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Research article

Effects of coal fly ash and fine sawdust on the performance of pervious concrete

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ABSTRACT

Pervious Concrete (PC) has long been used in surface runoff management. But one of its major drawbacks is its low strength. Several industrial wastes apparently contain properties that could aid the increase in strength of PC such as coal fly ash and fine sawdust. Thus, their utilization is a possible solution that could address the low-strength issues of PC along with industrial waste disposal management. This study was conducted to investigate the laboratory and field performance of PC while incorporating coal fly ash (CFA) as partial cement replacement and fine sawdust (FSD) as internal curing agent and filler admixture. Tests were performed in accordance with American Society for Testing and Materials (ASTM) standards. In general, the test results showed that PC with CFA and FSD as additives in PC gained enough strength to be considered for field application. In-situ infiltration and strength results showed that the pavement conformed to the typical values for a functional PC pavement.

1. Introduction

Flooding is common particularly in urban areas where concrete is extensively used. Concrete used in pavements is usually an impervious surface that does not allow rainwater to percolate through the soil. This leads to urban runoff and eventually causes flooding. This situation will become worse because of climate change, increasing urbanization and poor stormwater management systems. One of the best adaptation strategies to address this issue is the application of pervious concrete pavement in surface runoff management (Topličić-Ćurčić et al., 2015). Pervious concrete can be defined as an open-graded or "no-fines" concrete allows rainwater to percolate to the underlying sub-base due to its high permeability (ACI Committee 522 2006).

Pervious concrete (PC) is a composite material primarily made up of cement, water, and coarse aggregates that has a significantly high permeability compared to conventional concrete and is known to have the advantages of reducing runoff volume and possible improvement of water quality in ground water recharge (Legret et al., 1996). Other advantages of PC include better road safety because of increased skid resistance (Schaefer et al., 2006), road sound damping (Olek et al., 2003), and dampening of the "heat island "effect (Yang and Jiang, 2003; Shu et al., 2011). A significant drawback of pervious concrete that hinders its potential to be used in large scale is its relative weakness, low durability, and the maintenance due to clogging (Ghafoori and Dutta, 1995). Its use has been limited to parking lots, driveways, sidewalks, and roads with low traffic.

The compressive strength and permeability of a typical PC with cement to coarse aggregate ratio of 0.30 with aggregate size of 9.5 mm is generally around 10 MPa and 0.4 cm/s, respectively (Joung and Grasley, 2008). To address its strength and durability drawbacks, several studies during the recent years were conducted to create a pervious concrete structure with optimum permeability and compressive/flexural strength. These include the use of appropriate amount of water, cement, type and size of aggregate, optimum mix design proportion and the type of organic intensifiers (Yang and Jiang, 2003; Wang et al., 2006; Kevern et al., 2010) and addition of polymer to improve workability, strength, and freeze–thaw resistance while maintaining its high porosity and permeability (Kevern, 2008; Huang et al., 2010). Moreover, recent studies have shown that the compressive strength of PC could be enhanced above 20 MPa through addition of polymer, latex, fine aggregates and various types of admixtures without compromising its durability and permeability requirements (Shu et al., 2011).

One of the areas to be explored is the enhancement of the strength and durability of PC by adding fine sawdust as low-cost internal curing agent (Usman et al., 2018), filler material and/or as additive in lieu of fine sand (Belhadja et al., 2014). Water absorbed by sawdust (or wood

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aggregates in general) when it is mixed with other concrete components helps in hydration particularly in the interior where curing is impossible. It could lessen curing time in half (Ganiron, 2014). The ability of sawdust to absorb water and releasing it later suggests that it has the potential to serve as an internal curing agent in self-compacting cementitious systems at 2–7% replacement of cement (Usman et al., 2018) and at 60% replacement of sand in conventional sand concrete (Belhadja et al., 2014) but showed prominent strength reduction. However, improved bonding between wood chippings and cement paste could be observed when wood chippings were saturated with sodium silicate solution prior to its use (Coatanlem et al., 2006). Moreover, a better performance of mortar was observed by Corinaldesi et al. (2016) when using fine sawdust particle rather than using coarse size.

On the other hand, the addition of coal fly ash in the concrete mix is reported to increase the compressive strength of concrete (Thomas, 2007; Bremseth, 2010; Mallisa and Turuallo, 2017). When added to the mixture, coal fly ash reduces the water demand of the concrete by 5–15 percent. It also has a retarding effect (Helmuth, 1987) which is gainful in concreting in warm weather (Shi and Qian, 2003). Replacement of a portion of the cement with coal fly ash results in a low early strength of concrete, but exceeds that of Portland cement at 3–6 months in some cases. The higher strength is a result of pozzolanic reactions favouring calcium silicate hydrate (C–S–H) while decreasing $Ca(OH)_2$ (Shi and Qian, 2003; Opiso et al., 2017). Increased $Ca(OH)_2$ limits the strength of the concrete because $Ca(OH)_2$ tends to cleave under shear stress (Mindess and Young, 1981).

