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MECHANICAL AND FROST RESISTANCE PROPERTIES OF MORTAR WITH STEEL FIBRES

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The effectiveness of steel fibres in improving mortar is closely related to their length and dosage. To investigate the effect of different lengths and dosages of steel fibres on the performance of mortar, four lengths of steel fibres, namely 6 mm, 13 mm, 25 mm, and 30 mm, were selected, and each length of fibre was single-mixed and multi-mixed following the volumetric rates of 0.5 %, 1 %, 1.5 %, and 2 %. The frost resistance of the steel fibre mortar was also analysed by freeze-thaw cycles regarding the compressive strength and flexural strength loss rate. The results showed that the compressive strength of the specimens was significantly improved as the four lengths of fibres were mixed in equal proportions of 1 %. The flexural strength was most obviously increased when the four lengths of fibres were mixed in equal proportions of 1.5 %, and the compression-flexural ratio was the smallest. At this time, the mortar had the best comprehensive performance. It was also found that mixing the different lengths of steel fibres at a dosage of 1 ~ 1.5 % in equal proportions resulted in a more uniform distribution of fibres. It improved the mortar better than the single mixing. After the 100 freeze-thaw cycle tests, the loss rate of the steel fibre mortar specimen was significantly lower than the ordinary mortar specimen. Mixing different lengths of steel fibres can improve the mechanical properties and frost resistance of the mortar more effectively.

INTRODUCTION

Mortar is a building material that can be mixed with gelling materials and sand, extensively used in building masonry, plastering, and other engineering areas. With the development of the construction industry, the requirements for mortar performance are increasing. Still, the mortar itself is susceptible to cracking and lack of strength, limiting the structure's mechanical properties and durability [1]. In cold regions, the alternation of freezing and thawing can have a more unfavourable effect on the strength of mortar, thus affecting the normal use of building materials, which is the main cause of structural deterioration [2]. Adding fibres is one of the most common strategies to enhance the mortar properties [3]. Steel fibres have high strength, good tensile properties, and easily bond with cementitious materials, effectively reducing the brittle damage of the mortar and other cementitious materials [4]. It also makes up for the shortcomings of traditional mortar, significantly improving the mechanical properties and durability of the mortar [5, 6]. In the meantime, steel fibres have strong corrosion resistance, can be adapted to different environments, and are widely used in construction mortar materials [7, 8].

The effectiveness of the fibres in improving the mechanical properties of cementitious materials is influenced by their length and actual dosage [9]. Several studies have been carried out on the application of steel fibres [10-15]. Researchers generally believe that steel fibres with a dosage of 0.5 % to 2 % can make the structure of cementitious composites denser, prevent the emergence of microcracks, and transform it from a brittle material to a more extensible one, effectively improving its mechanical properties. Compared to a single fibre, incorporating different fibres can control the cracking of the material at different scales and ranges [16, 17]. When long and short fibres are blended, combining both works to produce a positive synergistic effect [18]. The fibres bridge the cracks, and the short fibres inhibit the formation of microcracks [19]. Moreover, because long fibres have a greater tensile capacity than short fibres [20], when macroscopic cracks appear, the fibres prevent the cracks from expanding and thus improves the structural strength and flexibility [21]. Wang et al. [22] found that mixing two lengths of steel fibres, 13 mm and 20 mm, at a 1 % admixture each improved the mechanical properties of concrete. Yoo et al. [23] observed that incorporating two lengths of steel fibres, 19.5 mm, and 30 mm, with a total dosage of 2 %, effectively enhanced the toughness and crack resistance of concrete. With the increasing dosage and size of steel fibres, the fluidity of the cementitious material decreases, reducing the effectiveness of the fibres [24]. Some scholars have also conducted related research [25-27], which discovered that mechanical interlocking and agglomeration are

more susceptible to occur between steel fibres in a large bulk and high dosage, thus increasing the porosity and affecting the performances of the cementitious materials. Therefore, controlling the dosage and length of the steel fibres has a crucial effect on mortar strength and other properties.

Regarding the frost resistance of steel fibre cementitious materials, Ding et al. [28] reported that steel fibres have a solid ability to restrain crack development and change the surface roughness of cracks, significantly improving the frost resistance of the specimens. Zeng et al. [29, 30] concluded that the presence of steel fibres reduces the porosity and the freezing pressure of water in concrete to reduce the damage to the material by the freeze-thaw action. Niu et al. [31] showed that steel fibres doped with 1.5 % could delay the rate of strength loss after freeze-thaw damage and significantly improve its internal structure through the freeze-thaw test. Gao et al. [32] analysed the effect of different steel fibre dosages on the frost resistance of concrete and found that steel fibre concrete at a 1% dosage has the maximum and best frost resistance.

The effect of the steel fibre length and dosage on the mortar performance has been explored in this paper. The tests were carried out using four fibre lengths of 6 mm, 13 mm, 25 mm, and 30 mm, at four dosages of 0.5 %, 1 %, 1.5 %, and 2 %. Two mixing modes were adopted using fibres of the same length (single length mixing – single-mixed) and different lengths (mixed length mixing – multi-mixed). Then, the optimal dosage of steel fibres was selected to conduct the single-mixed and multi-mixed freeze-thaw cycle tests to investigate the improvement effect of the steel fibres on the frost resistance of the mortar.

EXPERIMENT

Raw materials

P.O 42.5 Poland cement, river sand with a fineness modulus of 2.3 and mud content of less than 1.8 %, gravel with a particle grade ranging from 5 to 20 mm, PCA polycarboxylic acid water-reducing agent, and corrugated steel fibres were used in the study. The basic physical and mechanical properties of cement are shown in Table 1, and the physical properties of steel fibres are shown in Table 2.

Table 1. Basic physical and mechanical properties of cement.

Strength grade (MPa)		42.5
Density (kg·m^{-3})		3100
Stability		Qualified
Compression strength (MPa)	7d	24.9
	28d	48.2
Flexural strength (MPa)	7d	4.83
	28d	7.46

Table 2. Steel fibre performance indicators.

