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Textile-reinforced geopolymer mortar for strengthening reinforced concrete elements: Pilot study on mortar development

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Abstract

Externally bonded Fiber Reinforced Polymers (FRP's) are frequently used in civil engineering applications in order to rehabilitate or strengthen existing structural elements. FRPs have been successfully used as flexural or shear reinforcement. However, they exhibit some significant drawbacks such as impermeability, loss of strength at elevated temperatures, and combustibility during a fire. The main culprits for all these disadvantages are the organic matrices, used to impregnate the fibers and bond the composite to the concrete substrate. To remedy these shortcomings strengthening systems based on cementitious mortars in combination with textiles have been investigated. These systems are known as textile-reinforced mortars (TRM) or fabric reinforced cementitious matrices (FRCM). In this pilot study, a new type of inorganic matrix is being evaluated. More specifically, the matrix is a mortar based on geopolymers, specifically developed to replace cementitious matrices typically used in TRM/FRCM applications. In order to access their performance, four geopolymer mortar mixtures along with two commercially available cementitious mortars were examined. More specifically, standard mortar prism specimens were fabricated in order to obtain the mortar's flexural and compressive strength. The best performing geopolymer mixture was identified. The test results are quite promising, indicating that geopolymer mortars can exhibit similar, and in some cases even better flexural and compressive performance compared to the cementitious mortars.

Key words: textile reinforced mortar, TRM, geopolymer, polysialate, fibers, concrete strengthening, flexure

1 Introduction

Aging reinforced concrete structures cannot cope with modern-day requirements. The necessity to carry higher loads and meet newer, stricter design codes drives the need for their structural upgrade. This need was met by the introduction of fiber reinforced polymer (FRP) composites in the construction sector [1, 2]. FRP composites can effectively play many roles as strengthening materials, and exhibit several advantages, such as high strength, low weight, corrosion resistance, and application speed [3]. However, their use is also related to several disadvantages such as: lack of fire-resistance, high-cost of epoxies, inability to be applied on wet surfaces, and lack of vapor permeability [4,5]. In order to address these issues, researchers suggested the replacement of organic resins used in FRPs with inorganic mortars. Since mortars do not have the necessary viscosity to impregnate the fiber tapes or fabrics, open fiber mesh textiles were employed. Textile-reinforced mortar (TRM) is a composite material which consists of open-mesh high strength fiber textiles combined with inorganic matrices, such as cement-based mortars. Reinforced concrete structural elements strengthened with TRM have been used in several studies indicating that they can successfully replace FRPs [4-6]. The inorganic matrices used in TRM are cementitious. Although cement does work quite well as a binder, its production is associated with a large carbon footprint, and thus cannot be considered environmentally friendly. Hence, researchers examined other similar materials with a smaller carbon footprint that exhibit similar or even better performance, and consequently could effectively replace cement. One of these "green" materials is geopolymer [7-8]. More specifically, metakaolin based geopolymers have a carbon footprint which is 23-55 % lower than that of cement [9]. This experimental pilot study focused on the feasibility of using geopolymer as main binder for the development of a mortar which will be suitable for TRM strengthening applications.

2 Experimental program

In this study, six different mortars were examined. Two of these mortar mixtures were commercially available, while four were novel geopolymer trial mixtures. Mortars were examined in terms of workability and were tested in three point bending and uniaxial compression.

2.1 Materials

The first type of mortar, "Ma" is a ready-mix fiber-reinforced mortar. It is cement based and contains synthetic polymers. It is the product of mixing two components: a dry component and a liquid component. The dry component is cement based and contains dispersed chopped fibers as shown in Fig. 1a. These polypropylene fibers had a length of approximately 15 mm. The liquid component contains synthetic polymers (23 %) in water dispersion (also known as "latex"). These two components were mixed with a weight ratio of 1:4 (liquid to dry).

