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Comparative assessment of pervious concrete mixtures containing fly ash and nanomaterials for compressive strength, physical durability, permeability, water quality performance and production cost

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HIGHLIGHTS

- Fly ash- and nanomaterial-added pervious concrete (PC) mixtures were tested.
- Strength, durability, permeability, water quality and production cost were tested.
- Although stronger and more durable, the nanomaterial-added PCs were costly.
- All the PCs were good at the removal of fecal coliform and phosphate.
- A PC needs to be selected depending on the application purpose and other factors.

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ABSTRACT

Three optimized fly ash (FA)- and nanomaterial-added pervious concrete mixtures (PC_{NI}, PC_{GP}, PC_{NS}) and one control PC_{CT} were compared for five criteria: compressive strength, physical durability, permeability, water quality performance and production cost. Both nanoSiO_2-added PC_{NS} and nanoFe-added PC_{NI} had a higher compressive strength (~17 MPa), a greater resistance to abrasion (<30% mass loss), and a better water quality improvement (<12 Water Quality Index) and runoff volume control (>8 mm/s permeability) than other two PCs. Nevertheless, the production of the nanomaterial-added PCs was costly than the control PC_{CT}. For those areas where a high compressive strength is not required, a cost-effective (~$360/m^3) PC_{CT} could manage stormwater well for runoff quality and volume. Although PC_{GP} could be produced with a high-volume FA substitution (60%), it was poor in other four criteria, especially in the compressive strength (4.7 MPa) and physical durability (59% mass loss).

1. Introduction

Pervious concrete (PC) has attracted more attention in concrete industry in pursuit of environmental protection and sustainability. Due to a porosity of 15–30% and a permeability of 1.4–12.4 mm/s, PC can infiltrate stormwater and reduce the volume of stormwater runoff [1]. However, for the same reason, PC is structurally weaker and less durable than the conventional concrete. In general, the compressive strength of PCs ranges from 2.8–28 MPa, which is lower than that of conventional concrete of 17–40 MPa [1].

As such, various chemical and mineral admixtures have been tested with PC to increase strength and durability. For example, nano-sized materials, although expensive, were added to PC mix design as nuclei and/or fillers to improve microstructure and overall quality and performance [2–4]. And also, from the environmental and economic perspective, an industrial byproduct fly ash (FA) has been applied in the production of cement and concrete composites [5]. In addition, results have shown that partial replacement of cement with FA improves the workability of fresh concrete and the mechanical strength and durability of hardened concrete [6,7].

Recently, several studies have reported an improved water quality by PC. A geopolymer PC removed fecal coliforms (FC) and phosphate (PO_4^--P) by 54–100% and 25–85%, respectively, depending on the contact time (0.5–8 h) in a batch reaction system [2]. A reduction of FC at ~ 99% and PO_4^--P at ~50% by a PC was achieved in a flow-through system [8]. PCs have also shown other benefits. For example, heavy metals in acid mine drainage were removed by >75% in a column setting with a PC reactive barrier [9].

However, no studies have been conducted to assess PCs for multiple characteristics encompassing the strength, hydrological

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property, and economy. That being said, this study aims to comparatively assess the FA-added, nanomaterial-contained PCs for the compressive strength, physical durability, permeability, water quality performance, and production cost. To this end, one control PC and three optimized PCs were compared: one newly optimized PC in this study and two previously optimized PCs [2,3].

2. Materials and methods

2.1. Materials

The main materials used for the PC production were FA, Portland cements (Type IP and GU), nano-sized silica (nanoSiO_2), nano-sized iron (nanoFe), water reducing agent (WR) and coarse aggregates. FA was obtained from a local coal-fueled power plant in Puerto Rico. Portland cements were acquired from local cement producers and both cements comply with ASTM C595 [10]. The physiochemical characteristics of Portland cements and FA are shown in Table 1.

The nanoSiO_2 powder and nanoFe liquid were purchased and used as received. NanoSiO_2 powder has an average particle size of 20–30 nm and a specific surface area of 180–600 m^2/g. NanoFe solution consists of (in% vol.) nominal 10-nm magnetite (2.8–3.5), proprietary surfactant(s) (2.0–4.0) and water (92.5–95.2). WR was obtained from a local vendor. It is based on polycarboxylate chemistry and its characteristics are unknown.

