Modified geopolymer paste adhesive bond material for near surface mounted strengthening technique

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Abstract. Near surface mounted (NSM) is a promising strengthening technique for improving the flexural, shear and torsional strength of structures. Epoxy is the adhesive material used in this technique, but, the rapid failure happened in the mechanical properties of the epoxy matrix at high temperature, and the dangerous effects of epoxy fumes on the workers made the need of replacing epoxy with a new sustainable adhesive. Geopolymer Paste Adhesive and Modified Geopolymer Paste Adhesive were used in this study as adhesive materials in NSM strengthening technique to be an alternative to epoxy, where the geopolymer is a sustainable, environmentally friendly and less expensive material than epoxy. More importantly, it can better work at high temperatures. The test results showed that the modified geopolymer paste adhesive beat the epoxy adhesive by (4.1)% when adding (1)% micro steel fiber and (9.6)% when adding (0.6)% carbon fiber, while the bond strength reaches to (93)% of epoxy adhesive when adding (0.6)% polypropylene fiber.

1. Introduction
One of the important strengthening techniques is NSM technique for the strengthening and rehabilitate of Reinforced Concrete (RC) structures using epoxy adhesive. Epoxy is an adhesive material used in strengthening techniques, but this adhesive loses its mechanical properties at high temperatures [1],[2], and it also has some dangerous effects on the workers. Therefore, there is an increasing need to replace this adhesive with a new material. Geopolymer is a sustainable material having high mechanical properties [3],[4]. In a previous study using Geopolymer Paste Adhesive (GPA) as an adhesive in NSM technique, the pull out test results for strengthening prism GPA showed bond strength equals to (70) % of epoxy adhesive [5]. Fibers are short separated materials that are added to (mortars and concretes) to improve their mechanical properties [6]. There are several types of fibers such as steel fibers, carbon fibers, polypropylene fibers and natural fibers. Each type can be used according to different controlling parameters, like price, availability of the material and its function. Fibers are used to improve bond strength, develop compressive, tensile and rupture strength, control cracking due to drying and plastic shrinkage and reduce the permeability of concrete [7],[8].
This paper presents the first study aimed to reach the efficiency of epoxy bond strength, by adding different types and dosages of fibers to geopolymer paste adhesive.
2. Materials

2.1. Fly ash
Fly Ash (FA) is a fine powder, which is resulting from coal combustion during the production of electricity in a power station as a minor product, FA was classified to class-F and class-C according to (ASTM C618-08, 2012) [9],[10], the chemical composition of this material depends on the mineral composition of the source, but all FA contents silicon dioxide (SiO2), aluminum oxide (Al2O3), calcium oxide (CaO) and iron oxide (Fe2O3). Sodium, magnesium, potassium, sulfur and titanium also exist in lesser amounts.

2.2. Nano-silica
Nano-Silica (NS) is one of the common mineral admixtures to improve mechanical properties by accelerating chemical reactions. It has been added to get a mixture working at room temperature.

2.3. Sodium hydroxide
Sodium hydroxide (NaOH) flacks with (98%) purity. It has been used to produce NaOH solution. The reaction between sodium hydroxide and water was exothermic, therefore; it should be careful when using this material especially during the mix.

2.4. Sodium silicate
Sodium silicate (Na2SiO3) was manufactured in local chemical supplier, the concentration of Na2SiO3 is depending on the ratio of Na2O to SiO2 and H2O.

2.5. Fibers
Different types of fibers were selected and added to the mixes in different content to improve the mechanical properties:

2.5.1. Micro steel fiber
Steel fiber is one of the most common types of fiber used to improve concrete properties, especially shear, flexural, impact and fatigue strength. Micro steel fiber was used in this study for proper dimensions of the groove. Its length was (6mm) and aspect ratio (30 approximate), tensile strength equal to (2500MPa), young's modulus (200GPa) and density (7850kg/m3).

2.5.2. Carbon fiber
Carbon fibers have many advantages including: low weight, low thermal expansion, high tensile strength and high chemical resistance. These properties have made carbon fiber so popular in civil engineering. In this study, carbon fiber length was (8mm), diameter (7±2 micron), aspect ratio (1140), tensile strength (3500 MPa), young's modulus (230 GPa) and its density (1.75 g/cm3).

