



Developing Lignite Pervious Concrete for Application in Pedestrian Walkways and Urban Runoff Treatment

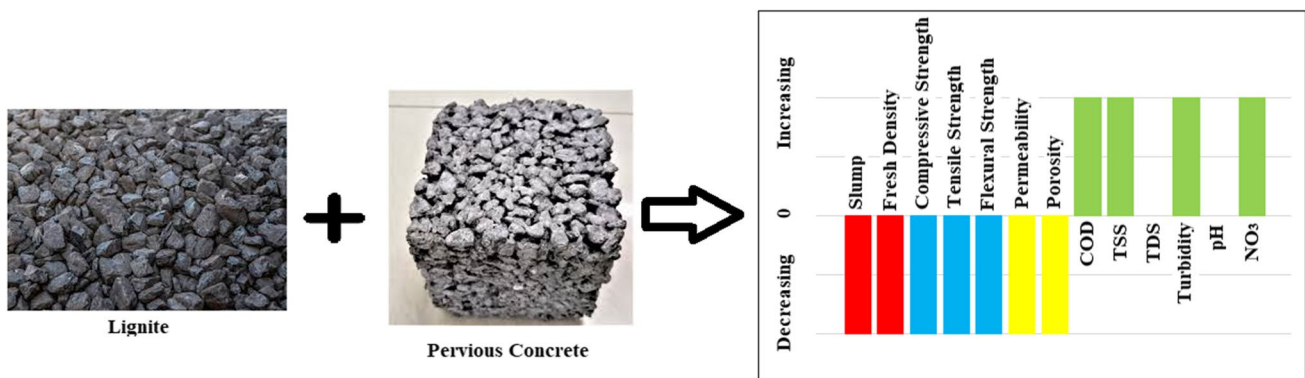
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Abstract

In the present study, the mechanical characteristics and environmental aspects of lignite pervious concrete (LPC) in reducing stormwater pollution were investigated. Therefore, fine-grained lignite (0.6–1.2 mm) in various portions (up to 15% w/w of coarse aggregate) was added to the PC mixture. The workability, strength, cementitious paste thickness, and physical properties of LPC were examined for further application in urban areas with a focus on stormwater treatment. The statistical analysis of the results of ANOVA and visualization of the microstructure of LPC by means of scanning electron microscopy and energy-dispersive X-ray spectroscopy were also presented. The results showed that LPC is a sticky paste with no slump (0). Adding lignite also slightly reduced the compressive strength of LPC up to 23% lower than the control sample (13.8 MPa). In addition, the presence of lignite led to a considerable reduction in permeability (40%) and porosity (51%) compared to the control sample. It was also found that the increase in cementitious paste thickness resulted in an increase of the compressive strength, which was mainly concentrated between 0.3 and 1.8 mm. However, the performance of LPC in reducing stormwater contamination was promising. Sample L15, with the highest removal efficiency, reduced the chemical oxygen demand, total suspended solids, and turbidity up to 42.14%, 63.38%, and 67.24%, respectively, while no significant changes were observed in pH, total dissolved solids, and nitrate (NO₃). In short, although adding lignite to PC caused a reduction in the strength and physical properties of LPC, its efficiency in reducing stormwater pollution is quite promising, and it is recommended for use in green spaces of urban areas.

Graphical Abstract



Keywords Lignite pervious concrete · Mechanical characteristics · Physical properties · Lignite · Stormwater treatment

1 Introduction

Stormwater and urban runoff carry a huge amount of freshwater and can be considered new water resources for agricultural and industrial purposes. Stormwater comes with environmental, social, and economic impacts, which can be predicted and controlled through proper and accurate planning and management. Accordingly, damage is reduced, and stormwater can be used for further purposes. Nowadays, urbanization is responsible for transforming the natural environment and open spaces through human actions that cause flooding and rapid runoff, and reduce the ground infiltration rate of the (Moretti et al. 2019; Wanielista et al. 2007). In addition, impervious surfaces are increasingly found in urban areas due to anthropization, contributing to lack of infiltration in more than half of urban areas. These areas reduce rainwater infiltration through the soil. As a rule, natural soil has more than 70% infiltration capacity, and only 10% should flow as runoff (Moretti and Loprencipe 2018). The natural water cycle is significantly affected by the absence of natural permeable surfaces, and cities are facing the challenge of managing increased runoff volumes, flooding, and degradation of water quality (Alimohammadi et al. 2021). Moreover, runoff on urban streets, roads, and parking lots causes organic and inorganic substances such as oils, salts, dirt, and chemicals to be washed away, which can be considered a runoff pollution problem (Bannerman et al. 1993). Therefore, a simple and cost-effective method is needed so that the stormwater quality can be enhanced after storage.

The use of permeable pavement such as pervious concrete (PC) in parts of a city such as parking lots, pedestrian walkways, and low-traffic areas can play a significant role in reducing the consequences of impermeability, flooding, urban runoff volume, and underground water level. Moreover, PC acts like a filter and traps some pollution in its pores and widespread cavities. Further examples of urban runoff pollution, which threaten both aquatic and terrestrial environments, are chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), nitrate, total phosphorus, bacteria, and heavy metals (Alimohammadi et al. 2017; Alimohammadi and Sedighi 2018; Tan et al. 2020).

Compared to conventional concrete, pervious/porous/permeable concrete (PC) has lower compressive strength, between 2.8 and 28 MPa, due to its open structure. This type of concrete has no or little fine-grained materials, causing interconnected pores in its structure for water and air passage (Elizondo-Martinez et al. 2020; James and Langsdorff 2003; Teymouri et al. 2020a). Pervious concrete pavement is considered an environmentally friendly system and one of the best practices (BMP) for stormwater

management, with significant advantages including managing and controlling stormwater and preventing flooding, recharging groundwater, reducing stormwater contamination, alleviating sound pollution, enhancing safety conditions, and decreasing the thermal gradient of surrounding areas (Karami et al. 2018; Noviandini et al. 2020; Sandoval et al. 2020; Teymouri et al. 2020b; Zhang et al. 2020). Alternatively, the main drawbacks of PC are lower strength, abrasion resistance, clogging, and low efficiency in removing contamination.

On the other hand, although PC can reduce some contaminants of stormwater, its removal efficiency can be enhanced by adding and replacing appropriate materials, such as mineral or industry waste adsorbents. These adsorbents, such as zeolite, perlite, red mud, metakaolin, and others of that nature, can improve the ability of PC to reduce stormwater contamination, mostly by their microscopic surface voids (Cai et al. 2014). Pollutants are trapped in the pores of the adsorbents, and as a result, through a physical process, the quality of stormwater is enhanced (Azad et al. 2021). Nevertheless, adding such adsorbent materials to the PC mixture affects its strength and physical properties either positively or negatively; therefore, the engineering properties of PC should be evaluated. In past studies, mineral adsorbents such as vermiculite, perlite, zeolite, pumice, LECA, fly ash, and iron slag have been utilized to improve the quality of water, wastewater, stormwater, and aqueous solutions (Al-Anber 2010; Aghakhani et al. 2011; Bildari and Moraci 2015; Körlü et al. 2015; Malamis and Katsou 2013; Malekian et al. 2011; Tasi et al. 2004; Verbinnen et al. 2016). Some studies have investigated the utilization of different mineral adsorbents in PC for different approaches ranging from mechanical characteristics to stormwater and wastewater treatment processes (Faisal et al. 2020; Huang et al. 2018; Javaheri-Tehrani et al. 2020; Mousavi et al. 2018; Sandoval et al. 2020; Teymouri et al. 2020a; Wang and Peng 2010).

Many studies have evaluated the engineering properties of PC under various conditions. AlShareedah and Nasiri (2021), Faisal et al. (2020), and Ibrahim et al. (2014) investigated the effects of different water-to-cement ratios, and water and cement content on the strength and physical properties of PC. The angularity, type, and size of different aggregates were studied by Ćosić et al. (2015), Faisal et al. (2020), Jaeel and Faisal (2018), and Sevgili et al. (2021). Also, replacing PC materials such as cement and coarse aggregate with waste materials such as red mud, steel slag, silica fume, metakaolin, and nanoparticles (TiO_2 and Fe_2O_3) was surveyed by Agar-Ozbek et al. (2013), Chen et al. (2019), Elizondo-Martinez et al. (2020), Ibrahim et al. (2016), Lang et al. (2019), Liang et al. (2019), Ortega-Villar et al. (2019), Tho-In et al. (2012), and Wang et al. (2020).

Nevertheless, further studies are needed to investigate the engineering properties of PC along with its environmental aspects.

Lignite, often referred to as brown coal and considered the lowest rank of coal because of its fairly low heat content, is one of the main subcategories of coal that is very cost-effective and can improve the performance of PC in reducing stormwater due to its microscopic surface voids, although it has not been used in PC mixtures before. Lignite has a carbon content of around 60–70% on a dry ash-free basis, a high inherent moisture content, and ash content ranging from 6 to 19%. The energy content of lignite ranges from 10 to 20 MJ/kg (9–17 million BTU per short ton) on a moist, mineral-matter-free basis (Di Gianfrancesco 2017). Lignite is mostly used to generate electricity; conversely, small amounts are used in agriculture and industry. The environmentally beneficial use of lignite is in agriculture. Lignite may have value as an environmentally benign soil amendment, improving cation exchange and phosphorus availability in soil while reducing the availability of heavy metals (Li et al. 2021; Lyons and Genc 2016). Lignite fly ash produced by the combustion of lignite in power plants may also be valuable as a soil amendment and fertilizer (Ram et al. 2007).

Keeping all advantages of PC and lignite in mind, adding lignite to the PC mixture could positively influence the mechanical characteristics of PC and improve its removal efficiency of polluted stormwater. Consequently, the objective of this study is to investigate the effects of adding fine-grained lignite (0.6–1.2 mm) in different proportions of 0%, 5%, 10%, and 15% of the weight of coarse aggregate on the

slump, fresh density, compressive strength, splitting tensile strength, flexural strength, porosity, and permeability of PC. In addition, the performance of LPC in reducing stormwater contamination, such as COD, pH, TSS, nitrate (NO₃), turbidity, and TDS, is studied. Statistical analysis of variance (ANOVA) and visualization of the microstructure of LPC using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) are also presented. Finally, the most appropriate mixture design for PC applications in urban areas is determined.

2 Material and Methods

2.1 Materials

Type II Portland cement, in accordance with the requirements of ASTM C150 (2012a, b, c), was used in the mixtures, and its chemical properties are presented in Table 1. Crushed aggregates with sizes ranging from 4.75 to 9.5 mm were used in the PC mixtures according to ASTM C33 (2003). This range of aggregate is the most common aggregate size that is used by previous studies (Azad et al. 2021; Elizondo-Martinez et al. 2020; Faisal et al. 2020). The grading of coarse aggregates, which is close to the lower limit of ASTM C33 (2003), is illustrated in Fig. 1. Tap water was used to make the pastes and curing process for all samples.

