Effect of Metakaolin on Properties of Lightweight Porcelinate Aggregate Concrete

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ABSTRACT

Research in Iraq has expanded in the field of material technology involving the properties of the lightweight concrete using natural aggregate. The use of the porcelinate aggregate in the production of structural light concrete has a wide objective and requires a lot of research to become suitable for practical application. In this work metakaolin was used to improve compressive strength of lightweight porcelinate concrete which usually have a low compressive strength about 17 MPa . The effect of metakaolin on compressive, splitting tensile, flexure strengths and modulus of elasticity of lightweight porcelinate concrete have been investigated. Many experiments were carried out by replacing cement with different percentages of metakaolin. The metakaolin was replaced by 5%, 10%, 15% and 20%. A control reference mix without metakaolin was made for comparison purpose. For all mixes, compressive, splitting tensile, flexure strengths and modulus of elasticity were determined at 28-day. The results showed that the using of metakaolin improve the compressive, splitting tensile, flexure strengths and modulus of elasticity of lightweight porcelinate concrete. The higher compressive, splitting tensile, flexure strengths and modulus of elasticity were found for 15% metakaolin.

Keywords: Lightweight concrete, porcelinate, metakaolin

الخلاصة

توسعت البحوث في العراق في حقل تكلنوجيا المواد من ضمنها دراسة خواص الخرسانة خفيفة الوزن باستخدام ركام طبيعي. استخدام البورسلينايت كركام خفيف الوزن في انتاج خرسانة انشائية يتطلب العديد من الدراسات لفهم وتحسين خواصها لتصبح مناسبة للتطبيقات العملية.

في هذه الدراسة استخدمت مادة ميتاكاؤلين كنسبة مئوية مِنْ وزن سمنت، لتحسين خواص خرسانة البورسلينايت الخفيفة الوزن التي تمتاز عادة بمقاومة انضغاط واطئة حوالي 17 ميكاباسكال. تم دراسة تاثير اضافة ميتاكاؤلين على كل من مقاومة الانضغاط، مقاومة الانفلاق، معامل التصدع، و معامل المرونة للخرسانة البورسلينايت الخفيفة الوزن. وقد استبدل جزء من السمنت بالنسب التالية من ميتاكاؤلين: 5%، 10%، 15%، و 20% من وزن السمنت، بالاضافة الى الخلطة المرجعية بدون اضافات لغرض المقارنة. لكل الخلطات تم قياس كل من مقاومة الانضغاط، مقاومة الانفلاق، معامل التصدع، و معامل المرونة بعمر 28 يوم. وقد وجد بان استبدال نسبة 15% من سمنت بميتاكاؤلين تحسن مقاومة الانضغاط، مقاومة الانفلاق، معامل التصدع، و معامل المرونة.

INTRODUCTION

Structural Lightweight Concrete: ACI committee 213 defined structural lightweight aggregate concrete as a concrete with an air-dried density at 28-day in the range of 1120 and 1920 kg/m^3 and a compressive strength above 17.2 MPa. The same committee defined high strength lightweight concrete as concrete with a 28-day compressive strength of 41.4 MPa or greater. Structural lightweight aggregate concrete is an important and versatile material in modern construction. It has many and varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types.

Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world. Structural lightweight concrete offers design flexibility and substantial cost savings by providing: less dead load, improved seismic structural response, longer spans, better fire ratings, and thinner sections, decreased story height, smaller size structural members, less reinforcing steel, and lower foundation costs. Lightweight concrete precast elements offer reduced transportation and placement costs (Sylva et al. 2002). There are many types of aggregates available that are classified as lightweight and their properties cover wide ranges. In 1986 the State Company of Survey and Mining discovered Porcelinate rocks in Traifawi in the Iraqi Western Desert, near Rutba (Bassam et al. 1986). Preliminary studies were made to find its mineral and chemical properties, as well as estimating reserve of this rocks. According to these studies the Company recommended the use of porcelinate as a coarse aggregate in the production of lightweight aggregate concrete (Bassam et al. 1986) and (1993خـــضير محمـــد و عبـــود افنـــان).

