Hamed Enayati et al. International Journal of Recent Research Aspects ISSN: 2349-7688, Vol. 7, Issue 1, March 2020, pp. 1-8

An Investigation of the Effect of Cement Replacement with Geopolymer in Geopolymer Lightweight Aggregate Concrete

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Abstract: **Concrete is frequently used in the construction industry because it is readily available and has proven high ductility. A primary component of concrete is cement, the production of which, however, is energy consuming and results in environmental pollutants. Consequently, researchers have begun to use geopolymers as an adhesive with chemical, thermal, or mechanical activators. The use of geopolymers is cost effective and energy saving because it is self-produced from industrial recycling. This research replaces cement with geopolymers to evaluate concrete behavior. Results show that use of geopolymers increases the compressive strength of concrete while lowering the temperature of the concrete environment due to decreased hydration rates.**

Keywords: **Geopolymer; Compressive strength; Hydration heat; Lightweight aggregate concrete.**

I. INTRODUCTION

Concrete is the preferred material in the construction industry and the second most widely used human substance after water [1]. The era of industrialization and technological development has prompted development of special concrete as well as new advancements in concrete materials. Because structures function generally improves when overall structural weight decreases, the concrete industry is the increasing use of structural lightweight aggregate concrete, which reduces building weight and consequently reduces the size of structural elements [1]. Recent research demonstrated the cost effectiveness of using lightweight materials in the construction of offshore structures [2].

Recent environmental considerations have impelled researchers to replace cement with environmentally friendly materials. On average, one ton of carbon dioxide is produced when fossil fuels are used to produce one ton of cement. Consequently, the cement industry has become a primary contributor to environmental pollution since cement production accounts for approximately 7% of the world's carbon dioxide [3]. In response, researchers have developed geopolymer concrete, or green concrete. Green concrete is defined as a concrete which uses waste material as at least one of its components, or its production process does not contribute to adverse environmental effects. It should also have high performance and life cycle sustainability. In other words, green concrete is an environment friendly concrete. Geopolymers have an aluminosilicate structure and, when mixed with alkali, they become an alkaline with adhesive properties.

Geopolymer cements like Portland cements are commonly used for concrete production in prefabricated industries. Geopolymer cement requires low energy consumption, thereby reducing greenhouse gas emissions. Compared to conventional concrete, geopolymer concrete has higher resistance to sulfated acid attacks, and its creep and contraction are less than concrete made with Portland cement [4].

This research specifically studied the mechanical properties of geopolymer concrete. Consumed cement was replaced with geopolymer percentages of 0, 10, 20, 30,.. 100, and compressive strength was compared at 7 days and 28 days. Sampling was carried out using 15-cm cubic molds; samples were processed in water ponds at 23°C.

II. GEOPOLYMERS

Recent extensive research has focused on the application of geopolymers for various engineering purposes. Geopolymers are resistant, durable cement materials that harden at temperatures below 100°C. Based on research he conducted throughout the 1970s, Davidovits argued that geopolymers are a new group of trimorphous aluminosilicates [5]. Products of a geopolymerization reaction have been shown to have excellent mechanical properties, increased resistance to high temperatures and chemical attacks, and low shrinkage [6]. Natural and synthetic aluminosilicate materials such as fly ash, rice husk ash, blast-furnace slag, electric arc furnace, silica fume, metakaolin, and natural pozzolans can be converted into construction products via geopolymerization [7]. In addition, less temperature is needed to produce these cements, resulting in the release of less CO2. Although alkali hydroxides are typically refined products, the production of geopolymer cements and concretes has less environmental impact than the production of normal Portland cements. Also, base materials (aluminosilicate materials) are found naturally and in many factory residues. The term “geopolymer” refers to a group of mineral binders that, similar to zeolites, have polymeric Si-O-Al structures. The Si/Al ratio in geopolymers is approximately equivalent to zeolites, except that zeolites are crystallized and geopolymers are amorphous [8]. Solutions of high alkalinity are used to dissolve Si and Al ions and to form geopolymer cements. The three main steps for geopolymerization are as follows:

1. Solubility of aluminosilicate compounds in high alkaline solution;
2. Orientation of Si and Al ions in the direction that the activators give them;
3. Start of the polymerization reaction, hardening and gain of resistance.

