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Study on Strength, Permeability and Micro-structure of Pervious Concrete Blended with Metakaolin

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ABSTRACT

Pervious concrete is a developing construction material used for sustainable solutions which helps restore the groundwater level based on its draining ability. The existing research studies address the strength and permeability of pervious-concrete materials and only limited data is available on the microstructural characteristics of pervious concrete. In this study, a characteristic analysis was carried out at micro-and macro-levels to identify the behaviour of pervious concrete using three aggregate gradations. To attain the wide pore network in pervious concrete, fine aggregates were not added in mixes and metakaolin was added at 5% intervals up to 20% of cement. At the macro-level, strength, porosity and permeability were tested and at the micro-level, XRD, FTIR, SEM and EDAX analyses were used for pervious-concrete mixes with metakaolin. The maximum strength of pervious-concrete was achieved in a 4.75-9.5 mm size aggregate mix at 10% addition of metakaolin with cement. Micro-structural studies revealed that the addition of metakaolin significantly reduces anhydrous calcium hydroxide. A significant draining performance of more than 1 cm/s was attained in most of the pervious-concrete mixes due to high porosity and permeability. Hence, pervious concrete is considered as a sustainable alternative material that can address environmental problems.

KEYWORDS: Pervious concrete, Porosity, Permeability, Metakaolin, Micro-structure.

INTRODUCTION

Natural resources are prodigiously consumed at present due to rapid urbanization and infrastructure development. Much of the world's land surfaces are covered by highly compact structures and impermeable concrete pavements, where the quantity of rainfall penetrating the ground is reduced because of the impervious nature of concrete surfaces. This can be partially reduced with the application of pervious concrete.

Recent research, especially on concrete structure, gives more emphasis to developing economical and eco-friendly concrete. This will be achieved by minimizing the extensive use of natural materials and increasing the use of waste materials from industries without compromising the performance of concrete. Partial replacement by waste materials of construction materials reduces the effects of several issues, such as landfilling, health concerns and environmental problems. Various waste materials, such as rice husk ash, quarry dust, crumb rubber, sewage sludge ash, paper mill sludge ash, fly ash, ground granulated blast furnace slag and metakaolin, are widely used in modern concrete with satisfactory performance. A considerable improvement in mechanical and durability properties was obtained in concrete mixes containing supplementary cementitious materials (Sancheti et al., 2020; Younis, 2021). The behaviour of concrete using waste materials needs to be predicted to understand the chemical interactions between various ingredients (Scholz & Grabowiecki, 2007). The utilization of natural resources in the form of fine aggregate is reduced by using pervious concrete for flat-work applications, such as parking areas, low-traffic areas, pedestrian pathways, … etc., due to improved stormwater mitigation and other properties. Apart from this, pervious concrete may be used as wall concrete in structural applications for light-weight or

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thermal insulation and surface course for tennis courts, zoo areas, stalls and greenhouse floors to prevent standing water (Bhutta et al., 2012; Huang et al., 2010; Yang & Jiang, 2003).

Pervious concrete is a special type of concrete with high porosity and permeability. It consists of coarse aggregate bonded with cement paste with or without admixtures and additives that harden over time. When the aggregate is mixed with dry Portland cement and water, the mixture can be moulded into any desired shape. This helps reduce the noise generated by tire-pavement interaction and the urban heat island effect. It also minimizes road splash, improves skid resistance, recharges groundwater, reduces stormwater run-off, restricts pollutant inflows into groundwater and protects native ecosystems (Obla, 2011; Shu et al., 2011).

Metakaolin is a pozzolanic material made by thermal activation of purified kaolin clay up to a temperature of 800°C. It is a mineral admixture used for specific purposes under controlled conditions by heating kaolin to a temperature of 650–900°C. It is then chemically altered by heat, so that it reacts aggressively with calcium hydroxide in normal-cement hydration to form additional cementitious compounds. It reacts with the free lime in cement, so that the concrete becomes a stronger and more durable mix (Guru Jawahar et al., 2013). Recently, the utilization of metakaolin as a supplementary cementitious material in the concrete industry has increased due to the material's high reactivity. The particle size of metakaolin is generally smaller than that of cement particles. Recent research works have shown that the inclusion of metakaolin greatly influences the mechanical properties of concrete due to its high reactivity (Viswanadha Varma et al., 2021). Metakaolin-blended concrete partially controls direct and indirect CO_2 emissions from the cement industry (Homayoonmehr et al., 2021).