The synergistic effect of the combined utilization of fine sawdust and coal fly ash which have properties that can possibly amplify the quality of PC could possibly aid in the development of a functional and durable PC pavement. However, studies concerning the effects of their combined utilization on the performance of PC are not yet elucidated. In this context, the objective of this work is to study the contribution of coal fly ash and fine sawdust to the development of eco-PC pavement without compromising its performance based on strength, permeability and mode of maintenance.

2. Materials and methods

The variables measured to determine the performance of the PC are compressive strength, flexural strength, permeability and in-place infiltration rate. Field application of the PC developed was also conducted and the same variables were measured. Furthermore, the mode of maintenance was also evaluated.

2.1. Materials

The Type I Ordinary Portland cement (OPC) used in this study conformed to ASTM Standard C150. The aggregate size that was used ranged from 5 to 19 mm. Also, potable tap water was used as per ASTM C1602. The sawdust was collected from a local sawmill site. It was dried either by sun-drying or oven-drying to remove moisture which can affect the final water-cementitious materials (w/c) ratio. It was then sieved through mesh no. 8 (2.36 mm) to produce fine sawdust (FSD) with bulk specific gravity of 0.359, water absorption capacity of 89.82%, and fineness modulus of 3.69. Class C fly ash with pozzolanic activity index of 75% (Sideris et al., 2018) was obtained from a coal power plant located in Mindanao and sieved through mesh no. 200 (75 μm) to ensure the fineness of the particles. The chemical composition of cementitious materials is summarized in Table 1.

2.2. Determination of optimal FSD amount

In order determine the optimal FSD amount to be added to the succeeding experiments on concrete mixture of PC blended with coal fly ash, a concrete mixture with cement to coarse aggregate ratio of 1:3 and w/c of 0.50 was prepared. The corresponding amount of FSD was added ranging from 0 to 12% by weight of cement at 2% interval and the coarse aggregate used had a range of 5–9 mm. The concrete mix was then cured for 28 days and the compressive strength was measured as a function of percentage of FSD added to the mix. The FSD percentage with the highest compressive strength is the optimal amount of FSD to be used for the development of PC incorporated with coal fly ash as partial cement replacement. On the other hand, the compressive strength and permeability of a PC is mainly determined by the aggregate size. Compressive strength is inversely proportional to aggregate size while permeability is directly related to aggregate size. Anent to this, the effect of the optimal amount of FSD on the compressive strength and permeability of PC using varying sizes of aggregates was also evaluated in order to give insights in the selection of appropriate aggregate size that will meet the strength requirement of the specific type of field application. Using the same concrete mixture, w/c ratio, and the optimal FSD, samples with aggregate sizes of 5–9 mm, 10–14 mm, and 15–19 mm were produced. Samples were cured for 28 days and then tested for compressive strength and permeability.

2.3. Preparation of PC samples with CFA and FSD

Based on the results of the effect of FSD on the compressive strength and permeability of PC, the final mix proportion selected for the production of PC with CFA and FSD was composed of 8% FSD by weight of cement and aggregate size range of 10–14 mm. Ten percent (10%) replacement of ordinary Portland cement (OPC) with coal fly ash (CFA) was considered in this study because the relative strength of the concrete is higher and changes less at the early and later ages compared to other proportions (Neville, 1981). However, the w/c used was 0.35 instead of 0.50 and the design mix ratio was also changed to 1:3.5 for permeability and mixture consistency purposes. It is noted that higher w/c ratio will cause the cement paste to settle at the bottom. Table 2 shows the summary of mix proportions. The mixing was performed using a one-bag concrete mixer. The components were allowed to be mixed until homogeneity was achieved. Subsequently, the freshly mixed PC was cast into steel rectangular beam molds (152.4 mm × 152.4 mm × 533.4 mm) and cylindrical molds (152.4 mm in diameter (Φ) × 304.8 mm and 101.6 mm Φ × 152.4 mm). The cylindrical and rectangular PC samples were removed from their molds after 24 and 48 h, respectively. They were stored in a laboratory with ambient conditions and cured for 7, 14, and 28 days through sprinkling. During curing, the PC samples were not covered with a plastic sheet, as was conventionally used. There were five specimens for each cylindrical and rectangular beam PC were made in which three were randomly selected for compressive and flexural strength test.

Table 2
Quantity of materials per m^3 of pervious concrete.

Mixture	Aggregate, kg	OPC, kg	CFA, kg	FSD, kg	Water, kg
Control	1700	486	-	-	170
Treated	1700	442	44	39	170

Table 1
Chemical composition of the cementitious materials.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	K_2O	SO_3	LOI
OPC	20.9	-	5.7	2.8	-	2.7	61.8	-	2.0	2.9
CFA	23.9	0.6	9.1	28.5	0.3	9.7	23.3	0.6	3.0	16.0

2.4. Experimental methods

2.4.1. Compression test

Compression test was performed in accordance with ASTM C39 or the "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens". Three cylindrical PC specimens with dimensions 152.4 mm $\Phi \times$ 304.8 mm were tested for compressive strength after the designated curing days. Before testing the PC samples, each was measured and weighed. The average of three samples was recorded as the final compressive strength in MPa.

