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Research article

Mix design and pollution control potential of pervious concrete with non-compliant waste fly ash

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ABSTRACT

Pervious concrete mix was optimized for the maximum compressive strength and the desired permeability at 7 mm/s with varying percentages of water-to-binder (W/B), fly ash-to-binder (FA/B), nano-iron oxide-to-binder (NI/B) and water reducer-to-binder (WR/B). The mass ratio of coarse aggregates in sizes of 4.75–9.5 mm to the binder was fixed at 4:1. Waste FA used in the study was not compliant with a standard specification for use as a mineral admixture in concrete. One optimum pervious concrete (Opt A) targeting high volume FA utilization had a 28-day compressive strength of 22.8 MPa and a permeability of 5.6 mm/s with a mix design at 36% W/B, 35% FA/B, 6% NI/B and 1.2% WR/B. The other (Opt B) targeting a less use of admixtures had a 28-day compressive strength and a permeability of 21.4 MPa and 7.6 mm/s, respectively, at 32% W/B, 10% FA/B, 0.5% NI/B and 0.8% WR/B. During 10 loads at a 2-h contact time each, the Opt A and Opt B achieved the average fecal coliform removals of 72.4% and 77.9% and phosphorus removals of 49.8% and 40.5%, respectively. Therefore, non-compliant waste FA could be utilized for a cleaner production of pervious concrete possessing a greater structural strength and compatible hydrological property and pollution control potential, compared to the ordinary pervious concrete.

1. Introduction

The presence of pathogens in urban runoff is a serious threat to human health and can also result in water body impairment. Fecal coliforms (FC) are indicator microorganisms of harmful pathogens in water bodies (USEPA, 2005). Another contamination of concern in urban runoff is nutrient over-enrichment primarily with phosphorous (P) and nitrogen. This over-enrichment promotes excessive growth and further decomposition of aquatic plants, resulting in oxygen depletion in water and the growth of toxic cyanobacteria (USEPA, 2005).

Pervious concrete pavements (PCPs) allow runoff water to infiltrate into the ground, reducing the risk of flash flooding caused by storm water runoff (Rahman et al., 2015) and also increasing water conservation (Nnadi et al., 2015). PCPs are also capable of reducing pollutant concentrations while infiltrating the captured water (Luck et al., 2009).

However, PCPs are structurally weaker than ordinary impervious concrete pavements due to their void content. To improve the mechanical strengths of PCPs, waste fly ash (FA) has been used to partially replace the cement in the mixture (Vázquez-Rivera et al., 2015). Using FA in the production of PCPs also generates additional environmental benefits by decreasing CO_2 emission in the production of cement and by reducing FA disposal in landfills. Engineered nanomaterials, for example, SiO_2 and Al_2O_3, have also been added to improve the mechanical strength and durability of cement and concrete materials (Li, 2004; Nazari and Riahi, 2011). Another common admixture is water reducer (WR) that enhances workability of fresh-state concrete and at the same time reduces the amount of water needed for cement hydration (Mardani-Aghbaglou et al., 2013). An enhanced mechanical strength of concrete with the WR admixture has also been documented (Barbudo et al., 2013).

As the extent and rate of cement hydration depend on the types and amount of the admixtures, it is critical to find an optimum mix ratio that produces the desired structural and hydrological properties of PCPs while possessing a substantial pollutant reduction potential. However, there are a few existing studies on this issue (Jo et al., 2015; Vázquez-Rivera et al., 2015).

In this regard, this study investigated a cleaner production of pervious concrete containing waste FA, a solid waste unless

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otherwise utilized, in combination with other admixtures of nano-iron oxide (NI) and WR. The mix design with the percentages of water-to-binder (W/B), FA/B, NI/B and WR/B was optimized for the desired permeability and compressive strength. Binder is defined in this study as the total amount of Portland cement and FA. Then, the optimized pervious concrete was tested for their pollution control potential in FC and P removal in water. Having said that, this study aimed to develop a construction material, i.e., pervious concrete, in line with both solid waste management by utilizing a non-compliant waste FA as an admixture in concrete and water quality management with the pervious concrete for the removals of FC and P that are commonly present in storm water runoff.

2. Materials and method

2.1. Materials

Portland cement Type IP in compliance with ASTM C595 was used in the study. Waste FA was obtained from a local coal-fueled power plant (AES Puerto Rico). The characteristics of the cement and FA are shown in Table 1. It should be noted that waste FA is non-compliant with a standard specification due to its SO_3 content (11.43%) which is much higher than the maximum value of 5% specified in ASTM C618.

