Analysis on The Performance of Carbon Fibre Reinforced Concrete in Cold Region

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Abstract. Carbon fibre reinforced concrete (CFRC) is a new kind of composite material which is made by adding appropriate amount of shear carbon fibre into ordinary concrete. Compared with ordinary concrete, carbon fibre can better adapt to the harsh environment in cold regions and overcome adverse conditions. As a result, it can be widely used in infrastructure construction along the “Belt and Road” in China. In this paper, through analysing many experiments, charts, and theoretical analyses, the frost resistance, crack resistance, and compressive resistance of CFRC have been analyzed and introduced and verified its excellent performance of CFRC. On this basis, the feasibility of CFRC's application in cold regions is discussed. The results show that compared with ordinary materials, it is stronger in adapting to the harsh environment in the cold zone and has a broad development prospect and considerable potential in the future cold zone engineering construction.

Keywords: CFRC; Pressure resistance; Crack resistance; Frozen resistance.

1. Introduction

Under the rapid development background of infrastructure construction all over the world, concrete is one of the most widely used building materials with the largest amount. It is well known that concrete has excellent compressive resistance performance. However, its poor impact, tensile and bending resistance performance etc. limit its application in certain situations. China is investing more in the Belt and Road Initiative. Because of complex geological conditions, concrete is subjected to extremely low temperatures, groundwater, and high stress. With complex geological conditions, it is difficult to use ordinary concrete to meet the needs of this project. CFRC can be produced by adding carbon fibre, which has the advantages of lightweight and high durability, to concrete, and has the characteristics of high strength, high ductility, and excellent basic mechanical properties such as tensile and impermeability. CFRC has a long development history. Humans began using straw fibres to enhance the performance of bricks in ancient Egyptian times. The first production of viscose-based carbon fibres began in the USA in 1959. Since then, fibre concrete has been extensively studied in various countries. In the 1970s, panels made from polyacrylonitrile (PAN) carbon fibre reinforced cementitious materials were first produced in the UK and used in construction. This set the precedent for CFRC research and application. As a result, carbon fibre concrete began to develop and was hailed as the new material of the twentieth century. This paper will explore the changes in the three performance indicators of CFRC under freeze-thaw cycles and mechanical performance tests for compressive and crack resistance and frost resistance. In this way, the valuable experience will be gained for the promotion of CFRC in low-temperature environments.

2. The principle of cfrc

Carbon fibre can be used to strengthen concrete. This paper mainly discusses its enhancing effect. Carbon fibre is mixed into the concrete. It not only improves the compressive strength, tensile strength, and fatigues strength of concrete. It can also enhance the stability of concrete, for instance impact resistance, freeze-thaw resistance, and wear resistance. Avoiding brittle fracture of components happens at low stress levels. At the same time, the apparent morphology of cement concrete can be fully improved. This makes its surface more dense, fine, smooth, and beautiful. According to the fibre spacing theory of fracture mechanics, the tensile strength of carbon fibre is far better than that of concrete. When carbon fibre is mixed into the concrete, in the concrete under the case of tension, its fibres will play a certain role in the connection. It can absorb some of the stress, thus inhibiting the further propagation of cracks.

When concrete is damaged by freeze-thaw, the water between cracks freezes and leads to volume expansion. The volume decreases as the moisture melts. The cracks in the concrete become larger after multiple cycles, causing more water to enter the cracks. A vicious cycle is formed. The addition of carbon fibre can increase the integrity of the concrete, moisture from entering the interior of the concrete and assume some of the internal stresses generated when the concrete freezes and thaws.

The addition of carbon fibre allows concrete to change the direction of expansion of the rupture and thus increase the dissipation of energy. The emergence of new cracks increases the dissipation of energy. The microstructure-mechanical properties relationship can be explained as follows: The randomly oriented tessellated optical texture distributed throughout the carbon matrix increases the energy required for crack propagation. Therefore, the mechanical failure of carbon due to the energy-consuming crack suppression and the manipulation of the transfer mechanism of the mosaic-mosaic interface. In carbon with a larger, anisotropic optical texture, less energy is required for mechanical failure. Because cracks preferentially spread along the low shear strength base surface present in the carbon.

