

Review of Fracture Properties and Research Methods of Fiber Recycled Concrete

Jin Tong

School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454003, Henan, China

Abstract: Aiming at the background of the application of fracture mechanics in fiber recycled concrete as well as the shortcomings of the current research, the relevant results and progress are summarized from three aspects, namely, the basic theory of fracture mechanics of fiber recycled concrete and the research progress of the fracture properties of fiber recycled concrete as well as the testing methods of the fracture of fiber recycled concrete, respectively. The development history of the application of fracture mechanics in concrete is described, three fracture forms, fracture process zones and three softening curve models of concrete are introduced, and it is proposed to combine the bilinear softening curve and the virtual crack zone model to construct the ontological relationship of the whole process of concrete cracking. The current research status of recycled brick aggregate concrete and polypropylene coarse fiber concrete is introduced. The incorporation of recycled brick aggregate adversely affects the workability, basic mechanical properties and fracture properties of concrete. The reinforcing effect of polypropylene fibers on concrete can effectively improve the adverse effects of brick aggregate on concrete, which opens up the research prospect of green concrete and has high research value. The applications of three-point bending test, four-point bending test and DIC technique in the study of concrete fracture characteristics are introduced.

Keywords: Fracture mechanics, Polypropylene crude fiber, Recycled brick aggregate, Fracture properties.

1. Introduction

The demolition of old buildings will inevitably lead to the continuous growth of construction solid waste, and new buildings require a large amount of concrete, so the demand for green concrete is bound to be higher and higher. Construction solid waste directly open piles or landfills, the environment will cause great harm, not only a large number of encroachment on the land, the soil, the atmosphere and the water flow have a considerable degree of pollution, and even "piles of solid waste into the mountain" will occur landslides, endangering the lives of people's health and safety.[1, 2] Therefore, the proper solution to the problem of construction solid waste, need to add environmental protection, more scientific approach. In the face of "garbage disaster" problem, promote the resource utilization of construction waste, "waste into treasure" is the most fundamental and effective way to solve the problem of construction solid waste. Construction solid waste is a misplaced resources, the main construction waste concrete, waste bricks, etc. can be used as recycled aggregates to prepare recycled concrete. Recycled aggregates, although there are differences with natural aggregates, but the treatment made into products, the quality is guaranteed, and even some performance is better than natural materials, but due to the complexity of the composition of recycled aggregates, put into use when the product quality ups and downs, the need for recycled aggregates for further research. As a new type of green concrete, recycled concrete will provide a new way to improve the disposal of construction solid waste. Proper disposal of construction solid waste not only reduces the harm to the natural environment, but also reduces the large use of natural aggregate resources. [3, 4] Defects in the properties of recycled aggregates will inevitably deteriorate the performance of concrete, especially the development of fracture and cracking of concrete has been a matter of great concern, and the incorporation of recycled aggregates will aggravate these problems.

At present, the demolition of waste buildings in the brick structure and masonry structure accounted for a considerable proportion, research shows that[5-7] the main components of construction solid waste for waste concrete and waste brick, of which waste concrete accounted for 41%, waste bricks accounted for up to 40% or more; and in small and medium-sized cities and rural areas, waste bricks accounted for a higher proportion of the even reached more than 70%. Therefore, in the face of the problem of solid waste utilization in construction, not only to deal with a large number of waste concrete, but also to solve a considerable number of waste bricks. Moreover, after the demolition of buildings, subject to the difficulty of sorting, the current main mixed crushing and disposal, resulting in large fluctuations in the performance of recycled aggregates. In order to control the quality of recycled products, further research on brick aggregate is needed. At present, many scholars mainly focus on the study of recycled concrete aggregate, and the study of recycled brick aggregate is still small.[8, 9] And it is important to study the effect of recycled brick aggregate on recycled concrete for the recycling of waste bricks. As a new type of green concrete, recycled brick aggregate concrete will provide a new way to improve the disposal of waste bricks in construction solid waste. Proper disposal of construction solid waste not only reduces the harm to the natural environment, but also reduces the large use of natural aggregate resources. Defects in the performance of recycled brick aggregate will inevitably deteriorate the performance of concrete, especially the development of concrete fracture and cracking has been a matter of great concern, the incorporation of recycled brick aggregate will aggravate these problems. And polypropylene crude fiber as a new type of reinforcing, toughening materials, mixed into the concrete can significantly improve its strength and toughness.[10, 11] Therefore, the incorporation of fibers to improve the performance of recycled concrete and offset the adverse effects of recycled aggregates on concrete will make the research of recycled concrete more promising.