Lightweight porcelinate concrete (LWPC) usually have low compressive strength about 17 MPa. Most efforts have concentrated on improving the properties of concrete and studying the factors that influence on these properties. Since the compressive strength is considered a valuable property and is invariably a vital element of the structural design, especially high early strength development which can be provide more benefits in concrete production, such as reducing construction time and labor and saving the formwork and energy. To improve the strength of lightweight concrete the using of supplementary cementitious materials like fly ash, ground granulated blast – furnace slag, silica fume, and natural pozzolans, such as calcined shale, calcined clay or metakaolin, which contribute to the strength gain of concrete, is necessary. Al–Musawi used porcelinate as lightweight aggregate. The cementitious materials considered type I Portland cement with 4% superplasticizer (% weight of cement) and maximum size of aggregate (MSA) 9.5 mm were used, 28-day compressive strengths were found between 13.2 and 21.9 MPa, with a density between 1761 and 1975 kg/m3 (Al–Musawi 2004). Al–Mohamady found 28-day compressive strength of lightweight porcelinate concrete between 20.9 and 29.03 MPa (The highest values were obtained for the 9.5 mm lightweight aggregate mixture with 650 kg/m3 of type I Portland cement with 2% superplasticizer), with a density between 17645 and 1815 kg/m3 (Al–Mohamady 2007).

EXPERIMENTAL INVESTIGATIONS AND SPECIFICATIONS

Properties of Materials

Cement; one type of Portland cement; ordinary portland cement (OPC) was applied. Total percentages for its oxides, compound composition and some properties were fulfilled to the requirement of Iraqi specification No.5/1984 as denoted in Table 1and 2 .

Aggregate; the fine aggregate used was local sand, it met the requirements of Iraqi specification No.45/1984 with respect the sieve analysis and physical properties as denoted in Table (3) and (4). While the coarse aggregate used was crushed porcelinate with maximum size 9.5 mm, it met the requirements of ASTM C330-05. Sieve analysis, chemical analysis and physical properties as denoted in Table (5,6 and 7), respectively.

Water; Normal tap water was used as mixing water.

Superplasticizer (SP);
The superplasticizer used in this research is Sikament –163 (high range water– reducing agent and superplasticizer); which complies with ASTM C494–05, type F. Table (8) shows the technical description for it.

Metakaolin (MK); metakaolin , which used in this research , is obtained by calcination of kaolinitic clay at temperatures from 700 °C for one hour. It has strength activity index 102% ≥ 75%, which is complying with the strength activity index for Portland cement requirements of ASTM C311–05. Chemical analysis of metakaolin is complying with ASTM C618–05 requirements as denoted in Table (9).

CONCRETE MIXES PROPORTION

The basic objective of this present research is to investigated the influence of metakolin on some properties of lightweight porcelinate concrete. Accordingly, other mix design variables were considered constant such as mix proportions, the aggregate-binder, coarse-medium-fine aggregate ratio, dosage of SP, curing conditions and testing procedure. The total binder content was fixed at 500 kg/m^3, total sand content was 500 kg/m^3, 0.33 w/c ratio and total porcelinate content was 520 kg/m^3 . The dosage of SP was fixed 3.5% (% weight of cement) and kept constant for all the mixes. The metakaolin was replaced by 5%, 10%, 15% and 20%. In additional to the reference mix w/o metakaolin for comparison purpose. In order to minimize variations in workability, the compaction energy was varied for obtaining proper compaction and the mixing procedure and time were kept constant for all the concrete mixes investigated.

PREPARATION OF SPECIMENS AND CURING

The cylindrical molds of size 150 *300 mm and 150*150*500 prism lightly oiled were filled with fresh concrete and compacted by using vibrating table. For each concrete mix, fifteen specimens were used,
three cylindrical specimens for density test, three for compressive strength test, three for splitting tensile strength test and three for modulus of elasticity test and three prism for modulus of rupture test. The molds after casting were covered with polyethylene sheet and kept in the laboratory environment for a period of 24-hr. After that, the specimens were demoulded and placed in the water curing tanks up to the wanted age for test (28-day).

HARDENED CONCRETE TESTS

Compressive Strength; Concrete compressive strength is measured by using (300x150mm) cylinder specimens for 28–day age according to ASTM C39–01. The average of three specimens for each mix was adopted.

Splitting Tensile Strength; The splitting tensile test is carried out on (150x300mm) concrete cylinders for 28–day age according to the ASTM C496–05. The average of three specimens for each mix was adopted.

Modulus of Rupture; The modulus of rupture test was carried out by using (100x100x500mm) prisms, loaded at 450mm span with one points loading hydraulic machine. The test is carried out according to ASTM C78–05, using three concrete prisms and the average of three results is adopted.

Static Modulus of Elasticity; Measurement of modulus of elasticity are made according to ASTM C469–02 at 40% of ultimate load. The average of three specimens for each mix was adopted.

Unit Weight (Density); An average of three cylinders (300x150mm) was used to determine fresh density and hardened unit weight according to ASTM C567–00.

