EFFECT OF MIXING METHODS ON THE DISPERSION PERFORMANCE OF TERNARY COPOLYMER FIBERS IN CONCRETE

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Based on the fiber dispersion and concrete compressive strength tests, the effects of mixing method, mixing time and fiber content on the dispersion performance of ternary copolymer fibers in concrete were studied. The experimental results show that a modified dry mixing method benefits the dispersion of the fibers in concrete and obtains a desirable mechanical performance as compared with wet mixing and ordinary dry mixing methods. With an increase in mixing time, the fiber dispersion coefficient and the compressive strength of concrete increased at initial stage and then decreased. In addition, the fiber dispersion coefficient and the compressive strength of concrete decreased with the increase of fiber content. Taking both the strength properties of the concrete and economic factors into consideration, the modified dry mixing method was considered the most desirable mixing method, with an optimum mixing time of 6 minutes and an ideal fiber content of 0.14%.

Keywords: *concrete; ternary copolymer fibers; dispersion; compressive strength*

1. Introduction

Concrete is one of the most widely used building materials, but its brittleness and low tensile strength restrict its application [1]. Many experimental studies [2-6] have verified that the incorporation of a proper amount of fibers in concrete can retard the expansion of concrete cracks and improves the toughness, impermeability and frost resistance of concrete, in turn enhancing its durability. Concrete has the advantage of high compressive strength under stress, and fiber has the advantage of high tensile strength [4, 5]. Thus, the comprehensive performance of concrete, such as bending, tensile, impact and abrasion resistance, were improved by mixing with fibers. However, to achieve these advantages of fiber reinforced concrete, the fibers need to be dispersed evenly within it and the concrete mixture should have a good workability [2, 7]. If the fibers are dispersed in the concrete unevenly, it could have side effect on the mechanical properties of the concrete.

In the past few years, several studies have been conducted to evaluate the dispersion of fibers in cement-based composites [8-14]. Based on AC-Impedance Spectroscopy (AC-IS), Woo et al. [8] used the intrinsic conductivity approach to assess the dispersion of steel fibers in cement composites. It has been observed that cement samples with steel fibers show two bulk arcs to the right of the low-frequency cusp. In addition to this, the AC-IS was sensitive to various dispersion states of fibers such as fiber formation, fiber separation and fiber orientation. Chung [9] studied the dispersion of short carbon and steel fibers in cement by electrical resistivity measurement, by analyzing the influence of admixtures and fiber surface treatment on fiber dispersion. The results indicated that acrylic particles dispersed more effectively than latex particles. It should be noted that the above two methods can only be used to analyze the fiber dispersion in cement-based composites where fibers are electrically conductive.

In recent years, the Scanning Electron Microscope (SEM) has been extensively applied in characterizing fiber dispersion in cement composites [10-13].Yazdanbakhsh and Grasley [10] used SEM to take image of carbon nanofibers in hardened cement samples. The SEM observations confirmed that the use of silica fume can stabilize the dispersion of carbon nanofibers in the cement paste. With the aid of SEM, the fracture surface of the cement-based composites using carbon fibers was observed by Wang et al. [11], whose results showed that with increasing fiber content, bending and tensile strength increased in cement samples with good fiber dispersion. Most recently, based on SEM observation and piezoresistance tests, research work carried out by

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Wang et al. [12] observed that, the addition of carboxymethylcellulose sodium (CMC) or silica fume can improve the dispersion of carbon nanofibers in cement paste, while the addition of granulated blast-furnace slag exhibits a negative influence. The influence of mixing methods on the dispersion of carbon fibers in cement-based composites has also been noted by Gao et al. [13]. Their X-ray computed tomography (CT) and SEM observations confirmed that cement samples cast with a pre-mixing method show better fiber dispersion than those made with post-mixing methods [13]. The results obtained by SEM are reliable, but it is difficult to reflect the dispersion of fibers in cement on a larger scale due to restrictions in the size of tested samples.

