Factors affect the bond strength of Geopolymer repair material: Review

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Abstract: One of the most important construction activities worldwide is the repair and rehabilitation of damaged concrete structures. Many concrete structures are decaying, sometimes early, and need remediation to restore their protection and serviceability. As a result, in recent years the need for repair and safety has increased dramatically. This paper reviewed some studies about the potential for geopolymer to be used as a repair material and highlighted the main factors effect bond strength between GP and OPCC. The bond strength of GP was assessed using splitting tensile test and slant shear test. The results of bond strength indicated that this form of GP could be employed as a potential repair material.

1. Introduction
Geopolymers are ceramic-like inorganic polymers, usually manufactured at low temperatures below 100 °C. These materials consist of mineral molecular chains or networks connected by covalent bonds. The raw materials are predominantly geologically based minerals and hence the term "geopolymer" [1]. The continued depletion of the ozone layer and the issue of global warming have caused the construction industry to become more environmentally aware in recent years, resulting in the use of more environmentally sustainable building materials. Under this context, geopolymer concrete has acquired considerable interest from research scholars and building practitioners, Because of its benefit in the use of by-product waste to replace cement as well as due to the reduced greenhouse gas emissions during its production [2].
The geopolymeric systems consists of two phases: the solid phase and the aqueous one which is called the activator. The solid phase consist of an aluminosilicate material, that have easily dissolved aluminum and silicon in a strongly alkaline solution. A wide range of solid aluminosilicate raw materials can be employed for geopolymer synthesis. Among the possible raw materials of solid aluminosilicates, industrial minerals such as, feldspars, kaoline, perlite, bentonite and so on, as well as solid industrial by-products, such as, alumina red mud, fired-coal fly ash, metallurgical slag tailings from bentonite and perlite exploitation, , etc. are the primary raw materials. The raw materials used to make geopolymer are determined by a variety of factors, including the application type, supply, cost, and end-user demand. On the other hand, the liquid phase is strong alkaline solution which is mainly composed of alkalis of sodium or potassium and water glass[3,4]
Concrete repair primarily entails removing faulty concrete and replacing it with appropriate repair or overlay material. The most important requirement for any kind of repair system is that it keep a strong bond between the concrete substrate and the overlay throughout its service life. It is also important that
the bond has sufficient strength to withstand stresses caused by mechanical loading and thermal effects while also providing extended service life efficiency[5]. Several deteriorated concrete structures around us are in desperate need of repair or rehabilitation. The interface region that exist between repairing material (RM ) and the OPCC substrate is referred to as interphase, which is the weakest area in the relationship between RM and this substrate. In the engineering industry, such materials are often used to patch wider cracks, defective sections, or gaps in concrete, as well as to return the affected concrete surface to its original appearance [6,7].

2. Techniques for testing bond strength.

Bond tests were conducted for determining the strength of the bond between the geopolymer and the OPCC. In recent studies, different sources of GP were used, including metakaolin (MK), granulated ground blast furnace slag (GGBFS), fly ash (FA) etc... These materials can yield promising bond strength results for partial or full replacement [8]. To use geopolymer as a repair material, the bond strength between the repairing material and existing concrete, which considered one of the most important variables affecting repair reliability, must be assessed using a several tests such as the splitting tensile test and slant shear test. [6,9].

The slant shear test method, based on the standard ASTM C 882 test procedure for repair material selection for durable concrete repair, is a widely used test technique for determining the bond strength of repair materials. The interface is exposed to both compressive and shear stress states in the SST, as shown in Figure.1, resulting in a stress distribution at the interface that is relatively uniform. The SST is commonly used due to the testing setup's ease of use and the test's high sensitivity to variations in influencing parameters such as specimen geometry (angle of shear plane and cross section height/width ratio); casting procedure; surface roughness; and use of a bonding agent at the interface. [10,11]

![Figure 1: Test set up of slant shear specimens](image)

This test method has been the most commonly known method over the year, and many international codes have followed it. The slant shear strength was determined by divided the maximum load by the bonding region, that can be stated in the following way::

\[
S = \frac{P}{AL} \tag{1}
\]

Where:
S: represent the bond strength (in MPa); while P is referred to the maximum load (in Kn) and A_L is the the slant surface area(in mm²) [13].

