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Material characterization and hydraulic conductivity modeling of macroporous recycled-aggregate pervious concrete

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HIGHLIGHTS

- Macroporous pervious concrete (MPC) with >30% voids was produced and characterized.
- Compressive strength of MPC is independent of aggregate type (virgin vs. recycled).
- Two binder additives, TiO_2 and sand, increased compressive strength of MPC.
- A modified Carman–Kozeny model more accurately predicts pervious concrete behavior.

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ABSTRACT

The objective of this work was to characterize the mechanical, physical, and hydraulic conductivity properties of macroporous (>30% voids) pervious concrete (MPC) containing recycled aggregates and two binder additives, namely sand and titanium dioxide (TiO_2). While MPC exhibited lower compressive strength and higher permeability than normal pervious concrete, the experimental data suggest that the high absorption and low specific gravity of recycled aggregates did not compromise the mechanical properties or permeability of MPC. A modification to the well-known Carman–Kozeny hydraulic conductivity model is proposed to more accurately predict the permeability of both normal and macroporous pervious concrete.

1. Introduction

The ability of pervious concrete to reduce the quantity and improve the quality of stormwater runoff in urban environments has been exploited in a wide variety of horizontal infrastructure applications (e.g., pavements). Previous studies have shown that pervious concrete can significantly reduce stormwater runoff volume through direct infiltration and can improve the quality of stormwater by reducing the concentrations of heavy metals (e.g., lead, zinc, chromium, copper) that are typically found in stormwater runoff [1]. Pervious concrete has also been shown to lower the risk of thermal pollution from urban stormwater and to help mitigate the urban heat island effect [2], thus contributing to an overall reduction in health risks to humans, plants, and wildlife [3–6].

1.1. Pervious concrete materials

The constituent materials of pervious concrete, including coarse aggregate, cement, water, and, occasionally, a small amount of fine aggregate, govern its macroscopic properties. Water-reducing admixtures are commonly used to maintain sufficient workability for pervious concrete with low water-to-cement ratios (0.26–0.40) [7]. The properties of coarse aggregates impact the performance of pervious concrete. Kevern et al. [8] found that aggregates with high absorption or low specific gravity yielded a pervious concrete with low freeze–thaw durability. Another study indicated that a small addition of sand (7% by weight) improved freeze–thaw resistance [9]. The best-performing mixture for freeze–thaw durability included No. 4 (4.75 mm) aggregates, a 7% by weight replacement of coarse aggregate with sand, and an air entraining admixture [9]. In this same study, the addition of sand marginally reduced the permeability of the pervious concrete. Unlike round aggregates, angular aggregates were found to yield higher actual porosities compared to the intended design porosities [8]. Finally, increases

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in bulk volume of aggregate, or the use of larger aggregates, were also reported to increase the porosity and decrease the compressive strength and modulus of elasticity of pervious concrete [10]. This loss in mechanical properties was attributed to a decrease in paste content at higher aggregate volumes [10].

The effects of using of recycled concrete aggregates (RCAs) in pervious concrete have also been investigated. According to the Federal Highway Administration, RCA is primarily used for aggregate road base. Currently, only eleven states permit the use of RCA as an aggregate for new concrete projects [11]. While a few studies have explored the use of RCA in pervious concrete, the body of literature is not extensive. Nonetheless, multiple authors have reported that the incorporation of RCA reduces the compressive strength of normal pervious concrete [12–14]. More specifically, at a 100% replacement of RCA, Berry et al. [12], Gaedicke et al. [13], and Rizvi et al. [14] have recorded compressive strength losses of 16%, 15% and 43%, respectively.

In addition to sand, the incorporation of titanium dioxide (TiO_2) in pervious concrete has been studied because of the photocatalytic properties of TiO_2. A number of studies have shown that TiO_2 can remove noxious pollutants from the environment through a photo-induced redox reaction [15,16]. It has also been shown that small additions of TiO_2 improve the mechanical strengths of cement mortar. Chen et al. [17] reported that additions of 5% and 10% TiO_2 by weight of cement increased the 28-day strength of mortar by approximately 10–25%. This increase in strength has been attributed to a nano-filler effect through which the TiO_2 nanoparticles provide additional nucleation sites for cement hydration, thereby increasing both the rate and degree of hydration [18].

1.2. Beyond horizontal infrastructure

While the vast majority of pervious concrete applications to-date concern horizontal infrastructure, there is increased interest in using pervious concrete in vertical infrastructure applications (e.g., buildings). Historical examples of using pervious concrete in building walls do exist [7], but these applications were limited to a few isolated examples in post-World War II Europe. More recently, pervious concrete has found application as non-structural components in transportation and building infrastructure, like sound barriers and reinforced insulation panels – applications that take advantage of its favorable acoustic and thermal properties [19]. Additional new applications of pervious concrete include underwater biological habitats that provide support for a wide variety of marine organisms [20].