2.5.3. Polypropylene fiber
Polypropylene fiber is an artificial type, and it's gradually replacing the other types of fibers because it has the lowest cost of all commercial fibers and there is no risk of corrosion when used in concrete. Polypropylene fiber has low thermal conductivity, excellent chemical resistance to acid and alkalis and high abrasion resistance. Polypropylene fibers used in this study have (12mm) length, diameter (20±2 micron), aspect ratio (600), tensile strength (300-400 MPa), and its specific gravity (0.91 g/cm3). Figure (1) shows the materials used in this study.
3. Experimental program

3.1. Casting and curing of concrete prisms

Normal concrete prisms were prepared, after trial of some experimental mixtures to reach the desired compressive strength of concrete based. Then casting prisms specimens (75 * 75 * 250 mm³) and curing in water for (28 days), figure 2 shows the dimension details for specimen and groove according to previous study [5].

![Figure 1. Materials used in this study.](image)

![Figure 2. Concrete prism, (a) Specimen details and (b) Section a-a.](image)
3.2. **Modified geopolymer paste adhesive**

To reach the efficiency of epoxy bond strength, geopolymer paste adhesive used in the previous study [5] was modified by adding different types of fiber. Eleven mixes of MGPA prepared under three groups, the first group by adding (0% to 2% by increment 0.5%) dosage of micro steel fiber, the second group adding (0% to 0.6% by increment 0.2%) dosage of carbon fiber and the third group adding (0% to 0.6% by increment 0.2%) dosage of polypropylene fiber. The mix proportions are given in table 1, the mixes in the table were named according to the added proportion of fiber used in the mix.

The alkaline solution was prepared and NS was mixing with the alkaline solution [3]. Then putting weighted fly ash in the mixer and addition of the solution with NS and mixing it for three minutes. The required dosage of fiber was adding into the mix and mixing it for five minutes [11]. Six cubes (50*50*50 mm), six cylinders (diameter 50* height 100 mm) and three prisms (40*40*160 mm) were taking from each MGPA mix in order to obtain the mechanical properties of each mix, whereas, these specimens were tested at the age 7 and 28 days accordance with the ASTM C109 standard [12].

| Groups           | Mixes            | Binder (%) | Fiber (%) | Percent of volume | F/B |
|------------------|------------------|------------|-----------|-------------------|-----|
|                  |                  | FA  | NS  | SF (a) | CF (b) | PPF (c) |     |
| Reference        | 0SF-0CF-0PP      | 99.2| 0.8 | 0.0    | 0.0    | 0.0     | 0.42|
| Group1 (MGPA SF) | 0.5SF-0CF-0PP    | 99.2| 0.8 | 0.5    | 0.0    | 0.0     | 0.42|
|                  | 1.0SF-0CF-0PP    | 99.2| 0.8 | 1.0    | 0.0    | 0.0     | 0.42|
|                  | 1.5SF-0CF-0PP    | 99.2| 0.8 | 1.5    | 0.0    | 0.0     | 0.42|
|                  | 2.0SF-0CF-0PP    | 99.2| 0.8 | 2.0    | 0.0    | 0.0     | 0.42|
| Group2 (MGPA CF) | 0SF-0.2CF-0PP    | 99.2| 0.8 | 0.0    | 0.2    | 0.0     | 0.42|
|                  | 0SF-0.4CF-0PP    | 99.2| 0.8 | 0.0    | 0.4    | 0.0     | 0.42|
|                  | 0SF-0.6CF-0PP    | 99.2| 0.8 | 0.0    | 0.6    | 0.0     | 0.42|
|                  | 0SF-0CF-0.2PP    | 99.2| 0.8 | 0.0    | 0.0    | 0.0     | 0.42|
| Group3 (MGPA PF)| 0SF-0CF-0.4PP    | 99.2| 0.8 | 0.0    | 0.0    | 0.2     | 0.42|
|                  | 0SF-0CF-0.6PP    | 99.2| 0.8 | 0.0    | 0.0    | 0.4     | 0.42|

(a) SF: Micro steel fiber.
(b) CF: Carbon fiber.
(c) PPF: Polypropylene fiber.
(d) MGPA SF: Modified geopolymer paste adhesive was named according to the type of fiber added.