TEST RESULTS AND DISCUSSION

Compressive Strength

Test results are shown in Table (9). The compressive strength of concrete is usually measured for the purpose of quality control. The isolated effect of MK on the compressive strength are investigated. Fig. (1). shows the variation of compressive strength with MK replacement percentages in addition to the control mix (0% MK). The percentages of gaining strength with respect to the control at 5%, 10%, 15% and 20% MK replacements are 40.0%, 104%, 135.5% and 80.0%, respectively. The results indicate that the highest compressive strength was 47.1 MPa at 15% MK replacement. These results show that the optimum MK replacement percentages for obtaining maximum 28-day compressive strength of lightweight porcelinate concrete > 40 MPa ranges from 10% to 15%. This can explained by particle packing, micro–filling, and chemical reaction of MK with calcium hydroxide (CH) released from cement hydrates (hydration of C_3S) to form additional strong calcium silicate hydrate i.e cement gel (CSH) providing higher strength, additionally to the CSH, it produces other cementitious compounds as hydrogarnet or hydrogrossular phases (Taylor 1997, and Frías and Cabrera 2002),and the one can see that for all mixing the one contain metakaolin gave the higher compressive strength than reference control mix.

SPLITTING TENSILE STRENGTH

Fig. (2) shows the variation of splitting tensile strength with the MK replacement percentages. The trend in the strength gain is almost similar to that in compressive strength. The percentages of gaining strength with respect to the control mix at 5%, 10%, 15% and 20% MK replacements are 29.5%, 66.7%, 80.5% and 42.9%, respectively. The results indicate that the highest splitting tensile strength was 3.79 MPa at 15% MK replacement. Metakaolin particles increase the packing of the solid materials by filling the spaces between cement grains thereby increasing of bond strength leading to a significant increase in splitting tensile strength (Taylor 1997 and ASTM: C642–06). Fig. (3) shows the relationship between the 28-day splitting tensile and compressive strength for MK replacement percentages 0%, 5%, 10%, 15% and 20%, respectively. The splitting tensile strength increase with the increasing of compressive strength, and results show that the optimum MK replacement percentages for obtaining maximum 28-day splitting tensile strength of lightweight porcelinate concrete is 15% which gave higher compressive strength as mentioned before.

MODULUS OF RUPTURE

Fig. (4) shows the variation of modulus of rupture with the MK replacement percentages. The percentages of gaining strength with respect to the control mix at 5%, 10%, 15% and 20% MK replacements are 24.5%, 78.5%, 97.4% and 50.2%, respectively. This increasing percentages in flexural strength attributed to improving properties of concrete by using metakaolin (Taylor 1997 and ASTM: C642–06). Fig. (5) show the relationship between the 28-day modulus of rupture and compressive strength for MK replacement percentages 0%, 5%, 10%, 15% and 20%, respectively. The modulus of rupture increase with the increasing of compressive strength and the results indicate that the highest modulus of rupture was 4.6 MPa at 15% MK replacement.

MODULUS OF ELASTICITY

Fig. (6) shows the variation of modulus of elasticity with the MK replacement percentages. The percentages increase in modulus elasticity of with respect to the control mix at 5%, 10%, 15% and 20% MK replacements are 33.6%, 77.3%, 99.2% and 50.4%, respectively. Fig. (7) show the relationship between the 28-day modulus of elasticity and compressive strength for MK replacement percentages 0%, 5%, 10%, 15% and 20%, respectively. The modulus of elasticity increase with the increasing of compressive strength and the results indicate that the highest compressive strength was 23.7 GPa at 15% MK replacement. Lightweight aggregates are weaker than normal weight aggregates, this decrease in stiffness can be seen in modulus of elasticity measurements of lightweight concretes. So higher cement contents are needed to get a required strength for a mixture (Nawy 2001).

UNIT WEIGHT (DENSITY)

Based on the experimental results one can see that the both fresh and dry density of lightweight Porcelinate concrete contain metakaolin were higher then reference control mix, and the density increase with increasing of compressive strength. The reaction between MK with CH as mentioned above provide a dense impermeable pore structure. The percentages of increasing of density with respect to the control mix at 5%, 10%, 15% and 20% MK replacements are 8.4%, 14.0%, 15.3% and 10.8%, respectively.

CONCLUSIONS

The following conclusions have been reached in this study;

1. The isolated effect of MK increases the compressive, splitting tensile strengths, modulus of rupture and modulus of elasticity. The highest increase has been found in the compressive strength.

