Study of aramid and carbon fibers on the tensile properties of early strength cement mortar

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Abstract: The sulfoaluminate cement was used to prepare the high early strength cement mortar specimens (HESCM) with 0.1%, 0.2% and 0.3% volume content of aramid and carbon fibers, and the contrastive studies of the specimens on compressive and tensile properties were presented in this paper by using of universal testing machine and electronic precision servo tensile test machine. The tests reveal that the addition of aramid and carbon fibers has a positive effect on compressive strength, tensile strength, tensile strain and tensile toughness of specimen, and the bigger the volume content of fiber, the more significant on improvement. What’s further, the tensile toughness has the maximum improvement, while the compressive strength increases minimum, and aramid fiber produces a better improving effect on these properties than that of carbon fiber.

1. Introduction

Studies on performance improvement of cement mortar by adding fibers, such as carbon fiber [1-2], steel fiber [3-4], basalt fiber [5-6], ceramic fiber [7-8], flax fiber [9-10], polyester fiber [11-12], polyethylene fiber [13-14], glass fiber [15-17] and aramid fiber [18-19], have been widely reported. After years of practice and exploration, fiber reinforced cementitious composites are extensively used in construction area. Lots of studies and practical projects found that [20-22], even though the addition of steel fiber has a significant positive effect on the physical and mechanical properties of cementitious composites, due to its soaring cost and low economic benefit, the broad use in construction area has been actually limited.

With more and more research available, carbon fiber has been received the favor of scholars with its excellent mechanical properties and a higher economic benefit than steel fiber [23-29]. As the researches going, the carbon fiber is considered as a kind of cost effective material. With the characteristics of lightweight, high strength and modulus, and excellent resistance to high temperatures and fatigue, the use of carbon fiber is on the rise not only in civil field, but also in the field of national defense and aerospace.

As a new high-tech synthetic fiber, aramid fiber [30-31] shows the performance of high strength and modulus, and the resistant to acid, alkali and high temperatures, especially the lightweight and easy in
fabrication. Aramid fiber has a five to six times strength, two to three times modulus, two times
toughness and one fifth weight than steel fiber. The found of aramid fiber was considered as an
important historical process in the material world. In recent years, aramid fiber is used more and more in
construction field [32-34], which presents broad application prospect.

As previously noted, the high early strength cement mortar specimens (HESCM) with 0.1%, 0.2%
and 0.3% volume content of aramid and carbon fibers are prepared in this paper, their 7-days
compressive and tensile properties are tested by using of universal testing machine and electronic
precision servo tensile test machine, and the difference of the performance duo to aramid and carbon
fibers are studied at the same time.

2. Experimental investigation

2.1 Materials and specimens

The materials listed below were used to prepared the HESCM: sodium gluconate retarder, sand with a
fineness modulus of 2.8 and a silt content of 1.1%, tap water, aramid and carbon fibers whose physical
and mechanical properties are presented in Table 1, polycarboxylic high performance water reducing
agent. Mix proportions of HESCM are given in Table 2. Group N presents the specimen without any
fibers, group AF presents the specimen with aramid fiber and CF presents the specimen with carbon
fiber. In group AF, the mixed samples were further divided into series AF1, AF2, AF3 according to the
increase of the volume fraction of fiber content from 0.1% to 0.3%. Similarly, the group CF is also
divided into three series of CF1, CF2 and CF3.

| Fibers          | Filament diameter (μm) | Tensile strength (MPa) | Elongation at break (%) | Density (kg·m⁻³) | Elasticity (GPa) |
|-----------------|------------------------|------------------------|-------------------------|------------------|-----------------|
| Aramid fiber    | 12                     | >2900                  | 2.6                     | 1450             | 70              |
| Carbon fiber    | 7                      | >3500                  | 1.5                     | 1760             | 200             |

The current documents presents a fact that, the many splitting experiments are conducted to explore
the tensile performance of cement mortar [35-37], or the “dogbone” shaped specimens are employed to
conducted direct tensile test [38-40], while the test in this paper is different from the traditional work. As
shown in Figure 1, a type of figure-of-eight directional specimen was used in this tensile test. The
specimen was placed in fixture to conduct direct tensile test (Figure 2), and the result was considered as
the tensile strength. The cube specimen with the side length of 70.7 mm was used for compressive
strength test, the size depends on Standard for test method of performance on building mortar
(JGJ/T70-2009) (In Chinese).

| Group | Series | Cement | Tap water | Sand | Water reducing agent | Retarder | Aramid fiber (%) | Carbon fiber (%) |
|-------|--------|--------|-----------|------|----------------------|----------|------------------|-----------------|
| N     | -      | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | -                | -               |
| AF    | AF1    | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | 0.1              | -               |
|      | AF2    | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | 0.2              | -               |
|      | AF3    | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | 0.3              | -               |
| CF    | CF1    | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | -                | 0.1             |
|      | CF2    | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | -                | 0.2             |
|      | CF3    | 609.1  | 335.0     | 1218.2 | 9.1                  | 21.3     | -                | 0.3             |
2.2 Experimental method

According to the mix proportions of Table 1, when the stir program finished, the mixture was moved into molds immediately and compacting on vibrostand, after 1-day standing, the specimens would be moved into the curing box for standard curing (temperature maintains in 20±2 °C and the relative humidity doesn’t less than 95%), all specimens were test at the age of 7 days.

