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Damage Processes of Polypropylene Fiber Reinforced Mortar in Different Fiber Content Revealed by Acoustic Emission Behavior

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Abstract: The performances of the cement-based materials can be improved by the incorporation of polypropylene fiber, but the damage processes become more complex with different fiber contents at the same time. The acoustic emission (AE) technology can achieve the global monitoring of internal damage in materials. The evolution process of failure mode and damage degree of polypropylene fiber reinforced mortar and concrete were analyzed by measuring the AE energy, RA value, AF value and *b* value. It was found that the cement matrix cracked on the initial stage, the cracks further developed on the medium stage and the fibers were pulled out on the last stage. The matrix cracked with minor injury cracks, but the fiber broke with serious damage cracks. The cumulative AE energy was proportional to the polypropylene fiber reinforced concrete and mortar's ductility. The damage mode and damage degree can be judged by identifying the damage stage obtained by the analysis of the AF value.

Key words: polypropylene fiber; different content; mortar; concrete; acoustic emission; damage processes

1 Introduction

Cement-based materials have weaker tensile strength, flexural strength, impact strength and energy-absorption capacity, as well as brittleness. So the structure is prone to crack in the condition of changed temperature or load[1,2], which affects the construction performance such as, waterproof, anti-permeability and durability, *etc*. The performance such as the splitting strength, tensile strength, compressive strength, flexural strength, rigidity, anti-permeability, crack resistance, wear resistance, ductility, durability and energy absorption ability could be improved by the incorporation of polypropylene fiber[3-9], but the increase of the compressive strength and flexural strength was not obvious[6,8], and the total porosity of the material would be slightly increased[10, 11].

Nia pointed out that the fiber content is an important parameter which affects the performance of concrete[12] and Jianhua pointed out that fiber content has great influence on the material's mechanical properties[13]. The internal stress distribution and damage process become more complicated due to the heterogeneity and the inhomogeneity of the material, which brings difficulties to the research on the properties and damage process of fiber reinforced cement based materials. In order to clarify the above problems, some deep research has been conducted by scholars. It was found that structure's freeze-thaw ability, dry shrinkage, refractoriness, water penetration length, carbonation depth, slump, elastic modulus decrease as the polypropylene fiber content increases[5,14,15]. With the further increase of polypropylene fiber content, the fire resistance would continue to decrease[16] and dry shrinkage reduced less obviously[17]. The splitting strength, flexural strength, impact strength, stiffness, failure energy and effective cracking width increased in pace with polypropylene fiber content[18,19]. The entirety and long-term tensile strength of low content polypropylene fiber reinforced concrete were better[20], but ductility decreased[21]. Kakooei found that the compressive strength and permeability of concrete in 1.5 kg·m^{-3} content were better than other content[22]. Singh designed fiber pull out test to conduct preliminary research on the role of the fiber which improved material's ductility[23].

It should be noted that the above studies focus more on the mechanical properties and materials per-

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formance of the polypropylene fiber materials, less on the damage processes. But acoustic emission (AE) technology can achieve the global monitoring of internal damage in materials. Additionally, it can obtain the damage AE characteristics of cement-based materials by the analysis of real-time monitoring signals. Wang conducted the analysis for polypropylene fiber reinforced concrete fatigue failure process by AE parameters such as hits, amplitude and energy[24]. Wu divided the steel fiber reinforced concrete failure processes into 9 different damage mechanisms based on the AE duration[25]. Kim found that the change of the AE cumulative energy can be used to describe the development of cracks[26]. Different failure mechanisms can produce different AE signals which can be identified by AE characteristic parameters[27], the cumulative AE energy and *b* value is closely related to the damage process and damage degree, and the change laws of the RA and AF values can characterize damage pattern.

The axial compression test recorded the whole damage process AE signals of five different content of polypropylene fiber reinforced mortar and four different content of polypropylene fiber reinforced concrete. The paper analyzes the relationship between the cumulative AE energy, *b* value and damage processes. And the influence on the damage processes produced by the change of polypropylene fiber content was analyzed. Corresponding relationship between damage pattern and AF as well as RA values was analyzed. And the influence on the damage pattern by different fiber contents was analyzed. Finally, the relationship between cumulative AE energy and ductility was analyzed, and the feasibility to judge the failure pattern and the damage degree based on the failure stage was studied as well.

2 Experimental

In order to analyze the AE characteristics of polypropylene fiber reinforced mortar and concrete specimens with different contents in the process of damage, five contents were designed for mortar, four contents were designed for concrete; Plain mortar and plain concrete group were set-up in order to reveal the effect of polypropylene fiber on the damage mechanism and other four kinds for illustrating the different AE characteristics caused by different contents. Actually, a batch of the same materials were used in the test, the preparation of the test specimens and the loading method were the same, so that the difference of the AE characteristics resulted from the different fiber contents.

2.1 Specimens preparation

Forty five mortar mixtures and thirty-six concrete mixtures were produced in total. Each mixture included nine specimens. The specimens' size was 100 mm× 100 mm× 100 mm as typically used for axial compression test. The specimens were cured under standard conditions for 28 days. In order to conduct comparative analysis of different contents, the polypropylene fiber content for mortar varied from 0% (plain mortar) to 0.5%, 1%, 1.5% and 2%; And that for concrete varied from 0% (plain mortar) to 0.5%, 1% and 1.5%. Main characteristics of polypropylene fiber are shown in Table 1. Tests were conducted to make it separate when inputting the fiber into the mortar, otherwise it may easily lead to fiber agglomerate phenomenon.

2.2 Apparatus and system parameter setting

Fig.1 shows the test apparatus, test specimens and press plate surface should be wiped clean before test. The load was applied at a constant rate of 0.3 Mpa/s and loading was automatically terminated at the moment of load drop. The type of YAW4306 microcomputer controlled electro-hydraulic servo pressure testing machine was used in the test.