2. The trend in the strength gain due to MK replacement in modulus of rupture is almost similar to that in splitting tensile strength for lightweight porcelinate concrete.
3. The optimum MK replacement percentages for obtaining maximum 28-day compressive strength of lightweight porcelinate concrete ranges from 10% to 15%.
4. The optimum MK replacement percentages for obtaining maximum splitting tensile strengths, modulus of rupture and modulus of elasticity of at 28-day for lightweight porcelinate concrete was 15%.
5. Splitting tensile strengths, modulus of rupture, modulus of elasticity and density of lightweight

porcelinate concrete were increasing with increasing of compressive strength.

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Table (1) Chemical oxide composition and components of Ordinary Portland cement

Chemical analysis	Test results % By weight	Limits of Iraqi specification No.5/1984
CaO	62.07	–
SiO_2	21.60	
MgO	1.93	5% (maximum)
SO_3	2.19	2.8(maximum)
Fe_2O_3	3.18	–
Al_2O_3	5.30	–
Loss of Ignition (L.O.I)	1.78	4%(maximum)
Insoluble Residue	0.5	1.5%(maximum)
Lime saturation factor (L.S.F)	0.89	0.66–1.02
Main compounds (Bogue's equation)		
C_3S	47.16	–
C_2S	26.62	–
C_3A	6.43	–
C_4AF	9.97	–

#Tests are carried out by the stat company of geological survey and mining (SCGSM).

Table (2) Physical properties of cement used

Physical properties	Test results	Limits of Iraqi specification No.5/1984
Fineness by Blaine method m^2/kg	350	230 (minimum)
Setting time (Vicat apparatus)		
Initial setting (min.)	140	45 (minimum)
Final setting (hr.)	4.083	10 (maximum)
Compressive strength for cement–mortar cube at:		
3 days (MPa)	24.7	15 (minimum)
7 days (MPa)	33.3	23 (minimum)

#Tests are carried out by the stat company of geological survey and mining (SCGSM).

Table (3) Grading of sand according to Iraqi specification No.45/1984

Sieve size (mm)	%Passing	Limits of Iraqi specification No.45/1984 % passing (Zone No. 1)
10	100	100
4.75	90	90– 00
2.36	75	60– 95
1.18	56	30–70
0.6	30	15–34
0.3	13	5–20
0.15	6	0–10

- Fineness modulus = 3.27

Table (4) Chemical and Physical properties of sand

Property	Results	Limit of Iraqi specification No.45/1984
Bulk specific gravity	2.5	–
Absorption %	2.2	–
Dry loose unit weight (kg/m^3)	1600	–
Sulphate content (SO_3)%	0.25	0.5 (max.)
Material finer than 0.075 mm sieve %	2.3	5.0 (max.)

- The test was carried out at the laboratory of Baghdad University/Civil Engineering.

Table (5) Grading of coarse porcelinate aggregate

Sieve size (mm)	Coarse aggregate % passing	ASTM C330–05 % Passing
12.5	100	100
9.5	83	80–100
4.75	36	5–40
2.36	10	0–20
1.18	0.7	0–10

Table (6) Chemical analysis of porcelinate aggregate

Oxides	By weight %
SiO_2	71.15
Fe_2O_3	0.92
Al_2O_3	3.2
TiO_2	7.31
CaO	5.5
MgO	0.16
SO_3	0.08
L.O.I	9.65

#Tests are carried out by the SCGSM.

Table (7) Physical properties of porcelinate aggregate

Property	Results	Specification
Specific gravity	2.0316	ASTM C127–84
Absorption %	46.249	ASTM C127–84
Dry loose unit weight (kg/m^3)	802*	ASTM C29–97

*Within the limit of ASTM C330 ($880 kg/m^3$).
#Tests are carried out by the stat Company Of Geological Survey and Mining (SCGSM).

Table (8) Properties of superplasticizer

Properties	Description
Main action	Highly effective water–reducing agent and superplasticizier for the production of high quality concrete in hot climates
Dosage	0.6% – 2.5% by weight of cement
Type	Polymer type dispersion
Appearance	Liquid
Color	Brown
Specific gravity	1.2 kg/l
PH value	10 ± 1.0.

Supply by manufacture

Table (9) Chemical analysis of metakaolin

Oxides	% By weight	ASTM C618–03 [(67)]
SiO_2	52.38	Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3)=70% (Min.)
Al_2O_3	37.31	
Fe_2O_3	1.21	
CaO	1.68	–
MgO	0.3	–
K_2O	0.44	–

#Tests are carried out by the stat company of geological survey and mining (SCGSM).

