International Journal of Civil Engineering and Machinery Manufacture
ISSN: 2518-0215, Volume 6, Issue 1, March, 2021

# Research on the Durability of RPC Mixed with Different Types of Fibers under Salt Freezing

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**Abstract:** This paper aimed to study the coupling effects of different fibers (steel-polypropylene hybrid fibers, steel-polyvinyl alcohol hybrid fibers, steel-polyvinyl alcohol- polypropylene hybrid fibers) and their contents on the salt frost resistance of RPC. The weight loss relative dynamic elastic modulus and splitting tensile strength of RPC were investigated. Results indicated that the increase of polypropylene fibers dosage played-negative roles in the durability index of RPC specimens. With the increase of polyvinyl alcohol fibers content, the durability index of RPC specimens decreased first and then increased. The threshold values of polyvinyl alcohol fibers and Polypropylene fibers were 1% and 0.3%.Finally, adding two kinds of fibers at the same time can effectively improve the spatial structure of RPC, produce positive hybrid effect, and greatly improve the salt frost resistance of RPC.

**Keywords:** RPC; NaCl freeze–thaw cycles; Mass loss; Splitting tension; Relative dynamic modulus

## 1. Introduction

In coastal areas, buildings are not only eroded by sea water all year round, but also suffer freezing disasters in winter, thus, salt-freezing damage has become a common form of concrete structure damage. Studies have shown that the combined effect of freezing-thawing cycle and chloride ion penetration has greater impact on concrete structure than the simple superimposition of the two [1-4]. Therefore, it is extremely important to conduct freezing-thawing test on concrete materials used in this area.

Reactive powder concrete (RPC) is a kind of compact cement composite material [5-6], whose advantages can be given to full play together with fibers by adding an appropriate amount of randomly distributed fibers. Its good mechanical properties have received widespread attention [7-10] and have been applied to various concrete structures. In recent years, scholars at home and abroad have extensively explored the durability of RPC, and obtained abundant results. Yan et al. [11] studied the durability of RPC through a rapid freezing-thawing cycle test, and compared its anti-freezing properties with those of the ordinary concrete; JU et al. [12] analyzed the influence of the content of steel fibers on the mechanical properties of RPC under the action of freezing-thawing cycle; Cwirzen et al. [13] found through test that steel fibers can reduce the internal damage caused by freezing-thawing cycle and effectively improve the anti-freezing-thawing performance of RPC. Regarding domestic research, Ju et al. [14] proved that the freezing-thawing resistance of RPC is mainly related to the water-binder ratio, and the content of the steel fibers added has a significant effect on the splitting strength of RPC; Zhu et al. [15] reported that polyvinyl alcohol fibers helps to improve RPC's anti-salt-freezing performance, and adding steel fibers and polyvinyl alcohol fibers at a reasonable ratio will produce a positive hybrid effect; Jiaet al. [16] studied the impact of the amount of steel fibers mixed on the durability of RPC under the salt-freezing action; Wang et al. [17] pointed out that RPC with 2% of steel fibers has good anti-salt-freezing properties; Ji et al. [18] concluded that steel fibers can reduce the mass loss and relative dynamic elastic modulus loss of RPC after freezing and thawing; Zhu et al. [19] investigated the anti-freezing performance of RPC under seawater condition and discussed the mechanism of the salt-freezing damage of RPC.

At present, domestic and foreign research on the freezing-thawing of RPC mainly focuses on single-blended steel fiber or polyvinyl alcohol fiber, while the freezing-thawing resistance of RPC mixed with hybrid fibers has rarely been explored. This article focuses on the influence of the incorporation of different types and percentages of fibers on the durability of RPC under the combined effects of repeated freezing-thawing and chloride ion penetration, and discussed the mechanism of salt-freezing damage of RPC mixed with hybrid fibers. This study provides a theoretical and experimental basis for promoting the application of RPC materials in the northern coastal area of China.

