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Comparative Analysis of Adsorbent Pervious Concrete: Engineering Properties and Environmental Consideration

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ABSTRACT

This study comprehensively compares various low-cost mineral and industrial waste adsorbents in the Adsorbent Pervious Concrete (APC) mixture, focusing on their engineering properties and environmental aspects. Fine-grained adsorbents, including anthracite, iron slag, lignite, LECA, perlite, pumice, and zeolite, were added at a proportion of 10% by weight of coarse aggregate (0.6-1.2 mm size range). Compressive strength, porosity, and permeability tests were conducted to assess APC's engineering properties, while its efficiency in reducing Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) in urban runoff was examined. ANOVA analysis was performed to evaluate the impact of different adsorbents on APC performance. Results showed that the specific gravity of the adsorbents significantly influenced APC's compressive strength. Anthracite, iron slag, and zeolite increased compressive strength, while all adsorbents, except zeolite, reduced porosity and permeability. Lignite-containing APC exhibited the lowest compressive strength, porosity, and permeability with reductions of 16.12%, 24.7%, and 21.07%, respectively. Furthermore, APC samples demonstrated improved urban runoff quality, with zeolite exhibiting the best performance by reducing COD and TSS by 50.1% and 45.79%, respectively. ANOVA analysis confirmed the substantial influence of different adsorbents on APC's mechanical, physical, and environmental properties. Based on affordability, zeolite, iron slag, and pumice are recommended for use in APC mixtures, offering potential applications in urban areas and building landscaping. This critical analysis provides valuable insights for developing sustainable stormwater management with APC while enhancing its mechanical properties. Further research is encouraged to optimize the selection and utilization of adsorbent materials in APC system.

1. Introduction

The actions of humans in urban areas, including the construction of buildings, city development, and the replacement of green spaces with impermeable surfaces like asphalt and concrete, have a substantial impact on the environment. The reduction of permeable surfaces in cities leads to

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anthropization and disrupts the natural water cycle, presenting cities with challenges in managing and controlling stormwater, flooding, and the contamination of urban runoffs, which are taken from past studies [1-3]. Asphalt and concrete pavements in urban areas and walkways accumulate organic and nonorganic pollutants, primarily from vehicle emissions, significantly influencing the quality of urban runoff.

To mitigate the detrimental environmental effects associated with stormwater in urban regions, the development of pervious concrete (PC) pavement systems has emerged as an environmentally friendly infrastructure solution. PC is a mixture of coarse aggregate, minimal or no fine materials, Portland cement, and water, which creates a porous structure allowing for the passage of water and air. The general porosity of PC ranges from 15% to 35%, with an infiltration rate of approximately 0.34 cm/s. Due to its higher void content, the compressive strength of PC is lower than that of conventional concrete, typically ranging from 3.5 to 28.0 MPa depending on the mixture design and expected porosity, which are taken from previous studies [4-7]. Consequently, PC is best suited for areas with light traffic loads such as green areas, sidewalks, walkways, building landscaping, and parking lots, are quoted from past studies [3, 8-10]. However, one important consideration for PC systems is the occurrence of the clogging phenomenon, which reduces the system's lifespan over time. Teymouri *et al.,* [11] reported a clogging phenomenon in a PC pavement that caused a 10% infiltration loss in the first four years of operation and an additional 20% loss over the following two years. After six years, the PC pavement was significantly clogged, resulting in a 57% reduction in infiltration rate, although no maintenance was performed during the system's operation. Despite the declining efficiency of PC over eight years without maintenance, it still maintains the capacity to infiltrate urban runoff and stormwater at a rate of 1.14 mm/s, by Teymouri *et al.,* [11]. PC also possesses heat-transfer abilities, facilitating snow melting during cold seasons and reducing hazards such as slipping for residents and pedestrians, quoted from Handbook for Pervious Concrete Certification in Greater Kansas City [12]. Previous studies have shown that mixtures with higher strength in Europe are preferred by adding 5% to 10% fine aggregates, while in the United States, a higher porosity is favored over increased strength, reported by previous studies [13-14].

The effectiveness of PC in managing and controlling stormwater runoff in urban areas is evaluated based on its ability to address the challenges associated with urban runoff, which is often contaminated by organic and non-organic materials, posing a threat to freshwater and surface water resources are taken from previous studies [15-16]. Urban runoff is also considered a potential water resource for irrigation if it can be adequately collected and treated. To this end, researchers have recently focused on Adsorbent Pervious Concrete (APC), an ordinary PC that incorporates various low-cost adsorbents such as minerals, industrial waste, biomass, or agricultural by-products, for treating stormwater and urban runoffs. PC itself has the ability to reduce impurities in stormwater and wastewater due to its porous structure that acts as a filter by Jaeel and Faisal [17], while APC enhances the removal efficiency of urban runoff contaminants while retaining the original properties of PC. Adsorbent materials have the capacity to absorb pollutants on their porous surfaces, and incorporating them as fine-grained materials in the PC structure can reduce pore size and increase the removal efficiency of APC. Developing low-cost APC systems can address issues related to polluted urban runoffs, particularly in developing countries that may lack resources for costly treatment technologies on a large scale. Additionally, collecting urban runoff for irrigation purposes can help reduce the consumption of freshwater. Mineral and industrial waste adsorbents, including anthracite, iron slag, lignite, LECA, perlite, pumice, and zeolite, have shown promising results in reducing urban runoff contaminations due to their affordability, accessibility, and previous success in removing impurities from water and wastewater, which are mentioned in the previous studies [18-

24]. Figure 1 illustrates various low-cost adsorbents that have been used in water and wastewater treatment.

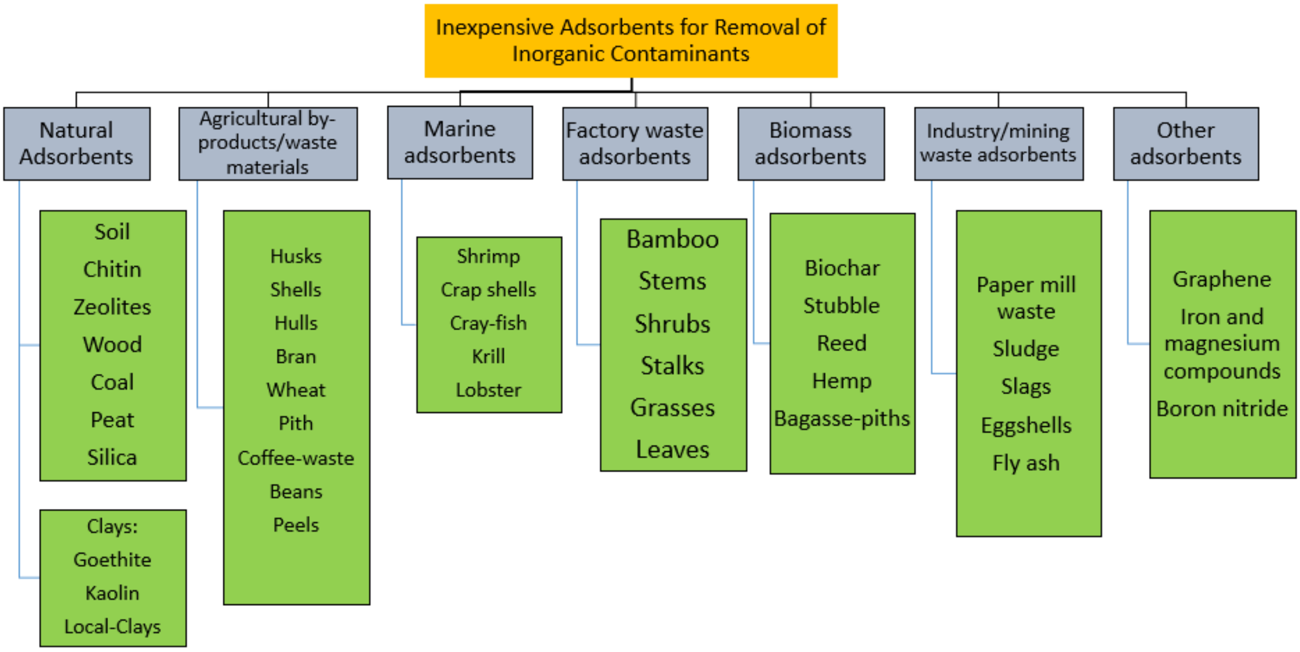


Fig. 1. Different types of adsorbents by Sing *et al.,* [25]

In recent years, there has been an increased utilization of adsorbents and recycled aggregates in the PC mixture to enhance the removal of pollutants from wastewater and stormwater and reduce waste production. Galishnikova *et al.,* [26] incorporated recycled aggregates and silica fume into the PC mixture and found that increasing the proportion of recycled aggregate led to a degradation of engineering properties, whereas higher percentages of silica fume had the opposite effect. Abedi-Koupai *et al.,* [27] added iron slag to the pervious concrete mixture to improve the quality of urban storm runoff, and their findings demonstrated that PC with iron slag enhanced the removal of COD, TSS, and lead concentration by 43%, 70%, and 91% respectively. Liang *et al.,* [28] utilized TiO2 in PC to reduce total phosphorus and ammonia nitrogen in stormwater by 17% and 13% respectively.

Another concern regarding pervious concrete is its strength and physical properties, especially since it is commonly used in low-traffic urban areas. Factors that can impact the strength and porosity of APC are similar to those of PC and include the types and sizes of aggregates, water-to-cement ratio, water, and cement content, the proportion of fine aggregates, and the type, size, and water absorption of adsorbents [29-36]. Karami *et al.,* [9] investigated the compressive strength, void content, and permeability of PC containing different fine-grained adsorbents and found that a higher percentage of adsorbents increased compressive strength while reducing porosity and infiltration rate. Chen *et al.,* [13] evaluated the engineering properties of three different PC mixtures with regular Portland cement, fly ash, and blast furnace slag, and the results revealed that mixtures with fly ash and slag had higher hydraulic conductivity due to larger air void ratios but resulted in lower strength.

