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Research Article

Degradation of Roller-Compacted Concrete Subjected to Freeze-Thaw Cycles and Immersion in Potassium Acetate Solution

Wuman Zhang , Jingsong Zhang, Shuhang Chen, and Sheng Gong

Department of Civil and Engineering, School of Transportation Science and Engineering, Beihang University, Beijing 100191, China

Correspondence should be addressed to Wuman Zhang; wmzhang@buaa.edu.cn

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Two sets of roller-compacted concrete (RCC) samples cured for 28 days were subjected to freeze-thaw (F-T) cycles and immersion in laboratory conditions. F-T cycles in water and water-potassium acetate solution (50% by weight) were carried out and followed by the flexural impact test. The weight loss, the dynamic elastic modulus (E_d), the mechanical properties, and the residual strain of RCC were measured. The impact energy was calculated based on the final number of the impact test. The results show that the effect of F-T cycles in KAc solution on the weight loss and E_d of RCC is slight. E_d, the compressive strength, and the flexural strength of RCC with 250 F-T cycles in KAc solution decrease by 3.8%, 23%, and 36%, respectively. The content (by weight) of K^+ at the same depth of RCC specimens increases with the increase of F-T cycles. The impact energy of RCC specimens subjected to 250 F-T cycles in KAc solution decreases by nearly 30%. Microcracks occur and increase with the increase of F-T cycles in KAc solution. The compressive strength of RCC immersed in KAc solution decreases by 18.8% and 32.8% after 6 and 12 months. More attention should be paid to using KAc in practical engineering because both the freeze-thaw cycles and the complete immersion in KAc solution damage the mechanical properties of RCC.

1. Introduction

Roller-compacted concrete (RCC) is a zero-slump concrete compacted with vibratory and rubber-tired rollers [1]. RCC has been used in the construction of dams, pavements, and airport runways because of the lower cost and the easier placement operations [2–4]. RCC requires long-term stable performance when it is applied in airport runways because reconstruction causes a great impact on the air travel industry. Although the mechanical properties of RCC have been widely recognized, its frost resistance is still the focus in this field.

Piggott [5] found that the field performance of RCC was excellent in harsh environments, including northern U.S. states and Canada. The investigation showed that RCC with a reasonable mixture composition [6], casting and curing process [7, 8] had a good frost resistance. RCC also had better salt frost resistance when it was mixed with mineral admixtures [9]. Delatte and Storey [10] found that the freeze-thaw (F-T) durability of RCC mainly depended on the amount of cement paste and the water to cement ratio, but the degree of compaction had a less effect. However, the results reported by ACI Committee 325 [11] had shown that RCC mixtures were easy to damage by F-T cycles.

For RCC used at airport pavements in cold climates, potassium acetate (KAc) is being used as a deicer because of its high performance and aggressiveness. However, recent researches showed that KAc deicers could affect concrete durability through physical deterioration of concrete and chemical reaction between the KAc deicer and the hydration products of cement [12]. It has been suggested the deterioration of the airport runway may be related to the alkali-silica reaction between the hydration products of cement and KAc [9]. Julio-Betancourt [13] found that even without alkali-silica reactive aggregates, KAc deicers can cause degradation of strength, excessive expansion, and reduce resistance to freezing and thawing. It seems that investigations look to the KAc deicer as a problem, but given the varying results, the deterioration associated with the deicer is not completely understood.

Table 1: Mix proportions of RCC.

Water	Cement	Fine aggregate	Coarse aggregate	SP	AG
109	315	895	1207	2	0.023

The flexural strength and impact behavior are the most important parameters for RCC used in airport pavements. However, there is little research on the impact properties of RCC after F-T cycles in KAc solution. The effect of F-T cycles in KAc solution on the mechanical properties and impact resistance of RCC also needs to be elucidated. The main objective of this research focuses on the frost resistance and impact resistance of RCC exposed to the KAc deicer.

2. Materials and Experimental Process

2.1. Materials. Ordinary Portland cement (P.I 42.5), river sand with fineness modulus 2.61, coarse aggregate with sizes of 5–25 mm, microair 202 (AG), and polycarboxylate-based superplasticizer (SP) were used in this study. The mix proportions of RCC are listed in Table 1.

2.2. Experimental Procedure

2.2.1. Vebe Time Test. The Vebe method was used to measure the workability of RCC. This test method is a variation of the simple slump test and subjects the concrete to vibration after the slump cone removal. The small vibrating table operates at a fixed amplitude and frequency, and in the test, a plastic disc is placed in contact with the upper surface of the concrete. The test is completed when the lower surface of the disc has been completely coated with cement grout. The time is the measured parameter here. The Vebe time of fresh RCC is 28 s.

2.2.2. Specimen Preparation. The fresh mixture was poured into the prism molds in three layers. The dimensions of the mold are $100 \times 100 \times 400$ mm. A vibrating hammer was fixed on a 5 kg steel plate to apply the uniform rolling load. The rolling time of each layer was 30 seconds. After 24 h, the specimens were demolded and placed in the curing room for 28 days. The temperature was $20 \pm 2^{\circ}$C, and the relative humidity was 90%.