2.4.2. Flexure test

Conforming to ASTM Standard C78 or the "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)", three rectangular beam specimens were tested and loaded as simple beams with a third-point loading setup for a flexural strength test. The test was performed using a Compression Machine with flexural test appurtenances. Prior to testing, each of the samples was measured and weighed. At both ends of every specimen, an inch from the edge was marked to easily locate the point where the support blocks of the machine would be aligned. The remaining length of each specimen was divided and marked into three equal parts. The average strength result of three samples was recorded as the final flexural strength in MPa.

2.4.3. Permeability test

Permeability test was conducted on the PC samples with dimensions 101.6 mm $\Phi \times$ 152.4 mm using the falling head method. Each of the PC samples was individually placed inside the cell of the apparatus and had three (3) timed trials. Prior to testing, the inside surface of the apparatus including the tubes was wetted first so as not to affect the speed and volume of water that flows through it. The average of 3 trials of 3 different samples was taken as the final hydraulic conductivity in cm·s^{-1}. The hydraulic conductivity was computed as in Eq. (1),

$$k = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right) \tag{1}$$

where a = cross-sectional area of the tube in cm^2, L = length of specimen in cm, A = cross-sectional area of the specimen in cm^2, t = time elapsed in s, h_1 = initial head of water in cm, and h_2 = final head of water in cm.

2.4.4. Morphological test

Field Emission Scanning Electron Microscopy (FESEM) Imaging was conducted to obtain microstructural details on the hardened bulk cement paste of the PC structure after 28 days of curing. The analysis was performed using a Dual Beam Helios Nanolab 600i instrument with an accelerating voltage of 5.0 kV in a Backscattered Electron (BSE) mode and a beam current of 0.17 nA.

2.5. Field application

A parking block with a dimension of 6 m × 2.6 m × 101.6 mm was prepared to be laid with PC (Fig. 1). The materials for the field application were obtained from the same sources and were prepared similarly. However, the aggregate size used was 15–19 mm typically due to practicality and availability. Also, its laboratory strength of 17.615 MPa could suffice for a parking lot application which does not require higher strength compared to roads.

Concrete core samples were obtained from PC pavement in accordance with ASTM Standard C42 or the "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete". The drilled cores had uneven surfaces especially on the bottom portion so that they were saw-cut to create a smooth surface. Compression testing of the polished core samples were then carried out. Since the length-to-diameter ratio of the core samples is not standard, necessary corrections were applied. The testing procedure performed is compliant to ASTM C39.

Fig. 1. Field application of pervious concrete in a parking lot during (a) pouring, (b) casting and (c) final laying of PC mix.

Field infiltration of pervious concrete was determined using ASTM C1701 or the "Standard Test Method for Infiltration of In-Place Pervious Concrete" which is a single infiltration ring set-up using a constant head methodology. ASTM C1701 can be used to verify the desired infiltration rates of specific mix designs, test initial permeability, and test permeability reduction over time. The ring was secured to the pavement with sealant (plumber's putty) to prevent water leakage. The pavement was pre-wetted by pouring about 3.6 kg of water into the ring at a rate sufficient to maintain a head between the marked lines at a distance of 10 and 15 mm from the bottom, until the 3.6 kg of water has been totally used. For the actual test, 18 kg of water was used. The time started as soon as the water impacted the pervious concrete surface and was stopped when free water was no longer present on the pervious surface. The appropriate mass of water M and the elapsed time t duration was then recorded. Finally, the infiltration rate was computed. The result was calculated using the formula

$$I = \frac{KM}{D^2 t} \tag{2}$$

where I = infiltration rate in cm·s^{-1}, K = 4 583 666 cm^3 kg^{-1}, M = mass of infiltrated water in kg, D = inside diameter of infiltration ring in cm, and t = time required for measured amount of water to infiltrate, in s.

2.6. Maintenance assessment

Maintenance assessment with regards to the serviceability of pervious concrete pavement was evaluated based on its infiltration rate, since debris and residues accumulate over time. The initial infiltration rate of the pavement was determined 48 h after construction in accordance with ASTM standards for Infiltration Rate of In-Place Pervious Concrete. The maintenance assessment of the parking was conducted after two months it was open to the public. The infiltration rate test was conducted on three randomly selected location points. The appropriate type of cleaning methods (vacuuming, power blowing and pressure washing) was determined based on the difference of infiltration rate before and after maintenance application.