Density (g·cm^3)	3.2
Length (mm)	6/13/25/30
Calibre (mm)	0.2
Tensile strength (MPa)	1100
Modulus of elasticity (GPa)	200

Mixture ratio

According to the requirements of the "Specification for mix proportion design of masonry mortar" (JGJ/T 98-2010) [33] and the "Standard for test method

Table 3. Mixture ratio of the mortar.

Number	Mass fraction (%)			Water-cement ratio	Dosage fraction (%)	Steel fibre (mm)
	Cement	Sand	Water reducer	Water	Steel fibre	
SF	100	300	1	0.5	–	–
S5-1	100	300	1	0.5	0.5	6
S10-2	100	300	1	0.5	1	6
S15-3	100	300	1	0.5	1.5	6
S20-4	100	300	1	0.5	2	6
S5-5	100	300	1	0.5	0.5	13
S10-6	100	300	1	0.5	1	13
S15-7	100	300	1	0.5	1.5	13
S20-8	100	300	1	0.5	2	13
S5-9	100	300	1	0.5	0.5	25
S10-10	100	300	1	0.5	1	25
S15-11	100	300	1	0.5	1.5	25
S20-12	100	300	1	0.5	2	25
S5-13	100	300	1	0.5	0.5	30
S10-14	100	300	1	0.5	1	30
S15-15	100	300	1	0.5	1.5	30
S20-16	100	300	1	0.5	2	30

of performance on building mortar" (JGJ/T 70-2009) [34], the mortar specimens were made from cement, sand, and water in a 1:3:0.5 ratio. The steel fibre was selected with a length of 6 mm, 13 mm, 25 mm, and 30 mm, with a dosage of each length at 0.5 %, 1 %, 1.5 %, and 2 % of the mortar volume. The mortar specimen size in the compressive strength and in the flexural strength test was 70.7 × 70.7 × 70.7 mm and 40 × 40 × 160 mm, respectively.

Experimental programme and instrumentation

Based on the mixture ratios, the steel fibre was sprinkled into the river sand evenly two times, put into a dry mixer (VC Instruments, NJ-160), and mixed for 30 s. Then, cement was added and mixed for 60 s. Finally, water was injected slowly and stirred for 2 min to prepare the mortar specimens. After mixing uniformly, the mortar was poured into a mould, vibrated for 2 min until the slurry appeared settled, and then left to stand for 24 hours. The samples were moulded and kept under standard maintenance conditions for 28 days in a maintenance box (ZKY-400).

The experiment was carried out to test the compressive strength (Zhongyu Instrument, YAD-2000) and flexural strength (Zhongyu Instrument, DYE-300A) of the steel fibre mortar specimens, with variations in the compressive and flexural strength under freeze-thaw cycles. In addition, the microscopic morphology of the mortar was analysed using scanning electron microscopy (SEM). By constant temperature immersion (Shanghai Jinghong, DK-8B), the specimens were immersed in water at 25 °C for 4 h and naturally air-dried for 0.5 h, and put into a refrigerator (OXO, BD40K98L) at –20 °C for 4 h, then left to be observed for 0.5 h, for a total of 9 h. With one cycle per day and one test point every 20 d, the experiment took 100 days to complete the freeze-thaw cycles. The experimental procedure is shown in Figure 1.

RESULTS AND DISCUSSION

Effect of the steel fibre length on the strength of the mortar

Single fibre length with different dosages

The compressive and flexural strength of the mortar specimens with a single length of the steel fibres at different dosages are shown in Figure 2. As can be seen from Figure 2a, it shows that the fibre dosage of 0.5 % had only a minor strength enhancement in all of the mortar specimens. The four lengths of fibres, 6 mm, 13 mm, 25 mm, and 30 mm, were most significantly enhanced in the compressive strength at a 1 % dosage, which was 12.3 %, 10.42 %, 13.76 %, and 9.93 % higher than that of the ordinary mortar, respectively. Of the four lengths, the 25 mm fibre provided the most significant increase in mortar strength. When the fibre dosage exceeded 1 %, the compressive strength of the four specimens showed different decreasing degrees, which showed that the fibres were homogeneously dispersed within the cementitious materials when the dosage was too low. Each bonding region, where the fibres were bonded to the slurry body, was also evenly dispersed relative to the entire specimen, making it less likely to form a whole entity. Though the

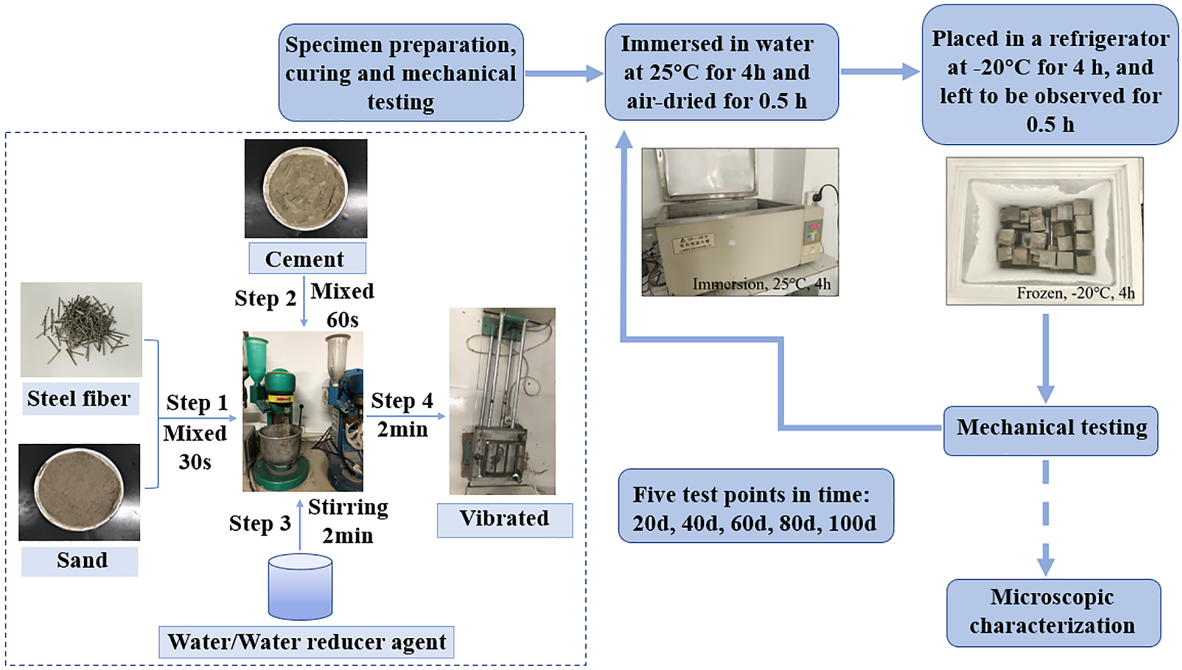


Figure 1. Experimental procedure.