Table 1 Chemical analysis of type II Portland cement

Component	Specification	Standard specification	Uncertainty	Standard method (ISIRI)
SiO ₂	21.0±0.5	>20	0.14	1692
Al ₂ O ₃	4.6±0.15	<6	0.02	
Fe ₂ O ₃	3.9±0.15	<6	0.02	
CaO	62.5±0.5	–	0.01	
MgO	2.9±0.2	<5	0.02	
SO ₃	2.0±0.2	<3	0.02	
Na ₂ O	0.5±0.05	–	–	1695
K ₂ O	0.45±0.05	–	–	
IOI	1.4±0.3	<3	0.03	1692
IR	0.3±0.1	<0.75	0.02	
Cl	–	–	–	
C ₃ S	54±4	–	–	1692
C ₂ S	23±4	–	–	
C ₃ A	5.6±0.5	<8	–	
C ₄ AF	12±1	–	–	

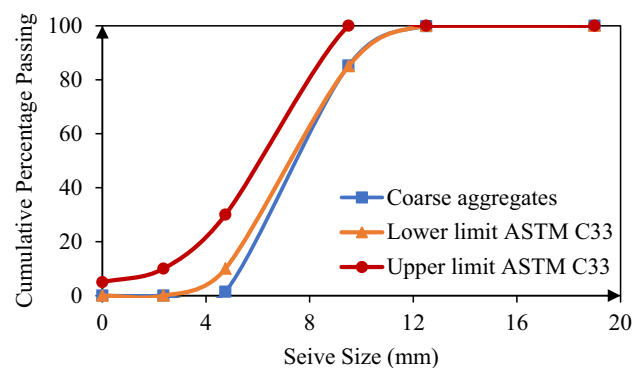


Fig. 1 Particle size distribution of coarse aggregate

Table 2 Specific gravity of coarse aggregate

Properties	Value
Bulk specific gravity (Gsb)	1559 kg/m ³
Bulk SSD specific gravity (Gsb SSD)	1574 kg/m ³
Apparent specific gravity (Gsa)	1582 kg/m ³
Absorption (% Abs.)	0.947%
Bulk density	1559 kg/m ³

The specific gravity of coarse aggregate is listed in Table 2, followed by the requirement of AASHTO T85 (2004).

2.2 Lignite (L)

Coal encompasses a variety of solid carbon and minerals, characterized by density, carbon content, moisture, calorific value, and specific gravity. Anthracite, bituminous coal, and lignite are the three main categories. Lignite, generally known as brown coal, is a soft brown inflammable

sedimentary rock formed from naturally compressed peat. This material has a high moisture content (water absorption of about 56%) and is assumed to be the lowest coal rank because of its low heat content. In the present study, fine-grained lignite (0.6–1.2 mm) was used in the PC mixture. Evaluating the effects of lignite with a high specific surface to adsorb stormwater pollution is one reasons for utilizing this material in the PC. Apart from that, the effects of lignite on the strength and physical properties of PC should be investigated to evaluate its performance for further utilization in urban areas. The proportions of 0%, 5%, 10%, and 15% by weight of coarse aggregate were chosen for lignite content. Figure 2 shows the used lignite in this research. Figure 3 illustrates the SEM and EDS results of lignite and its observed element, which contains a high proportion of carbon (62.75%) and oxygen (30.64%). The surface of lignite seems very rough and rugged, along with high water absorption that contributes to trapping stormwater pollution.



Fig. 2 Lignite used in this study

2.3 Mixture Design of LPC

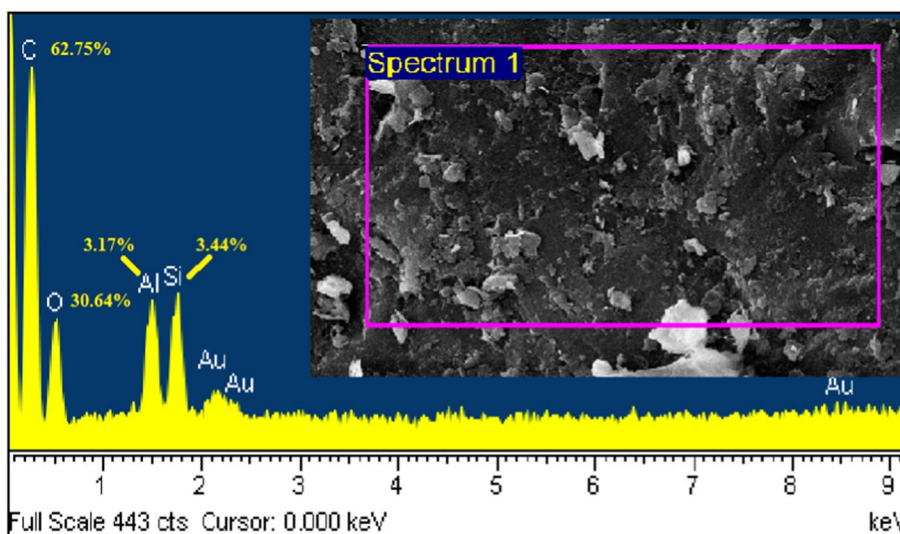
Table 3 shows the proportions of different LPC mixtures following ACI 211 3/R (2006). The water-to-cement ratio

Table 3 Mixture design proportions

Mix nomina-tions	Lignite proportion (%)	w/c ratio	Cement content (kg/m ³)	Water content (kg/m ³)	Lignite content (kg/m ³)
C	0	0.37	330.0	122.1	0.00
L5	5	0.37	330.0	122.1	80.0
L10	10	0.37	330.0	122.1	160.0
L15	15	0.37	330.0	122.1	240.0

The weight of coarse aggregate is 1600 kg/m³ for all treatments

Fig. 3 SEM image and EDS results of the lignite surface and its observed elements proportions



and cement content selected are constant for all mixtures (0.37 and 330 kg/m³, respectively). To prevent water loss of the paste due to adsorption by lignite, adsorbents were submerged for 24 h before mixing and were kept at room temperature for 1 h before mixing to remove their excess water.

2.4 Experimental Program

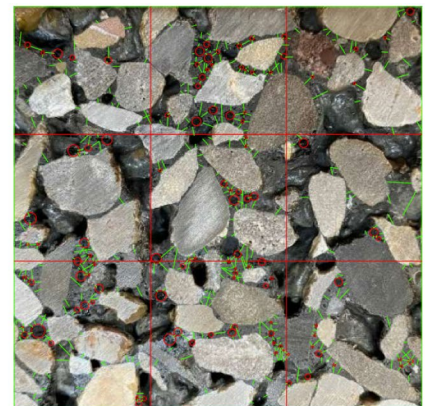
The dry forms of coarse aggregate, cement, and lignite were mixed in a Hobart mixer for 1.5 min after weighing them on a digital scale. Then, water was added to the mix and the wet mixing process continued for another 2 min. When the paste was sufficiently mixed, the fresh LPC was tested for slump (ASTM C143 2012a, b, c) and fresh density (ASTM C1688 2008) followed by casting in molds. The de-molding process was performed after 24 h, and all specimens were placed in a water tank for 28 days to cure. The compressive strength was tested on cube specimens of 150 mm in length with a constant rate of loading based on BS 1881 standard (1983). The flexural strength tests were performed according to EN 12390-5:2002 (2009) on LPC specimens of 100 × 100 × 400 mm³ by a constant loading rate of 0.05 MPa/s. The splitting

tensile strength tests were conducted in 150Ø × 300 mm cylinders based on EN 12390-6:2009 (2009). In addition, to provide a better understanding of the behavior of the compressive strength of LPCs, the cementitious paste thickness (CPT) test was carried out. CPT is the average thickness of the cement paste that surrounds each aggregate in PC (Torres et al. 2015; Yu et al. 2019). Although it was done with manual hand measurement by Torres et al. (2015), a semi-manual procedure used by Yu et al. (2019) was applied in this research. Firstly, the LPCs were cut in cross sections and smoothed to clear the residual stone debris. A photo of the sample was transferred to AutoCAD. It is better to wet the surface before taking an image to simplify distinguishing the materials. The length from the edge of an individual aggregate and lignite to the outermost edge of another aggregate or lignite which surround them is the CPT. The “l” and “di” commands in AutoCAD were used to calculate the exact length of each line segment. After drawing lines, the image was deleted to facilitate the procedure of measuring and extracting the CPT. The difference between the real length in the sample and the one in the image was imposed by a coefficient for each image. The measurement method

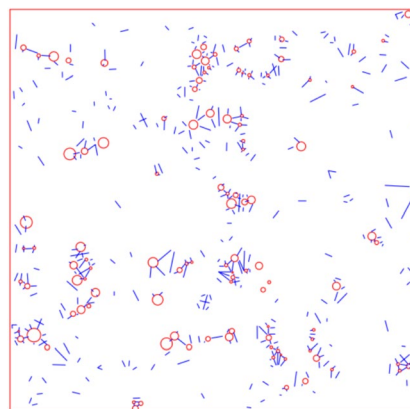
Fig. 4 Method of measuring CPT



Step 1: Taking image from the cross-section of LPC



Step 2: Draw line segment between aggregates and lignite and determining the position of lignite by drawing circle around them



Step 3: Count the length of all line segments

is shown in Fig. 4. Also, the lignite distribution and position in the pervious concrete are determined by drawing a circle around them.

The permeability of LPC specimens was tested using a falling-head device made of plexiglass with dimensions of $101 \times 101 \times 800$ mm, where PC samples could fit in following the ACI 522 (2006). The samples were put on a layer of coarse aggregate, to simulate the real conditions in sidewalks, and their edges were sealed tightly so that water could just pass vertically through the samples. The infiltration rate of LPCs was determined using Eq. 1. In addition, the porosity of LPC samples was determined through the following process of ASTM C1754 (2012a, b, c) based on Archimedes' principle of buoyancy. The 100-mm LPC cube samples were dried at a temperature of 105°C for 24 h. After weighing the dry LPC samples, their immersed weights were measured, and their porosity was calculated using Eq. 2. To conduct the urban runoff qualitative tests, the same device for permeability tests were used. The bottom of the device was filled with a gravel filter with a height of 200 mm. Then, two PC cubes with dimensions of $100 \times 100 \times 100$ mm were placed on top of each other and sealed with foam on the four sides so that the runoff could pass through vertically. LPCs were placed on the gravel layer and sealed on the edges. A sampling of urban runoff was done at 20:45 on 1 February 2022 in the ninth region of Mashhad while it was raining, as shown in Fig. 5. The quality parameters of urban runoff that was accumulated from the surface of the street are represented in Table 4. The quality tests were performed on 2 February 2022. After preparing the specimens in the device, about 6 L of polluted runoff was used for each test. The contact time between runoff and LPC samples was about 30 min, and then a sampling of runoff that passed through LPCs was

performed. The qualitative experiment process is shown in Fig. 6. Each data point is based on the average value of three specimens to reduce the possibility of measurement errors, and all tests were carried out according to valid standards.

$$K = \frac{al}{At} \text{Ln} \left(\frac{h_1}{h_2} \right) \quad (1)$$

where K is the coefficient of permeability (mm/s), a is the area of the cross section of device (mm^2), L is the length of PC sample, A is the cross section of the concrete sample (mm^2), h_1 and h_2 are initial and final height of water column (mm), and t is time (s) required for water to reach from h_1 to h_2 .

$$A_t = \left(1 - \left(\frac{W_2 - W_1}{\rho_w V} \right) \right) 100\% \quad (2)$$

where A_t is porosity (%), V is volume (cm^3), ρ_w is water density (g/cm^3), and W_1 and W_2 are the specimen's weight in water and dry weight (g).

