Optimization of Geopolymer Concrete Based on Local Iraqi Metakaolin

Basil S. Al-Shathr, Tareq S. Al-Attar, and Zaid A. Hasan

Abstract— Geopolymer concrete is one of the building materials that has become more popular in recent years due to the fact that it is significantly more environmentally friendly than normal concrete. Geopolymer is manufactured by using aluminate and silicate compounds that react with alkaline material (sodium hydroxide and sodium silicate or potassium hydroxide with potassium silicate). This paper presents an optimization for mix design purposes for Iraqi Metakaolin based Geopolymer concrete. The concentration of the alkaline solution used was 10 Molar. Two ratios of sodium silicate to sodium hydroxide solutions by weight were adopted. They were 3.5 and 1.0. Naphthalene sulphonate-based superplasticizer was used. Specimens were cured by different methods inside and outside the laboratory. The optimum mix proportions of Geopolymer concrete based on compressive strength at 7 days were 400 kg Metakaolin, 180 kg alkaline solution (sodium hydroxide and sodium silicate), 40 kg extra water, 1100 kg coarse aggregate and 720 kg fine aggregate. The results showed that the optimum dose of superplasticizer was 12 kg/m^3. By increasing this content, the compressive strength will be decreased by 32.5%. Results indicated also that the fineness of Metakaolin has an important role on strength development of the Geopolymer. Compressive strength at 7 days age for the optimum mix was 27.53 MPa. This result was recorded for specimens made with Metakaolin had a specific surface area of 23m^2/g and cured under ambient environment outside the laboratory.

Keywords — alkaline solution, compressive strength, Geopolymer concrete, Metakaolin.

I. INTRODUCTION

IN order to reduce carbon dioxide emission into the air as a side effect of producing Portland cement, Geopolymer concrete now has been developed. Researchers [1,2] reported that the production of one ton of Portland cement produces one ton of carbon dioxide to the air and that contributes much to the global warming. Therefore, now Geopolymer concrete becomes popular material because it does not use Portland cement as a binder. But it uses natural materials such as Metakaolin, Fly Ash and Rice Husk Ash as a binder. Davidovits [3] stated that natural material for replacing Portland cement in Geopolymer concrete must contain high percent of silica and alumina. These elements react with alkaline liquids to develop a polymerization process results in producing Geopolymer concrete.

The Metakaolin, which has high content of silica and alumina, reacts with alkaline solution like sodium hydroxide NaOH or potassium hydroxide KOH, and sodium silicate Na_2SiO_3 or potassium silicate K_2SiO_3, to form a gel which binds the fine and coarse aggregate. Geopolymer concrete do not require any water for matrix bonding, instead the alkaline solution react with silicon and aluminum present in the Metakaolin or fly ash. The polymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals [4].

Geopolymer concrete produced without using elevated heat for curing will widen its application to the areas beyond precast members. Hence this study aims to produce Geopolymer concrete suitable for ambient curing condition under sunlight and compare it with other types of available curing systems.

Manuscript received March 2015
Basil S. Al-Shathr, is with UOT team, Iraq.
Email:basil1958a@yahoo.com
Tareq S. Al-Attar, is with UOT team, Iraq, Email: drtattar@yahoo.com
Zaid A. Hasan, Diwanyah Technical Institute, Iraq.

II. RESEARCH SIGNIFICANCE

There are too limited previous studies on Metakaolin based Geopolymer concrete. In Iraq, kaolin clays are available in large deposits and need only to be calcined to transform to Metakaolin. Thus these clays after calcination could be a good resource of silica and alumina and could be employed in producing Geopolymer concrete. This research may be considered as the first trials to produce sustainable Geopolymer concrete by using Iraqi Metakaolin.

III. MATERIALS

The origin of Metakaolin was Iraqi kaolin clay brought from Dewekhla region, Al-Anbar Governorate. Metakaolin prepared by grinding the clay by air blasting and then burnt in furnace up to 700ºC ± 20ºC for 1 hour, then the Metakaolin was cooled to room temperature for 24 hrs. This preparation procedure was recommended by Ibrahem and Wahab [5].The chemical composition of Metakaolin is shown in Table 1. Specific surface area of the prepared Metakaolin was 16.5m^2/g.

The alkaline solution consisted of sodium hydroxide NaOH and sodium silicate Na_2SiO_3. Sodium hydroxide is available in the local markets in the pellet form with purity of more than 98 percent. 10 Molar solution was prepared for this study. The sodium silicate solution has a ratio of SiO_2 to Na_2O of 2.4, which include 32.5 percent SiO_2, 13.4 percent Na_2O and 54.1 percent of water.

A high-range water reducer, was used for the production of rheoplastic concrete. It is based on a sulphonated naphthalene polymer.