The device used for tensile test is HS-3001B-S electronic precision servo tensile test machine (Figure 3) and this apparatus can precisely measure the tensile and flexure properties of materials. Because of the shrinkage deformation of cement mortar, the thickness and with of middle layer (fracture surface) should be measured before test, as shown in Figure 4, and the loading rate was set as 5 mm/min.

3. Experimental results and discussion

3.1 Evaluation of strength

3.1.1 Tensile strength

It is well know that test date of mechanical behavior of cementitious composites shows great discreteness, and with reference to the Standard, more than six specimens will be tested in each group, remove the maximum and the minimum, and the rest values’ average is took as the final result (similarly hereinafter). The tensile strength of each series is illustrated in Figure 5.
As shown in Figure 5, the addition of fibers has a positive effect on tensile strength, and the bigger the volume content of fiber, the more significant on improvement. Figure 6 shows the changes in tensile strength of each series, in comparison to group N, there are increments of 1.04 MPa, 1.22 MPa and 1.51 MPa in group CF1, CF2 and CF3, respectively, thus the increase of 17.32%, 37.08% and 69.66%. Furthermore, aramid fiber produces a better improving effect properties than carbon fiber, and under the same fiber volume content of 0.1%, 0.2% and 0.3%, there are improvements of 50.06%, 35.88% and 20.13%, respectively.

3.1.2 Compressive strength
Consulted researches that have been done, the effect of fiber on the compressive strength remain controversial, most researchers [3-6] asserted that the addition of fiber has a significant positive effect on compressive strength of cement mortar, while some other researchers [17] found it has a negative effect on the workability. Results of the work in this paper are plotted in Figure 7.

Figure 7 shows that, similarly to the tensile strength, the addition of fibers also has a positive effect on compressive strength, but the increments are relatively low when comparing with tensile strength. Figure 8 shows the increase rate of compressive strength of each series, in comparison to group N, the increase of group CF1, CF2 and CF3 are only 3.31%, 8.56% and 12.86%, respectively, and the improvements of group AF1, AF2 and AF3 to group CF1, CF2 and CF3 are only 5.52%, 5.75% and 6.3%, respectively.

Table 3. The proportion of tensile strength and compressive strength of each group

| Group | Series | PTC | Change of PTC | Change rate of PTC (%) |
|-------|--------|-----|---------------|------------------------|
| N     | -      | 0.0599 |              |                       |
The change ruler of the proportion of tensile strength and compressive strength (PTC) is further studied, which can be seen in Table 3. The PTC of cement mortar in group N keeps in 0.06, and there has different increase to the PTC by adding fibers, the PTC of specimens in group AF keeps in 0.09, while the PTC of specimens in group CF keeps increasing with the increase of the fiber volume content, and ultimately achieves 0.09.

Whether the specimen subjects to the tensile loading or the compressive loading, the physical essence of its failure is the result of cracks run through the whole specimen. According to the causes, the types of cracks inside cement mortar can be divided into two kinds: cracks result from the free shrinkage and from the loading. The free shrinkage of mortar at early age causes a large number of micro-cracks, that is the initial damage, after incorporating fibers into HESCM mixture, because of the high strength of fiber and the bonding strength between mortar matrix and fiber, the micro-cracks can be partly blocked [10], thus the initial damage is relatively reduced. According to the mechanics of composites material [41], the failure surface shares partial loading when the specimen under tensile loading or compressive loading, and the effect of share loading is more significant when subjects to the tensile loading. Therefore, the addition of fibers has a positive effect both on compressive and tensile strength, and has a better improving effect on tensile strength.

### 3.2 Tensile strain

Strain is an important indicator to characterise the properties of material, the tensile strain can reflect the deformability, and from which the ability of material that absorbs the external energy can be measured. The tensile strain of each series is illustrated in Figure 9.

![Figure 9. Relationship between fiber content and tensile strain](image)

As shown in Figure 9, the addition of fibers also has a positive effect on tensile strain, and the bigger the volume content of fiber, the more significant on improvement, thus the better deformability of specimens. The changes in tensile strain of each series are illustrated in Figure 10, in comparison to group N, there are increments of 0.007, 0.009 and 0.016 in group CF1, CF2 and CF3, respectively, thus the increase of 29.17%, 37.5% and 66.67%. Furthermore, aramid fiber produces a better improving effect properties than carbon fiber, and under the fiber volume content of 0.3%, the tensile strain of AF3 is almost doubled.