The doping of carbon fibre and the volume fraction of carbon fibre can increase the strength of carbon fibre concrete. When the performance of CFRC is optimal, the compressive resistance, crack resistance, and frost resistance are improved. Fibre can form more efficient three-dimensional network structures that prevent cracks from germinating and developing. Greatly reduces the connectivity of concrete.

3. CFRC performance analysis

3.1 Compression resistance analysis of CFRC

3.1.1. Compression Principle of CFRC

Due to snow, frozen soil and other reasons, buildings and structures in cold regions often receive greater compressive stress, so the compression performance of concrete is higher. From the perspective of the microscopic failure mechanism of concrete, the compressive strength is mainly realized through the ability to resist transverse deformation, which is positively correlated with it. Therefore, In order to improve the physical properties, CFRC restrained the transverse deformation trend inside concrete by adding carbon fibre, forming a dense three-dimensional network space structure inside concrete. The reinforcement effect is like that of steel bars, which limits the free development of internal micro-cracks, thus reducing the deformation caused by compressive stress and improving the compressive resistance of CFRC. Furthermore, when concrete is subjected to external pressure, carbon fibre in CFRC spans micro-cracks. The effect is equivalent to a bridge bonded to concrete, containing the tendency of compression deformation and assuming the ability to block the expansion of internal cracks in cement mortar, thus achieving compression resistance.

3.1.2. Effect of Carbon Fibre Content on Compressive Strength

The electro-hydraulic servo compression testing machine (Figure 1) is used to conduct a compression test on the specimen. When the specimen is at the critical point of failure, the compression is stopped, and its maximum load capacity is recorded. Figure 2 is the final compression test result table. According to it, the compressive strength of CFRC increases first and then goes down with the rise of the ratio of carbon fibre, and the compressive strength reaches a peak value of 50MPa when the ratio is 0. 3%. When the content is less than 0.3%, carbon fibre content is positively correlated with compressive strength. When the content is more than 0.3%, the carbon fiber content is negatively related with the compressive strength of concrete, and any fibre addition does not further enhance the compressive strength of concrete. It means that if the addition amount of carbon fibre is reasonably controlled, the resource allocation can be reasonably allocated to achieve the optimal compression effect. It is worth mentioning that the higher the content of carbon fiber, the better the effect, exceeding the limit value (0. 3%), the compression performance will not improve, but will decrease.

Figure 1. Compression testing machine

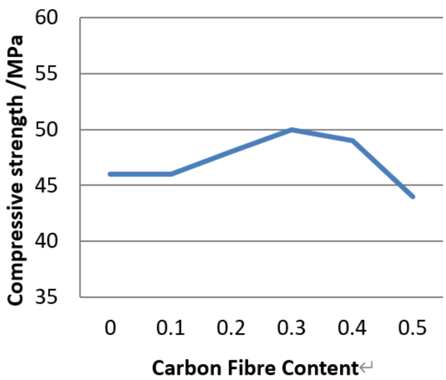

Figure 2. Table of experimental results of stress

3.1.3. Effect of Carbon Fibre Length on Compressive Strength

To study the influence of carbon fibre length on compressive strength, 3.6 and 9mm short carbon fibres were used for control experiments. The experimental method was consistent with the carbon fibre content test method (compression test), and the final test data were obtained, as shown in FIG. 3 . According to the data in the figure, no matter how much carbon fibre is mixed (except 0), the compressive strength of CFRC reaches its maximum peak value when the carbon fibre length is 6mm; when the carbon fibre length is less than 6mm, the compressive strength is positively proportional to the carbon fibre length; when the carbon fibre length is greater than 6mm, the compressive strength is inversely proportional to the carbon fibre length. According to this rule, by increasing the diversity of sample lengths and testing more CFRCS with lengths between 4mm and 10mm, the exact length to maximize the compressive strength can be theoretically obtained. According to this length, the influencing factors of carbon fibre length can be effectively utilized to achieve the best compressive performance of CFRC.