3.3. **Apply of NSM-technique in prisms specimens**

After getting the optimum MGPA, apply it in the NSM technique to evaluate the bond strength. A groove in the surface of each prism was cut in the longitudinal direction by using cutting machine. Then, the grooves were cleaned well by pressed water and then dried. The grooves are partially filled with the MGPA, and then pressed the bars in groove, and the remaining of the groove is filled with MGPA, after that the surface is leveling. The specimens were put in isolated bags during curing period and cured in room temperature (35 ± 2)°C, Figure 3 shows the stage of works. After that applied single lap shear test for specimens and compared the results with the epoxy adhesive using to strengthen prisms by NSM in our previous study [5].
4. Results and Discussions

4.1. Fresh properties of modified geopolymer paste adhesive

4.1.1. Flowability
Flow table test was made on fresh MGPA immediately after mixing [13]. There was a significant decrease in the paste flowability with the adding of carbon and polypropylene fibers, that’s due to the shape of fiber and the small diameter (high surface area) made it absorbed the water from mixture. Also, a decrease in flowability with the addition of micro steel fiber but it's less than the other types of fiber because the steel fiber diameter is larger than carbon and polypropylene fiber (less surface area).

4.1.2. Fresh density
The fresh density of the mixture changes with the addition of fiber because the fiber will remove part of the mixture and take its place. Fresh density increases with the addition of micro steel fiber because the density of the steel is very high up to (7800 kg/m³) and decrease with the addition of other types because of its low weight and density, which is less than the density of the mixture (equal to 1750 kg/m3 and 910 kg/m3 for carbon and polypropylene fiber), respectively [14]. The fresh properties of the MGPA show in table 2.
4.2. Hardened properties of modified geopolymer paste adhesive

Hardened properties of MGPA represented the compressive strength, the splitting tensile strength and the modulus of rupture. The hardened properties of MGPA are showing in the table 3.

### 4.2.1. Compressive strength

Compressive strength at (7 and 28) days was tested for (50*50*50 mm³) cubes [15]. The results of this test showed slight development in compressive strength with adding different proportions of fibers. The highest increase was shown at dosage (1%) of micro steel fiber, and (0.6%) in carbon and polypropylene fibers. It's higher than the reference mix by (5%, 8.3%, and 8.1%) for optimum (micro steel fiber, carbon fiber, and polypropylene fiber), respectively. For (group1), dropping happened in the strength when adding micro steel fiber more than (1%) due to the decrease of the bond material about steel fiber causing weakness in the matrix. While (group2) and (group3), the compressive strength continues to increase. We were stopped at (0.6%) proportion of carbon and polypropylene fibers; because the matrix became stiff (super-plasticizer didn’t used to keep the same conditions for all mixes).

### 4.2.2. Splitting tensile strength

The splitting test is one of the indirect methods to find tensile strength of brittle materials. Cylinder (50 mm diameter * 100 mm height) was using for this test [16]. As shown in table 3, the splitting tensile strength (at age 28 days) increased (12.59%) more than the reference mix when added (1%) micro steel fiber, and when added (0.6%) carbon fiber the increased in splitting tensile strength was equal to (16.59%), while the splitting tensile strength increased by (14.12%) when added (0.6%) polypropylene fiber.

### 4.2.3. Modulus of rupture of modified geopolymer paste adhesive

Three points load at (40*40*160 mm3) prisms was the test that used to find the behavior of materials subjected to flexural strength [17]. Modulus of rupture increased with adding different dosages of fibers, where the increases in flexural strength were (15.82%, 20.44%, and 17.72%) at the optimum dosage of (micro steel fiber, carbon fiber and polypropylene fiber), respectively.

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### Table 2. Fresh properties of MGPA.

| Groups  | Mixes               | Flow diameter (mm) | Fresh density (kg/m³) |
|---------|---------------------|--------------------|-----------------------|
| Group1  | 0SF-0CF-0PP (a)     | 185                | 1926                  |
|         | 0.5SF-0CF-0PP       | 175                | 1946                  |
|         | 1.0SF-0CF-0PP       | 165                | 1961                  |
|         | 1.5SF-0CF-0PP       | 160                | 2016                  |
|         | 2.0SF-0CF-0PP       | 155                | 2035                  |
|         | 0SF-0.2CF-0PP       | 172                | 1920                  |
| Group2  | 0SF-0.4CF-0PP       | 155                | 1898                  |
|         | 0SF-0.6CF-0PP       | 140                | 1885                  |
|         | 0SF-0CF-0.2PP       | 170                | 1918                  |
| Group3  | 0SF-0CF-0.4PP       | 160                | 1888                  |
|         | 0SF-0CF-0.6PP       | 140                | 1876                  |

(a) Names of mixes according to proportions and types of fibers (such as 0SF-0CF-0PP means: this mix contented 0.5% micro steel fiber and zero proportions of carbon and polypropylene fibers).
Table 3. Hardened properties of MGPA.