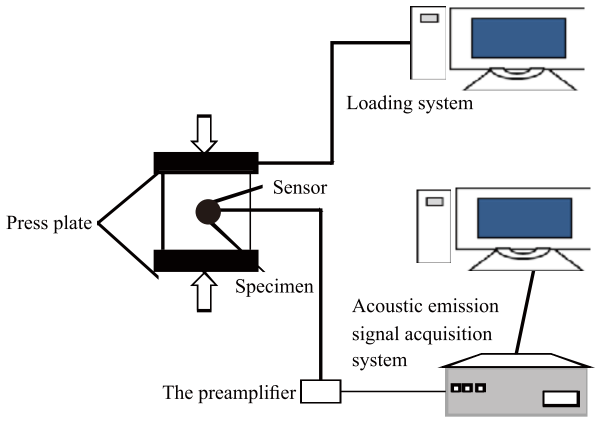


Fig.1 Schematic diagram of the experimental apparatus

As to AE monitoring, one AE broad band sensor was fixed on the center of the specimen surface by the rubber band. Additionally, the surface of specimen which placed sensor should be ground smooth and

Table 1 Properties of polypropylene fiber

Shape	Diameter/μm	Length/mm	Density/(g/cm^3)	Tensile strength/MPa	Modulus/MPa
Single bundle	18-48	6	0.91	>500	>3 850

coated with Vaseline in order to obtain the high quality of AE signals. The signals were recorded in one-channel monitoring board PCI-2; PAC with a sampling rate of 5 MHz, band-pass filter was 1 kHz - 3 MHz. The threshold was set as 35 dB to avoid environmental noise and the acquired signals were pre amplifier by another 40 dB, bandwidth was 10 kHz - 2.0 MHz.

3 Mechanical properties

Three small discrete specimens were selected from 9 specimens for each of content, and the specimen's number and average strength are shown in Fig.2. It was found that the average strengths of polypropylene fiber reinforced mortar and concrete were in the range of 34-39 MPa. The compressive strength of 0.5%, 1.0% and 1.5% polypropylene fiber reinforced mortar is lower than that of the plain mortar about 7%, but that with 2% is higher than that with about 4%. The compressive strength of that with 0.5%, 1.5% and 1% polypropylene fiber reinforced concrete is higher than that of the plain concrete with about 4%, 7% and 8% respectively. This shows that the addition of polypropylene fiber has no significant improvement on the compressive strength of mortar and concrete.

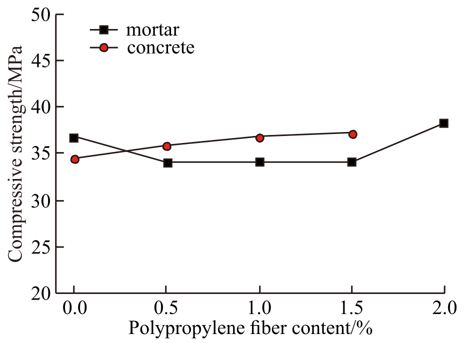


Fig.2 Compressive strength of polypropylene fiber reinforced mortar and concrete

Polypropylene fiber is a kind of low elastic modulus fiber. It is difficult to bear large stress in the matrix material, so it has little effect on the compressive strength. Polypropylene fiber plays the role in two aspects. On the one hand, the fiber could restrain the crack of the matrix, which would improve the strength of the specimen. On the other hand, the increase of the original defects would decrease it. The strength of the specimen was the result of two aspect actions. There was slight change in the strength of the fiber reinforced mortar specimens with different fiber contents, but the failure process was significantly different.

4 Analysis of the AE characteristics and damage processes

4.1 Cumulative AE energy curve

The cumulative AE energy curves are shown in Fig.3. In order to facilitate the analysis of the AE cumulative energy characteristics in different content polypropylene fiber, the curves were divided into three stages: A stage (0-15% stress level), B stage (15%-90% stress level) and C stage (90%-100% stress level).

On A stage, the cumulative AE energy of polypropylene fiber reinforced mortar and concrete is lower than that of the plain mortar and plain concrete respectively, and higher fiber content leads to lower cumulative AE energy. Because the initial stage is mainly the development of crack of the matrix and the original defects, and some of the destruction of the aggregate for concrete specimens, the AE energy shows rapid growth trend. The higher cumulative AE energy of plain mortar indicated that the main role of fiber is to prevent the development of crack to cause defects. And the crack resistance is enhanced with increasing fiber content. Therefore, using fiber reinforced materials has been suggested as an effective way to alleviate the early cracking of concrete[28, 29].

