Study on the Mechanical Properties and Durability of Carbon Fiber Reinforced Lime-Based Mortar

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Abstract. In this study, the changes in mechanical properties and durability of Portland cement lime-based mortar due to the addition of chopped carbon fibers (CFs) have been studied. Compressive strength (CS), split tensile strength (STS) and flexural strength were determined in relation to the volume of CFs, water to binder ratio and SP dosage. Additionally, the durability, i.e. immersion water absorption (IWA) and capillary water absorption (CWA), has also been investigated. The results show that the CS, STS, IWA and CWA of the mortar with 1 vol.% CFs are increased by 11.24%, 3.69%, 5.41% and 46.50% respectively, comparing with that of the mortar with 0.5 vol.% CFs. The lime mortar with 1 vol.% fiber shows 6.59% higher energy absorption than that with 0.5 vol.% fiber in aspect of flexural strength.

Keywords. Carbon fiber, mechanical properties, durability, mortar.

1. Introduction

Utilization of fibers in enhancement of engineering properties of cement composites has been a great interest to researchers for the last few decades. In recent times, the demand and application of fiber reinforced cement-based composites has increased in the diverse fields including civil engineering, architectural and construction industry. Carbon fibers (CFs) in particular have gained much of attention in that regard due to superior mechanical properties, low density and low production cost as well as high production rate [1, 2]. Previous studies have shown that carbon fibers can improve cement composites with higher tensile strength [3, 4], flexural strength, toughness [5], electrical resistivity [6], thermal conductivity, reduced drying shrinkage and cracking problems [2, 7], and higher corrosion resistance along with improved freeze-thaw durability [4, 8]. Further improvement can be achieved by changing the fiber length [1] and degree of dispersion [8].

Portland cement is the most common construction material with a worldwide production rate of approximately 1700 million tons per year [9], which is high CO₂ emission intensive. One of the sustainable approaches to plunge the environmental burden is to use lime as a partial replacement for cementitious materials. Use of lime-mortar in masonry works and plastering is growing interest in recent times [10]. Lime can act as filler for the gap between aggregates and cement and can also improve the consistency of the cement mortar. Lime-based mortar is often prone to plastic shrinkage
due to quick water evaporation which can be possibly overcome by addition of fiber in the matrix [11]. Fibers inhibit the crack propagation by distributing the crack induced stresses to adjacent particle [12].

In spite of extensive studies on the potential advantages of CFs on cement composites, there is limited study on the combined effect of volume fraction of CFs and water to binder ratio on the mechanical properties and durability of Portland cement and lime-based mortar.

Therefore, the aim of the study is to find out the effect of varying volume fraction of carbon fiber on the air void, capillary porosity, mechanical strength of Portland cement and lime-based mortar in context of varying water to binder ratio.

2. Materials and Methodology

2.1. Materials
Portland cement was used as the cementitious material to make carbon fiber reinforced mortar (CFRM) samples in this study. The chemical component of this Portland cement is shown in table 1. At the same time, in order to protect the environment and reduce the amount of cement, 10 wt.% lime powder was added to the mix as a partial replacement of the Portland cement. In addition, the lime powder can also fill the gap between cement and aggregate as fine particles to improve the consistency of the mix.

Table 1. Chemical component of Portland cement used in this study.

| Component (wt.%) | SiO₂  | Al₂O₃ | Fe₂O₃  | CaO    | MgO    | SO₃    | Na₂O   | K₂O    |
|-----------------|-------|-------|--------|--------|--------|--------|--------|--------|
|                 | 20.424| 3.944 | 3.844  | 63.407 | 0.964  | 2.606  | 0.015  | 0.468  |

The sand was prepared in saturated surface dry (SSD). The properties of sand, i.e. specific gravity (SG), absorption capacity (AC), dry rodded unit weight (DRUW), are summarized in table 2. The sand used in the study conforming to ASTM C33 [13], and the particle size distribution of the sand is displayed in figure 1.

Table 2. Properties of sand used in this study.

| SG          | AC  | DRUW |
|-------------|-----|------|
| 2.65        | 0.40%| 1.70 g/cm³ |

Figure 1. Particle size distribution of the sand.