3 Results and Discussion

3.1 Workability and Fresh Density

Figure 7 illustrates the effect of different proportions of lignite on the slump of LPC samples. As shown in Fig. 7, the increase in the proportion of lignite decreases the slump substantially. Compared to the control sample, adding lignite at only 5% w/w of coarse aggregate to the PC mixture reduced the workability and slump considerably, up to 94%, and no slump was observed in samples of L10

Fig. 5 Urban runoff sampling from the street surface



Table 4 Qualitative parameters of urban runoff

Qualitative parameter	COD (mg/l)	TDS (ppm)	pH	NO ₃ (ppm)	TSS (ppm)	Turbidity (NTU)
Quantity	980	637	6.46	23	478	290



Fig. 6 Qualitative test process

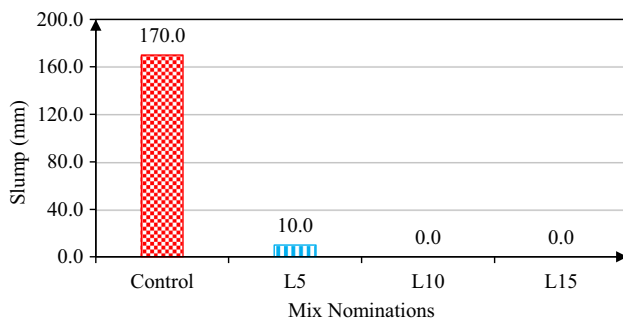
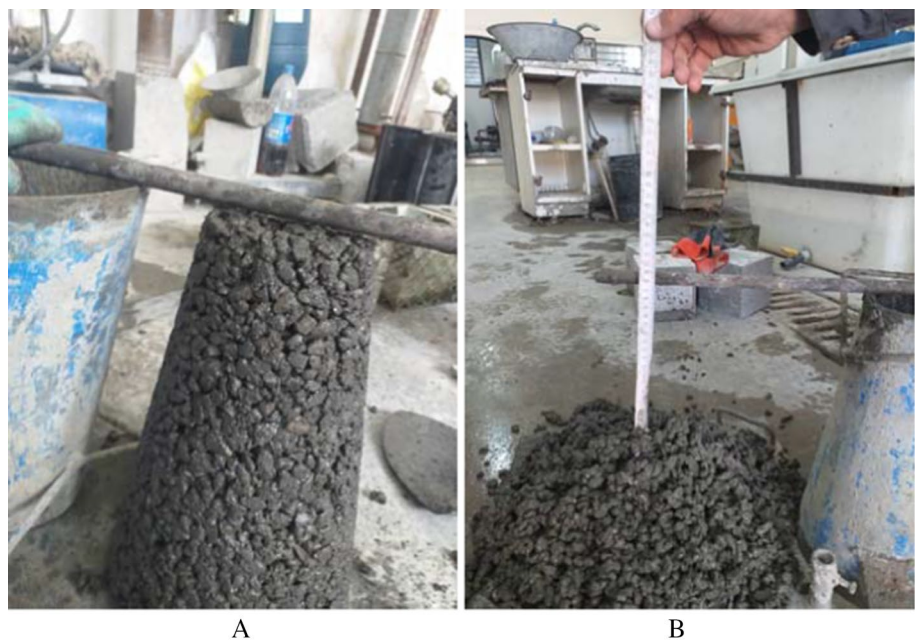


Fig. 7 Effects of lignite proportions on the slump of LPC samples

and L15. This finding indicated that due to the high inherent moisture content of lignite, which ranges from 24 to 66% (Di Gianfrancesco 2017; Grammeils et al. 2016), it absorbs water to make a sticky paste that holds the ingredients together with no slip, as shown in Fig. 8. Although the lignite was pre-soaked for 24 h before mixing, it significantly affected the slump of the LPC. Hot summer weather and spreading the lignite at room temperature for 1 h after pre-soaking resulted in the evaporation of the water absorbed by lignite in the pre-soaking stage. It should be mentioned that spreading the lignite at room temperature was done so that the lignite surface was dried even though it was wet inside, to avoid increasing the water content in the paste. Previous studies had pointed out that the high

Fig. 8 a Slump of LPC samples, and b Slump of control sample



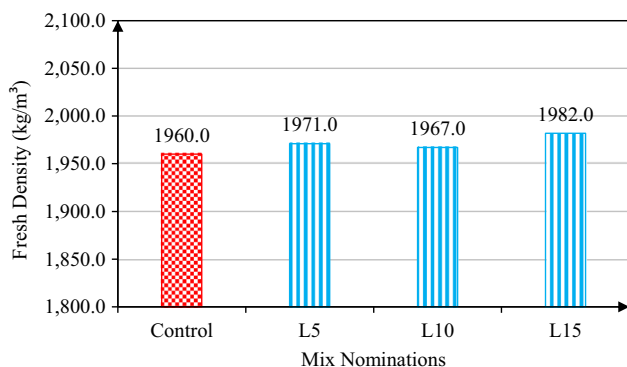


Fig. 9 Effects of lignite proportions on the fresh density of LPC samples

moisture content of lignite indicated that it adsorbed a considerable amount of water (Jellali et al. 2021). Water molecules tend to aggregate around functional groups, and hydrogen bonds play a significant role in the interactions. Therefore, it is highly recommended to pre-soak lignite before utilizing it in the concrete mixture to avoid losing the workability of the paste, as pointed out by Karami et al. (2018). Based on the findings of the present study, it is recommended not only to pre-soak the adsorbents with a high level of water adsorption before mixing but also to consider the weather and room temperature, and to observe the surface of the adsorbents while spreading them to achieve a dry surface before mixing.

Figure 9 indicates the effect of lignite proportion on the fresh density of LPC samples. No considerable changes were found in the fresh density of samples with different percentages of lignite due to its low specific gravity (1.29 g/cm^3). Among all the different coal categories, lignite has the lowest specific gravity. In their study, Teymouri et al. (2020b) used perlite, a mineral adsorbent with low specific gravity (0.29 g/cm^3) and high-water adsorption (around 56%) in porous concrete, and perlite reduced the workability and strength markedly. Nonetheless, increasing the proportion of lignite would not markedly increase the fresh density of LPC mainly because of the low specific gravity of lignite. However, higher proportions of lignite would cause a minimal increase in the LPC's fresh density. LPC containing 15% lignite had a slightly higher fresh density (1980.0 kg/m^3) compared to the control sample due to its high lignite content. Also, sample L10 experienced a slight reduction in the fresh density compared to L5, while it contained a higher proportion of adsorbents. The mixing step, scaling materials, and laboratory conditions might be the reasons for the lower fresh density of L10 as it was expected to be slightly higher than L5. In short, using lignite in LPC reduces its workability considerably and shows some increases in the fresh density.

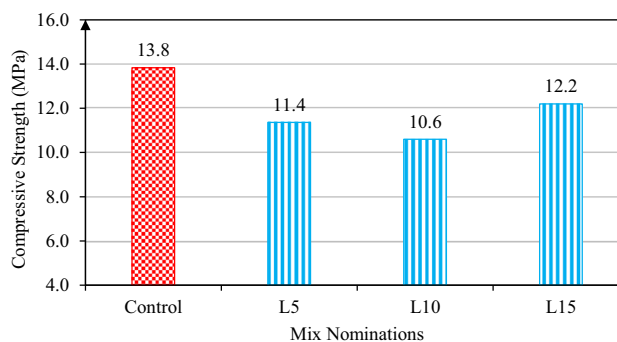


Fig. 10 Effects of lignite proportions on the compressive strength of LPC

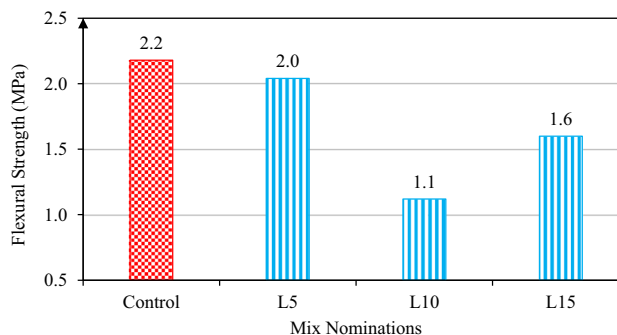


Fig. 11 Effects of lignite proportions on the flexural strength of LPC

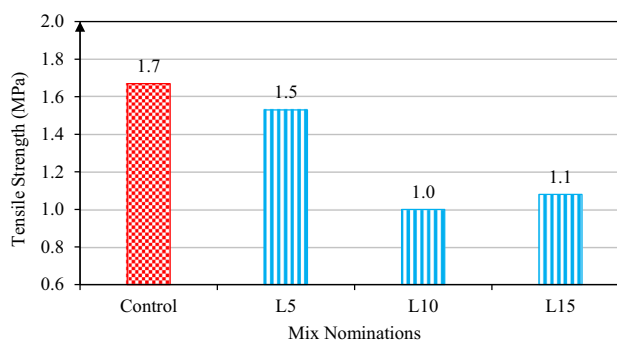


Fig. 12 Effects of lignite proportions on the splitting tensile strength of LPC

3.2 Mechanical Strength

Figures 10, 11, 12 depict the compressive strength, flexural strength, and splitting tensile strength of LPC specimens, respectively. As shown in Fig. 10, L5, L10, and L15 had an average compressive strength of 11.4, 10.6, and 12.2 MPa, respectively, which were all lower (between 11 and 23%) than the control sample. The lower compressive strength of L10 compared to L5, despite its higher proportion of lignite,

could be explained by its fresh density. In general, a denser concrete with higher fresh density contributes to a higher compressive strength (Othman et al. 2021). Othman et al. (2021) reported that the compressive strength of foamed concrete directly depends on its fresh density. Also, Tijani et al. (2019) reported that different types of coarse aggregate with different specific gravity affect the compressive strength of PC markedly due to increasing the fresh and hardened density of the PC. Therefore, LPCs with a higher fresh density tend to have a higher compressive strength as it was observed in this study.