In summary, the use of low-cost APC can improve the quality of urban runoff, although its strength and physical properties can be influenced by the type and size of adsorbents. The optimal adsorbent with best performance in both quality and mechanical characteristics needs to be determined, which have not been compared in previous studies. Therefore, in this study, various types of fine-grained adsorbents (0.6-1.2 mm) including anthracite, iron slag, lignite, LECA, perlite, pumice, and zeolite were added to the PC mixture to evaluate the compressive strength, porosity, and permeability of APC. The capacity of APC to reduce COD and TSS in urban runoff was also assessed. Furthermore, the study recommends analyzing the performance of the most effective adsorbent in APC in terms of engineering properties, treatment efficiency, and cost. Table 1 presents the cost of each adsorbent in Iran.

Table 1
Cost of Adsorbents in Iran provided by Foolad Takfaravar Asia Company [37]

Adsorbent	Cost per ton ($)
Anthracite	14
Iron Slag	2
Lignite	11
LECA	13
Perlite	25
Pumice	8
Zeolite	5

2. Materials and Methods

2.1 Adsorbents

The adsorbents employed in this study consist of anthracite, iron slag, LECA, lignite, perlite, pumice, and zeolite, with a size range of 0.6 to 1.2mm. These adsorbents were added to the APC mixture at a proportion of 10% of the weight of the coarse aggregate. This percentage is considered suitable for the APC mixture as it avoids a significant reduction in the porosity and permeability of the system. Table 1 provides a summary of the chemical analysis and specific gravity of the adsorbents. Figure 2 illustrates the utilized adsorbents in this study, along with an explanation of their source and properties.

Anthracite (A) Iron Slag (IS) Lignite (Li) LECA (LE)

Perlite (Pe) Pumice (Pu) Zeolite (Z)

Fig. 2. Used adsorbents in this study

2.1.1 Anthracite (A) and Lignite (Li)

Coal includes 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 or brown coal is a soft brown combustible sedimentary rock that is formed from naturally compressed peat with high moisture content and is considered the lowest rank of coal due to its relatively low heat content. Moreover, the water adsorption rate of lignite is around 56%. Furthermore, anthracite is hard, has the highest carbon content (between 92.1% and 98%), and includes bituminous coal and lignite, by Di Gianfrancesco *et al.,* [38]. This mineral is widely used as fuel supplied to the boiler, although it is difficult to burn out because of its low volatile and high carbon content, by Chien *et al.,* [39]. Lignite has the capacity to be used for wastewater treatment for the removal of phenol and color, by Sriramoju *et al.,* [40] Anthracite is commonly used in water treatment, and past studies claimed that when anthracite is used in combination with filtering sand, it acts as an excellent filter media for water clarification because of its low density. It is because although the size of anthracite is larger than the river sand, due to its low density, it will settle after the sand during the backwashing process, and thus the filter can always remain a coarser media at the top and finer media at the bottom to enhance the capacity of physical filtration, mentioned in past studies [41-44].

2.1.2 Iron Slag (IS)

Slags are considered the ultimate waste from the steel industry. They are categorized as waste materials but have been extensively reused for various purposes. Therefore, slags are considered a product nowadays and are widely used as a filler material in road construction, water and wastewater treatment, and phosphatic fertilizer, reported by previous studies [45-46]. Iron slag has the capacity to adsorb contamination in water and wastewater due to having lots of pores in its instruction, and it has been used for the adsorption of lead, nickel dye, and phosphorous in a range of research, concluded in the past studies [47-49].

2.1.3 LECA (LE)

LECA is the raw material for producing lightweight aggregates. Generally, its production methods are rotary kiln and sedimentation. In both methods, raw materials are heated until the expansion and the release of internal gas. Then, the materials become soft and flexible but have not yet melted completely. The internal gas bubbles create a mass of separated air cells, and these substances remain inside them after cooling. Therefore, raw materials are expanded, and aggregates with lower specific gravity are obtained, by Kimura *et al.,* [50]. LECA, an adsorptive substrate, has a high removal capacity for phosphorus and nitrogen in aquaculture wastewater, by Hamid *et al.,* [51].

2.1.4 Perlite (Pe)

Perlite stone is heated to a temperature of 850 to 900˚C using a rotary kiln and is obtained in the form of soft class. At this stage, the water is completely drained from layers, and the rock masses increase in volume by 7 to 15 times. The new materials, which have become large and bulky in terms of shape, are white in color, large, and irregular in size and parts. The whiteness is due to the vapors resulting from the evaporation of liquids and water inside the stone. The specific weight of perlite stone is about 100 kg/m^3 in the raw and unexpanded state, while it is between 30 and 250 kg/m^3 in the expanded state, by Zeatang *et al.,* [52]. Perlite has shown promising performance in the field of oily wastewater treatment, by Li *et al.,* [53].

2.1.5 Pumice (Pu)

Mineral pumice is formed as a result of the entry of volcanic molten materials into water reservoirs such as seas and lakes and gas discharge during the rapid flow of magma. From a macroscopic point of view, mineral pumice is dark grey in color, turning brown, and looks like a pebble, by Grotheer *et al.,* [54]. Pumice can adsorb contamination due to having a vesicular texture, characterized by the presence of cavities both on the surface and the interior of the rock. This adsorbent provided significant efficiency in treating tannery wastewater, by Bahare *et al.,* [55].

2.1.6 Zeolite (Z)

Zeolite mineral in nature is magmatic origin along with igneous rocks, or it may be formed as a secondary mineral due to an alteration process. In general, the diversity of zeolites in sedimentary rocks is more than the types of zeolites known in igneous rocks of magmatic origin, and in addition, the amount of silicon in zeolites in sedimentary rocks is greater and has an alkaline composition. Zeolites are white, yellow, and green. A substantial amount of mesopores and ion exchange capacity (CEC) is one of the zeolite's most valuable properties, which reaches approximately 54.2 milliequivalents/g, by Pasha *et al.,* [56].

2.2 Materials

The size of coarse aggregate used in this study was based on the requirements specified by ASTM C33 [57], which ranges from 4.75 to 9.5 mm for all mixtures. This size of coarse aggregate is defined as an optimum range for PC mixture, which results in higher compressive strength [58]. Type II Portland cement was utilized in the mixtures, and its chemical properties followed ASTM C150 [59]. Figure 3 shows the granulometric curve of used coarse aggregates, which is close to the lower limit of ASTM C33 [57]. The specific gravity of coarse aggregate is 1600 kg/m^3, which meets the requirement of AASHTO T85 [60]. In addition, tap water was used in this study for the mixing and curing processes.

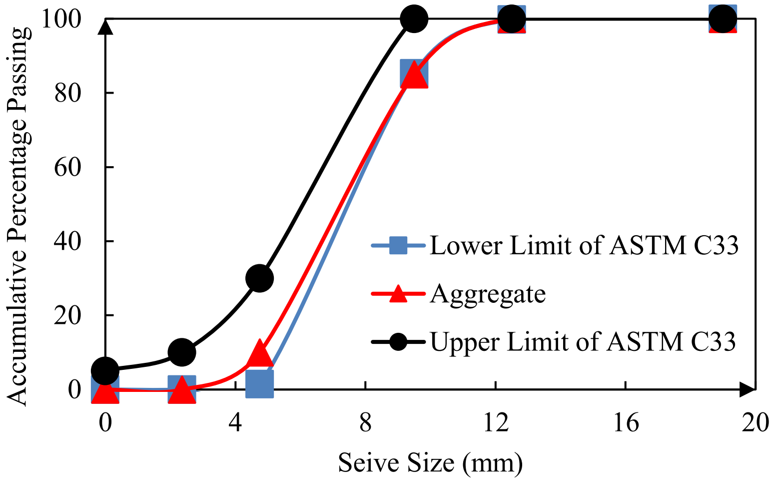


Fig. 3. Granulometric curve of coarse aggregate

Table 2 shows the material proportions of APC based on the standard of ACI 211 3/R [61]. The water-to-cement ratio (0.37) and cement content (340) were constant for all mixtures [9]. All adsorbents were pre-soaked for 24 hours before mixing and spread at room temperature to be contacted with air to have a dry surface before mixing. Pre-soaking prevents adsorbents from absorbing the water of the paste and maintains workability.

Table 2
Material proportions of pervious concrete containing different adsorbents

Mix Nominations	Control Sample (C)	Anthracite	Iron Slag	Lignite	LECA	Perlite	Pumice	Zeolite
Adsorbent Portion (%)	0	10	10	10	10	10	10	10
w/c ratio	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Cement Content (kg/m^3)	340	340	340	340	340	340	340	340

Note: The weight of coarse aggregate is 1600 kg/m^3 for all treatments

2.3 Experimental Tests

X-ray Fluorescence Spectrometry (XRF) results of adsorbents were provided by the seller company, and a summary is presented in Table 3. Also, AASHTO T85 [60] was used to measure the specific gravity of adsorbents. A calibrated scale was used to weigh all materials before mixing. Firstly, the dry form of coarse aggregate, cement, and adsorbents was mixed for one minute, followed by adding water to the mixture, and continued mixing for two more minutes in a Hobart mixer. Then, the paste was cast into the molds, where their internal surfaces were coated with oil and compacted into three layers with 25 standard strokes per layer. De-molding was performed after 24 hours, and all specimens were put in a water tank for 28 days for curing.