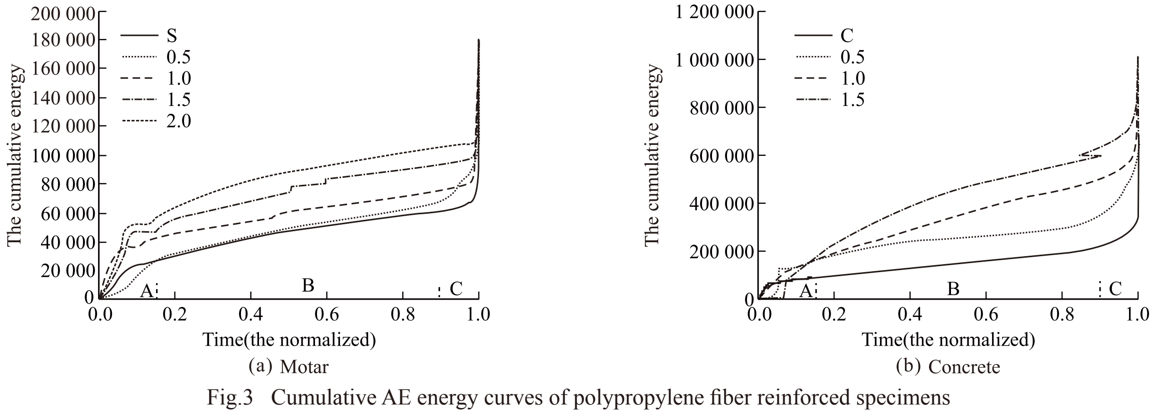
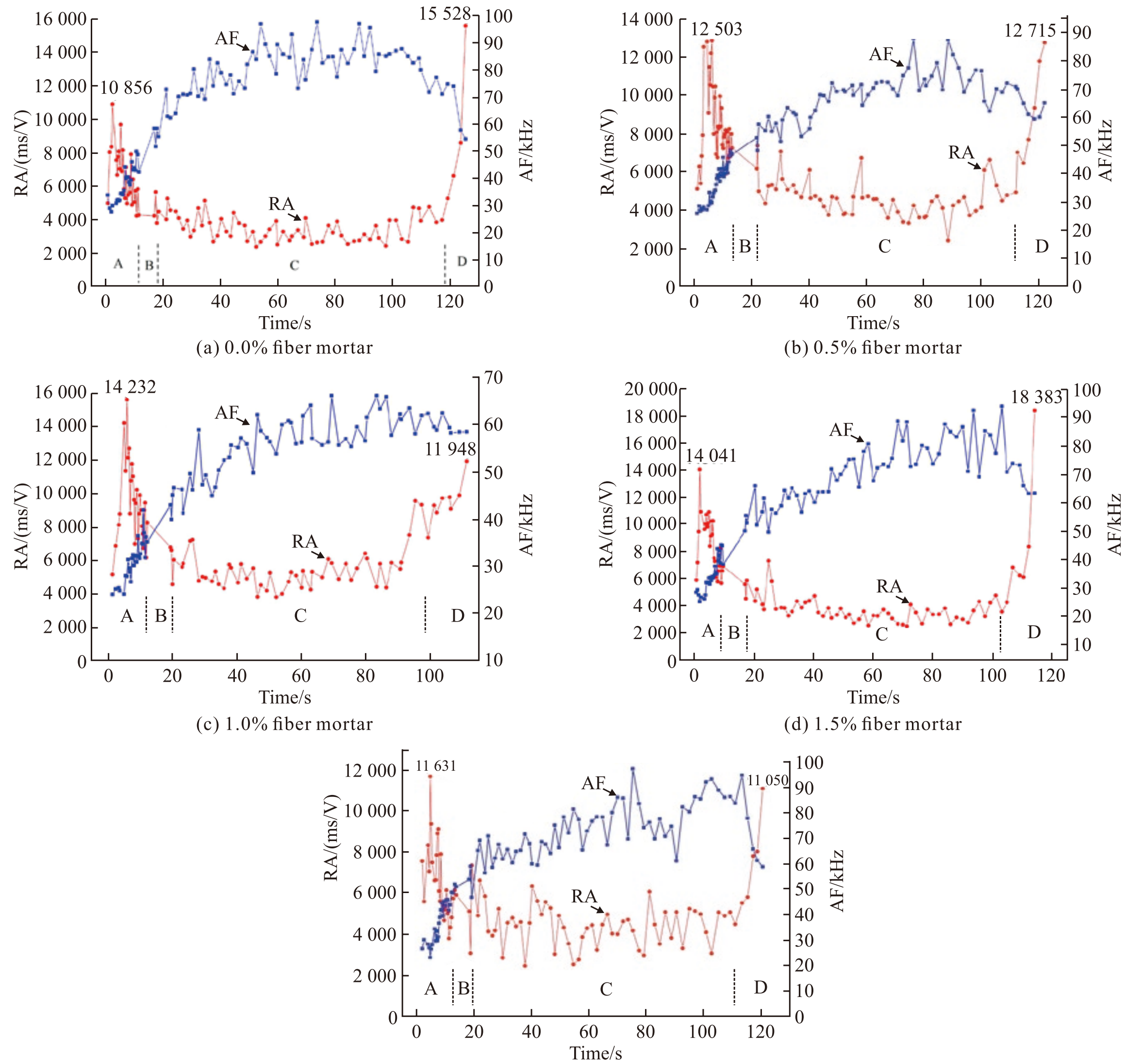


Fig.3 Cumulative AE energy curves of polypropylene fiber reinforced specimens



(a) 0.0% fiber mortar (b) 0.5% fiber mortar (c) 1.0% fiber mortar (d) 1.5% fiber mortar (e) 2.0% fiber mortar

Fig.4 Curves of RA and AF values of different content polypropylene fiber reinforced mortar