Moreover, based on Figs. 11 and 12, the flexural and splitting tensile strength values of LPC samples were also lower than the control sample. Samples L5 and L15 had maximum and minimum flexural strength of 2.0 MPa and 1.1 MPa and splitting tensile strength of 1.5 MPa and 1.0 MPa. Increasing the proportion of lignite in LPC mixture reduced the flexural and splitting tensile strength up to 50%, and 41%, respectively. Unlike the compressive strength, the flexural and splitting tensile strength values of L5 were higher than L15. Thus, increasing lignite proportions degraded the flexural and splitting tensile strength as more lignite particles were positioned between aggregates and weakened cement bond.

Findings of mechanical strength of LPC indicated a small reduction in the compressive strength, and major reductions in flexural and splitting tensile strength occurred in all samples containing lignite compared to the control sample. This is mainly because of the low specific gravity of lignite, which could not play the role of fine-grained material in the LPC structure. Another reason for the strength reduction in LPC is the high level of water absorption of lignite that prohibits the complete interaction between water, lignite, and cement paste. Previous studies by Abedi-Koupai et al. (2016), Sonebi and Bassuoni (2013), and Yap et al. (2018) highlighted that the increased water-to-cement ratio between 0.30 and 0.45 increases the strength of PC markedly. Consequently, while lignite adsorbs the paste's water, it reduces

the strength of the LPC. Increasing the lignite proportion from 5 to 10% decreased the compressive strength at first; however, a slight increase in compressive strength was observed in L15. As a result, 15% lignite could play the filling role of fine-grained materials but not have the impact of sand in the pervious concrete. Past studies reported that fine-grained materials could increase the strength of PC as long as their specific gravity is very high (Azad et al. 2021; Bildari et al. 2015; Karami et al. 2018). In other words, lignite can fill the pores of PC and increase its compressive strength marginally when its proportion is more than 10%, while it would substantially decrease the workability, porosity and permeability of LPC. Furthermore, the ANOVA results of the compressive, flexural, and splitting tensile strength represented that the models were significant, the lack of fit was nonsignificant, and R^2 values were 0.87, 0.79, and 0.89, respectively. The ANOVA results confirmed that the presence of lignite affects the strength of PC considerably due to high F -value and the model's significance. The suggested quadratic models for all strength characteristics are as follows:

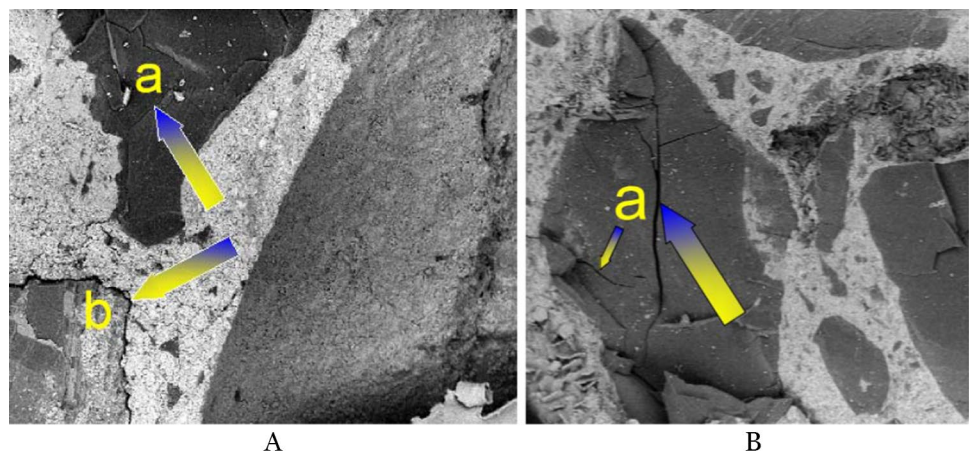
$$\text{Compressive Strength of LPC} = 10.75 - 0.84 \times L(\%) + 2.27 \times L(\%)^2$$

$$\text{Flexural Strength of LPC} = 1.51 - 0.35 \times L(\%) + 0.40 \times L(\%)^2$$

$$\text{Tensile Strength of LPC} = 1.23 - 0.32 \times L(\%) + 0.17 \times L(\%)^2$$

Figure 13 shows the SEM image of LPC samples. It can be seen that there are some cracks inside lignite and lignite itself has a low resistance to compression and can be crushed between the fingers. Also, the bonds between cement paste and lignite are quite weak. Thus, rather than low specific gravity and high water adsorption of lignite, its low resistance to compression and weak bond with cement paste are other reasons for the lower compressive strength of LPC samples.

Fig. 13 **a** Presence of cracks inside lignite and **b** cracks between lignite and cement paste



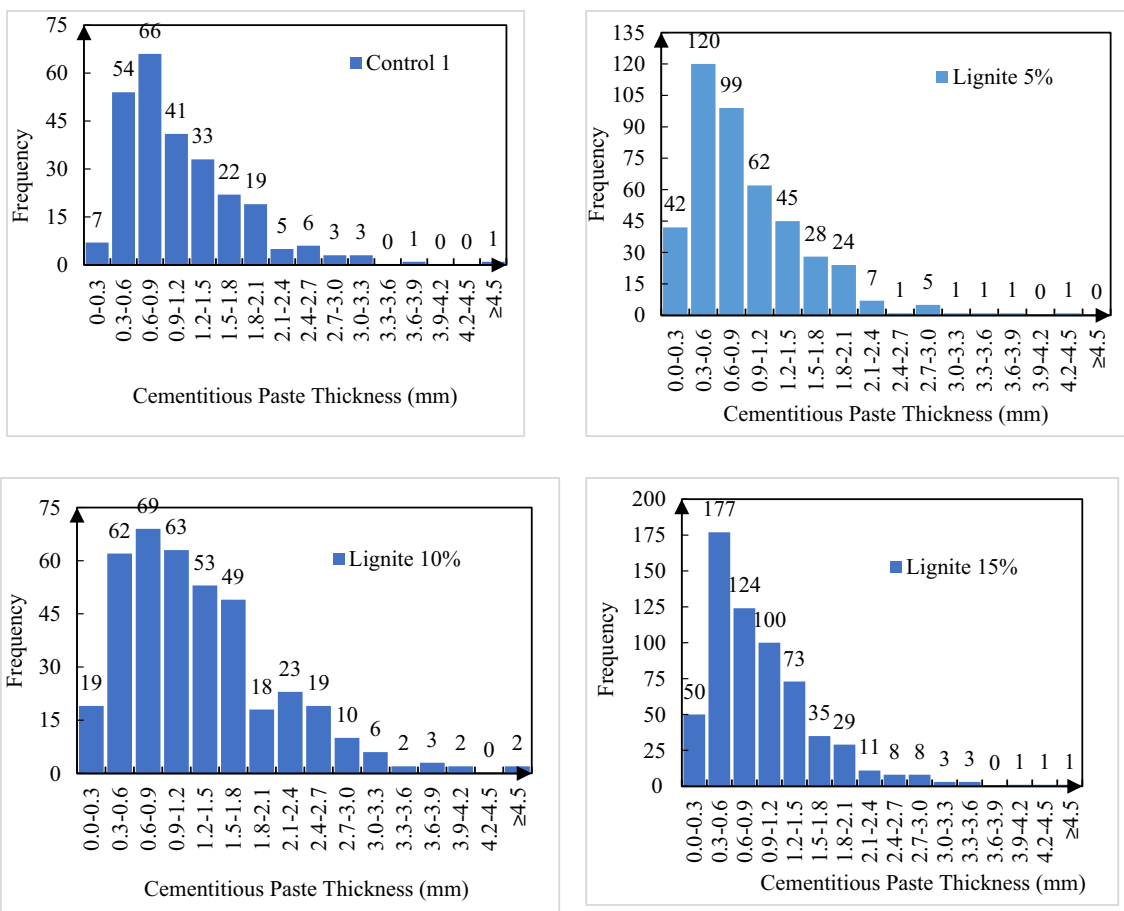


Fig. 14 Distribution of CPT

Table 5 Results of CPT

Mixture	CPT (mm)			Variance	Total number of line segments
	Minimum	Maximum	Average		
C	0.168	4.512	1.113	0.4706	261
L5	0.1215	4.266	0.912	0.3702	437
L10	0.159	4.584	1.293	0.6550	400
L15	0.092	4.813	0.959	0.4335	624

3.2.1 Effects of Cementitious Paste Thickness on the Compressive Strength

The results of CPT are represented in Fig. 14 and Table 5. As displayed in Fig. 14, the CPT distribution is mostly between 0.3 and 1.8 mm. Nonetheless, the distribution in L10 is quite different, and the range of cementitious paste thickness lies between 0.00 and 3.0 mm. Rather than laboratory conditions, the complicated CPT of L10 might be one of the reasons for its lower compressive strength compared to L5 and L15. With the increase of lignite

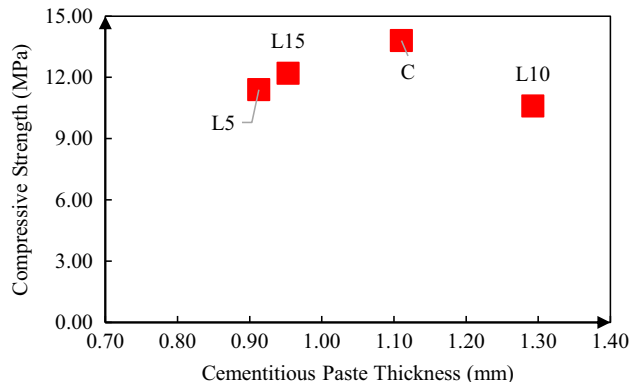


Fig. 15 Effect of CPT on the compressive strength

proportion, the peak value of frequency gradually moves to the left, even though L10 did not follow this trend. Further, the variance of CPT decreases with the increase of the lignite proportion, but this trend was not observed in L10. The relationship between the compressive strength and average CPT is illustrated in Fig. 15. As can be seen in

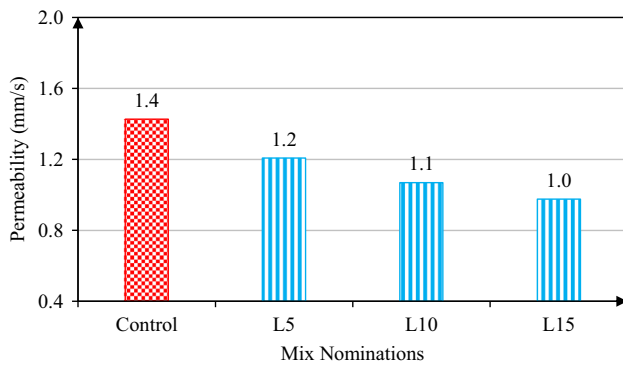


Fig. 16 Effects of lignite proportions on the permeability of LPC

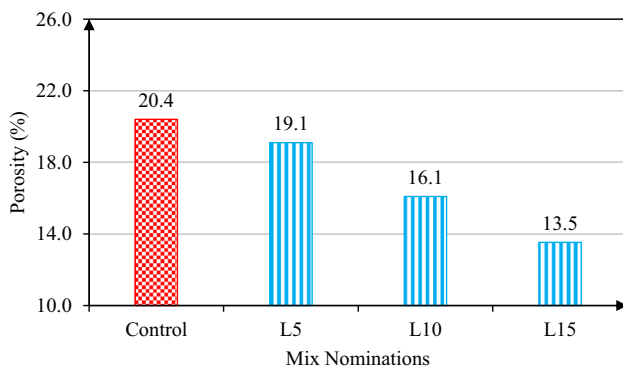


Fig. 17 Effects of lignite proportions on the porosity of LPC

Fig. 15, in general, the increase in the average CPT results in an increase in the compressive strength.