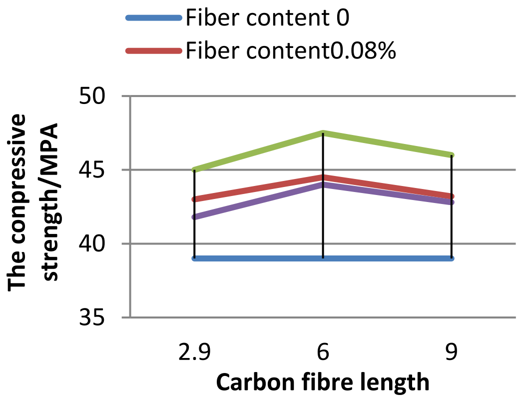

Figure 3. Experimental results of the effect of carbon fibre length on compressive strength

3.1.4. The Significance of Carbon Fibre Factors in CFRC for Cold Regions

According to the experiment, the compressive properties of CFRC are affected by the following aspects: the proportion of carbon fibre in concrete and the length of carbon fibre. These two factors are first positively related with the compressive strength of CFRC, and then negatively correlated with it. Therefore, if its value is adjusted to the optimal peak state, the compressive strength can be maximized. This rule of CFRC has great value in the application of the cold, because of the cold and snow for a long time, permafrost, pavement concrete engineering, construction and other perennial received a large load, presents the downward pressure. Therefore, building materials in cold areas need to have good compression performance, which can resistance to overcome these disadvantages, enhance the performance of the building. Under this circumstance, CFRC meets these conditions well based on improving ordinary concrete and has a wide range of application value.

3.2 Crack resistance analysis of CFRC

3.2.1. Crack Resistance Principle Of CFRC

Carbon fibre can effectively upgrade the brittle damage of concrete. The appropriate amount of carbon fibre can effectively enhance the mechanical properties of concrete such as compression failure deformation. In a freeze-thaw cycle for fibre-free concrete and steel fibre and polypropylene fibre concrete test blocks, the reference concrete surface produces many irregular cracks. After penetrating deep into the interior of the concrete, the concrete peels off and is damaged. Conversely, there are relatively few cracks in the concrete incorporated into the fibres, there is no obvious spalling damage, and with the increase of the amount of doping, the specimen tends to be intact. The concrete with the addition of fibres plays a role in resisting cracking.

3.2.2. Introduction and Analysis of Crack Resistance Test

In the study of Guo et al., it can be seen that: The carbon fibres are evenly distributed in the concrete without any fibre additive. As the carbon fibre content increases, the more carbon fibre is found on the fracture surface of the concrete specimen. When the carbon fibre content is 1.4wt, the mechanical properties of CFRC are reduced. When carbon fibre is added to concrete, the bubbles and pore size of CFRC are significantly smaller than those of ordinary concrete. However, in Safi-Uddin et al. 's study of carbon fibre-reinforced self-condensing concrete (CFRSCC). CFRSCC mixtures containing 0.25% carbon fibre achieve the highest level of mechanical properties. Carbon fibre can completely develop the brittle failure of concrete, and the CFRC failure deformation is especially important when the carbon fibre dosage is 0. 24% to 0. 52%, as shown in Figure 4. For carbon fibre failure modes, relatively high fibre content, CFRSCC with fibre content of 0. 75% and 1.0%, respectively. As the carbon fibre content increases, the number of bubbles and pores in the concrete matrix improves considerably. Zhan-Yang Chen also concluded, the high strength of the carbon fibre itself consumes energy during the extraction or fracture process, improving the mechanical properties of CFRC. On the other hand, the addition of carbon fibre creates some bubbles and pores in the material. Some weak surfaces are created between the fibres and the substrate, which impairs the integrity of the concrete substrate.