Table (9) Properties of lightweight concrete

No. of mix	MK % of cement weight	Compressive strength (MPa)	Splitting tensile strength (MPa)	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Unite weight (Density) kg/m^3	
						Fresh unit weight	Dry unit weight
1.	5%–MK	28.0	2.72	2.90	15.9	1773	1698
2.	10%–MK	40.8	3.50	4.16	21.1	1868	1787
3.	15%–MK	47.1	3.79	4.60	23.7	1898	1806
4.	20%–MK	36.0	3.00	3.50	17.9	1806	1736
5.	0%–RC	20.0	2.10	2.33	11.9	1620	1567

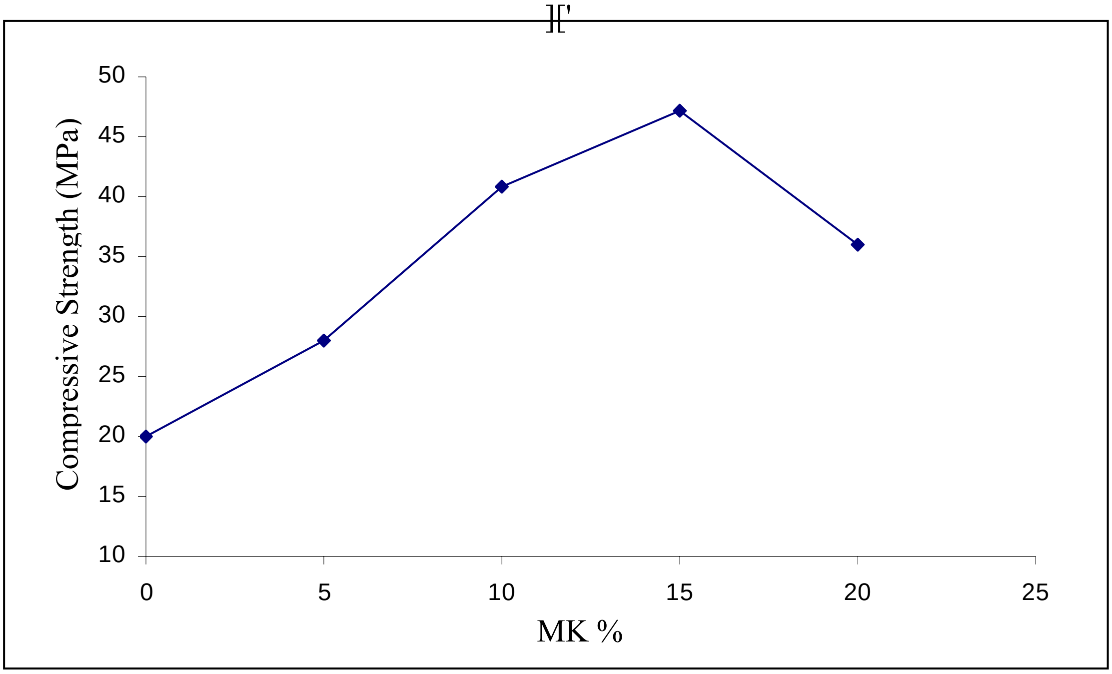

Fig. 1 Relationship between 28 day compressive strength and percentage replacement of Metakaolin