The strength of APCs was evaluated by testing the compressive strength of the samples, which was tested on cube specimens of 150 mm in length with a constant rate of loading according to BS 1881 standard [62]. Besides, the physical properties of APCs were determined by measuring porosity and permeability, in which the porosity of APC specimens was assessed based on ASTM C1754 [63] using the water displacement method. This method is based on Archimedes' principle of buoyancy. Cube samples of 100 mm in length of APC were oven-dried for 24 hours at 105 °C and weighed to measure the dry weight of the samples. Also, the immersed weights of APCs were measured, and the porosity was calculated using Eq. (1). Moreover, a falling-head device that could fit the cubic APC samples was used according to ACI 522 [64] to determine the permeability APCs. The edges of each specimen were sealed to ensure the water only flowed vertically through the specimens. The permeability coefficient of APC was conducted on cube specimens of 100 mm in length and calculated using Eq. (2).

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

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

$$K = \frac{al}{At} Ln\left(\frac{h_1}{h_2}\right) \tag{2}$$

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

Apart from this, the performance of APCs on removing COD and TSS of urban runoff were assessed. The permeability device, as shown in Figure 4, was used to conduct the urban runoff quality tests. For this reason, two similar APC cube samples of 100 mm were placed on each other and sealed with foam on their four sides to prevent adjacent drainage. To simulate the actual conditions in urban areas, the specimens were placed on top of a coarse aggregate layer of 200 mm in height. Also, to prevent the by-passing of polluted urban runoff from the voids between APCs and the device, the top of the APCs samples was sealed. When the drainage valve was closed, 7 liters of polluted runoff was poured from the top surface of the APC specimens, and the runoff remained in the concrete specimens for 25 minutes. Finally, the valve was opened to sample the discharge of the system for measuring the concentration of COD and TSS. All the tests were conducted based on the necessary standards, and each data point represents the average value with three repetitions to minimize the possibility of measurement errors.

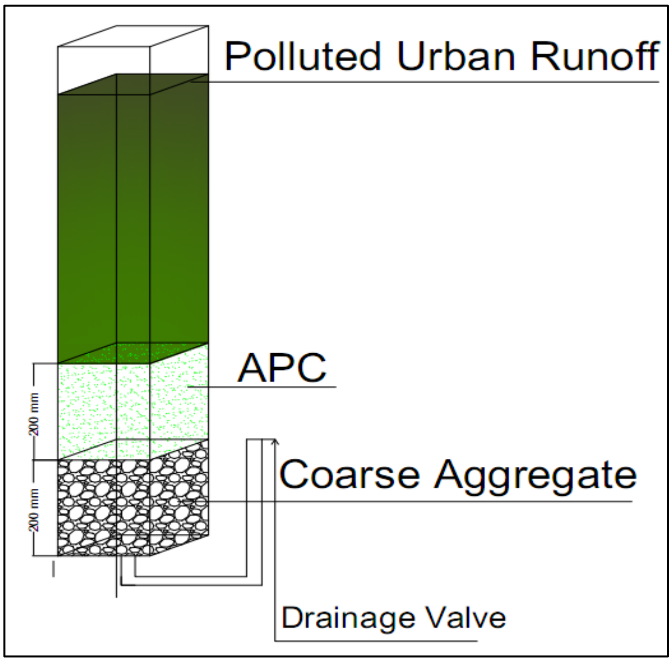


Fig. 4. Permeability device and scheme of test conditions for performing quality tests

3. Results and Discussion

3.1 Characteristics of Adsorbents

The chemical analysis and specific gravity of both the coarse aggregate and adsorbents are presented in Table 3. According to the table, iron slag exhibits the highest apparent specific gravity of 1800 kg/m^3, followed by anthracite at 1370 kg/m^3. On the other hand, perlite demonstrates the lowest specific gravity, measuring only 240 kg/m^3. In terms of silica content, lignite and pumice contain 35.99% and 48.37% SiO^2, respectively. In contrast, iron slag, LECA, zeolite, and perlite have SiO_2 levels exceeding 60%. Notably, anthracite possesses the lowest SiO_2 content, with a mere 5.4%. It is worth mentioning that both anthracite and lignite exhibit significantly higher amounts of CaO compared to other adsorbents.

Table 3
Chemical analysis and specific gravity of coarse aggregates and adsorbents

Chemical Feature	Anthracite (%)	Iron Slag (%)	Lignite (%)	LECA (%)	Perlite (%)	Pumice (%)	Zeolite (%)	Coarse aggregate (%)
SiO_2	5.4	67.15	35.99	66.05	69.5	48.37	65.15	38.2
Al_2O_3	2.67	5.65	3.33	16.75	12.8	12.49	11.83	15.4
Fe_2O_3	0.4	8.82	*	7.1	0.94	8.07	1.2	13.6
CaO	77.45	6.75	58.15	2.46	0.8	8.43	2.51	4.3
MgO	*	8.58	*	1.99	0.5	9.58	0.64	18.2
Na_2O	*	*	*	0.69	3.0	4.36	1.96	*
K_2O	*	1.12	*	*	*	*	*	7.0
P_2O_5	*	*	*	0.21	*	1.79	0.27	*
Ash	13.65	*	2.47	*	*	*	*	*
Specific Gravity (kg/m^3)	1370	1800	660	600	240	920	800	1600

* Zero or less than 0.1%

3.2 Compressive Strength

Figure 5 showcases the compressive strength of APC samples at a 28-day age. The relatively low strength of APC can be attributed to its high porosity and open structure. Enhancing the strength of pervious concrete involves reducing porosity through the addition of fine-grained materials or decreasing aggregate size, provided that these materials possess a substantial specific gravity, reported by previous studies [9-24]. It is widely reported that denser concrete with higher fresh density generally leads to higher compressive strength, taken from previous studies [65-66].

As depicted in Figure 6 and Table 1, the compressive strength of APC containing adsorbents with low specific gravity, such as lignite, perlite, and LECA, was lower than that of the control sample (13.83 MPa). Conversely, adsorbents with higher specific gravity, including zeolite, pumice, iron slag, and anthracite, increased the compressive strength of APC. Notably, APC containing zeolite exhibited higher compressive strength compared to APC with iron slag, despite zeolite having only about half the specific gravity of iron slag. This can be attributed to zeolite's high water adsorption capability, which retains water within its mesopores and releases it into the APC mixture during casting. Additionally, zeolite's pozzolanic reaction positively impacts bonding strength and enhances the compressive strength of APC, by Teymouri *et al.,* [67].

The compressive strength of APC is considerably affected by the porosity features in which decreasing the porosity might increase the compressive strength. Adding fine-grained materials to the APC mixture will affect the porosity and compressive strength. In other words, fine-grain materials will definitely reduce the porosity; however, based on their specific gravity the compressive strength might increase or decrease. High specific gravity fine materials positioned between the pores reduce their size and numbers and will strengthen the bonds while using low specific gravity fine materials will weaken the bonds in APC. The addition of fine-grained adsorbents to the APC mixture reduces pore size and number, thereby decreasing APC's porosity. Consequently, when adsorbents possess relatively high specific gravity, they contribute to increased compressive strength. Conversely, some adsorbents such as LECA, lignite, and perlite are unable to withstand compression and easily crush even between fingers. As a result, APC containing LECA, lignite, and perlite exhibit weaker cement bonds and lower compressive strength. Figure 6 visually illustrates the changes in APC's compressive strength for each adsorbent, along with their corresponding specific gravities on the right.

Moreover, the level of water adsorption of adsorbents significantly impacts APC's compressive strength. Most adsorbents possess relatively high water adsorption capacity, which facilitates the adsorption of pollutants from aqueous solutions. Adsorbents with high water absorption ability tend to absorb water from the APC paste, reducing workability and slump, weakening cement bonds, and decreasing compressive strength. Previous studies [7, 15, 27] have highlighted that increasing the water-to-cement ratio between 0.30 to 0.45 substantially enhances the strength of PC, while adsorbents reduce the water content of the paste, consequently diminishing APC's strength. To prevent water loss from the paste, all adsorbents in the present study were pre-soaked.

The APC samples containing zeolite and iron slag exhibited the highest compressive strengths, with increases of 15.82% and 9.19% compared to the control sample, respectively. Conversely, the APC samples containing lignite and perlite demonstrated the lowest compressive strengths, with decreases of 16.12% and 10.33% relative to the control sample. It can be concluded that adsorbents with high specific gravity play a role similar to that of sand in PC, while adsorbents with low specific gravity tend to weaken the bond between cement and aggregates. Furthermore, according to ANOVA results (F(13,1) = 165.19, P < 0.0001, R^2 = 0.993), the model is significant, indicating that the different adsorbents in the APC mixture have a notable impact on compressive strength.