3. Results and discussion

3.1. Determination of optimal FSD amount

Fig. 2 shows the average compressive strength results which showed that the compressive strength of treatments passed the minimum requirement for pervious concrete standards which is 3.5 MPa according to the provisions of National Ready Mix Concrete Association (NRMCA, 2011) and were therefore suitable for a wide range of application. Moreover, the addition of fine sawdust influenced the compressive strength of pervious concrete. The compressive strength increases from T_1 (24.253 MPa) to T_4 (29.127 MPa) and decreased abruptly as the amount of fine sawdust increases from T_4 (29.127 MPa) to T_6 (10.123 MPa). The observed increasing strength could be due to the presence of fine sawdust acting probably as filler material. Moreover, the decrease in compressive strength beyond T_4 may be again caused by the lack of

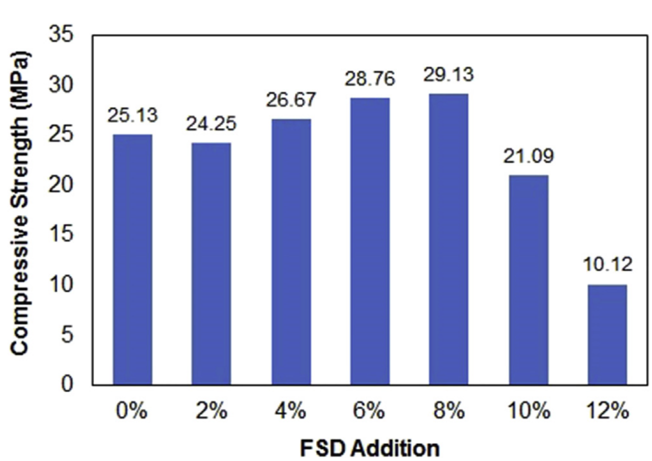

Fig. 2. Average compressive strengths of pervious concrete samples with varying amount of fine sawdust.

available water during hydration and possible increase in porosity due to sawdust addition. It can be observed that T_4 showed the highest compressive strength compared to other treatments including the control mix. Moreover, only T_3 and T_4 showed relatively higher compressive strength compared to the control mix. The optimum amount of fine sawdust that can be used as internal curing agent and filler materials was, therefore, 8% by mass of cement. Also, the results of the compressive strength were comparable and even higher compared to the similar study of Joung and Grasley (2008).

Table 3 shows the average compressive strengths and permeability of samples with different aggregate sizes added with 8% of FSD. It can be observed that the compressive strength decreases as aggregate size increases; whereas, the permeability increases with aggregate size. This can be attributed to increased void content as aggregate size increases which results to higher hydraulic conductivity (Kováč and Sičáková, 2018). However, increased void content results to a weaker compressive strength due to fewer surfaces available for binding. The results also revealed that the most desirable aggregate size in terms of compressive strength is 5–9 mm similar to a study by Maguesvari and Narasimha (2013). Also, the results of the permeability test were much lower compared to the similar work of Huang et al. (2010) since the earlier study utilized a cement to aggregate ratio of 1:4.5. However, the effect of the optimal amount of FSD on permeability was not prominent which implies that the addition of optimal amount of FSD will not have a significant consideration in the selection of aggregate size that will meet the strength requirement of the specific type of field application such as paving blocks, sidewalks, parking lots and secondary roads.

3.2. Laboratory performance of PC with CFA and FSD

3.2.1. Compressive strength

Strength development of PC with different mixtures is shown in Fig. 3. The general trend of the compressive strength is increasing with curing time. The compressive strength of blended PC achieved the minimum value of the usual range (f_c = 3.5–28 MPa) for pervious concrete standards set by National Ready Mix Concrete Association (NRMCA, 2011). The blended PC also showed no significant difference compared to control PCs used in this study but significantly gained more strength in the latter stage obtaining 10.8 MPa (at 28 days). The slow strength development of PC with CFA & FSD could be attributed to the slow reaction of CFA in the formation of calcium aluminate precipitates (De Weerdt et al., 2011). Moreover, the compressive strength of blended PC after 28 days of curing was slightly lower to the maximum value obtained by Vázquez-Rivera et al. (2015) of 13.5 MPa on blended PC incorporated with coal fly ash and iron oxide nanoparticles.

3.2.2. Flexural strength

Third-point bending test was performed to determine the flexural strength. The average flexural strengths for different curing days are presented in Fig. 4. It can be observed that after 28 curing days, the flexural strength of PC with CFA & FSD passed the domestic and international standard requirement for flexural strength of concrete parking lots of 3.5–4.5 MPa (ACI Committee, 2001) by gaining 4.167 MPa. The flexural strength values were much higher compared to the study of Muthaiyan and Thirumalai (2017) on blended PC with 10% coal fly ash replacement which could be attributed to their higher cement to coarse aggregate ratio of 1:6.7. Similar to the results of compressive strength, the flexural strength of PC with CFA & FSD gained more strength at the

Table 3
Compressive strength and permeability of samples at 28 days.

Aggregate Size, mm	Average Compressive Strength, MPa	Permeability, cm·s^{-1}
5–9	29.127	0.02450
10–14	21.047	0.02551
15–19	17.615	0.02664

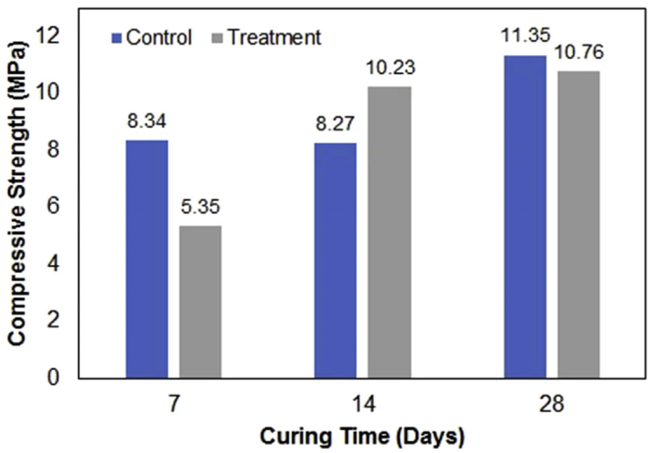

Fig. 3. Compressive strength of PC with coal fly ash and optimum amount of fine sawdust at different curing time.

