Cement & Concrete Composites 57 (2015) 68–74

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Hydrophobic engineered cementitious composites for highway applications

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ARTICLE INFO

Article history:
Received 10 May 2013
Received in revised form 30 September 2014
Accepted 16 December 2014
Available online 26 December 2014

Keywords:
Superhydrophobic
Overhydrophobic
Mechanical properties
Pore size distribution
Fiber reinforcement

ABSTRACT

The U.S. highway infrastructure is in desperate need of repair, especially in areas exposed to harsh environments. Freezing and thawing cycles in northern regions lead to serious durability problems in bridges and early need for repair or replacement. The effective use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) enables one to design a durable concrete capable of withstanding large deformations from heavy loading and temperature variations such as freezing and thawing. Greater longevity is achieved in the service life of roadways due to the increased ductility induced by the multi-cracking and strain hardening behavior of the ECC. Combining ECC with overhydrophobic and superhydrophobic admixtures results in a material with controlled, evenly-spaced air voids and improved multi-cracking response. In superhydrophobic engineered cementitious composites (SECC), small, evenly spaced air voids act as artificial flaws, promoting crack formation while still maintaining high flexural and compressive strength. This research demonstrates that high ductility can be achieved in ECC with a stronger cementitious matrix.

1. Introduction

The highway infrastructure throughout the northern United States is subjected to severe weathering from salt-scaling and freeze–thaw cycles, and many of the highways in this region are in urgent need of repair or replacement. Reinforced concrete bridges are even more susceptible to weathering, as chlorides penetrate the concrete and reach the enclosed steel reinforcement, thereby accelerating corrosion; as the corrosion progresses, a reinforced concrete bridge will require repair if not complete replacement. In saturated concrete, water becomes trapped in capillary pores and expands upon freezing, resulting in internal stresses. These stresses create significant pressure and cause the concrete to crack. In addition, freezing and thawing cycles lead to progressive widening cracks and facilitate the ingress of chlorides, resulting in premature deterioration.

Concrete approach slabs, which are critical elements located on either side of a bridge, are very susceptible to deterioration. These elements are used to create a smooth transition between heavily reinforced bridge superstructure and unreinforced Portland cement based, or, in most cases, asphalt concrete pavements. Such a transition is usually rarely observed because of many reasons. Differential settlement between the concrete approach slab and adjacent pavement creates a bump resulting in discomfort for motorists; also, impact forces from heavy trucks produce cracks at this transition. Differential rutting between the two pavements will also result in similar phenomena. Differential thermal expansion/contraction between the two pavements may also leave a void space allowing the ingress of water and chlorides and eventually corrosion if steel reinforcement or dowel bars are present. Additionally, differential settlement between the unsupported end of the approach slab (transition between the approach slab and pavement) and the supported end on the bridge abutment cause a tilt in the approach slab resulting in high bending stresses and cracking. An approach slab that is capable of withstanding these bending stresses without failure may result in a longer service life for these elements.

The use of a durable and impact-resistant construction material for bridge approach slabs can extend the life of this particular bridge component and contribute to the service life of the entire structure. Engineered cementitious composites with polyvinyl alcohol fibers (PVA-ECC) have proven to be a more durable alternative than

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http://dx.doi.org/10.1016/j.cemconcomp.2014.12.009
0958-9465/

conventional concrete. These materials exhibit resilient ductile performance under tension similar to steel [1]; however, research has demonstrated that in order to achieve high ductility and strain hardening capability, the strength of the cementitious matrix must be limited so that the maximum tensile cracking strength does not exceed the maximum fiber bridging strength [2]. This design requirement limits the application of high-performance cementitious matrices in ECC.

The ability of concrete to resist freezing and thawing can be improved by the use of air entrainment (AE), which reduces the internal stresses by providing additional area for water to expand upon freezing. The use of many conventional air entraining admixtures, however, often results in an air void system with large, irregular-shaped and poorly dispersed air voids reducing the strength of the material. The loss of designed air due to mixing or vibration is also often realized [3]. The use of superhydrophobic admixtures results in an improved air void structure [4] as seen by higher void frequency and better spacing factor with the same quantity of air as analyzed using ASTM C457 Rapid Air Testing Method (Fig. 1).

The addition of hydrophobic, overhydrophobic, or superhydrophobic admixtures to the cementitious material (known as superhydrophobic hybridization) can be very beneficial. The superhydrophobic hybridization of concrete combines the interdisciplinary work of biomimetics (lotus effect), chemistry (the use of siloxane polymers), and nanotechnology (the use of nano-SiO_2 particles) to resolve concrete's fundamental problems such as insufficient durability and corrosion-resistance [4–7]. In fiber reinforced concrete, superhydrophobic modification can be used to change volume, size, and distribution of air voids in the concrete, as well as reduce the bond with PVA fibers to realize a controlled pull-out behavior [8]. These engineered flaws created by hydrophobic admixtures can initiate the formation of cracks within the high-strength cementitious matrices. As soon as fiber bridging arrests the crack formation, new cracks are initiated from these engineered voids and the process is repeated facilitating multi-cracking and strain hardening behavior [1,2]. It was proposed that a controlled air void structure can be tailored to result in a "preferred" fracture mode [8].