ISSN: 2518-0215, Volume 6, Issue 1, March, 2021

## 2. Description of the Test

### 2.1. Raw materials and mixing proportion

The cement is P·O42.5 grade ordinary Portland cement produced in Jingzhou, Hubei; the fine aggregate is the sands with a size of 2.5mm and fineness modulus of 2.6, and good grain grading; the silica fume is the high-performance micro-silica fume powder produced by SLT in Sichuan Province; the water-reducing agent is HPWR high-performance water-reducing agent, with the water-reducing rate of 26%; there are three types of fibers added, namely copper-coated steel fibers, polypropylene fibers and polyvinyl alcohol fibers. The detailed indicators are shown in Table 1.

**Table 1. Fiber performance parameters**

| Types | Size/mm | Diameter | Ultimate strength/Mpa | Elastic modulus/Gpa | Density /(g/cm³) |
|---|---|---|---|---|---|
| **Copper-coated steel fibers** | 13 | 0.22mm | ＞2850 | - | 7.8 |
| **Polypropylene fibers** | 12 | 48um | ＞400 | ＞3.5 | 0.91 |
| **Polyvinyl alcohol fibers** | 12 | 26um | ＞1500 | ＞30 | 1.3 |

In order to study the influence of the content of polypropylene fiber and polyvinyl alcohol fiber on the durability of RPC, a total of 10 RPC test specimens mixed with fibers were designed. The material ratio of RPC prepared in the experiment is shown in Table 2.The water-binder ratio is 0.2, and the percentage of the fibers mixed and the compressive strength after 28d are shown in Table 3.

**Table 2. Mixture proportions of RPC**

| Cement(kg/m³) | Sand(kg/m³) | Water(kg/m³) | Silica fume(kg/m³) | Water-reducing agent(%) | Antifoamer(%) |
|---|---|---|---|---|---|
| 810 | 1080 | 180 | 90 | 2.5 | 0.05 |

As presented in Table 3, each test specimen can be identified by its label: PXP-AXA(P0.1-A0.5), where XP represent the content of polypropylene fibers added and XA represents the content of polyvinyl alcohol fibers mixed;For example, P0.1-A0.5 represents the content of the polypropylene fibers is 0.1%, and the content of polyvinyl alcohol fibers is 0.5%.

**Table 3. Fiber content and compressive strength of RPC**

| Specimen | Copper-coated steel fibers(%) | Polypropylene fibers (%) | Polyvinyl alcohol fibers(%) | Ultimate strength (MPa) | Quantity |
|---|---|---|---|---|---|
| **P0-A0** | 1 | 0 | 0 | 112.3 | 12 |
| **P0-A0.5** | 1 | 0 | 0.5 | 107.5 | 12 |
| **P0-A1** | 1 | 0 | 1 | 105.1 | 12 |
| **P0-A1.5** | 1 | 0 | 1.5 | 91.6 | 12 |
| **P0.1-A0** | 1 | 0.1 | 0 | 111.8 | 12 |
| **P0.2-A0** | 1 | 0.2 | 0 | 110.9 | 12 |
| **P0.3-A0** | 1 | 0.3 | 0 | 110.6 | 12 |
| **P0.3-A0.3** | 1 | 0.3 | 0.3 | 108.7 | 12 |
| **P0.1-A0.5** | 1 | 0.1 | 0.5 | 106.8 | 12 |
| **P0.5-A0.1** | 1 | 0.5 | 0.1 | 107.3 | 12 |

### 2.2. Test specimen preparation and test

A total of 120 concrete test specimens with the dimension of 100 mm×100 mm×100 mm were prepared, including 90 specimens for material strength test. The preparation process of the test specimens is: the concrete was stirred by machine. In order to make the mixing of various materials more uniform, the concrete was input three times during the mixing and forming process. First, powder materials such as cement, silica fume and sands were mixed for five minutes, then the steel fibers, polypropylene fibers and polyvinyl alcohol fibers were input for mixing for five minutes, and finally the mixed water, water reducing agent and defoamer were input for mixing for five minutes. The whole process lasts about 15 minutes. After that, the test specimens were poured and vibrated on a high-frequency vibrating table for 30s until the test specimens were formed, after which they were placed in a natural laboratory environment for 48h and then demolded. Finally, the test specimens were cured for 28d under standard curing conditions, and then the strength test was carried out. Some test specimens are shown in Figure 1.