Non-structural applications of pervious concrete require different properties to suit a wide range of material requirements. For example, the requirements for durable pervious pavements (e.g., high strength, ~20% porosity) may not be appropriate in other applications, like sound barriers or biohabitats, where higher porosities are favored. While the majority of pervious concrete materials research completed to-date has been primarily limited to pavement materials with porosities that range from 15% to 30%, there have been a few isolated studies that reported outlier samples with porosities greater than 30% [21,22]. To the authors' knowledge, however, no deliberate research has yet been conducted on pervious concrete with ultra-high porosities greater than 30%.

1.3. Research objective

The objective of this study was to characterize the mechanical, physical, and hydraulic properties of macroporous pervious concrete (MPC), which is defined herein as pervious concrete with a minimum porosity (air void content) of 30%. The effect of incorporating recycled concrete aggregates (RCA) on the material properties of MPC was also investigated. Prior to mixing, the physical properties of the RCA were first characterized to better understand the composition and inherent variability that exists in reclaimed aggregates.

Due to ultra-high porosities and the incorporation of RCA, low compressive strengths and higher sensitivities to field-condition curing (rapid evaporation) were anticipated [12]. Thus, methods to maintain or improve the mechanical performance of MPC were explored. The need for an improved paste strength and paste-aggregate interface in pervious concretes has been previously identified and achieved through small additions of fines [9]. Therefore, this study analyzed the impact of both sand and TiO_2 additions on the mechanical, physical, and hydraulic properties of MPC. Material property relationships between unit weight and compressive strength and between porosity and permeability of MPC were compared with the behavior of conventional pervious concrete (<30% porosity). In addition, the suitability of a well-known hydraulic conductivity model based on the Carman–Kozeny relationship in predicting the permeability-porosity relationship of MPC was investigated herein. Finally, a modification to the model was proposed to more accurately predict the hydraulic conductivity of both normal and macroporous pervious concrete.

2. Materials and methods

2.1. Materials

Type I/II cement, virgin coarse aggregate (pea gravel), and sand was obtained from a local hardware store. RCA, which consisted of crushed mortar, reclaimed virgin aggregate, crushed masonry, and asphalt was acquired from Allied Recycled Aggregates in Commerce City, Colorado USA. Both virgin coarse aggregate and RCA were sieved to yield a uniform No. 4 (4.75 mm) particle size. Rutile TiO_2 with an average particle size of 0.41 µm was acquired from DuPont. MasterGlenium 3400 was obtained for use as a high-range water reducer.

2.2. Experimental methods

This study comprised three experimental phases. In the first phase, plain cement and TiO_2-cement blend mortar samples were formulated and cast to analyze the impact of TiO_2 on the compressive strength at 3-, 7- and 28-days. In the second phase, the RCA was characterized for composition, gradation, unit weight, specific gravity, and absorption. In the third phase, a MPC mix was designed and cylinders were cast to study the impact of RCA, sand, and TiO_2 on the mechanical, physical, and hydraulic properties of MPC.

2.2.1. Mortar preparation and mechanical characterization

Three (3) sets of six (6) mortar cube specimens were cast for each of five (5) sample formulations according to ASTM C109 [23]. Each set was used for 3-, 7-, and 28-day compressive strength tests. Table 1 shows the mix designs of the five (5) sample formulations. The Control sample was proportioned according to ASTM C109 for portland cement mortars. The remaining four mortar mixes were modified with binder additives (either cement, "C", or TiO_2, "T"). The number ("2.5" or "5") in the mix nomenclature indicates the percent addition of additional cement or TiO_2 by weight of cement. Given that both cement and TiO_2 additions were treated as binder components, a total water-to-binder (w/b) ratio is reported in lieu of a typical water-to-cement (w/c) ratio.

To simulate worst-case field conditions, mortar specimens were exposed to ambient air during the curing process. One additional set of Control specimens was cast and placed in a curing room in order to compare ideal conditions to the simulated field conditions. This additional set of Control specimens was cured for 28 days prior to mechanical testing. Compressive testing of the mortar cubes was

Table 1
Mortar constituents and mix design proportions.

Mix	Cement, lb [g]	Sand, lb [g]	Water, lb [g]	TiO_2, lb [g]	w/b
Control	1.10 [500]	3.03 [1375]	0.53 [242]	–	0.48
2.5C	1.13 [512.5]	3.03 [1375]	0.53 [242]	–	0.47
5C	1.16 [525]	3.03 [1375]	0.53 [242]	–	0.46
2.5T	1.10 [500]	3.03 [1375]	0.53 [242]	0.03 [12.5]	0.47
5T	1.10 [500]	3.03 [1375]	0.53 [242]	0.06 [25]	0.46