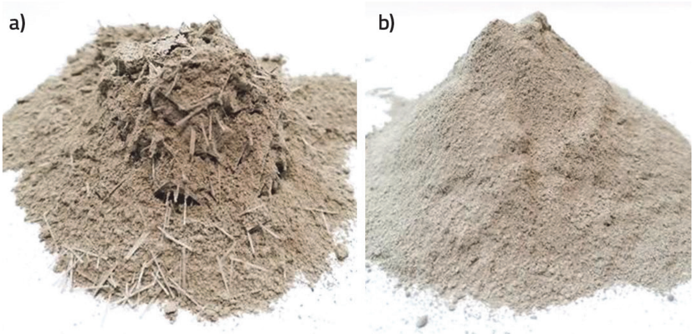

Figure 1. Dry components of cement-based mortars Ma and Mb

The second mortar type, “Mb” is a one-component ready-mix mortar. It is also cement based with pozzolanic additives and contains synthetic microfibers. It is produced by mixing 1:4.2 by weight (water to dry mix). The maximum aggregate size is 1.4 mm, while the synthetic microfibers made of polypropylene and are pre-dispersed in the mix as shown in Fig. 1b.

Both mortars were mixed using a handheld high revolution mixer for approximately five minutes. After the completion of mixing, three steel molds were filled with fresh mortar in three equal layers. After each layer was cast, the molds were shaken and tapped until no air pockets appeared in the surface.

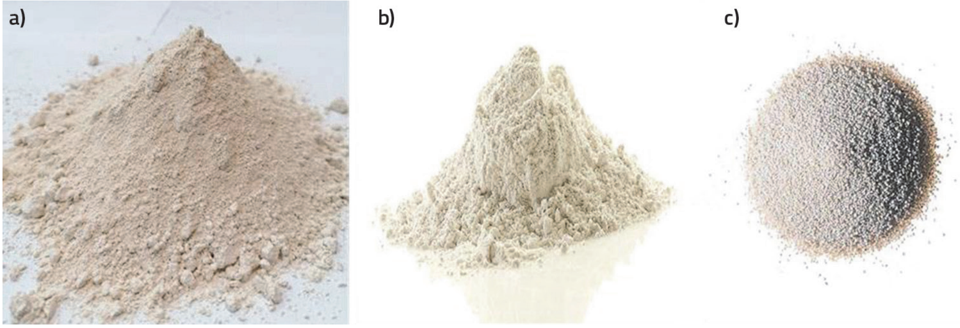

Figure 2. Geopolymer dry components (a) metakaolin, (b) aggregate <0.5mm (c) aggregate 0.5-1mm

The four geopolymer mixtures (denoted hereafter as MGa, MGb, MGc, and MGd) were based on the same type of metakaolin (MK). MKs are typically used as Al_2O_3 source for geopolymerization. For the synthesis of geopolymers, MK was mixed with an activator solution (aqueous potassium silicate), and fine aggregate with a grain diameter of less than 1mm. The fine aggregate was sieved using a 0.5 mm sieve in order to separate it into two parts (up to 0.5 mm and up to 1 mm). The target was to achieve a better control of the mix design. The aggregate size plays an important role in the workability of the mortar, which is essential for TRM applications. The dry components used in the geopolymer mortar mixtures are illustrated in Fig. 2. The main difference between the four mortars was the weight ratios of MK to alkaline activator and sand particles used. More specifics of the mix design are provided in Table 1, which contains specific information on the different weight ratios of the geopolymer mortar components. It should be noted, that the four geopolymer mortars were selected out of a much larger pool, based on their apparent viscosity and workability.

The geopolymer mortars were prepared in a small mortar mixer at maximum rotational speed. First the MK and the fine aggregate was added in the mixer. Initially the dry components were mixed together for about a minute and afterwards the activator solution was slowly added in the mix while the mixer was mixing the components. After approximately five minutes of mixing the geopolymer mortar was ready and was placed in the steel forms using exactly the same procedure as the one described previously for the cementitious mortars.

