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Effect of High Calcium Precursor (HCP) Content on Bonding Strength of Geopolymer Concrete Exposed at Different Curing Temperatures

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ABSTRACT

Geopolymer is a green cementitious binder that can be used to replace Portland cement binder and possesses exceptional physical, mechanical, and durability properties. Its mechanical properties such as bonding strength against the substrate were comparable to the Portland cement based repair products which can provide high durability and adhesive strength to the repaired structure. Geopolymer comprises two primary components which are the precursor and alkali activator. High Calcium Precursor (HCP) is the new repair material that was developed by Innovation Construction Materials (INCOM) Research Group to be used as a geopolymer's precursor in Malaysia. In this research, the effect of HCP contents on the bonding strength of geopolymer concrete was assessed at different curing conditions. Based on the result, it found that 100 g of HCP gave an optimum bonding strength of 21.3 MPa after 28 days of normal curing. In addition, in this research, the bonding strength also was measured after the geopolymer/substrate composite was exposed at different temperatures (60, 80, and 100 °C). The bonding strength between HCP based geopolymer and the substrate does not significantly affected by the temperature's exposure.

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Hence, HCP showed a high potential to be used as a precursor for geopolymer production.

Keywords: Alkali Activator Content; High Calcium Precursor; Bonding Strength; Geopolymer Concrete

INTRODUCTION

Concrete has been widely used in the construction industry owing to its low cost and usability. Normal concrete mixture is composed of cement, water, and aggregates. When these elements are mixed, a strong and harder binder is produced that hardens and matured at 28 days of water curing. To suit the needs of the construction industry and for repair and rehabilitation purposes, a range of repair binders are now available. Geopolymer or known as alkali-activated materials is a recent technology that was introduced by Joseph Davidovits in 1979. Geopolymer is a chemical bond created by silica and alumina and activated by high alkali solutions such as sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate, and potassium silicate. Initially, geopolymer was used to recycle industrial waste such as kaolin, slag, bottom ash and fly ash which produced Pyrament and its associated cement blends. The objective of geopolymer optimization is to strengthen the properties and performance of the concrete, ensuring that the concrete design will last a long period. Geopolymer can be utilized similarly to OPC concrete in that it can be used as a repair material to remedy structural problems like cracking and deterioration.

Owing to the novelty of geopolymer concrete, few studies related to the properties and performance in different applications have been conducted [1-5]. Cement production has contributed to a substantial quantity of CO_2 emissions, leading to an exponential increase in the research and development of geopolymer [2]. Industrial by-product or agriculture waste can serve as the primary raw materials for geopolymers, which are synthesized through geopolymerization process with an alkaline or acid activation procedure [1]. Several precursors have been utilized in the production of geopolymer. First, fly ash which is industrial by-product from combustion of charcoal has been utilized widely in the geopolymer production. Class F and Class C are the two possible classifications for coal fly ash. The combustion of bituminous coal produces a type of fly ash known as class F fly ash (FFA), which contains a negligible amount of CaO [1]. As alternative energy sources, lignite and sub-bituminous coal are used to produce Class C fly ash (CFA) with a high calcium concentration [3]. Typical fly ash consists of microscopic spherical particulates and frequently used as a raw material for geopolymer production [4]. Blast Furnace Slag (BFS) is another type of geopolymer precursor. BFS is a by-product of the iron making process that can be produced at temperatures of approximately 1,500 °C [5]. BFS is also known as ground granulated blast furnace slag (GGBS) if it was chilled in water. Due to its hardness and pozzolanic activity, this type of slag is frequently used in place of Ordinary Portland Cement (OPC). When slag is substituted for cement, it generates less heat during hydration, thereby reducing the likelihood of a concrete structure fracturing [6].