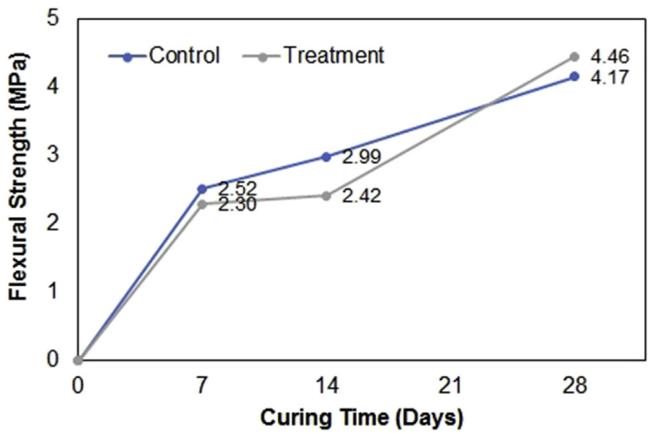

Fig. 4. Flexural strength of PC with coal fly ash and optimum amount of fine sawdust at different curing time.

later age with increasing trend and it may suggest that it will still increase as curing progresses over time.

3.2.3. Permeability

As shown in Fig. 5, the hydraulic conductivity (coefficient of permeability) for all mixtures and sizes ranged from 0.0192 to 0.0269 cm s^{-1}. The obtained hydraulic conductivity values were not comparable and even much lower compared to works of Muthaiyan & Thirumalai (2017) and Vázquez-Rivera et al. (2015) due to the different design mix proportion used in this study. However, these hydraulic conductivity values already exceeded the minimum acceptable permeability of greater than 0.0100 cm s^{-1} which could aid in the reduction of runoff water and in the decrease of flood volume and depth in flood-prone urban areas (Kevern et al., 2008). Also, it can be observed that as the aggregate size increase, the permeability also increased which was true in all mixtures. This is because permeability is mainly dependent on the volume of interconnected pores (Maguesvari and Narasimha, 2013) which is proportional to the aggregate size. However, increasing the aggregate size which could lead to larger volume of pores and higher permeability will consequently decrease its strength. It can also be observed that PC with CFA and FSD has a higher hydraulic conductivity compared to the control PC which could be attributed to the increased porosity of the cementitious material after reacting with CFA and water (Opiso et al., 2017).

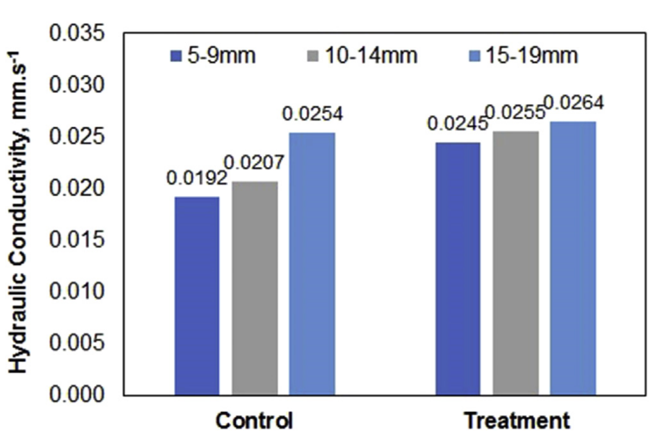

Fig. 5. Hydraulic conductivity of different PC with coal fly ash and fine sawdust using different coarse aggregates sizes.

3.2.4. Morphology of hardened cement paste

Scanning electron micrographs of hardened cement pastes from control and treated PC after 28 days of curing are shown in Figs. 6 and 7, respectively. It can be observed in the following figures that the three basic phases (viz. hydrated cement particles, outer hydration product and large pores [Thomas and Jennings, 2009]) are present in all mixtures. For the control PC, portlandite, ettringite, and CSH were visible and more refined which indicate partial hydration of cement. On the other hand, the treated PC has a relatively less resolved image of portlandite and CSH. Ettringite was also not observed in treated PC samples. Ettringite

