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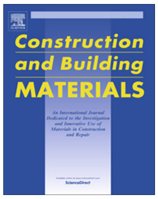

Internal curing of pervious concrete using lightweight aggregates

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HIGHLIGHTS

- Internal curing provided by prewetted lightweight aggregates in pervious concrete.
- Prewetted lightweight aggregates improve pervious concrete workability.
- Internal curing increased compressive strength and improved freeze-thaw durability.

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ABSTRACT

Pervious concrete is an important stormwater management technique for the urban environment. Surface raveling is the single most common distress caused primarily by plastic drying and paste shrinkage. Internal curing is one mechanism to provide additional moisture to elevate internal humidity and reduce shrinkage and is most commonly provided through prewetted lightweight aggregates (PLWA). This study evaluated how fine PLWA influence properties when used to completely replace the small portion of conventional fine aggregate present in pervious concrete. Samples were placed at a fixed void content to not confounded results with changes in density. Strength, degree of hydration, shrinkage, and freeze–thaw testing all showed substantial improvements over the control mixture, strongly suggesting that internal curing become routine for pervious concrete.

1. Introduction

Portland Cement Pervious Concrete (PCPC) is a type of permeable pavement containing narrowly-graded coarse aggregate, cementitious materials, water, admixtures, and a small portion of fine aggregate, which combines to produce concrete with the ability to rapidly transmit water [1]. This ability to rapidly transmit water results in a plethora of intended and unintended benefits which makes PCPC a critical component for adoption in ever-changing climate. Initially permeable pavements were only used for stormwater quantity management, however additional uses including pollutant removal, urban heat island mitigation, slip and fall prevention, and even noise mitigation are common [2–7]. A great deal of research has been performed globally to better understand how materials and mixture proportions influence strength, durability, and permeability [8–15]. One common, and understandable, finding is that strength and durability are inversely proportional to permeability and voids [16–19]. Many mixture proportions suggest an adequate balance of performance around 20% voids with recommendations from 15% to 25% common [1,20–22]. However, mixtures developed in the laboratory often have difficulty translating to the field with surface raveling still a major obstacle to more wide-spread use [23–25].

PCPC is created by coating the coarse aggregate particles with a paste/mortar mixture. This coating is achieved by creating a paste workable enough to thoroughly coat the aggregate without draining down and clogging the lower pores with cementitious paste [26]. The optimal consistency for many mixtures is achieved at a water-to-cementitious ratio (w/cm) between 0.29 and 0.35, which typically includes high-range water reducing agents, hydration stabilizing agents, and often other viscosity modifying admixtures [1,7,8]. The low w/cm and high amount of exposed paste surface area makes curing more important for pervious concrete than any other type of concrete. Evaporation during mixing and transportation further lowers the w/cm and if PCPC is not placed and covered with plastic quickly, surface raveling occurs [12,23,24]. Additionally, the high friction during mixing further pulverizes the cement particles creating a mix, that while batched using an

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ASTM C150 Type I or II cement, behaves in the field as batched with a Type III, high early strength, cement. The low w/cm, combined increased cement fineness, and curing under plastic often produces high shrinkage mixtures. Unlike in conventional concrete, shrinkage in pervious concrete results in raveling.

For PCPC, raveling is the single most common distress and biggest issue preventing more wide-spread use. Raveling is the dislodging of cement-coated aggregate pieces or the separation of aggregate from the paste and occurs at the pavement surface. Efforts to reduce raveling and improve surface performance have included contractor training requirements and modifications to mixture proportions [27,28]. Besides proper curing, the addition of micro or macro fibers to PCPC mixtures significantly reduces raveling [20,29]. One technique that has previously shown benefit to reducing PCPC raveling has been the inclusion of super absorbent polymers (SAPs) [30]. SAPs are salts which absorb hundreds to thousands of times their weight in water. SAP inclusion in PCPC allows inclusion of extra water, not part of the original mixing water, which provides increased degree of hydration, improved strength, durability, and reduced shrinkage [30–32]. The hydrated gel also helps improve workability by lubricating cementitious and aggregate particles. Interestingly, although extra water is provided in the hydrated SAP particles, moisture loss as measured using ASTM C156 does not increase. The extra water is present to further provide increased degree of hydration. However, SAP particles hydrate to a much lesser degree in alkaline solutions and may clump when added in large quantities resulting in gel balls visible on the pavement surface which provides motivation for current research [33].