The partial replacement of cement with metakaolin improves the mechanical and durability performance of concrete (Poon et al., 2006; Rashad, 2013; Saboo et al., 2019; Siddique & Klaus, 2009; J. Wang et al., 2012; Zibara et al., 2008). Metakaolin improves strength and durability properties and reduces cracking in concrete (Cheng et al., 2017; Kannan & Ganesan, 2014). Previous research studies have reported on the high specific surface area and pozzolanic activity of metakaolin, as well as improvements in the micro-structure of concrete by the formation of stable hydration products (Duan et al., 2013; Kim et al., 2012; Qian et al., 2019; Sujjavanich et al., 2017). The addition of metakaolin in concrete mixes improves filling ability (Supit & Pandei, 2019) and pozzolanic reactions, which contributes to densification of weak zones (Younis et al., 2020).

Three phases of concrete-cement paste, aggregate phase and the interfacial transition zone (ITZ)-are well known with regard to pervious concrete. Aggregate properties, such as density, shape, size, pore structure, stability and surface characteristics, are responsible for the bonding of the paste. The ITZ phase is the weakest phase because of higher porosity and cracks generally initiate in this zone (Poon et al., 2003). The ITZ varies depending upon water-to-cement ratio, cement content, aggregate size, aggregate content, curing and presence of cementitious materials (Zhang et al., 2020). Understanding the ITZ characteristics for various types of concrete requires the investigation of the internal arrangement of cement paste (Diamond & Huang, 2001). Setting and hardening occur in concrete during the hydration process between the oxides in cement and water, rendering a complex micro-structure which determines the properties of hardened materials (Chen et al., 2020). The cement grain consists of C_3S, C_2S, C_3A and C_4AF as the main components which play a vital role in the hydration process. A systematic micro-structural characterization is required to evaluate the mechanical, durability and hydraulic properties of pervious concrete. The present work compares a pervious-concrete mix containing natural coarse aggregate only to one with partial substitution of ordinary Portland cement blended with metakaolin, focusing on micro-structural studies using XRD, FTIR, SEM and EDAX. It is necessary to optimize the mechanical and hydraulic properties to avoid clogging of pores in pervious concrete (Vieira et al., 2020). Pervious concrete made with a coarser aggregate fraction allows smooth passage of water through the pore system, implying better hydraulic conductivity (Grubeša et al., 2018).

The micro-structure is a fundamental component of materials, providing qualitative information about the morphology and elemental composition which influence the behaviour and physical properties. Material compositions play a significant role in achieving better strength properties. A detailed study is required on the micro-structure of perviousconcrete without the addition of fine aggregate. Hence, experimental tests were carried out to examine and explain the strength, hydraulic properties and characteristics of pervious-concrete materials with admixtures. Most research studies address the strength behaviour of pervious concrete, but limited literature is available on the reasons for the variation in strength at the micro-structural level. This study focuses on the root causes for the variation in strength and structural arrangements of different compositions of metakaolin.

EXPERIMENTAL INVESTIGATIONS

The right quality of materials along with the right quantities are required to prepare a suitable pervious-concrete mix.

Materials

Various materials, such as cement, coarse aggregate, metakaolin and water, were used in this study. The chemical compositions of ordinary Portland cement (OPC) of 53 grade and metakaolin are given in Table 1.

Table 1. Chemical compositions of cement and metakaolin

Compound		SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O	K_2O	Loss on Ignition
Value (%)	Cement	21.78	4.94	3.56	63.78	1.95	0.97	0.46	0.64	1.92
	Metakaolin	54.71	39.67	2.01	2.31	-	-	-	-	1.31

Locally available crushed granite stones were used as the coarse aggregate. Aggregate passing through a 9.5-mm sieve and retained on a 4.75-mm sieve (S1), aggregate passing through a 12.5-mm sieve and retained on a 9.5-mm sieve (S2) and aggregate passing through a 16-mm sieve and retained on a 12.5-mm sieve (S3) were selected and used in this research work. The properties of coarse aggregate are listed in Table 2. Potable water available in the laboratory with a pH value of not less than 6 was used for the mixing and curing of the concrete specimens.

