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Superhydrophobic coatings on Portland cement concrete surfaces

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HIGHLIGHTS

- Portland cement concrete (PCC) surfaces were coated with low surface energy materials.
- Layer-by-layer (LBL) deposition technique was utilized for coating the PCC substrates.
- The coated PCC substrates reached high levels of hydrophobicity (water-repellency).
- Effect of concrete surface texture was studied on the skid resistance of coated concrete.
- Turf drag surface texture greatly enhanced the skid resistance of superhydrophobic PCC.

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ABSTRACT

The objective of this study was to synthesize, characterize and evaluate the nanomaterials-based superhydrophobic (super water-repellent) coatings on Portland cement concrete (PCC) surfaces. These coatings are synthesized with nanomaterials such as polytetrafluoroethylene (PTFE), polyether ether ketone (PEEK) and silanized diatomaceous earth (DE). Using layer-by-layer (LBL) deposition technique, each coating type was deposited at four different spray durations. The water-repellency of the coated surfaces were characterized by measuring static water contact angles (WCAs). These measurements were evaluated through a statistical design-based experimental test program which revealed that the spray duration and coating type are significant variables. A skid-resistant coating composed of PTFE and PEEK was utilized to evaluate the impact of superhydrophobic coatings on pavement skid resistance.

1. Introduction

Presence of ice and snow on the surface of rigid pavements and penetration of water into the Portland cement concrete (PCC) have always been constant sources of concern. During the wintertime, slippery conditions on sidewalks and critical areas of roadways – such as steep slopes and intersections – impose injuries on pedestrians and traveling passengers. Each year, agencies spend millions of dollars for removing ice and snow from these surfaces. In airports, since the beginning of "all-weather" aircraft operations, there have been landing and aborted takeoff incidents or accidents during each winter because of slippery and icy conditions on aprons, taxiways and runways. In addition to the pavement winter maintenance issues due to presence of ice and snow, penetration of surface water into PCC causes durability-related problems like freezing-induced damage [1] and sulfate attack [2] which leads to expansion, cracking, scaling and crumbling of the concrete. In

Abbreviations: PTFE, polytetrafluoroethylene; PEEK, polyether ether ketone; DE, diatomaceous earth; LBL, layer-by-layer; PFDTS, perfluorodecyltrichlorosilane; WCA, water contact angle.

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order to overcome the winter maintenance related problems, the use of heated pavements [3,4] and superhydrophobic (super water-repellent) coating techniques [5,6] have received recent attention as alternatives to costly and time consuming conventional ice and snow removal practices. Superhydrophobic surfaces, which are typically icephobic (ice-repellent) [7], can make the concrete more durable [8] by repelling the surface water.

Lotus leaf is the most famous superhydrophobic surface in the nature [9], and there have been biomimetic approaches to mimic the "lotus effect" for producing hydrophobic (water-repellent) surfaces [10,11]. Hydrophobicity is governed by chemical properties of the materials – or surface energy – and a nano to micro scale hierarchical topographical or surface roughness structure [12]. Although transferring the fascinating "lotus effect" to artificial surfaces has been widely researched, there is very limited literature dealing with bio-inspired superhydrophobic concrete.

So far, superhydrophobic PCC, which can also be icephobic [7], has been produced by either applying siloxane-based coatings or emulsions on concrete with either an integrated microtexture [13] or on concrete with embedded hierarchical structure [14]. In both of these methods, the micro roughness and hierarchical structures were produced in the fresh concrete; however, PCC can become superhydrophobic without changing the original structure of concrete [15]. For example, there are cases in which super water-repellent asphalt concrete was created by using only polymeric nanostructured coatings like fluoroacrylate [11] or fluorocarbon [5]. There are numerous low surface energy materials like polytetrafluoroethylene (PTFE) [16], polyether ether ketone (PEEK) [17] and perfluorodecyltrichlorosilane (PFDTS) [18] that can become nanostructured using appropriate techniques at the laboratory, and then can be utilized for producing super ice/water-repellent coatings on concrete.