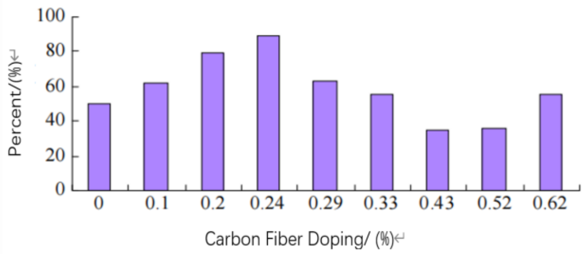

Figure 4. Effect of different dosages on the force performance of CFRC test blocks

Wang 's experiments were monotonically tested on all reference and reference beams subjected to bending cyclic loads. Table 1 exhibits the first cracking load and the ultimate load specified in the Chinese standard. According to the references, the form of the curve becomes nonlinear. As can be seen in Table 1, the first cracking and limiting loads of CFRC reinforced beams (J-2-J-4 group) are slightly larger than those of the original reinforced concrete beams (J-1 group). The first cracking load and the limit load increase monotonically with the increase in the degree of reinforcement. Compared to CFRC reinforced beams, reinforced concrete beam spacing is wider, the number of cracks is small. Beam J-4 cracks appear at relatively closed spacing. It shows that the reinforcement of the CFRC layer strengthens the constraint of the concrete. The increase in rigidity due to the influence of the CFRC on the suppression force can lead to the increase in the first crack and limit load of the CFRC beam.

Table 1. Test results of different beams

Group	First cracking load Average (KN)	Ultimate load Average (KN)	Deflection at ult load Average (mm)
J-1	9. 8	84. 5	10. 55
J-2	10. 4	91. 2	10. 5
J-3	11. 0	92. 6	10. 8
J-4	11. 2	92. 8	10. 85

Scholars have summarized the influence of micron-sized, millimeter-level and two-size Carbon Fibres (CFs) on the mechanical properties of Portland cement mortar. All three types of CFs improve the peak preload energy absorption capacity of the mortar. The mixed mortar of the two sizes of CFs exhibits excellent tensile properties and fracture resistance. can improve the dispersibility of CFs in CFRC. CFs are evenly distributed in CFRC as enhanced phases, helping to overcome the growth of microcracks. As a result, the mechanical properties are improved.

3.2.3. Crack Resistance Test Analysis

Carbon fibre can adequately delay the expansion of cracks, balance cracks, and enhance the critical effective crack length. Bridging can also be provided to delay the rapid opening of cracks, thereby preventing concrete cracking. The experiment shows that, CFRC layers can enhance the crack resistance of the authentic ferro concrete, and the higher the degree of reinforcement, the more the mechanical properties increase.

3.3 Frozen resistance analysis of CFRC

3.3.1. Statement of Basic Principles for CFRC Freeze-thaw Experiments

The process of the freeze-thaw experiments uses the quick-freeze method as a theoretical basis. The rapid freezing method is mainly used for tests that measure the number of cycles that concrete can withstand during rapid thawing and rapid setting. The freeze-thaw experiments are carried out in accordance with GB/T 50082-2009. The test will be carried out using a rapid freeze-thaw tester. In the experiment, the specimens with pre-built temperature sensors will first be placed in a rubber drum.

The rubber drum is then placed in the centre of the freeze-thaw cycle machine and filled with a water solution. In turn, all specimens are placed into the tester for freeze-thaw cycle testing. The freeze-thaw temperature is set in combination with the high and low temperature and freeze-thaw seasonal climate of the Sichuan-Tibet Railway. The freeze-thaw temperature was set to 40 °C for high temperatures and -27 °C for low temperatures. During the test, a mass loss measurement was carried out every 8 to 10 freeze-thaw cycles. After measurement, the specimens were put back into the rubber drum and the next freeze-thaw cycle continued. The frost resistance of the concrete was analyzed in conjunction with the experimental data. The freeze-thaw test should be stopped immediately if any of the following conditions occur firstly, the number of cycles specified for the test has been completed; secondly, the relative dynamic modulus of elasticity of the test specimen is less than 60% before the test; thirdly, the mass of the test specimen is less than 95% before the test.

Table 2. Physical and mechanical properties of cement

SO_3 /%	Cl- /%	Desulphurization gypsum /%	Flyash /%	Loss on ignition /%	Time of setting /Min		Flexural strength /MPa		Compression strength /MPa	
					Initial set	Final set	3d	28d	3d	28d
2.8	0.053	6.5	9	4.46	185	230	5.4	6.6	28.6	42.5

3.3.2. Test Material Preparation

The physical and mechanical properties are shown in Table 2 and Table 3. Methylcellulose was used as a dispersant and tributyl phosphate as a deflating agent.