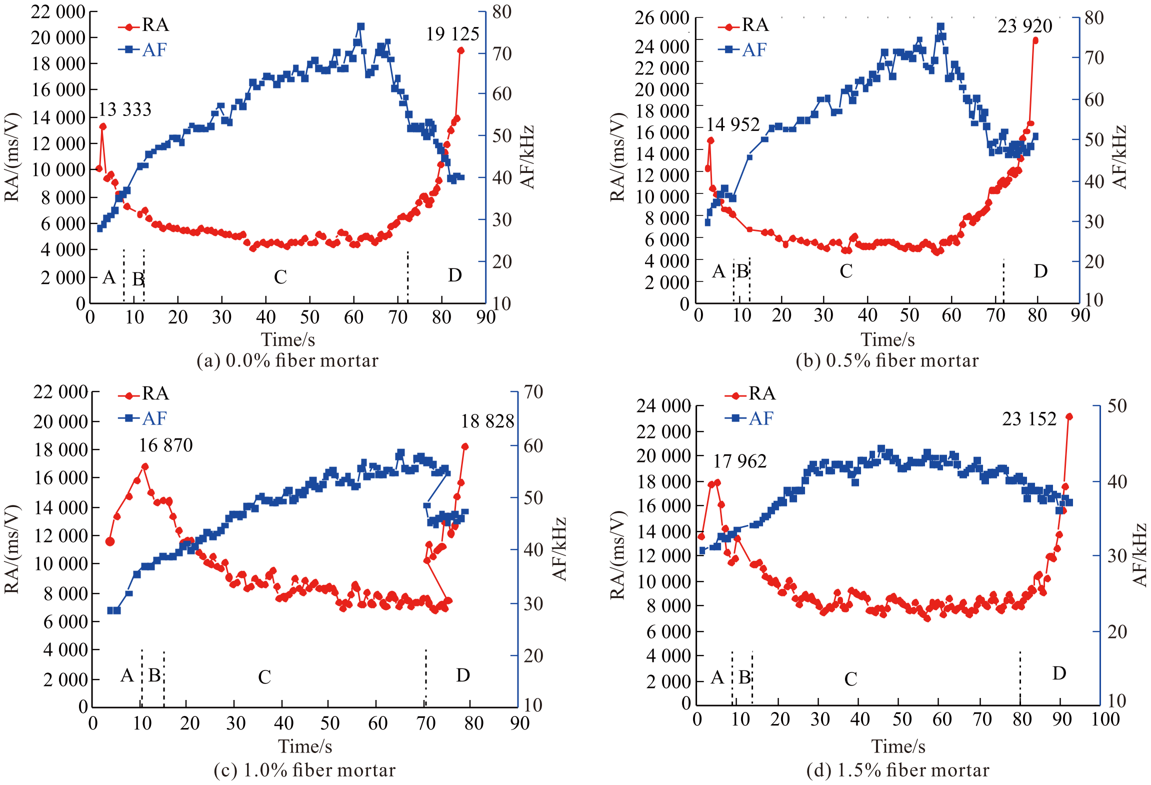
On B stage, the cumulative AE energy of polypropylene fiber reinforced mortar and concrete starts to exceed that of the plain mortar and plain concrete respectively, and the AE energy increases with increasing fiber content. On this stage, the matrix further cracks and fiber begins to deform which absorbs energy, so the trend is relatively slow, the more fiber content the higher absorption capability.

On C stage, the cumulative AE energy of the polypropylene fiber reinforced mortar still exceeds that of plain mortar and plain concrete respectively, and the AE energy increases with increasing fiber content. Fibers were pulled out or broke in this stage, the energy stored by the fiber deformation released soon in the failure time, the higher fiber content, the higher energy released. Particularly, that with 2% content was the most obvious.

4.2 RA and AF values

Studies show that[30-32] corresponding relationship between RA and AF values can be used for the classification of crack type, RA value which is the rise time over the amplitude, measured in ms/V. AF is the number of threshold crossing over the duration of the signal, measured in kHz. When the RA value is high, the AF value is low, which can be thought of as a shear crack. On the contrary, when the RA value is low, the AF value is high, which can be considered as tensile crack. In this paper, we select 100 consecutive points as a point to reduce the discreteness of the computational results.

Different contents of polypropylene fiber reinforced mortar and concrete RA and AF values with time are shown in Fig.4 and Fig.5. In order to judge the failure mode of different stages by RA and AF values, it were divided into four stages, A stage (0%-10% stress



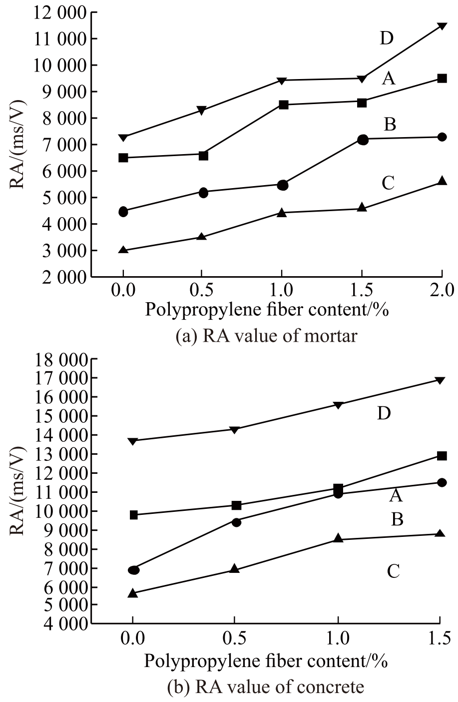
(a) 0.0% fiber mortar
(b) 0.5% fiber mortar
(c) 1.0% fiber mortar
(d) 1.5% fiber mortar

Fig.5 Curves of RA and AF values of different content polypropylene fiber reinforced mortar

level), B stage (10%-15% stress level), C stage (15%-90% stress level), and D stage (90-100% stress level).

The change trend of the RA value is contrary to that of the AF value, the RA value decreases while the AF value increases on the A stage, the failure pattern is gradually dominated by the tensile. On the C stage, RA value is maintained at a low level but AF value is maintained at a high level, dominated by the tensile failure. In the D stage, the RA value rises sharply, the AF value decreases rapidly, failure pattern is gradually dominated by the shear.