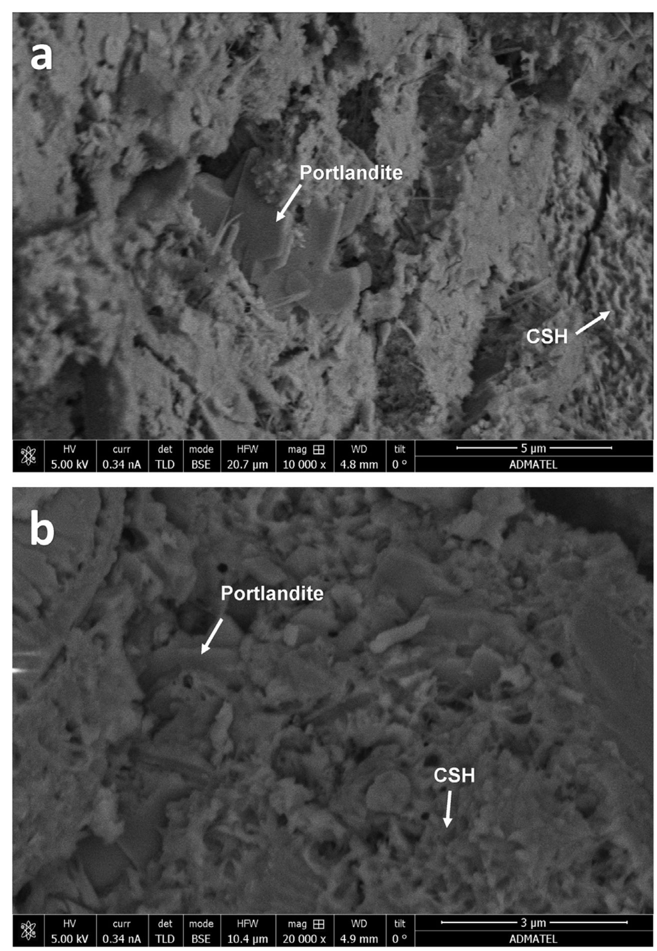

Fig. 6. FESEM images of hardened cement paste of control PC after a 28-day curing period at 10000x (a) and 20000x (b) magnification.

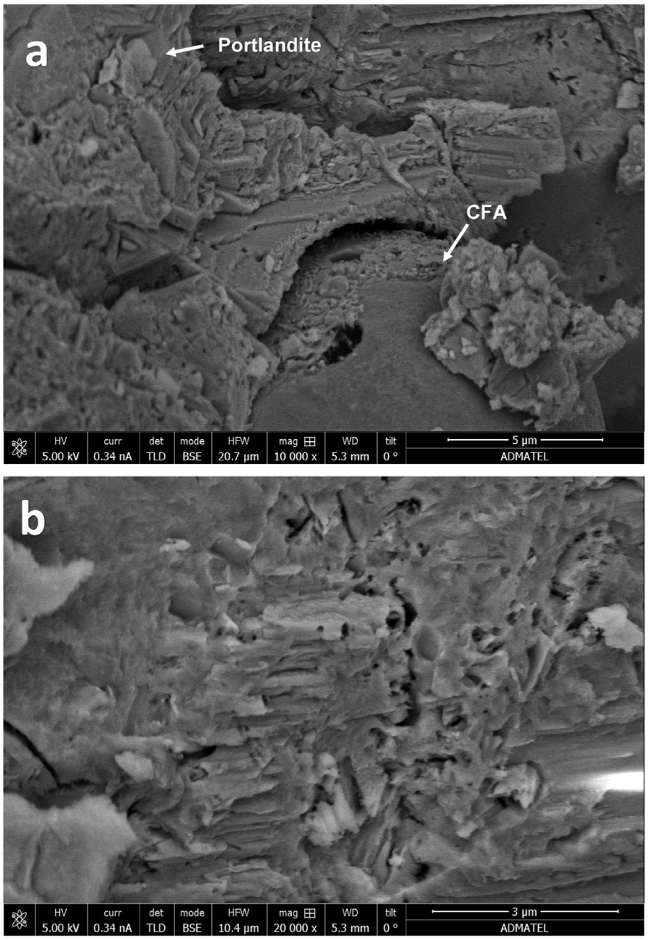

Fig. 7. FESEM images of hardened cement paste of PC with CFA and FSD after a 28-day curing period at 10000x (a) and 20000x (b) magnification.

has a tendency to accelerate the deterioration of concrete as it dissolves and recrystallizes in larger spaces (Kosmatka et al., 2002). This could indicate that treated PC will not be susceptible to deterioration due to ettringite formation in the long-term. It can also be noticed that there is accumulation on CFA surface which indicates partial formation of calcium aluminate silicate hydrate (CASH). Treated PC has a visible gap in the interfacial transition zone between the cement and CFA particle which could otherwise have been filled by CSH gel. This indicates the slow reactivity of CFA which could explain the relatively weaker strength of the treated PC. In the long-term, it is expected that the CFA will fully react and fill those gaps to further strengthen the treated PC.

3.3. Field performance

3.3.1. Compressive strength of core samples

The core samples from in-place PC pavement gained an average compressive strength of 6.7 MPa. This lower compressive strength in the field compared to laboratory results indicates that the cores samples have been probably “overworked” during installation and inconsistencies occurred during placement and curing of the PC pavements (Radlińska et al., 2012). This result was also expected as larger aggregate sizes were used. However, this value is still within the normal range for compressive strength of PCs.