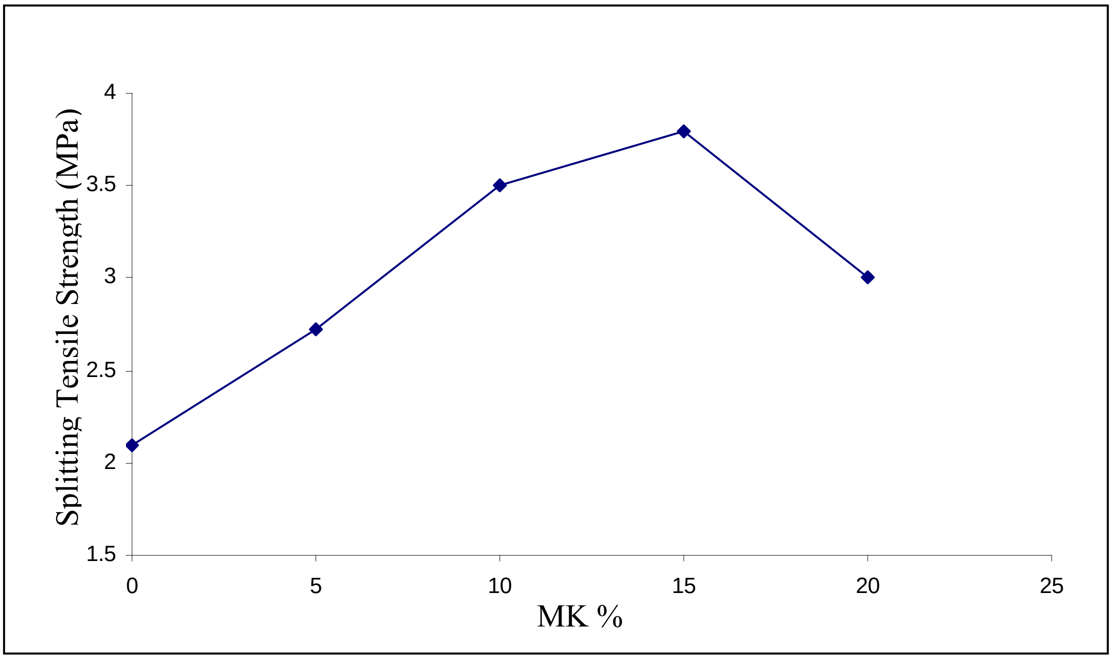

Fig. 2 Relationship between 28 day splitting tensile strength and percentage replacement of Metakaolin

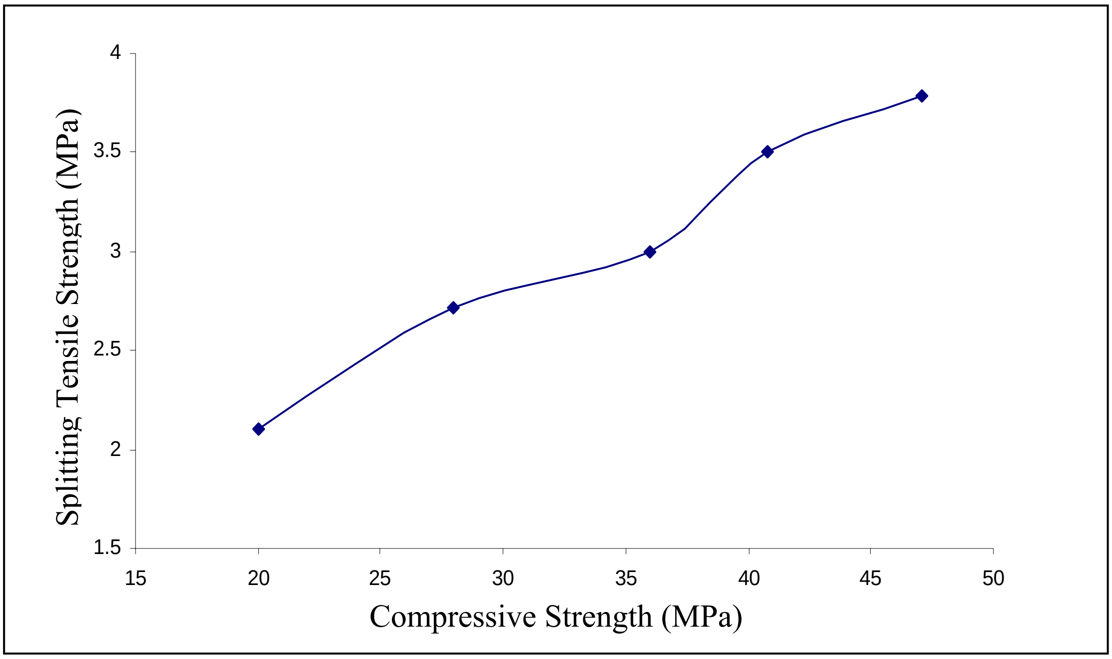

Fig. 3 Relationship between 28-day splitting tensile strength and compressive strength