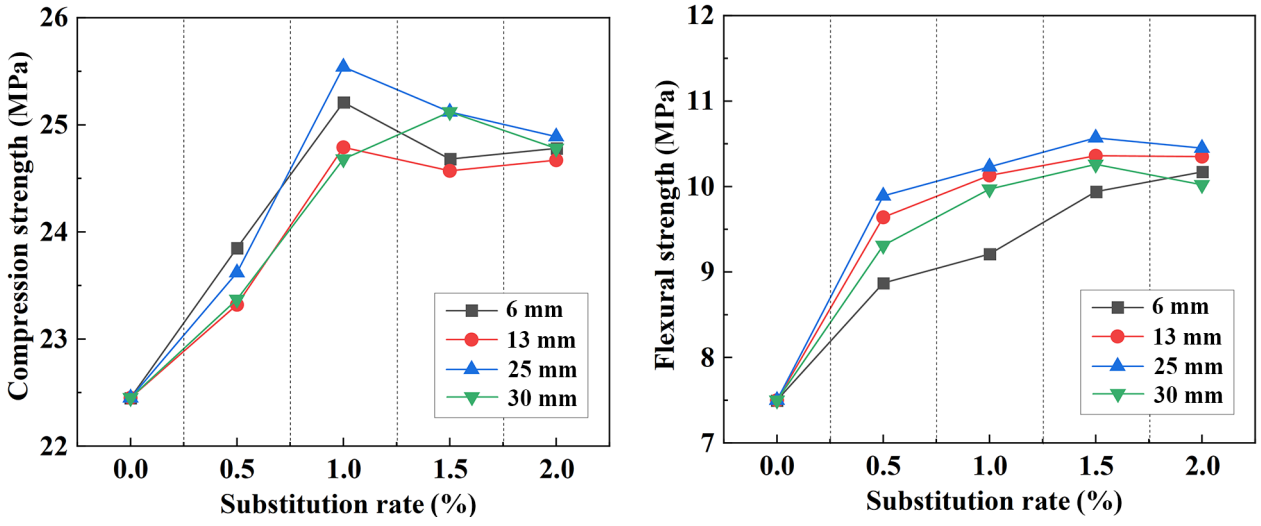


Figure 2. Variation in the cement mortar strength with the different dosages of a single fibre length: a) Compressive strength; b) Flexural strength.

fibres could inhibit the deformation of the weak zones of mortar and improve the strength when the dosage was too high, it was found that with an increase in the fibre dosage, it was difficult for the slurry to wrap the fibre materials thoroughly. Therefore, the weak zones also began to increase. At the same time, too many fibres led to the phenomenon of "unity," so the fibre distribution inside the specimens was not homogeneous, negatively affecting the strength [35].

As shown in Figure 2b, similar to the compressive strength, steel fibres at different dosages positively affected the flexural strength of the specimens. However, the difference was that the flexural strength of the mortar increased with the dosage of fibres to 1.5 %. The maximum flexural strength of the four specimens appeared at the dosage of 1.5 %. The flexural strength of the four lengths of fibres, 6 mm, 13 mm, 25 mm, and 30 mm, was improved by 32.53 %, 38.13 %, 40.93 %, and 36.8 %, respectively, compared with the ordinary mortar. The 25 mm fibre, among the four lengths, significantly improved the flexural strength of the samples. When the dosage exceeded 1.5 %, the lifting effect of the fibres on the mortar decreased.

It was found that the same length of steel fibres at different dosages enhanced the compressive and flexural strength of the specimens. The most remarkable improvement in compressive strength was observed with the 25 mm and 1 % steel fibre dosage, and the highest increase in flexural strength was obtained with the 25 mm and 1.5 % dosage. Meanwhile, the compression flexural ratios of the 25 mm steel fibre at 1 % and 1.5 % dosage were 2.5 and 2.48, respectively, which were less than 3, as shown in Figure 3. In the subsequent experiment, the mixing of different lengths of steel fibres was carried out according to the 1 % to 1.5 % dosage.

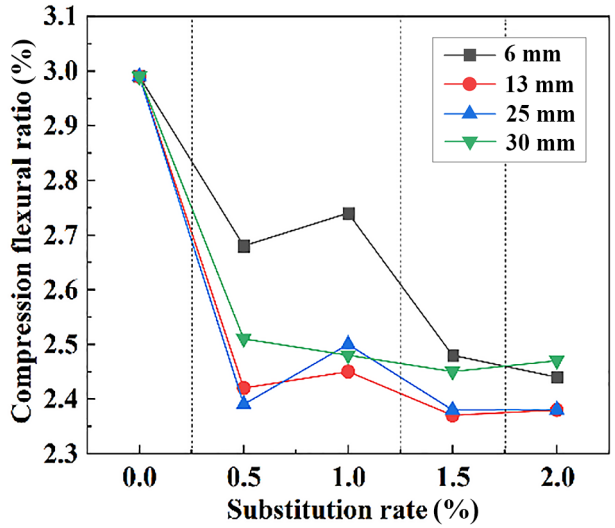


Figure 3. Compression flexural ratio with the different dosages.

Different fibre lengths with different dosages

Following the results of the tests in section 2.1, the strength of the mortar specimens was improved more significantly when the steel fibre dosage was 1 % to 1.5 %. Therefore, the total dosage of the four lengths of fibres was controlled at 1 % and 1.5 %, and the mixing of different lengths of fibres was carried out according to Tables 4 and 5.

