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Development of shrinkage limit specification for high performance concrete used in bridge decks

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ABSTRACT

Early-age cracking of high performance concrete (HPC) structures, in particular bridge decks, results in additional maintenance costs, burden on serviceability, and reduced long-term performance and durability. The causes behind cracking in HPC are well known and documented in the existing literature. However, appropriate shrinkage limits and standard laboratory/field tests are not clearly established in either the technical literature or in specifications. The purpose of this research was to provide shrinkage threshold limits for specifications which allow proper criteria to ensure crack-free or highly cracking-resistant HPC. The restrained ring test (ASTM C1581) was used to identify the cracking potential of 14 different HPC mixtures. By comparing free shrinkage (ASTM C157, 75 × 75 × 285 mm specimen) and restrained shrinkage tests results, a free shrinkage limit of 450 microstrain at 28 days was proposed to ensure satisfactory cracking resistance.

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1. Introduction

Among 605,000 bridges across the country monitored by the United States Department of Transportation (USDOT), 26.9% of them were reported “structurally deficient” (bridge having major deterioration and cracks that reduce its load-carrying capacity) or “functionally obsolete” (bridge no longer meeting the current design standards) in 2010 [1]. In 2013, a grade of C+ was given to the national bridge system by the American Society of Civil Engineers (ASCE), and an annual investment of $20.5 billion was estimated to improve current bridge conditions [2]. In 2003, a nationwide state DOTs survey conducted by the Michigan DOT [3] on early-age bridge deck cracking issues indicated that 78% of the 31 responding states identified transverse cracking, which indicates the presence of drying shrinkage. Cracking, especially at early age, in high performance concrete (HPC) may result in a significant decrease in concrete durability and service life of the structure. Concrete bridge decks demand qualities from HPC such as low permeability, high abrasion resistance, superior durability, and long design life. To meet these requirements, concrete used for bridge decks is usually produced with a low water to cementitious material ratio (w/cm), typically less than 0.40, high overall cement contents, inclusion of supplementary cementitious materials (SCMs, e.g. silica fume, fly ash and slag), and smaller maximum aggregate size (due to reinforcement constraints). All these features in the mixture design make HPC bridge decks inherently susceptible to shrinkage and increased cracking risk [4,5]. A comprehensive report on factors that affect shrinkage of hardened concrete can be found in literature [6].

From a concrete materials perspective, it is a significant challenge to overcome cracking risk is to reduce the shrinkage, and ultimately the stresses generated as a result of such shrinkage. To mitigate cracking issues due to shrinkage, many methods have been studied and documented. During the last 15 years, internal curing with pre-wetted fine lightweight aggregate (FLWA) has been proven to be effective in mitigating concrete cracking potential [7–9], and has been steadily progressing from laboratory research [10–14] to field applications [11,15–18]. Another focus over the last 20 years has been shrinkage reducing admixtures (SRAs), which have also proved to be successful in reducing shrinkage induced cracking [19–25]. Some other techniques that have proven effective in controlling cracking in concrete bridge decks are fiber reinforced concrete [26], shrinkage-compensating concrete [27], and special construction practices (i.e. extended curing duration, controlled slump, and proper environmental conditions during placement). Moreover, the type of aggregate has a significant impact on the amount of shrinkage in concrete. Research showed that sandstone

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aggregate concrete exhibited the highest drying shrinkage, while concrete made from limestone aggregate proved to be the most cracking-resistant [28,29]. Other authors have shown that higher aggregate content (in volume or/and in maximum size) could reduce shrinkage due to relatively low cement paste content [29,30].

The free shrinkage test specified in ASTM C157 [31] is a simple and widely used test to assess shrinkage of a given concrete mixture. Due to its simplicity, the free shrinkage limits have been set up based on ASTM C157 test by many agencies, including Unified Facilities Guide Specifications (UFGS) [32] and some state DOTs [33–36]. The Federal Highway Administration (FHWA) has also implemented a single value shrinkage limit in the new specifications (FP-14) [37]. Table 1 gives a brief summary of free shrinkage limits used by different agencies in United Stated. There is also shrinkage requirement in CEB-FIB [38], New Zealand [39], Canada [40], and UK [41]. However, there is no shrinkage threshold limit commonly agreed upon to ensure a crack-free or highly cracking-resistant concrete.