Table 2. Properties of coarse aggregate

Test parameter	Observed results		
	4.75-9.5 mm	9.5-12.5 mm	12.5-16 mm
Specific gravity	2.87	2.75	2.65
Bulk density (kg/m^3)	1644	1625	1618
Water absorption	1%	1%	1%
Fineness modulus	5.86	6.45	6.98

Mix Proportion and Specimen Details

The mix proportions for pervious concrete were based on ACI guidelines (ACI 522R - 2010), as shown in Table 3. Metakaolin was added at a 5% interval from 5% to 20% to achieve the properties of pervious concrete. The water-to-cement ratio was considered in the mix proportions based on workability for all sets of mixes (Lian & Zhuge, 2010). A total of 135 specimens were cast for experimental work, of which 45 cube specimens of dimensions 150 mm X 150 mm X 150 mm were used for conducting compression tests and 90 cylinder specimens of 100-mm diameter and 200-mm height were used for porosity and permeability tests.

Table 3. Mix details

Mix ID	Materials required per m^3 of concrete			
	Cement (kg)	Coarse aggregate (kg)	Metakaolin (kg)	Water (litre)
MK00S1	259	1349	0	85
MK05S1	259	1349	13	92
MK10S1	259	1349	26	97
MK15S1	259	1349	39	101
MK20S1	259	1349	52	106
MK00S2	261	1330	0	84
MK05S2	261	1330	13	90
MK10S2	261	1330	26	95
MK15S2	261	1330	39	99
MK20S2	261	1330	52	103
MK00S3	262	1324	0	81
MK05S3	262	1324	13	88
MK10S3	262	1324	26	92
MK15S3	262	1324	39	96
MK20S3	262	1324	52	101

EXPERIMENTAL METHODS

Compressive strength, porosity and permeability were examined to understand the behaviour of pervious concrete. These properties determine the behaviour of pervious-concrete under different conditions.

Workability

The workability of fresh pervious concrete was determined as per ASTM C143:2010. The water-to-cement ratio was selected to be 0.31 and subsequent iterations were made to obtain better results. Hardened-concrete properties were tested after 28 days of curing.

Compressive Strength Test

The characteristics of concrete are related to its compressive strength. The compressive strength test was conducted at 28 days as per IS 516:2018 and the results were recorded based on the average of three tested specimens.

Porosity

Porosity affects compressive strength, permeability and draining capacity, which are considered as important parameters in the design of pervious concrete (Dean et al., 2005). Porosity is the ratio of the volume of voids to the total volume of the specimens. Porosity was measured by the volumetric method or the water displacement method based on Archimedes principle of buoyancy (Rama, 2016; Park & Tia, 2004). The porosity of pervious concrete was calculated from the following equation as per ASTM C1688:2014:

$$P = \left[1 - \left(\frac{w_1 - w_2}{\rho_w V}\right)\right] \times 100\%$$

where P is the total porosity of pervious concrete (%), w_1 is the weight of the pervious-concrete sample air-dried for 24 hours (kg), w_2 is the weight of the pervious-concrete sample submerged under water (kg), V is the volume of the pervious-concrete sample (m^3) and ρ_w is the density of water (kg/m^3).

Permeability Test

Permeability is a property indicating the rate at which water will flow through the pore spaces of pervious concrete. The permeability test of pervious-concrete specimens was conducted as per ASTM D2434:2019 based on the falling-head permeability principle in a one-dimensional flow approach (McCain & Dewoolkar, 2010; Rama & Shanthi, 2018). Water was allowed to flow through the specimens by opening the valve and the time required for the flow of water from h_1 to h_2 was recorded. The coefficient of permeability was calculated using Darcy's law:

$$k = \frac{A_1 L}{A_2 t} \ln\left(\frac{h_2}{h_1}\right)$$

where A_1 is the area of the cross-section of the tube in cm^2, A_2 is the area of the cross-section of the sample in cm^2, L is the length of the specimen in cm, t is the time required for water to flow from h_1 to h_2 in sec, h_1 is the initial head in cm and h_2 is the final head in cm.

Micro-structural Analysis

X-ray diffraction (XRD) patterns were recorded at room temperature at a scanning rate of 0.02°/min and a diffraction angle in the range of 10-80° using a PANalyticalX'Pert-Pro diffractometer with Cu Kα1 radiation (λ = 1.5406A°). The diffraction analysis was used to identify the composition of compounds and crystalline phases present in concrete.

Fourier transform infrared (FTIR) spectroscopy was performed with a Bruker Tensor 27 using KBr pellet techniques in the range of 4000-400 cm^{-1} with a resolution of 2 cm^{-1} and a scanning rate of 16. Samples were mixed with potassium bromide (KBr) to prepare the pellets and a spectrum was taken to obtain peak values.