Using the process of geo-polymerization, a variety of natural and synthetic aluminosilicate materials such as fly ash, rice husk ash, blast-furnace slag, electric arc furnace, silica fume, metakaolin, and natural pozzolans can be converted into construction products [7]. Geopolymerization involves the chemical reaction of aluminum and silicon oxides with alkali silicates to form a polymeric bond of Si-O-Al with a three-dimensional amorphous [9] or semi-crystallized structures. Davidovits [10] defined three forms for this structure:

Poly (sialite) (-Si-O-Al-O-),
Poly (sialite-siloxo) (-Si-O-Al-O-Si-O-), and
Poly (sialite-disiloxo) (-Si-O-Al-O-Si-O-Si-O-).

The distribution and amount of these three structures affect the chemical and physical properties of the geopolymer. The most critical factors influencing geopolymerization are the mole ratio of O2/Na2SiO6 (i.e., the ratio is 3–6 M in silicate blue solution) and the mole ratio of 3O2/Al2SiO6 (i.e., the ratio is 3.3–6.5 in the admixture).

The type of base material and the concentration of alkalinity in the solution affect the formation and stabilization of the gel phase. The concentration of Si is greater than the concentration of Al in geopolymerization because more Si is present in the base material and Si has greater solubility than Al. Moreover, increased concentration of alkalinity increases the solubility of natural pozzolans. Previous studies have shown that factors such as CaO percentage, ratio of Si/Al in the base material, Si solubility, mole ratio of soluble Si/Al, mineral hardening, and use of KOH as activator positively affect the compressive strength of geopolymer cements, while the percentage of K2O in the base material and the use of NaOH adversely affect the compressive strength of geopolymer cements [11]. Geopolymers are a family of mineral polymers with chemical compositions similar to zeolite but with amorphous microscopic structures rather than crystalline structures [12].

III. GEOPOLYMER CONCRETES

Geopolymer lightweight concrete is environmentally friendly because geopolymers require minimal use of fossil fuels, thereby preventing environmental pollution. Use of geopolymers in concrete reduces energy consumption and concrete production costs.

Concrete currently plays a critical role in the development of civil and economic infrastructures of societies. However, the high demand for concrete and the increasing need for cement production have significantly increased the consumption of electrical power and fossil fuels. Therefore, the development of alternative products is essential for sustainable development. An environmentally friendly concrete production method reduces the consumption of activated pozzolan binders. In addition, the use of geopolymers as adhesives in concrete has led to the development of geopolymer concrete, which is a practical, environmentally sound alternative to conventional concrete with Portland cement [13]. Razmi et al. examined the mechanical properties of geopolymer cement and its potential use as a replacement for Portland cement in concrete [14]. Their study, which was based on tensile and point load tests on the samples as well as determining the optimal amount of mechanical properties of the geopolymer cement, replaced consumed cement with the optimal amount of geopolymer cement composition in concrete, and resulted in the improvement of its mechanical properties. Kouhpaee et al. used two geopolymers to produce geopolymer concrete. They showed that the moisture content of the concrete materials affects product resistance [15].

The geopolymers in green concrete must be activated to identify the adhesive cement property. In general, geopolymers can be activated using thermal, mechanical, or chemical activation. Chemical activation, which requires the use of a strong alkali, is the most effective and economical activation method. Although either a strong acid or a strong base can be used for chemical activation, the use of a strong acid such as hydrochloric acid is suitable for low-calcium pozzolans to increase the resistance in the early age. However, activation with acids has higher risks and costs than activation with strong alkalis such as sodium hydroxide and potassium hydroxide [16]. This study also used an alkali, potassium hydroxide, to activate the geopolymers.

IV. TYPES OF ACTIVATORS

High alkalinity solutions are used to increase the solubility of Al and Si ions in base materials (pozzolans) and to form a geopolymer mortar. Potassium compounds have also been used in laboratory experiments. Results have shown that alkaline silicate solutions are the most effective activator for geopolymer cements [17].