Before the freezing-thawing cycle test, the test specimens were soaked in 3.5% NaCl salt solution for 3 days, and then dried to determine its initial mass and dynamic elastic modulus. After that, the test pieces were placed in 3.5% NaCl salt solution for salt-freezing test. The British Standard BS EN 480-1-2006 was used for reference for the freezing-thawing cycle test on the concrete. In each freezing-thawing cycle, the lowest temperature of the center of the test specimen was controlled to -15°C and the highest temperature to 7°C. Each freezing-thawing cycle was completed in about 30 hours. The test machine is a ZDDR-9 concrete freezing-thawing test box, as displayed in Figure 2. After every 25 freezing-thawing cycles, the test specimens were taken out, and the mass and dynamic elastic modulus were measured until the end of the 150 cycles. After every 50 freezing-thawing cycles, the specimens were taken out for the concrete splitting strength test until the end of the 100 cycles. In order to reduce the test error, each set of the test data in the article was obtained by obtaining the arithmetic average of test data of three identical specimens.

**Figure 1. Picture of specimens**

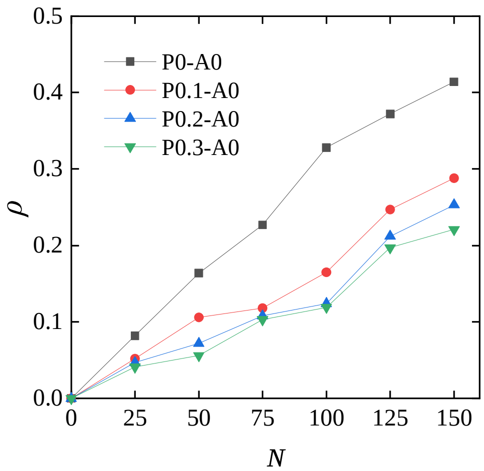
**Figure 2. Concrete freezing-thawing test box**

## 3. Test Results and Analysis

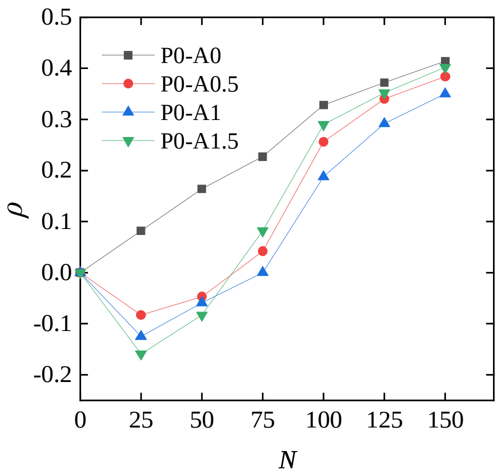
### 3.1. Mass loss rate

Figure 3 shows the mass loss rate (ρ) of each group of test specimens under different times of salt freezing (N). It can be seen from Figure 3a that the mass loss rate of the test specimens gradually decreased with the increase of the amount polypropylene fibers mixed (0-0.3%). When the content of polypropylene fibers was 0.2%-0.3%, the mass loss rate of the specimens remained basically unchanged. Figure 3b shows that the mass loss rate of the specimens first dropped and then rose with the increase of content of the polyvinyl alcohol fibers(0-1.5%). When the fiber content is 1%, the mass loss rate of the specimens reached the minimum. After 150 times of salt freezing, the mass loss rate of the P0-A0 specimen reached the maximum, at 0.414%, and the mass loss rate of the P0-A1.5 specimen was close to that of the plain RPC. The reason is that when the fiber content is large, the fibers cannot be uniformly distributed in the matrix, which weakens the workability of RPC during the mixing process, resulting in a decrease in the compactness of the RPC matrix, thereby accelerating the damage of the RPC specimens under the action of salt freezing. In addition, when the number of the salt freezing cycles was less than 50, the mass of the test specimens mixed with polyvinyl alcohol fibers increased instead of decrease, and the mass increase was proportional to the content of polyvinyl alcohol fibers. There are two reasons: (1) in the early stage of the salt freezing cycle, water will penetrate into the micro-cracks on the surface of the test specimen. The polyvinyl alcohol fibers with a good water absorption performance are distributed in random directions in the RPC matrix, and they overlap each other, so that the water can be prevented from seeping from the matrix. (2) RPC has a relatively small water-binder ratio, and the cementing material in the matrix is incompletely hydrated. After the solution penetrates into the RPC during the salt freezing process, a part of the solution will accumulate in the concrete to crystallize, and the other part will react with the insufficiently hydrated cementing material to generate other products, which in turn leads to an increase in the mass of the specimen [20]. The former is the main factor, and the latter is the secondary factor. It can be seen that the incorporation of polyvinyl alcohol fiber has a positive effect on improving the early freezing-resistance of RPC.