The use of fracture mechanics theory to study the cracking and expansion of fiber concrete cracks is a feasible technical approach. The application of fracture mechanics in fiber concrete can be analyzed and interpreted from several aspects such as evaluating the fracture energy of fiber concrete, fracture parameters and analyzing the fracture process zone.

2. Basic Theory of Fracture Mechanics of Fiber Recycled Concrete

2.1. Development of fracture mechanics in the study of concrete fracture characteristics

Since the development of fracture mechanics, Griffith[12] firstly proposed the concept of fracture mechanics in the study of glass, and Kaplan[13] firstly introduced linear fracture mechanics into the study of concrete and proposed the concept of fracture toughness. Subsequently, scholars found that concrete as a quasi-brittle material has the characteristics of nonlinear fracture, and successively proposed a variety of nonlinear fracture models to describe and judge the crack extension of different kinds of concrete. Hillerborg[14] proposed a virtual crack model, which believes that there is a fracture process zone in the process of crack extension of concrete. In the process of concrete crack expansion, micro-cracks breeding, aggregation, through the formation of macro-cracks, micro-cracks to macro-cracks in the transition that is the fracture process zone, this region despite the damage, but due to the bonding effect of the material, concrete still exists in a certain load-bearing capacity, and its cohesion has a non-linear and softening characteristics, and it is this softening characteristics of the fracture process zone, resulting in the linear-elastic fracture mechanics can not directly be applied to the concrete, which is important for the concrete fracture mechanics. Bažant[15] proposed the crack zone model, which suggests that the fracture properties of a material can be characterized by only three parameters - the fracture energy, the uniaxial strength limit and the width of the crack zone (fracture processing zone) - and that the strain softening modulus is a function of these parameters. The model shows a significant improvement in error compared to linear fracture and strength theories. As a result, the applicability of fracture mechanics in concrete is firmly established. Y Jenq[16] proposed a two-parameter fracture model which determines the state of concrete crack instability in terms of two parameters: the critical instability fracture toughness and the critical crack tip opening displacement. The model incorporates the nonlinear slow crack expansion that occurs prior to the peak loading of the concrete, thus addressing the dimensional effects caused by it. Karihaloo[17] proposed an effective crack model, which determines the concrete crack instability in terms of the effective stress intensity factor at the crack tip and the critical effective crack length. The model describes a method for determining the fracture toughness of plain concrete from a three-point bending specimen that accounts for the pre-peak crack expansion that occurs during loading. The fracture toughness so determined does not depend on the size and geometry of the specimen, but only on the mixing variables. The results show that the predictions of the effective crack model are in good agreement with the two nonlinear models (the two-parameter model and the size effect law).

2.2. Study of fracture forms and fracture process zones of concrete

There are three basic types of fracture formation in concrete fracture, depending on the force applied, which are type I cracking (tension), type II cracking (shear), and type III cracking (tear). Although cracks in actual concrete structures may experience Type I loading, Type II loading, Type III loading, or a mixture thereof, the Type I cracking pattern is of great interest because of its high number of occurrences and the extent of damage.[18]

