Mechanical Properties and Development of Steel Fiber, Polypropylene Fiber and Steel-Polypropylene Fiber Concrete Structures

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Abstract. Fibre concrete is a commonly improved concrete. Compared with ordinary concrete, it has more excellent characteristics and has been widely used in engineering structures and other fields. This paper describes the mechanical properties of polypropylene fibres, steel fibres, and hybrid fibres (steel fibres and polypropylene fibres); it discusses the use and development of these three kinds of fibre concrete in various professional fields. Steel fibre concrete overcomes the shortcomings of concrete, such as low tensile strength, slight ultimate elongation, brittle, et al., with excellent tensile, flexural, shear, crack resistance, fatigue resistance, high toughness and other properties, has been applied in the field of hydraulics, roads and bridges, construction and other engineering fields. Polypropylene has better crack and impact resistance because of its ability to be uniformly dispersed in the concrete; chemically stable, simple construction has been widely used in the world. Steel-polypropylene hybrid fibre concrete has excellent mechanical properties and economy due to the integration of steel fibres and polypropylene fibres with high strength and toughness. It has a broader prospect in the application of engineering materials.

Keywords: Steel fiber; polypropylene fiber; steel-polypropylene fiber; concrete structure.

1. Introduction

Concrete is a multi-phase composite material because of its easy access to materials and low cost; while more functional, the preparation process is relatively simple, can be combined with steel reinforcement and other materials to form load-bearing components in construction projects, is the most widely used construction materials in the current civil engineering and construction industry. However, there are different volumes and shapes of micro-cracks within the traditional concrete, and due to its low tensile strength, low flexural strength, poor toughness and durability and other shortcomings, it is a significant limitation to the development of the construction industry. In such a background, lightweight aggregate concrete is studied.

Lightweight aggregate concrete uses light coarse aggregate, light sand (or ordinary sand), cementitious materials and water-formulated, moulded dry apparent density of not more than 1950 kg/m^3 concrete. The use of lightweight aggregate concrete instead of traditional concrete in building structures effectively reduces the self-weight of the structure while also reducing the sectional size of the structure. However, lightweight aggregate concrete has many drawbacks. Under the same strength level, the compressive and tensile strength of lightweight aggregate concrete is lower than that of ordinary concrete, and the creep and shrinkage of lightweight aggregate concrete are giant, which is prone to brittle damage, which significantly limits the application of lightweight aggregate concrete. The addition of fibre materials in concrete can make the performance of concrete better optimized. Research on fibre concrete has always continued, and many fibre concrete materials with better performance have been obtained.

Scholars in various countries have taken the mechanical properties as the research focus for mixed fibre concrete, such as concrete mixed with different ratios of the same variety of fibres or one with only one kind of fibre concrete for comparison. This paper selects three classical fibre materials for the study: steel fibres, polypropylene fibres, and hybrid fibres (steel and polypropylene fibres).

2. Steel Fiber

2.1. Basic mechanical properties

Steel fibre concrete is ordinary concrete mixed with a small amount of mild steel, stainless steel and fibreglass formed after forming a relatively uniform and multi-directional concrete reinforcement. The amount of steel fibre mixed by volume is generally 1% ~ 2%, and by weight per cubic meter of concrete mixed with 70 ~ 100kg of steel fibre, steel fibre length of 25 ~ 60mm, a diameter of 0.25 ~ 1.25mm, length and diameter of the optimal ratio of 50 ~ 700. Compared with ordinary concrete, it improves the tensile, shear, bending, and abrasion and cracking properties, dramatically enhances the fracture toughness of concrete and the strength of the concrete, and impacts the resistance of concrete. It significantly improves the structure's fatigue resistance and its durability since the toughness can be increased by 10 to 20 times.

Most existing tests use split tensile strength to determine the axial tensile strength of steel fibre recycled concrete. In addition, Liu et al. investigated the effects of steel fibre incorporation rate and age of curing on the compressive properties of concrete using uniaxial compression tests [1]. They pointed out that as the amount of steel fibre infiltration into the concrete increases, the compressive strength of steel fibre concrete increases. If the infiltration rate of steel fibre remains constant, the compressive strength of concrete increases slightly with the growth of the curing age. Adding steel fibres can significantly improve the toughness and crack resistance of concrete; at the same time, it enhances the plastic deformation ability of concrete so that the final damage pattern of concrete is apparent oblique cross-section shear damage.

