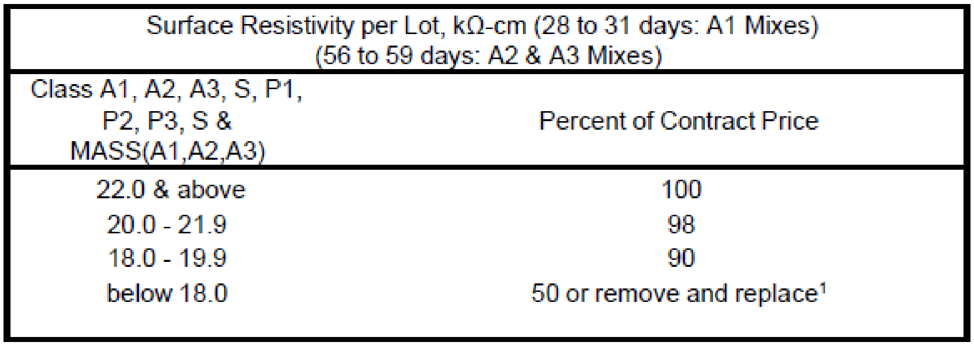
Table 2. Acceptance and payment schedules for cast-in-place structural concrete



Average Compressive Strength per Lot, psi (28 to 31 days: A1 Mixes) (56 to 59 days: A2 & A3 Mixes)	Percent of Contract Unit Price[1]
Class A1, S & MASS (A1)	
4500 & above	100
4301 - 4499	98
4000 - 4300	90
below 4000	50 or remove and replace[2]
Class A2 & MASS (A2)	
6500 & above	100
6301 - 6499	98
6000 - 6300	90
Below 6000	50 or remove and replace[2]
Class A3 & MASS (A3)	
9000 & above	100
8801 - 8999	98
8500 - 8800	90
Below 8500	50 or remove and replace[2]

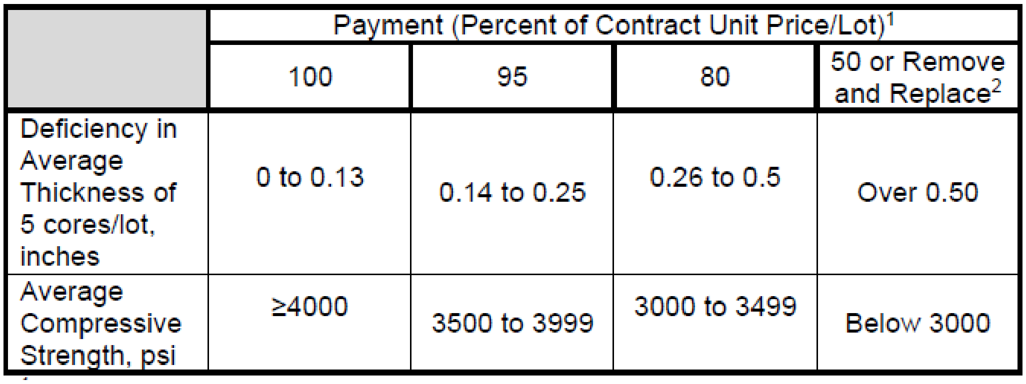


Average Compressive Strength, psi (28 to 31 days)		
Class M	Class R	Percent of Contract Price[1]
3000 & Above	1800 & Above	100
Below 3000	Below 1800	50 or remove and replace[2]



Surface Resistivity per Lot, kΩ-cm (28 to 31 days: A1 Mixes) (56 to 59 days: A2 & A3 Mixes)	
Class A1, A2, A3, S, P1, P2, P3, S & MASS(A1,A2,A3)	Percent of Contract Price
22.0 & above	100
20.0 - 21.9	98
18.0 - 19.9	90
below 18.0	50 or remove and replace[1]