The fine aggregate (sand) were obtained from Al-Ukhadir region, Karbala Governorate. The grading and sulfate content were conforming to the requirements of Iraqi Standard, IQS No.45/ 1984 – Zone 2.The coarse aggregate was crushed gravel with maximum size of 19 mm. The grading of this aggregate conforms to the Iraqi Standard, IQS No.45/ 1984, (5-19 mm).

Table 1
Chemical composition for Metakaolin

Oxide composition	Oxide content %
SiO_2	51.59
Al_2O_3	38.11
Fe_2O_3	1.82
CaO	0.45
MgO	0.23
SO_3	0.14
K_2O	0.43
Na_2O	0.11
L.O.I	6.12

IV. MIXING and CASTING of GEOPOLYMER CONCRETE

The Metakaolin, fine and coarse aggregate were mixed by pan mixer in dry condition for three minutes and then the alkaline solution was added (with superplasticizer , with or without extra water) and mix for another four minutes to prepare the Geopolymer concrete [6]. The Geopolymer concrete was casted in 100×100×100 mm cube molds and compacted by a vibrating table. After 24 hours, the specimens were demolded and started the specified curing system until the age of test. The Geopolymer concrete was white in color with an acceptable appearance.

V. MIX PROPORTIONS OPTIMIZATION

Twelve mixes were made to study the effect of different variables on strength. These mixes were produced with Metakaolin has the fineness of 16.5 m^2/g and cured by sunlight. The studied variables were: alkaline solution to Metakaolin ratio, extra water to Metakaolin ratio, superplasticizer to Metakaolin ratio and Metakaolin content. The details of these mixes and the resulted compressive strength are listed in Table 2.

The optimization for mix proportions was according to the following factors:

1. Silicate to hydroxide ratio of the alkaline solution.
2. Curing system.
3. Specific surface area (fineness) of Metakaolin.

Davidovits [3] recommended that the sodium silicate solution and the sodium hydroxide solution are mixed together one day prior to the use in preparing the Geopolymer concrete. This recommendation was followed for this study. Many trials have been made to select the optimum silicate to hydroxide ratio. This selection was made according to the compressive strength of concrete at 7 days age, as shown in Table 3, the optimum ratio of sodium silicate solution to sodium hydroxide solution is 3.5.

Different systems of curing were studied in this research. The sunlight curing started after removing specimens from molds, where the specimens kept under sunlight outside the laboratory in June when the ambient temperature ranged from 34 to 48 °C. The halogen curing system was implemented by using 500 watt halogen lamp concentrated on specimens till the age of test. In addition to that, a mixed system for curing was investigated. It consisted of a heat curing in oven at 60 °C for 6 hours, then starting either sunlight or halogen curing and continues for the age of test. Table 4 displays the effect of different curing systems on compressive strength of Geopolymer concrete.

Table 2
Details of the Geopolymer concrete mixes produced with different variables

Mix	MK, kg/m³	Alkaline solution, (% of MK)	Extra Water, (% of MK)	Coarse Aggregate, kg/m³	Fine Aggregate, kg/m³	Superplasticizer, kg/m³	Comp. Strength at 7 days, MPa
M1	400	0.45	0.15	1100	720	12	10.3
M2	400	0.4	0.2	1100	720	6	2.84
M3	400	0.4	0.3	1100	720	8	1.72
M4	400	0.4	0.25	1100	720	10	2.10
M5	400	0.45	0.25	1100	720	10	3.16
M6	400	0.4	0.25	1100	720	10	2.48
M7	400	0.45	0.1	1100	720	12	13.72
M8	400	0.45	0.1	1100	720	16	9.26
M9	400	0.45	0.1	1100	720	8	9.24
M10	400	0.45	0.05	1100	720	12	11.03
M11	500	0.45	0.05	1100	720	12	11.96
M12	400	0.45	0.0	1100	720	12	8.49

Table 3
Effect of hydroxide to silicate ratio on Geopolymer concrete strength

NaOH to Na_2SiO_3 ratio	Compressive Strength at 7 Days Age, MPa
1:2.5	7.32
1:3.5	13.72
1:4.5	4.40

Table 4
Effect of curing systems on compressive strength of Geopolymer concrete

Type of curing	Compressive Strength at 7 Days Age, MPa
Sunlight	27.53
Halogen (500W)	26.48
Heat curing (60°C for 6hrs) +sunlight	15.60
Heat curing (60°C for 6hrs) + halogen	18.64

Table 5
Effect fineness of Metakaolin on concrete compressive strength

Specific surface area of Metakaolin, m^2/g	Compressive Strength at 7 Days Age, MPa
16.5	13.72
19.6	22.69
23.0	27.53

To study the effect of specific surface area (fineness) of Metakaolin on Geopolymer strength, mix M7 (in Table 2) was reproduced by using Metakaolin with fineness of 19.6, and 23m^2/g. The results are shown in Table 5.