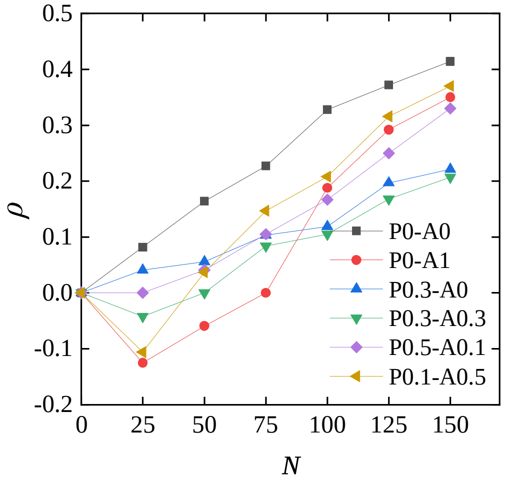
When only one kind of fiber was added, the specimens with the least mass loss rate (ie P0.3-A0 and P0-A1) were compared with the specimens mixed with hybrid fibers, as shown in Figure 3c. It can be seen from the figure that when the total content of the two kinds of fibers was 0.6%, the mass loss rate of the test specimen P0.3-A0.3 was the smallest. The reasons are as follows: (1) after the polypropylene fibers introduce a small amount of air into the concrete, the number of micro-bubbles is increased, thereby reducing the salt-freezing damage; at the same time, it also relieves the internal temperature stress of the concrete and slows down the expansion of the cracks; (2) polypropylene fibers and polyvinyl alcohol fibers can effectively mitigate the early cracking of RPC and enhance the anti-stripping ability of concrete. In addition, Figure 3 reveals that with the increase in the number of salt freezing cycles, the mass loss rate of each group of specimens generally increased. When only one type of fiber was mixed, the P0-A1 test specimen was better than the test piece P0.3-A0 in the early stage (the number of the times of salt freezing is less than 100), and the opposite trend was found in the later stage (the number of the times of salt freezing is more than 100). The RPC specimen mixed with two kinds of fibers at the same time has the advantages of both fibers, which is more reasonable in comparison. In general, salt freezing has little effect on the mass loss rate of RPC specimen. After 150 times of salt freezing, each specimen had less than 0.5% of mass loss, showing good anti-stripping ability.




**(a)Influence of polypropylene fiber on concrete**




**(b) Influence of Polyvinyl alcohol fibers on concrete**




**(c)Influence ofpolyvinyl alcohol- polypropylene hybrid fiber on concrete**

**Figure 3. Mass loss of RPC under salt freezing**

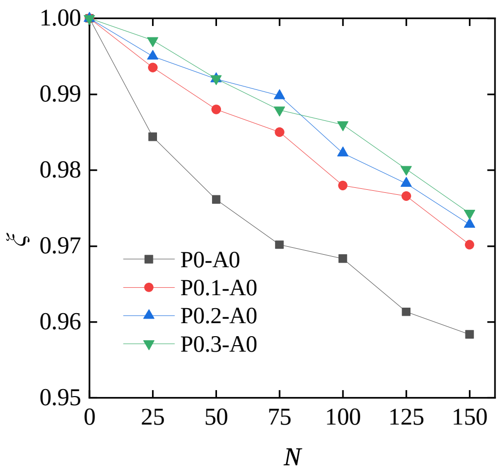
### 3.2. Relative dynamic elastic modulus