Table 3. Acceptance and payment schedules for concrete pavement



	Payment (Percent of Contract Unit Price/Lot)[1]			
	100	95	80	50 or Remove and Replace[2]
Deficiency in Average Thickness of 5 cores/lot, inches	0 to 0.13	0.14 to 0.25	0.26 to 0.5	Over 0.50
Average Compressive Strength, psi	≥4000	3500 to 3999	3000 to 3499	Below 3000

Form and falsework removal currently rely on a strength criterion to be satisfied. DOTD employees cast additional cylinders in order to determine when concrete has met early form and falsework removal strengths. Currently these cylinders are tested at ages significantly earlier than 28 days, usually between three and seven days of age.

High early strength mixtures currently require the use of maturity for opening strengths. With the chief construction engineer's approval, 28-day compressive strength testing is not required if the measured maturity exceeds that of the required design strength. Surface resistivity testing is not required for high early strength mixtures.

In the current end-result specifications, strength and surface resistivity are used for hardened concrete property measurements; both being tested at 28 days of age; 56 days of age for mass concrete applications. While the specification is considered end-result, a true end-result specification would not place a date or age upon the satisfactory result. The Department could make a move toward this specification by piloting projects where age of testing is not required, but rather only specify the required compressive strength and surface resistivity. Such a transition may lead to a decrease in construction costs to the Department associated with a perceived shift in risk away from the contractor and/or the producer. Changing to a true end-result specification will ultimately not influence construction costs significantly due to construction schedule being the driving factor for many of DOTD's projects.

Additionally, there are newer technologies being piloted, invented, and improved upon that may change this dynamic in the near future. Currently, the Department could take the step of allowing the use of maturity on all concrete related projects using the results to accept and pay for concrete placed on those projects. However, consistency between the technology used to determine design maturity and the technology used in the field should be consistent (i.e., same sensor and analysis software).

Furthermore, there are many new non-destructive testing devices coming onto the market at a very rapid pace. One such device relies on piezoelectric potential to measure strength gain. This technology may prove to be the panacea for measuring strength gain in real time. Once the device is calibrated to the mixture design, a sensor can be embedded in as many loads of concrete as desired and the sensors read wirelessly at any time interval desired. This would allow the Department to monitor nearly every load of concrete effortlessly.

In addition, there are devices in prototype stages that can measure resistivity continually. This is accomplished using an embedded sensor within the concrete that applies a current to the concrete over a short distance, measures the resistance to that current, and stores the value until reporting wirelessly to a handheld device. LTRC, with DOTD, has agreed to pilot this technology on a small number of projects once the prototype has been fully developed and beta tested in a laboratory setting.

LTRC, along with DOTD construction, is actively looking into these new technologies to determine their benefit to the Department and/or contractors and producers/suppliers. By working together towards this common goal, the Department intends to remain on the leading edge of innovation as far as strength and resistivity measurements are concerned.

Conclusion

The objective of this synthesis was to investigate the feasibility and advantages of accepting concrete at testing ages other than the standard 28 days. Earlier testing ages are possible with maturity and later testing ages are more representative of durability. Evaluating properties such as maturity and resistivity at testing ages other than 28 days for acceptance could be more representative of performance; help balance the risks and responsibilities associated with concreting; reduce variability in materials and construction practices; and extend the service life of pavements and structures.

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Acronyms, Abbreviations, and Symbols

Term	**Description**
AAR	Alkali Aggregate Reactivity
AASHTO	American Association of State Highway Transportation Officials
CIP	Cast in Place
CRCP	Continuously reinforced concrete pavement
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
FHWA	Federal Highway Administration
IRI	International Roughness Index
JRCP	Jointed reinforced concrete pavement
LTRC	Louisiana Transportation Research Center
ME	Mechanistic Empirical
NHS	National Highway System
PCC	Portland cement concrete
QA	Quality Assurance
SCM	Supplementary Cementitious Material
w/cm	Water to cementitious materials ratio

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