In order to clarify the comprehensive influence mechanism of steel fibre content on the dynamic compression and tensile mechanical properties of concrete, Peng et al. selected steel fibre concrete with different volume contents and used the Hopkinson Pressure Bar (SHPB) device to carry out dynamic compression and dynamic Brazilian splitting tests of steel fibre concrete under different impact air pressures. They concluded that under the same impact of air pressure, the dynamic compression strength and dynamic splitting tensile strength of steel-fibre concrete were positively correlated with the steel fibre content. The degree of energy absorption and crushing were positively correlated, indicating that the presence of steel fibres inhibits the crushing of the concrete. It is not conducive to the absorption and dissipation of the impact energy of the steel-fibre concrete specimens, and there exists an upper limit interval of 30% to 36% of the absorption rate. The steel fibres had a significant effect on the concrete's dynamic splitting tensile strength is significantly higher than its dynamic compressive strength, and the strength of concrete is enhanced more significantly when the steel fibre content is 2%~3% [2].

Sun et al. studied the early cracking resistance of steel fibre concrete, and their study indicated that steel fibres can effectively reduce the initial strain, improve the early tensile properties and cracking resistance, and control the expansion of cracks [3]. However, the effect of suppressing the number of cracks has yet to be apparent. Compared to plain concrete, steel fibre concrete performs better in terms of cracking resistance and flexural strength. There exists an optimum interval for the infiltration of steel fibres. Too little infiltration could result in the concrete not reaching the best performance, and too much infiltration could increase the concrete performance.

2.2. Development and application of steel fibres

Steel fibre concrete first appeared in 1849. The French florist Monier (1823-1906) added fine wire mesh to cement made of wire cement buckets and subsequently experienced many years of development until the 1940s. The United States, Britain, France, Germany and other countries have issued patent literature on the basic mechanical properties of steel fibre concrete. Furthermore, in the late 1970s, China only began to research steel fibre concrete and has done much work in these years. Steel fibre concrete has been gradually promoted and utilized in various professional fields such as civil engineering, water conservancy and construction. As steel fibre concrete has better crack resistance and flexural strength, it can be used in roof waterproofing and underground waterproofing

projects. In addition to being widely used in railroad projects, explosion-proof projects and so on. There are obvious disadvantages of steel fibre concrete, such as larger dosage, higher price, rust, and almost no resistance to fire-induced bursting.

3. Polypropylene Fiber

3.1. Basic mechanical properties

The ultimate tensile rate of concrete is low, generally 0.01% to 0.20%, while the tensile rate of polypropylene fibres is as high as 15% to 18%, uniformly dispersed in the concrete of polypropylene monofilament fibres. Polypropylene fibre prevents the sinking of aggregates, improves compatibility and water seepage, and reduces segregation. It also effectively withstands the tensile strain due to the contraction of the concrete, delaying or preventing the occurrence of internal micro-cracks in the concrete and the development of macro-cracks on the surface, and improving the seepage resistance of the concrete. Under the impacts of load, polypropylene fibre concrete could prevent the expansion of concrete cracks and improve the impact resistance of concrete, frost resistance, and anti-carbonation properties.

Many scholars at home and abroad have studied polypropylene concrete. For example, Liu conducted a split tensile test [4]. The test results show that compressive strength and split tensile strength increase with the increase in mixing amount, more than 0.9kg/m3, compressive and split tensile strength is a decreasing trend; polypropylene fibre concrete, regardless of the mixing amount of the size of the polypropylene concrete at different ages, compressive strength and split tensile strength have different degrees of compressive strength and split tensile strength. The split tensile strength has a different degree. The tensile strength of polypropylene fibre concrete, regardless of the dosage, the compressive strength and splitting tensile strength of polypropylene concrete of different ages have different degrees of increase. In the dosage of 0.9kg/m, the mechanical properties of polypropylene concrete of different ages have the most significant increase, and they concluded that the optimum length of fibres of polypropylene fibre concrete is 19mm. The 6mm group and 12 mm group of concrete compressive and splitting tensile test results are smaller than 19mm group.

Wang et al. analyzed the performance of polypropylene fibres and came to a similar conclusion to Liu [5]. The polypropylene fibre concrete has good working and mechanical properties and is suitable for structural reinforcement and complex, difficult-to-pour parts, polypropylene fibres and expansion agent composite superposition effect of the two can be effective in inhibiting concrete cracking. Based on different fibre dosages of polypropylene concrete compressive and splitting tensile tests, they found that the addition of polypropylene fibres on the compressive strength of concrete and splitting tensile strength has a different degree of effect. It enhanced the tensile and flexural strength of concrete, and there is an optimal dosage to make the concrete tensile and compressive strength to improve the maximum; the optimum dosage of C30 polypropylene fibre concrete is 0.9kg/m3 with the highest compressive strength and splitting tensile strength of concrete. When the dosage is more than 0.9kg/m3, the compressive strength and splitting tensile strength of concrete decreases.