The relative dynamic modulus of the specimens in each group after the salt freezing cycles is shown in Figure 4. It can be seen from Figure 4a that the relative dynamic modulus loss of the specimens reduced with the increase in the content of polypropylene fibers (0-0.3%). When the content of polypropylene fibers was 0.2%-0.3%, the relative dynamic elastic modulus loss of the specimen remained basically unchanged. It can be found from Figure 4b that the relative dynamic elastic modulus loss of the test specimens first decreased and then increased with the increase of the content of the polyvinyl alcohol fibers added (0-1.5%). When the content of the polyvinyl alcohol fiberswas 1%, the relative dynamic elastic modulus loss was the minimum. After 150 times of salt freezing, the P0-A0 specimen showed the largest loss of relative dynamic modulus, falling to 95.84% of the initial value, followed by the P0-A1.5 specimen. The reason is that when the content of the polyvinyl alcohol fibers is too large, the steel fibers with the content of 1% are not enough to overlap all the polyvinyl alcohol fibers, so that the fibers will agglomerate in the RPC matrix, the concrete compactness decreases, and the weak interface and micro-cracks of the component increases, thereby accelerating the damage of the RPC matrix in the salt-freezing environment.

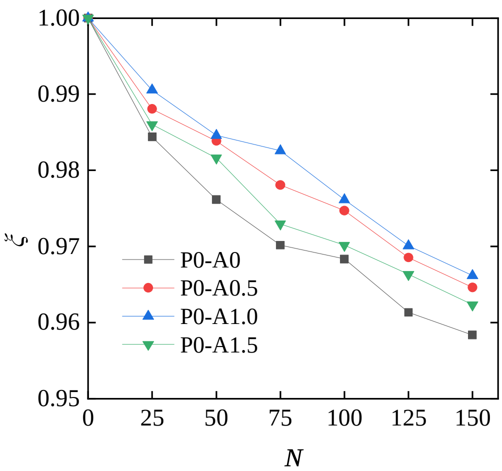
When only one kind of fiber was blended, the specimens with the least relative dynamic modulus loss (ie P0.3-A0 and P0-A1) were compared with the specimens mixed with hybrid fibers, as shown in Figure 4c. The results suggested that when the total content of the two kinds of fibers was 0.6%, the relative dynamic modulus loss of

International Journal of Civil Engineering and Machinery Manufacture
ISSN: 2518-0215, Volume 6, Issue 1, March, 2021

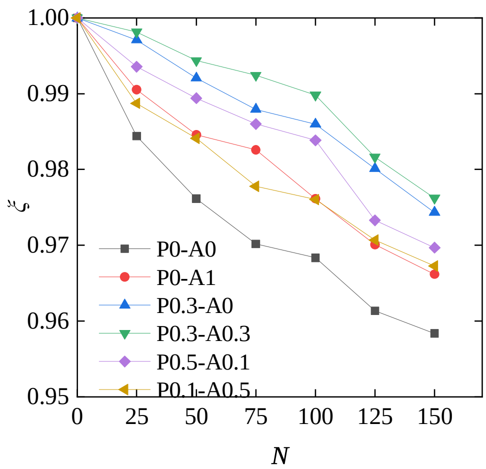
the P0.3-A0.3 specimen was the smallest. The reason is that adding polypropylene fibers and polyvinyl alcohol fibers at a reasonable ratio can improve the spatial structure of concrete, contributing to more compact RPC matrix and producing a positive hybrid effect. In addition, as shown in Figure 4, from the perspective of improving the relative dynamic modulus of RPC specimens under the action of salt freezing, adding two kinds of fibers simultaneously achieved the best results, followed by the incorporation of the polypropylene fibers alone, and polyvinyl alcohol fibers alone. The relative dynamic modulus loss of the specimen mixed with only polyvinyl alcohol fibers was the largest.