Next, an alkali activator is a material that produces geopolymer. In the production of geopolymer concrete, the alkali activator is essential. Because the alkaline activator can facilitate the geopolymerization procedure. The activator aids in the dissolution of alumina and silica during the formation of three-dimensional sialate and poly(sialate) (Si-O-Al-O) chains [7]. Additionally, experimentally, BFS-based geopolymer concrete has greater strength than fly ash. This is because BFS reduces the concrete's water content, causing it to contract and lose its porosity. As a consequence, the strength of the concrete increases [8]. Due to its low cost and wide availability, sodium-based activators have typically been used in the production of geopolymers. The sodium-based activator, such as Sodium Hydroxide (NaOH), was crucial for dissolving Si^{4+} and Al^{3+} at the correct molarity and accelerating the geoplymerization process [9]. In order to accelerate the geopolymerization process, alkaline activator solutions are frequently employed. Sodium silicate solution (Na_2SiO_3) is one example of an alkali activator solution. In terms of concrete strength, the combination of sodium silicate and sodium hydroxide outperformed sodium hydroxide and sodium silicate throughout the entire curing period [10]. Lastly, the principal function of geopolymer concrete is as a repair material. According to Yodsudjai et al.,[11], the 28 days tensile strength of geopolymer concrete repair is equivalent to that of commercial concrete patching materials. This material may be utilized to repair concrete [11].

The objective of this study is to analyse the effect of the different High Precursor Calcium (HCP) content on the bonding strength of geopolymer concrete and determine the optimum curing temperature of geopolymer based on bonding strength. The bonding strength of geopolymer concrete in the presence of High Calcium Precursors (HCPs) when subjected to various curing temperatures was evaluated. The scope of this project will be divided into four stages where the material used, sample preparation, testing of geopolymer and standard use in this research.

EXPERIMENTAL DETAILS

Preparation of High Calcium Precursor (HCP)

For the preparation of HCP based geopolymer concrete, the material was mixed with the FILGAP and fine aggregates to produce mortar. The production of the mortar is important to cope with the strength test of the research which is the bonding strength test. Additionally, to carry out the bonding strength test, the geopolymer mortar was filled in the steel prism where the other half of the prism was filled with Asphaltic concrete. The sample after the moulding process was left to dry and cure at a controlled room temperature (27.0 °C).

Preparation of FILGAP

The FILGAP was a new product developed by the Innovation Constructions Material (INCOM) Research Group which was the main supplier for this research. Table 1 shows the chemical composition of FILGAP.

Table 1: Chemical Composition of FILGAP

Chemical Composition	FILGAP (%)
NaOH	15
Na_2SiO_3	38
H_2O	46
Others	1

Aggregate

The fine aggregate used in this research was sand. Sand has been used due to its lower cost and nature. The sand was a quart of river sand, and it is used to produce a geopolymer mortar when mixed with the HCP and alkali activator. The size will be determined from the particle size distribution sieve (PSD) which requires the sand to go through the size of 150 µm, 300 µm, 600 µm, 1.18 mm, 2.36 mm, 4.75 mm, and 9.5 mm sieve set. The PSD as shown in Figure 1 was conducted by referring to the ASTM C33. Based on the ASTM C33, the size required for the sand to be mixed in the mixture are range from 150 µm and 9.5 mm. Additionally, the sand was submerged in clean tap water and was left to dry on the plastic sheet to avoid the sand from absorbing the alkali solution during the mixing process.