Lu et al. studied the influence law of concrete frost resistance [6]. They designed fibre concrete specimens and ordinary concrete specimens at different compressive stress ratios for freeze-thaw cycle tests. They concluded that in the compressive stress ratio of 0 ~ 0.2 range, the stress compression of the concrete structure of the internal pores bubbles reduces the expansion pressure formed by water icing, the structure of the freeze-thaw damage is inhibited, the concrete frost resistance enhanced; compressive stress ratio greater than 0.6, the concrete is basically in the plastic stage, freeze-thaw damage process accelerated, the concrete is in the external compressive stress as well as the internal expansion and infiltration of the pressure of deterioration faster under the combined effect of the pressure, the concrete in the external compression and internal expansion and infiltration, the freeze-thaw resistance is increased. Under the combined effect of deterioration faster, reducing the freezing resistance of concrete, mixing the right amount of fibre and applying appropriate compressive stress is conducive to promoting the improvement of the freezing resistance of concrete.

3.2. The development of polypropylene fiber

Although polypropylene already has many characteristics of high-performance concrete, its mobility and mixability still need to be improved. With the rapid development of modern science and technology today, one can rely on various means to improve polypropylene fibre concrete without significantly increasing the cost of fluidity, mixability and other poor performance defects. It can not only improve the durability of the building to extend the service life of the building but also can positively contribute to cost savings [7]. On the other hand, as the complexity of the building and its height increases, the fire resistance of the building is also put to the test. By adding polypropylene fibres to high-performance concrete, when the temperature exceeds 165°C, the polypropylene fibres melt and evaporate, leaving many openings in the concrete. It is helpful for the discharge of gases and other gases generated by high temperatures in buildings. Therefore, polypropylene fibre concrete could have a broad future in modern construction.

On the other hand, due to the superior seepage resistance of polypropylene fibre concrete, it is used in seepage control of channels, dam construction, and harbours and wharves. Among them, channel seepage control is still in its infancy in China's rural water conservancy. Professional masonry repair and maintenance can significantly improve the seepage and frost resistance of concrete and then improve the service life and engineering efficiency, which can make the comprehensive economic benefits significantly improved, which is also very obvious to the positive effects of China's water conservancy project construction.

4. Mixed fibres (steel and polypropylene)

4.1. Basic mechanical properties of blended fibres (steel and polypropylene fibres)

The current research on steel-polypropylene fibre concrete (SPRFC) mainly focuses on the mixing effect of fibres, mechanical properties, bursting resistance and durability. For the mechanical properties of SPRFC, scholars at home and abroad have carried out a large number of experimental studies and reached a consensus: steel fibres mixed with polypropylene fibres can improve the compressive, flexural and splitting strength of concrete and significantly improve the cracking performance and toughness of concrete, thus improving the seismic performance of concrete columns, concrete beams, shear performance and high-temperature concrete. Performance of concrete columns, shear resistance of concrete beams and bursting resistance of concrete under high temperature.

Song Junjie et al. for the Gobi large temperature difference area road concrete cracking problem, steel-polypropylene fibres into the concrete, test the indicators, and through the micro-morphology and fibre spacing theory, to explore the role of fibres on the cracking mechanism of concrete [8]. The study shows that with the increase of fibre admixture, the cohesion and water retention of concrete is good, the slump value is 100~120mm, the compressive strength, flexural strength and refractive compression ratio (RFC) show an increasing trend, and the elastomeric strength ratio (PSR) shows a decreasing trend. Wavy steel fibre (WSF) produces strong adhesion and mechanical occlusion between WSF and concrete, and polypropylene fibre (PPF) can be uniformly dispersed in the concrete, dispersing and releasing a certain amount of stress and acting as a reinforcing bar. They combined the fibre spacing theory, SEM analysis and mechanical property analysis. They found that the mixing method with a volume ratio of 1:2 between WSF and PPF is the most excellent.