Table 3. Physical and mechanical properties of fibres

Tensile strength /GPA	Elastic modulus /GPA	Elongation /%	Diameters /μm	Fibre Length /Mm
4	230	1. 9	7	50、30

CFRC specimen preparation: The amount of carbon fibre doping of CFRC will directly affect its frost resistance and various mechanical properties. To determine the appropriate carbon fibre dose for CFRC, the corresponding literature was consulted to determine the carbon fibre dose of 0.10%, 0.20%, 0.24%, and 0.30% for the preparation of CFRC. At the same time, the CFRC specimens were prepared by the dry method, considering the length to diameter ratio and the uniformity of fibre distribution. During the preparation process, the mixed concrete is loaded into a cube which prism length is 100 mm, 100 mm, and 400 mm. When the concrete is one third of the way into the mould, it is repeatedly pounded with a pounding bar. After the concrete has been compacted, the mould is then filled. The test mould is then placed on the vibrating table and vibrated. When a cement paste appears on the surface of the concrete, the concrete is cut off with a scraper and covered with plastic film. Finally, the concrete moulds were placed in a constant temperature and steam curing room for 24h and then demoulded. After demoulding, the specimens are kept for 24d before being removed. After removal, the specimens are immersed in water at 20°C. After soaking for 4d, remove the specimen and carry out the freeze-thaw test. C30 concrete was made in accordance with JGJ/T221-2010 Technical Specification for the Application of Fibre Concrete, and the CFRC proportions are shown in Table 4.

3.3.3. Results and Analysis of CFRC Freeze and Thaw Experiments

C30 concrete is make as per JGJ/T 221-2010 Technical Specification for fibre Concrete Application. The CFRC mix ratio is shown in Table 4. The ratio of CFRC with different amounts of CFRC.

According to the experimentally obtained quality loss rate of CFRC with different carbon fibre doping (Figure 5). The change of CFRC quality loss rate with the number of freeze-thaw cycles for different carbon fibre doping is divided into five stages. Stage [I], freeze-thaw cycles is 0~30 times, and the specimen mass loss rate is basically 0. This stage is called the freeze-thaw adaptation period. Stage [II], freeze-thaw cycle 30~40 times, the specimen quality loss rate along

Table 4. CFRC mix design

Number	Fibre admixture%	Draw ratio	Cement /Kg	Water /Kg	Thick, fine aggregate/Kg	No Foam /g	Dispersant/g
N	0	0	16	6.08	14.14	0	0
CO	0.1	4 286	16	6.08	14.14	6.74	67.4
C1	0.2	4 286	16	6.08	14.14	13.48	134.8
C2	0.24	4 286	16	6.08	14.14	16.18	161.8
C3	0.24	7 143	16	6.08	14.14	16.18	161.8
C4	0/30	4 286	16	6.08	14.14	20.22	202.2
C5	0.30	7 143	16	6.08	14.14	20.22	202.2

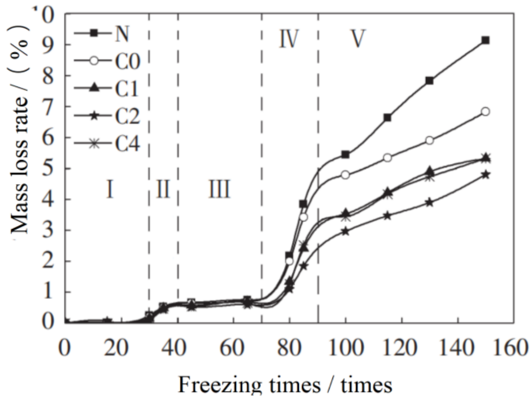

Figure 5. Quantitative loss of different amounts of CFRC

A straight line slightly increased. This stage is called the initial loss of quality period. Stage [III] when the freeze-thaw cycle is 40~70 times. Test piece quality loss rate changes more slowly, this stage is called the quality loss resistance period. Stage [IV], freeze-thaw cycles 70 ~ 90 times, and the quality loss rate increases rapidly. This stage is called the test piece damage period. Stage [V], freeze-thaw cycle ≥ 90 times, the quality loss rate of the specimen at this stage rises more quickly is called the specimen damage period. The mass loss at this stage is less than the damage period.