**(a) Influence of polypropylene fiber on concrete**




**(b) Influence of Polyvinyl alcohol fibers on concrete**




**(c) Influence ofpolyvinyl alcohol- polypropylene hybrid fiber on concrete**

**Figure 4. Relative dynamic elastic modulus of RPC under salt freezing**

### 3.3. Splitting strength

The failure mode of the RPC specimens in each group is basically the same during the split test, as shown in Figure 5. The failure process is as follows: first, vertical micro-cracks appeared on the upper and lower pressure surfaces, and then as the load increased, the cracks gradually expanded, and finally penetrated the test specimen. During the process, the click of the fibers being pulled out can be heard. The specimens all showed split failure. Adding fibers makes the external load uniformly distributed on the RPC matrix. It was observed that there were some micro-cracks around the cracks [21-23]. The experiment showed that different types and content of fiberswill affect the crack expansion speed.

**(a) P0-A0.5**

**(b) P0-A0**

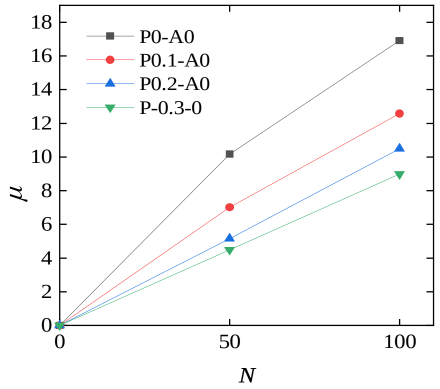
**Figure 5. Failure mode**

Table 4 shows the splitting tensile strength of RPC specimens with different content of fibers in each group after salt freezing. The results showed that as the number of the times of salt freezing increased, the splitting strength of the specimens continued to drop. Before freezing-thawing, the splitting strength of the test specimens slowly improved with the increase of the polypropylene fiber content (0-0.3%). When the content of the polypropylene fibers blended increased from 0.1% to 0.3%, the splitting strength of the test specimens improved by 1.39%, 2.13% and 5.08% respectively; with the increase of the amount of polyvinyl alcohol fibers (0-1.5%), the splitting strength first increased and then decreased. When the content of the polyvinyl alcohol fibers increased from 0.5% to 1.5%, the splitting strength of the specimens increased by 12.38%, 20.52% and 20.06%. In addition, after 50 and 100 salt freezing cycles, the splitting strength of the specimens mixed with polyvinyl alcohol fibers was greater than that of the specimens blended with polypropylene fibers, indicating that the polyvinyl alcohol fiber has better ability to improve the splitting strength of the specimen than the polypropylene fiber.