Wu designed a three-factor, three-level orthogonal test to study the effects of steel fibre type, steel fibre mixing amount, and polypropylene fibre mixing amount on the mechanical properties of SPRFC [9]. The three factors' degree of influence and significant influence factors on the mechanical properties of SPRFC were obtained by polar analysis of variance and analysis of variance on the compressive and flexural strength of SPRFC cubes. Relative to the type of steel fibre and the amount of polypropylene fibre admixture, the steel fibre admixture has the most significant effect on the compressive strength of concrete, which is realized as steel fibre admixture > steel fibre type > polypropylene fibre admixture. Steel fibre admixture is the main factor affecting the flexural strength

of concrete. When the steel fibre admixture is increased from 0 to 1%, the flexural strength of concrete is increased by 14.7%; the addition of fibres could increase the initial defects within SPRFC, and at the same time, the interface between the concrete and the steel fibres could form a weak layer so that it reduces the concrete's compressive strength; when micro-cracks appear in the concrete, the high modulus of elasticity of the fibre through the bond with the matrix concrete and mechanical occlusion to bear the main load, the greater the admixture of fibre concrete, the higher its tensile strength, the higher the flexural strength of SPRFC; polypropylene fibres could be incorporated to increase the deformability of the concrete with the ductility, but there is no significant effect on the compressive and flexural strength of concrete.

4.2. Development of hybrid fibre

The low modulus of elasticity of the fibre used to prevent early shrinkage cracks in mortar concrete has been widely recognized by academics and the engineering community, and its application areas continue to expand. Polypropylene fibre is cheaper than other kinds of fibres, and the cost advantage gives it a better application prospect. However, the following problems still exist in terms of the current development trend:

Much research has been carried out in the engineering field for the durability of SPRFC. The current research results have been the consensus of the academic community on the environmental impact of single durability indicators fibre factor research [10]. However, SPRFC durability research must be more comprehensive for the complex environment.

Although there have been fibre concrete design specifications, they cannot meet the needs of a variety of complex, large-scale projects. Therefore, it is necessary to continue to test specimen components to carry out experimental research and a comprehensive understanding of the performance of fibre concrete components in a variety of loads in order to improve the structural design specifications to provide a strong basis.

Nowadays, the durability degradation law and modelling research of SPRFC under multi-factors should be carried out, which is the trend of development and provides the theoretical basis and technical support for the promotion and application of SPFRC in actual projects.

5. Discussion

The technical characteristics of steel fibre concrete are that it can improve the toughness and tensile strength of concrete, but the steel fibre is easy to agglomerate when mixing. The concrete has poor compatibility, is difficult to pump, is challenging to construct and is easy to rust. Coupled with the weight of steel fibre concrete, it is tremendous, resulting in higher costs and no advantage in price over similar products.

Polypropylene fibre crack-blocking effect plays the necessary conditions, is concrete in the early stages of hardening at the same time in the state of deformation restriction and water loss and contraction, and such a state in the indoor or on-site production of small specimens do not have. Polypropylene fibre's fluidity will weaken, and the cost per cubic meter is also higher.

China's research on SPRFC is still in its infancy, and most of the research focuses on the mechanical properties of steel fibres mixed with polypropylene fibres can improve the compressive, flexural and splitting strength of concrete, and significantly improve the cracking resistance and toughness of concrete has basically formed a consensus, but like the SPRFC in complex environments, SPRFC structure seismic performance also need to be studied.

6. Conclusion

This paper has selected three typical fibre materials for study, and their principles of action, basic mechanical properties and development are discussed.

Steel fibres are compared with polypropylene fibres in terms of mechanical properties. Steel fibres cannot effectively eliminate or reduce the number and scale of primary cracks due to their relatively small amount in concrete. However, their higher modulus of elasticity gives them a solid ability to transfer loads and restrain crack expansion. The above functions of steel fibres make the pavement concrete slab withstand the vehicle's impact. It can be diffused in a more extensive range of the slab, and the local stress concentration phenomenon can be reduced. The impact resistance and fatigue resistance of the pavement bridge deck commercial concrete is thus improved. Although SPFRC in complex environments and structural seismic performance and other aspects still need to be studied, according to the mechanical properties that have formed a consensus on the mechanical properties, SPFRC considers the mechanical properties of the two fibre materials.

In terms of development, the mechanical properties of steel fibre concrete and polypropylene fibre concrete and the application in the actual construction of SPRFC are relatively perfect. Therefore, steel fibre and polypropylene fibre have been widely used in various professional fields. While steel-polypropylene fibre has been studied for a shorter period of time, some of the basic mechanical properties have not yet been researched and formed a consensus, so SPRFC has not yet been practically used in the engineering field. Binary fibre concrete with steel fibre and polypropylene fibre as the main admixture has great advantages in the application of concrete durability, but there are also some defects. In recent years, SPRFC has been the basis of the composite durability study of multiple mixed fibres, admixtures, and high-strength or recycled concrete matrices.

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