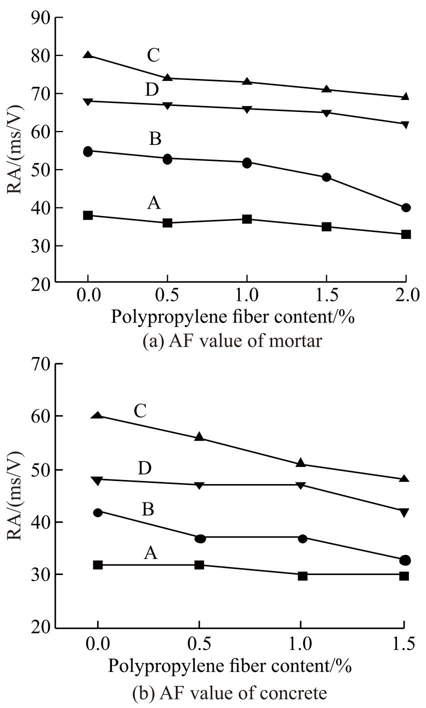
Compared with the plain mortar, the extreme points of the RA values of four contents of polypropylene fiber reinforced mortar are higher, 15%, 31%, 29%, 7% respectively on the A stage, showing that shear damage is more significant after the incorporation of polypropylene fiber. But the improvement effect does not increase with the increase of the fiber content, first increases and then decreases. Compared with plain concrete, the extreme points of the RA values of three contents of fiber concrete are higher, 12%, 27% and 35% respectively on the A stage, which shows that the shear failure is more obvious. On the C stage, the RA value of polypropylene fiber reinforced mortar (3 000-6 000 ms/V) is higher than that of the plain mortar (2 000-4 000 ms/V); The RA value of polypropylene fiber reinforced concrete (5000-9 000 ms/V) is higher than that of the plain concrete (4 000-6 000 ms/V). It is showed that the tensile pattern has developed into the shear pattern with the addition of polypropylene fiber. On the D stage, the occurrence of macro cracks is accompanied by fiber pull-out which belongs to the shear failure.



(a) RA value of mortar
(b) RA value of concrete

Fig.6 Relationship between average RA value and polypropylene fiber content for fiber reinforced specimens in different stage

Figs.6(a) and 6(b) show the relationship between average RA value and polypropylene fiber content for fiber reinforced mortar and concrete specimens on different failure stages. From Fig.6.1, it can be seen that the average RA value of polypropylene fiber reinforced mortar and concrete increases with the increase of fiber content, the average RA value is relatively steep on the D stage, which shows that the fiber content has significant influence on the RA value on the D stage. From Figs.7(a) and 7(b), it can be seen that the average AF value of polypropylene fiber reinforced mortar and concrete decreases with the increase of fiber content, the average AF value is relatively steep on the C stage, which shows that the fiber content has significant influence on the AF value on the C stage. Comparing Fig.6(a) with Fig.7(a), it can be found that the growth of RA value is steep and the decrease of AF value is slow with the increase of the polypropylene fiber content. It means that the change of polypropylene fiber content has great effect on RA value in each stage, while has relatively small effect on AF value. Compared to the RA value, the AF value was used to identify the different contents of polypropylene fiber reinforced mortar specimens damage stage that would get excellent results. The conclusion is also applicable to the polypropylene fiber reinforced concrete from the analysis of Fig.6(b) and Fig.7(b).



(a) AF value of mortar

(b) AF value of concrete

Fig.7 Relationship between average RA value and polypropylene fiber content for fiber reinforced specimens in different stage

4.3 AE based *b* value

In addition, it can be used to analyze the fracture process of the fiber reinforced mortar based on the variation of the AE based b value. The formula of b value in the AE technology is[33]:

$$\log N = a - b(A_{dB}/20) \quad (1)$$

where A_{dB} is the peak amplitude of AE events in decibels, N is the increment frequency, that is the number of AE events with amplitude greater than the threshold, a is the empirical constant and b is the AE based b value.

By Formula (1), b value is calculated by the distribution of amplitude. The more the low amplitude AE events the larger the b value, and the more the high amplitude AE events the smaller b value, so the b value represents the proportional relationship between small amplitude events and large amplitude events[34]. Generally, micro cracks generate a large number of low amplitude events, b value becomes large, and macro cracks are accompanied by a large number of high amplitude AE events, and b value becomes small. Alireza pointed out that 5% is the number of the total hits as the sample number in order to clearly recognize the tread of the b value if there are lots of AE hits[35]. In this paper, we choose 500 consecutive points as a point in order to compare the b value under the same stress level, with linear interpolation in every 5% stress level.

Fig.8 shows the variation of AE based b value on different stages corresponding to different fiber contents, based on the rule of the AE based b value[36]. The curve of the AE based b value with stress is divided into three stages: A (0-15% stress level), B (15%-90% stress level), and C (90%-100% stress level). From Fig.8, it is observed that AE based b values of polypropylene fiber reinforced mortar and concrete are lower than that of the plain mortar and plain concrete respectively in the whole loading process.

On the A stage, the AE based b value shows increasing trend and the higher fiber content the lower the AE based b value. This stage is mainly the formation and development of micro cracks[37], accompanied by low amplitude AE signals. The polypropylene fiber can form small polymer film to enrich the mortar inside pores and then the internal porosity decreases significantly[38]. Under the axial compression loads, the matrix crack decreases because polypropylene fiber could bear small part of the stress. Then, the low amplitude AE signal ratio of polypropylene fiber mortar is smaller than that of the plain mortar, so the AE based b value