The split tensile test is a systematic procedure for determining the tensile strength of cylindrical specimens, and has been used to calculate the strength of the bond between concrete and GP based on ASTM C496 standard.

The quality of a bond is assessed based on the value of the bond strength obtained during testing and the failure mode. The quantitative bond quality is presented in Table 1. Equation (2) was employed to determine the split tensile strength, as shown in Figure.2 [7, 9].
where:
\[ T = \frac{2F}{\pi L d} \]  

Table 1: Explain the quality of bond strength [9]

| Bond strength, MPa | Quality   |
|-------------------|----------|
| \( \geq 2.1 \)    | Excellent|
| 1.7 to 2.1        | Very good|
| 1.4 to 1.7        | Good     |
| 0.7 to 1.4        | Fair     |
| 0 to 0.7          | Poor     |

3. Concrete - Geopolymer interface

Table 2: Summary of bond strength of GP from previous studies.

| Author | GP type          | Repair angle ° | Max Slant shear | Max Splitting tensile strength |
|--------|------------------|----------------|-----------------|------------------------------|
| [17]   | FA* based GP cement | 30             | 11              | -                            |
| [12]   | HCFA* based GP cement | 45             | 24.2            | -                            |
| [18]   | FA based GP cement | 30             | 20.1            | -                            |
| [7]    | GBFS* based GP cement | 45             | 36.9            | 27.3                         | 1.97 |
4. Parameters controlling the bond strength

The bond strength of geopolymer are effected by many factors which summarized as follow:

4.1 NaOH concentration

NaOH concentration significantly affects the setting time, bonding strength, and compressive strength of geopolymers. However, a study performed by [17] investigate effect of using different NaOH concentrations on the setting time, compressive strength in addition to the bond strength between FA based GP paste and (OPC) concrete. The study found that a shorter setting period is associated with a higher molarity of NaOH. However, the authors also concluded that a dense and compacted interface are obtained when the NaOH concentration was 12 M as shown in Figure 4.

4.2 Surface pretreatment

Mechanical treatment of the substrate surface were not influenced significantly on the adhesive strength of GP. Pacheco-Torgal et al. [15] Studied potential use of Tungsten mine waste mud (TMWM) based GP as a repair material of OPC concrete and compared its strength with two commercial repair products. In this study the surface of concrete substrate were treated with four kind of treatment namely, as cast against wood formwork, saw cut, as cast against metallic formwork, and acid etching. A high bond strength was achieved with TMWM geopolymeric binders in which this behavior was not influenced by low surface treatment roughness, while on the other hand, Commercial repair products exhibited low bond strength.
strength and their behavior were strongly depend on the roughness of surface treatment. Another study by Zailani et al. [18] investigate the effect of mechanical treated of OPCC surface on bond strength of GP, by which the authors employed three methods to prepare concrete substrate surface: wire-brushed, with drilled holes, and left as-cast. The results found that GP offer a high bonding strength and this behavior was not greatly influenced by roughness of concrete substrate by which a slight difference in bond strength were obtained between the three methods of treated OPCC surface as shown in Figure.5. The presence of (Ca(OH)$_2$) on the OPCC substrate surface, which is rich in (Ca$^{2+}$), reacted with the GP; leading to formation of $\text{C-A-S-H}$ at GP - OPCC interface.

**Figure 4.** SEM images of the interface area with; (a) 8 M, (b) 10 M, (c) 12 M, (d) 14 M.

4.3 Effect of additive

Wen-Ten Kuo et al. [7] used FA/ GGBFS geopolymer as the repair material for OPC concrete. The bond strength of the GP was investigated with different addition ratio of flyash of 0%, 10%, 20%, and 30% and with liquid/ solid L/S ratios of 0.4 and 0.5. The results detected that by increasing L/S ratio from 0.4 to 0.5, the bond strength of GP decreased, in which the split tensile strength results reduced from 1.97 MPa to 1.87 MPa as well as the slant shear strength decreased from 36.9 MPa to 33.8 MPa, however, the optimum fly ash ratio achieved which has a noticeable effect on the bond strength was 10%.