To assess the cracking potential of HPC, the restrained ring test has been used by many researchers [35,36,42–47] in the last decade. This test had been standardized as ASTM C1581 [48] and AASHTO T334 [49] (formerly known as AASHTO PP34-98). It is a practical tool to evaluate cracking potential of concrete and mortar, especially after the quantitative analysis of this test has come into existence by implementing strain gauges to quantify the stress rate development of the specimens [50]. Based on either time-to-cracking (ToC, time in days between initiation of drying and crack formation in the concrete ring) or stress rate (calculated from strain gauge recording), ASTM C1581 suggests a cracking potential classification, as shown in Table 2. If a connection were made between free and restrained shrinkage tests results, a shrinkage limit could be identified to assess the cracking potential of given HPC mixtures.

Cracking of high performance reinforced concrete structures, in particular bridge decks, is of concern to the Oregon Department of Transportation (ODOT) and in fact most Departments of Transportation. Cracking at early ages (especially within the first year after placement) results in additional costs and a significant maintenance burden. A commonly agreed upon testing method and subsequent shrinkage threshold limit will ensure a higher degree confidence in specifying and receiving high-cracking resistant or crack-free concrete. This research is part of a comprehensive effort to reducing cracking issues in HPC bridge decks. In total, 14 mixtures were investigated, including different curing durations, shrinkage reducing strategies (internal curing, SRAs, or synergetic effect), and different aggregate sources. By comparing free and restrained shrinkage tests results, a free shrinkage limit was proposed to ensure a satisfactory cracking resistance. The testing protocols could be used to establish shrinkage limits for bridge decks made with HPC in other locations using "local" materials.

It should be noted that the main focus of the proposed study was the effect of material properties on shrinkage and cracking of HPC for bridge decks. In the field, there are many other issues that may affect cracking, including structural effects (loading and restrain conditions), temperature variations, construction practices (finishing, curing, etc.). More detailed information can be found in literature [28,51,52]. Results presented in this study was meant to help with materials (mixture design) selection.

2. Experimental

2.1. Materials

The cementitious materials used in this research were an ASTM Type I/II ordinary Portland cement, an ASTM C618 Class F fly ash, and an ASTM C1240 silica fume. The oxide analysis of the cementitious materials is shown in Table 3.

An ASTM C494 Type F polycarboxylate-based high-range water reducer was used to achieve consistent workability (target 150 mm slump). An air-entraining admixture was also added to achieve a target air content of 5 ± 1.5% to ensure proper freeze/thaw resistance. One SRA (hexylene glycol type), which is compatible with the air entrainer, was used in some mixtures at a dosage rate of 2% of the total cementitious materials by mass.

The coarse and fine aggregate used in this study were from several different sources. Four local siliceous aggregate sources were used. Three (Local A, B, and C) were the local river gravels and river sands from different areas in the state of Oregon. Another (Local D) was manufactured local siliceous gravel and sand, known as high strength aggregate. A siliceous limestone was also used. The maximum size of all aggregates was 19 mm. Petrographic study was done and was not presented for brevity reasons. In addition, in some of the mixtures, a fine lightweight aggregate (FLWA) of expanded shale was used as a partial replacement of the normal sand to provide internal curing. Determination of the absorption capacity and desorption of the FLWA, as well as the replacement level can be found in Ref. [53]. The replacement level of FLWA was based on the Bentz Equation [54] and the calculation can be found in Ref. [55]. The properties of the aggregates are shown in Table 4.

In addition, a proprietary mortar mixture (MasterEmaco S 440MC Repair Mortar, formerly LA Repair Mortar) was evaluated. This particular mortar was used in the field as crack sealing mortar by Oregon DOT.

2.2. Methods

Fresh properties (slump, air content, unit weight, and temperature) were measured for quality control purposes. The target slump was 150 mm, and the target air content was 5 ± 1.5%. A pressure air meter was used for concrete without lightweight aggregate (pressure method, ASTM C231), and a roll-a-meter was used for concrete with FLWA (volumetric method, ASTM C173). Fresh concrete temperature was measured at the end of each mixing using an infrared thermometer. Mechanical properties, including compressive strength, splitting tensile strength, and modulus of elasticity were tested on ∅100 mm × 200 mm concrete

Table 1
Summary of shrinkage control limit(s) by different agencies in U.S.

Agency (Date)	Shrinkage limit(s)
FHWA [37]	500 microstrain maximum.
UFGS[a] [32]	For OPC: 500 microstrain at 28 day; For HVFA[b]: 500 microstrain at 56 day.
Virginia DOT [33,34]	Varied (mixture and age specified, ranging 350 to 800 microstrain at 28 day).
New Jersey DOT [35]	450 microstrain at 56 day.
Washington DOT [36]	320 microstrain at 28 day.

[a] UFGS – Unified Facilities Guide Specifications, for military service constructions.
[b] HVFA – High volume fly ash, minimum 50% class F fly ash.