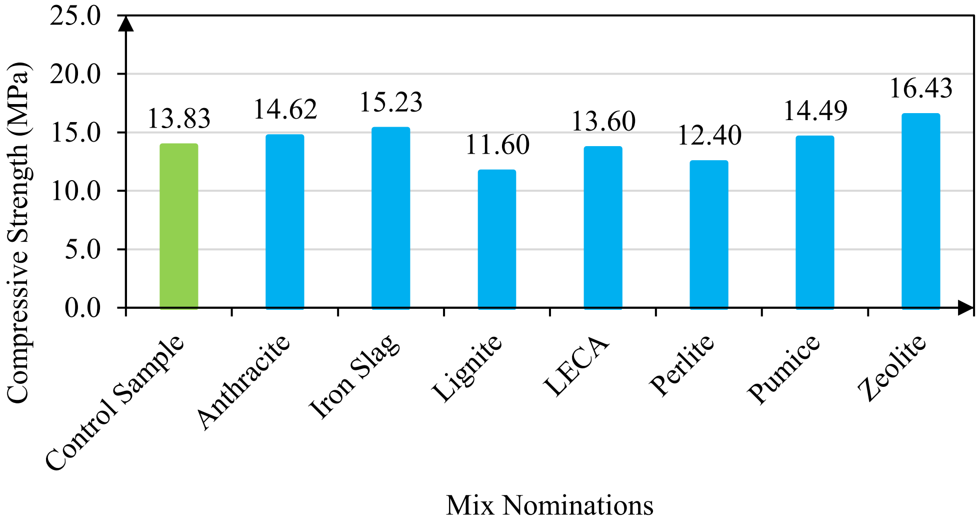


Fig. 5. Compressive strength of pervious concrete containing various adsorbent

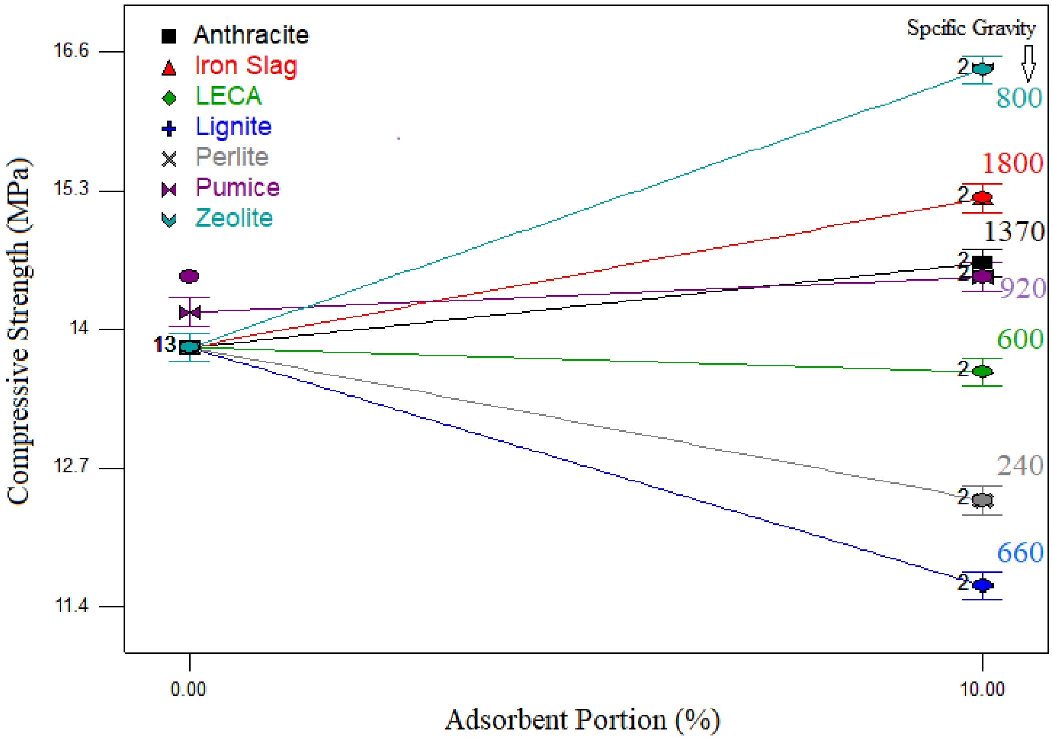


Fig. 6. Changes in APC's compressive strength for each adsorbent

3.3 Porosity

Figure 7 illustrates the porosity of APC samples incorporating various adsorbents. Except for zeolite (21.33%), all APC samples exhibited lower porosity than the control sample. It is estimated that the presence of zeolite in the APC mixture, along with its numerous mesopores, led to a slight increase (4.6%) in porosity compared to the control samples. However, when the zeolite portion exceeds 10%, the porosity is expected to decrease. Previous studies [11, 68-69] have also reported a reduction in porosity when fine-grained materials are present, as the size and number of pores decrease.

The APC samples containing anthracite and lignite demonstrated the lowest void content, with percentages of 21.07% and 16.12%, respectively, which were lower than that of the control sample. It is important to note that in porosity measurements, all pores, including those on the surface of adsorbents, are considered effective pores. However, in terms of permeability, only the pores that allow water to pass through play a significant role, while the dead-end pores do not contribute. Figure 8 visually represents the changes in porosity of APC samples incorporating different adsorbents.

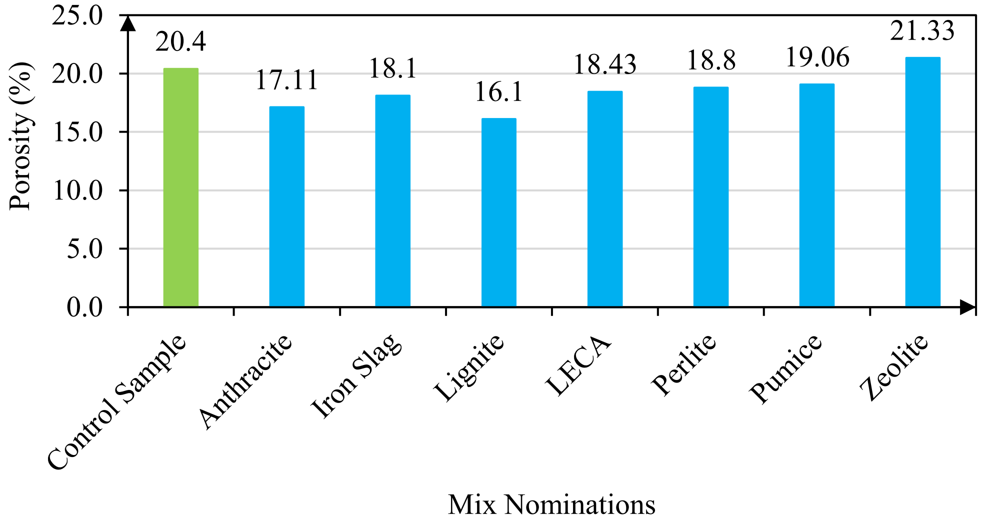


Fig. 7. Porosity of pervious concrete containing different adsorbents

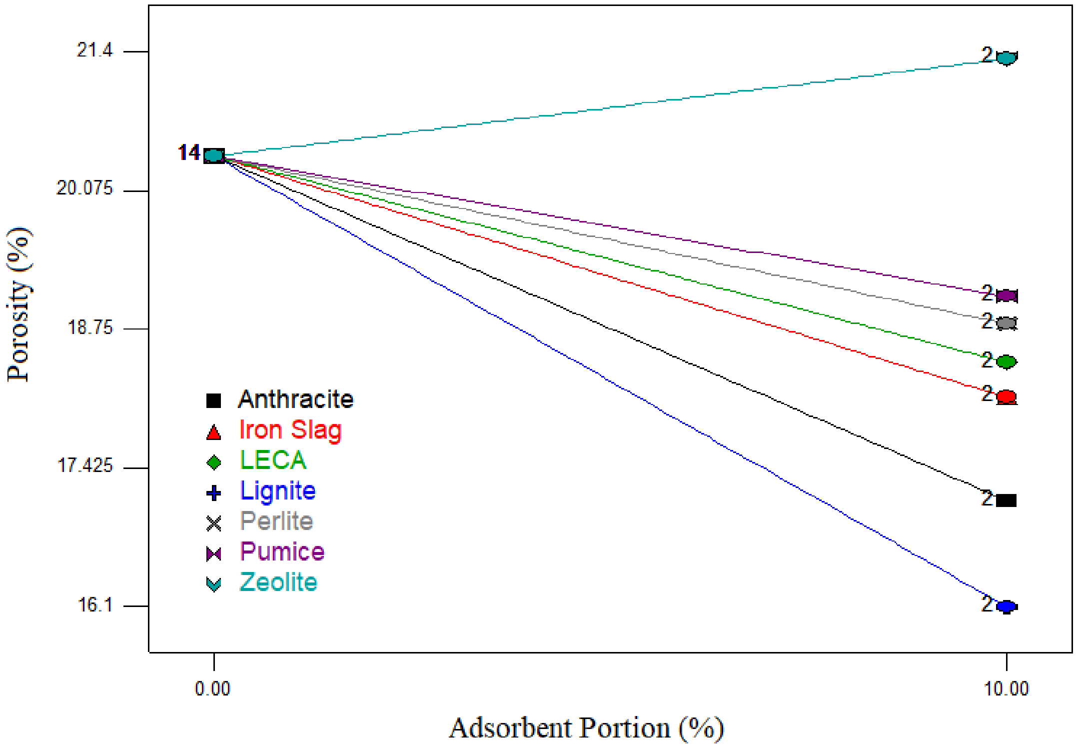


Fig. 8. Porosity of APC samples containing different adsorbents

3.4 Permeability

Figure 9 provides a summary of the infiltration rate observed in APC samples incorporating various adsorbents. The addition of fine-grained adsorbents to pervious concrete results in a reduction in the size and number of pores, thereby decreasing the infiltration rate of APC. In Figure 9, all APC specimens exhibited a lower hydraulic conductivity compared to the control sample, with the exception of zeolite. The presence of zeolite in the APC mixture, the compacting process, and other laboratory conditions may account for this observation. However, it is important to consider the presence of numerous mesopores in zeolite and its rectangular shape.

The APC samples containing lignite and anthracite displayed the lowest permeability, with reductions of 24.71% and 18.80%, respectively, compared to the control sample. Iron slag and perlite also significantly decreased the permeability, while LECA and pumice caused only a minimal reduction (approximately 4%). This can be attributed to the properties of LECA and pumice, which contain a significant number of pores within their structures. These findings align with the results reported by previous studies [6, 9, 11]. Figure 10 visually illustrates the changes in permeability of APCs incorporating different adsorbents.