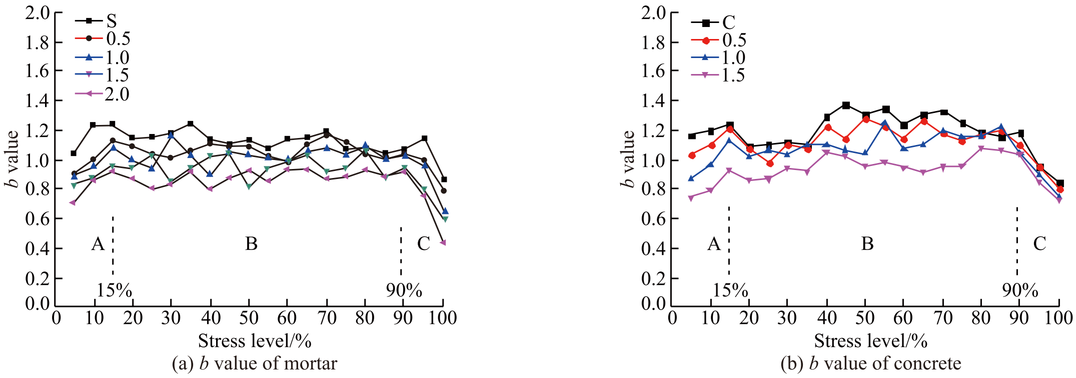


Fig.8 Curves of the AE based *b* value with the stress level for polypropylene fiber reinforced specimens

is lower. Although a small amount of fiber reinforced concrete aggregate is damaged, it could produce high amplitude signal, but the proportion is small, so the *b* value is lower. On the other hand, new crack is produced continuously under axial compression loads, the proportion of low amplitude signal is growing and then the AE based *b* value becomes bigger. The polypropylene fibers bear more stress with the increase of fiber content, so the proportion of low amplitude AE signal decreases with the increase of fiber content, then the AE based *b* value decreases with the increase of fiber content.

The AE based *b* value is in the state of fluctuation on the B stage. Probably when the micro crack propagates to a certain extent, the crack tips connect with each other under high stress, then forms a large crack and stop propagating, the AE based *b* value decreases. When new cracks occur and begin to spread, the AE based *b* value begins to increase. So the AE based *b* value shows that state. No rule with the fiber content change is shown. Compared with the fiber mortar, the fluctuation of the fiber reinforced concrete is mainly due to the uniformity of the concrete which is not uniform than mortar, so the damage process is different, and thus the *b* value fluctuates obviously.

The AE based *b* value shows decreasing trend on the C stage and the higher fiber content the lower the AE based *b* value. This stage is mainly macro cracks and polypropylene fiber damage, accompanied by high amplitude AE signals[37], so the AE based *b* value is small. For fiber reinforced concrete, the macro damage of this stage is mainly the destruction of the aggregate. But the proportion of high amplitude signals is increasing due to the continence of producing high amplitude signal, so the AE based *b* value shows a downward trend. The polypropylene fiber bears more stress in the early stage with more fiber, then more high amplitude AE signal is generated on the failure stage, so the AE based *b* value gets lower with the increase of polypropylene fiber content.

5 Discussion

The cumulative AE energy of polypropylene fiber reinforced mortar and concrete in different stages is shown in Fig.3. The results showed that it accounted for 45% on the A stage, 45% on the B stage and 10% on the C stage for plain mortar; 40%-45% on the A stage, 35%-40% on the B stage and 10%-15% on the C stage for fiber reinforced mortar; 35% on the A stage, 25% on the B stage and 40% on the C stage for plain concrete; 25%-35% on the A stage, 45%-50% on the B stage and 20%-25% on the C stage for fiber reinforced concrete. That is in accordance with the energy dispersion of fiber reinforced cement-based materials studied by Trainor[39]. However, the cumulative AE energy gap between the plain mortar and polypropylene fiber reinforced mortar at different stages is about 5%, which shows that the effect of polypropylene fiber on fiber reinforced mortar damage process is uniform at each stage. But the gap for fiber reinforced concrete is close to 20% on the B and C stages, which indicates that the effect of polypropylene fiber on fiber reinforced concrete is especially important in B and C stages, especially for C stage. It also shows that the failure processes of polypropylene fiber reinforced concrete and polypropylene fiber mortar are obviously different.

The cumulative AE energy is positively related with the damage release energy[26]. It is found that the cumulative AE energy is from 7 000 to 20 000 due to the polypropylene fiber content from 0.0% to 2.0%; The cumulative AE energy is from 300 000 to 800 000 due to the polypropylene fiber content from 0.0% to 1.5%. It means that the damage energy increases with the increase of polypropylene fiber content. The ductility can be characterized by the damage energy, ductility increases with the increase of damage energy, while the damage energy cannot be easily measured. The relationship between the cumulative AE energy and damage energy has shown that the ductility has a positive correlation with cumulative AE energy. Through the above analysis, it is proved that the cumulative AE energy can be used for the characterization of structural ductility, which offers early warning for the failure of the material. From Fig.8, the AE based *b* value obviously decreases in the final failure stage, the plain mortar decreases from the 95% stress level and the polypropylene fiber reinforced mortar decreases from the 90% stress level; the plain concrete decreases from the 90% stress level and the polypropylene fiber reinforced concrete decreases from the 85% stress level. It decreases earlier with more polypropylene fiber. Thus, the fact that the duration of the AE based *b* value in the decline stage increases with the increase of polypropylene fiber content also shows that the ductility of the specimens increases with the increase of polypropylene fiber content.