Table 1. Geopolymer mortar mix ratios (by weight)

Geopolymer Mortar	MK	$\Phi < 0{,}5$ mm Sand	0,5 mm $< \Phi <$ 1 mm Sand	Alkaline Activator
MGa	1	4	1,5	2
MGb	1	6.5	3	3
MGc	1	2	1	1,5
MGd	1	6	2	2,5

2.2 Test setup and instrumentation

The experimental program consisted of flexural and compressive testing. In the first phase, the flexural strength of the mortar was tested based on the ASTM C348–20 [10] and EN 1015-11:2019 [11]. The flexural strength of each mortar were measured using three prismatic specimens of 40 × 40 × 160 mm. The specimens were tested under three-point bending, over a span of 100 mm as shown in Fig. 3a.

After the end of the flexural test the failed specimens, that were split in half, were used for the compression tests. More specifically using two 40 by 40 mm steel bearing plates the mortar was tested in uniaxial compression as described in EN 1015-11:2019 [11].

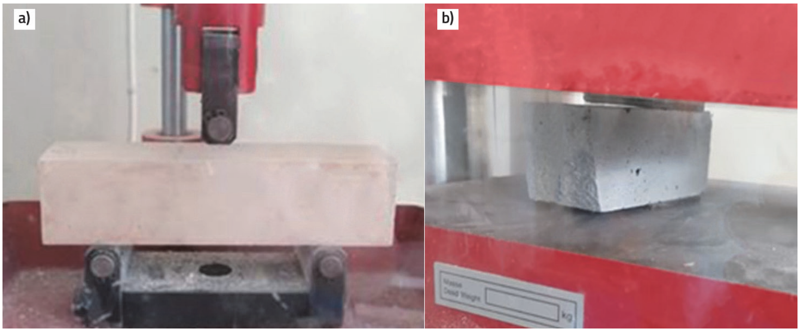

Figure 3. Specimen testing: a) flexural, b) compressive

Table 2. Test Results

Mortar	Density [kg/m^3]	Flexural Strength [MPa]	Compressive Strength [MPa]
Ma	1686	7.2	22.8
Mb	1748	5.2	17.2
MGa	2064	7.66	33.88
MGb	2251	6.07	24.06
MGc	2074	5.13	30.86
MGd	2174	6.01	33.08

3 Results and discussion

3.1 Mortar properties

Three main properties that are known to play an important role in TRM applications were examined. Namely viscosity, flexural and compressive strength. Viscosity plays an important role during the application phase. A low viscosity may result in high flow, which in turn causes the mortar to drip on vertical surfaces (Fig. 4b) or expand in horizontal surfaces (Fig. 4a). In these two cases textile fibers may be left exposed.

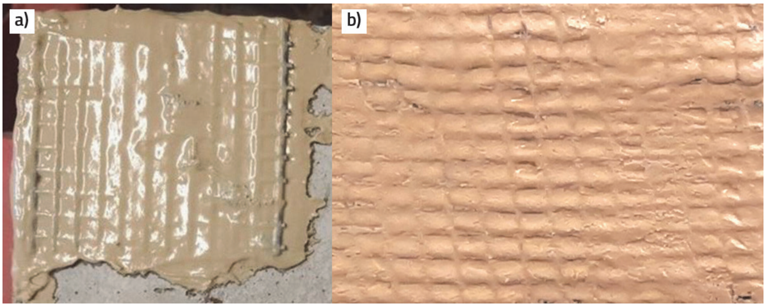

Figure 4. High viscosity Geopolymer flow in: a) horizontal surface, b) vertical surface

A series of different geopolymer mortar mixtures were applied on concrete surfaces (horizontal and vertical) together with basalt and glass textiles. The basalt textile had a mesh size of 6 mm x 6 mm, while the glass textile had a mesh size of 18mm x 14mm. The target at this stage of the study was to identify the mortar mixtures that were easier to apply on textile fibers without the negative effects resulting from low viscosity and high flow. The four geopolymer mixtures (MGa, MGb, MGc, and MGd) that were finally selected for the next stages of the experimental program were viscous enough while maintaining acceptable workability.