The fiber distribution in fracture section of specimens is shown in Fig. 11, from which the following verdicts can be obtained: the aramid fiber can be uniformly distributed in specimen (Figure 11(a)), and a
6

firm cement between fiber and mortar is obtained, while the specimen in group CF1 shows a poor uniformity of fiber distribution, even appears the phenomenon of fiber aggregation (Figure. 11(b)). Therefore, under the same fiber volume content, aramid fiber produces a better improving effect property of tensile strain. In addition, aramid fiber contains more continuity than carbon fiber in the number of former under the same volume due to its smaller density, if they have the same distribution uniformity. That is, the number of aramid fiber which share the load in fracture section is more than that of carbon fiber. It reflects the impact that aramid fiber produces a better improving effect property of tensile strain than carbon fiber.

Figure 11. Fiber distribution in fracture section of specimens

3.3 Tensile toughness
It has a great significance to study the energy characteristics of cementitious during the failure process, since energy is also a very important indicator to evaluate the material performance. Tensile toughness, which is defined as the area surrounded by stress-strain curve and the horizontal axis, is quoted to characterise the energy property of material, the higher the tensile strength, the stronger the ability of absorb energy, and the tensile strength of each series is illustrated in Figure 12.

Figure 12. Relationship between fiber content and tensile toughness
As shown in Figure 12, the addition of aramid and carbon fibers can markedly improve the tensile toughness of specimen due to their high strength and the bonding strength with mortar. The increase rate of tensile toughness is shown in Figure 13, in comparison to group N, under the fiber volume content of 0.1%, the tensile toughness of specimens in group CF1 have an increase of 38.87% and an increase of 45.35% in group AF1. When under the fiber volume content of 0.3%, carbon fiber and aramid fibers result in an increase of 121.67% and 172.79% in tensile toughness, respectively.

As known from the definition of tensile toughness, it is affected by the two main factors of tensile strength and strain, or the strength and deformability. As analyzed above, the addition of fibers has a positive effect on tensile strength, and the higher the strength, the more external loading it can offset, thus the stronger the capacity of energy absorption; with the increase of fiber volume content, the tensile
strain keeps increasing, or the deformability continuously increase, thus the capability of energy absorption which depends on deformation is stronger keeps increasing.

4.Conclusions
The 7-day compressive and tensile properties of the HESCM with 0.1%, 0.2% and 0.3% volume content of aramid and carbon fibers are studied by using of universal testing machine and electronic precision servo tensile test machine. The main conclusions can be obtained below:

(1) The addition of aramid and carbon fiber both have a positive effect on tensile strength, and the bigger the volume content of fiber, the more significant on improvement. In comparison to group N, the specimens in group CF1, CF2 and CF3 have the the increase of 17.32%, 37.08% and 69.66%, respectively. Furthermore, aramid fiber produces a better improving effect properties than carbon fiber, and under the same fiber volume content of 0.1%, 0.2% and 0.3%, there are improvements of 50.06%, 35.88% and 20.13%, respectively.

(2) Also, the addition of fibers also has a positive effect on compressive strength, but the increments are relatively low when comparing with tensile strength. The increase are only 3.31%, 8.56% and 12.86% when the fiber volume content are 0.1%, 0.2% and 0.3%, respectively, and the improvements of group AF1, AF2 and AF3 to group CF1, CF2 and CF3 are only 5.52%, 5.75% and 6.3%, respectively.

(3) The PTC of cement mortar in group N keeps in 0.06, and there has different increase to the PTC by adding fibers, the PTC of specimens in group AF keeps in 0.09, while the PTC of specimens in group CF keeps increasing with the increase of the fiber volume content, and ultimately achieves 0.09.

(4) It is clear that, the bigger the fiber volume content, the higher the tensile strain, thus the better deformability of specimens. In comparison to the strain of specimens in group N, there are increase of 29.17%, 37.5% and 66.67% in group CF1, CF2 and CF3. Additionally, aramid fiber produces a better improving effect properties than carbon fiber. Under the fiber volume content of 0.3%, the tensile strain of AF3 is almost doubled.

(5) The addition of aramid and carbon fibers can markedly improve the tensile toughness of specimen due to their high strength and the bonding strength with mortar. In comparison to group N, under the fiber volume content of 0.1%, the tensile toughness of specimens in group CF1 have an increase of 38.87% and an increase of 45.35% in group AF1. When under the fiber volume content of 0.3%, carbon fiber and aramid fibers result in an increase of 121.67% and 172.79% in tensile toughness, respectively.

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