Nevertheless, L10, with the highest average of CPT and variance, did not experience an increase in the compressive strength. Overall, the lower compressive strength of LPCs as compared to the control sample was due to the low

specific gravity, high water adsorption of lignite, and the position of lignite particles in the cement paste between aggregates. The lower compressive strength of L10 compared to L5 and L15, which was anticipated to be higher than L5 and lower than L15, was also justifiable based on the CPT results.

3.3 Permeability and Porosity

It is understood that water plays a crucial role in the degradation of the mechanism of PC; thus, it is necessary to identify the permeability and porosity of LPC samples.

Figures 16 and 17 show the permeability and porosity of LPC samples, respectively. As represented in Fig. 16, the control sample and L15 has the highest and lowest permeability of 1.4 mm/s and 1.0 mm/s, respectively. Similarly, Fig. 17 displays that the porosity of the control sample (20.4%) is 33% higher than L15. These findings indicate that increasing the content of lignite led to a significant reduction of permeability and porosity, mainly due to the filling effect of fine-grained lignite in LPC. Figure 18 depicts the distribution of different proportions of lignite in LPC samples. The distribution of lignite increases in LPC, and, obviously, permeability and porosity are significantly reduced. The circles shown in Fig. 18 indicate that lignite covers the space between aggregates and minimizes the pore size. Compared to L5, where the distribution of lignite is not significant, in L15 almost all aggregates are surrounded by lignite particles. On the other hand, the high water absorption of lignite could affect the porosity and permeability of PC markedly, and it should not be forgotten to consider in the mixing design because water content can affect permeability and porosity. Tables 6 and 7 present the results of ANOVA for permeability and porosity, respectively. The proportion of added lignite to PC resulted in $F(1,1) = 17.01$, $P = 0.0146$, $R^2 = 0.762$, for permeability, and $F(1,1) = 226.09$, $P = 0.0001$, $R^2 = 0.978$

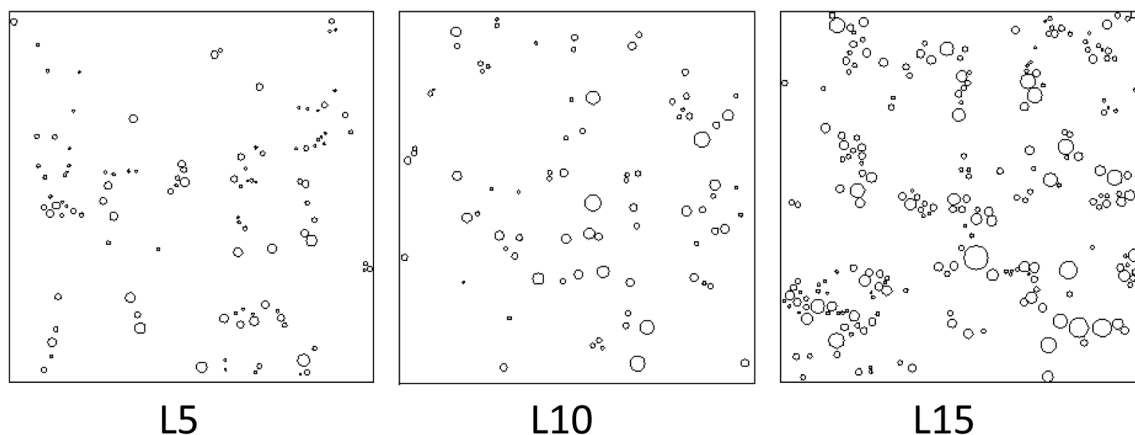


Fig. 18 Distribution of different proportions of lignite in LPC samples

Table 6 ANOVA for permeability of LPC

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model	0.095	1	0.095	17.01	0.0146*
Lignite proportion (L)	0.095	1	0.095	17.01	0.0146
Residual	0.022	4	5.583E–003		
Lack of fit	0.013	2	6.667E–003	1.48	0.4030**
Pure error	9.000E–003	2	4.500E–003		
Cor total***	0.12	5			

*Significant, **not significant, SD=0.075, CV%=6.14, $R^2=0.809$, Adj $R^2=0.762$

***Cor total: corrected total sum of squares

Table 7 ANOVA for porosity of LPC

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model	51.88	1	51.88	226.09	0.0001*
Lignite proportion	51.88	1	51.88	226.09	0.0001
Residual	0.92	4	0.23		
Lack of fit	0.80	2	0.40	6.50	0.1334**
Pure error	0.57	2	0.29		
Cor total***	52.80	5			

*Significant, **not significant, SD=0.48, CV%=6.09, $R^2=0.98$, Adj $R^2=0.978$

***Cor total: corrected total sum of squares

for porosity. Obviously, the effect of lignite on the reduction of porosity is far significant than permeability. Linear models, which are significant, are suggested for permeability and porosity with the nonsignificant lack of fit.

$$\text{Permeability} = 1.22 - 0.15 \times L(\%)$$

$$\text{Porosity of LPC} = 17.17 - 3.51 \times L(\%)$$

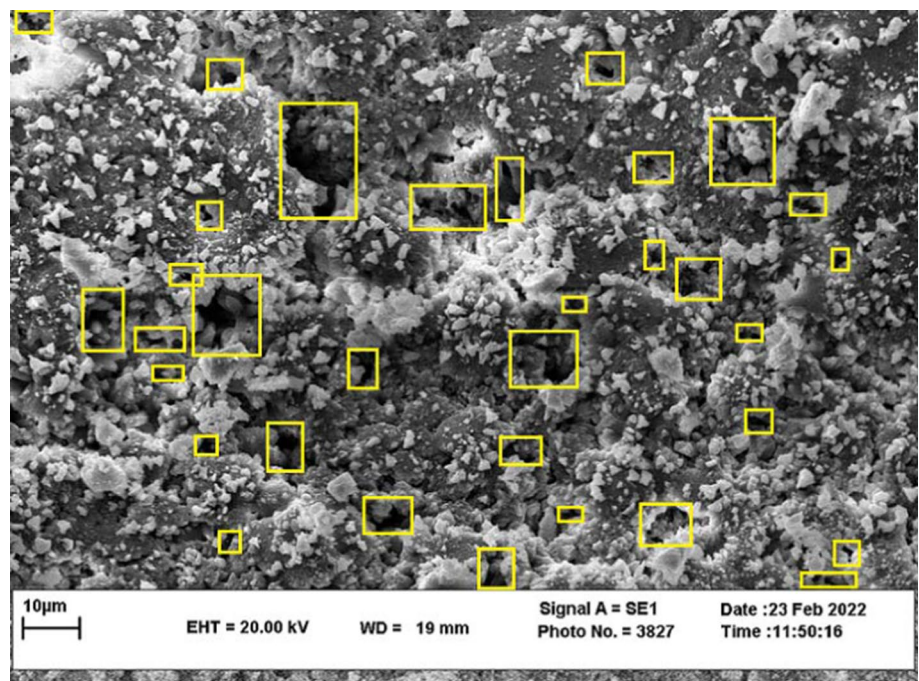
Porosity and permeability follow the same trend (Teymouri et al. 2020a; Yap et al. 2018), increasing or decreasing based on the mixture design, although their variations might not be the same. Figure 19 demonstrates the position of pores in the control sample. The positions of pores are important in the permeability of LPC, and some might be ineffective in passing water and become dead-ends, while all pores have a direct impact on porosity.

3.4 Relationship between Mechanical Performance and Porosity

Compressive strength and porosity are important factors in the PC mixture design and mostly depend on the interaction between the mixture design and the materials. Based on previous studies (Chang et al. 2019; Tennis et al. 2004; Thisani et al. 2021; Uma Magesvari and Sundararajan

2017), PC strength increases as the porosity decreases mainly because of the reduction in the number and size of pores and thus greater integration of the mixture. However, in the present study, it was found that the LPC did not follow the same trend because of lignite's low specific gravity, high water absorption, and complicated behavior in the LPC mixture. Although the control sample had higher void content, its compressive strength was surprisingly higher than that of LPC. Adding 15% lignite to the PC mixture led to a minimal increase in the compressive strength of L15 compared to L5 and L10, which was mainly because of the filling role of fine-grained lignite that appeared when higher proportions of lignite were added to LPC. The same trend of compressive strength was found for flexural and splitting tensile strength. Adding lignite to PC caused a reduction in the strength, workability, and physical properties of LPC. Although higher proportions of lignite may improve LPC strength, losing the considerable range of permeability and porosity properties might be one of the main consequences. Apart from this, the effect of lignite on the porosity was much more significant than other parameters, where by adding 15% lignite, the compressive strength increased by 11.6%, while the loss of porosity was greater than 50%. Consequently, although a large proportion of fine-grained lignite could improve the compressive strength of LPC, it strongly reduced the porosity and permeability of LPC. The high degree of porosity reduction, which stemmed from the decreased

Fig. 19 SEM image of the position of pores in control sample



number and size of the pores, led to a reduction in the lifetime of the LPC system when it encountered clogging.

3.5 Effects of LPC Samples on Reducing Stormwater Pollution

Table 8 presents the concentration of qualitative parameters in the urban runoff after passing through LPC samples. Polluted urban runoff had an initial COD concentration of 980 mg/l, followed by a reduction of 23%, and reached 752 mg/l after passing through the control sample. Faisal et al. (2020) reported a COD reduction through pervious concrete pavement. The main aspect of COD removal is physical adsorption, as PC acts like a filter and adsorbs solids in stormwater (Rodriguez-Rajas et al. 2018; Torres et al. 2015). LPC samples, however, improved the COD removal of urban runoff by up to 42%, in which L5, L10, and L15 decreased the COD concentration of urban runoff by 36.4%, 39.6%, and 42%, respectively. An increase in the lignite proportion in the LPC mixture causes an increase in COD removal due to the adsorption of dissolved organics,

which are responsible for high COD rates in urban runoff (Abedi Koupai et al. 2016; Liu et al. 2004), on the lignite surface. In addition, decreasing the pore size of LPC in the presence of fine-grained lignite is another reason for decreasing COD concentration (Tennis et al. 2004). These results are supported by the findings of past studies, which indicated that adding fine-grained adsorbents, such as zeolite, perlite, quartz, vermiculite, and pumice, to the PC mixture improves its ability to reduce stormwater and wastewater pollution (Paliulis 2016; Rastegar et al. 2016; Rostami et al. 2015; Subrahmanyam et al. 2008).