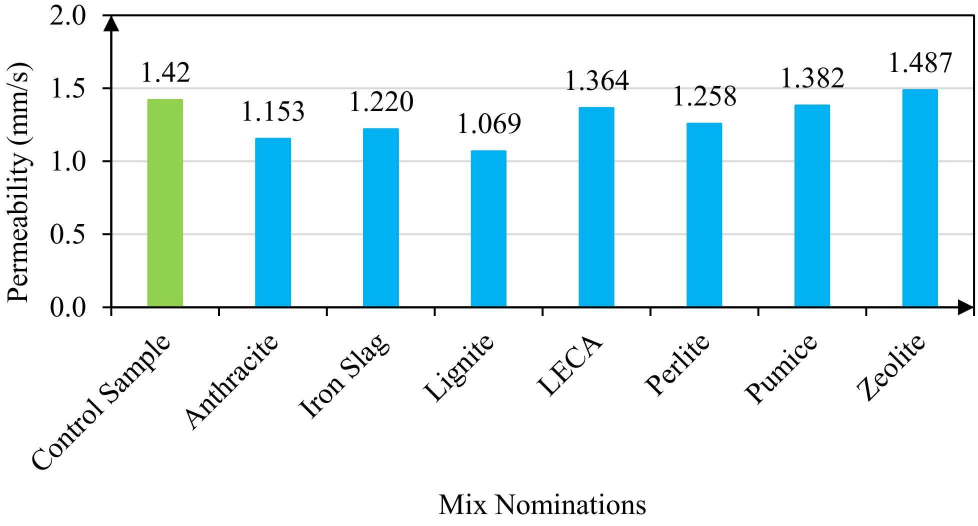


Fig. 9. Permeability of pervious concrete containing various adsorbents

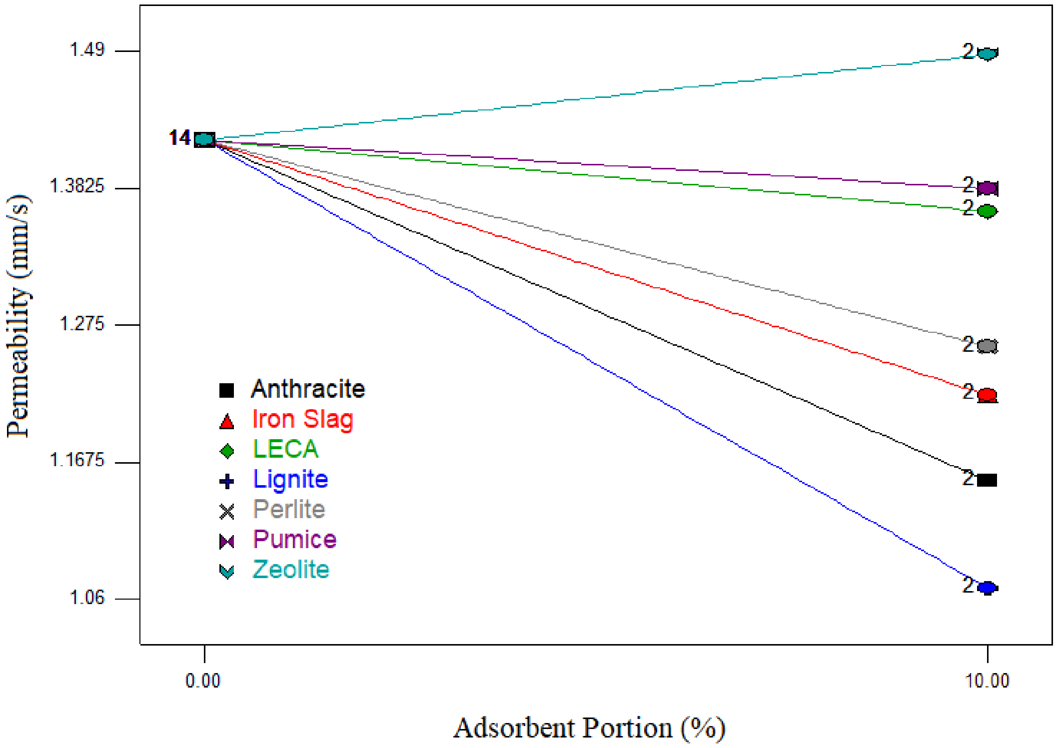


Fig. 10. Permeability of APC samples containing different adsorbents

3.5 Relationship Between Compressive Strength and Porosity

Figure 11 illustrates the relationship between the compressive strength and porosity of APC samples. Generally, an inverse correlation exists between PC strength and porosity, as reducing the number and size of pores enhances the integration of the mixture are taken from previous studies [6, 69]. However, a critical analysis reveals that the APC samples incorporating perlite, lignite, and LECA deviated from this trend due to their low specific gravity, which could weaken the cement paste. This highlights the importance of considering specific gravity as a factor influencing the compressive strength of APC.

Furthermore, upon analyzing Figure 12, it is evident that the addition of zeolite to the PC mixture resulted in an increase in both compressive strength and void content, showcasing its superior performance among all the adsorbents investigated in this study. Conversely, APC samples containing iron slag, anthracite, and pumice demonstrated increased compressive strength alongside a reduction in porosity and permeability. This observation emphasizes the positive impact of these adsorbents on the mechanical properties and overall quality of APC.

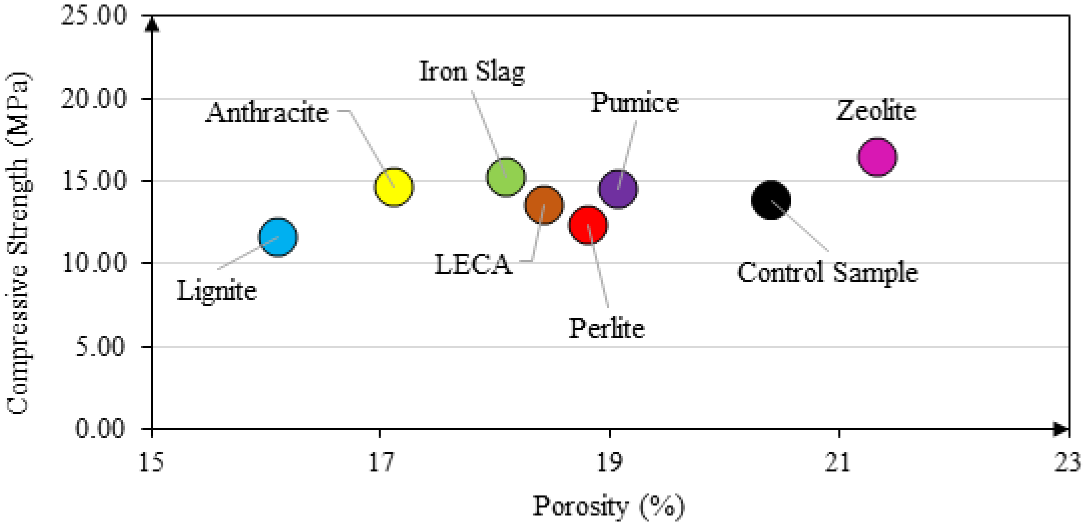
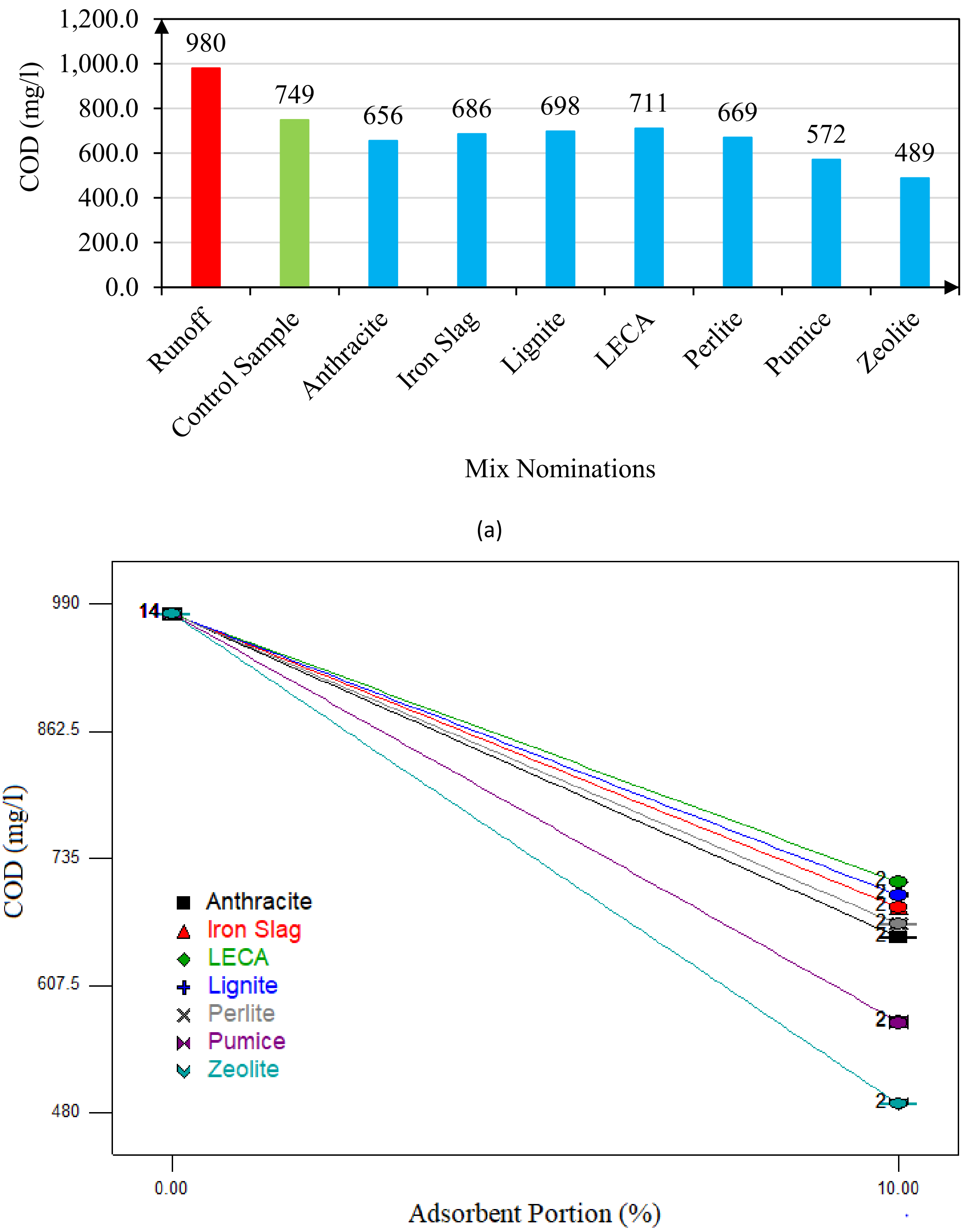