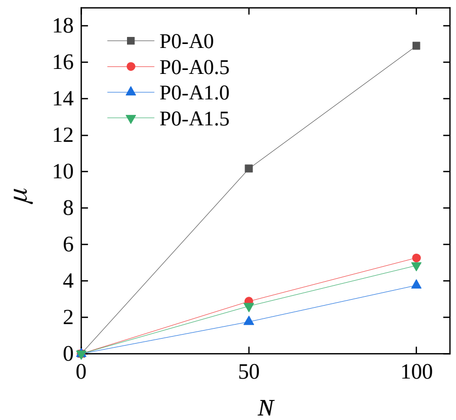
The splitting strength loss rate($\mu$) of the specimens in each group varies with the number of the times of salt freezing, as shown in Figure 6. The results showed that the incorporation of the two kinds of fibers enhanced the splitting strength loss rate of RPC to varying degrees. It can be seen from Figure 6a that the splitting strength loss rate of the test specimens reduced with the increase of the amount of polypropylene fibers. Figure 6b shows that the splitting strength loss rate of the specimens first dropped and then rose with the increased content of polyvinyl alcohol fibers. When the content of the polyvinyl alcohol fibers was 1%, the splitting strength loss rate of the specimens was the smallest. The reason is that when the content of the polyvinyl alcohol fibers exceeds 1%, the fibers cannot be well combined with the matrix during the mixing and molding process of RPC, leading to loose internal structure and the reduced splitting strength. When only one kind of fiber was added, the specimens with the least splitting strength loss rate (ie P0.3-A0 and P0-A1) were compared with the specimens mixed with hybrid fibers, as displayed in Figure 6c. It can be seen from the figure that when the total content of the two kinds of fibers was 0.6%, the splitting strength loss rate of the test specimens reduced with the increase in the content of the polyvinyl alcohol fibers. The reason is that polyvinyl alcohol fiber has high tensile strength, which is about three times that of the polypropylene fiber. Therefore, increasing the content of polyvinyl alcohol fiber can significantly increase the splitting strength of the specimen. It can be found from Figure 6 that with the increase in the number of the times of salt freezing, the splitting strength loss rate of specimens showed an increasing trend. After 100 salt freezing cycles, the splitting strength loss rate of the P0-A0 specimen was the maximum, at 16.91%, followed by the splitting strength loss rate of the P0.1-A0 specimen, at about 12.58%. When the amount of the fibers mixed was close, the simultaneous blending of the two kinds of fibers achieved a better effect on reducing the splitting strength loss rate of the test specimen. This is because the polypropylene fibers and the polyvinyl alcohol fibers blended into RPC will be closely combined with the matrix. and distributed in random directions in the RPC matrix, showing a “support network structure” in any direction, which makes the RPC stress distribution more uniform, thereby enhancing the splitting strength of RPC.

**Table 4. Splitting tensile strength of RPC with different fiber content after salt freezing / MPa**

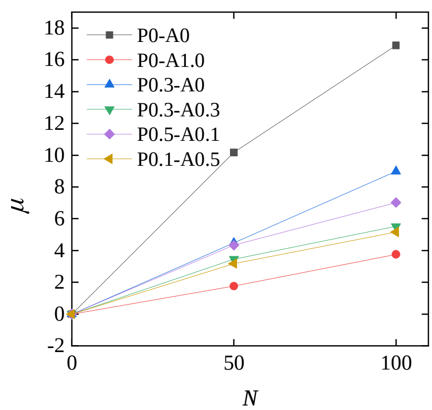
| Specimen | Freeze–thaw cycles | | |
|---|---|---|---|
| | 0 | 50 | 100 |
| **P0-A0** | 10.82 | 9.72 | 8.99 |
| **P0-A0.5** | 12.16 | 11.81 | 11.52 |
| **P0-A1** | 13.04 | 12.81 | 12.55 |
| **P0-A1.5** | 12.99 | 12.65 | 12.36 |
| **P0.1-A0** | 10.97 | 10.2 | 9.59 |
| **P0.2-A0** | 11.05 | 10.48 | 9.89 |
| **P0.3-A0** | 11.37 | 10.86 | 10.35 |
| **P0.3-A0.3** | 12.14 | 11.72 | 11.47 |
| **P0.1-A0.5** | 11.96 | 11.44 | 11.12 |
| **P0.5-A0.1** | 12.59 | 12.19 | 11.94 |




**(a) Influence of polypropylene fiber on concrete**




**(b) Influence of Polyvinyl alcohol fibers on concrete**




**(c) Influence of polyvinyl alcohol- polypropylene hybrid fiber on concrete**

**Figure 6. Loss rate of splitting strength of RPC under salt freezing**

### 3.4. Analysis of the mechanism of salt-freezing damage of RPC

During the freezing-thawing cycle of concrete, the capillary pore wall will bear both expansion pressure and seepage pressure. When these two types of pressures exceed the tensile strength of the concrete, cracks will appear. As the freezing-thawing cycle develops repeatedly, the cracks will gradually expand and penetrate until the concrete strength is completely lost [24-25]. The salt solution obviously increases the water saturation degree of the concrete and reduces the saturation time, which leads to an increase in the amount of internal ice and aggravates the freezing damage of the concrete specimen.