Concrete is a quasi-brittle multiphase composite material, and the mechanism of fracture damage is very complex.[19, 20] In the process of concrete crack extension, microcracks breeding, aggregation, through the formation of macro-cracks, micro-cracks to macro-cracks of the transition that is the fracture process area, this region despite the damage, but due to the bonding effect of the material, the concrete still exists a certain load-bearing capacity, and its cohesion has a nonlinear and softening characteristics, so the study of this region is more difficult. The incorporation of polypropylene crude fiber and recycled brick aggregate in concrete will affect the crack extension of concrete, the crack opening width and FPZ will be changed, the softening characteristics will be changed during fracture, and the important fracture parameters such as fracture toughness and fracture energy will also be affected, so it is important to clarify the characteristics of the displacement field distribution in the fracture process zone of concrete and the extension characteristics of FPZ to reveal the influence mechanism of polypropylene crude fiber and recycled brick aggregate on the fracture properties of concrete. Therefore, it is valuable to clarify the displacement field distribution characteristics and FPZ expansion characteristics of the fracture process zone of concrete to reveal the influence mechanism of polypropylene coarse fiber and recycled brick aggregate on the fracture properties of concrete.

The developmental damage process in the fracture process zone will affect the average intrinsic relationship of the material. In fiber recycled concrete, due to the incorporation of fibers and recycled aggregates, the diversity of material types and the uncertainty of distribution, there are unknown forms of pores, hardened cement paste, recycled aggregates, fibers, etc., on the path of crack extension; different materials play different roles in crack extension, and they provide different resistance and consume different amounts of energy; however, the crack extension follows a principle: cracks are always located along the path that consumes the least amount of energy Expansion. Therefore, the incorporation of fibers and recycled aggregates will affect the crack expansion process, especially the incorporation of fibers will change the mechanism of FPZ, but not fundamentally. The crack extension of concrete after fiber admixture is still from the interface of hardened cement paste and aggregate, when the crack extension meets fiber, the fiber can absorb part of the energy, to a certain extent, to preclude crack extension, so that the fracture zone affects a wider range, which makes the fracture characteristics of fiber concrete show different characteristics from ordinary concrete, but the fracture mechanics theory and model of ordinary concrete fiber concrete is still applicable However, the fracture mechanics theory and model of ordinary concrete fiber concrete are still applicable, only the crack extension is more complicated.

Fibers and recycled aggregates mixed in concrete will

affect the crack extension of concrete, the crack opening width and fracture process area will change, the softening characteristics at fracture will also change, fracture toughness and fracture energy and other important fracture parameters will be affected, so clarify the displacement field distribution characteristics of the fracture process area of the concrete, the extension characteristics of the fracture process area of the concrete, it is valuable to reveal the influence mechanism of fibers and recycled aggregates on the fracture performance of the concrete. properties are of great value. The matrix crack is divided into the traction-free zone, fiber bridging zone and matrix processing zone, and the fiber-induced crack closure pressure depends on (Mode I) crack opening displacement (COD), in which the calculation of COD is based on the concept of linear-elastic fracture mechanics but the energy absorbed in the fiber bridging zone is also included in the analysis. Interpretation of the test results on the fracture characteristics of plain and fiber

concrete using linear and nonlinear fracture mechanics concepts, the nonlinear fracture parameters aptly describe the positive effect of the fiber volume fraction on the fracture characteristics of the concrete, which helps to assess the effectiveness of the fibers in controlling crack opening and slip.[21]

Under the external load, as the crack opening displacement COD from the tip to the bottom of the FPZ gradually changed to the opening displacement w_0 , the cohesive force σ_c of the FPZ gradually decreased from the tensile strength f_t until it was 0, and its distribution was in the form of a decreasing function, reflecting the softening relationship between the cohesive force σ_c and the crack opening displacement COD. The softening curves reflecting the cohesion-crack tension softening relationship mainly have the following three forms: linear softening, exponential softening, and bilinear softening.[22] As shown in Figure 1.