Fig. 11. Compressive strength of pervious concrete samples containing various adsorbents versus Porosity

3.6 Effects of Pervious Concrete Containing Various Adsorbents on the COD and TSS of Stormwater

Figures 12 (a) and (b) illustrate the effects of APC on the removal of COD from polluted urban runoff. Initially, the COD concentration was 980 mg/l, and the control sample exhibited a reduction of 23.54%. This reduction aligns with previous studies highlighting the capability of stormwater runoff to decrease COD levels, mentioned in previous studies [3, 11, 31]. In this study, APC functions as a filter, and the removal of COD is primarily a physical action, with solids, debris, and fine materials being trapped in the pores of APC and adsorbing onto the surface of the adsorbents. The addition of adsorbents to the PC mixture enhances its ability to remove COD, as demonstrated by all APC samples significantly reducing the COD of urban runoff, as shown in Figure 12 (b). Notably, APC containing zeolite exhibited the highest COD removal, with a reduction of 50.10%.

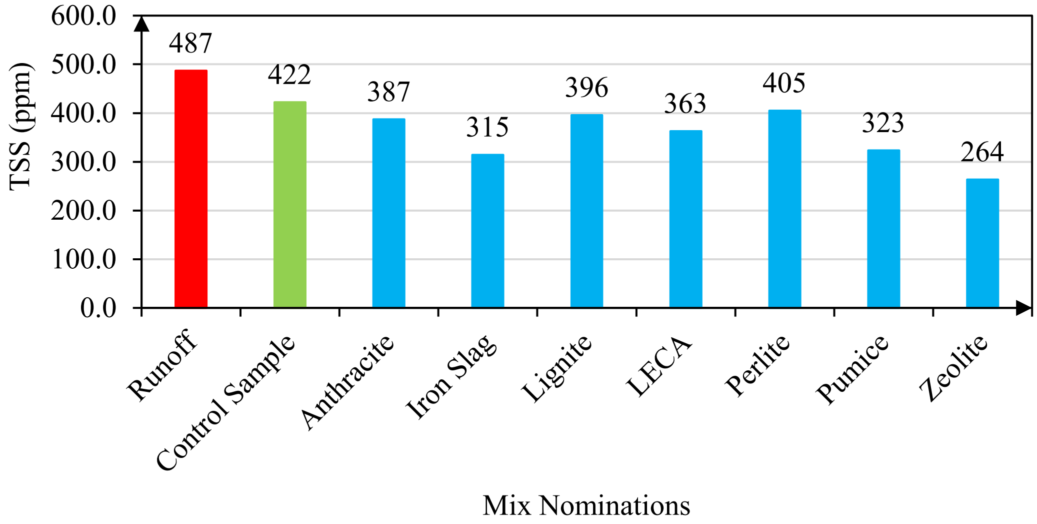
Turning to Figures 13 (a) and (b), depict the impact of APC on reducing the TSS of urban runoff. Initially, the TSS concentration was 487 ppm, which decreased by 13.3% to 422 ppm after passing through the control sample. Previous research has shown that a sand filter can reduce TSS concentration in urban storm runoff, by Hatt *et al.,* [70], and in this study, PC acts as a consistent filter. The relatively high rate of dissolved particles in urban runoffs can be attributed to surface flow on roads and other areas, as well as various physiochemical and molecular forces influencing TSS rates [28]. Notably, APC containing zeolite exhibited the highest TSS removal, with a reduction of 45.79%. Additionally, among all the adsorbents, LECA and perlite exhibited the lowest reductions in both COD (27.44%) and TSS (16.83%), while iron slag and pumice demonstrated favorable treatment performance for both COD and TSS. These findings highlight the varying effectiveness of different adsorbents in improving the removal of pollutants in urban runoff when incorporated into APC.



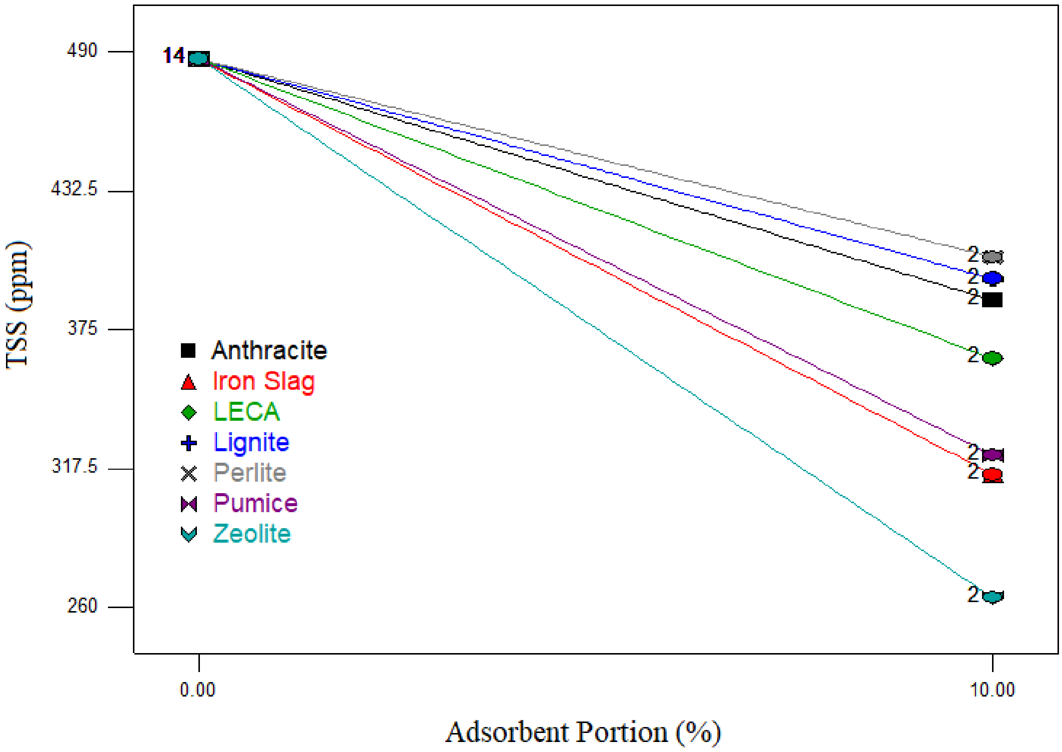
(a)

(b)

Fig. 12. Effects of APC samples on COD reduction



(a)



(b)

Fig. 13. Effects of APC samples on TSS reduction

4. Conclusions

In conclusion, this study has provided valuable insights into the engineering properties and environmental considerations associated with various adsorbents in Adsorbent Pervious Concrete (APC). The investigation focused on evaluating the impact of different inexpensive adsorbents in the APC mixture, with a particular emphasis on compressive strength, physical properties, and APC's ability to improve the removal of Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) from urban runoff. The findings highlight the significant role of specific gravity in determining the compressive strength of APC. Zeolite, iron slag, and pumice proved to be favorable adsorbents, contributing to increased strength. APC samples containing zeolite displayed the highest compressive strength, reaching an impressive 16.43 MPa, which was 15.82% higher than the control sample. These results underscore the potential of zeolite as a promising adsorbent in APC mixtures, offering opportunities for enhancing structural integrity.

In terms of physical properties, all APC samples demonstrated desirable void content and infiltration rates, indicating their effectiveness as sustainable stormwater management solutions. Zeolite, in particular, exhibited a marginal increase of approximately 4.5% in both porosity and permeability, enhancing the overall performance of APC in managing stormwater. Furthermore, all adsorbents incorporated into APC showcased significant reductions in COD and TSS levels in urban runoff. Zeolite emerged as the most effective adsorbent, exhibiting remarkable removal rates of 50.10% for COD and 45.79% for TSS, surpassing other adsorbents. These findings highlight the potential of zeolite in improving urban runoff quality and addressing the challenges posed by pollutants. Based on affordability, strength, and quality performance, zeolite, iron slag, and pumice are recommended for future applications in managing and controlling stormwater and treating urban runoff. These adsorbents offer cost-effective and efficient solutions, making them suitable for various applications in urban areas and contributing to sustainable stormwater management strategies.

In summary, this research provides valuable insights into the engineering properties and environmental considerations associated with various adsorbents in APC. The findings emphasize the importance of specific gravity, compressive strength, physical properties, and the efficacy of adsorbents in pollutant removal. By optimizing the selection and utilization of adsorbent materials in APC systems, it is possible to enhance both the mechanical properties of APC and its ability to improve urban runoff quality, thereby mitigating the impact of urban runoff in urban areas.