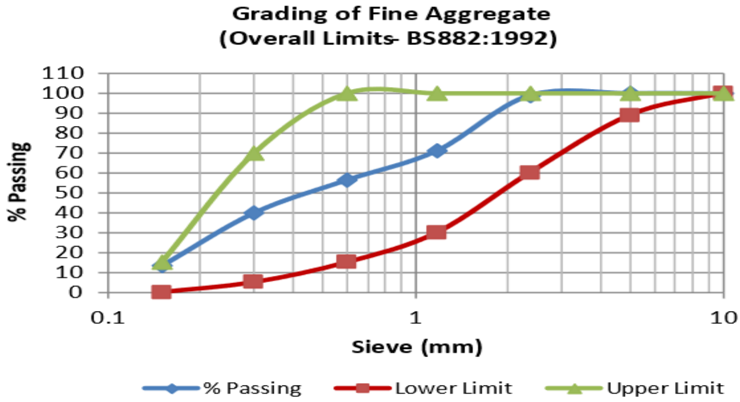

Figure 1: Particle Size Distribution of fine aggregates

Preparation of Asphaltic Concrete Substrate

For the bonding strength test, Asphaltic concrete (AC) substrate was needed to fill the other half of the steel cube mould. In this research, the type of Asphaltic concrete used was bitumen. The type of bitumen used in this research is cold-mixed asphalt. Where there was no need to prepare for its mix. The amount of bitumen used was 100 g for every sample. The finished product (hardened state) of the Asphaltic concrete was attached to the geopolymer mortar and next, the bonding strength test was conducted.

Mix Proportion

In this research study, initially, to begin the research, Sodium Hydroxide (NaOH) was mixed with HCP to produce geopolymer paste. Then, the mixed solution was added with sand and Sodium Silicate (Na_2SiO_3) to produce the geopolymer mortar in order to cope with the bonding strength test. The addition of small gravel is needed to prepare the Asphaltic concrete substrate. The proportion of the material used in the mixing process was shown in Table 2. Additionally, the value of the mix proportion was chosen based on the trial-and-error method.

Table 2. Mixing Proportion of the Sample

Mix	High Calcium Precursor (HCP) (g)	Sand (g)	Gravel(g)	FILGAP (g)	Water (g)
1	100	200	200	75	15
2	90	200	200	75	15
3	80	200	200	75	15
4	70	200	200	75	15
5	60	200	200	75	15
6	50	200	200	75	15

Sample preparation and testing

Slant Shear Test

Referring to ASTM C882, the combination of geopolymer mortar and Asphaltic Concrete (AC) substrate was used to determine the bonding strength. The combination of the sample was filled with half of the geopolymer mortar and AC substrate in (50 mm × 50 mm × 50 mm) volume steel cube mould and it was placed stacked on each other (Geopolymer mortar and Asphaltic Concrete) for every sample. An example of the combination of both specimens is shown in Figure 2.

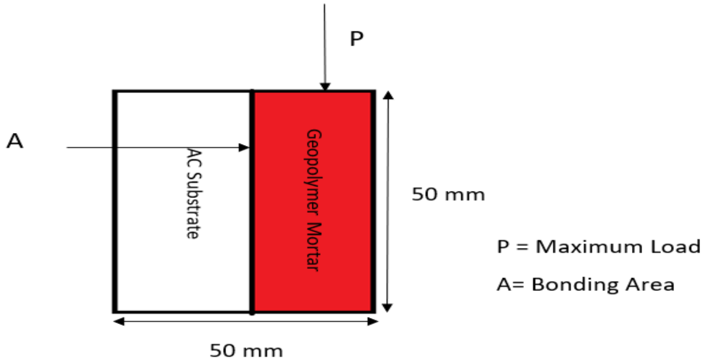

Figure 2: Schematic Diagram of Testing

The pacing loading rate at 0.5 MPa/second was used in this experiment. Then, the average reading from the three specimens from each HCP mix was jotted down. The bonding strength can be calculated as the formula shown in Equation (1):

$$S = \frac{P}{A} \tag{1}$$

Where S= Bonding Strength P= Maximum Load and A= Bonding Area

RESULTS & DISCUSSION

The six different HCP mixes had been chosen in this research which varied in HCP contents. Figure 3 shows the bonding strength of different HCP content. aAccordingly, Mix 1 has the highest strength compared to other samples. This is due to its HCP content which was 100 grams/sample that was optimum to prepare the sample. The trend of Figure 3 was decreasing following the decrease of HCP content by 10 %.