Limestone gravel in the range size of 4.75–9.5 mm was used as a coarse aggregate. The mass ratio of coarse aggregate to the binder was fixed at 4:1 and no fine aggregates were used in the study. The NI solution consisted of (in % vol.) nominal 10-nm magnetite (2.8–3.5), proprietary surfactant(s) (2.0–4.0) and water (92.5–95.2). It was purchased from Ferrotec (Bedford, NH). The BASF Glenium 3030 NS was used as the WR. It is based on polycarboxylate chemistry and its characteristics are unknown.

2.2. Specimen design, curing and testing

Pervious concrete specimens were prepared in a four-factor, two-level (2^4), central composite design (Table 2). A total of 20 experiments in triplicate were run with six replicates at the center points. The mixture was prepared in a mechanical mixer and then cast in the cylindrical molds (10 × 20 cm) using the rodding consolidation method in accordance to ASTM C192. After 24 h, the specimens were demolded and cured for 28 days in lime-saturated tap water at ambient temperature (24 ± 2 °C).

The compressive strength of the pervious concrete specimens was tested in accordance to ASTM C39 by a 3000 kN Forney universal testing machine. Permeability of the pervious concrete specimens was measured in a constant-head permeameter modified from ASTM D2434 to accommodate the pervious concrete specimens. The testing results were averaged from the triplicate pervious concrete specimens.

2.3. Optimum design mix

Two different optimum pervious concretes (Opt A and Opt B) were prepared in triplicate with the optimum mix design results from the Response Surface Methodology of the central composite design. The selection of the Opt A and the Opt B was based on the intention to achieve a high volume FA utilization in one optimum mix design (Opt A) and to use less water and admixtures of NI and WR in the other optimum mix design (Opt B), while achieving the desired permeability and maximum compressive strength for both mixtures.

An ordinary Portland cement pervious concrete (the Control) was also prepared in triplicate at 34% W/B without the addition of FA, NI, and WR. The permeability, compressive strength, and FC and P removals of the Control were also measured in the same manner as the optimum pervious concretes Opt A and Opt B for comparison purposes.

Table 1
Mineralogical composition of PC and FA used in the study.

	Oxide content (wt. %)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5
PC	27.14	6.68	3.71	55.47	1.62	3.48	0.59	0.48	0.32	0.11
FA	30.84	9.93	5.01	39.61	0.35	11.43	0.9	1.01	0.45	0.11

Table 2
Four-factor, two-level (2^4) central composite design.

Factor	Level				
	Axial	Low	Center	High	Axial
W/B	30	32	34	36	38
FA/B	0	10	20	30	40
NI/B	0	1.7	3.4	5.1	6.8
WR/B	0	0.4	0.8	1.2	1.6

2.4. FC and P removals

Treated wastewater effluent (TWE) prior to disinfection was collected from a local wastewater treatment plant and was used for the FC and P removal experiment. Its main biochemical characteristics are: pH 7.44 ± 0.40 (n = 10), 13.2 ± 3.3 mg COD/L (n = 10), 26.5 ± 11.6 mg PO_4^{3-}—P/L (n = 10), and 4.7 ± 6.1 × 10^3 colony-forming unit (CFU) of FC per 100 mL (n = 7). The reactors were initially filled with 400 mL of fresh TWE. After 2 h of contact time, water was decanted for the FC and P analyses. The aqueous pH was measured by submerging a pH probe in the decanted water. On the following day, another set of the experiment was conducted in the same manner. In this way, FC and P removals were repeated 10 times.

FC analysis was done by a membrane filtration technique with a 0.45-μm cellulose ester membrane. The filtered membrane was placed on the HACH m-FC broth in Petri dish and incubated for 24 h at 44.5 °C. Blue colonies were considered as FC and expressed in CFU/100 mL. A Shimadzu Prominence IC system (Kyoto, Japan) was used for the P analysis as PO_4^{3-}—P. A chromatographic separation was achieved at 45 °C with a Shodex SI-52 4E anion column (4.0 mm i.d. × 250 mm) (Showa Denko, Tokyo, Japan). The mobile phase was 3.6 mM sodium carbonate passing through the column at a flow rate of 0.9 mL/min. The sample injection volume was 20 μL.

3. Results and discussion

3.1. Responses and prediction models

The compressive strength was measured in a range of 6.0–24.3 MPa (Fig. 1a) which was congruent with the reported compressive strength of ordinary Portland cement pervious concrete (2.8–28 MPa) (ACI, 2010). However, the pervious concrete in this study had a greater compressive strength than those reported in the previous study (2.5–13.5 MPa, Vázquez-Rivera et al., 2015) where the same types of FA, NI and coarse aggregates were used. This disparity could have been attributed to the WR used in the current study. Barbudo et al. (2013) also reported an enhanced mechanical strength and workability of concrete when addition WR.