VI. RESULTS AND DISCUSSION

Table 2 shows the compressive strength of the different Geopolymer mixes produced with different variables.

1. Superplasticizer dose:

The increase in superplasticizer content leads to increase the compressive strength of Geopolymer up to an optimum level, 12 kg/m^3, at which strength reaches 13.72 MPa at 7 days age. After that limit, the strength decreases, as shown in Figure 1. By increasing the dose from 12 kg/m^3 to 16 kg/m^3, mix M7 and M8, the reduction in compressive strength was 32.5 percent. Moreover, decreasing superplasticizer content from 12 kg/m^3 to 8 kg/m^3, mix M7 and M9, the reduction was 32.6 percent.

2. Extra water content:
Table 2 and Figure 2 show that it is preferable to add extra of water to the mix, 10 percent by the weight of Metakaolin, to get the optimum strength. This may be due to some impurities in Iraqi Metakaolin that absorb water causing reduction in workability which lead to incomplete compaction without this extra water content. For mixes M7 and M10, when the extra water reduced from 10 to 5 percent, the strength reduced by 19.6 percent. Moreover, mix M12, which was made with no extra water, showed 38.1 percent reduction in compressive strength as compared with the optimum mix M7.
On the other hand, increasing extra water more than 10 percent by weight of Metakaolin caused the lowering of strength. For mixes M7 and M1, by increasing extra water from 10 to 15 percent, the compressive strength decreased by 25 percent. The reduction in compressive strength of Metakaolin based Geopolymer concrete could be attributed to the increase in water in alkaline solution which lowers the NaOH concentration. This behavior is similar to normal concrete as the effect of increasing the water to cement ratio would lower the compressive strength [7].

3. Alkaline solution to Metakaolin ratio:
The results indicate that increasing the ratio of solution to Metakaolin from 40 to 45 percent causes an improvement in strength by 33.5 percent. For the alkaline Geopolymerisation reactions, more Si aids in the production of Si-O-Si bonds, and significantly increases the compressive strength of the Geopolymer. If the content of Si exceeds the suitable limit, the Geopolymerisation rate is negatively affected, leading to Geopolymer of low strength [8].

4. Curing system:
According to Table 4, it can be seen that curing the specimens outside the laboratory under sunlight gives the highest strength. This is reasonable because Geopolymerisation need high temperature. Such a case is very convenient and economical in hot weather countries such as Iraq. In cold weather it is recommended to adopt another system of curing such as curing with halogen light. The compressive strength at 7 days of specimens cured by this system was 26.48 MPa which is too near to the value of hot weather sunlight curing system.

5. Specific surface area (fineness) of Metakaolin:
Table (4) shows that the Metakaolin fineness has a great role in gaining Geopolymer strength, as the increase in surface area from 16.5 to 23 m^2/g causes an increase in strength by about 100 percent to reach 27.53 MPa at 7 days, which could be considered as a good early strength that encouraging producing precast units from this material.

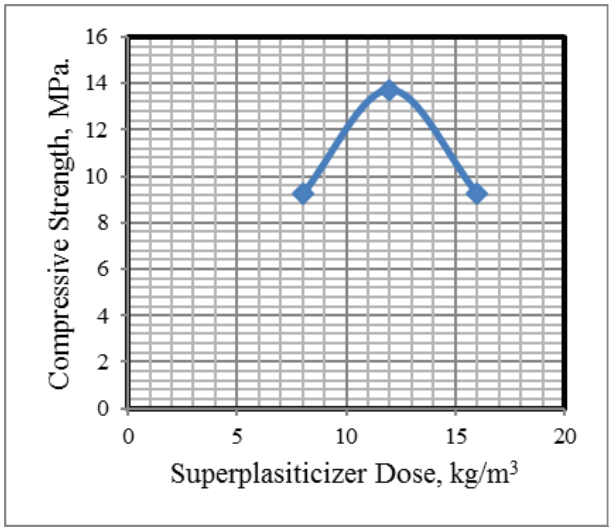

Figure 1: Effect of superplasticizer dose on compressive strength of Geopolymer concrete.