At a total dosage of 1 %, the compressive strength and flexural strength of the mortar mixed with different lengths of steel fibres are shown in Figure 4a. As can be seen from the figure, M10-7 has the highest compressive and flexural strength at 28 days. It proved that the fibres of 6 mm, 13 mm, 25 mm, and 30 mm in length were mixed at 0.25 % each, which increased the strength of the specimens most significantly. Contrary to the ordinary mortar specimens and the highest compressive

Table 4. Steel fibres of different lengths mixed at a 1 % dosage.

Number	6 mm (%)	13 mm (%)	25 mm (%)	30 mm (%)
M10-1	0.5	0.5	0	0
M10-2	0	0	0.5	0.5
M10-3	0.5	0	0	0.5
M10-4	0	0.5	0.5	0
M10-5	0.33	0.33	0.33	0
M10-6	0	0.33	0.33	0.33
M10-7	0.25	0.25	0.25	0.25

Table 5. Steel fibres of different lengths mixed at a 1.5 % dosage.

Number	6 mm (%)	13 mm (%)	25 mm (%)	30 mm (%)
M15-1	0.75	0.75	0	0
M15-2	0	0	0.75	0.75
M15-3	0.75	0	0	0.75
M15-4	0	0.75	0.75	0
M15-5	0.5	0.5	0.5	0
M15-6	0	0.5	0.5	0.5
M15-7	0.375	0.375	0.375	0.375

strength mortar specimens mixed with the single-length fibre, the compressive strength was increased by 14.25 % compared to the latter one, and 0.49 % higher than the 25 mm steel fibre mortar with a single dosage of 1 %. The flexural strength was enhanced by 39.33 % compared to the latter one and decreased by 1.6 % compared to the 25 mm steel fibre mortar with a single dosage of 1.5 %.

At a total dosage of 1.5 %, the strength of the mortar mixed with different lengths of steel fibres is shown in Figure 4b. As seen from the figure, M15-7 showed the highest strength enhancement of the specimens, indicating that the four lengths of fibres were the most effective when mixed at 0.375 % of each length. The compressive strength of M15-7 was 13.32 % higher than the ordinary mortar and 0.44 % lower than the specimens mixed with 1 % of the 25 mm single-mixed fibre. The flexural strength was 44 % higher than the ordinary mortar and 3.07 % higher than the specimens mixed with 1.5 % single-mixed fibre. The tests showed that the length combination of fibres had an effect on the strength of mortar, and the mixing of the four steel fibres significantly affected its improvement. Overall, the improvement effect on the flexural strength was more remarkable.

The lowest compression flexural ratio was achieved with a total dosage of 1.5 % and equal proportions of the four lengths of fibres. At this point, the mortar had strong flexibility, which improved the tensile and flexural strength while maintaining a high resistance to cracking, as shown in Figure 5.

In general, the four lengths of steel fibres were each mixed at 0.25 % to enhance the compressive strength of the specimens most significantly (i.e., M10-7), and each mixed at 0.375 % to improve the flexural strength most obviously (i.e., M15-7), at which time the compression

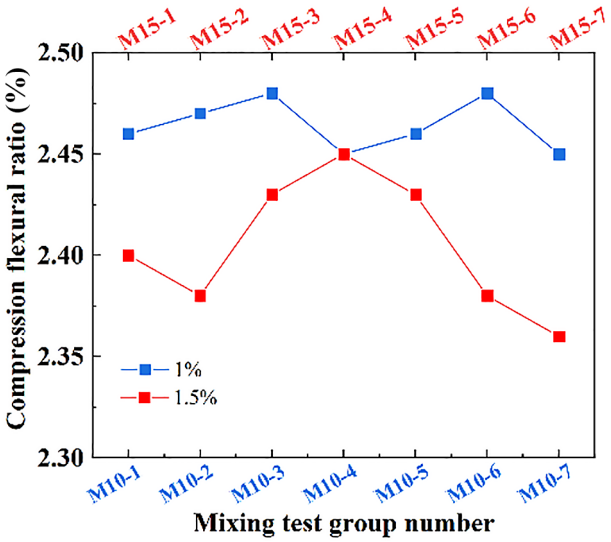
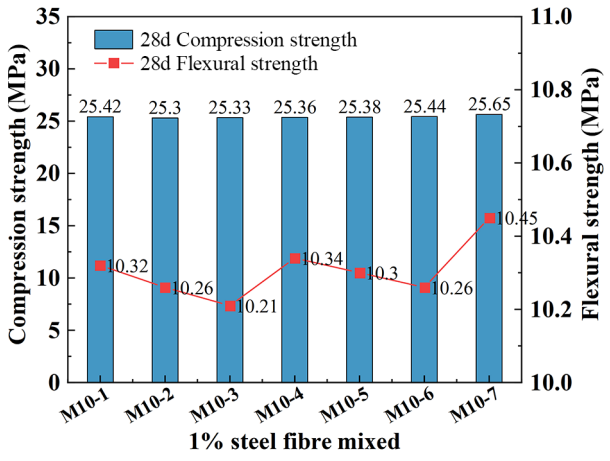
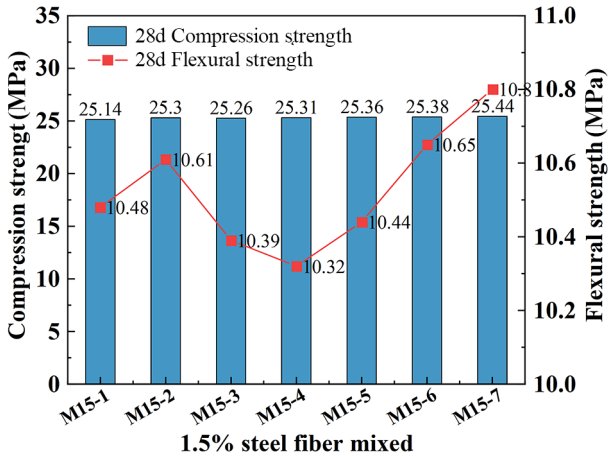


Figure 5. Compression flexural ratio with the different dosages.



a)



b)

Figure 4. Variation in the cement mortar strength with different lengths of steel fibres: a) 1 % dosage; b) 1.5 % dosage.

flexural ratio was the lowest. It was found that controlling the dosage at 1 % to 1.5 % for mixing different steel fibre lengths can further strengthen the improvement effect of the fibres on the mortar. At this point, the fibre dosage was proper, and the short and long fibres acted in a positive synergistic effect to enhance the strength of the mortar specimens further[18].