2.2.3. Strength of Specimens. Equations (1) and (2) were used to calculate the compressive strength, splitting tensile strength, and flexural strength.

$$f_c = \frac{F}{A}, \quad (1)$$

where f_c is the compressive strength (MPa), F is the maximum load (N), and A is the area of the cube loading face (mm).

$$f_f = \frac{Fl}{bh^2}, \quad (2)$$

where f_f is the flexural strength (MPa), F is the maximum load (N), l is the distance between the supporting rollers (mm),

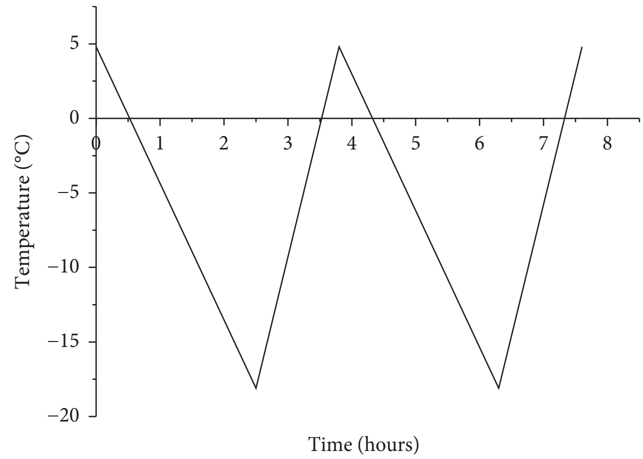


Figure 1: Temperature required by the standard of the specimen during the freeze-thaw cycles.

b is the width of the cross section (mm), and h is the height of the cross section (mm).

2.2.4. Freeze-Thaw Cycles and Immersion Test. Two sets of samples cured for 28 days were subjected to the following:

(a) F-T cycles, while samples were immersed in two different medias: water and 50% KAc solution (by weight).

(b) Laboratory conditions (RH 90%, $20 \pm 2^{\circ}$C), while samples were immersed in 50% KAc solution (by weight) for 6 and 12 months, respectively.

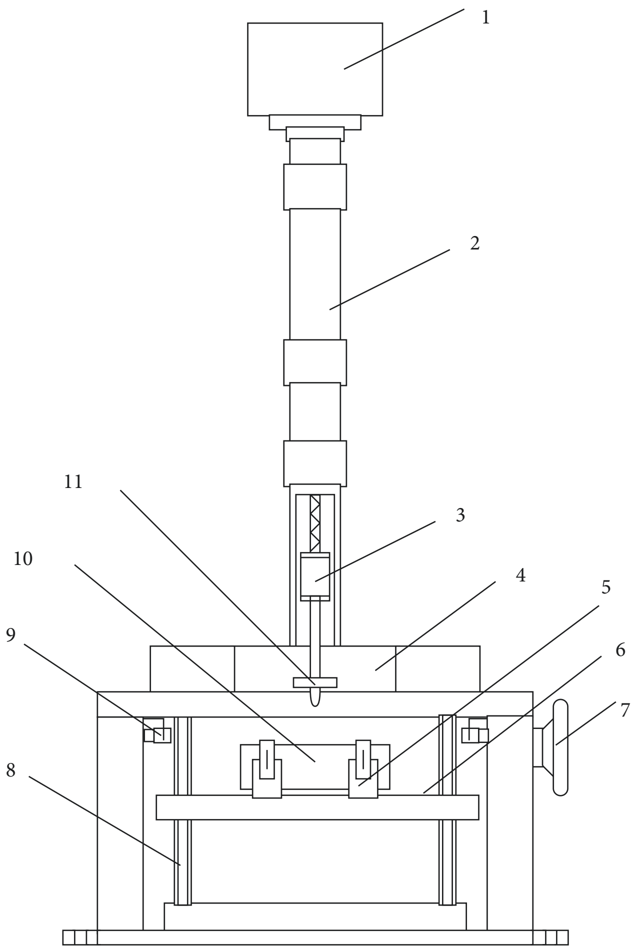
The F-T cycles were carried out according to GB-T50082-2009 [14]. A thermometer embedded at the center of the specimen was used to control the temperature. The maximum temperature and the minimum temperature are 5 ± 2 and $-18 \pm 2^{\circ}$C, respectively. Figure 1 shows the temperature of the specimen during the freeze-thaw cycles. The temperature curve was required by the standard. The real temperature of the sample itself can be different, depending, for example, on the properties of the sample and the accuracy of temperature sensors. Two different medias: water and 50% KAc solution (by weight) were used as the freezing medias. The total number of F-T cycles was 250.

The weight loss was calculated by the following equation:

$$\Delta W_n = \frac{W_0 - W_n}{W_0} \times 100, \quad (3)$$

where ΔW_n is the weight loss of the specimens at the nth freeze-thaw cycle (%), W_0 is the average weight of the concrete specimens before freeze-thaw cycles (kg), and W_n is the average weight of the concrete specimens at the nth freeze-thaw cycle (kg).

The DT-16-type dynamic modulus instrument was used to measure the relative dynamic modulus of elasticity. The relative dynamic modulus of elasticity was calculated by the following equation:



1. