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Properties of Metakaolin Based Pervious Geopolymer Concrete

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Abstract. Utilizing Geopolymer binder instead of Portland cement in pervious concrete or ordinary concrete is the one solution toward reducing emission of carbon dioxide in the environment. Metakaolin (MK) used as a binding material to produce Pervious Geopolymer Concrete (PGC) in this investigation. Different PGC mixes were prepared and their, density, void content and compressive strength were tested. The effects of different proportions of alkaline liquid to metakaolin ratio AL/MK (0.5, 0.55 and 0.6); metakaolin to coarse aggregate MK:CA ratio (1:5, 1:6 and 1:7); superplasticizer dosages (0, 1, 2 and 3% by weight of MK); and the effect of using a fine aggregate at levels of 5 and 10% by weight of coarse aggregate were investigated. Sodium hydroxide (NaOH) having a concentration of 12 molarity with sodium silicate (Na_2SiO_3) to (NaOH) ratio of 2 are used as an alkaline activator to produce all PGC mixes. All PGC specimens cured at elevated temperature of 50°C for five hours after 24 hours of casting and tested after 7 days. The Results show that the optimum AL/MK ratio and superplasticizer dosage were 0.6 and 2% respectively. The compressive strength and oven-dry density were increased by about (19%, 20% and 32%) and (4.5%, 7.2% and 5.2%) for 1:5, 1:6 and 1:7 MK:CA ratio, respectively, while porosity was decreased up to 18% with the inclusion of 10% fine aggregate by weight of coarse aggregate.

1. Introduction

Compared to conventional concrete, the pervious concrete considered as a special type of highly porous concrete that contains relatively high porosity and possesses high permeability for water. It is used for a many of civil and architectural engineering work for instance in park regions, pedestrian walkways, regions with low traffic and courts for tennis, for this reason it is considered an environmentally lower effect [1,2]. Additionally, the pervious concrete with high interconnected voids allow water to move through and thus it was used to diminish runoff of storm water and in further applications for instance acoustic absorption, water refining and thermic insulation [3,4]. Generally, pervious concrete has void contents from 18% to 35% with connected pores ranging in size from 2 to 8 mm in diameter. Its compressive strength is relatively low and varying between 2.8 and 28.0 MPa depending on its ratio of void content [5]. The mixture of pervious concrete is routinely consists of coarse aggregate, binder material, water, little or no fine aggregates, and a number of admixtures if required. This combination forms a clot of coarse aggregates enclitic by a fluffy layer of hardened cement post at their contact points. This configuration results high interconnected voids between the aggregate, that allows water to pass at a higher rate than conventional concrete. In pervious concrete, the binder layer of cement paste is very thin. Thus, this thin layer of hardened cement has a direct effect on the strength of pervious concrete [2].

Portland cement causes a high amount of greenhouse gas emissions with gross emissions result from the production of cement estimated by about 1.35 billion tons in each year [6]. The production of cement causes production of about 0.8-1 tonne of carbon dioxide for any tonne of portland cement,



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that is equated to about 3 percent of global gross greenhouse emissions [7]. The utilizing of geopolymer concrete is one option led to reduce the Portland cement.

Geopolymer binder is one of these alternative to portland cement, which produced by mixing material having high aluminosilicate and high alkaline liquid solution [8]. It uses by-product materials for instance metakaolin or fly ash as alumino-silicate source to interact with high alkaline solutions of sodium or potassium based. Geopolymer concrete produced by fly ash had studied by numerous researchers and found to have high later age strength, high early strength and good resistance to acid and sulfate attack [9–11]. Many researchers studied the ability of production pervious geopolymer concrete by utilizing fly ash as a binding material [12–14].

Therefore, this work focuses on the production of pervious geopolymer concrete PGC by using the metakaolin as a source of aluminosilicate material, solution of sodium hydroxide and sodium silicate as an alkali solution, and crushed coarse aggregate. The density, compressive strength and void content of the metakaolin based pervious geopolymer concrete were tested. The data obtained from this study will certainly be beneficial for the use in future for construction of pervious concrete by using metakaolin as a geopolymer binding material. Thus, this will cause to the reduction of cement consuming and preserving the environment.

2. Materials

2.1. Metakaolin

Iraqi kaolin clay brought from the Dewekhlra region (Al-Anbar) was used in this study. Kaolin was ground by air blast, then burned in a furnace up to 700 ± 20 °C, for two hours, after that metakaolin was cooled for 24 hours at room temperature as shown in Figure 1.a.

The chemical tests for metakaolin were carried out by, Iraq geological survey and central laboratories department. The main chemical composition of metakaolin is observed in Table 1. The metakaolin has a surface area of 14300 m²/kg, specific gravity of 2.54, strength activity index of 113. The results show that the metakaolin used conform the specifications of ASTM 618 [15].

Table 1. Chemical analysis for Metakaolin.

Chemical composition (%)	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	SO ₃	TiO ₂	K ₂ O	Na ₂ O	LOI
Metakaolin	54.2	39.0	1.37	0.92	0.15	0.45	0.8	0.27	0.22	0.71

2.2. Alkaline Liquid

The sodium hydroxide (NaOH) with 98 percent purity in flak form is commercially available as shown in Figure 1. The solids liquefied in distilled water to make a solution with the required concentration of 12 molarity. Table 2 observes the properties of sodium silicate used. The ratio of Sodium silicate to sodium hydroxide was kept constant 2.

Table 2. Properties of sodium silicate.

Description	Value
Ratio of SiO ₂ to Na ₂ O	2.4 ± 0.05
Na ₂ O percent by weight	13.10 – 13.70
SiO ₂ percent by weight	32.00 – 33.00
Density - 20° Baumé	51 ± 0.5
Specific gravity	1.534 – 1.551
Viscosity (CPS) 20°C	600 – 1200
Appearance	Hazy

**Figure 1.** a. Metakaolin powder

b. Sodium hydroxide (NaOH)

2.3. Aggregates

Normal weight aggregate of 10mm nominal single size was used in this investigation. The grading and sulfate content of coarse aggregate conforms to the requirements of Iraqi specification No.45/1984, as shown in Table 3. Fine aggregate undergoes to Zone 1 with, fines modulus, specific gravity, absorption, and SO_3 percentages of 3.3, 2.58, 1.6 and 0.063 respectively. The aggregate with surface saturated dry condition (SSD) was used in all the experimental work.

Table 3. Physical properties and grading of crashed coarse aggregate used.

Sieve size (mm)	Cumulative passing (%)	Limits of Iraqi specification No. 45 / 1980, 10mm nominal single size
14	100	100
10	89.3	85-100
5	5	0-25
2.36	1.5	0-5
Specific gravity = 2.66		
Sulfate content = 0.09%		
(Iraqi specification requirement $\leq 0.1\%$)		
Absorption = 0.56%		

2.4. High-range water reducing admixture

Conplast SP2000 was used in this study. It is a chloride free superplasticizer admixture based on selected organic and synthetic polymers. The water content become more effective when using this admixture because of it separates the fine particles in the fresh concrete mix. Higher levels of water reducing possible allow great increases in strength of concrete. Conplast SP2000 complies with ASTM C494 Type G. The properties of Conplast SP2000 illustrated in Table 4.

Table 4. Properties of superplasticizer used (Conplast SP2000)^a.

Appearance	Brown liquid
Specific gravity	1.215 @ 25° C
Chloride content	Nil to BS 5075
Air-entrainment	Normally, less than 2%.
Alkali content	56.5 g. Na_2O equivalent/ liter of admixture.

^a According to the manufacturer

3. Mix proportions, mixing, and casting of pervious geopolymer concrete

The saturated surface dry crushed coarse aggregates were prepared before mixing. Different alkaline to metakaolin (AL/MK) ratios (0.5, 0.55 and 0.6), metakaolin to coarse aggregate (Mk:CA) ratios (1:5, 1:6 and 1:7), SP dosages (0, 1, 2 and 3) by weight of metakaolin, with constant extra water of 0.1 by weight of MK were used. Fine aggregate used as two percentages of 5 and 10 % by weight of total coarse aggregate. Table 2 shows the details of pervious geopolymer concrete mix proportions used in this investigation.

The surface saturated dry aggregate mixed with the metakaolin powder in a pan mixer of 0.1m³ capacity for one minute. Then, the alkaline liquid with SP and extra water added to those ingredients, and mixed with them for 5 minutes until the mixture be homogeneous.

After mixing process, the PGC placed in three cubs of 100mm for compressive strength test, and 100 mm diameter, 200 mm height of cylindrical molds for density and void content test, and then using vibrating table for compaction. All the specimens covered with a fluffy plastic sheet to prevent or minimize moisture loss and allowed to stand for 24 hours at room temperature. The specimens then cured at 50°C for 5 hours and stored under the sunlight until the testing age.



Figure 2. a. Fresh PGC mix

b. Casting molds

Table 5. Mix proportions of Metakaolin based pervious geopolymers concrete.

Mixes	Mk:CA ratio	AL/MK ratio (%)	FA/CA (%)	Extra water by wt. of MK	NaOH (Molarity)	Sp (%)
Mix1	1:5	0.5	0	0.1	12	3
Mix2	1:5	0.55	0	0.1	12	3
Mix3	1:5	0.6	0	0.1	12	3
Mix4	1:6	0.5	0	0.1	12	3
Mix5	1:6	0.55	0	0.1	12	3
Mix6	1:6	0.6	0	0.1	12	3
Mix7	1:7	0.5	0	0.1	12	3
Mix8	1:7	0.55	0	0.1	12	3
Mix9	1:7	0.6	0	0.1	12	3
Mix10	1:5	0.6	0	0.1	12	0
Mix11	1:5	0.6	0	0.1	12	1
Mix12	1:5	0.6	0	0.1	12	2
Mix13	1:5	0.6	5	0.1	12	2
Mix14	1:5	0.6	10	0.1	12	2
Mix15	1:6	0.6	0	0.1	12	2
Mix16	1:6	0.6	5	0.1	12	2
Mix17	1:6	0.6	10	0.1	12	2
Mix18	1:7	0.6	0	0.1	12	2
Mix19	1:7	0.6	5	0.1	12	2
Mix20	1:7	0.6	10	0.1	12	2

4. Testing details

4.1. Density and void content

The density and void content of pervious concrete was determined in accordance with ASTM C1754/C1754M – 12 [16]. Cylindrical specimens with 100 × 200 mm were used for determine

determining the density and void content; and the average result was calculated for three specimens at 7 days for each mix.

The density of the specimen calculated using the following equation:

$$\text{Density} = \frac{K \times A}{D^2 \times L} \quad (1)$$

where:

A = dry mass of the sample, gm.

D = average diameter of the sample, mm.

L = average length of the sample, mm and

$K = 1\,273\,240$ in SI unit.

The void content of the specimen calculated using the following equation:

$$\text{Void Content} = \left[1 - \left(\frac{K \times (A - B)}{\rho_w \times D^2 \times L} \right) \right] \times 100 \quad (2)$$

where:

B = submerged mass of the sample, gm, and

ρ_w = water density of the water bath, kg/m³.

D , K , L , and A have the same definition as in equation (1).

4.2. Compressive strength

The measurement compressive strength of pervious geopolymer concrete was carried out by a compression machine with a capacity of 2000 kN, according to British Standard BS 1881 part 116:1983 [17] using cubical specimens of 100 mm. The average result of three specimens at 7 days age was calculated for each mix.

5. Results and discussions

The results of test for density, void content, and compressive strength of pervious geopolymer concrete shown in Table 6.

Table 6. Density, void content and compressive strength of metakaolin pervious geopolymer concrete.

Mixes	Density (kg/m ³)	Void content (%)	Average compressive strength (MPa)
Mix1	1945	21.3	8.1
Mix2	1921	21	9.3
Mix3	1913	21	10.7
Mix4	1886	26	6
Mix5	1845	27.1	8.75
Mix6	1829	26.8	9.4
Mix7	1765	29	4.13
Mix8	1734	29	5.3
Mix9	1720	30	5.6
Mix10	1873	24	7.4
Mix11	1885	24	9.1
Mix12	1910	23	11.8
Mix13	1955	21	13.0
Mix14	1997	18	14.1
Mix15	1810	27	9.6
Mix16	1868	25	9.8
Mix17	1941	23	11.6
Mix18	1718	30	5.5
Mix19	1763	28.1	6.8
Mix20	1808	26	7.3

5.1. Compressive strength

The effect of MK: CA ratio, SP dosage and fine aggregate content on the compressive strength of pervious geopolymer concrete at the age of 7 days shown in Figures 3, 4 and 5 respectively. The results indicate that the increase of past content (MK) enhances the compressive strength. The compressive strength with AL/MK ratio of 0.6 and SP dosage of 3% was 10.7, 9.4 and 5.6 MPa for MK: CA ratio of 1:5, 1:6 and 1:7 respectively. The high past content (1:5) increases the thickness of the paste and enhances the compressive strength accordingly. While, low paste content (1:7) results in a thin layer of paste and increases air void content, this reduces the mechanical properties. For all mixes, the compressive strength increases with the increase of AL/MK ratio. For example, mix with 1:5 MK: CA ratio has a compressive strength of 8.1, 9.3 and 10.7 MPa for AL/MK ratio of 0.5, 0.55 and 0.6 respectively. The compressive strengths of PGC increases by 32%, 56.7% and 35.6% when AL/MK ratio increased from 0.5 to 0.6 for mixes with 1:5, 1:6 and 1:7 MK:CA ratio respectively. The reduction in compressive strength at low AL/MK ratio is due to the difficulties in compaction of PGC. This is consistent with the results observed by Sathonsaowaphak et al [18].

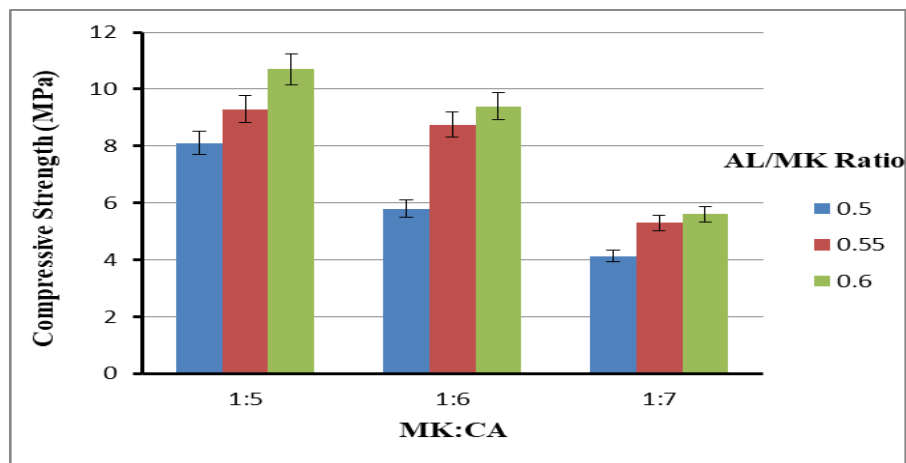


Figure 3. Effect of MK: CA ratio and AL/MK ratio of compressive strength of PGC.

Figure 4 shows the effect of superplasticizer dosage on the compressive strength of PGC with MK:CA ratio of 1:5. The results observe that the compressive strength increases with the superplasticizer dosage increase up to 3% compared with specimens without superplasticizer. The increase percentage in compressive strength was 23, 59.5 and 44.6 for superplasticizer dosage of 1, 2 and 3% by weight of MK respectively. This is because the superplasticizer disperses the fine particles in the concrete mix and enabling the water content of the concrete to perform more effectively. The maximum compressive strength obtained was for 2% superplasticizer dosage.

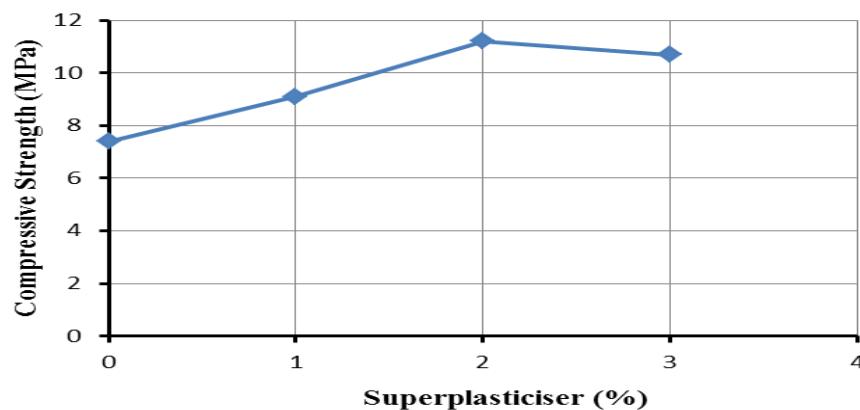


Figure 4. Effect of SP dosage by weight of metakaolin on compressive strength of PGC.

'Figure 5' illustrates the effect of inclusion fine aggregate (sand) on compressive strength of PGC. The results show that the inclusion of 5% and 10% sand led to increase the compressive strength. The increase is 10% and 19.5% of the PGP mix with MK:CA ratio of 1:5, 2% and 20.8% for mix with MK:CA ratio of 1:6, and 23.6% and 32.7% for mix with MK:CA ratio of 1:7 respectively relative to the corresponding mixtures not containing sand. The aim of inclusion fine aggregate to PGC is to improve the compressive strength, but not reducing the void content to less than 15%. Maximum compressive strength of 14.1 MPa was obtained for mix with metakaolin paste content of 20% (MK:CA ratio of 1:5), 0.6 AL/MK ratio and 10% fine aggregate. While the minimum compressive strength of 4.13 MPa was obtained for mix with metakaolin paste content of 14.3% (MK:CA ratio of 1:7), 0.5 AL/MK ratio and without any fine aggregate.

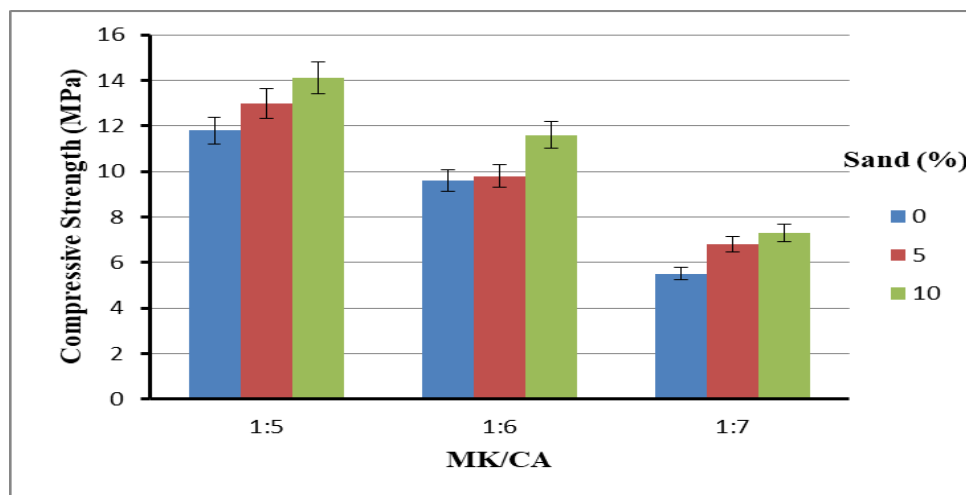


Figure 5. The effect of fine aggregate inclusion on compressive strength of PGC.

5.2. Oven dry density

The density of PGC at age of 7 days is shown in Figures 6 and 7. The increase in coarse aggregate content resulted in a decrease in density and the increase of void content in the PGC mixes. The densities of PGC with MK:CA ratios of 1:5, 1:6 and 1:7 are 1913, 1829 and 1720 kg/m³ respectively for the same AL/MK ratio and superplasticizer dosage. In addition, the results illustrate that the density decreases as the alkaline solution to metakaolin ratio (AL:MK ratio) increases. This is because the high water content in fresh mix led to high air content in dry condition of PGC.

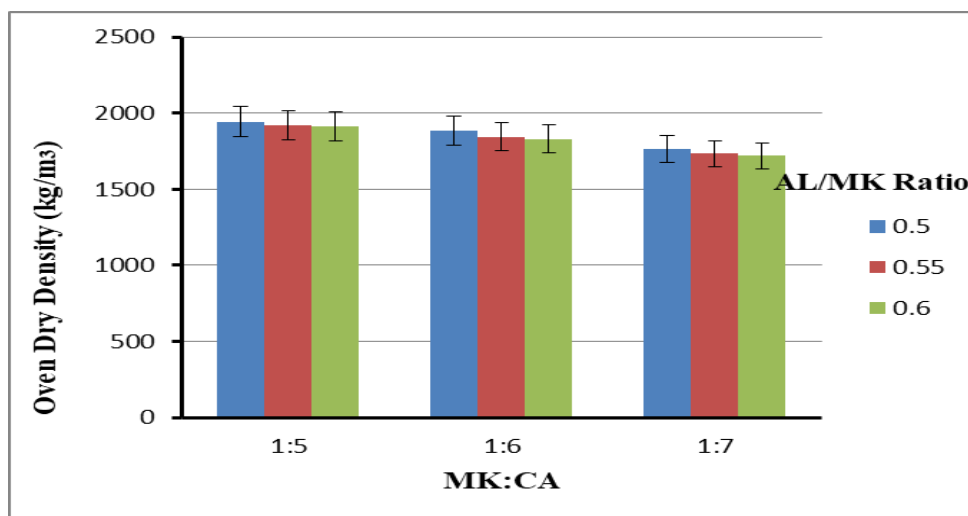


Figure 6. Effect of MK: CA ratio and AL/MK ratio on oven-dry density of PGC.

Figure 7 shows that the inclusion of sand to PGC increases the density. For example, the density of PGC with MK: CA ratio of 1:5 is 1910, 1955 and 1997 when the sand content is 0, 5 and 10% respectively. This is because the inclusion of fine aggregate led these fine particles to occupy the voids between coarse aggregate particles in PGC matrix. The addition of 10% fine aggregate by weight of total coarse aggregate causes a slight increase in density of about 4.5%, 7.2% and 5.2% for mixes with 1:5, 1:6 and 1:7 MK:CA ratio. While the enhancement in compressive strength for this addition of sand is 19.5%, 20.8% and 32.7%, respectively, and the void content was not less than 15% that is the requirement of ACI [6]. These results encourage the use of sand up to 10% in PGC at metakaolin paste content of 20% (with MK:CA ratio of 1:5) or more. The density for all PGC is in the range from 1997 kg/m³ to 1718 kg/m³.

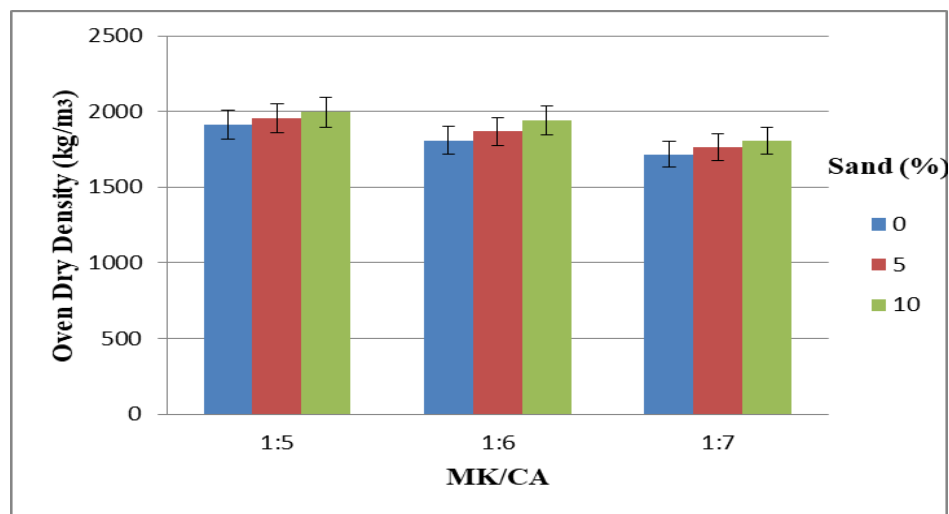


Figure 7. The effect of fine aggregate inclusion on oven-dry density of PGC.

5.3. Void content

The results of porosity or void content for all PGC are given in Table 5. The porosity of metakaolin PGC is between 18% and 30%. Generally, the porosity of pervious concrete depends upon the aggregate gradation and compaction methods [19, 20]. During this investigation, the aggregate gradation and the compaction method were constant.

Figure 8 shows the influence of different metakaolin to coarse aggregate and alkaline liquid to metakaolin ratios on the void content of pervious geopolymer concrete. From this figure, it can be observed that the void content of PGC decreases with the decrease of coarse aggregate content. This is because of the high metakaolin paste content in PGC with low aggregate content that led to fill the voids between the coarse aggregate in PGC matrix. For example, The porosity of mixtures with MK:CA ratio of 1:5, 1:6 and 1:7 are 21, 26.8 and 30%, respectively, at MK/AL ratio of 0.6 and SP dosage of 3% by weight of metakaolin. The results show that the void content of metakaolin PGC slightly affected by the AL/MK ratio for the mixes with the same paste content.

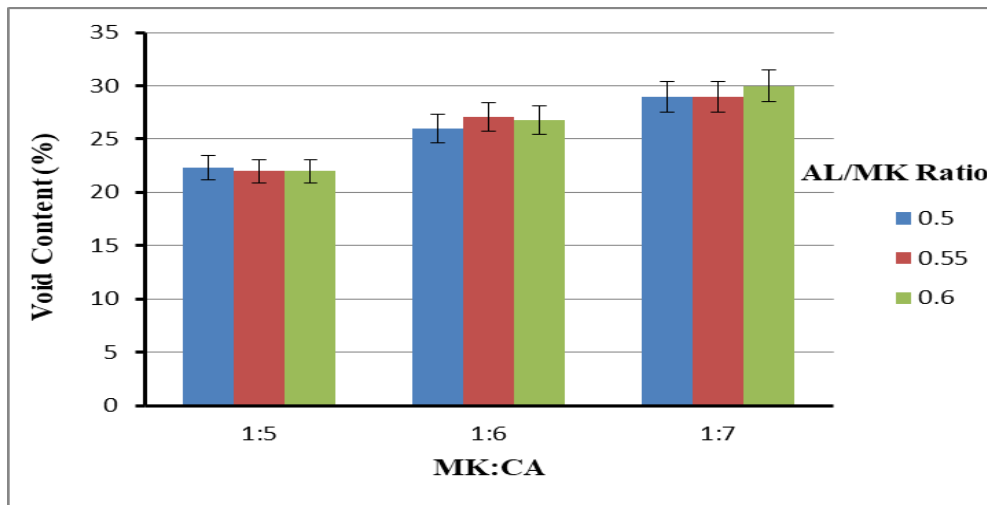


Figure 8. Effect of MK: CA and AL/MK ratio on void content metakaolin pervious geopolymer concrete.

Figure 9 illustrates the effect of fine aggregate on the void content of PGC. When fine aggregate added by 10 percent, the reduction in void content for 1:5, 1:6 and 1:7 MK:CA ratio is 21.7%, 14.8% and 13.3% respectively relative to PGC without fine aggregate. This effect of fine aggregate considered as inversely effect on PGC, because this property has a direct relation to acoustic and thermal insulation, purification and unit weight of PGC. When PGC with higher compressive strength is required, the inclusion of 10% fine aggregate can be use with void content not less than 15%.

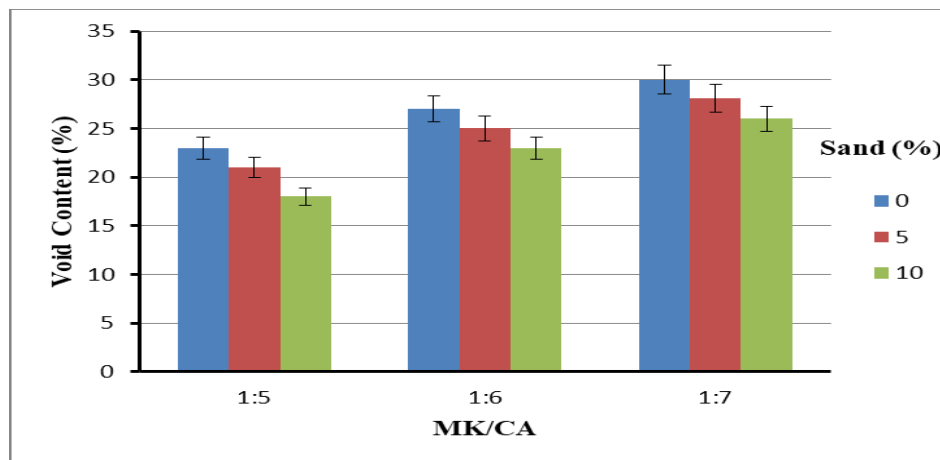


Figure 9. The effect of fine aggregate inclusion of void content of PGC.

6. Conclusions

Based on the results and discussions, many conclusions are drawn:

1. The maximum compressive strength for metakaolin PGC is for specimens with AL/MK ratio of 0.6 and SP dosage 2% for all MK/CA ratios.
2. The densities of PGC with MK:CA ratios of 1:5, 1:6 and 1:7 were 1913, 1829 and 1720 kg/m³, respectively for mixtures with the same AL/MK ratio and SP dosage. The density decreases as the alkaline solution to metakaolin ratio increases.
3. The inclusion of 10% fine aggregate by weight of total coarse aggregate causes a slight increase in density of about 4.5%, 7.2% and 5.2% for mixes with 1:5, 1:6 and 1:7 MK:CA ratio, while the enhancement in compressive strength is 19.5%, 20.8% and 32.7% respectively, and the void content was not less than 15%.

4. The void content of PGC increases with the increase of coarse aggregate content in the mixture. The porosity of mixtures with MK:CA ratio of 1:5, 1:6 and 1:7 were 21, 26.8 and 30% respectively at MK/AL ratio of 0.6.

5. The inclusion of fine aggregate by 10 percent in mixtures with 1:5, 1:6 and 1:7 MK:CA ratio causes reduction in void content of 24%, 14.8% and 13.3%, respectively, but the value of void content is not less than 15% which is comply with ACI 522 requirements.

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