To find out the distinction in the upgrading properties of cementitious materials between the single-mixing of the same length of fibres and the multi-mixing of different lengths of fibres, the model proposed by Dupont D for calculating the fibre directional effectiveness coefficient with a rectangular cross-section [36] was introduced, as shown in Equation 1

$$\alpha = \{\alpha_1 \times (b - l_f) \times (h - l_f) + \alpha_2 \times \\ \times [(\alpha - l_f)\, l_f + (h - l_f)\, l_f] + \alpha_3 \times l_f^2\} \div bh \quad (1)$$

where α is the cross-section fibre direction effectiveness coefficient, the steel fibre is entirely parallel to the mortar cross-section when $\alpha = 0$, evenly distributed in all directions when $\alpha = 0.5$, and utterly perpendicular to the mortar cross-section when $\alpha = 1$. b and h are the mortar cross-section width and height, respectively, and l_f is the fibre length. α_1, α_2, and α_3 are the orientation factors for different boundary conditions of the cross-section, corresponding to the three regions A, B, and C in Figure 6. Neglecting the effect of the boundary template on the fibre orientation (the steel fibre does not extend beyond the template), and depending on the different boundary conditions, Dupont D et al. calculated that $\alpha_1 = 0.5$ in region A, which is entirely unaffected by the boundary conditions, $\alpha_2 = 0.6$ in region B, which is affected by the boundary conditions on one side, and $\alpha_3 = 0.84$ in region C, which is affected by the boundary conditions on both sides.

As seen from Figure 6, the cross-section size is a fixed value, and α is only associated with the fibre length l_f. When calculating the effectiveness coefficient of the fibre direction of the cross-section of the cube specimens. The specimens mixed with fibres of different lengths were calculated according to Equation 1, and the average sum of the results was taken. The calculations are shown in Table 6.

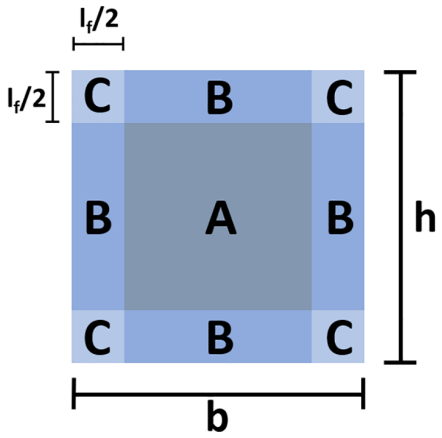


Figure 6. Direction coefficient zoning.

Table 6. Steel fibres of different lengths mixed at a 1.5 % dosage.

Length of steel fibre (mm)	α_1	α_2	α_3	α
6	0.5	0.6	0.84	0.518
13	0.5	0.6	0.84	0.542
25	0.5	0.6	0.84	0.588
30	0.5	0.6	0.84	0.610
6, 13, 25, 30	0.5	0.6	0.84	0.565

As seen in Table 6, the fibre direction effectiveness coefficient of the mortar mixed with different lengths of steel fibres was closer to 0.5, which is smaller than the fibre direction effectiveness coefficient of the mortar mixed with 25 mm single-mixed fibre. It was proven that the mixing of steel fibres of different lengths makes the direction of the fibres more dispersed and homogeneous, which can make the mortar specimen bond with the fibres more uniformly. It was also observed that the smaller the fibre length, the closer the α value is to 0.5 when the fibre distribution is even, and it can be considered unadulterated when the fibre length is short enough. The tests showed that the strength of the mortar specimen without any fibres was lower than that of the steel fibre mortar specimen. In addition, the cross-sectional fibre orientation was used to characterise the homogeneity of the steel fibre in the mortar specimen, and the parameter α was used to analyse the orientation of the fibre distribution only after defining the dosage and length of the steel fibres.

Variation in the strength of the mortar under freeze-thaw cycles

Variation in the compressive strength

The variation in the compressive strength of the mortar specimens under the effect of freeze-thaw cycles is shown in Figure 7. After 100 freeze-thaw cycles, the loss in the compressive strength of the ordinary mortar was 17.28 %. As shown in Figure 7a, when the total dosage of the single fibre length was 1 %, the loss in the compressive strength of the 6 mm, 13 mm, 25 mm, and 30 mm mortar specimens was 13.33 %, 14.76 %, 13 %, and 13.98 %, respectively. As shown in Figure 7b, the loss rate of the compressive strength of 6 mm, 13 mm, 25 mm, and 30 mm cement mortar specimens was 13.93 %, 14.33 %, 13.06 %, and 13 %, respectively, when the total dosage of the single fibre length was 1.5 %. When a single fibre length was mixed, all four lengths reduced the damage to the mortar by the freeze-thaw cycles to varying degrees. Among them, the cement mortar with 25 mm fibres at 1 % dosage showed the best frost resistance in the compressive strength loss rate.