Although a few studies have researched the activation of natural aluminosilicates using sodium or potassium hydroxide mixed with sodium silicate, the use of potassium hydroxide has produced better products than sodium hydroxide. The pozzolan material has been shown to dissolve better when the alkalinity concentration in the alkaline solution is increased, especially in the NaOH solution. The existence of K+ causes the formation of silicate oligomer. Therefore, the amount of geopolymer increases in the presence of KOH, thereby effectuating increased adhesion and resistance compared to when NaOH is present [18]. However, the amount of activators is expressed in terms of weight, molarity, etc. Use of an optimal rate of activator is vital because excessive use may result in efflorescence, reduced ductility, and concrete workability. The optimum value of potassium hydroxide used in the study presented in this paper was found to be between 5 and 10 M; and subsequently it was decided to use a value of 8 M.

V. TEST METHODS

This study specifically evaluated the effect of replacing cement with geopolymer for 11 cases in which the ratio of cement and geopolymer ranged between 0% and 100%. Aluminosilicate was used as the geopolymer, and the chemical method (namely potassium hydroxide) was used for activation.

In most research on geopolymer concrete lightweight expanded clay aggregate (LECA) is typically used in mix designs to reduced the weight of a concrete. This study utilized a fine LECA of 0–3 mm. Since the relationship between compressive strength and water/cement ratio (W/C) of lightweight aggregate concrete is similar to that of normal aggregate concrete, a conventional mixing method can be implemented when using lightweight aggregate in concrete design. However, it is difficult to determine how much of the total water in the mixture and concrete is occupied by the light aggregates. This is because the water absorption process varies and may continue more than one day for some light aggregates. Because application of the W/C ratio is also relatively difficult in calculating mixing ratios, it is therefore preferable to determine ratios based on the amount of cement. In this study, the amount of cement, the W/C ratio, the unit weight of the concrete, and 20% of the aggregates were 500 kg, 0.45, 2300 kg/m^3, and gravel, respectively. Moreover, the remaining aggregates were 50% sand and 50% LECA. Not all the estimated amount of LECA was used, but it was mixed in proportion to its volume. Figure 1 shows the weighing process of fine aggregates in the lab.

Figure 1- Weighing Fine Aggregates

In this research, 50% of the weight of fine aggregates was from sand, as shown in the grading diagram in Fig. 2. This sand was provided from washed river materials.