A visual examination of the flexural specimens made obvious that the open pores in the Geopolymer mortars were significantly smaller in both size and quantity. This is quite obvious in Fig.5 were three close-up photos from sections of Ma, Mb and MGa are presented. Ma and Mb are associated with more and larger pores. On the contrary, MGa shown in the middle, has very few pores with a significantly smaller size. Although it was only visually observed, the porosity should be associated with the measured density. As expected, the cementitious mortars exhibited lower densities (around 1700 kg/m^3) compared to geopolymer mortars that had densities of more than 2000 kg/m^3. The two distinct groups (cementitious and geopolymer mortars) can be easily identified in Fig. 6a.

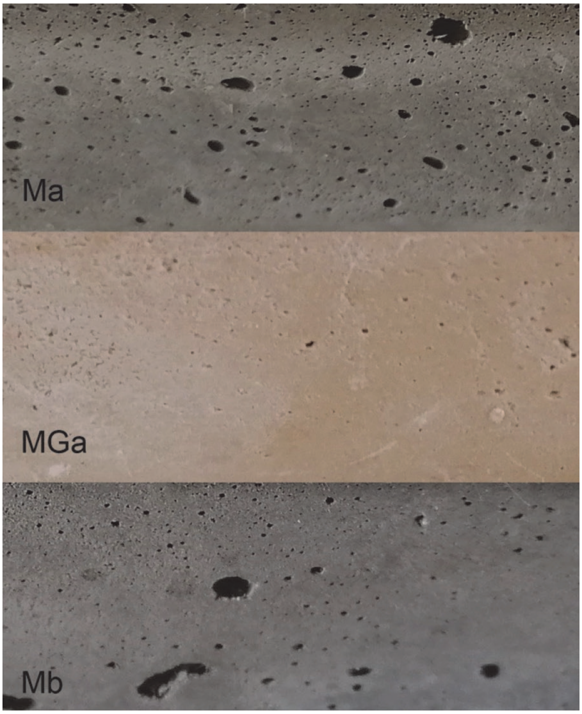

Figure 5. Apparent porosity of Ma, Mb and MGa

3.2 Flexural strength

As expected, all beam specimens tested in three-point bending conditions, failed in a typical brittle manner. Having a much lower tensile strength compared to compressive, failure occurred when the tensile stress at the bottom face of the beam reached the maximum tensile strength of the mortar. All mortars exhibited a similar brittle behavior, regardless of the fact that the cementitious mortars (Ma and Mb) contained short, dispersed fibers. One would expect that the fibers, especially in mortar Ma that contains relatively long fibers with larger diameter, would bridge the flexural crack and provide higher flexural strength. However, this did not materialize during the experiments.

The flexural test results are shown in Table 2 and Fig. 6b. It is clear that mortar Ma and MGa demonstrated a much better performance compared to the remaining four mortars, with flexural strengths of more than 7MPa. The flexural strength of the remaining four mortars (Mb, MGb, MGc, and MGd) had values of lower than 6 MPa. MGa however, was the clear winner in terms of flexural strength, with an average flexural strength of 7.66 MPa. It is clear, that in terms of flexural performance geopolymer mortars can perform equally, if not even better, than cementitious mortars. A typical failed geopolymer flexural specimen can be seen in Fig. 7a. The specimen split almost in half from the development of one major flexural crack. No other cracks appear on the specimen. The same exactly performance describes all tested specimens, regardless of the binder (cement or geopolymer).