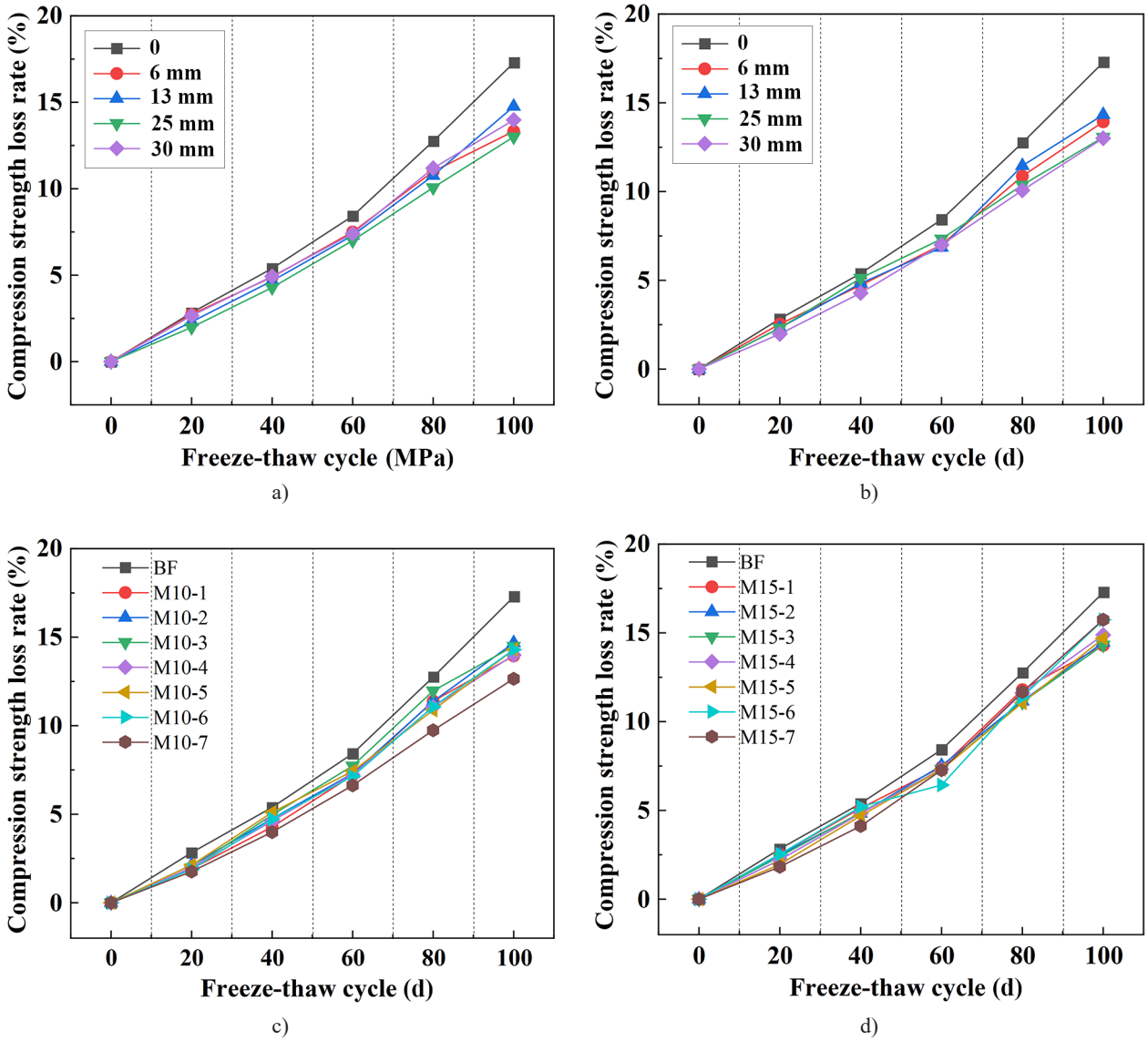


Figure 7. Loss rate in the compressive strength of the steel fibre mortar: a) single-mixing with 1 % dosage; b) single-mixing with 1.5 % dosage; c) multi-mixing with 1 % dosage; d) multi-mixing with 1.5 % dosage.

As shown in Figure 7c, the lowest rate of loss in the compressive strength when mixed with different lengths of steel fibres at a dosage of 1 % was in M10-7, which was a mixture of four lengths of fibres in equal proportions. After 100 freeze-thaw cycles, the loss rate was 12.65 %, which was 4.63 % lower than that of ordinary mortar. As shown in Figure 7d, the best frost resistance of M15-1 was obtained when 1.5 % of the different lengths of steel fibres were mixed with 0.75 % each of the 6 mm and 13 mm fibres. When mixed with different lengths of steel fibres at a total dosage of 1.5 %, the loss rates of M15-1, M15-2, M15-3, M15-4, M15-5, M15-6, and M15-7 was 14.3 %, 14.7 %, 14.32 %, 14.88 %, 14.69 %, 15.74 %, and 15.74 %, respectively.

Based on the rate of loss in the compressive strength, comparing the two ways of mixing, the mortar specimen with the lowest loss in the compressive strength was a mix of four steel fibres in equal proportions at a total dosage of 1 %. In this case, the four fibres were better reduced by the deterioration of the mortar by the freeze-thaw cycle. This was consistent with the results of the tests in which the four lengths of fibres at a 1 % dosage provided the most significant increase in the compressive strength of the mortar in the unfrozen-thawed environment.

Variation in the flexural strength

The variation in the flexural strength of the mortar specimens under the effect of the freeze-thaw cycles is shown in Figure 8. After 100 freeze-thaw cycles, the loss in the flexural strength of the ordinary mortar specimens was 16.57 %. As can be seen from Figure 8a, when mixed with a single length of steel fibre dosage of 1 %, the loss in the flexural strength of the 6 mm, 13 mm, 25 mm, and 30 mm mortar specimens were 15.02 %, 13.81 %, 13.46 %, and 14.24 %, respectively. From Figure 8b, when mixed with a single length of steel fibre