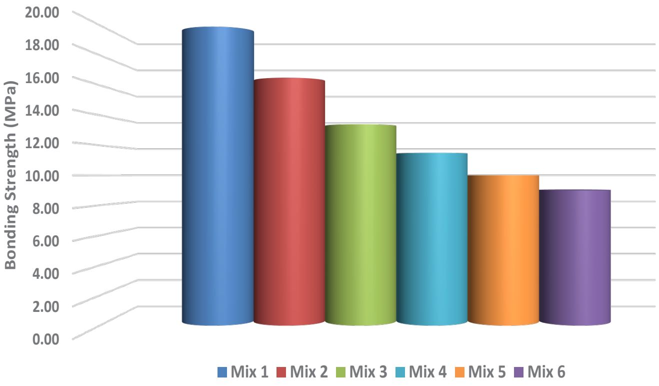

Figure 3: Bonding Strength based on different HCP content

This occurs due to the mix that has high HCP content will have a higher geopolymerization rate that will affect the increase of bonding strength. Additionally, from this research, we also can observe the failure mode of the concrete after being tested. Failure mode in this research was observed based on cracks that occur after the concrete was tested. Table 2 shows the type of failure mode.

Table 2: Failure Mode of Concrete

Type of Failure Mode	Description
A	Crack at the Geopolymer Mortar
B	Crack at the Bonding Area
C	Crack at the Asphaltic Concrete

Based on Figure 4 to 6 and Table 3, it shows the failure mode of the sample. Mix 1 shows fewer cracks in its sample whereas only one sample has failure mode A which is a crack in the geopolymer mortar. Based on the observation, this sample indicates the highest bonding strength due to the high content of HCP in it. Next, for mix 3, it shows failure mode was type C where it has a crack in the asphaltic concrete. This failure occurs due to the less content of HCP in it. Less amount of HCP content resulting in a low value of bonding strength due to the HCP mix did not fully fill the Asphaltic concrete part hence producing a huge amount of void in the bitumen structure. Finally, in mix 6, it can see two types of failure modes occur in its sample which were type A and B. The main reason for this type of failure occurring is due to the lowest amount of HCP content which results in the lowest bonding strength. Other than that, for mix 6, even the HCP had filled the bitumen void as in mix 1 but due to the unbalanced ratio between the HCP and the water, this had caused low stability to the structure hence resulting in low bonding strength. Therefore, it can be concluded that higher HCP content will lead to higher bonding strength of concrete.

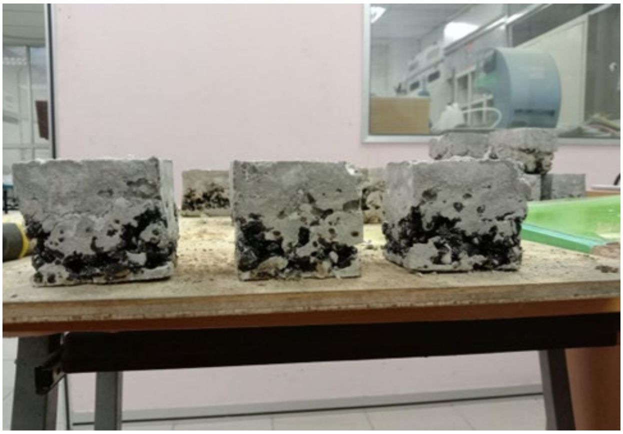

Figure 4: Failure Mode A (Mix 1)

Figure 5: Failure Mode C (Mix 3)

Figure 6: Failure Mode A & B (Mix 6)

Table 3: Type of failure mode for the six mixes based on different HCP content.

Mix	Type of Failure Mode
1	A
2	A
3	C
4	C
5	B
6	A & B

Bonding Strength Analysis Based on Different Curing Temperature

Since Mix 1 had the highest bonding strength among all the mixes, mix 1 was cured in different curing temperatures to obtain the optimum heat curing temperature. Figure 7 shows the bonding strength of Mix 1 which undergoes different curing temperatures which are 60, 80 and 100 ^{0}C. The days of curing were fixed where it is between one and three days.

Based on Figure 7, we can state that 60 ^{0}C was the optimum heat curing temperature in this research. The trend from Figure 7, was declining following the increase of temperature. This can be supported by the research made by Tan & Liu [12] which states that "curing concrete at a high temperature of 65 °C for 6 h has a detrimental effect since the strength of the concrete at maturity is much lower than it would be under normal curing conditions". The main reason for the declining bonding strength trend to occur is due to high curing temperature rapidly increasing the rate of hydration which could result in the formation of loose structure at the early stage of strength development and hence will lead to the lower bonding strength of concrete compared to normal curing. This statement can be referred to in the figure below which shows the physical appearance of the sample after being cured in different curing temperatures.