For RPC, during the salt freezing cycle, due to the different thermal expansion coefficients of the fibers and the matrix, the fiber-matrix interface is a weak interface, which easily produces stress concentration. In the early stage of the salt freezing cycle, the fibers and the matrix are tightly combined. Polypropylene fibers and polyvinyl alcohol fibers can effectively mitigate the early cracking of RPC, and the steel fibers can also inhibit the generation and development of cracks. Therefore, when the number of the times of salt freezing is small, RPC has small damage and the strength decreases slowly. Moreover, owing to the good water absorption ability of the polyvinyl alcohol fiber, the mass of the test specimen mixed with polyvinyl alcohol fiber will even increase. As the number of the times of salt freezing increases, the weak fiber-matrix interface is subjected to repeated temperature stress, so that micro-cracks will gradually appear and continue to develop, and the bonding strength of the fiber-matrix interface will drop. At this time, polypropylene fibers and polyvinyl alcohol fibers can bear part of the transverse tensile stress of the concrete, and the crack resistance and toughening performance of steel fibers gradually drop, resulting in increased RPC damage and accelerated strength decline. In this process, RPC changes from a dense state to a loose state, accompanied by the appearance and development of cracks. The fibers are distributed in random directions in the matrix and overlap each other to form a fiber network and give full play to their respective advantages. The steel fibers play a role in crack resistance and toughing, which can inhibit macro cracks and make the cracks continuous; polypropylene fibers can well connect micro-cracks and prevent them from developing into macro-cracks; polyvinyl alcohol fibers have high tensile strength and can bear part of the tensile stress borne by the concrete. In addition, the bridging effect of fibers can also alleviate the concentrated stress at the crack tip during salt freezing, and delay the development of cracks. However, when the content of fibers is too large, the fibers are not easy to disperse in the RPC matrix, and are easy to agglomerate during the mixing process, leading to the increase in the number of weak interfaces and harmful pores, and the reduction in compactness, thereby resulting in a negative hybrid effect and accelerating the damage of RPC under the influence of salt freezing.

## 4. Conclusions

The loss rate of the mass, relative dynamic elastic modulus and splitting strength of RPC specimens gradually decrease with the increase of the content of polypropylene fibers, and first reduce and then in crease with the increase in the amount of polyvinyl alcohol fibers. When only a type of fiber is blended, the optimal content of the two kinds of fibers is 0.3% and 1% respectively.

RPC has good salt-freezing resistance performance. After 150 salt-freezing cycles, its mass and relative dynamic elastic modulus loss is within 0.5%. After 100 salt-freezing cycles, the splitting strength loss rate does not exceed 18%.

Polypropylene fiber can achieve better results in reducing the mass loss and relative dynamic modulus loss of RPC specimens than the polyvinyl alcohol fiber. After 150 times of salt freezing, the reduction rate achieved by the former is about 1.5 times that of the latter.

Incorporating polypropylene fibers and polyvinyl alcohol fibers has a significant impact on the splitting strength of RPC specimens. After 100 times of salt freezing, the splitting strength of the specimen mixed with the polypropylene fibers can be increased by 10%, and the splitting strength of the specimen mixed with the polyvinyl alcohol fibers can be improved by 35 %.

When two kinds of fibers are blended simultaneously and the total content is 0.6%, the polypropylene fibers with the content of 0.3% and polyvinyl alcohol fibers with the amount of 0.3% can effectively mitigate the early cracking of RPC, and the loss of mass and relative dynamic modulus of specimens is the smallest; when the content of the polypropylene fibers is 0.1% and the content of the polyvinyl alcohol fibers is 0.5%, the splitting strength of the specimen decreases the least.

Adding polypropylene fibers and polyvinyl alcohol fibersat a reasonable ratio can improve the spatial structure of concrete, contributing to more compact RPC matrix and producing a positive hybrid effect. Compared with the RPC specimen mixed with only one type of fiber, the specimen blended with two kinds of fibers has better anti-salt-freezing performance.

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