Scanning electron microscope (SEM) analysis was carried out to identify the distribution of particles and the structure of materials. The SEM instrument was operated in a sample chamber under an accelerating voltage of 20 KeV, a pressure of 4 torr and a relative humidity of 80%. The powdered samples were coated with gold to offer a conductive surface and images were recorded at various magnifications to identify the morphology of the samples. Energy-dispersive X-ray analysis was performed to determine the various elements present in pervious-concrete samples.

RESULTS AND DISCUSSION

Workability

The workability of pervious-concrete mix is influenced by the cement-paste lubrication between aggregate particles. A mix with low workability indicates that the coarse aggregate may not be coated properly with stiff cement paste. A high water-to-cement ratio contributes to a more workable mix and yields more available water than the hydration process requires, which reduces the functional performance of pervious-concrete samples.

Compressive Strength Test

Metakaolin was mixed with cement at 5% intervals up to 20% in the pervious-concrete mix to test the compressive strength. It was observed that the strength gradually increased from normal pervious-concrete mix results up to 10% addition of metakaolin and further addition of metakaolin reduced the strength. The different compressive strengths obtained in the metakaolin-blended pervious-concrete (MKPC) mix were 16 MPa, 15 MPa and 13 MPa for 10% metakaolin added to the MK10S1, MK10S2 and MK10S3 mixes, respectively, as shown in Figure 1. The maximum strength was obtained in the MK10S1 mix due to better contact between the aggregate and the cement paste, resulting in a better bonding behaviour.

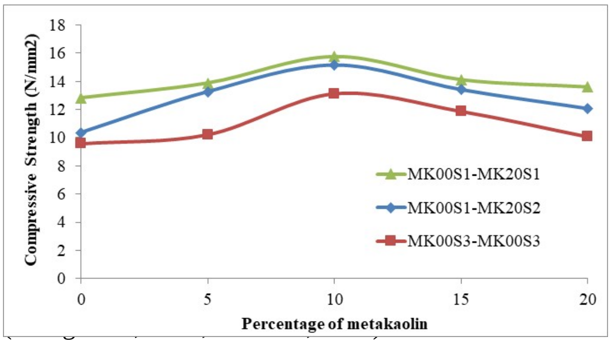

Figure (1): Compressive strength of MKPC

Porosity

The porosity values of metakaolin-added mixes ranged from 22% to 15% for the MKPC S1 mix, from 26% to 18% for the MKPC S2 mix and from 28% to 20% for the MKPC S3 mix, as shown in Figure 2. Decreases in porosity of 30%, 32% and 29% were obtained between the control pervious-concrete mix of

MK00 and the MK20 mix. The increasing paste thickness around the aggregate reduces the active pores, which results in the reduction of the overall porosity. The obtained porosity values fall within the acceptable limit of 15% to 30% for pervious concrete (Deo & Neithalath, 2010; Tennis et al., 2004). The pore distribution pattern and the size of the pore lead to a significant variation in porosity results.

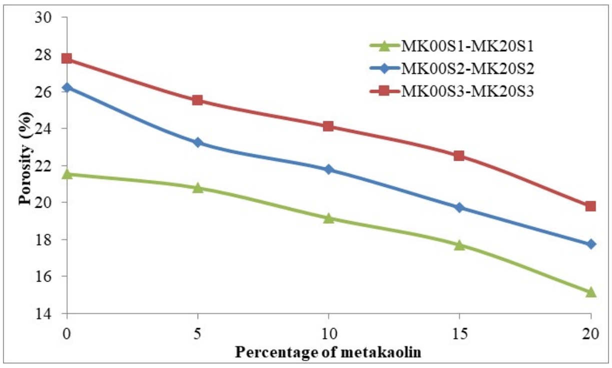

Figure (2): Porosity of MKPC

Permeability

The permeability values of metakaolin-blended mixes range from 1.18 cm/s to 0.62 cm/s for the S1 aggregate mix, from 1.77 cm/s to 0.79 cm/s for the S2 aggregate mix and from 2.11 cm/s to 1.14 cm/s for the S3 aggregate mix, as shown in Figure 3. Decreases in permeability of 47%, 55% and 46% were obtained between the control pervious-concrete MK00 mix and the MK20 mix.

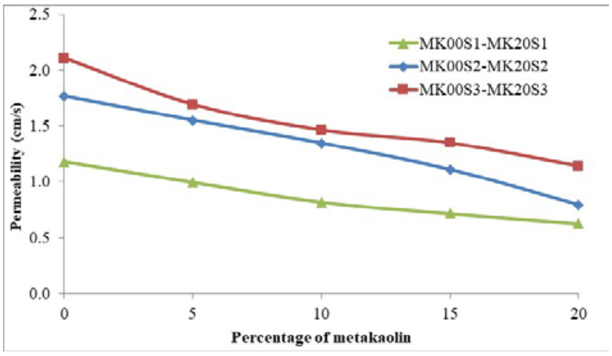

Figure (3): Permeability of MKPC

A compressive strength of 16 MPa was obtained with a porosity of 21% and a permeability of 0.8 cm/s for the S1-type aggregate, a compressive strength of 15 MPa was obtained with a porosity of 23% and a permeability of 1.4 cm/s for the S2-type aggregate and a compressive strength of 13 MPa was obtained with a porosity of 24% and a permeability of 1.5 cm/s for the S3-type aggregate mix. The wide interconnected pores present in pervious-concrete mixes improve the infiltration rate, leading to the deviation in permeability values.

The permeability of pervious-concrete mix above 1 cm/s allows for better infiltration of stormwater run-off into the underground surface. Hence, the results obtained from the S2 and S3 aggregate-type pervious-concrete mixes satisfy the above criteria.

Relation between Porosity, Permeability and Compressive Strength

A variation in permeability and compressive strength concerning the porosity was observed for different pervious-concrete mixes. The plots were established to obtain the combined effect of porosity, permeability and compressive strength of metakaolin-blended mixes, as represented in Figures 4-6.

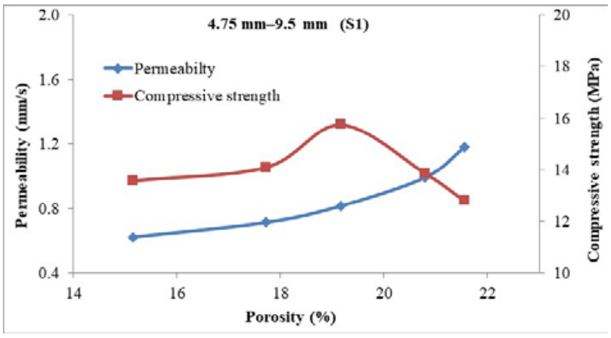

Figure (4): Optimum results for MK00S1-MK20S1

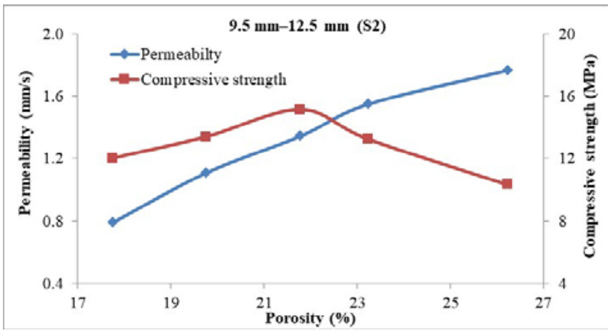

Figure (5): Optimum results for MK00S2-MK20S2

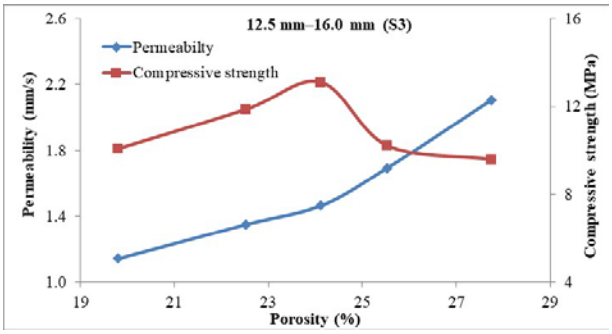

Figure (6): Optimum results for MK00S3-MK20S3

The obtained ranges of results for porosity, permeability and compressive strength were 15% to 28%, 0.5 cm/s to 2.3 cm/s and 10 MPa to 16 MPa, respectively. Based on the porosity of all mixes, it was observed that the optimum results of compressive strength and permeability were obtained for mixes with 5% to 10% additions of metakaolin. These results show that an adverse correlation relationship exists between permeability and compressive strength. A direct relationship is observed between permeability and porosity (Najah et al., 2021).