Superhydrophobic pavements should maintain skid resistance at an acceptable level in the absence of ice or snow. Two components affect the tire-pavement friction, which are adhesion and hysteresis [19–21]. Adhesion results from the molecular bonds developed between the pavement surface and the tire. The hysteresis component is related to the rubber deformation due to the pavement surface asperities. Presence of superhydrophobic coatings can slightly decrease the skid resistance because of changing the surface chemistry; however, producing the correct surface texture (asperity pattern) on PCC can solve this problem [22]. Among the orders of pavement surface asperities, micro texture (irregularities between 0.005 and 0.3 mm) and macro texture (irregularities between 0.3 and 4 mm) are the most influential in terms of skid resistance [19]. The frictional property of PCC, at microtexture level, can be measured using British pendulum tester (BPT) either at the laboratory or in the field [23].

The purpose of this research is to investigate the feasibility of producing superhydrophobic concrete, at laboratory scale, for ice-and snow-free pavement applications. To this end, a statistical design-based experimental test program was developed to create and evaluate nanostructured superhydrophobic coatings on PCC substrates. The layer-by-layer (LBL) method of spray deposition was utilized to coat the PCC substrates with PTFE, PTFE/PEEK and diatomaceous earth (DE) which was silanized with PFDTS. The superhydrophobicity of the coated samples were evaluated by measuring the water contact angles (WCAs). Then, a statistical analysis was performed so that the significant design variables could be identified. The PTFE/PEEK was selected for coating PCC specimens with different surface textures at the laboratory. After coating the specimens, the effect of different asperity patterns on enhancing the skid resistance was evaluated. It is hoped that the findings of this study will provide guidance on the field implementation of superhydrophobic PCC.

2. Materials and methodology

In order to investigate the effect of different variables on the superhydrophobicity of the nano-coated PCC substrates, a statistical design was developed prior to the preparation of the substrates. The selected design variables include the types of water-repellent materials (PTFE, PTFE/PEEK and silanized DE) and spray durations (4, 6, 8 and 10 s). After preparing the substrates and coating all of them, the superhydrophobicity of the samples were characterized by measuring the static WCAs. For evaluating the effect of nanotechnology-based materials on the skid resistance, seven different types of surface textured PCC specimens were prepared. The textured specimens were coated with PTFE/PEEK and the skid resistance was measured on them using a British pendulum tester (BPT) before and after the coating.

2.1. Preparation of water contact angle (WCA) measurement substrates/specimens

The concrete used in this study was prepared in accordance with Iowa DOT mix design (Materials I.M.529) for constructing PCC pavements which is similar to the FAA advisory circular [24] for construction of airports. The selected water-to-cement ratio was 0.43, and the utilized cement was ASTM C 150 type I/II [25] which was manufactured by Holcim. The coarse aggregate was limestone – conforming to ASTM C 33's D-57 gradation category [26] – with nominal maximum aggregate size of 25 mm. Fine aggregate was river sand conforming to ASTM C 33 specifications. After preparing the concrete, it was cast in cylindrical molds (100 mm in diameter and 200 mm in height); the specimens were demolded after one day and were cured for 28 days at 23°C and 100% relative humidity. Then, the cylindrical concrete specimens were cut using a diamond saw to obtain twelve 10-mm-thick disk-shaped specimens with smooth cut surfaces. In order to obtain replicates, each specimen was cut further to obtain quarters (Fig. 1).

2.2. Preparation of skid resistance measurement specimens

Microtexture is fine-scale roughness and is the result of presence of fine aggregates and pores in the concrete. On the other hand, macrotexture is the measureable striations that are formed through texturization on fresh or hardened concrete [27]. In order to investigate the influence of superhydrophobic coatings on the skid resistance of PCC, it was decided to prepare different surface textures on the fresh concrete specimens that were cast in beam molds – concrete mixture and curing regime were identical to those used in preparation of cylindrical specimens. In this way, the effect of surface texture (see Fig. 2) on enhancing the potential drop in skid resistance of coated PCC could be evaluated. The surface areas of the specimens were big enough to accommodate the required width and length (78 × 127 mm) for measuring the skid resistance by BPT. It is worth noting that, a smooth control surface was also prepared by finishing the surface of fresh concrete with a steel trowel.

Burlap, broom and turf drag surfaces usually have 1.5–3 mm deep striations [27]. The tine depth, width and spacing of the tine texture surfaces produced in this study were 5, 3 and 10 mm, respectively, which are all within the recommended ranges [27].

2.3. Coating the substrates/specimens

This research mostly highlights the production of three different nanostructured superhydrophobic coatings on the surface of PCC for ice-and snow-free rigid pavement applications. The