Superhydrophobic surfaces, or surfaces with a water contact angle θ larger than 150° and over hydrophobic surfaces with θ between 120° and 150° (Fig. 2), have generated much interest due to their potential for industrial applications (such as self-cleaning) [9–11], but they have not yet been employed for enhancing concrete durability. This nature-inspired approach can improve the performance of hydrophobic materials to enhance the durability of concrete [6,7]. To manufacture superhydrophobic and overhydrophobic (SOH) admixtures, the hydrogen-containing siloxane compound (e.g., polyethyl hydrosiloxane, PEHSO or polymethyl hydrosiloxane, PMHS) is combined with small quantities of submicro- or nano-sized particles (Fig. 2) [12].

A modified PEHSO/PMHS admixture (used at a dosage between 0.01% and 0.1% of cement weight) releases hydrogen and forms small (10–200 μm), uniform air voids evenly distributed within the cement paste (Fig. 3b). The volume, size, and distribution of air voids within the hardened cement phase can be tailored by preparing the water-based emulsion of PMHS with a certain droplet size. For optimal performance, more than 70% of the PMHS-based emulsion must be dispersed to the droplet size of less than 10 μm [4]. The surfaces of the voids become coated with a PEHSO/PMHS layer to provide a certain degree of hydrophobicity (Fig. 3d). When micro- and nano-sized particles are incorporated with PMHS and distributed on the surface of the voids (Fig. 3c), the desired surface roughness and SOH effects are achieved. When compared to conventional air entraining admixtures (Fig. 3a), the use of PMHS-based emulsions provides a controlled air void structure without loss of air during compaction as the voids are formed by the PMHS reacting with $Ca(OH)_2$ up to the end of the setting process [4].

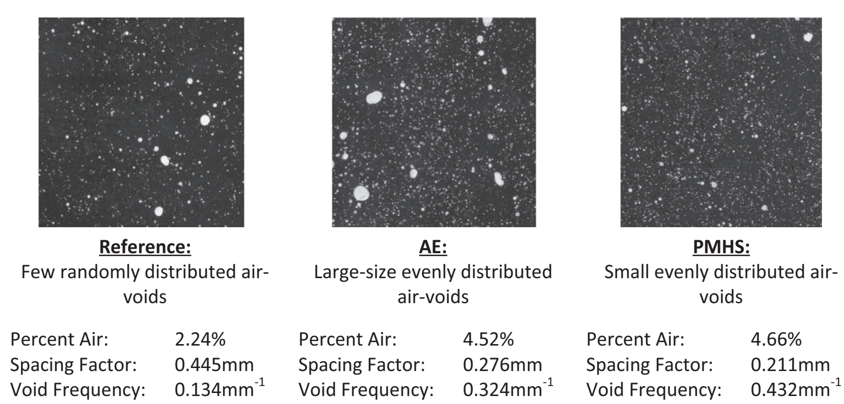

Fig. 1. The air void structure of reference, air-entrained (AE), and PMHS-based ECC/SECC and corresponding air void properties based on ASTM C457 rapid air testing.

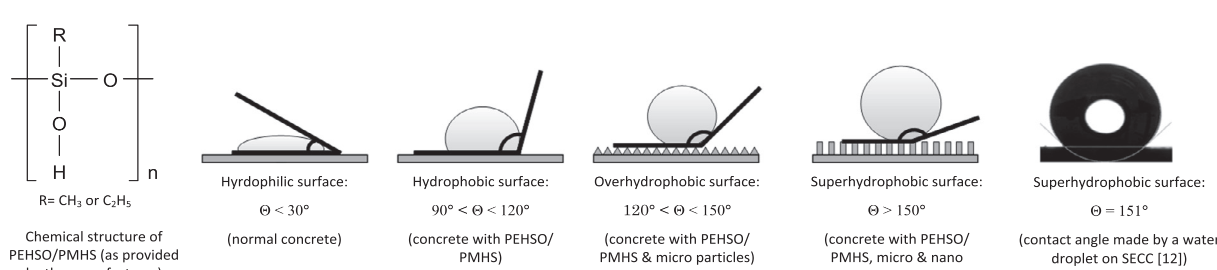

Fig. 2. The concept of superhydrophobic hybridization of concrete.