Moreover, the LPC samples had a slight impact on reducing TDS, and the proportions of lignite had no significant impact on TDS removal. The control and LPC samples decreased TDS by less than 10%. Abedi Koupai et al. (2016), Sonebi and Bassuoni (2013), and Teymouri et al. (2020b) reported that PC containing adsorbents could not greatly contribute to reducing electric conductivity (EC) and TDS, and a slight increase in EC and TDS was also observed due to the contact of cement and urban runoff. In addition, polluted runoff had a pH of 6.46, which

Table 8 Concentrations of qualitative parameters before and after passing through different PC samples

Mixture	COD (mg/l)	TDS (ppm)	pH	NO ₃ (ppm)	TSS (ppm)	Turbidity (NTU)
Urban runoff	980.0	637.0	6.46	23.0	478.0	290.0
C	752.0	602.0	6.69	17.0	372.0	183.0
L5	623.0	583.0	6.69	18.0	205.0	110.0
L10	592.0	588.0	6.69	18.0	215.0	130.0
L15	567.0	586.0	6.70	19.0	175.0	95.0

experienced an increase up to 6.69 after passing through LPC samples, and LPC did not result in a considerable change in pH. Generally, polluted urban runoff has a pH close to a neutral zone of 8, and the interaction of runoff and cement is the cause of a small increase in pH after passing through LPCs (Abedi Koupai et al. 2016; Huang et al. 2016).

Furthermore, the effect of LPCs on NO_3 removal is similar to the pH changes. The initial concentration of NO_3 is 23.0 ppm, which is reduced to 17.0 ppm (26% reduction) after passing through the control sample. As the proportion of lignite in the LPC mixture increases, the concentration of NO_3 in runoff increases slightly. L15, for example, has a NO_3 concentration of 19.0 ppm, which is 2.0 ppm higher than the control sample. The 30-min contact time of runoff and LPCs could explain this increase in the concentration of NO_3 . Anaerobic conditions are created during the contact time, which leads to increasing NO_3 in the urban runoff phase. Other studies have reported similar findings. Collins et al. (2010) reported a higher concentration of $\text{NO}_{2,3}\text{-N}$ in a permeable pavement. Brown et al. (2012) mentioned that the concentration of $\text{NO}_{2,3}\text{-N}$ is higher than runoff after passing through permeable pavement due to denitrifying conditions. Huang et al. (2016) reported a 3–10% reduction of total nitrate (TN) in stormwater pollution by permeable pavement. It can be concluded that due to the considerable decrease of the porosity of L15 as compared to L5, the anaerobic conditions have strong effects on increasing NO_3 .

Additionally, the TSS concentration of the polluted runoff was 478.0 ppm and reduced by 22.2% after passing through the control sample. Nevertheless, the addition of lignite improved the removal efficiency of LPC substantially. Samples L5 and L15 removed TSS up to 57% and 63.4%, respectively. Increasing the lignite portion leads to reducing the porosity of the LPC and increasing the surface of lignite, which contributes to trapping small suspended solids in runoff (Hatt et al. 2006; Mehrabi et al. 2021; Teymouri et al. 2016). Eventually, a promising reduction in turbidity was observed after polluted runoff passed through LPCs. A similar trend as TSS reduction occurred in turbidity. The control samples removed turbidity by up to 36.8%, and LPCs improved the removal efficiency of turbidity by up to 67.2% (L15).

Overall, comparing different samples of LPC, adding 5% lignite to the PC mixture has a relatively similar performance to L15, while L5 has a permeability and porosity considerably higher than L15. Therefore, considering the mechanical strength, porosity, permeability, and removal efficiency of LPCs, L5 was the best mixture design.

3.6 Results of Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) on Contamination Removal

Figure 20a, b shows the SEM–EDS results and pore structure in the control sample, respectively. It can be seen in Fig. 20a that the surface texture of the aggregate is relatively smooth with a minimal number of micropores. Also, the pore structure of the control sample represents that solid contamination of relatively large size could be trapped in these pores. For this reason, the capacity of control samples in reducing urban runoff contamination is lower than for LPC. Also, the observed elements in the control sample are CaCO_3 (46.48%), SiO_2 (49.66%), Al (2.79%), and Mg (0.99%). On the other hand, Fig. 21a, b illustrates the SEM–EDS results of L15, and surface of lignite. Based on Fig. 21a, b, the lignite has a relatively rougher surface texture than aggregate and control samples and contains more micropores on its surface. Hence, the lignite surface could be a suitable bed for settling runoff pollutants, especially solids, and increases the capacity of LPC in stormwater treatment.

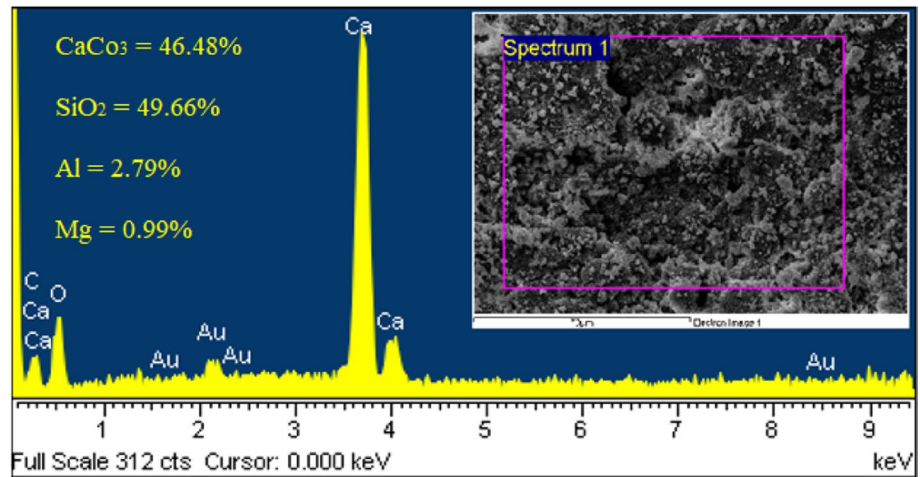
Figure 22 demonstrates how cement surrounds lignite in LPC paste, the distribution and proportion of lignite compared to the cement paste is relatively suitable for capturing most of the contamination in urban runoff. Fig. 22 attempts to show the difference by lines drawn between cement paste and lignite based on their properties and EDS results.

4 Conclusion

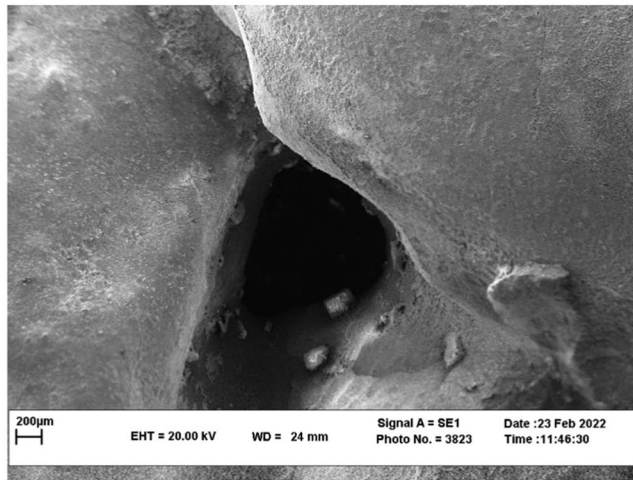
The effects of adding fine-grained lignite as an adsorbent on the engineering properties and environmental aspects of LPC was investigated in this study, and the following conclusions are drawn:

- Adding lignite to the PC mixture decreased the slump substantially up to 100% and made a zero-slump LPC due to the high waste absorption of lignite. Hence, pre-soaking is highly recommended.
- LPCs have lower compressive strength, flexural strength, and splitting tensile strength than the control samples due to high water absorption and low specific gravity of lignite.
- The increase of lignite portion in the LPC mixture gradually shifts the frequency peak value of the cementitious paste thickness to the left and increases the compressive strength minimally. Also, increasing the average thickness of the cementitious paste increases the compressive strength.

Fig. 20 **a** SEM–EDS results of control sample and **b** pore structure of the control sample



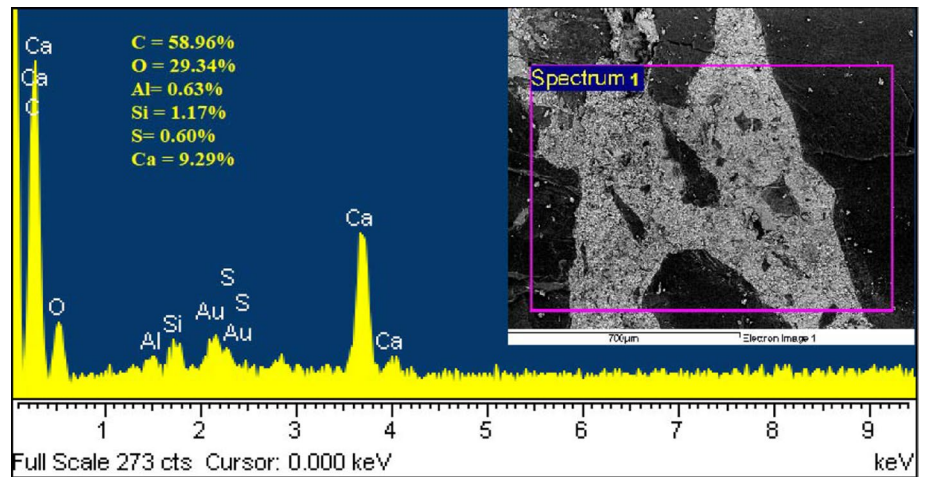
(a)



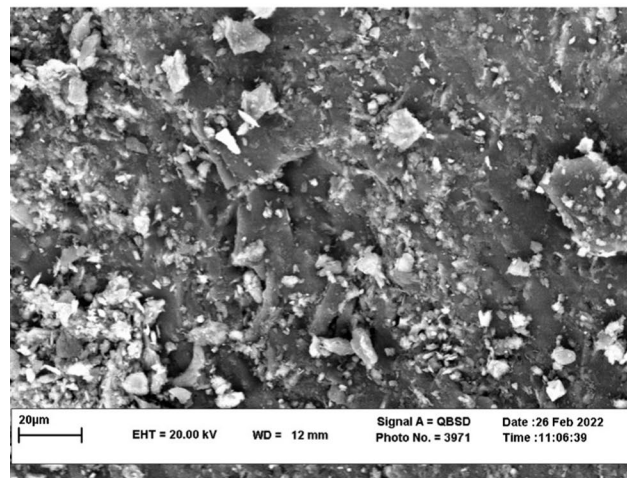
(b)

- Fine-grained lignite significantly reduces the permeability and porosity of LPC samples. The control sample had the highest permeability and porosity of 1.4 mm/s and 20.4%, and L15 had the lowest amounts of 1.0 mm/s and 13.5%, respectively.
- Based on ANOVA, quadratic models were fitted to the mechanical strength and linear models were preferred for permeability and porosity.
- As the proportion of lignite is increased, the removal of urban runoff contamination increases, and the maximum removal is observed in L15 by 42%, 63.4%, and 67.2% removal of COD, TSS, and turbidity, respectively. No significant reduction is observed with respect to pH, NO_3 , and TDS.
- Ultimately, the use of LPC with 5% lignite is recommended for use in green spaces and walkways to control stormwater, collect urban runoff, and improve the quality of urban runoff. In addition, using superplasticizers is highly recommended to improve the engineering properties of LPC.