Polycarboxylate-based superplasticizer (SP) (Sika® ViscoCrete®-2100, USA) used in the study, was conforming to ASTM C494 [14]. It has a very compatible property with volcanic mixtures. The properties of this polycarboxylate-based superplasticizer (SP) are summarized in table 3.
### Table 3. Properties of the polycarboxylate-based superplasticizer (SP).

| Phase   | Color | Density  |
|---------|-------|----------|
| Liquid  | Blue  | 1.08 g/mL|

Chopped carbon fibers (CFs) (Haning Anjie Composite Material Co., Ltd, China) with a length of 6 mm was used for the mortar reinforcement. The properties and parameters of the chopped carbon fiber i.e. Filament Diameter (FD), Tensile Strength (TS), Tensile Modulus (TM), Carbon Content (CC) and Electrical Resistivity (ER), are shown in table 4. A sample of these carbon fibers is illustrated in figure 2.

### Table 4. Properties and parameters of CFs.

| FD  | TS    | TM      | CC   | Elongation | Density | ER       | Appearance |
|-----|-------|---------|------|------------|---------|----------|------------|
| 7.0-10 μm | 3.6-3.8 GPa | 220-240 GPa | ≥95% | 1.5%  | 1.76 g/cm³ | 1.5×10⁻³ Ω.cm | Black      |

#### Figure 2. Chopped carbon fiber used in the CFRM

2.2. Methodology

For comparing the effects of different volume of CFs addition on the mechanical properties and durability of Portland cement lime-mortars, mechanical properties tests and durability tests were carried out in this study respectively. Three types of mechanical properties tests were carried out, i.e. the compressive strength (CS) test, the split tensile strength (STS) test and the flexural strength (FS) test. Two types of durability tests were carried out, i.e. immersion water absorption (IWA) test and capillary water absorption (CWA) test.

The CFRM samples for CS and IWA tests were made through 50×50×50 mm cube molds which are according to ASTM C109 [15] standard. Samples for STS and CWA tests were made through 50×100 mm cylindrical molds which are according to ASTM C496 [16] standard. Samples for FS test were made through 5×25×285 mm beam molds which are according to ASTM C78 [17] standard. CS, FS, STS, IWA and CWA tests were carried out according to ASTM C109, ASTM C78, ASTM C496, ASTM C642 [18] and ASTM C1585 [19] standards respectively. The time interval of CWA test was 24 hours. And tap water was used to make the mortar mix.

2.3. Mix Design and Sample Preparation

A proper binder content of 700 kg/m³ was selected for this study. After several trial tests, the minimum dosage of SP was selected as 16 ml/kg of binder (cement and lime powder) for the design of carbon fiber reinforced mortar (CFRM) mixes. Two volume fraction of carbon fiber, 0.5% and 1% of CFRM, were chosen for the study. 6 mm long fibers were used for the study. 3 sets of experiments were performed for each volume fraction of fibers which are shown in table 5. The mixtures weight for CFRM is presented in table 6.
Table 5. Mix design for the CFRM mixes.

| Design No. | Fiber % | w/b | SP |
|------------|---------|-----|----|
| C1         | 0.5     | 0.35| 16 |
| C2         | 0.5     | 0.4 | 19 |
| C3         | 0.5     | 0.45| 22 |
| C4         | 1       | 0.35| 19 |
| C5         | 1       | 0.4 | 22 |
| C6         | 1       | 0.45| 16 |

Table 6. Mixtures weight for CFRM mixes.

| Design No. | Cement (kg) | Lime powder (kg) | Water (kg) | Sand (kg) | SP (kg) | Fiber (kg) |
|------------|-------------|------------------|------------|-----------|---------|------------|
| C1         | 3.0240      | 0.3360           | 1.1760     | 6.0240    | 0.0575  | 0.0422     |
| C2         | 3.0240      | 0.3360           | 1.3440     | 5.8560    | 0.0683  | 0.0422     |
| C3         | 3.0240      | 0.3360           | 1.5120     | 5.6880    | 0.0791  | 0.0422     |
| C4         | 3.0240      | 0.3360           | 1.1760     | 6.0240    | 0.0683  | 0.0845     |
| C5         | 3.0240      | 0.3360           | 1.3440     | 5.8560    | 0.0791  | 0.0845     |
| C6         | 3.0240      | 0.3360           | 1.5120     | 5.6880    | 0.0575  | 0.0845     |

Once the mix design was determined and the mixtures were measured, the fine aggregates, cementitious materials, and CFs were mixed in dry state for one minute. At this point, SP mixed water was added to the dry mixture while mixing of dry components was going on. The mixing was performed for two minutes. Then a 30 seconds rest was given to the mix, and the mixing was performed for another three minutes.

The well-mixed mixture was placed into 50×50×50 mm cube molds, 50×100 mm cylindrical molds and 25×25×285 mm beam shaped molds immediately after mixing. After light tapping and covering with plastic sheets, the molds were moved to a 20°C temperature and 95% relative humidity controlled room. The mechanical properties tests and durability tests were carried out after 28 days of curing age.