It is important to consider infiltration capacity and pore characteristics in addition to the strength of pervious concrete. The increase in strength depends on the ITZ and paste characteristics, whereas permeability depends on pore characteristics.

XRD Analysis

XRD patterns were analyzed to identify the various compounds present in metakaolin-blended pervious-concrete, as shown in Figure 7. The XRD pattern indicates that the presence of SiO_2 at two-theta values of 21.1°, 26.8°, 35.5°, 50.3° and 60.8° coincides with the JCPDS file 89-1668 of SiO_2. Al_2O_3 was observed at peak values of 16.6° and 68.3° for cement, whereas it was observed at 29.1°and 68.3° for metakaolin, which matches with the JCPDS No. 88-0107.

Two-theta value of 42° coincides with the JCPDS No. 82-1690 for calcium oxide. Magnesium oxide shows the peak value at 42.8°, matching with the JCPDS No. 89-7746. Ferrous oxide indicates the peak values at 29°, 33.4°, 38.7° and 55°, which coincides with the JCPDS No. 39-1346.

The XRD pattern of metakaolin-blended pervious-concrete mix indicates a decrease in the rate of production of crystalline calcium hydroxide, which is predicted by the reduction of calcium hydroxide peaks as compared to the control mix. The pozzolanic reaction of metakaolin with calcium hydroxide to form calcium silicate hydroxide gel was observed during the early stage of hydration of C_3S, as shown in Figure 8. It is understood that the addition of metakaolin in pervious-concrete mixes influences the strength characteristics by reducing the quantity of non-hydrous compounds, thereby increasing the quantity of stable hydrous compounds.

FTIR Analysis

The FTIR spectrum of metakaolin-blended concrete is shown in Figure 8, where the spectral bands range from 715 cm^{-1} to 873 cm^{-1}, representing the presence of alkali groups in the sample.

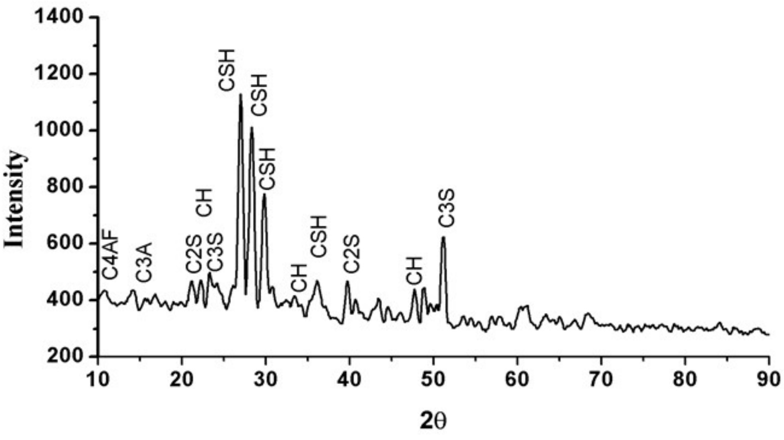

Figure (7): XRD result for MKPC

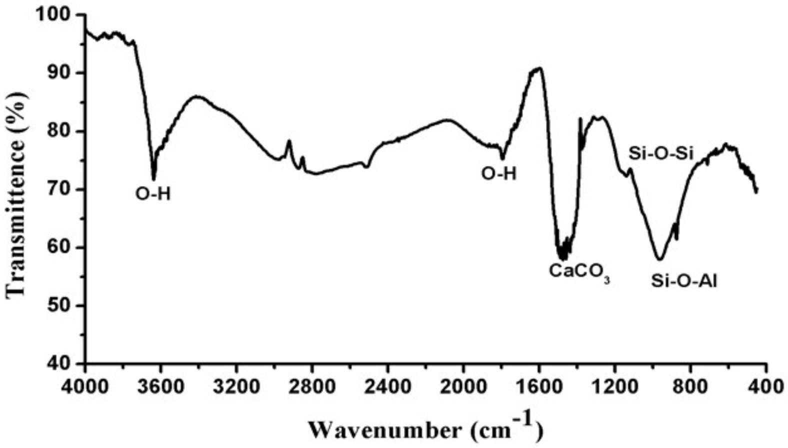

Figure (8): FTIR of MKPC

The intensity of the spectral band at 3634 cm^{-1} and 1798 cm^{-1} indicates stretching and bending vibration of the OH group, which confirms the presence of $Ca(OH)_2$ (Varas et al., 2005). The spectral band of carbonate presence in the range of 1491-1422 cm^{-1} can be assigned to calcium oxide and calcium hydroxide. The strong spectral band of Si-O stretching and Si-O bending assigned at 1149 cm^{-1} and 961 cm^{-1} indicates the formation of C-S-H (Ylmén & Jäglid, 2013). The FTIR spectrum also confirms the changes from the unstable phase to the stable phase before and after the addition of metakaolin.