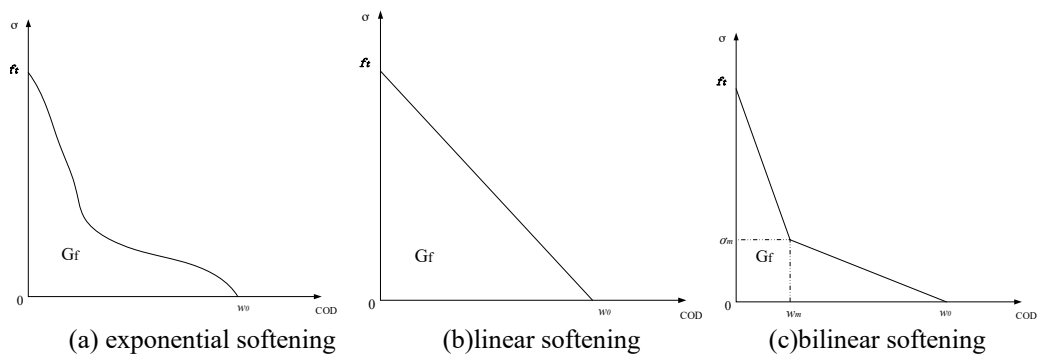


Figure 1. Model of common softening curves

For the analysis of fracture process zone based on the virtual fracture model, the selection of softening curves is crucial, and the softening curve relationship reflects the virtual fracture opening and determines the maximum degree of fracture process zone breeding. The displacement field calculated by the DIC method can be well combined with the bilinear softening curve, and the bilinear softening curve is simple in form and easy to calculate, which has obvious advantages compared with the linear softening and exponential softening. The bilinear softening curve and virtual crack zone model are combined to construct the ontological relationship of the whole process of concrete cracking,[23] as shown in Figure 2.

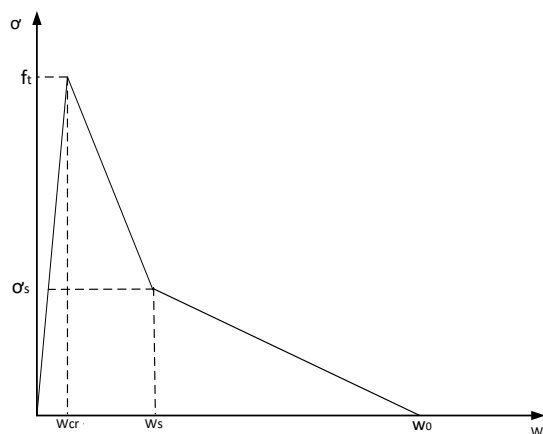


Figure 2. Concrete cracking whole process ontological relationship

3. Study on the Fracture Properties of Polypropylene Crude Fiber Reinforced Recycled Brick Aggregate Concrete

3.1. Current Research Status of Recycled Brick Aggregate Concrete

Recycled brick-mix aggregate refers to recycled coarse aggregate mixed with recycled concrete aggregate and recycled brick aggregate in different proportions. When the building is demolished, due to the difficulty of sorting, the disposal of construction solid waste is mainly mixed and crushed, resulting in a complex composition of recycled products, mostly recycled concrete aggregate and recycled brick aggregate at the same time as recycled brick mix aggregate. Moreover, recycled brick aggregate, as a relatively large component of construction solid waste, has gradually become the focus of research in the field of green concrete. The small apparent density, high water absorption, high void ratio, and high crushing value of recycled brick aggregate will significantly deteriorate the basic properties of recycled aggregate. Studies have shown that as the percentage of recycled brick aggregate in the recycled brick mix increases, it will lead to a decrease in the apparent density of the recycled brick mix aggregate, an increase in water absorption, and an overall decreasing trend in the crushing value. This leads to the limited utilization of recycled brick aggregate, and the high-value utilization of recycled brick aggregate has gradually become a research hotspot of construction solid waste. The classification of recycled brick aggregate is not

perfect, in order to realize the large-scale application of recycled brick aggregate, it should be diversified according to the characteristics of the aggregate on the basis of unified classification and grading. In order to solve the problems faced by the popularization and application of brick mixed recycled aggregates, the technical indexes of brick mixed aggregates application should be systematized, and the performance of each group of concrete should be tested under different brick aggregates mixing, and the class level of the corresponding technical indexes in the national standard reached by each group of concrete should be pointed out, so as to basically realize the expected goal of efficient and convenient evaluation of the performance of brick concrete construction waste mixed recycled aggregates.

Recycled brick mix aggregate concrete refers to recycled concrete with recycled brick mix aggregate as coarse aggregate. Relevant scholars focus on the working properties, basic mechanical properties, fracture properties and damage analysis of recycled brick aggregate concrete, and other aspects of recycled brick aggregate on the performance of recycled concrete to carry out research.