3. Results and Discussion

3.1. Impact of Water to Binder Ratio on Test Results

The compressive strength (CS), split tensile strength (STS), flexural strength (FS), immersion water absorption (IWA) test and capillary water absorption (CWA) test were conducted after 28 days of hydration of the carbon fiber reinforced lime mortar samples. The broken cube, cylinder, beam samples after CS, STS and FS tests and the carbon fibers, visible to the naked eye on the fracture surface, are shown in figure 3.

Figure 3. Broken samples after mechanical tests and carbon fibers on the fracture surface.
From figure 4, the results show that for the same volume fraction of Carbon fibers, the compressive strength (CS) and modulus of rupture (MR) increased with lower water to binder ratio. For the 1 vol.% fiber lime-mortars the trend is similar for split tensile strength (STS). However, for the lime-mortars with 0.5 vol.% fiber, the STS for the water to binder ratio of 0.35 is slightly lower than that of 0.4 water to binder ratio, which are 5.55 MPa and 5.6 MPa respectively.

It can be observed from figure 5 that for the same volume carbon fiber, the higher the w/b ratio, the higher is the immersion water absorption (IWA) and the capillary water absorption (CWA) underlying higher porosity. Thus, the durability decreases as the water to binder ratio increases. Comparing figure 4 and figure 5, for the same volume CFs, the mechanical properties decrease with increasing the porosity.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** The results of mechanical properties tests of CFRM

**Figure 5.** The results of durability tests of CFRM

### 3.2. Impact of Different Volume Fractions of CFs on the Test Results

The average values of CS, STS, MR, IWA and CWA are shown in table 7 with varying CFs addition which are 0.5 vol.% and 1 vol.%. It can be seen that the CS, STS, IWA and CWA of the CFRM with 1 vol.% CFs are increased by 11.24%, 3.69%, 5.41% and 46.50% respectively, comparing with that of the mortar with 0.5 vol.% CFs. It is clear that though the increase in CFs leads to higher porosity, the mechanical properties were not compromised, rather, improved CS and STS were achieved with higher addition of CFs. The higher carbon fibers contributed to the toughness of CFRM which suppressed the effect of porosity. However, the MR is reduced by 5.80% with the increase of CFs from 0.5 vol.% to 1 vol.%, which is in agreement with Park et al. [20]. For FS test, the optimal combination of CFs and MR requires further research.

| Fiber (%) | CS (MPa) | STS (MPa) | MR (MPa) | IWA (g) | CWA (mm) |
|-----------|----------|-----------|----------|---------|----------|
| 0.50      | 36.32    | 4.96      | 7.42     | 6.92    | 2.00     |
| 1.00      | 40.40    | 5.14      | 6.99     | 7.29    | 2.93     |

The load-displacement curve of flexural strength test is shown in figure 6. The values of the area under curve are shown in table 8. For flexural strength test, the energy absorption is increased by 6.95% with increasing amount of CF from 0.5 vol.% to 1 vol.%. Comparing table 7 and table 8, although the MR is reduced, the energy absorption is still increased as the amount of CFs increases. This means that in the process of resisting bending failure, the CFRM with 1 vol.% CFs can absorb more energy before rupture comparing with that of 0.5 vol.% CFs.
Figure 6. The load-displacement curve of modulus of rupture.

Table 8. The energy absorption of flexural strength.

| Fiber (%) | Energy absorption (J) |
|-----------|-----------------------|
| 0.50      | 0.2374                |
| 1.00      | 0.2539                |

4. Conclusion
The study has been conducted to understand the effect of carbon fiber and water cement ratio in CFRM. The major findings are enlisted in the following:

1) With the increase of carbon fiber content, the mechanical properties of CFRM can be expected to improve.

2) With the same volume percentages of CFs, the compressive strength and modulus of rupture has increased with the decrease of water to binder ratios, meanwhile, the immersion water absorption and the capillary water absorption has decreased correspondingly.

3) When the amount of CFs increases from 0.5 vol.% to 1 vol.%, the compressive strength, split tensile strength, immersion water absorption and capillary water absorption all increased by 11.24%, 3.69%, 5.41% and 46.50% respectively. The increase in porosity did not lead to a decrease in compressive strength and split tensile strength due to the increase of CFs.

4) In this study, the increase in the amount of CFs did not increase the modulus of rupture, but increased the energy absorption of flexural strength test by 6.95% as the amount of CFs increases from 0.5 vol.% to 1 vol.%.

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