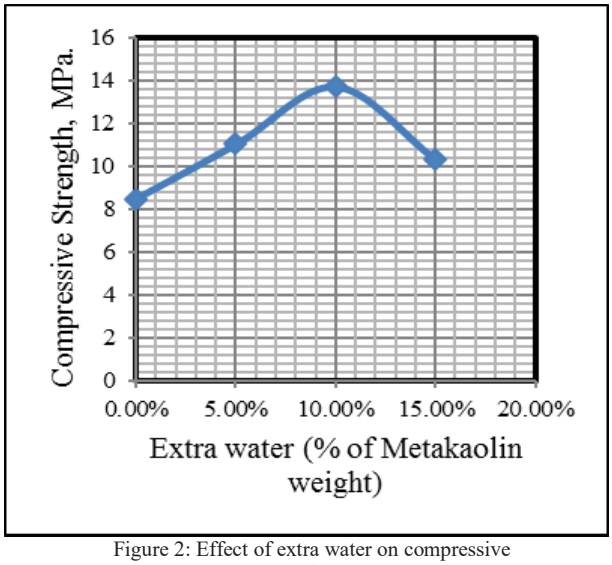

Figure 2: Effect of extra water on compressive strength of concrete

6. Metakaolin content:
The results also show that increasing the content of Metakaolin from 400 to 500 kg/m^3 leads to a slight increment in compressive strength. There is only an 8 percent difference in strength between mixes M10 and M11. Increasing the Metakaolin content could lead to an increase in Si and Al content and may increase Geopolymer gel that binds aggregate and increase compressive strength [9].

VII. CONCLUSIONS

1. Geopolymer could be considered as significant alternative for Portland cement because it has a good early compressive strength. The optimum mix proportion of Geopolymer concrete based on compressive strength at 7 days are 400 kg Metakaolin,

180 kg alkaline solution (sodium hydroxide and sodium silicate), 40 kg extra water, 1100 kg coarse aggregate and 720 kg fine aggregate.

2. The specific surface area (fineness) of Metakaolin has a great role in strength development, i.e. the relationship is positive between Metakaolin fineness and the Geopolymer concrete strength.
3. Geopolymer cured outside the laboratory under sunlight shows the highest strength. This case is very convenient and economical in hot weather countries such as Iraq in summer season.
4. In cold weather it is recommended to adopt another system of curing such as curing with halogen lights.
5. The extra added water has the same effect on Geopolymer concrete strength as that on Portland cement concrete strength.

REFERENCES

[1] D.M. Roy, "Alkali – Activated Cement, Opportunities and Challenges." Cement and Concrete Research, Vol. 29, Issue 2, 1999, pp. 249-254.

[2] E. Worrell, L. Price, N. Martin, C. Hendriks, and L.O. Meida, "Carbon Dioxide Emissions from the Global Cement Industry" Annual Review of Energy and the Environment Journal, USA, Vol. 26, 2001, pp. 303 – 329.

[3] J. Davidovits, "Properties of Geopolymer Cement" 1st International Conference on Alkaline Cement and Concrete, Kiev, Ukraine, 1994.

[4] M. I. Abdul Aleem and P. D. Arumairaj, "Optimum Mix for the Geopolymer Concrete" Indian Journal of Science and Technology, Vol. 5, No. 3, 2012, pp. 2299 – 2301.

[5] A.M. Ibrahem and A.A. Wahab, "Effect of Temperature on the Pozzolanic Properties of Metakaolin Produced from Iraqi Kaolin Clay". AL- Fatih Journal, Diyala University, Iraq, Vol. 4, Issue 32, 2008, pp. 268-285.

[6] D. Hardjito and S.E. Wallah, "On the Development of Fly Ash-Based Geopolymer Concrete" ACI Materials Journal, Vol. 101, Issue 6, 2004, pp. 467-472.

[7] G.S. Patil and K. Manojkumar, "Factors Influencing Compressive Strength of Geopolymer Concrete" International Journal of Research in Engineering and Technology, 2013, pp. 372 – 375.

[8] H. Kamarudin and A.K. Omar, "The Effect of Alkaline Activator Ratio on the Compressive Strength of Fly Ash-Based Geopolymer" Australian Journal of Basic and Applied Sciences, ISSN 1991-8178, 2011, pp. 1916-1922.

[9] J.N.Y. Djobo and H.K. Tchakoute, "Synthesis of Geopolymer Composites from a Mixture of Volcanic Scoria and Metakaolin" Journal of Asian Ceramic Societies, Vol. 2, Issue 4, 2014, pp. 387–398.

Dr. Basil S. Al-Shathr was born in Baghdad, Iraq in 1958. He received his BSc in building & construction engineering in 1979, his MSc in concrete design and technology in 1983, and he received his PhD in building materials engineering in 2009. These degrees were all from the University of Technology, Iraq.

At present, he is an assistant professor of civil engineering in the Building and Construction Engineering Department, University of Technology, Iraq. His research interests include sustainability of building materials, in addition to the behavior of high performance and ultra-high performance concrete. He published more than 20 research paper and has three patents in the field of building materials.

Dr. Al-Shathr is a member of the Iraqi Union of Engineers since 1979.