The research on the working performance shows that[24-26] the increase of recycled brick aggregate content decreases the ease of recycled concrete and the slump decreases. Due to the high water absorption of recycled brick aggregate, the concrete compatibility decreases with the increase of recycled brick aggregate content, and the larger the percentage of recycled brick aggregate, the larger the decreasing trend. The slump of concrete increases with increasing percentage of recycled brick aggregate. However, if the aggregate is pre-wetted, the recycled brick aggregate has little effect on the slump.

Studies on the basic mechanical properties showed that[27-29][27-29] the mechanical properties of recycled concrete showed a decreasing trend with increasing recycled brick aggregate content. With the increase of recycled brick aggregate, the compressive strength and split tensile strength of concrete gradually decreased. With the proportion of recycled brick aggregate and recycled concrete aggregate decreases, mixed fiber recycled brick aggregate concrete compressive strength and splitting tensile strength increases. The compressive strength and modulus of elasticity of low-polymer recycled brick aggregate concrete and ordinary recycled brick aggregate concrete decreased, and the slump, strain corresponding to peak stress, transverse deformation coefficient, and Poisson's ratio increased with the increase in the admixture of recycled brick aggregate.

Studies addressing the aspect of fracture properties showed that[30-32] an increase in the content of recycled brick aggregate led to a decrease in the fracture toughness and fracture energy of recycled concrete. With the increase of recycled brick aggregate dosage, the fracture parameters of concrete gradually decreased. Moreover, the cracking toughness was more affected than the destabilizing toughness by the inclusion of recycled brick aggregate. The modulus of elasticity of recycled brick aggregate is lower than that of the surrounding hardened mortar, resulting in only two strain concentration zones in brick-aggregate-containing concrete, while natural aggregate concrete has four vertical compressive strain concentration zones. Shear cracks in natural aggregate concrete first appeared in the interfacial transition zone and extended until shear damage, but brick-containing aggregate concrete shear cracks extended through the recycled brick aggregate. Therefore, there is no

compressive strain concentration zone near the recycled brick aggregate.

3.2. Current Research Status of Polypropylene Rough Fiber Concrete

Concrete being a quasi-brittle material, crack hazards have always been a major safety issue in concrete construction, and unattended cracks may lead to the destruction of an entire large building. In order to improve the fracture properties of concrete and make it tough and strong, numerous scholars have proposed the addition of fibers to improve concrete. There are two main mechanisms of fiber action in fiber concrete: (1) bonding action. Relying on the bond with the concrete matrix to jointly bear the fracture load, (2) bridging role. Across the cracks at both ends of the bridging cracks, relying on its own tensile properties to continue to transfer stress, so that the cracks at both ends of the concrete continue to absorb the fracture energy, slowing down the tensile region of the concrete tensile material tensile capacity of the shrinkage rate. Polypropylene fiber as a new type of reinforcing, toughening materials, can significantly improve the toughness of concrete. The advantages of polypropylene fiber are as follows: (1) chemically stable, will not occur corrosion phenomenon that occurs in steel fibers (2) higher economic efficiency (3) good performance, a strong toughening effect. As shown above, polypropylene fiber has high research value. Related scholars for polypropylene fiber reinforced concrete basic mechanical properties, especially the fracture properties to carry out more research.

For the basic mechanical properties of the research shows that[33-36] polypropylene crude fiber on the compressive strength of concrete will play a certain role in enhancing, but the impact is not great. Concrete tensile strength and flexural strength will get a greater enhancement, and there is an optimal mixing of polypropylene fibers, with the increase in fiber dosage, the enhancement effect first increased and then decreased. With the increase of fiber admixture, the concrete unconfined compressive strength, flexural strength and splitting tensile strength first increases and then decreases; there is an optimal admixture of fibers, the flexural strength and splitting tensile strength reaches the maximum value, and the unconfined compressive strength reaches the maximum value. With the change of polypropylene crude fiber admixture, the slump, extension, compressive strength and split tensile strength of concrete were enhanced to different degrees. With the incorporation of polypropylene crude fiber, the tensile strength and peak strain of concrete increased, the optimum amount of fiber exists, and the tensile strength and peak strain of polypropylene crude fiber reinforced concrete increased significantly compared to plain concrete. With the increase in the admixture of recycled aggregate, the workability and mechanical properties of the concrete decreases. And with the increase of fiber admixture, the working properties of concrete will be reduced significantly, the compressive strength has no significant effect, and the flexural strength, split tensile strength and elastic model will be improved. With the increase of fiber admixture, concrete cracks show a tendency to increase first and then decrease. With fiber admixture, concrete compressive strength, axial compressive strength, compressive cracking energy, destructive energy and compressive toughness are enhanced, concrete crushing damage is reduced, brittleness is improved and ductility is increased.