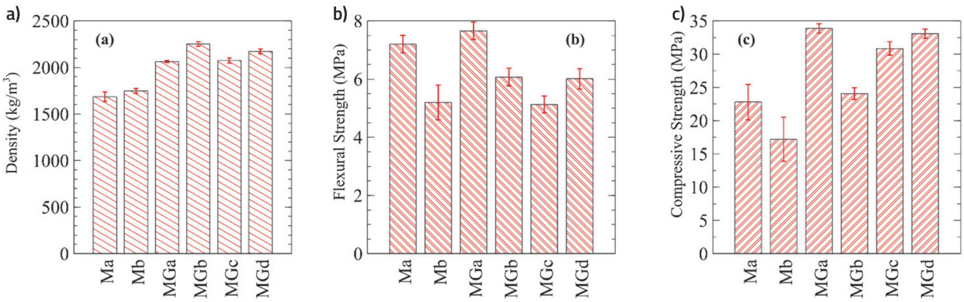

Figure 6. Test results: a) density, b) flexural strength, c) compressive strength

3.3 Compressive strength

Compressive strength testing establishes one of the most important characteristics of hardened mortars. In mortar specimens tested under compression test, initial cracks were developed typically at the top surface and propagated to the bottom. The cracks were almost parallel to the loading direction. Very few cracks appeared at an angle of the applied load. After failure and removal of the cracked sides of the cubes it was noticed that internal cracks formed a truncated pyramid at top and sometimes bottom, inverted over each other (Fig. 7b).

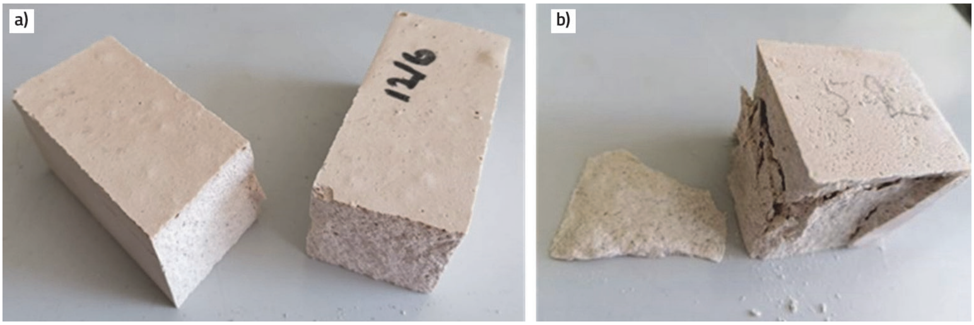

Figure 7. Typical geopolymer mortar specimens after: a) flexural testing, b) compressive testing

The experimental results as shown in Fig. 7c and Table 2 reveal that geopolymer mortars exhibited higher compressive strength compared to cementitious mortars. The minimum recorded compressive strength of geopolymer mortar (MGa to MGd) was 24MPa, which is higher than maximum strength of 22.8 MPa recorded for the two cementitious mortars. This finding can be related to the observed densities and thus porosities of the mortars. As mentioned previously, geopolymer mortars had higher densities and therefore lower apparent porosities. In almost all brittle structural materials the pores introduce weak links in the mass of the material and result in a decrease of compressive strength.

The highest compressive strength was recorded for MGa, which also exhibited the highest flexural strength and density. This particular mortar was used in a second phase of the experimental program as the main matrix in a basalt fiber textile reinforced geopolymer mortar used as a flexural strengthening system for a reinforced concrete beam.

4 Conclusions

The present pilot study experimentally investigated the properties of geopolymer mortars to be used as matrix in TRM strengthening applications. Four different mixtures of geopolymer mortars were investigated along two commercially available cementitious matrices. The main conclusions drawn from this study are:

- Geopolymer mortars even without dispersed fibers exhibit equivalent flexural strengths comparable, and in some cases even higher, to the strength of cementitious mortars containing dispersed fibers.
- The compressive strength of the geopolymer mortars is significantly higher compared to the strength of cementitious mortars.
- Geopolymer mortars exhibit higher density due to lower porosity.
- Overall, it is feasible to produce a geopolymer mortar with equal or better properties compared to commercially available cementitious ready-mix mortars.

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