Prewetted lightweight aggregate (PLWA), especially fine aggregate, have been shown by numerous studies to provide increased degree of hydration, reduced shrinkage, and general improvements to concrete properties [34–40]. PLWA generally consist of expanded shales, clays, slates, or slag aggregate, however other high absorption materials such as drinking water treatment waste residuals, also possess the desired absorption and pore size to provide internal curing benefits [34,41]. Lightweight aggregates have been previously investigated in pervious concrete as a coarse aggregate for the purposes of improving acoustic and thermal insulation [42]. Selection of addition rate for optimal internal curing is provided using the Bentz equation shown in Eq. (1) [40].

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{\max}}{S \times \phi_{LWA}} \tag{1}$$

where: C_f is the cement content, CS is the chemical shrinkage of the cement, $\alpha_{\max}$ is the expected degree of hydration, S is the degree of saturation of the aggregate, and Φ_{LWA} is the absorption of the lightweight aggregate.

However, this methodology only provides a desired mass of water needed to mitigate autogenous shrinkage and does not consider distribution of the water within the cementitious paste. Much like Power's paste protection theory describes how a fine air bubble system is more desirable for freeze-thaw durability [43], small, well-distributed particles are also more beneficial for internal curing. While not designed for PCPC, the National Institute of Standards and Technology (NIST) has developed a hardcore/soft shell microstructural model (HCSS) which uses aggregate gradation and volume replacement to provide an estimate for degree of paste hydrated by the lightweight particles [44]. Since PCPC typically includes little to no fine aggregate, a deficit exists between the optimal amount needed for internal curing and complete replacement of conventional fine aggregate with PLWA. The objective of this research was to determine if replacing a typical amount of fine aggregate in PCPC with PLWA is enough to provide sufficient benefit.

2. Methodology

2.1. Materials and mixtures

The testing program was designed to determine the effects of including various prewetted lightweight fine aggregates (PLWA) on pervious concrete properties and durability. The experimental plan included a combination of standard concrete verification tests and tests specific to pervious concrete.

The mixture proportions used in the study are shown in Table 1. Testing included one pervious concrete control mixture (PC) designed for adequate freeze-thaw durability and strength. The selected baseline pervious concrete mixture was similar to ones currently used around the U.S. The selected mixture contained freeze-thaw durable limestone coarse aggregate, 7% fine aggregate by weight of total aggregate, and a water to cement ratio of 0.34. Chemical admixtures were dosed by weight of cement and included air entraining agent dosed at 0.06%, water reducing agent 0.25%, and a hydration stabilizer at 0.38%. The design porosity was fixed at 25% for all specimens. For the mixtures containing normal weight aggregates, prewetted lightweight fine aggregate was used to replace the entire volume of the sand used in the control mixture. One mixture was included which replaced both the volume of normal weight coarse aggregate and fine aggregate with lightweight coarse aggregates.

The three prewetted aggregates were used as fine aggregate replacement to the control mixture and selected for a relative low, medium, and high absorption content. Wetted surface dry (WSD) condition was determined after a 72 h saturation period according to ASTM C1761 [45]. The low absorption material (BDX) was from New Market, Missouri and had a WSD condition of 16%. The medium absorption material (HPB) was from Brooklyn, Indiana and arrived prewetted at 19% moisture. The high absorption material (BRF) was from Livingston, Alabama and had a WSD condition of 39%. One additional pervious concrete mixture (PC-LW) was included which replaced both coarse and fine aggregate with the medium absorption source material. The medium absorption coarse aggregate arrived prewetted at 11% moisture.

All samples were mixed according to ASTM C192 [46]. Fresh concrete was weighed for each individual specimen prior to placing. Fresh concrete was placed into the molds in a single lift using a hydraulic press. Controlling the unit weight of each specimen ensured consistent density and void content for comparable data analysis. Hardened unit weight, voids, and strength were tested on 100 mm by 200 mm cylinders. After hardened unit weight and voids were performed, the top and bottom 25 mm removed using a concrete slab saw. Permeability was then tested on the remaining 100 mm diameter and 150 mm tall cylinders. All tests were performed in triplicate with a total of 12 cylinders were produced for testing from each mixture.

2.2. Testing procedures

Fresh density was determined using ASTM C1688 [47]. The void content and hardened unit weight of the pervious concrete was determined using ASTM C1754 [48]. All unit weight and void data represents an average of three specimens. Moisture loss was determined according to ASTM C156 on 225 mm by 325 mm by 50 mm samples [49]. ASTM C156 is designed to determine the acceptable moisture loss of membrane-forming curing compounds and is performed on samples placed in an environmental chamber at 38 °C and 32% relative humidity for 72 h. The permeability of mixtures was determined using a falling head permeability test apparatus. The samples were confined in PVC shrink wrap and sealed in a rubber sleeve which was surrounded by adjustable hose clamps. The