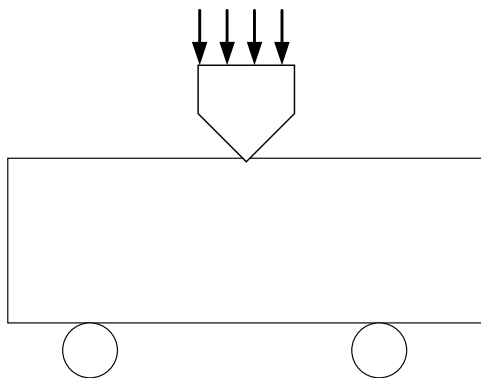
Research on fracture properties shows that[37-41]

polypropylene fibers have good toughening effect, which can effectively inhibit crack expansion, change the softening characteristics of concrete, and improve the fracture parameters of fracture toughness and fracture energy of concrete. Polypropylene coarse fibers have strong bridging stress, especially prominent in the concrete after cracking, can effectively inhibit the expansion of macro-cracks. Fine fibers can inhibit the generation of micro-cracks and increase the percentage of tiny pores; coarse fibers can prevent the development of macro-cracks and improve the post-cracking properties. With the increase of fiber doping, the macroscopic crack initiation toughness and structural destabilization toughness increased, and the length-to-diameter ratio was inversely proportional to the crack initiation toughness and positively proportional to the destabilization toughness. The improvement of concrete crack initiation toughness and instability toughness is good with the optimum admixture and optimum length-to-diameter ratio of polypropylene fibers, and can be introduced in the empirical equation of the bilinear softening principal structure of the polypropylene coarse fibers. The fracture energy and fracture toughness of concrete were improved with increasing polypropylene fiber admixture. Aggregate plays an important role in the fracture behavior of polypropylene fibers in concrete. J-integral method has good applicability to the fracture toughness of cementitious composites reinforced with polypropylene fibers.

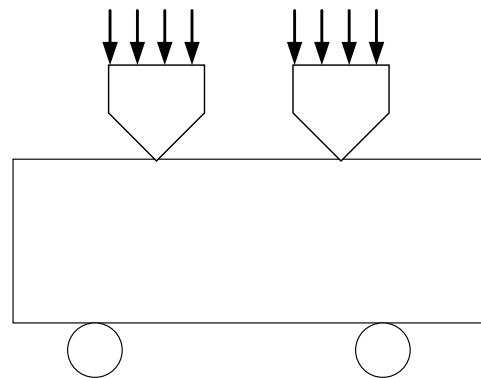
4. Progress in Fiber Concrete Research Methods

4.1. Three-point bending test and four-point bending test

The interlaminar fracture tests based on fracture mechanics are three-point bending test and four-point bending test, as shown in Figures 3 and 4. Three-point bending test is an experimental method to test the bending mechanical properties of materials, and is mostly used to test the specifications of related material products. The specimen will be placed on the two support points with a certain distance, in the two support points above the midpoint of the specimen to apply downward load, the specimen's three contact points to form an equal two moments that is, three-point bending, the specimen will be in the mid-point of the fracture. Four-point bending refers to the specimen is placed at a certain distance from the two force points (four-point bending fixture of the lower part) on the formation of a simply supported beam form, support the specimen of the distance between the two lower support points depending on the length of the specimen can be adjusted in the force point of the two symmetrical loading points (four-point bending fixture on the upper part) to the sample to exert pressure on the upper and lower there are a total of four points are respectively the application of force points and force points, the process is known as the four-point The process is called the four-point bending experiment[42, 43].