References

[1] Alimohammadi, Vahid, Mehdi Maghfouri, Delaram Nourmohammadi, Pejman Azarsa, Rishi Gupta, and Mohammad Saberian. "Stormwater runoff treatment using pervious concrete modified with various nanomaterials: A comprehensive review." *Sustainability* 13, no. 15 (2021): 8552. https://doi.org/10.3390/su13158552

[2] Behfarnia, Kia, Hossein Faghihian, and Shahrokh Soltaninia. "Sustainable Design of Pervious Concrete Using One-Part Alkali-Activated Slag with Zeolite and Walnut Shell Activated Carbon to Absorb Runoff Contaminants". *Available at SSRN*. https://dx.doi.org/10.2139/ssrn.3974339

[3] Teymouri, Ehsan, Nurul Noraziemah Mohd Pauzi, and Kwong Soon Wong. "Developing Lignite Pervious Concrete for Application in Pedestrian Walkways and Urban Runoff Treatment." *Iranian Journal of Science and Technology, Transactions of Civil Engineering* (2023): 1-19. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001025

[4] Putman, Bradley J., and Andrew I. Neptune. "Comparison of test specimen preparation techniques for pervious concrete pavements." *Construction and Building Materials* 25, no. 8 (2011): 3480-3485.. https://doi.org/10.1016/j.conbuildmat.2011.03.039

[5] Schaefer, V. R., K. Wang, M. T. Suleiman, and J. Kevern. "Mix design development for pervious concrete in cold climates." National Concrete Pavement Technology Center, Iowa State University, Ames, Iowa (2006).

[6] Tennis, Paul D., Michael L. Leming, and David J. Akers. *Pervious concrete pavements*. Vol. 8. Skokie, IL: Portland Cement Association, 2004.

[7] Yap, Soon Poh, Paul Zhao Chiat Chen, Yingxin Goh, Hussein Adebayo Ibrahim, Kim Hung Mo, and Choon Wah Yuen. "Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates." *Journal of* Cleaner Production 181 (2018): 155-165. https://doi.org/10.1016/j.jclepro.2018.01.205

[8] Jato-Espino, Daniel, Nora Sillanpää, Susanne M. Charlesworth, and Ignacio Andrés-Doménech. "Coupling GIS with stormwater modelling for the location prioritization and hydrological simulation of permeable pavements in urban catchments." *Water* 8, no. 10 (2016): 451. https://doi.org/10.3390/w8100451

[9] Karami, Hojat, Ehsan Teymouri, Sayed-Farhad Mousavi, and Saeed Farzin. "Experimental investigation of the effect of adding LECA and pumice on some physical properties of porous concrete: some physical properties of porous concrete." *Engineering Journal* 22, no. 1 (2018): 205-213. https://doi.org/10.4186/ej.2018.22.1.205

[10] Rodríguez-Rojas, M. I., F. Huertas-Fernández, B. Moreno, G. Martínez, and A. L. Grindlay. "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." *Journal of environmental management* 205 (2018): 151-162. https://doi.org/10.1016/j.jenvman.2017.09.075

[11] Teymouri, Ehsan, Kwong Soon Wong, Masoud Rouhbakhsh, Mahdi Pahlevani, and Mehdi Forouzan. "Evaluating the Clogging Phenomenon in Pervious Concrete from January 2015 to December 2022." *Civil and Sustainable Urban Engineering* 3, no. 1 (2023): 70-80. https://doi.org/10.53623/csue.v3i1.236

[12] Handbook for Pervious Concrete Certification in Greater Kansas City. https://www.academia.edu/42850088/Handbook_for_Pervious_Concrete_Certification_in_Greater_Kansas_City_This_support_material_is_part_of_the_CPG_Pervious_Concrete_Certification_Program (2012).

[13] Chen, Xiaodan, Hao Wang, Husam Najm, Giri Venkiteela, and John Hencken. "Evaluating engineering properties and environmental impact of pervious concrete with fly ash and slag." *Journal of cleaner production* 237 (2019): 117714. https://doi.org/10.1016/j.jclepro.2019.117714

[14] Kevern, J. T. (2008). “Advancements in pervious concrete technology”. Iowa State University.

[15] Bannerman, Roger T., David W. Owens, R. B. Dodds, and Nancy J. Hornewer. "Sources of pollutants in Wisconsin stormwater." *Water Science and technology* 28, no. 3-5 (1993): 241-259. https://doi.org/10.2166/wst.1993.0426

[16] Javaheri-Tehrani, Mohsen, Sayed-Farhad Mousavi, Jahangir Abedi-Koupai, and Hojat Karami. "Treatment of domestic wastewater using the combination of porous concrete and phytoremediation for irrigation." *Paddy and Water Environment* 18 (2020): 729-742. https://doi.org/10.1007/s10333-020-00814-7

[17] Jaeel, Ali Jwied, and Ghufran Haider Faisal. "COD removal from synthetic wastewater using pervious concrete." In *2018 international conference on advance of sustainable engineering and its application (ICASEA)*, pp. 174-178. IEEE, 2018. 10.1109/ICASEA.2018.8370978

[18] Aghakhani, A., S. F. Mousavi, B. Mostafazadeh-Fard, R. Rostamian, and M. Seraji. "Application of some combined adsorbents to remove salinity parameters from drainage water." *Desalination* 275, no. 1-3 (2011): 217-223. https://doi.org/10.1016/j.desal.2011.03.003

[19] Bilardi, S., P. S. Calabró, and N. Moraci. "Simultaneous removal of CuII, NiII and ZnII by a granular mixture of zero-valent iron and pumice in column systems." *Desalination and Water Treatment* 55, no. 3 (2015): 767-776. https://doi.org/10.1080/19443994.2014.916234

[20] Malamis, S., and E. Katsou. "A review on zinc and nickel adsorption on natural and modified zeolite, bentonite and vermiculite: Examination of process parameters, kinetics and isotherms." *Journal of hazardous materials* 252 (2013): 428-461. https://doi.org/10.1016/j.jhazmat.2013.03.024

[21] Malekian, Raheleh, Jahangir Abedi-Koupai, Sayed Saeid Eslamian, Sayed Farhad Mousavi, Karim C. Abbaspour, and Majid Afyuni. "Ion-exchange process for ammonium removal and release using natural Iranian zeolite." *Applied Clay Science* 51, no. 3 (2011): 323-329. https://doi.org/10.1016/j.clay.2010.12.020

[22] Teymouri, Ehsan, Sayed-Farhad Mousavi, Hojat Karami, Saeed Farzin, and Maryam Hosseini Kheirabad. "Municipal Wastewater pretreatment using porous concrete containing fine-grained mineral adsorbents." *Journal of Water Process Engineering* 36 (2020): 101346. https://doi.org/10.1016/j.jwpe.2020.101346

[23] Paliulis, Dainius. "Removal of Formaldehyde from Synthetic Wastewater Using Natural and Modified Zeolites." *Polish Journal of Environmental Studies* 25, no. 1 (2016). 10.15244/pjoes/60727.

[24] Teymouri, Ehsan, Kwong Soon Wong, and Nurul Noraziemah Mohd Pauzi. "Iron slag pervious concrete for reducing urban runoff contamination." *Journal of Building Engineering* 70 (2023): 106221. https://doi.org/10.1016/j.jobe.2023.106221

[25] Singh, Surinder, Kailas L. Wasewar, and Sushil Kumar Kansal. "Low-cost adsorbents for removal of inorganic impurities from wastewater." In *Inorganic pollutants in water*, pp. 173-203. Elsevier, 2020. https://doi.org/10.1016/B978-0-12-818965-8.00010-X

[26] Galishnikova, V. V., Abdo Sh, and A. M. Fawzy. "Influence of silica fume on the pervious concrete with different levels of recycled aggregates." *Magazine of civil engineering* 1 (93) (2020): 71-82.

[27] Koupai, Jahangir Abedi, Soheila Saghaian Nejad, Saman Mostafazadeh-Fard, and Kiachehr Behfarnia. "Reduction of urban storm-runoff pollution using porous concrete containing iron slag adsorbent." *Journal of Environmental Engineering* 142, no. 2 (2016): 04015072. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001025

[28] Liang, Xiao, Suhua Cui, Hui Li, Ahmed Abdelhady, Hanbing Wang, and Haonan Zhou. "Removal effect on stormwater runoff pollution of porous concrete treated with nanometer titanium dioxide." *Transportation Research Part D: Transport and Environment* 73 (2019): 34-45. https://doi.org/10.1016/j.trd.2019.06.001

[29] Agar-Ozbek, Ayda S., Jaap Weerheijm, Erik Schlangen, and Klaas Van Breugel. "Investigating porous concrete with improved strength: Testing at different scales." *Construction and Building Materials* 41 (2013): 480-490. https://doi.org/10.1016/j.conbuildmat.2012.12.040

[30] AlShareedah, Othman, and Somayeh Nassiri. "Pervious concrete mixture optimization, physical, and mechanical properties and pavement design: A review." *Journal of Cleaner Production* 288 (2021): 125095. https://doi.org/10.1016/j.jclepro.2020.125095

[31] Faisal, Ghufran H., Ali J. Jaeel, and Thaar S. Al-Gasham. "BOD and COD reduction using porous concrete pavements." *Case Studies in Construction Materials* 13 (2020): e00396. https://doi.org/10.1016/j.cscm.2020.e00396

[32] Ibrahim, Ahmed, Enad Mahmoud, Mohammed Yamin, and Varun Chowdary Patibandla. "Experimental study on Portland cement pervious concrete mechanical and hydrological properties." *Construction and building materials* 50 (2014): 524-529. https://doi.org/10.1016/j.conbuildmat.2013.09.022

[33] Lang, Lei, Haijuan Duan, and Bing Chen. "Properties of pervious concrete made from steel slag and magnesium phosphate cement." *Construction and Building Materials* 209 (2019): 95-104. https://doi.org/10.1016/j.conbuildmat.2019.03.123

[34] Ortega-Villar, Rosangel, Liliana Lizárraga-Mendiola, Claudia Coronel-Olivares, Luis D. López-León, Carlos Alfredo Bigurra-Alzati, and Gabriela A. Vázquez-Rodríguez. "Effect of photocatalytic Fe2O3 nanoparticles on urban runoff pollutant removal by permeable concrete." *Journal of environmental management* 242 (2019): 487-495. https://doi.org/10.1016/j.jenvman.2019.04.104

[35] Sonebi, Mohamed, and M. T. Bassuoni. "Investigating the effect of mixture design parameters on pervious concrete by statistical modelling." *Construction and Building Materials* 38 (2013): 147-154. https://doi.org/10.1016/j.conbuildmat.2012.07.044

[36] Wang, Guotong, Xueqin Chen, Qiao Dong, Jiawei Yuan, and Qianzhe Hong. "Mechanical performance study of pervious concrete using steel slag aggregate through laboratory tests and numerical simulation." *Journal of Cleaner Production* 262 (2020): 121208. https://doi.org/10.1016/j.jclepro.2020.121208

[37] Foolad Tak Faravar Asia Company, Attar Neishabur Industrial Estate, Neishabur, Unnamed Road, 4J57+JG6, Iran.