SEM Analysis

The SEM images of metakaolin and hydrated cement paste with metakaolin are shown in Figure 9. The calcium hydroxide present in the pervious-concrete sample reacts with metakaolin and the intensity of calcium hydroxide in MKPC is reduced during the hydration process. MKPC mix has the potential for pozzolanic reactivity, which facilitates its secondary hydration with $Ca(OH)_2$, resulting in the formation of the major hydration product CSH and ensuring compactness in the mix. Hence, the results confirm that larger portions of CH are consumed and converted into calcium hydroxide silicate.

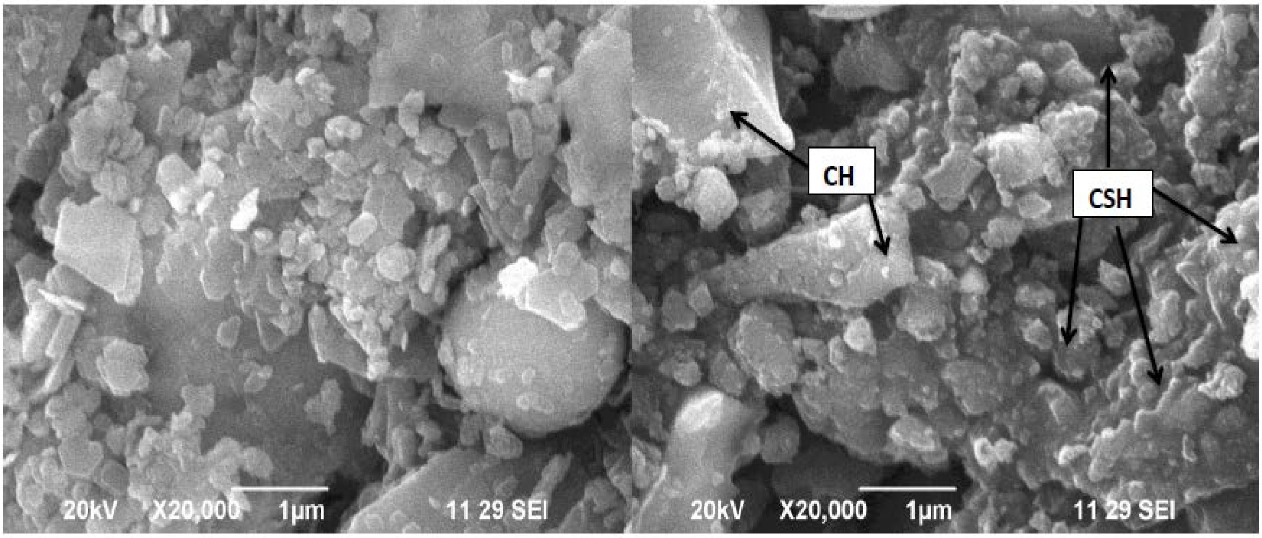

Figure (9): SEM images of metakaolin and MKPC

The particle size of metakaolin is smaller than the particle size of cement; so, the density of the porous structure is increased by mixing metakaolin with the cement paste. The pores in the MKPC mix are confined using hydrated products. The micro-structure of metakaolin-blended perviousconcrete exhibited a denser structure than that of normal pervious-concrete mix, which confirms the formation of higher-hydration products. Hence, a dense and compacted structure was obtained in the MKPC mix, which leads to strength improvement.

EDAX Analysis

Energy-dispersive X-ray analysis (EDAX) was carried out to identify the various elements present in the pervious-concrete samples and their respective quantities. EDAX analysis revealed the composition of the metakaolin-blended mix as 15.38 wt% and 14.54 wt% of Ca and Si, respectively. These elements play an important role in the hydration process, as shown in Figure 10. Al and Fe were present at 5.76 wt% and 3.75 wt%, respectively and few alkali elements were present in MKPC. Alkali elements included 1.05 wt% Na, 1.00 wt% Mg and 0.78 wt% K, respectively. The strength increased based on the presence of composites of silica and calcium. The obtained ratio of Ca/Si was less than 1 for the MKPC mix, leading to an improvement in the strength of the MKPC mix.