The coarse aggregates used were limestone gravels purchased from a local hardware store. Prior to use, they were sieved to collect the sizes in the range of 4.75–12.5 mm. The mass ratio of coarse aggregates to binder was fixed at 4:1. The binder is defined in this study as the total amount of Portland cement and FA. No fine aggregates were used in the study.

Table 1
Mineralogical compositions of Portland cements and fly ash used in the study.

	Cement Type IP	Cement Type GU	Fly Ash
SiO_2	27.14	19.80	30.84
Al_2O_3	6.68	5.10	9.93
Fe_2O_3	3.71	3.10	5.01
CaO	55.47	67.3	39.61
MgO	1.62	0.8	0.35
K_2O	0.48	–	1.01
Na_2O	0.59	–	0.90
SO_3	3.48	2.7	11.43
TiO_2	0.32	–	0.45
P_2O_5	0.11	–	0.11

Tap water was used for rainfall simulation in the water quality performance experiment. A mixture of treated wastewater effluent and fertilizer solution were used as the source of non-point source (NPS) pollutants, fecal coliform (FC) and phosphate (PO_4^--P). Treated wastewater effluent was collected at a local wastewater treatment prior to the chlorination process to ensure FC presence. A commercial fertilizer was dissolved in the treated wastewater effluent to increase the PO_4^--P concentration. Table 2 shows the physiochemical and biological characteristics of rainwater and NPS water.

2.2. New PC_{NS} optimization

The mix design for a nanoSiO_2-added PC (namely, PC_{NS}) was newly optimized in the current study for 28-day compressive strength and permeability by Response Surface Methodology (RSM) in a four-factor, two-level (2^4) central composite design (CCD) (Table 3). Type GU Portland cement, shown in Table 1, was used. The PC_{NS} mixtures were prepared with a mechanical mixer in accordance to the ASTM C192 [11] and were cast in a cylindrical plastic mold (10 cm in diameter × 20 cm in height). A total of 90 specimens were prepared (i.e., 30 combinations in triplicate, Table 4). The specimens in the mold were immediately put in an individual airtight plastic bag to minimize moisture loss. After a 24-h curing under ambient environment (20–30 °C), the specimens were demolded and further cured for 28 days in lime-saturated water under ambient environment.

2.3. Production of the optimized PCs

In addition to the newly optimized PC_{NS}, two other nanomaterial-added PCs (namely PC_{NI} and PC_{GP}) optimized by RSM in the previous studies [2,3] were used. A control PC (namely, PC_{CT}) was also produced with only cement, water and coarse aggregates. Table 5 shows the mix designs of three optimized PC_{NS}, PC_{NI}, and PC_{GP} and the control PC_{CT}.

2.4. System setup for water quality performance testing

The system consisted of a circular PC slab (25.4 cm in dia. × 10.2 cm in height), reservoir layer, and underdrain pipes in a high density polyethylene bucket (29.8 cm in dia. × 36.8 cm high). The reservoir layer was 25.4 cm deep and filled with 2.54-cm gravels. The perforated underdrain pipes (2.54 cm in dia.) were embedded on the top and bottom of the reservoir layer.

Table 2
Physiochemical and biological characteristics of rainwater and NPS water. Data are the average with standard deviations (in parenthesis, n = 8)[*].

	Rainwater			NPS water	
	Phase I	Phase II	Phase IV	Phase II	Phase IV
pH	8.03 (0.31)	7.61 (0.33)	7.71 (0.32)	7.28 (0.19)	7.16 (0.14)
Turbidity (NTU)	1.10 (0.71)	1.97 (1.69)	1.80 (1.84)	1.21 (0.41)	1.48 (0.25)
PO_4^--P (mg/L)	0 –	0 –	0 –	0.75 (0.54)	6.53 (3.14)
Fecal coliform (CFU/100 mL)[†]	0 –	0 –	0 –	83×10^3 (106×10^3)	95×10^3 (56×10^3)

[*] Phase I was with rainwater application only. Phase III was a dry period where neither rainwater nor NPS water was applied.
[†] CFU: colony forming unit.