The most common technical methods of evaluating the dispersion performance of fibers in cement-based composites are SEM, CT and AC-IS. These techniques are mainly applied to detect conductive fibers such as steel [8, 9] or carbon fiber [9-14]. Non-conductive fibers (such as PVA fibers [15]) cannot be accurately detected; therefore, their dispersion in cement-based composites cannot be quantitatively evaluated. The works previously mentioned also focus on cement rather than concrete specimens. It seems that, compared with cement specimens, the coarse aggregate in concrete specimens had a disadvantageous influence on the dispersion performance of fibers.

This paper aims to study the dispersion of ternary copolymer fibers in concrete with three different mixing methods. A testing method based on the ASTM C1229-94 was proposed to characterize fiber dispersion in concrete. The effect of mixing methods, mixing time and fiber content on fiber dispersion in concrete was analyzed and the corresponding compressive strength of concrete specimens at 28d was tested.

2. Experimental

2.1 Concrete mix design

The research background of this work was a reclamation project on the coast of Zhejiang Province, China. Due to the requirements of this project, the designed concrete mix ratio used in this work had a strength grade of C30 with water-binder ratios of 0.45, 0.47 and 0.50. Marine cement has a grade of MEC 42.5 and an apparent density of 2,850 kg/m^3, the basic properties of the marine cement is presented in Table 1. For coarse aggregate, gravel with a particle-size range of 4.75~40 mm was adopted. For fine aggregate, river sand was collected from the Qiantang River in east China. The range of particle sizes for this aggregate was 0.15~4.75 mm and its apparent density was 2,650 kg/m^3. The concrete specimens were cast with local tap water with the addition of 1% water-reducing agent per weight of cementitious material. The ternary copolymer fiber, as shown in Fig.1, is mixed by three different special resins with best ratio and modified by special methods to form a composite, then, with drawing and twisting process to form the ternary copolymer fiber. The basic physical properties of ternary copolymer fiber are given in Table 2.

The properties of the concrete mixtures are presented in Table 3.

Fig.1 - Ternary copolymer fibers

Table 1

Basic properties of the marine cement

Compressive strength (MPa)		Flexural strength (MPa)		Setting time (min)		Specific area (m^2/kg)	MgO (%)	SO_3 (%)
3d	28d	3 d	28 d	initial set	final set			
22.8	50.5	4.7	8.1	176	243	451	4.91	0.96

Table 2

Physical properties of the ternary copolymer fibers

Initial modulus (MPa)	Tensile strength (MPa)	Elongation (%)	Density (g/m^3)	Nominal length (mm)	Equivalent diameter (mm)	Aspect ratio
≥12000	≥800	15~30	1.38	30~50	0.8±0.2	30~83

Table 3

Mixture proportions

No.	W/C	Concrete mixing ratio /(kg/m^3)					Fibers (%)
		Cement	Water	Sand	Coarse aggregate	Water reducing agent	
A0	0.45	494	223	665	919	4.94	0
A	0.45	494	223	665	919	4.94	0.14
B0	0.47	473	223	659	945	4.73	0
B	0.47	473	223	659	945	4.73	0.14
C0	0.50	445	223	685	946	4.45	0
C	0.50	445	223	685	946	4.45	0.14

2.2 Mixing methods

In order to study the effect of mixing methods on the dispersion performance of ternary copolymer fibers in concrete, three different mixing methods were adopted in this work as follows:

(1) Ordinary dry mixing method (M1)

Sand, coarse aggregate and fibers were mixed evenly, and then cement was added. Water and water reducing agent were then added and the mixture was stirred.

(2) Modified dry mixing method (M2)

Sand, coarse aggregate and fibers were mixed evenly, and then 70~75% of the water and water reducing agent were added. Next, the cement was added, then finally the remaining water and water-reducing agent were added and the mixture was stirred.

(3) Wet mixing method (M3)

Sand, coarse aggregate and cement were mixed evenly, and then water and water reducing agent were added. Finally, the fibers were added and the mixture was stirred.