The compositions of different hydrated products, such as calcium silicate hydrate, calcium hydroxide (portlandite) and ettringite (calcium mono sulfoaluminate or AFm), were used to determine the thickness of the interfacial transition zone (ITZ). The criteria mentioned in Table 4 are to be satisfied as per the Rossignolo criteria (Rossignolo, 2009).

The atomic-mass ratio values of the MKPC mix from EDAX analysis, including Ca/Si, (Al+Fe)/Ca and S/Ca ratios, were identified and fulfilled per the above-mentioned criteria. The ITZ characteristics are close to published data (Awoyera et al., 2018), which confirms the presence of CSH, CH and ettringite in pervious-concrete samples. Based on the obtained criteria, it was inferred that the dominant hydrous phases are present in the cement paste of the MKPC mix.

The improvement in the strength of metakaolin-blended cement mortar was achieved because of the reaction of calcium carbonates with the alumina present in metakaolin to form ettringite and mono-sulphoaluminate.

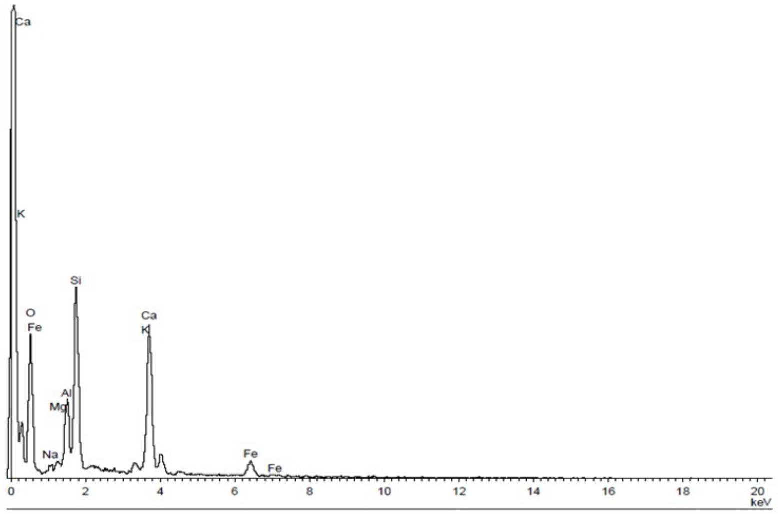

Figure (10): EDAX result of MKPC

Table 4. Criteria for hydration products

Hydration products	Criteria		
C–S–H	$0.8 \leq Ca/Si \leq 2.5$	$(Al + Fe)/Ca \leq 0.2$	---
CH	$Ca/Si \geq 10$	$(Al + Fe)/Ca \leq 0.04$	$S/Ca \leq 0.04$
AFm	$Ca/Si \geq 4.0$	$(Al + Fe)/Ca > 0.4$	$S/Ca > 0.15$

CONCLUSION

Experimental investigations were conducted on metakaolin-blended pervious-concrete mixes to determine their mechanical and hydraulic properties. The optimum pervious-concrete mixes blended with metakaolin were selected from the obtained results of strength, porosity and permeability. The influence of metakaolin on the strength properties of pervious-concrete was observed at the micro-structural level using XRD, FTIR, SEM and EDAX analyses without the addition of fine aggregate in pervious-concrete mixes. Based on the test results, the conclusions are as follows.

The highest compressive strength was obtained for the 10% metakaolin-blended pervious-concrete mix with 4.75–9.5 mm aggregate size, whereas normal pervious-concrete mix with 12.5–16 mm aggregate size showed the highest porosity and permeability results.

It was found that most pervious-concrete mixes have better infiltration capacity values of above 1 cm/s.

The addition of metakaolin significantly reduces anhydrous calcium hydroxide and enhances the quantity of CSH and ettringite, thus paving the way for strength improvement.

The functional performance of pervious-concrete depends more on the presence of its open-pore network structure than its strength characteristics.

Pervious concrete can be cast with a significantly reduced amount of cement and coarse aggregate, excluding sand, to maintain a wide pore network to drain the surface run-off, leading to a more sustainable material. It is also considered as an alternative for stormwater management and urban heat-mitigation practices.

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