Figures 3. Three-point bending test



Figures 4. Four-point bending test

Due to the different loading methods and specimen shapes, there are different flexural strength calculation formulas, and the obtained flexural strength is also different. Usually more commonly used in general is the three-point bending test, but some materials also need to do four-point bending test, the two loading methods have their own advantages and disadvantages. Three-point bending test loading method is simple, but due to the loading method is centralized, the bending distribution is not uniform, a certain part of the defects may not show up to achieve the effect. Four-point bending test is a uniform distribution of bending moment, the test results are more accurate, but the pressure clamp structure is complex, less used in industrial production. Simply from the test equipment, with the development of materials science, from the past large size of the traditional testing machine gradually to miniaturization, integration, in-situ development, these advances for people to understand the microscopic mechanical properties of materials has a very important significance.

4.2. Application of DIC Technique in Fracture Characterization of Concrete

Although the study of the fracture process zone (FPZ) of concrete is of great significance, most of the traditional testing methods are not able to effectively observe the changes in the FPZ of concrete, while the DIC method, as a non-contact optical measurement, can effectively observe the FPZ of concrete by analyzing the surface deformation field obtained by analyzing the surface scattering grayscale of the concrete surface.

The DIC method is widely used due to its advantages of high accuracy and high precision and the ability to obtain the surface displacement field non-destructively in real time. Gehri et al.[44][44] proposed a set of fully automated procedures for detecting cracks and measuring the crack kinematics in laboratory tests using a DIC instrument. Crack lines are extracted using well-established image processing methods, showing excellent agreement with physical crack patterns. Its proposed crack detection is based on the DIC

main tensile strain field, which allows the extraction of finer cracks and more reliable crack locations. Crack width and slip are measured using the DIC displacement field, which takes into account the local rotation of the specimen. Skaryński et al.[45] propose a consistent method to determine the width of the localized region uniformly and accurately, thus avoiding the effects of searching for patch sizes and cutoffs in the displacement and strain profiles when applying the DIC technique. Surface displacements measured by DIC are fitted by an error function, ERF, and surface strains computed from the displacement are fitted by the usual normal strain function. The surface displacements measured by DIC are fitted by the ERF, and surface strains computed from the displacements are fitted by the usual normal strain field, ERF. surface strains were fitted by the usual normal distribution (Gaussian) function.

There are two methods for researchers to determine the location of the crack tip based on the DIC results: (1) strain field (2) displacement field. Bu et al.[46] used the digital image correlation (DIC) method to obtain the full-field displacement of the concrete. The evolution of crack opening displacement (COD) and FPZ was determined on the basis of full-field displacement. It was shown that the FPZ length increases and then decreases with the increase of effective crack length. Bhosale[47] used DIC technique to study the fracture behavior of fiber concrete and it was shown that polypropylene fiber admixture can increase the length of the fracture process zone of concrete and improve the toughness of concrete.

5. Conclusion

(1) The admixture of recycled brick aggregate adversely affects the working performance, basic mechanical properties and fracture properties of concrete, and the admixture of recycled brick aggregate will change the damage mechanism of recycled concrete. The fracture properties of concrete, as an engineering design and construction need to focus on the problem, is the current research hotspot, in order to make the brick aggregate more widely used, the strength of recycled brick aggregate in recycled concrete role mechanism and fracture mechanism need to be further studied.

(2) Polypropylene fibers are able to produce favorable effects on the compressive strength, flexural strength, tensile strength and fracture properties of concrete. The reinforcing effect of polypropylene fibers on concrete can effectively improve the adverse effects of brick aggregate on concrete, which opens up the research prospect of green concrete and has high research value.

(3) The nonlinear fracture model is more suitable for the study of concrete fracture properties, and the DIC technique is used for the observation of the concrete fracture process area with good results; the crack extension mechanism of the concrete fracture process area will be changed with the addition of fibers, which needs to be further studied.

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