2.3 Testing method

As the ternary copolymer fiber is a type of insulation material, and taking the ASTM C1229-94 into consideration, a modified testing method proposed by and utilized in this work is as follows:

1) The concrete mixture was poured into a 50 L container and stirred with water, and then the mixture was filtered through a 0.63 mm standard sieve. The fibers on the sieve were collected, the filtrate was retained and the concrete slag was left in the original container. This procedure was repeated twice.

2) The filtrate that collected during the first step was filtered through a 0.16 mm standard sieve, and the fibers on the sieve were collected.

3) The concrete slag retained in step 1 was filtered through a 10.0 mm standard sieve, and the standard sieve was placed on a 50 L container. The concrete slag was repeatedly rinsed with water and the coarse aggregate was retained on the sieve while the cement, sand and fibers were allowed to fall into the container.

4) The small amount of fibers that attached to the coarse aggregate were collected and the coarse aggregate was then discarded.

5) The mixtures remaining in the container from step 3 were filtered through a 0.63 mm standard sieve, the fibers were collected and the filtrate was retained. The remaining solid mixture in the container was stirred with water, filtered and then the fibers were collected. This procedure was repeated three times until the solid mixtures no longer contained the fibers, at which point the solid mixtures were discarded.

6) The filtrate retained in step 5 was filtered through a 0.16 mm standard sieve, and the fibers on the sieve were collected.

7) The fibers collected in the above steps were dried in an oven at 105 °C, and then weighed and recorded.

The recorded data was calculated as follows:

$$\psi(x) = S(x) / \overline{x} \quad (1)$$

$$\beta = e^{-\psi(x)} \quad (2)$$

where $S(x)$ is standard deviation and $\overline{x}$ is the mean value of the fiber mass fraction from the three samples.

The coefficient of variation ($\psi(x)$) and fiber dispersion coefficient (β) were introduced to reflect the dispersion performance of the fibers in concrete. The closer $\psi(x)$ is to 0, the closer β is to 1 and the better dispersion performance of fibers in the concrete.

3. Results and discussion

3.1 Effect of mixing methods

According to the concrete mixing ratio listed in Table 3, 7L of concrete mixtures were prepared with the addition of 0.14% of ternary copolymer fibers. The mixture was stirred for 6 minutes. Three concrete samples of similar weight were selected to analyze the dispersion performance of ternary copolymer fibers in concrete.

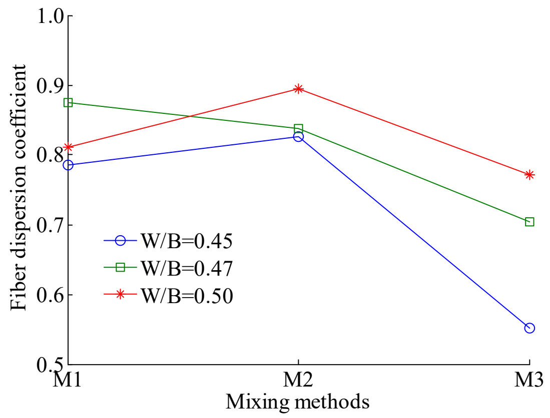

Fig.2 - Fiber dispersion coefficient.

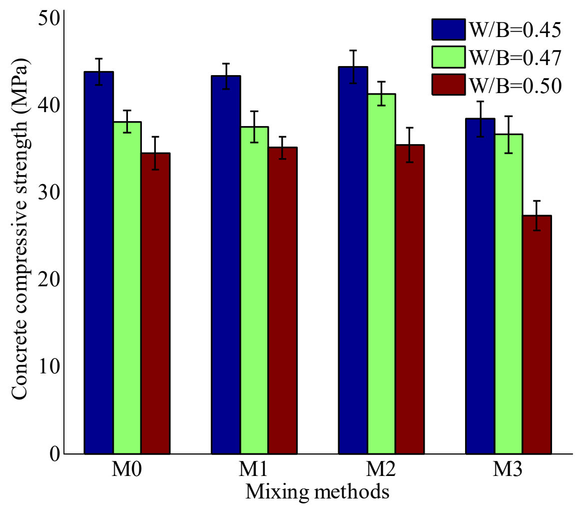

Fig.3 - Concrete compressive strength.

Meanwhile, three standard cube specimens with a size of 150×150×150 mm were cast and the compressive strength at 28d were tested. The corresponding fiber dispersion coefficient and the concrete compressive strength with different mixing methods are demonstrated in Fig. 2 and Fig. 3, respectively.

It can be seen from Fig. 2 that the fiber dispersion coefficient (β) remained in the range of 0.85±0.05 when the concrete was cast with the modified dry mixing method. As mentioned above, the higher value of β indicates the better dispersion performance of fibers in concrete. Hence, it seems that the concrete cast by modified dry mixing methods exhibits the best fiber dispersion. Fig. 2 shows that although the fiber dispersion performance of the ordinary dry mixing method is not as good as the modified dry mixing method, the difference between these two methods is not so great. Poor fiber dispersion performance has been observed when concrete is mixed using the wet mixing method. The fiber dispersion coefficient obtained by the wet mixing method is less than 0.80, and when the water-cement ratio is 0.45, the corresponding fiber dispersion coefficient is only 70% of that obtained with the modified dry mixing method. This can be attributed to the fact that, in the dry mixing methods, the fibers are first mixed with the sand and coarse aggregate, in which they easily disperse [16-18]; then, when the cement is added, the small cement particles can also scatter easily amongst the fibers during the stirring process [16-18] so that the fibers are well dispersed before the addition of water. In the wet mixing method, small agglomerated cement particles formed together before fibers are added, so that it is difficult for them to scatter amongst the fibers; moreover, the ternary copolymer fibers have strong hydrophobicity, which makes it difficult for the fibers to disperse in the concrete mixture. Therefore, the concrete cast by the wet mixing method exhibits poor fiber dispersion performance. Abtahi et al. [19] also noted that the dry mixing method is the easiest to perform and allows for the best fiber distribution in the mixture.

So we have established that the concrete cast by dry mixing methods shows better fiber dispersion performance than those cast with wet mixing methods. Correspondingly, as Fig. 3 illustrates, the compressive strength of concrete specimens cast by dry mixing methods are also higher than those cast by wet mixing methods. In particular, it can be seen from Fig. 3 that when the water-cement ratio is 0.50, the compressive strength of concrete specimens at 28d is only 27.3MPa, failing to meet the design requirement of 30MPa. The flocculent structure and hydrophobic properties of ternary copolymer fibers are not conducive to their dispersion in the concrete mixtures; this fact coupled with an improper mixing method led to an increase of fiber clumping or balling, which in turn weakened the interfacial bond strength between the fibers and the concrete, increasing the porosity of the concrete [20, 21]. As a result, the compressive strength of the concrete was reduced. Additionally, as shown in Fig. 3, compared with plain concrete (that does not contain fibers), the compressive strength of fiber concrete cast using the modified dry mixing method has slightly improved, although the increase is not significant. The compressive strength of fiber concrete cast with the ordinary dry mixing method has slightly decreased, but again, the size of the decline is not large. This suggests that concrete incorporating the appropriate amount of ternary copolymer fibers and cast with dry mixing methods does not have significantly reduced compressive strength. We can conclude that the modified dry mixing method is beneficial to the even dispersion of ternary copolymer fibers in concrete and obtains a desirable mechanical performance from the concrete specimens.

In the following sections, the concrete will be cast using the modified dry mixing method.

3.2 Effect of mixing time

The fiber dispersion coefficient and the corresponding compressive strength of concrete specimens at 28d using different mixing times are shown in Fig. 4 and Fig. 5 respectively.

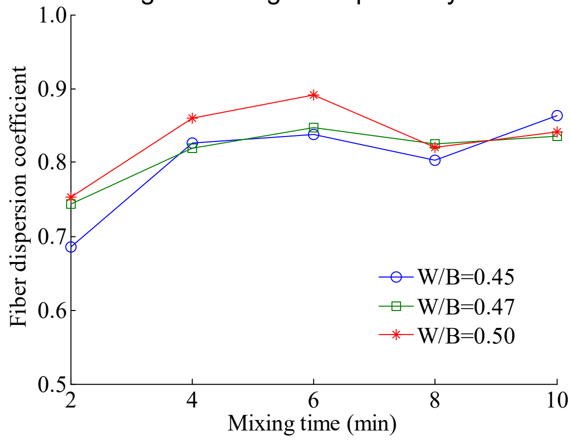

Fig.4 - Fiber dispersion coefficient.

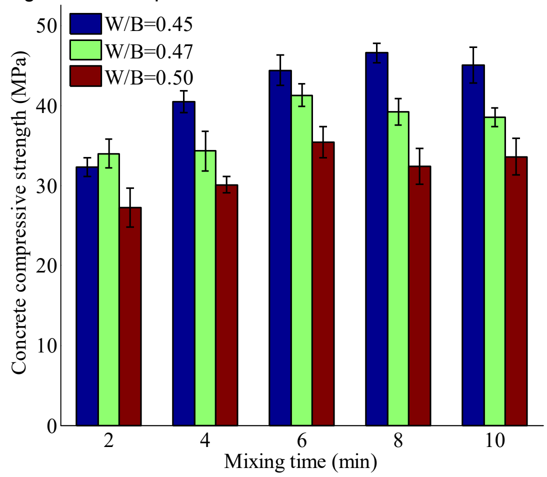

Fig.5 - Concrete compressive strength.

It can be seen from Fig. 4 that the fiber dispersion coefficient increases as mixing time at the initial stage increases. When the mixing time is more than 6 minutes, the fiber dispersion coefficient begins to decrease, but when the mixing time exceeds 8 minutes, the fiber dispersion coefficient once again increases with the increase of mixing time. According to this pattern, the mixing process may be divided into three stages: in the first stage, the cement is mixed with fibers, and the cement particles are gradually scattered among the fibers as mixing time increases. Balázs et al. [20] reported that increasing mixing time results in more even mixing of materials in concrete. Consequently, the fiber dispersion coefficient also increases. At the next stage, the friction coefficient between the materials is raised, so that the resistance during the stirring process is also increased. To continue stirring would result in fiber clumping or balling, thereby reducing the fiber dispersion coefficient. In the third stage, as the mixing time continues to increase, the clumps or balls of fibers disintegrate into smaller groups due to fibers being damaged, so the fiber dispersion coefficient increases again.

The compressive strength of the concrete specimens also increases as mixing time at the initial stage increases, as shown in Fig. 5. The compressive strength changes slightly when the mixing time is more than 6 minutes. Moreover, by comparing Fig. 3 and Fig. 5, we can see that the compressive strength of fiber concrete is almost the same as plain concrete. This can be attributed to relatively short mixing times not only restricting the even dispersion of fibers in concrete, but also limiting the sticking of cement paste to the aggregate, which in turn causes an uneven mixture of materials in the concrete [20], thereby reducing its compressive strength. However, when the mixing time exceeds a certain level, the aggregate has been fully mixed into the cement paste [21], and in this case, the dispersion performance of the fibers in the concrete becomes the primary factor that influences the compressive strength of the concrete. However, as mentioned earlier, the compressive strength of concrete incorporating the appropriate amount of the ternary copolymer fibers and cast with the modified dry mixing method is seemingly not affected. Consequently, as Fig. 4 shows, the compressive strength of concrete with a different water-cement ratio stabilizes when the mixing time exceeds 6 minutes.