Fig. 21 a SEM–EDS results of L15 and b lignite surface



(a)



(b)

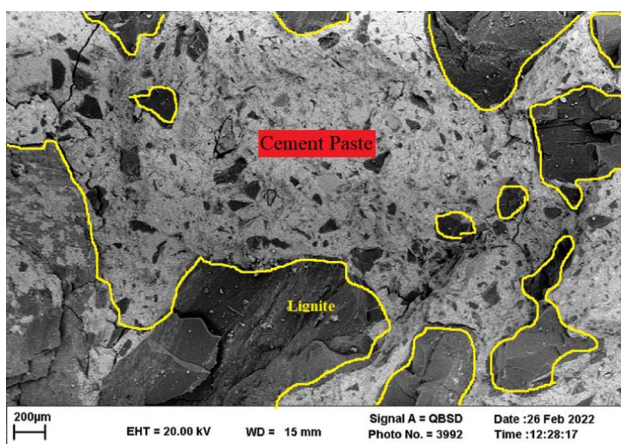


Fig. 22 SEM–EDS image of L15; black parts represent lignite in PC structure

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References

- AASHTO (2004) Standard method of test for the specific gravity and absorption of coarse aggregates. American Association of State Highway and Transportation Officials, Washington
- Abedi-Koupai J, Nejad SS, Mostafazadeh-Fard S, Behfarnia K (2016) Reduction of urban storm-runoff pollution using porous concrete containing iron slag adsorbent. *J Environ Eng* 142(2):04015072. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001025](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001025)
- ACI Committee 211 (2006) Guide for selecting proportions for no slump concrete. ACI 211.3R Report
- ACI Committee 522 (2006) Pervious concrete, ACI522R-06 report
- Agar-Ozbek AS, Weerheijm J, Schlangen E, Van Breugel K (2013) Investigating porous concrete with improved strength: testing at different scales. *Constr Build Mater* 41:480–490. <https://doi.org/10.1016/j.conbuildmat.2012.12.040>
- Aghakhani A, Mousavi SF, Mostafazadeh-Fard B, Rostamian R, Seraji M (2011) Application of some combined adsorbents to remove salinity parameters from drainage water. *Desalination* 275(1–3):217–223. <https://doi.org/10.1016/j.desal.2011.03.003>
- Al-Anber MA (2010) Removal of high-level Fe³⁺ from aqueous solution using natural inorganic materials: bentonite (NB) and quartz (NQ). *Desalination* 250(3):885–891. <https://doi.org/10.1016/j.desal.2009.06.071>
- Alimohammadi V, Maghfouri M, Nourmohammadi D, Azarsa P, Gupta R, Saberian M (2021) Stormwater runoff treatment using pervious concrete modified with various nanomaterials: a comprehensive review. *Sustainability* 13(15):8552. <https://doi.org/10.3390/su13158552>
- Alimohammadi V, Sedighi M (2018) Reduction of TDS in water by using magnetic multiwalled carbon nanotubes and optimizing with response surface methodology. *J Environ Eng* 144(3):04017114. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0001328](https://doi.org/10.1061/(ASCE)EE.1943-7870.0001328)
- Alimohammadi V, Sedighi M, Jabbari E, Nasrollahzadeh M (2017) Phosphate removal from aqueous solutions using magnetic multiwalled carbon nanotube; optimization by response surface methodology. *Desalin Water Treat* 82:271–281. <https://doi.org/10.1016/j.jece.2016.10.017>
- AlShareedah O, Nassiri S (2021) Pervious concrete mixture optimization, physical, and mechanical properties and pavement design: a review. *J Clean Prod* 288:125095. <https://doi.org/10.1016/j.jclepro.2020.125095>
- ASTM (2003C) Standard specification for concrete aggregates. ASTM C33/C33M, West Conshohocken
- ASTM (2012a) Standard specification for Portland cement. ASTM C150/C150M, West Conshohocken
- ASTM (2008a) Standard test method for density and void content of freshly mixed pervious concrete, ASTM C1688/C1688
- ASTM (2012b) Standard test method for density and void content of hardened pervious concrete, ASTM C1754/1754M
- ASTM (2012c) Standard test method for slump of hydraulic-cement concrete, ASTM C143/C143M
- Azad A, Mousavi SF, Karami H, Farzin S, Singh VP (2021) The effect of vermiculite and quartz in porous concrete on reducing storm-runoff pollution. *ISH J Hydraul Eng* 27(2):144–152. <https://doi.org/10.1080/09715010.2018.1528482>
- Bannerman RT, Owens DW, Dodds RB, Hornewer NJ (1993) Sources of pollutants in Wisconsin stormwater. *Water Sci Technol* 28(3–5):241–259. <https://doi.org/10.2166/wst.1993.0426>
- Bilardi S, Calabró PS, Moraci N (2015) Simultaneous removal of Cu^{II}, Ni^{II} and Zn^{II} by a granular mixture of zero-valent iron and pumice in column systems. *Desalin Water Treat* 55(3):767–776. <https://doi.org/10.1080/19443994.2014.916234>
- British Standard (1881) Testing concrete method for making test cubes from fresh concrete. Part 108
- Brown RA, Line DE, Hunt WF (2012) LID treatment train: Pervious concrete with subsurface storage in series with bioretention and care with seasonal high water tables. *J Environ Eng* 138(6):689–697. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0000506](https://doi.org/10.1061/(ASCE)EE.1943-7870.0000506)
- Cai X, Gao Y, Sun Q, Chen Z, Megharaj M, Naidu R (2014) Removal of co-contaminants Cu (II) and nitrate from aqueous solution using kaolin-Fe/Ni nanoparticles. *Chem Eng J* 244:19–26. <https://doi.org/10.1016/j.cej.2014.01.040>
- Chen X, Guo Y, Ding S, Zhang H, Xia F, Wang J, Zhou M (2019) Utilization of red mud in geopolymer-based pervious concrete with function of adsorption of heavy metal ions. *J Clean Prod* 207:789–800. <https://doi.org/10.1016/j.jclepro.2018.09.263>
- Cheng YY, Lo SL, Ho CC, Lin JY, Yu SL (2019) Field testing of porous pavement performance on runoff and temperature control in Taipei City. *Water* 11(12):2635. <https://doi.org/10.3390/w11122635>
- Collins KA, Hunt WF, Hathaway JM (2010) Side-by-side comparison of nitrogen species removal for four types of permeable pavement and standard asphalt in eastern North Carolina. *J Hydrol Eng* 15(6):512–521. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000139](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000139)
- Ćosić K, Korat L, Ducman V, Netinger I (2015) Influence of aggregate type and size on properties of pervious concrete. *Constr Build Mater* 78:69–76. <https://doi.org/10.1016/j.conbuildmat.2014.12.073>
- Di Gianfrancesco A (2017) The fossil fuel power plants technology. In: *Materials for ultra-supercritical and advanced ultra-supercritical power plants: 1–49*. Woodhead Publishing. <https://doi.org/10.1016/B978-0-08-100552-1.00001-4>
- Elizondo-Martinez EJ, Andrés-Valeri VC, Jato-Espino D, Rodriguez-Hernandez J (2020) Review of porous concrete as multifunctional and sustainable pavement. *J Build Eng* 27:100967. <https://doi.org/10.1016/j.jobe.2019.100967>
- EN 12390-5 (2009) Testing hardened concrete—Part 5: Flexural strength of test specimens
- EN 12390-6 (2009) Testing hardened concrete—Part 6: tensile strength of test specimens
- Faisal GH, Jaeeel AJ, Al-Gasham TS (2020) BOD and COD reduction using porous concrete pavements. *Case Stud Constr Mater* 13:e00396. <https://doi.org/10.1016/j.cscm.2020.e00396>
- Grammelis P, Margaritis N, Karampinis E (2016) Solid fuel types for energy generation: coal and fossil carbon-derivative solid fuels. In: *Fuel flexible energy generation 29–58*. Woodhead Publishing. <https://doi.org/10.1016/B978-1-78242-378-2.00002-X>
- Hatt BE, Siriwardene N, Deletic A, Fletcher TD (2006) Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal. *Water Sci Technol* 54(6–7):263–271. <https://doi.org/10.2166/wst.2006.626>
- Huang J, Kankanamge NR, Chow C, Welsh DT, Li T, Teasdale PR (2018) Removing ammonium from water and wastewater using cost-effective adsorbents: a review. *J Environ Sci* 63:174–197. <https://doi.org/10.1016/j.jes.2017.09.009>
- Huang J, Valeo C, He J, Chu A (2016) The influence of design parameters on stormwater pollutant removal in permeable pavements. *Water Air Soil Pollut* 227(9):1–17. <https://doi.org/10.1007/s11270-016-3020-y>
- Ibrahim A, Mahmoud E, Yamin M, Patibandla VC (2014) Experimental study on Portland cement pervious concrete mechanical and hydrological properties. *Constr Build Mater* 50:524–529. <https://doi.org/10.1016/j.conbuildmat.2013.09.022>
- Ibrahim HA, Razak HA (2016) Effect of palm oil clinker incorporation on properties of pervious concrete. *Constr Build Mater* 115:70–77. <https://doi.org/10.1016/j.conbuildmat.2016.03.181>