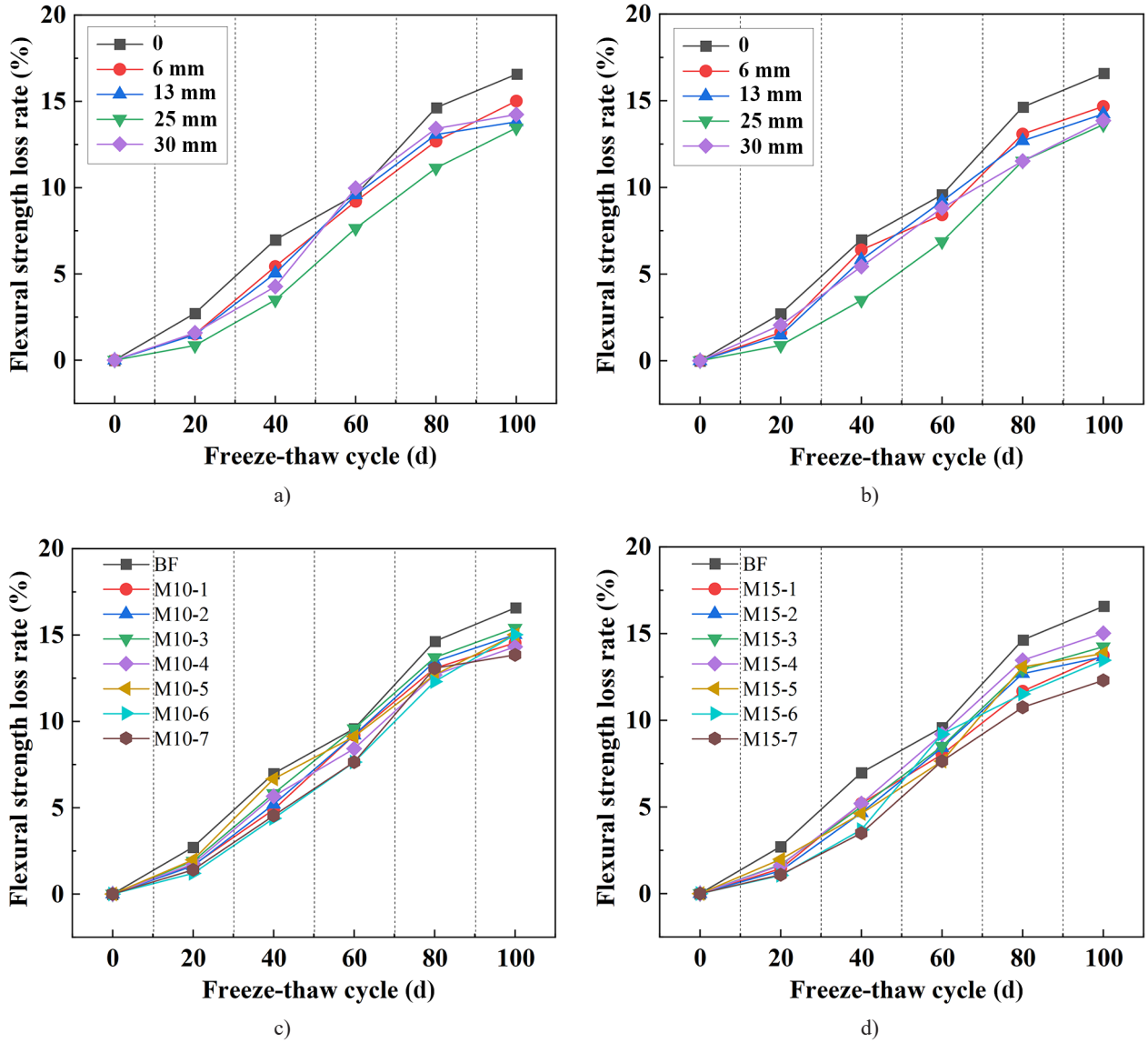


Figure 8. Loss rate in the flexural strength of the steel fibre mortar: a) single-mixing with a 1 % dosage; b) single-mixing with a 1.5 % dosage; c) multi-mixing with a 1 % dosage; d) multi-mixing with a 1.5 % dosage.

dosage of 1.5 %, it can be seen that the loss in the flexural strength of the 6 mm, 13 mm, 25 mm, and 30 mm specimens were 14.67 %, 14.24 %, 13.62 %, and 13.85 %, respectively. When the same fibre length was mixed alone, the mortar specimen with the 25 mm fibre also had the lowest loss in the flexural strength at a dosage of 1 %, which was 3.11 % lower than the loss of the ordinary mortar.

As shown in Figure 8c, the lowest rate of loss in the flexural strength for different lengths of steel fibres with a total dosage of 1 % was found in M10-7. After 100 freeze-thaw cycles, the flexural strength of M10-7 lost 13.85 %, which was 2.72 % lower than the ordinary mortar. From Figure 8d, the lowest loss in the flexural strength at a 1.5 % total dosage was seen in M15-7, with a loss of 12.3 %, which was 4.27 % lower than that of the ordinary mortar.

Based on the rate of loss in the flexural strength, the mortar specimen with the lowest loss in the flexural strength was the four lengths of steel fibres in equal proportions at a total admixture of 1.5 %, which minimises the freeze-thaw damage to the mortar. This corresponded to the combination of the lengths and dosage that most effectively improved the flexural strength effect in the unfreeze-thaw environment.