Determining the optimum mixing time involves achieving a relatively large fiber dispersion coefficient, and damage to the fibers should also be minimized. When the mixing time is more than 10 minutes, the fiber dispersion coefficient may be even higher than it is at 6 minutes; however, prolonging the mixing time would increase not only the damage sustained by the fibers but also the power consumed, both of which are undesirable effects. Altoubat et al. [22] also suggested that the mix design of concrete should not only consider the practicality of the concrete itself but also the most economically attractive option. Therefore, as Fig. 4 illustrates, the first inflection point (with a mixing time of 6 minutes) can be considered as the best mixing time.

3.3. Effect of fiber content

In order to clarify the influence of fiber content on fiber dispersion performance and compressive strength, the fiber dispersion coefficient of concrete mixtures and the corresponding compressive strength of concrete specimens at 28d with varying dosages of ternary copolymer fibers are shown in Fig. 6 and Fig. 7 respectively.

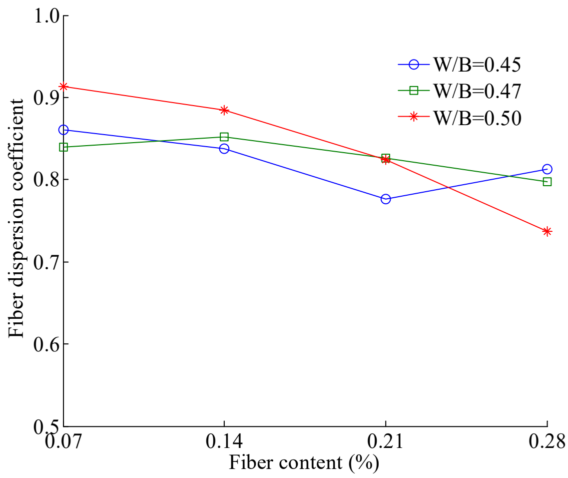

Fig.6 - Fiber dispersion coefficient.

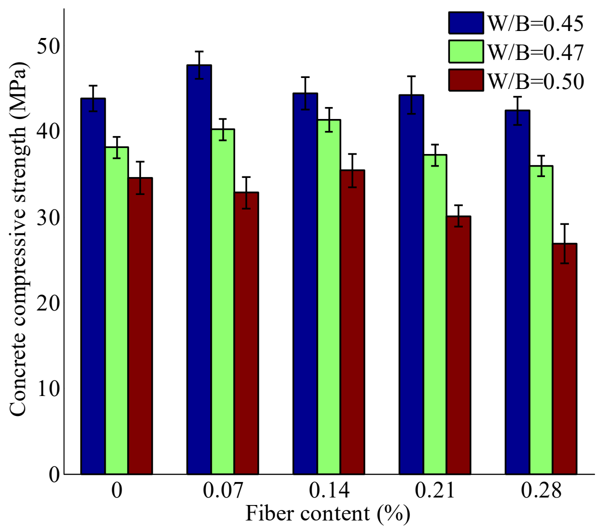

Fig.7 - Concrete compressive strength.

As Fig. 6 clearly illustrates, the fiber dispersion coefficient decreases as the fiber content increases. Taking concrete with a water-binder ratio of 0.50 as example, its fiber dispersion coefficient decreases by at least 20% when the fiber content is increased from 0.07 to 0.28%. This may be due to the fact that, using the same mixing method, the potential of fiber clumping or balling increases with the increase of fiber content, thereby affecting fiber dispersion. Research carried out by Figueiredo and Ceccato [23] and Cao et al. [2] confirmed that increasing the fiber content greatly reduces the mobility of fibers in concrete. Consequently, the potential for fiber clumping or balling in concrete mixtures is increased.