Analysis of the experimental results shows that the quality loss rate of CFRC specimens with different carbon fibre admixtures was almost the same as that of normal concrete specimens before 70 freeze/thaw cycles. However, after 70 freeze-thaw cycles freeze/thaw cycles, the quality loss rate of all concrete specimens showed a rapid increase. As the number of freeze/thaw cycles continued to increase, the mass loss of normal concrete became significantly higher than that of CFRC. This was because the carbon fibre in CFRC effectively resisted the tensile stresses caused by the expansion and cracking of the concrete caused by the freeze-thaw cycles and offset some of the quality loss rate. As the amount of carbon fibre increases, the mass loss rate of CFRC becomes smaller and smaller. The CFRC mass loss rate reaches a peak when the carbon fibre dose is increased to 0.24%. This leads to the conclusion that CFRC with 0.24% of carbon fibre has a better frost resistance than ordinary concrete, and that CFRC with 0.24% of carbon fibre has a 67% higher frost resistance than ordinary concrete.

The analysis of the experimental results shows that the incorporation of carbon fibre into the concrete can counteract the temperature stresses that occur in concrete due to temperature changes. This allows for a significantly less in the rate of quality loss of concrete specimens subjected to repeated freezing and thawing in complex environments such as extremely low temperatures, high stresses, and groundwater. The greatest improvement in the frost resistance of CFRC compared to normal concrete is achieved when the carbon fibre dose is 0.24%. The improvement is about 67%.

This prevents frost cracks in the concrete to a certain extent. In this way, the frost resistance and the basic mechanical properties of the concrete are improved.

4. Conclusion

In summary, many excellent properties of CFRC perfectly meet the requirements of building materials in cold regions, and it is an excellent choice to replace ordinary concrete. Through compression experiment, fibre spacing theory, quick freezing method and other experimental methods, it is verified that its compression resistance, crack resistance and frost resistance are the main unique advantages to overcome the harsh conditions in cold regions. The results are summarized as follows: (1) Compressive strength: the compressive strength of carbon fibre shows a positive correlation with the content and length of carbon fibre and becomes a negative correlation after reaching the peak value. The compressive strength can be improved at the appropriate peak point. (2) Crack resistance: carbon fibre can effectively provide bridge relay, delay the rapid opening of cracks, increase crack resistance. (3) Frost resistance: with the increase of freeze-thaw cycles, the mass loss rate of ordinary concrete is obviously higher than that of ordinary concrete. Carbon fiber can effectively resist the negative effects of freeze-thaw cycle in CFRC, and the higher the content of carbon fiber, the stronger its resistance, and the higher the carbon fibre content, the stronger its resistance.

In China, there is a large area of cold region, in which CFRC has promising future. The policy of “the Belt and Road” enlarges the investment of infrastructure; allowing CFRC to be substituted for ordinary concrete material used in foundation engineering of highway, tunnel and increase the service life of the project, improve performance and economic benefit. However, CFRC’s frost resistance, crack resistance and compressive property is well enough to reduce unfavorable factors of materials, such as freeze-thaw damage, crack, compression deformation. On top of that, by finding the balance point of performance to these advantages, CFRC can then become an excellent material for widespread use in cold regions. Carbon fibre with its unique characteristics on the part of concrete performance is improved effectively, but at present the study of carbon fibre concrete is still in the experimental research stage. Additionally, the development of the theory research remains to be further evenly dispersed in the carbon fibre in cement mortar and concrete evaluation and dosage of dispersants, sand, stone the reasonable collocation of problems need to be further solved. However, this does not affect CFRC to become a material with broad prospects in cold areas; it is believed that after solving such problems, it will be widely used in cold area engineering construction.

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