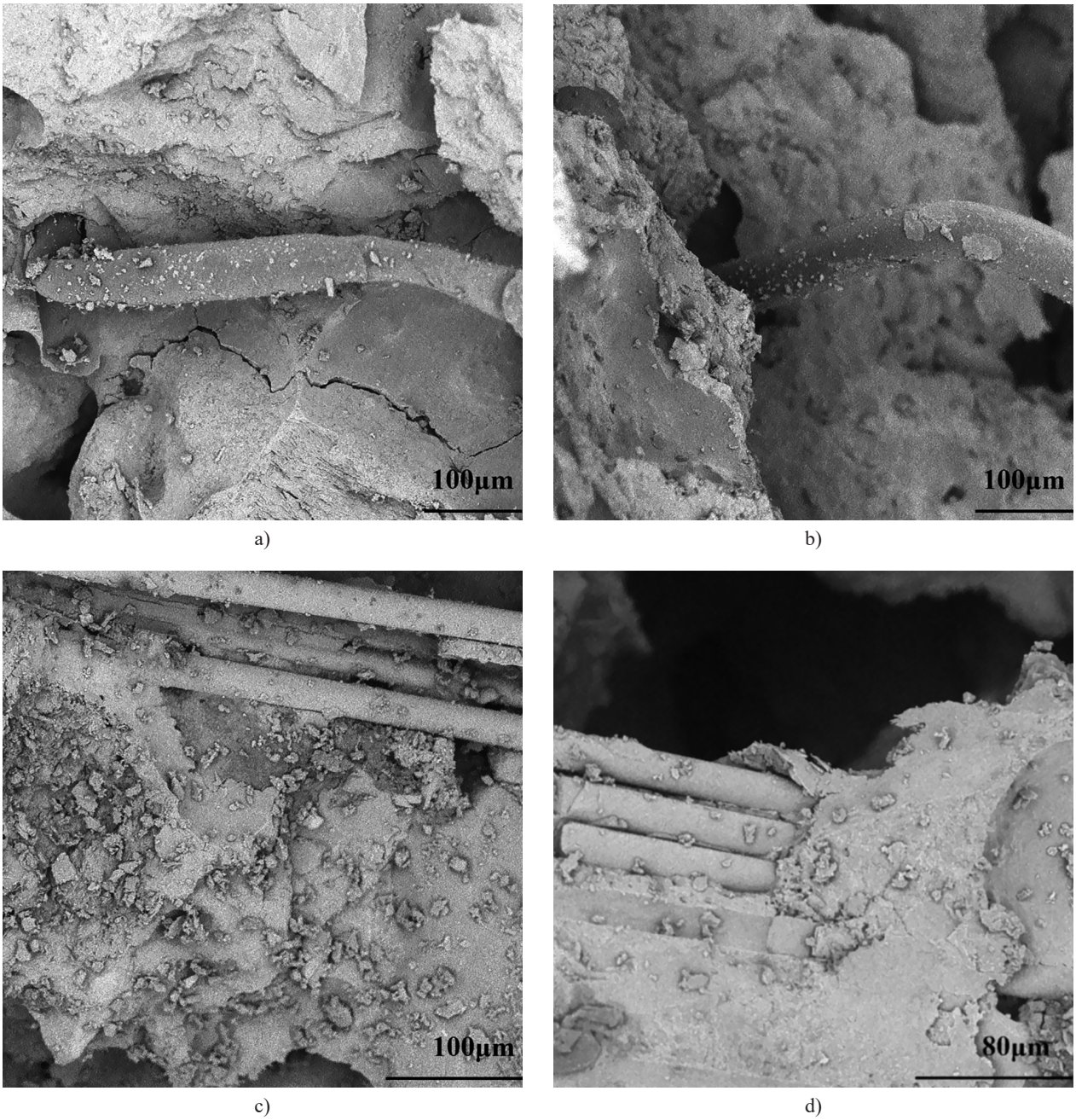
The freeze-thaw cycle tests found that the compressive strength and flexural strength loss rate of the mortar specimens were significantly reduced after adding steel fibres, and different lengths and dosages of fibres could inhibit the mortar degradation. Combining the enhancement effect of the steel fibres on the strength of the mortar specimens and the loss rate after the freeze-thaw cycles, it was observed that steel fibres with four lengths were more effective in enhancing the performance

of the mortar specimens compared to the incorporation of a single length of fibre. The rate of the strength loss decreased with the increase in the enhancement effect, at which time the improvement of the frost resistance was more significant.

Microstructure of the steel fibre mortar

Experiments have found that steel fibres can enhance the performance of mortar specimens to a certain extent, and many scholars have analysed the mechanism of the role of steel fibres. The theory of composite mechanics revealed [37] that steel fibres had a large modulus of elasticity. When the mortar is exposed to external forces, especially tensile forces, the fibres can effectively distribute the external forces and avoid stress concentrations within the mortar specimen, thus delaying damage. As shown in Figure 9a and Figure 9b, the cement slurry was damaged along the cracks, and the damaged cement slurry relied on the steel fibres to connect, ensuring that the cementitious materials and the steel fibres could work better together. Selecting steel fibres with a large surface area could improve the bonding of the fibres to the mortar materials.

From the fibre spacing theory, it was revealed [38] that factors such as the dosage and different lengths of



a) b)

c) d)

Figure 9. SEM of the steel fibre mortar.

steel fibres influenced the materials. Too low a dosage or too short fibres had no noticeable effect on the overall improvement of the sample. Too high a dosage or too long fibres in the sample production process results in an uneven and unidirectional fibre distribution. In addition, the fibres were not closely bonded to the cementitious materials in the part of the mortar with the high fibre content.

Besides, the fibres were not densely bonded to the cementitious materials in the fibre-intensive part of the mortar. It also made the mortar less fluid and caused the cementitious materials to become more porous, thus affecting the mechanics of its performance. As shown in Figures 9c and 9d, different lengths of steel fibres showed a higher gradient distribution in the cement slurry, longer steel fibres could provide greater tensile strength, and shorter fibres were more likely to be evenly distributed, making up for the shortcomings of the uneven distribution of long steel fibres.

CONCLUSIONS

The main conclusions of this study, according to the effect of steel fibres on the properties and frost resistance of mortar by mixing the same length by themselves and different lengths all at once are as follows:

- Steel fibres of 6 mm, 13 mm, 25 mm, and 30 mm improve the compressive strength and flexural strength of mortar at the dosage of 0.5 %, 1 %, 1.5 %, and 2 %. The most significant improvement in the compressive strength was obtained when the 25 mm fibre was mixed alone at a 1 % dosage, and the largest increase in the flexural strength was observed when the 25 mm fibre was mixed alone at a 1.5 % dosage.
- Mixing fibres of different lengths enhanced the mortar performance. The maximum values of the compressive and flexural strengths were achieved by mixing four lengths of fibres in equal proportions at a total dosage of 1 % and 1.5 %.
- According to the fibre direction effectiveness coefficient and electron microscope morphology, it was found that the fibre direction effectiveness coefficient of the mixed different lengths steel fibre mortar is smaller than that of single mixed 25 mm in length steel fibre mortar, which is closer to 0.5. The steel fibre dosage of 1 % and 1.5 % was more uniformly distributed inside the cement mortar, which effectively share some of the stresses when subjected to external forces, and improved the performance of the cement mortar more effectively.
- Through the freeze-thaw tests, it was noticed that different dosages and lengths of steel fibres were able to reduce the rate of the strength loss of the mortar to a certain extent. The greater the steel fibres enhance the performance of the mortar, the less its strength loss is and the better its frost resistance.

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