It can be seen from Fig. 7 that the influence of fiber content on compressive strength is only significant when the fiber content is more than 0.14%. For concrete with a water-binder ratio of 0.50, the compressive strength with a fiber content of 0 and 0.14% are almost the same, about 35MPa, while when the fiber content raised to 0.28%, the corresponding compressive strength is only 27MPa. This verifies once again that the compressive strength of concrete is not affected when an appropriate amount of ternary copolymer fibers is added. However, with the addition of excessive amounts of ternary copolymer fibers, the mobility of the materials in the concrete mix is reduced [17, 24] and the clumping or balling of fibers during the stirring process leads to uneven fiber dispersion, which in turn not only weakens the interfacial bond strength between the concrete and fibers but also increase the air voids in the concrete, thereby reducing its compressive strength. The same trend has been observed by Balázs et al. [20], i.e. the compressive strength reduces as the fiber content increases, while Oliveira et al. [25] reported that fiber content does not significantly influence the compressive strength of concrete as compared with water-binder ratio, which is also confirmed by the observational results of Fig. 7 in this work. In addition, Fig. 8 demonstrated the influence of fiber content on the concrete slump. As Fig. 8 vividly shows, the slump of concrete mixture decreased significantly with the addition of ternary copolymer fiber, especially when the fiber content exceeded 0.14%. Therefore, it can be concluded that the most desirable dosage of ternary copolymer fibers is 0.14%.

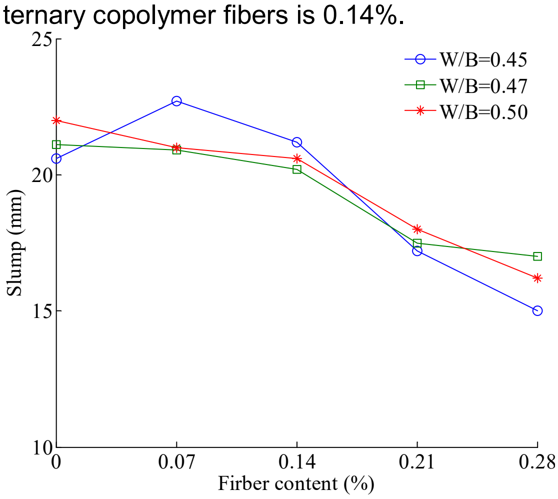

Fig.8 - Concrete slump

4. Conclusions

In this work, the influences of mixing method, mixing time and fiber content on the dispersion performance of ternary copolymer fibers in concrete have been studied on the basis of the fiber dispersion test and the concrete compressive strength test results, the following conclusions are drawn,

(1) Compared with the wet mixing method and the ordinary dry mixing method, the modified dry mixing method is beneficial to the even dispersion of ternary copolymer fibers in concrete mixtures, and also obtained a desirable mechanical performance from the concrete specimens.

(2) The fiber dispersion coefficient and the compressive strength of concrete initially increases but then decreases with the increase of mixing time. Moreover, the fiber dispersion coefficient and the compressive strength of concrete decrease with the increase of fiber content.

(3) The modified dry mixing method should be adopted for ternary copolymer fibers reinforced concrete, with an optimum mixing time of 6 minutes and an optimum fiber content of 0.14%. The specific mixing method is sand, coarse aggregate and fibers being mixed for 120 seconds, then 70~75% of the water and water reducing agent being added and the mixture being stirred for 60 seconds. Cement should then be added and stirred for 60 seconds. Finally, the remaining water and water-reducing agent should be added and the mixture stirred for a further 120 seconds.

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MANIFESTĂRI ȘTIINȚIFICE / SCIENTIFIC EVENTS

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To address the aforementioned challenges, the first international conference on Innovation in Low-Carbon Cement and Concrete technology (ILCCC) will be held on the 24 - 26th June 2019 in London. The conference aims at exchanging the latest global scientific and technical achievements on low-carbon cement and concrete technology in order to promote their wide industrial applications.

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- Low-carbon cement and concrete technology based on non-Portland cement systems (e.g., alkali-activated cement and concrete, calcium sulfoaluminate, and MgO-based systems, etc.)
- Chemical admixtures for low-carbon cement and concrete
- Durability of low-carbon concrete
- Standards and specifications for low-carbon cement and concrete

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