3.3.2. Initial infiltration rate

The surface infiltration rate at the parking lot pavement was tested. As observed, the average infiltration rate of 0.4613 cm s^{-1} is significantly high. According to the National Ready-Mix Concrete Association (NRMCA, 2011) (n.d.), typical values for PCs range from 0.20 to 0.54 cm s^{-1}. By this standard, the parking lot PC pavement can be considered as a “pervious concrete” pavement. Also, the infiltration rate results correspond with the results of the compressive strength since the more porous the structure is, the more permeable and weaker its strength.

Table 4
Surface infiltration rates of parking lot pavement.

Site	Maintenance Method	Average Infiltration Rate, cm/s		% increase
		Before maintenance	After maintenance	
1	Vacuum	0.1446	0.1705	17.9
2	Blower	0.0783	0.0787	0.5
3	Pressure Washer	0.0600	0.0730	21.7

3.3.3. Maintenance

Three maintenance methods—vacuuming, blowing and pressure washing—for PC pavements were evaluated. Infiltration rates prior to maintenance of pavements were recorded as references to be compared with the infiltration rates after implementing maintenance to assess the effectivity and efficiency of maintenance methods as summarized in Table 4. The data show that after maintenance an increase in infiltration rate was observed in all site locations wherein Site 1 (pressure washing) gained the overall highest increase in permeability of 21.7%, followed by Site 3 (vacuuming) which recorded a 17.9% increase while Site 2 (blowing) only improved by 0.5%. Based on the acquired data on infiltration rates, pressure washing is the most effective maintenance method for pervious concrete pavement, followed by vacuuming. Furthermore, the infiltration rates at the test sites showed no indication of ponding although the assessment showed significant increase.

4. Conclusion

Based on the results, the selected design mix ratio of 1:3.5, at a w/c ratio of 0.35 for the PC with CFA and FSD passed the compressive, flexural and permeability requirements and it was within the typical range of values for both strength and permeability properties of a well-functioning PC pavement as per NRMCA. The laboratory assessment revealed that the blended PC showed no significant difference compared to the plain PC. This implies that the use of cement could be minimized up to 10% in blended PC with CFA and FSD without compromising its strength and permeability performance. In-situ tests for compressive strength of core samples and infiltration rate were acceptable and in conformity to standard values for PC pavements. Comparison of surface infiltration rates confirms that pressure washing is the most effective maintenance method followed closely by vacuuming. Furthermore, the use of CFA and FSD as additives could be a viable sustainable application of these industrial wastes in improving the performance of PC that could be considered for field application.

Declarations

Author contribution statement

Einstine M. Opiso: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Reinerio P. Supremo: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Jemima R. Perodes: Performed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