- Jaeel AJ, Faisal GH (2018) COD removal from synthetic wastewater using pervious concrete. In: 2018 international conference on advance of sustainable engineering and its application (ICASEA), 174–178. <https://doi.org/10.1109/ICASEA.2018.8370978>
- James W, Von Langsdorff H (2003) The use of permeable concrete block pavement in controlling environmental stressors in urban areas. In: 7th international conference on concrete block paving, Sun City, South Africa (1215)
- Javaheri-Tehrani M, Mousavi SF, Abedi-Koupai J, Karami H (2020) Treatment of domestic wastewater using the combination of porous concrete and phytoremediation for irrigation. *Paddy Water Environ* 18(4):729–742. <https://doi.org/10.1007/s10333-020-00814-7>
- Jellali S, Azzaz AA, Jeguirim M, Hamdi H, Mlayah A (2021) Use of lignite as a low-cost material for cadmium and copper removal from aqueous solutions: assessment of adsorption characteristics and exploration of involved mechanisms. *Water* 13(2):164. <https://doi.org/10.3390/w13020164>
- Karami H, Teymouri E, Mousavi SF, Farzin S (2018) Experimental investigation of the effect of adding LECA and pumice on some physical properties of porous concrete: some physical properties of porous concrete. *Eng J* 22(1):205–213. <https://doi.org/10.4186/ej.2018.22.1.205>
- Körlü AE, Yapar S, Perinçek S, Yılmaz H, Bağiran C (2015) Dye removal from textile waste water through the adsorption by pumice used in stone washing. *Autex Res J* 15(3):158–163. <https://doi.org/10.1515/aut-2015-0012>
- Lang L, Duan H, Chen B (2019) Properties of pervious concrete made from steel slag and magnesium phosphate cement. *Constr Build Mater* 209:95–104. <https://doi.org/10.1016/j.conbuildmat.2019.03.123>
- Li C, Xiong Y, Zou J, Dong L, Ren P, Huang G (2021) Impact of bio-char and lignite-based amendments on microbial communities and greenhouse gas emissions from agricultural soil. *Vadose Zone J* 20(2):e20105. <https://doi.org/10.1002/vzj2.20105>
- Liang X, Cui S, Li H, Abdelhady A, Wang H, Zhou H (2019) Removal effect on stormwater runoff pollution of porous concrete treated with nanometer titanium dioxide. *Transp Res D Transp Environ* 73:34–45. <https://doi.org/10.1016/j.trd.2019.06.001>
- Liu CF, Shih SM (2004) Iron blast furnace slag/hydrated lime sorbents for flue gas desulfurization. *Environ Sci Technol* 38(16):4451–4456. <https://doi.org/10.1021/es030347c>
- Lyons G, Genc Y (2016) Commercial humates in agriculture: real substance or smoke and mirrors. *Agronomy* 6(4):50. <https://doi.org/10.3390/agronomy6040050>
- Malamis S, Katsou E (2013) A review on zinc and nickel adsorption on natural and modified zeolite, bentonite and vermiculite: examination of process parameters, kinetics and isotherms. *J Hazard Mater* 252:428–461. <https://doi.org/10.1016/j.hazmat.2013.03.024>
- Malekian R, Abedi-Koupai J, Eslamian SS, Mousavi SF, Abbaspour KC, Afyuni M (2011) Ion-exchange process for ammonium removal and release using natural Iranian zeolite. *Appl Clay Sci* 51(3):323–329. <https://doi.org/10.1016/j.clay.2010.12.020>
- Mehrabi P, Shariati M, Kabirifar K, Jarrah M, Rasekh H, Trung NT, Jahandari S (2021) Effect of pumice powder and nano-clay on the strength and permeability of fiber-reinforced pervious concrete incorporating recycled concrete aggregate. *Constr Build Mater* 287:122652. <https://doi.org/10.1016/j.conbuildmat.2021.122652>
- Moretti L, Di Mascio P, Fusco C (2019) Porous concrete for pedestrian pavements. *Water*. <https://doi.org/10.3390/w11102105>
- Moretti L, Loprencipe G (2018) Climate change and transport infrastructures: state of the art. *Sustainability* 10(11):4098. <https://doi.org/10.3390/su10114098>
- Mousavi SF, Karami H, Farzin S, Teymouri E (2018) Effects of adding mineral adsorbents to porous concrete for enhancing the quality performance of urban runoff systems. *World J Eng* 15(4):489–497. <https://doi.org/10.1108/WJE-10-2017-0314>
- Noviandini ZP, Dewi OC, Laksitoadi B, Widyarta MN (2020) The effect of permeable pavement on pedestrian walkway for human comfort. *IOP Conf Ser Earth Environ Sci* 409(1):012009
- Othman R, Jaya RP, Muthusamy K, Sulaiman M, Duraisamy Y, Abdullah MMAB, Przybył A, Sochacki W, Skrzypczak T, Vizureanu P, Sandu AV (2021) Relation between density and compressive strength of foamed concrete. *Mater* 14(11):2967. <https://doi.org/10.3390/ma14112967>
- Ortega-Villar R, Lizárraga-Mendiola L, Coronel-Olivares C, López-León LD, Bigurra-Alzati CA, Vázquez-Rodríguez GA (2019) Effect of photocatalytic Fe₂O₃ nanoparticles on urban runoff pollutant removal by permeable concrete. *J Environ Manag* 242:487–495. <https://doi.org/10.1016/j.jenvman.2019.04.104>
- Paliulis D (2016) Removal of formaldehyde from synthetic wastewater using natural and modified zeolites. *Pol J Environ Stud* 25(1):251–257. <https://doi.org/10.15244/pjoes/60727>
- Ram LC, Srivastava NK, Jha SK, Sinha AK, Masto RE, Selvi VA (2007) Management of lignite fly ash for improving soil fertility and crop productivity. *Environ Manag* 40(3):438–452. <https://doi.org/10.1007/s00267-006-0126-9>
- Rastegar A, Anvaripour B, Jaafarzadeh N (2016) Application of modified LECA in removing nickel from wastewater. *Iran J Oil Gas Sci Technol* 5(1):1–12. <https://doi.org/10.22050/IJOGST.2016.13825>
- Rodríguez-Rojas MI, Huertas-Fernández F, Moreno B, Martínez G, Grindlay AL (2018) A study of the application of permeable pavements as a sustainable technique for the mitigation of soil sealing in cities: a case study in the south of Spain. *J Environ Manag* 205:151–162. <https://doi.org/10.1016/j.jenvman.2017.09.075>
- Rostamian R, Heidarpour M, Mousavi SF, Afyuni M (2015) Preparation, characterization and sodium sorption capability of rice husk carbonaceous adsorbents. *Fresenius Environ Bull* 24(5):1649–1658
- Sandoval GF, Galobardes I, Campos A, Toralles BM (2020) Assessing the phenomenon of clogging of pervious concrete (Pc): experimental test and model proposition. *J Build Eng* 29:101203. <https://doi.org/10.1016/j.jobe.2020.101203>
- Sarin V, Pant K (2006) Removal of chromium from industrial waste by using eucalyptus bark. *Bioresour Technol* 97(1):15–20. <https://doi.org/10.1016/j.biortech.2005.02.010>
- Sevgili İ, Dilmaç ÖF, Şimşek B (2021) An environmentally sustainable way for effective water purification by adsorptive red mud cementitious composite cubes modified with bentonite and activated carbon. *Sep Purif Technol* 274:119115. <https://doi.org/10.1016/j.seppur.2021.119115>
- Sonebi M, Bassuoni MT (2013) Investigating the effect of mixture design parameters on pervious concrete by statistical modelling. *Constr Build Mater* 38:147–154. <https://doi.org/10.1016/j.conbuildmat.2012.07.044>
- Subrahmanyam M, Boule P, Kumari VD, Kumar DN, Sancelme M, Rachel A (2008) Pumice stone supported titanium dioxide for removal of pathogen in drinking water and recalcitrant in wastewater. *Sol Energy* 82(12):1099–1106. <https://doi.org/10.1016/j.solener.2008.05.007>
- Tan TH, Mo KH, Ling TC, Lai SH (2020) Current development of geopolymer as alternative adsorbent for heavy metal removal. *Environ Technol Innov* 18:100684. <https://doi.org/10.1016/j.eti.2020.100684>
- Tennis PD, Leming ML, Akers DJ (2004) Pervious concrete pavements. Skokie IL: Portland Cement Association:2828
- Teymouri E, Mousavi SF, Karami H, Farzin S, Javaheri-Tehrani M (2016) Experimental investigation of the effect of different additives on characteristics of porous concrete, applicable in urban

- runoff system. *J Transp Infrastruct Eng* 2(2):51–64. <https://doi.org/10.22075/JTIE.2016.464>
- Teymouri E, Mousavi SF, Karami H, Farzin S, Kheirabad MH (2020a) Municipal Wastewater pretreatment using porous concrete containing fine-grained mineral adsorbents. *J Water Process Eng* 36:101346. <https://doi.org/10.1016/j.jwpe.2020.101346>
- Teymouri E, Mousavi SF, Karami H, Farzin S, Kheirabad MH (2020b) Reducing urban runoff pollution using porous concrete containing mineral adsorbents. *J Environ Treat Tech* 8(1):429–436
- Thisani SK, Kallon DVV, Byrne P (2021) A fixed bed pervious concrete anaerobic bioreactor for biological sulphate remediation of acid mine drainage using simple organic matter. *Sustainability* 13(12):6529. <https://doi.org/10.3390/su13126529>
- Tho-In T, Sata V, Chindaprasit P, Jaturapitakkul C (2012) Pervious high-calcium fly ash geopolymer concrete. *Constr Build Mater* 30:366–371. <https://doi.org/10.1016/j.conbuildmat.2011.12.028>
- Tijani MA, Ajagbe WO, Ganiyu AA, Agbede OA (2019) Effect of aggregate type on properties of pervious concrete. *J Mod Technol Eng* 4(1):37–46
- Torres A, Hu J, Ramos A (2015) The effect of the cementitious paste thickness on the performance of pervious concrete. *Constr Build Mater* 95:850–859. <https://doi.org/10.1016/j.conbuildmat.2015.07.187>
- Tsai WT, Hsien KJ, Yang JM (2004) Silica adsorbent prepared from spent diatomaceous earth and its application to removal of dye from aqueous solution. *J Colloid Interface Sci* 275(2):428–433. <https://doi.org/10.1016/j.jcis.2004.02.093>
- Uma Maguesvari M, Sundararajan T (2017) Influence of fly ash and fine aggregates on the characteristics of pervious concrete. *Int J Appl Eng Res* 12(8):1598–1609
- Verbinnen B, Block C, Vandecasteele C (2016) Adsorption of oxyanions from industrial wastewater using perlite-supported magnetite. *Water Environ Res* 88(5):408–414. <https://doi.org/10.2175/106143015x14362865226932>
- Wang G, Chen X, Dong Q, Yuan J, Hong Q (2020) Mechanical performance study of pervious concrete using steel slag aggregate through laboratory tests and numerical simulation. *J Clean Prod* 262:121208. <https://doi.org/10.1016/j.jclepro.2020.121208>
- Wang S, Peng Y (2010) Natural zeolites as effective adsorbents in water and wastewater treatment. *Chem Eng J* 156(1):11–24. <https://doi.org/10.1016/j.cej.2009.10.029>
- Wanielista M, Chopra M, Spence J, Ballock C (2007) Hydraulic performance assessment of pervious concrete pavements for stormwater management credit. Final Report. Florida Department of Transportation, Tallahassee
- Yap SP, Chen PZC, Goh Y, Ibrahim HA, Mo KH, Yuen CW (2018) Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates. *J Clean Prod* 181:155–165. <https://doi.org/10.1016/j.jclepro.2018.01.205>
- Yu F, Sun D, Wang J, Hu M (2019) Influence of aggregate size on compressive strength of pervious concrete. *Constr Build Mater* 209:463–475. <https://doi.org/10.1016/j.conbuildmat.2019.03.140>
- Zhang G, Wang S, Wang B, Zhao Y, Kang M, Wang P (2020) Properties of pervious concrete with steel slag as aggregates and different mineral admixtures as binders. *Constr Build Mater* 257:119543. <https://doi.org/10.1016/j.conbuildmat.2020.119543>

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