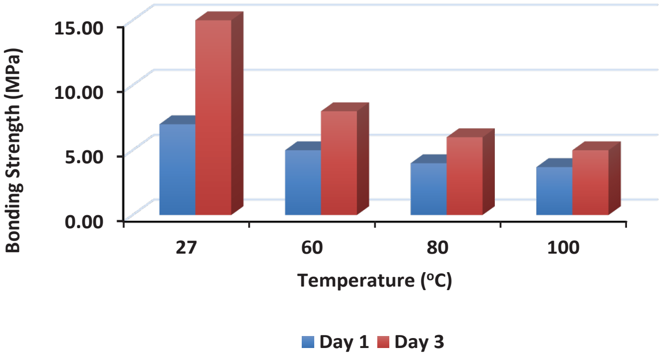

Figure 7: Bonding Strength Based on Different Curing Temperatures

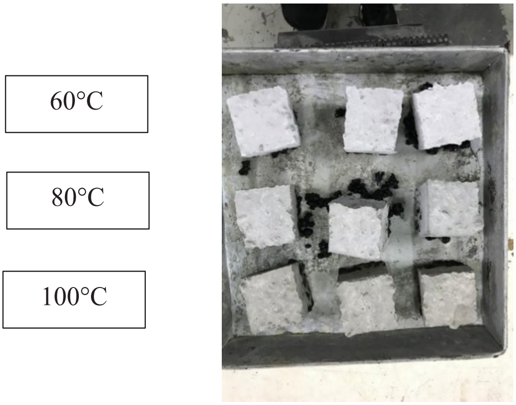

Figure 8: Physical Appearance of the Sample

Based on Figure 8, we can observe the physical colour of the sample after they were cured in curing temperatures. The sample that was cured at 100 °C of curing temperature had a slightly darker physical colour than other curing temperatures which indicates a high hydration rate occurred. The effect of a high hydration rate occurring in high curing temperature also can be seen in the figures below:

(a) (b) (c)

Figure 9: Curing at (a) 60 °C, (b) 80 °C and (c)100 °C

Figure 9 shows the image of geopolymer concreate after testing. We can observe that the bitumen attachment of the sample that had been through 100 °C of heat curing had completely ripped off compared to other samples which shows the low bonding strength because of high in temperature. The sample from 60 °C of heat curing shows less of a crack on its sample which shows the good attachment between the concrete and bitumen hence resulting in the highest bonding strength.

CONCLUSIONS

Based on the findings, Mix 1 which contains 100 g of HCP tends to provide the highest value of bonding strength which is 21.3 MPa. Additionally, the trend of bonding strength value was decreasing following the reduction of HCP content by 10 %. According to the data obtained, the main reason for the highest HCP content having the highest bonding strength is the geopolymerization rate. The geopolymerization process increases the development of concrete strength rapidly and it depends on the Geopolymer binder content. Hence, it is safe to say that the higher the HCP content the higher the concrete bonding strength. Since Mix 1 had the highest bonding strength based on the previous objective, hence it was cured for one and three days in different curing temperatures which were 60, 80 and 100 ⁰C. Based on the finding, it was found that 60 ⁰C provides the highest bonding when it was cured for about one and three days which are 32.26 MPa and 34.46 MPa, respectively. The trend of the data also shows the decreasing of bonding strength value following the increase of curing temperature. Referring to the resulting trend, the main reason for this to happen is due to the high curing temperature tending to increase the hydration rate of the concrete hence producing a loose structure resulting in lower bonding strength. Additionally, a rapid increase in the hydration rate cause unstable concrete particle distribution hence resulting in most of its particles to accumulated and finally causing an unstable structure. A low hydration rate is really important to ensure the development of the early strength of the concrete. Therefore, it can be concluded that the higher the curing temperature the lower the bonding strength of geopolymer concrete.

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