ACI Committee 330, 2001. Guide for Design and Construction of concrete Parking Lots. American Concrete Institute, Michigan.
ACI Committee 522, 2006. Pervious Concrete, 24pp. American Concrete Institute, Michigan, USA.
Belhadja, B., Bederinaa, M., Montrelayb, N., Houessoub, J., Quéneudecb, M., 2014. Effect of substitution of wood shavings by barley straws on the physico-mechanical properties of lightweight sand concrete. Constr. Build. Mater. 66 (2014), 247–258.
Bremseth, S.K., 2010. Fly Ash in concrete: A Literature Study of the Advantages and Disadvantages. SINTEF Building and Infrastructure, Oslo, Norway.
Coatanlem, P., Jauberthie, R., Rendell, F., 2006. Lightweight wood chipping concrete durability. Constr. Build. Mater. 20, 776e781.
Corinaldesi, V., Mazzoli, A., Siddique, R., 2016. Characterization of lightweight mortars containing wood processing by-products waste. Constr. Build. Mater. 123, 281e289.
De Weerdt, K., Kjellsen, K., Sellevold, E., Justnes, H., 2011. Synergy between fly ash and limestone powder in ternary cements. Cement Concr. Compos. 33 (1), 30–38.
Ganiron, T.U., 2014. Effect of sawdust as fine aggregate in concrete mixture for building construction. Int. J. Adv. Sci. Eng. Inf. Technol. 63, 73–82.
Ghafoori, N., Dutta, S., 1995. Laboratory investigation of compacted no-fines concrete for paving materials. J. Mater. Civ. Eng. 7 (3), 183–191.
Helmuth, R., 1987. Fly Ash in Cement and concrete. Portland Cement Association, Skokie, Illinois.
Huang, B., Wu, H., Shu, X., Burdette, E.G., 2010. Laboratory evaluation of permeability and strength of polymer-modified pervious concrete. Constr. Build. Mater. 24 (2010), 818–823.
Joung, Y., Grasley, Z.C., 2008. Evaluation of Optimization of Durable Pervious Concrete for Use in Urban Areas. Southwest Region University Transportation Center. Research Report SWUTC/08/167163-1.
Kevern, J.T., 2008. "Advancements in Pervious concrete Technology". *Retrospective Theses and Dissertations*. Digital Repository @ Iowa State University.
Kevern, J.T., Schaefer, V.R., Wang, K., Suleiman, M.T., 2008. Pervious concrete mixture proportions for improved freeze-thaw durability. Article in J. ASTM Int. (JAI) 5 (2).
Kevern, J.T., Schaefer, V.R., Wang, K., 2010. Effect of coarse aggregate on the freeze-thaw durability of pervious concrete. J. Mater. Civ. Eng. 22 (5), 469–475.
Kosmatka, S.H., Kerkhoff, B., Panarese, W., 2002. Design and Control of Concrete Mixtures, fourteenth ed. Portland Cement Association, Skokie, Illinois.
Kovač, M., Sičáková, A., 2018. Pervious concrete as an environmental solution for pavements: focus on key properties. Environments 5 (11), 1–9.
Legret, M., Colandini, V., LeMarc, C., 1996. Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. Sci. Total Environ. 189/190 (1996), 335–340.
Maguesvari, M.U., Narasimha, V.L., 2013. Studies on characterization of pervious concrete for pavement applications. Procedia Soc. Behav. Sci. 104 (2013), 198–207.
Mallisa, H., Turuallo, G., 2017. The maximum percentage of fly ash to replace part of original Portland cement in producing high strength concrete. Proceedings of the 3rd International Conference on Construction and Building Engineering (Iconbuild) 2017: Smart Construction towards Global Challenges. American Institute of Physics, Palembang, Indonesia.
Mindess, S., Young, J.F., 1981. Concrete. Prentice-Hall, Englewood Cliffs, New Jersey.
Muthaiyan, U.M., Thirumalai, S., 2017. Studies on the properties of pervious fly ash–cement concrete as a pavement material. Cogent Eng. 4 (2017), 131880.
National Ready Mix Concrete Association, 2011. Pervious Pavement: Engineering Properties. Retrieved from. http://perviouspavement.org/engineering.html.
Neville, A.M., 1981. Properties of Concrete, *fourth ed.* John Wiley & Sons, Inc, New York.
Olek, J., Weiss, W.J., Neithalath, N., Marolf, A., Sell, E., Thornton, W.D., 2003. Development of Quiet and Durable Porous Portland Cement concrete Paving materials". Final Report SQDH 2003-5, September. Purdue University, p. 172.
Opiso, E.M., Sato, T., Otake, T., 2017. Microstructural properties of hardened cement paste blended with coal fly ash, sugar mill lime sludge, and rice hull ash. Adv. Concr. Constr. 5 (3), 183–199.
Radlińska, A., Welker, A., Greising, K., Campbell, B., Littlewood, D., 2012. Long-term field performance of pervious concrete pavement. Advances in Civil Engineering. Article ID 380795.
Schaefer, V.R., Wang, K., Suleiman, M.T., Kevern, J.T., 2006. Mix Design Development for Pervious concrete in Cold Weather climates". Report from the National Concrete Pavement Technology Center. Iowa State University, Ames.
Shi, C., Qian, J., 2003. Increasing coal fly ash use in cement and concrete through chemical activation of reactivity of fly ash. Energy Sources 25, 617–628.
Shu, X., Huang, B., Wu, H., Dong, Q., Burdette, E.G., 2011. Performance comparison of laboratory and field produced pervious concrete mixtures. Constr. Build. Mater. 25 (2011), 3187–3192.
Sideris, K., Justnes, H., Soutsos, M., Sui, Tongbo., 2018. Chapter 2 Fly Ash. Retrieved from. https://www.springer.com/cda/content/document/cda_downloaddocument/9783319706054-c2.pdf?SGWID=0-0-45-1628141-p181236227. March 11, 2019.
Thomas, M., 2007. Optimizing the Use of Fly Ash in concrete. Portland Cement Association, Skokie, Illinois.
Thomas, J., Jennings, H., 2009. Materials of Cement Science Primer: The Science of Concrete. Infrastructure Technology Institute, Northwestern University, Evanston, Illinois, USA.
Topličić-Ćurčić, G., Grdić, D., Ristić, N., Grdić, Z., 2015. Порозни бетон при пројектовању Тротоара у светлу одрЖивог развоја (Pervious concrete in sustainable pavement design). Međународна Конференција СавреМена Достигнућа У Грађевинарству (International Conference Contemporary Achievements in Civil Engineering). Faculty of Civil Engineering, Subotica, Serbia.
Usman, M., Khan, A.Y., Farooq, S.H., Hanif, A., Tang, S., Kushnood, R.A., Rizwan, N.A., 2018. Eco-friendly self compacting cement paste incorporating wood as cement replacement: a feasibility Study. J. Clean. Prod. 190 (2018), 679e688.
Vázquez-Rivera, N.I., Soto-Pérez, L., St John, J.N., Molina-Bas, O.I., Hwang, S.S., 2015. Optimization of pervious concrete containing fly ash and iron oxide nanoparticles and its application for phosphorus removal. Constr. Build. Mater. 93 (2015), 22–28.
Wang, K., Schaefer, V.R., Kevern, J.T., Suleiman, M.T., 2006. Development of mix proportion for functional and durable pervious concrete. May 24-25, 2006 NRMCA Concrete Technology Forum: Focus on Pervious Concrete. Nashville. TN.
Yang, J., Jiang, G., 2003. Experimental study of pervious concrete pavement materials. Cement Concr. Res. 33 (3), 381–386.