**Figure 5.** Bonding strengths of GP with different OPCC surface preparations.
Phoon-ngernkham et al. [19] investigate the effect of adding a different ratio of nano-SiO$_2$ and nano-Al$_2$O$_3$ particles on the bond strength of HCFL based GP pastes. These particles were added at the ratios of 0, 1, 2, and 3% by weight. The results indicated that the bond strength of GP enhanced with addition of both nano-SiO$_2$ and nano-Al$_2$O$_3$. The maximum shear bond strength was obtained with 1% nano-SiO$_2$ and 2% nano-Al$_2$O$_3$ at 45° shear angle were 23.36 and 20.61 MPa, respectively in comparing with 10.73 MPa for the control specimen as shown in Figure.6.

Figure.6 bond strength results of GP with different addition ratio of nano SiO$_2$ and Al$_2$O$_3$ particles.

Tanakorn et al. [12] studied the influence of using sodium hydroxide concentrations and ordinary Portland cement OPC with different dosages on the properties of high calcium fly ash geopolymer mortars (GPM) for use as repair material. The results showed that the optimum NaOH concentration was 14 M and the addition ratio of 10 % OPC yield highest shear bond strength of 24.2 MPa for GPM.

Ghasan F. et al. [6] investigated the effect of adding different ratios of metakaolin, Na$_2$O:dry binder and SiO$_2$:Na$_2$O, on bond strength of granulated blast furnace slag based geopolymer mortar for potential repair applications. GPM prepared with 5 mass% of MK, 8% of Na$_2$O:dry binder and 1.16 of SiO$_2$:Na$_2$O exhibited the highest slant shear strength with a contact angle 45° of (9.9 and 22.4 MPa) at 1 day and 28 days, respectively as shown in Figure.7. On the other hand, the max. splitting tensile strength achieved was > 5 MPa (see Figure.8), and after 24 h, the splitting strength was 2.95 MPa which was about ten times greater than that of OPC mortar (0.32 MPa).

Figure.7 show the slant shear strength of GPM at angle of 45°[6].
Laskar et al. [20] studied the effect of fly ash and superplasticizer (SP) on the bond strength of ultra-fine blast furnace slag-based geopolymer concrete UGGBS. The researchers discovered that the strength of UGGBS after one day was around 60% of its strength after 28 days. Amounts of FA in the mixes greater than 30% produced a noticeable and consistent drop in bond strength. Bond efficiency improved in the mixes when a certain amount of PE-based SP was added. A mix containing 0.5 percent PE-based SP yielded the highest bond strength. Amounts greater than this improved workability but diminished bond strength.

4.4 Effect of aggressive environments

Hani Alanazi et al. [9] investigated the possibility of using MK-based geopolymer mortar as a repair material under various aggressive conditions. The authors found an excellent bond strength between GPM and cement mortar substrate without soaking in the acid. However, a fair bond strength was obtained after soaking for 24 h and three days, while the bond strength after 5 five days soaking is Poor as shown in Figure 9 dependent on the quality of bond strength described in Table 1. The slant shear test results with a repair angle of 30° was 15.6 MPa while for repair angle of 45° was 42.2 MPa. Meanwhile, After 3 days of curing, MK-based GPM achieves 80% of its 28-day strength as shown in Figure 10, and the splitting tensile strength was about 3.63 MPa.

Figure 8: Illustrates the splitting tensile strength of GPM compared to OPC mortar [6].

Figure 9: The bond strength results between GPM and cement mortar under different deterioration time.
Conclusion
This paper reviewed several studies about the use of geopolymer cement, mortar and concrete as a repair material. However various factors influence on the bond strength between GP and OPCC include NaOH concentration, the effect of adding flyash, MK, OPC and nano materials with a certain percentage has also a significant effect in enhancing the bond strength of GP. Meanwhile, The efficiency of such material to achieve a high bond strength even at early age showed their ability to be used as a potential repair material.

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