| Groups   | Mixes       | $f_{cu}{(a)}$ (MPa) | $f_t{b})$ (MPa) | $f_r{c})$ (MPa) |
|----------|-------------|---------------------|----------------|----------------|
|          |             | 7 days   | 28 days | 7 days   | 28 days | 7 days   | 28 days |
| Group 1  | 0SF-0CF-0PP | 24.0     | 72.8    | 4.14     | 12.13  | 5.18     | 18.26   |
|          | 0.5SF-0CF-0PP | 24.9     | 74.0    | 4.57     | 13.59  | 6.69     | 19.88   |
|          | 1.0SF-0CF-0PP | 25.0     | 76.5    | 4.61     | 14.05  | 6.73     | 20.56   |
|          | 1.5SF-0CF-0PP | 23.1     | 72.0    | 4.19     | 13.28  | 6.18     | 19.38   |
|          | 2.0SF-0CF-0PP | 22.0     | 70.6    | 4.07     | 13.12  | 5.84     | 19.70   |
|          | 0SF-0.2CF-0PP | 24.5     | 73.3    | 4.57     | 13.63  | 6.65     | 19.79   |
| Group 2  | 0SF-0.4CF-0PP | 25.8     | 77.6    | 4.77     | 14.39  | 6.97     | 20.97   |
|          | 0SF-0.6CF-0PP | 27.6     | 78.7    | 5.18     | 14.61  | 7.48     | 21.29   |
|          | 0SF-0CF-0.2PP | 23.9     | 68.4    | 4.44     | 12.68  | 6.43     | 18.44   |
| Group 3  | 0SF-0CF-0.4PP | 25.0     | 76.3    | 4.68     | 14.16  | 6.71     | 20.58   |
|          | 0SF-0CF-0.6PP | 27.5     | 77.1    | 5.29     | 14.28  | 7.46     | 20.84   |

(a) $f_{cu}$: Compressive strength for cubic (50*50*50)mm$^3$.
(b) $f_t$: Splitting tensile strength for cylinder (50 mm diameter * 100 mm height).
(c) $f_r$: Modulus of rupture for prism (40*40*160) mm$^3$.

4.3. Bond strength

Bond strength of MGPA was found by a single lap shear test for strengthening concrete prism by NSM-steel bar technique with MGPA material. A hydraulic machine (1000 kN capacity) was used to find the pull-out force and the displacement by computerized method. Figure 4 shows pull-out machine.

![Figure 4.](image_url) (a) Hydraulic machine used for pull out test, (b) Sketch of the specimen under test.
4.3.1. Group 1 (geopolymer paste modified by adding different proportions of micro steel fiber)

Four concrete prisms were strengthened by NSM and tested; where the adhesive was MGPA with the addition of different proportions of micro steel fiber, and then comparing the results with the reference specimen (reference specimen used the adhesive GPA without fiber content). The contents of micro steel fiber were (0.5, 1.0, 1.5 and 2.0) percent of volume. The results show significant developed in bond strength for all specimens. The increases were equal to (13.8%, 47.7%, 35.1% and 17.9%) of the reference at (0.5, 1.0, 1.5, and 2.0%) contents of micro steel fiber, respectively. As shown in Table 4, the optimum proportion of micro steel fiber was (1.0%), which was giving a maximum increase in the force of bond. A dropping happened in the bond strength when adding micro steel fiber more than (1%) due to decrease of the bond material about steel fiber causing weakness in the matrix.

Table 4. Results of single lap shear test for group 1.

|            | Load at failure (kN) | Stress at failure (MPa) | Displacement (mm) |
|------------|----------------------|-------------------------|-------------------|
| MGPA       |                      |                         |                   |
| 0SF-0CF-0PP| 24.5                 | 311.90                  | 5.037             |
| 0.5SF-0CF-0PP| 27.9               | 355.17                  | 6.838             |
| 1.0SF-0CF-0PP| 36.2               | 460.80                  | 9.056             |
| 1.5SF-0CF-0PP| 33.1               | 421.35                  | 7.662             |
| 2.0SF-0CF-0PP| 28.9               | 368.67                  | 7.850             |

4.3.2. Group 2 (geopolymer paste modified by adding different proportions of carbon fiber)

To evaluate the effect of carbon fiber on the bond property, three specimens were tested and compare with the reference specimen. The content of carbon fiber was (0.2, 0.4 and 0.6) percent of volume. The bond strength was developing for all specimens. It had been increasing equal to (13.8, 56.7 and 25.3%) of the reference at (0.2, 0.4 and 0.6%) contents of the volume, respectively. The proportion (0.4%) was the optimum proportion of carbon fiber, this proportion gave the maximum increasing in the force of bond, as shown in Figure 5.