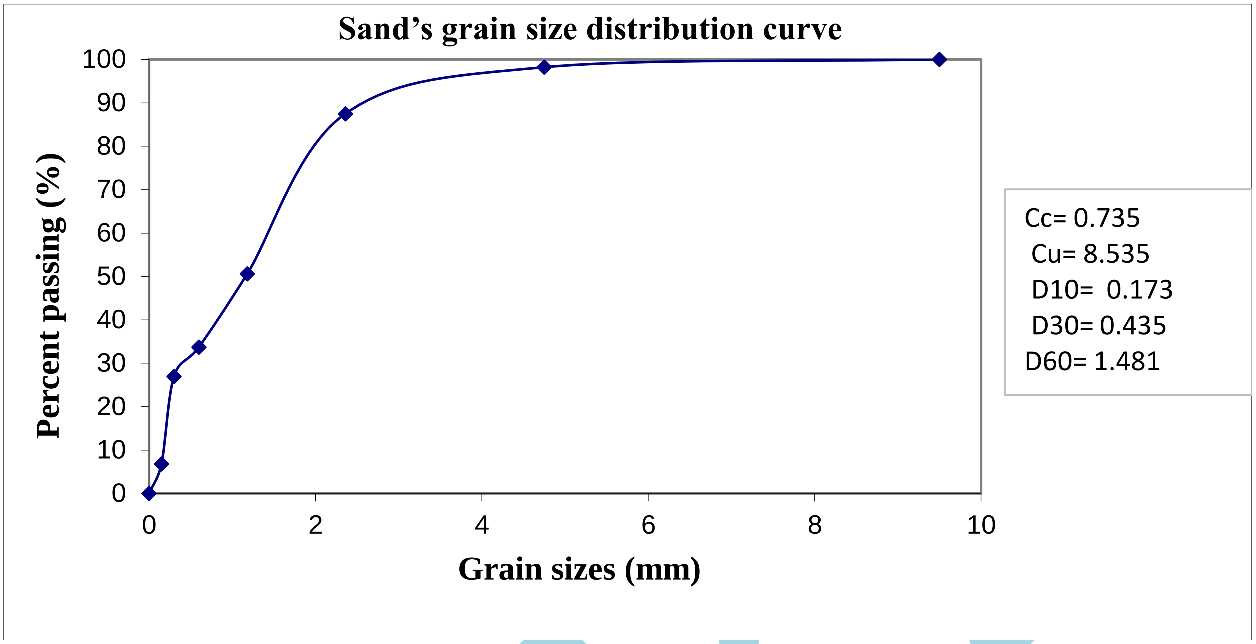

Figure 2. Grading Diagram of Used Sand

Table 1 shows the basic mix design used in this study. The first number in the first column refers to the percentage of cement, and the second number in that column refers to the percentage of geopolymer used to replace standard cement.

Table 1. Ccrete Mix Design

Label of Mix Design	Cement (Kg)	Water (Kg)	Coarse Aggregate (Kg)	Sand (Kg)	LECA (Kg)	Geopolymer (Kg)
C100-0	500	225	315	630	630	0
C90-10	450	225	315	630	630	50
C80-20	400	225	315	630	630	100
C70-30	350	225	315	630	630	150
C60-40	300	225	315	630	630	200
C50-50	250	225	315	630	630	250
C40-60	200	225	315	630	630	300
C30-70	150	225	315	630	630	350
C20-80	100	225	315	630	630	400
C10-90	50	225	315	630	630	450
C0-100	0	225	315	630	630	500

For example, in the case C20-80 in Table 1, 80% cement weight was replaced with geopolymer. In other words, 80% of the weight of adhesive materials was geopolymer and 20% was Portland cement Type II.

VI. METHODOLOGY

As mentioned earlier, this study investigated the effect of replacing cement with geopolymers. Compressive strengths of cubic samples were measured at 7 days and 28 days to determine the effect of geopolymer on concrete. The samples were made by mixing the dry components of the concrete for approximately 4 minutes, as shown in Figure 3. Then the chemical activator, potassium hydroxide, was added to the mix, followed by water. A day later, the samples were removed from the molds and cured in a water pond at 23 °C. Figures 3 and 4 illustrate material mixing and making and compacting the samples, respectively.

Figure 3. Mixing the Materials

Figure 4. Making the Samples and their Compaction

After the samples were cured, two 7-day tests and three 28-day samples were tested for compressive strength; results are presented in Table 2. Compressive strength values in the table are the average compressive strengths of the test pieces. In other words, the 7-day compressive strength of a sample is the average compressive strength of two tests, and that of a 28-day sample is the average compressive strength of three tests. Figure 5 shows a sample being tested for compressive strength.

Table 2. Compressive Strength of 7 & 28-Day Samples

Label of Mix Design	7-Day Strength (MPa)	28-Day Strength (MPa)
C100-0	14.8	23.2
C90-10	14.9	23.3
C80-20	15.6	23.3
C70-30	15.4	23.4
C60-40	15.8	23.6
C50-50	15.9	24
C40-60	17.0	24.4

C30-70	17.7	24.8
C20-80	17.8	25.5
C10-90	18.0	26
C0-100	18.2	27

Figure 5. The Sample is Tested for Compressive Strength

Figure 6 presents the compressive strengths of all the samples tested. As shown, increasing the percentage of geopolymer in the samples led to an increase in the samples' compressive strengths, although the increase was minimal in the sample with 40% geopolymer. In other words, increasing the amount of geopolymer and reducing the amount of cement in a sample increased the growth of compressive strength when their ratio was identical (C50-50) or the geopolymer proportion was higher than the proportion of cement.