The AF value used to identify the damage stage would get excellent results. It was also found that the AF value rose from 20-25 kHz to 40-50 kHz on the A stage, fluctuated between 60 and 80 kHz on the C stage, eventually dropped to 55-60 kHz on the D stage. Therefore the AF value can be used as an important monitoring indicator for the damage prediction of the polypropylene fiber reinforcing mortar engineering. When the AF value rises from 20-25 kHz to 40-50 kHz, it indicats the engineering on the initial damage stage, when the AF value fluctuates in 60-80 kHz, it indicates the engineering on the damage development stage, when the AF value shows a downward trend and close to 55-60 kHz, it indicates actual project near failure. Similar conclusions were found for fiber reinforced concrete: when the AF value rises from 25-30 kHz to 35-40 kHz, it indicates the engineering on the initial damage stage, when the AF value shows a downward trend and close to 45-55 kHz, it indicates actual project near failure. And through the analysis of Fig.4 and Fig.5, we know that the A stage is shear failure; the C stage is mainly affected by tensile failure, while the D stage is mainly shear failure. Different damage stages correspond to the corresponding failure modes, so it can identify the failure modes by the damage stages.

Compared with the analysis results of the *b* value, the results showed that the A stage was slight damage corresponding to the micro cracks, and the C stage was serious damage corresponding to the macro cracks. Different damage stages correspond to different degrees of damage, and the damage degree can also be identified by the damage stage. By the change laws of the AF value, failure mode and damage degree can be determined through the identification of the damage stage. The health monitoring of the structure could be simplified to study and grasp the change laws of the AF value.

6 Conclusions

In this paper, the failure mode and damage degree evolution process of different polypropylene fiber reinforced mortar and concrete were studied by the method of AE characteristic parameters analysis. The following conclusions are obtained:

a) The compressive strength of polypropylene fiber reinforced mortar and concrete has no obvious change with the increase of fiber content, but the failure processes of them have obvious difference with the change of fiber content and the failure processes between fiber mortar and fiber concrete are obviously different. With the increase of fiber content, AE cumulative energy decreased on the A stage and increased on the B stage. The AE cumulative energy is positively related to the ductility of the specimen. And the ductility of the specimens increases with the increase of the polypropylene fiber.

b) The change laws of AF and RA values on each damage stage could reveal the different failure modes. In the A stage, the proportion increased firstly and then decreased with the increase of fiber content, which is the RA value extreme points of the polypropylene fiber reinforced mortar more than that of the plain mortar. And the tensile performance increased firstly and then decreased, the 1% was the best, the tensile failure shifted obviously to shear failure. However, the tensile performance of fiber reinforced concrete increased with the increase of fiber content in the range of this paper.

c) The AE based b value increases on the A stage, drops in the C stage. And it decreases with the increase of polypropylene fiber content. It reveals that the matrix cracked with lots of low amplitude micro cracks on the A stage and the fiber was pulled out with a large number of high amplitude macro cracks on the C stage.

d) Different damage stages have different AF values, while the content of polypropylene fiber has little effect on the AF value. The analysis of the change laws of the AF value can identify the damage stage which could be used to realize the identification of failure mode and damage degree.

References

[1] Balaguru P. Contribution of Fibers to Crack Reduction of Cement Composites the Initial and Final Setting Period[J]. *ACI Mater. J.*, 1994, 91(3): 280-288

[2] Mindess S, Francis Young J, Darwin D. *Concrete*[M]. NJ: Prentice Hall, 2003

[3] Gao D, Yan D, Li X. Splitting Strength of GGBFS Concrete Incorporating with Steel Fiber and Polypropylene Fiber after Exposure to Elevated Temperatures[J]. *Fire Safety J.*, 2012, 54(54): 67-73

[4] Bošnjak J, Ožbolt J, Hahn R. Permeability Measurement on High Strength Concrete without and with Polypropylene Fibers at Elevated Temperatures using a New Test Setup[J]. *Cem. Concr. Res.*, 2013, 53: 104-111

[5] Qadi A L, Arabi N S, Mustapha B, *et al*. Effect of Polypropylene Fibers on Thermogravimetric Properties of Self-compacting Concrete at Elevated Temperatures[J]. *Fire Mater.*, 2013, 37(3): 177-186

[6] Grdic Z J, Curcic G A T, Ristic N S, *et al.* Abrasion Resistance of Concrete Micro-reinforced with Polypropylene Fibers[J]. *Constr. Build. Mater.*, 2012, 27(1): 305-312

[7] Wu Y, Sun Q, Fang H, *et al.* Surface-treated Polypropylene Fiber for Reinforced Repair Mortar Cementitious Composites[J]. *Compos. Interfaces*, 2014, 21(9): 787-796

[8] Behfarnia K, Behravan A. Application of High Performance Polypropylene Fibers in Concrete Lining of Water Tunnels[J]. *Mater. Des.*, 2014, 55(6): 274-279

[9] Segre N, tonella E, Joekes I. Evaluation of the Stability of Polypropylene Fibers in Environments Aggressive to Cement-based Materials[J]. *Cem. Concr. Res.*, 1998, 28(1): 75-81

[10] Sideris K K, Manita P, Chaniotakis E. Performance of Thermally Damaged Fiber Reinforced Concretes[J]. *Constr. Build. Mater.*, 2009, 23(3): 1 232-1 239

[11] Ouaar A, Doghri I, Delannay L, *et al.* Micromechanics of the Deformation and Damage of Steel Fiber-reinforced Concrete[J]. *Int. J. Damage Mech.*, 2007, 16(2): 227-260

[12] Nia A A, Hedayatian M, Nili M, *et al*. An Experimental and Numerical Study on How Steel and Polypropylene Fibers Affect the Impact Resistance in Fiber-reinforced Concrete[J]. *int. J. Impact Eng.*, 2012, 46(6): 62-73

[13] W Jianhua, L Jun, Y Haiping. The Study on Steel Fiber Reinforced Concrete under Dynamic Compression by Damage Mechanics Method[J]. *Journal of Chemical and Pharmaceutical Research*, 2014, 6(7): 1 759-1 767

[14] Zhang P, Li Q. Effect of Polypropylene Fiber on Durability of Concrete Composite Containing Fly Ash and Silica Fume[J]. *Composites Part B*, 2013, 45(1): 1 587-1 594