Table 5. Results of single lap shear test for group 2.

|            | Load at failure (kN) | Stress at failure (MPa) | Displacement (mm) |
|------------|----------------------|-------------------------|-------------------|
| MGPA       |                      |                         |                   |
| 0SF-0CF-0PP| 24.5                 | 311.90                  | 5.037             |
| 0SF-0.2CF-0PP| 27.9               | 355.17                  | 6.838             |
| 0SF-0.4CF-0PP| 38.4               | 489.00                  | 6.713             |
| 0SF-0.6CF-0PP| 30.7               | 390.47                  | 7.037             |
4.3.3. Group 3 (geopolymer paste modified by adding different proportions of polypropylene fiber)

The effect of the addition of polypropylene fiber on the bond strength of MGPA was studied by testing three specimens and comparing the results with the reference specimen. The content of polypropylene fiber was (0.2, 0.4 and 0.6) percent of volume. The bond strength was increasing by (19.5, 32.2 and 12.5%) of the reference at (0.2, 0.4 and 0.6%) contents of the volume, respectively. The proportion (0.4%) was the optimum proportion of polypropylene fiber. Table 6 summarized the results of single lap shear test for this group.

| MGPA               | Load at failure (kN) | Stress at failure (MPa) | Displacement (mm) |
|--------------------|----------------------|-------------------------|-------------------|
| 0SF-0CF-0PP        | 24.5                 | 311.9                   | 5.037             |
| 0SF-0CF-0.2PP      | 29.3                 | 373.3                   | 3.963             |
| 0SF-0CF-0.4PP      | 32.4                 | 409.2                   | 5.188             |
| 0SF-0CF-0.6PP      | 27.5                 | 351.1                   | 4.613             |

4.3.4. Comparing the bond strength of the optimum geopolymer paste adhesive with epoxy adhesive

The results showed significant improvement in the bond force of MGPA when adding fibers to the mixes comparing with the epoxy adhesive used in our previous study [4]. Where, MGPA with (1%) micro steel fiber outweigh on the epoxy adhesive by (4.3%) and (10.6%) increase in bond force when using MGPA with (0.4%) carbon fiber. MGPA with (0.4%) polypropylene fiber gave bond force less than epoxy adhesive by (7%). When applying geopolymer paste in the external strengthening of structures used the suitable MGPA with work and available fiber in the local market, where, all the MGPA with the optimum proportion of the fibers had excellent bond property compare the epoxy adhesive.

Table 7 shows the results of all adhesives, while figure 5 shows the curve of the tensile force and displacement for optimum MGPA and epoxy adhesive.

| Adhesive     | Load at failure (kN) | Stress at failure (MPa) | Displacement (mm) |
|--------------|----------------------|-------------------------|-------------------|
| MGPA-1.0%SF(a) | 36.2                 | 460.8                   | 9.056             |
| MGPA-0.4%CF  | 38.4                 | 489.0                   | 6.713             |
| MGPA-0.4%PF  | 32.4                 | 409.2                   | 5.188             |
| Epoxy        | 34.7                 | 442.4                   | 8.000             |

(a) The name of the adhesive depended on the optimum proportion of the used fiber.
5. Conclusions

Fresh properties, mechanical properties and bond strength of modified geopolymer paste adhesive with different type and dosage of fibers were studied at ambient temperature curing. The following conclusions can be found:

- Adding (1%) of micro steel fiber to the mixture, the (compressive strength, splitting tensile strength, modulus of rupture and bond strength) increased by (5.0%, 12.6%, 15.8% and 47.7%), respectively. Also the bond force (results from single lap shear test) exceeded the bond force with using epoxy adhesive by (4.3%).
- Adding (0.4%) of carbon fiber to the mixture, the (compressive strength, splitting tensile strength, modulus of rupture and bond strength) increased by (8.3%, 16.6%, 20.4% and 56.7%), respectively. Also the bond force exceeded the bond force with using epoxy adhesive by (10.7%).
- Adding (0.4%) of polypropylene fiber to the mixture, the (compressive strength, splitting tensile strength, modulus of rupture and bond strength) increased by (8.1%, 14.1%, 17.7% and 32.2%), respectively, and the efficiency of the bond force equal to (93%) of the efficiency of epoxy bond force.

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