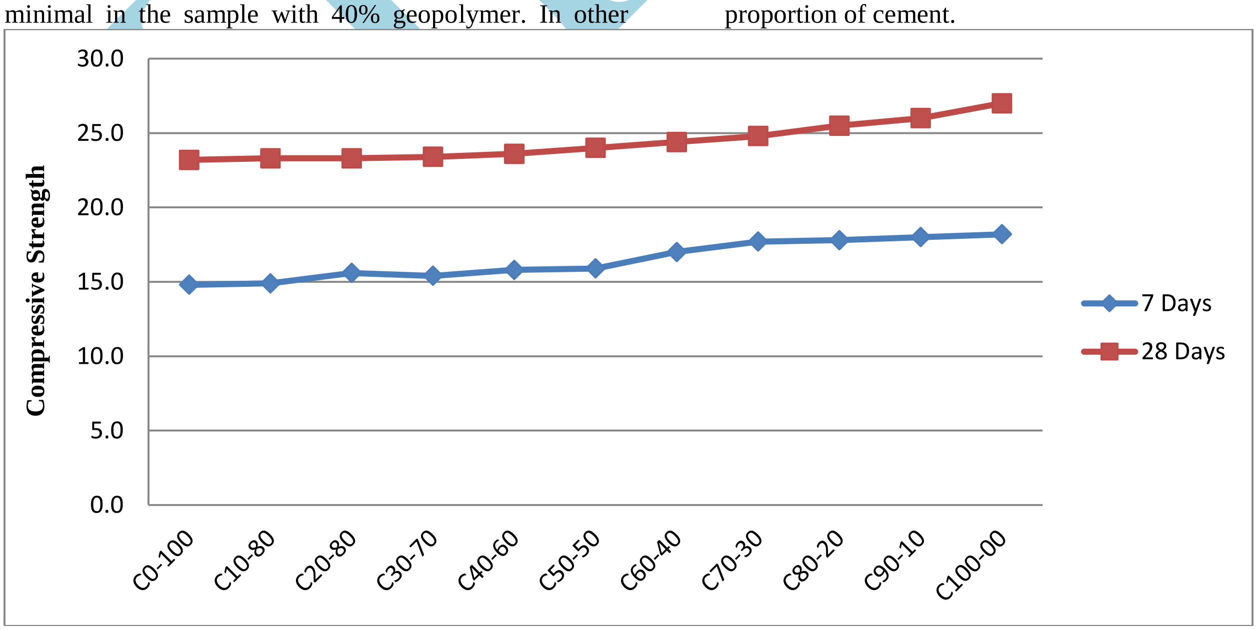

Figure 6. 7 & 28-day Compressive Strength of the Concrete Samples

The concrete temperature and concrete surface temperature were measured after the samples were poured into the molds. Results showed that increasing the percentage of geopolymers decreased the concrete temperature and the concrete surface temperature, possibly due to a lower hydration rate, thereby reducing the potential for surface cracking.

Table 3 shows the conversion of compressive strength ratio from 28 days to 7 days. Results showed the coefficient to be 0.64–0.71, with an average of 0.67 for concrete with cement and geopolymers.

Table 3. Coefficient of Compressive Strength Conversion from 28 Days to 7 Days

Label of Mix Design	Conversion Coefficient	Label of Mix Design	Conversion Coefficient
C100-0	0.64	C40-60	0.70
C90-10	0.64	C30-70	0.71
C80-20	0.67	C20-80	0.70
C70-30	0.66	C10-90	0.69
C60-40	0.67	C0-100	0.67
C50-50	0.66	----	----

VII. CONCLUSION

Recent research has discovered geopolymers to be an environmentally friendly alternative to fossil fuel-based cement. Geopolymers are comprised of industrial waste such as smelting slag, which increases their economic feasibility and environmental advantage. This study replaced Portland Type II cement with geopolymers and evaluated the effect of this replacement on the compressive strength of the concrete. Study results showed the following:

1. Increasing the percentage of geopolymers in the concrete increased the compressive strength of the samples.
2. Increasing the percentage of geopolymers to exceed the percentage of cement in concrete samples maximized the compressive strength of the samples.
3. Increasing the percentage of geopolymers in the concrete reduced the release of heat from hydration, thereby reducing cracking on the concrete surface.
4. The ratio of resistance conversion from 28 days to 7 days in the concrete samples was 0.67.

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