

Effect of wollastonite microfiber on the performance of engineered cementitious composites

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Abstract. The effects of 75 μ m wollastonite microfibers on the workability, mechanical properties and shrinkage properties of cementitious composites were studied by mechanical and shrinkage tests. The results show that the addition of microfiber reduces the fluidity of fresh mixture, but appropriate content can still meet the needs of self-compaction. WF has no gain effect on the compressive strength of the mixture, but when the dosage is 20%~30%, the flexural strength and tensile strength can be significantly increased by 87% and 28%. The shrinkage test indicates that WF has a good inhibiting effect on shrinkage deformation. It can be used as a good mineral admixture in ECC.

Keywords: Engineering cementitious composites; Wollastonite; Workability; Mechanical properties; Shrinkage.

1. Introduction

ECC is a composite material with a tensile strain capacity greater than 3%, which is based on micromechanics and fracture mechanics and is systematically designed for optimization [1]. The mixture does not contain any coarse aggregates, and the randomly distributed fibers significantly improve the flexural strength, toughness, and durability of the overall structure by inhibiting the generation and propagation of microcracks. Xu successfully developed ECC with fiber volume dosing less than 2.5%, stable tensile strain above 3%, and crack width less than 100 μ m, he considered direct tensile testing as the key to determine whether the material is an ultra-high toughness cementitious composite [2]. Natural wollastonite is a trigonal crystal system with theoretical chemical composition of CaO (48.25%) and SiO₂ (51.75%). According to research, wollastonite can be classified as powder (<25 μ m), microfiber (25~150 μ m), and fiber (>150 μ m) depending on its particle size [3]. Wollastonite is widely used in ceramics, metallurgy, rubber, paper making and other industries because of its needle-like and fibrous crystal form, high whiteness, and unique physical and chemical properties. Now it is also used in the construction industry as a new green material that can improve the mechanical properties and durability of concrete and play a role in energy saving and emission reduction. Hatice concluded that although the needle-like morphology of WF reduces the HPM's compatibility, its presence also improves the mechanical properties and durability to some extent [4]. Biwan found that wollastonite inhibited the segregation of mortar and weathering of specimens, and that the internal structure was continuously dense and strengthened with age [5]. Kalla's study showed that partial replacement of cement in concrete by wollastonite powder led to an increase in pore discontinuity and density of the mix, resulting in improved resistance to chloride ion erosion and permeability [6]. Another study indicated that when the water-cement ratio was 0.45~0.55, the replacement rate of wollastonite-fly ash composites (W-FA) could reach up to 55%~60% and still improve the strength of concrete [7]. Recent studies by Zhu showed that the mechanical properties of oil well cement mixes were significantly better than those of fibers alone or without fibers when carbon fibers were blended with wollastonite fibers, and the deformability was enhanced and the elastic modulus was reduced [8].

Wollastonite is widely distributed in many countries in the world, and it is a worthy direction to explore how to develop and utilize wollastonite rationally and apply it to the engineering practice of cementitious composites.

2. Experimental procedure

2.1 Raw materials

This test material does not contain coarse aggregate, and the main raw materials are P•O 42.5R cement, fly ash, wollastonite fiber (WF), PP fiber (PF), and superplasticizer (SP). In the study, 75 μ m-WF varied by mass of the binding material from 0 to 40% with a gradient of 5%. The PF is a short fiber of 12 mm length (1% by volume) and the SP is a Sika-3301C water reducer. The physicochemical properties of the two fibers are shown in Tables 1 and 2, and the specific proportioning parameters are shown in Table 3 (in which M-0 is the control group).

Table 1. Physical and chemical properties of wollastonite microfiber (%).

Size (μ m)	SiO ₂	CaO	Al ₂ O ₃	MgO	Fe ₂ O ₃	Ignition loss
75	45.78	44.26	0.71	1.28	0.56	6.81

Table 2. Physical properties of polypropylene fiber.

Diameter (μ m)	Length (mm)	Density (g/cm ³)	Tensile strength (MPa)	Elastic modulus (MPa)	Limit extension rate (%)	Moisture content (%)
25	19	0.91	490	3800	37	0.2

Table 3. Mix proportion parameters of each group (g/L).