[15] Zhang Y F, Liu H, Chen J P, *et al.* Numerical Simulation on PPFRC with Different Contents[J]. *Appl. Mech. Mater.*, 2013, 477-478: 1 019-1 025

[16] Shihada S. Effect of Polypropylene Fibers on Concrete Fire Resistance [J]. *J. Civ. Eng. Manag.*, 2011, 17(2): 259-264

[17] Saje D, Bandelj B, Šušteršič J, *et al.* Shrinkage of Polypropylene Fiber-reinforced High-performance Concrete[J]. *J. Mater. Civ. Eng.*, 2011, 23(7): 941-952

[18] Zhang P, Li Q. Effect of Polypropylene Fiber on Fracture Properties of High-performance Concrete Composites[J]. *Sci. Eng. of Compos. Mater.*, 2012, 19(4): 407-414

[19] Nili M, Afroughsabet V. The Effects of Silica Fume and Polypropylene Fibers on the Impact Resistance and Mechanical Properties of Concrete [J]. *Constr. Build. Mater.*, 2010, 24(6): 927-933

[20] Wu Y, Wenhui Z. Effect of Polypropylene Fibers on the Long-term Tensile Strength of Concrete[J]. *J. Wuhan University of Technology-Mater. Sci. Ed.*, 2007, 22(1): 52-55

[21] Izaguirre A, Lanas J, Alvarez J I. Effect of a Polypropylene Fibre on the Behaviour of Aerial Lime-based Mortars[J]. *Constr. Build. Mater.*, 2011, 25(2): 992-1 000

[22] Kakooei S, Akil H M, Jamshidi M, *et al.* The Effects of Polypropylene Fibers on the Properties of Reinforced Concrete Structures[J]. *Constr. Build. Mater.*, 2012, 27(1): 73-77

[23] Singh S, Shukla A, Brown R. Pullout Behavior of Polypropylene Fibers from Cementitious Matrix[J]. *Cem. Concr. Res.*, 2004, 34(10): 1 919-1 925

[24] Wang C, Zhang Y, Ma A. Investigation into the Fatigue Damage Process of Rubberized Concrete and Plain Concrete by AE Analysis[J]. *J. Mater. Civ. Eng.*, 2010, 23(7): 953-960

[25] Wu K, Chen B, Yao W. Study on the AE Characteristics of Fracture Process of Mortar, Concrete and Steel-fiber-reinforced Concrete Beams [J]. *Cem. Concr. Res.*, 2000, 30(9): 1 495-1 500

[26] Kim B, Weiss W J. Using Acoustic Emission to Quantify Damage in Restrained Fiber-reinforced Cement Mortars[J]. *Cem. Concr. Res.*, 2003, 33(2): 207-214

[27] Aggelis D G, Soulioti D V, Barkoula N M, *et al.* Influence of Fiber Chemical Coating on the Acoustic Emission Behavior of Steel Fiber Reinforced Concrete[J]. *Cem. Concr. Compos.*, 2012, 34(1): 62-67

[28] Shah S P, Weiss W J, Wei Y. Shrinkage Cracking - Can It Be Prevented? [J]. *Concr. Int.*, 1998, 20(4): 51-55

[29] Grzybowski M, Shah S P. Shrinkage Cracking of Fiber Reinforced Concrete[J]. *ACI Mater. J.*, 1990, 87(2): 138-148

[30] Japan Federation of Construction Materials In Ustries. *Monitoring Method for Active Cracks in Concrete by AE*[S]. JCMS-III B5706. 2003, 2003

[31] Ohno K, Ohtsu M. Crack Classification in Concrete Based on Acoustic Emission[J]. *Constr. Build. Mater.*, 2010, 24(12): 2 339-2 346

[32] Ohtsu M, tomoda Y. Corrosion Process in Reinforced Concrete Identified by Acoustic Emission[J]. *Mater. Trans.*, 2007, 48(6): 1 184-1 189

[33] Sagar R Vidya, Prasad BK Raghu, Kumar S Shantha. An Experimental Study on Cracking Evolution in Concrete and Cement Mortar by the B-value Analysis of Acoustic Emission Technique[J]. *Cem. Concr. Res.*, 2012, 42(3): 1 094-1 104

[34] Kurz JH, Finck F, Grosse CU, *et al.* Stress Drop and Stress Redistribution in Concrete Quantified Over Time by the B-value Analysis[J]. *Struct. Health Monit.*, 2005, 5(1):69-81

[35] Farhidzadeh A, Dehghan-Niri E, Salamone S, *et al.* Monitoring Crack Propagation in Reinforced Concrete Shear Walls by Acoustic Emission[J]. *J.Struct. Eng.*, 2012, 139(12)

[36] Sagar R V, Prasad B K R. A Review of Recent Developments in Parametric Based Acoustic Emission Techniques Applied to Concrete Structures[J]. *Nondestruct. Test. Eva.*, 2012, 27(1): 47-68

[37] Shah S G, Kishen J M C. Use of Acoustic Emissions in Flexural Fatigue Crack Growth Studies on Concrete[J]. *Eng. Fract. Mech.*, 2012, 87: 36-47

[38] Zhou M, Li B, Shen W. Influences of Polypropylene Fiber and SBR Polymer Latex on Abrasion Resistance of Cement Mortar[J]. *J. Wuhan University of Technology-Mater. Sci. Ed.*, 2010, 25(4): 624-627

[39] Trainor K J, Foust B W, Landis E N. Measurement of Energy Dissipation Mechanisms in Fracture of Fiber-reinforced Ultrahigh-strength Cement-based Composites[J]. *J. Eng. Mech.*, 2014, 139(7): 771-779