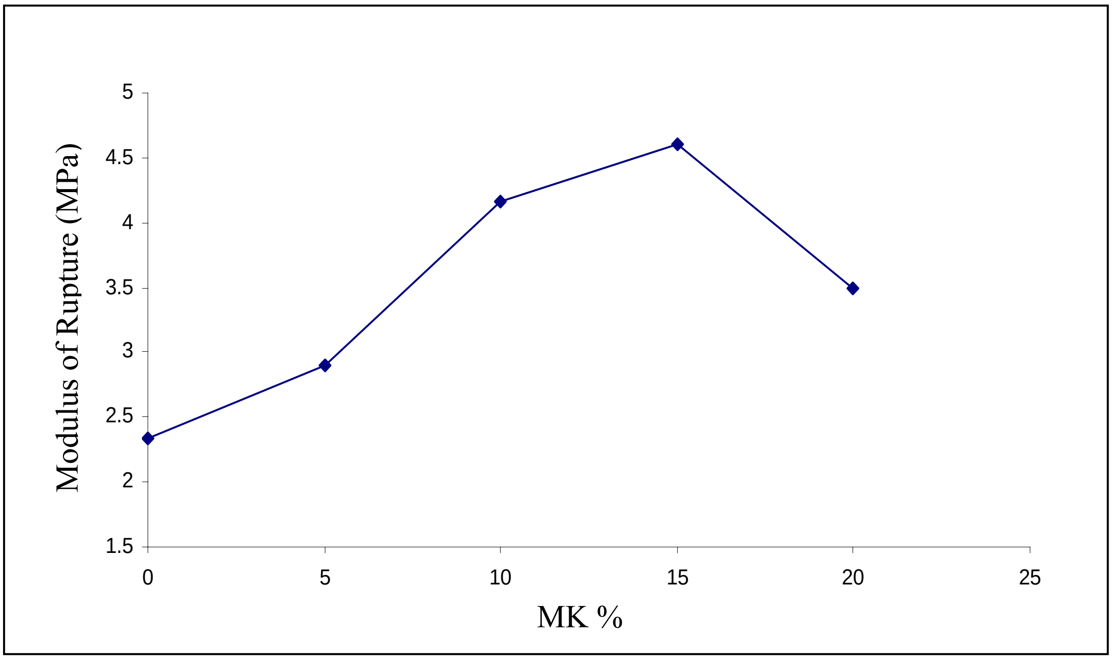

Fig. 4 Relationship between 28 -day modulus of rupture and percentage replacement of Metakaolin