Mixture	Water	Cement	WF	Fly ash	PF	SP
M-0	502.6	1077	0	359	9.1	9.3
M-5	502.6	1005.2	71.8	359	9.1	9.3
M-10	502.6	933.4	143.6	359	9.1	9.3
M-15	502.6	861.6	215.4	359	9.1	9.3
M-20	502.6	789.8	287.2	359	9.1	9.3
M-25	502.6	718	359	359	9.1	9.3
M-30	502.6	646.2	430.8	359	9.1	9.3
M-35	502.6	574.4	502.6	359	9.1	9.3
M-40	502.6	502.6	574.4	359	9.1	9.3

2.2 Testing method

Since coarse aggregates were not present in the mixture, the workability was evaluated mainly in terms of deformability and flowing rate with reference to EFNARC. The target values were 240~260mm for slump and 7~11s for V-funnel time. Mechanical strength tests were carried out on an electro-hydraulic servo universal testing machine in the range of 300kN, and the corresponding curves were recorded on the computer in time. Referring to the literature, both ends of the direct tensile specimens were reinforced with wooden plates [2]. The shrinkage test was conducted using a CABR-NES non-contact concrete shrinkage instrument, which automatically records shrinkage and temperature and humidity. The corresponding specimens were 100mm \times 100mm \times 515mm with a standard distance of 435mm.

3. Results and discussion

3.1 Workability

The workability of fresh ECC was evaluated by measuring its slump and outflow time, and its shear yield stress and cohesion were assessed by calculating the deformability and flowing rate. The deformability and flowing rate are calculated as $\Gamma=(D^2-D_0^2)/D_0^2$, $D_0=100$ mm, $R=10/t$.

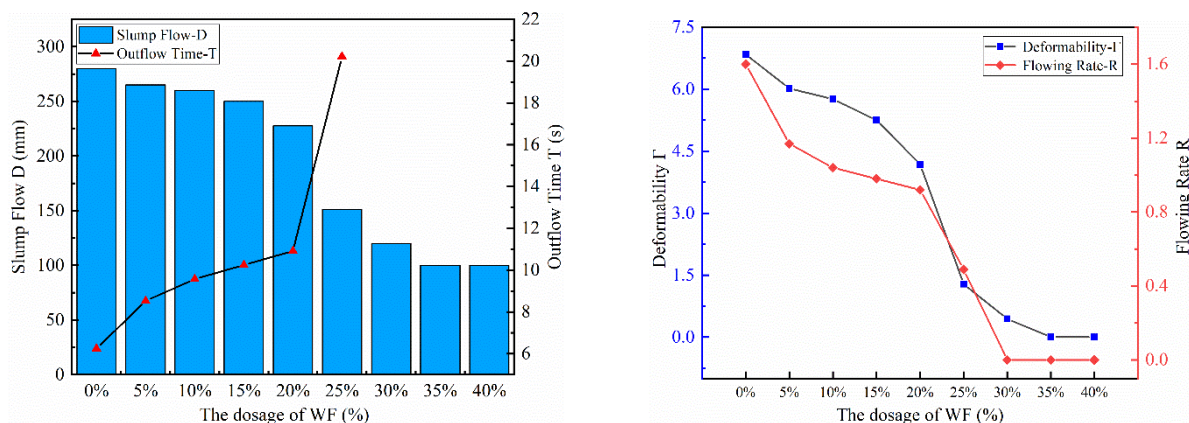


Figure 1. Relationship between workability and dosage. (a) Slump flow and outflow time. (b) Deformability and flowing rate.

It can be seen from Figure 1 that the fluidity of slurry decreases with the increase of the replacement level of WF, and literature [9] shows the same result. The variation of slump flow is roughly divided into three stages: 0-15%, 15%-30% and 30%-40%. Below 15%, there is a slight tendency for the fluidity to decrease as the replacement level rises. This phenomenon may be due to the reduction in the proportion of cement, resulting in less water required for hydration, and the lubricating effect of excess free water on the slurry masking the undesirable effect of WF. As the WF continues to grow, its elongated angular shape together with the mixture generates greater frictional resistance, resulting in a larger shear yield force to be overcome to flow. This adverse effect is greater than the lubricating effect caused by the excess water due to the reduced amount of cement, and the deformability is dramatically declined. When the dosage is greater than 30%, with the higher level of substitution, the fluidity of the fresh mix is completely lost due to the wrapping effect of fibers, and the deformability is basically lost. When the amount of mixture in the range of 0~15% changes, the fluidity is reduced by a maximum of 11%. When the dosage is 15%~30%, the slump flow is reduced by up to 52%. However, the mixture is basically in a non-fluid state when the amount of admixture exceeds 30%.

The amount of WF is proportional to the outflow time of the mixture and inversely proportional to the flowing rate. With the growing replacement level of cement, the outflow time gradually lengthens and the flowing rate decreases, also in three stages of 0~20%, 20~30% and 30~40%. In the range of 0~20%, the outflow time increases slightly with the increase of the dosing level. When the dosage is between 20% and 30%, a large number of microfibers in the binding play a locking effect material, offset the lubrication effect brought by water molecules and dispersion effect caused by the SP. The cohesion of the mixture is greatly raised, and the time to flow out of the V-funnel is significantly prolonged. When the substitution amount exceeds 30%, the binding material basically fills the gap between WF and PF, and the slurry forms a whole. In fact, when the WF from 0 to 20%, the outflow time is extended by 75%. When the replacement level is increased from 20% to 25%, the outflow time is enlarged by 85%. However, when its mass is more than 30% of the total binding material, the fresh mixture loses its workability.

3.2 Mechanical properties

3.2.1 Compressive strength.

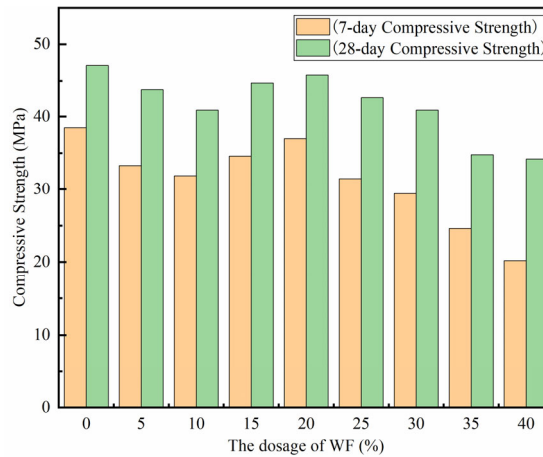


Figure 2. Relationship between dosage and compressive strength.

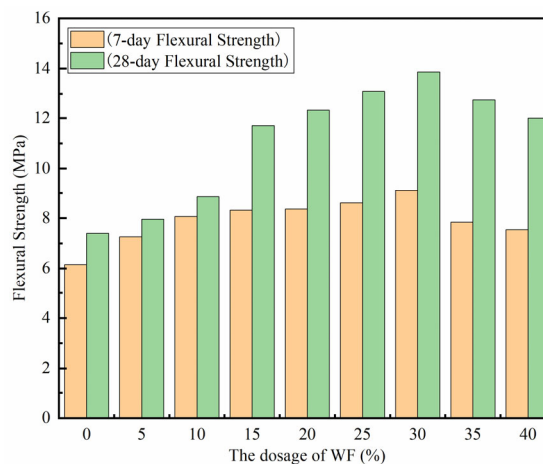


Figure 3. Relationship between dosage and flexural strength.

It can be seen from Figure 2, that the 7 and 28 days compressive strength increased and then decreased with the rise of dose. Except for the group with 40%, the compressive strength of all groups at 7 days could reach 70% ~ 80% of the strength at 28 days. The compressive strength of each group with WF was lower than that of the control group (38.5MPa and 47.1MPa), and reached the maximum value when the content was 20%, 37MPa at 7 days and 45.8MPa at 28 days. When the dosage is in the range of 5%~25%, the difference of 28 days compressive strength between the test group and control group is less than 10%, which can be used as a reference value under the premise that other properties are significantly improved.

Compared with cement and fly ash, the particle size of 75 μ m-WF is larger. Therefore, when a small number of microfibers are added, the spacing between microfibers is just suitable for cement hydration and the gaps are just adequate for the filling of hydration products. At this time, WF acts as a skeleton in mixture and the binding material fills the gaps between the skeletons, making the whole structure denser and more reliable [10]. When the dosage is less than 20%, the compressive strength of ECC increases with the amount of WF. Once the content is more than 20%, the reduction of cement per unit volume will indirectly lead to the enlargement of water-binder ratio while keeping the total amount of water unchanged, and the compressive strength will inevitably decrease.

3.2.2 Flexural strength.

It is clear from Figure 3 that the addition of WF is beneficial to the development of flexural strength, especially for the 28 days flexural strength. Benefiting from the development of the strength of matrix,

the 28 days flexural strength of the M-15 to M-40 groups were significantly higher than that of the control group due to the higher content of WF and the greater anchoring force to the matrix. Among them, M-30 had the highest flexural strength of 9.11MPa at 7 days and 13.87MPa at 28 days, which were elevated by 48% and 87%, respectively, from that of the control group. Abhishek also found in his previous study that the compressive strength of SCC wrapped WF was lower than that of conventional SCC, but the flexural strength was significantly improved [11].

WF can serve to bridge the microcracks in the matrix and enhance the ability to inhibit generation and propagation of cracks [12]. When WF exceeds the range of optimum dosage, the overall strength of the mixture falls due to the reduction of cement. Higher WF dosing can significantly contribute to the 28 days flexural strength of the mixture, which may be attributed to the low matrix strength and weak fibers-matrix bonding due to insufficient hydration of the cement in the early age. With the extension of the curing age, the degree of hydration of the cement goes up and the pozzolanic reaction occurs between the fly ash and $\text{Ca}(\text{OH})_2$ in the hydration products, and the matrix strength becomes higher and the bonding force between fibers and matrix is greater [13]. When the exterior is subjected to ultimate load, the fibers is damaged by slip-fracture. In the three-point bending test of small beams, the flexural strength is more dependent on the bonding force between the various fibers and the matrix. Under external load, PF and WF inhibit the formation and propagation of cracks from macroscopic and microscopic perspectives, respectively. When the external load effect is greater than the bonding force between fibers and matrix, the weakest part of the structure cracks first. As the load continues to grow, the structure is destroyed when the cohesive force between fibers and matrix is not enough to create new cracks in the matrix and the fibers pull out or fracture.

3.2.3 Tensile strength.

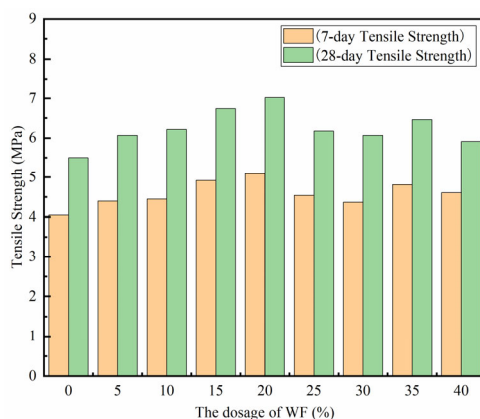


Figure 4. Relationship between dosage and tensile strength.

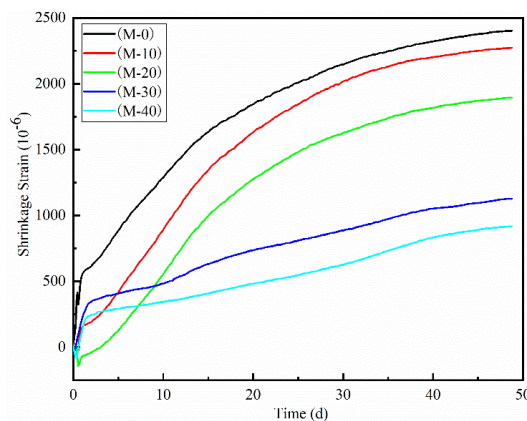


Figure 5. Trend of shrinkage strain over time.

From Figure 4, it can be seen that the tensile strength of the microfiber-doped specimens is significantly greater than that of the control group. It shows that WF and PF have mixed effect and can improve the tensile strength of ECC. The tensile strength gradually increases and then diminishes

with the growth of the dosage, and the tensile strength of the mixture with different dosing amounts could be higher by 9%~26% and 10%~28% when the curing age was 7 days and 28 days. It is thought that 20% is the best dosage, and the maximum tensile strength is 5.09MPa at 7 days and 7.02MPa for 28 days. The latter is about 30%~40% higher than the former.

During the test, it was found that the matrix cracked when some of the specimens cured for 28 days reached the ultimate bearing capacity and the load dropped sharply with a "boom" sound. The reason for this may be related to the method of casting the specimens. Yoo argued that the way of allowing concrete to flow freely from one side to the other was better than that of the specimen formed by pouring from both ends and the middle of mold, resulting in better arrangement of internal fibers per unit area in the tensile direction [14]. It should be noted that the mixture in this study had less PF and appeared less multi-cracking compared to the ECC in the literature [2]. And the strain-hardening occurred after the sudden drop of load and sometimes before the ultimate load. As the load continued to increase after the test started, fine cracks began to appear on the surface of the specimen when it was greater than the ultimate strength of matrix. At this time, the fibers at the openings acted as a stress transfer and slowly started to slip. When the load continues to increase until the bond between the fibers and the matrix is insufficient for the matrix to produce new cracks, the fibers pull out or fracture and the structure is destroyed. Essentially, although the strength of the matrix is too high to meet the conditions for multi-cracking, the WF in the ECC facilitates tensile strength.

3.3 Shrinkage performance

The total shrinkage strain of the mixture diminishes with growth of the microfiber content in Figure 5. Similar to the previous results of the workability and mechanical properties tests, 20% microfiber amount is also a critical point. Compared with M-0, the shrinkage rate of M-10 and M-20 was slow, then accelerated, and finally stabilized. It is easy to know that the shrinkage resistance is significantly better than that of the control group when the dosage exceeds 20%, and the shrinkage strain at the end of test is only half of that of M-0. Meanwhile, it was found that M-30 and M-40 had faster early shrinkage rate and larger shrinkage strain. The analysis suggested that the reduction of cement led to the decrease of early strength and the enlargement of effective water-cement ratio made the cement fully hydrated, so that the autogenous shrinkage of cement was greater. The WF is known not to participate in hydration [4], and the water trapped between its molecules is partly consumed by cement hydration and partly evaporates outward causing additional dry shrinkage.

Compared with M-0, it was observed that the test groups with wollastonite microfibers had different degrees of micro-expansion in initial stage. This phenomenon may be due to the fact that part of the free water entrapped between microfibers provides internal curing for the early hydration of binding material, preventing shrinkage due to early hardening of the mixture. The other part is evaporated to the outside during hydration by the heat of hydration, and the mixture is subjected to compressive stress and swelling in the interior [9]. The total amount of water remains unchanged and the reduction of cement allows the creation of additional free water inside the mixture, which produces a slight expansion when flowing outwards. As the age prolongs, however, the free water on surface of WF is fully utilized and the shrinkage value becomes positive. In summary, the shrinkage deformation of WF-doped mixture is less, the addition of wollastonite improves the drying shrinkage of concrete.

4. Conclusions

In this paper, application of wollastonite microfiber in ECC has been presented. The conclusions are summarized in the following points:

(1) WF can partially replace cement in cementitious composites, but the workability of fresh mixture will decrease with the increase of dosage. When the dosage is greater than 30%, the mixture mainly loses fluidity.

(2) When 75 μ m wollastonite is added into ECC, the mechanical properties of hardened composites first improved and then deteriorated. Because of the dilution effect of cement, microfibers are not conducive to the development of compressive strength. In contrast, the replacement level of microfibers varies from 0 to 40%, and the flexural strength and tensile strength enhanced to different degrees. The maximum values were 13.87MPa and 7.02MPa, respectively, which were 87% and 28% higher than those of the control group, showing a remarkable gain effect.

(3) The mixing of WF and PF can effectively inhibit the shrinkage of ECC, and the ability of the mixture to inhibit shrinkage improved with the increase of microfibers. The shrinkage strain can be reduced about 50% when the dosage of wollastonite is more than 30%.

Acknowledgments

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