[38] Di Gianfrancesco, Augusto, ed. *Materials for ultra-supercritical and advanced ultra-supercritical power plants*. woodhead Publishing, (2016). https://doi.org/10.1016/B978-0-08-100552-1.00001-4

[39] Chien, C. C., C. M. Kao, C. D. Dong, T. Y. Chen, and J. Y. Chen. "Effectiveness of AOC removal by advanced water treatment systems: a case study." *Desalination* 202, no. 1-3 (2007): 318-325. https://doi.org/10.1016/j.desal.2005.12.070

[40] Sriramoju, Santosh Kumar, Pratik Swarup Dash, and Saptarshi Majumdar. "Meso-porous activated carbon from lignite waste and its application in methylene Blue adsorption and coke plant effluent treatment." *Journal of Environmental Chemical Engineering* 9, no. 1 (2021): 104784. https://doi.org/10.1016/j.jece.2020.104784

[41] Drogui, Patrick, Rimeh Daghrir, Marie-Christine Simard, Christine Sauvageau, and Jean François Blais. "Removal of microcystin-LR from spiked water using either activated carbon or anthracite as filter material." *Environmental technology* 33, no. 4 (2012): 381-391. https://doi.org/10.1080/09593330.2011.575186

[42] Razvigorova, M., T. Budinova, N. Petrov, and V. Minkova. "Purification of water by activated carbons from apricot stones, lignites and anthracite." *Water Research* 32, no. 7 (1998): 2135-2139. https://doi.org/10.1016/S0043-1354(97)00446-6

[43] Shirey, T. B., R. W. Thacker, and J. B. Olson. "Composition and stability of bacterial communities associated with granular activated carbon and anthracite filters in a pilot scale municipal drinking water treatment facility." *Journal of water and health* 10, no. 2 (2012): 244-255. https://doi.org/10.2166/wh.2012.092

[44] Xu, Like, Luiza C. Campos, Jianan Li, Kersti Karu, and Lena Ciric. "Removal of antibiotics in sand, GAC, GAC sandwich and anthracite/sand biofiltration systems." *Chemosphere* 275 (2021): 130004. https://doi.org/10.1016/j.chemosphere.2021.130004

[45] Geiseler, J. "Use of steelworks slag in Europe." *Waste management* 16, no. 1-3 (1996): 59-63. https://doi.org/10.1016/S0956-053X(96)00070-0

[46] Ramakrishna, Konduru R., and T. Viraraghavan. "Use of slag for dye removal." *Waste Management* 17, no. 8 (1998): 483-488. https://doi.org/10.1016/S0956-053X(97)10058-7

[47] Dimitrova, S. V. "Use of granular slag columns for lead removal." *Water Research* 36, no. 16 (2002): 4001-4008. https://doi.org/10.1016/S0043-1354(02)00120-3

[48] Mann, R. A., and H. J. Bavor. "Phosphorus removal in constructed wetlands using gravel and industrial waste substrata." *Water Science and Technology* 27, no. 1 (1993): 107-113. https://doi.org/10.2166/wst.1993.0027

[49] Ortiz, N., M. A. F. Pires, and J. C. Bressiani. "Use of steel converter slag as nickel adsorber to wastewater treatment." *Waste management* 21, no. 7 (2001): 631-635. https://doi.org/10.1016/S0956-053X(00)00123-9

[50] Kimura, Satoshi, Hidehiro KAMIVA, Masayuki HORIO, and Kaoru KIMURA. "A novel fluidized bed manufacturing of high performance artificial lightweight aggregate." In *Second international symposium on structural lightweight aggregate concrete (Kristiansand, 18-22 June 2000)*, pp. 613-622. 2000.

[51] Hamid, Siti Hajar Abdul, Fathurrahman Lananan, Noordin Asimi Mohd Noor, and Azizah Endut. "Physical filtration of nutrients utilizing gravel-based and lightweight expanded clay aggregate (LECA) as growing media in aquaponic recirculation system (ARS)." *Aquacultural Engineering* 98 (2022): 102261. https://doi.org/10.1016/j.aquaeng.2022.102261

[52] Zaetang, Yuwadee, Ampol Wongsa, Vanchai Sata, and Prinya Chindaprasirt. "Use of lightweight aggregates in pervious concrete." *Construction and Building Materials* 48 (2013): 585-591. https://doi.org/10.1016/j.conbuildmat.2013.07.077

[53] Li, Shuai, Dejun Sun, Shiying Wang, Tao Wu, and Yujiang Li. "Effective treatment of simulated ASP flooding produced water by modified perlite." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 634 (2022): 127952. https://doi.org/10.1016/j.colsurfa.2021.127952

[54] Grotheer, Sarah Jo. "Evaluation of lightweight concrete mixtures for bridge deck and prestressed bridge girder applications." PhD diss., Kansas State University, 2008.

[55] Bahare, Radhe Shyam, Swastika Ganguly, Kiattawee Choowongkomon, and Supaporn Seetaha. "Synthesis, HIV-1 RT inhibitory, antibacterial, antifungal and binding mode studies of some novel N-substituted 5-benzylidine-2, 4-thiazolidinediones." *DARU Journal of Pharmaceutical Sciences* 23 (2015): 1-15. https://doi.org/10.1186/s40068-021-00238-0

[56] Pasha, T. N卌̂, M. U卌̂ Farooq, F. M. Khattak, M. A. Jabbar, and A. D. Khan. "Effectiveness of sodium bentonite and two commercial products as aflatoxin absorbents in diets for broiler chickens." *Animal Feed Science and Technology* 132, no. 1-2 (2007): 103-110. https://doi.org/10.1016/j.anifeedsci.2006.03.014

[57] ASTM Standard specification for concrete aggregates. (2003). “ASTM C33/C33M”. West Conshohocken, PA.

[58] Yu, Shujun, Xiangxue Wang, Hongwei Pang, Rui Zhang, Wencheng Song, Dong Fu, Tasawar Hayat, and Xiangke Wang. "Boron nitride-based materials for the removal of pollutants from aqueous solutions: a review." *Chemical Engineering Journal* 333 (2018): 343-360. https://doi.org/10.1016/j.cej.2017.09.163

[59] ASTM Standard specification for Portland cement. (2012). “ASTM C150/C150M”. West Conshohocken, PA.

[60] AASHTO, “Standard Method of Test for the Specific Gravity and Absorption of Coarse Aggregates”, T 85. (2004). Washington DC: American Association of State Highway and Transportation Officials.

[61] ACI Committee 211. (2006). “Guide for Selecting Proportions for No slump Concrete ACI 211.3R. Report”. Farmington Hills, MI: American Concrete Institute.

[62] British Standard. (1983). “Testing Concrete Method for making test cubes from fresh concrete”. BS 1881. Part 108.

[63] ASTM Standard test method for density and void content of hardened pervious concrete. (2012) “ASTM C1754/1754M”. International 2012, USA.

[64] ACI Committee 522. (2006). “Pervious concrete. ACI522R-06 Report”.

[65] AlShareedah, Othman, and Somayeh Nassiri. "Pervious concrete mixture optimization, physical, and mechanical properties and pavement design: A review." *Journal of Cleaner Production* 288 (2021): 125095. https://doi.org/10.1016/j.jclepro.2020.125095

[66] Tijani, M. A., W. O. Ajagbe, O. A. Agbede, and A. A. Ganiyu. "EFFECT OF AGGREGATE TYPE ON PROPERTIES OF PERVIOUS CONCRETE." *Journal of Modern Technology & Engineering* 4, no. 1 (2019).

[67] Teymouri, Ehsan, Kwong Soon Wong, Yee Yong Tan, and Nurul Noraziemah Mohd Pauzi. "Mechanical behaviour of adsorbent pervious concrete using iron slag and zeolite as coarse aggregates." *Construction and Building Materials* 388 (2023): 131720. https://doi.org/10.1016/j.conbuildmat.2023.131720

[68] Bonicelli, Alessandra, Filippo Giustozzi, and Maurizio Crispino. "Experimental study on the effects of fine sand addition on differentially compacted pervious concrete." *Construction and Building materials* 91 (2015): 102-110. https://doi.org/10.1016/j.conbuildmat.2015.05.012

[69] Mousavi, Sayed-Farhad, Hojat Karami, Saeed Farzin, and Ehsan Teymouri. "Effects of adding mineral adsorbents to porous concrete for enhancing the quality performance of urban runoff systems." *World Journal of Engineering* 15, no. 4 (2018): 489-497. https://doi.org/10.1108/WJE-10-2017-0314

[70] Hatt, Belinda Elizabeth, N. Siriwardene, Ana Deletic, and Timothy David Fletcher. "Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on pollutant removal." *Water Science and Technology* 54, no. 6-7 (2006): 263-271. https://doi.org/10.2166/wst.2006.626