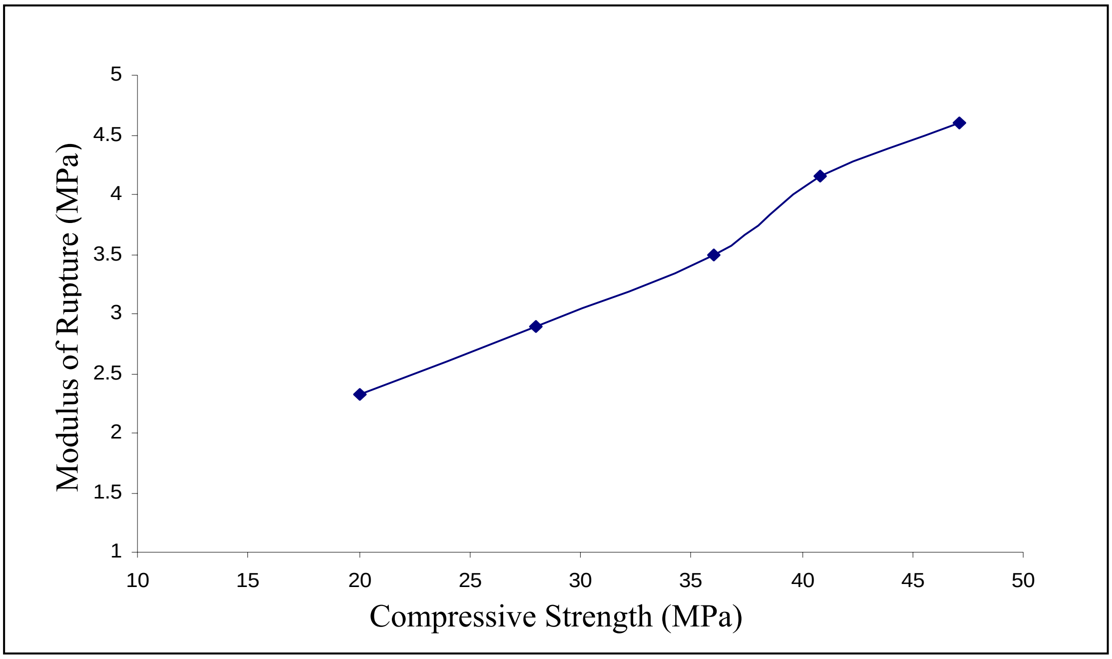

Fig. 5 Relationship between 28-day modulus of rupture and compressive strength

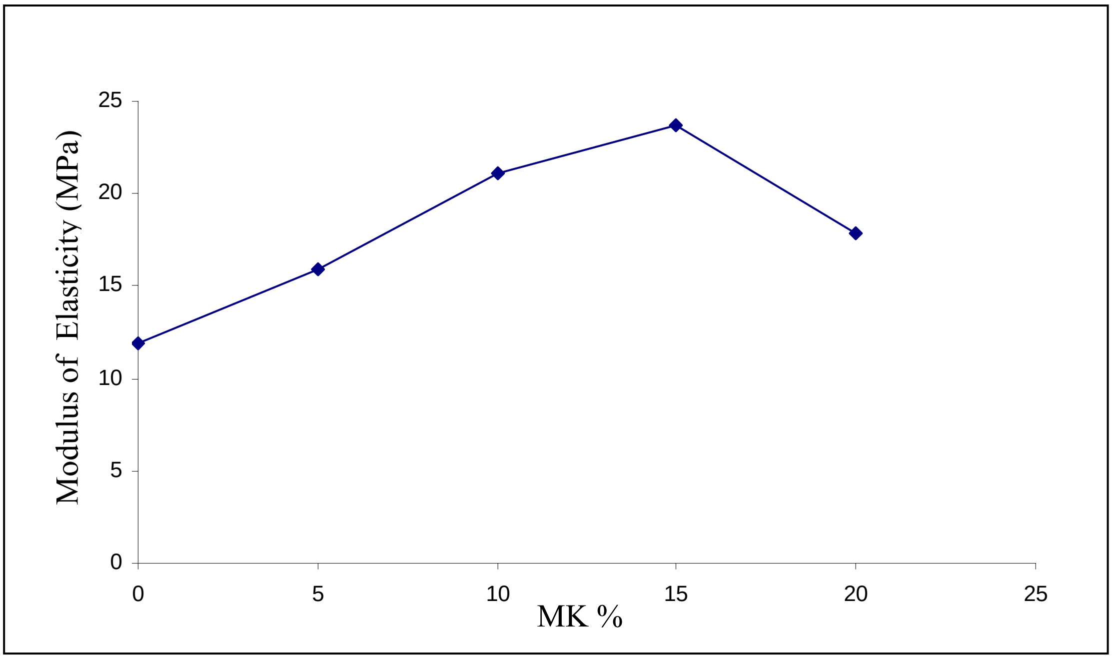

Fig. 6 Relationship between 28 -day modulus of elasticity and percentage replacement of Metakaolin

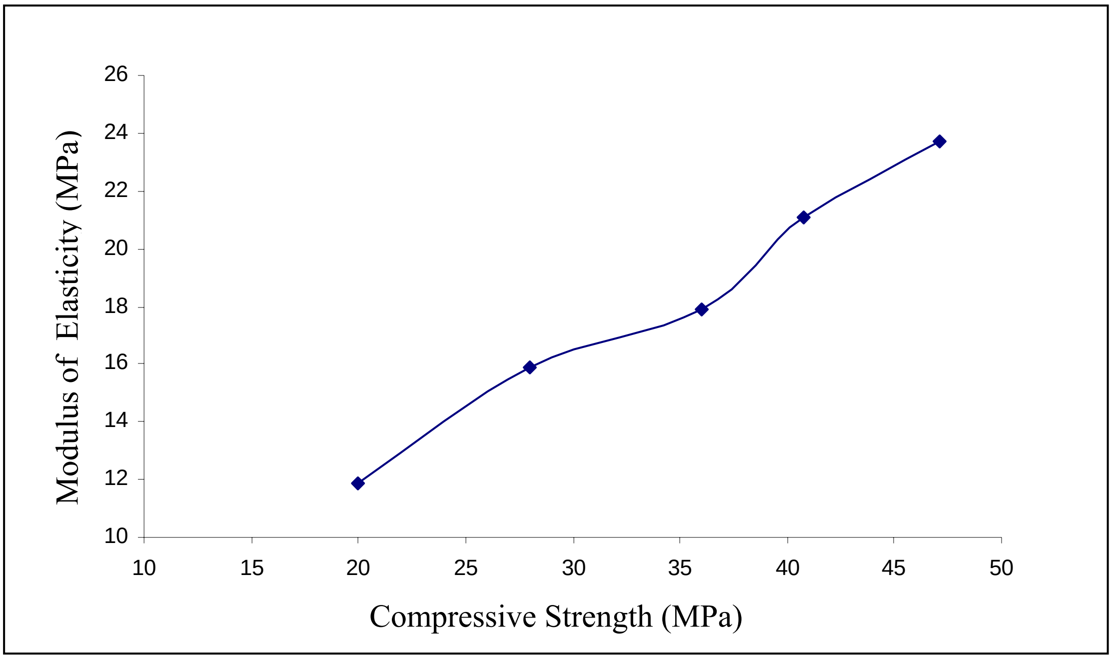

Fig. 7 Relationship between 28-day modulus of elasticity and compressive strength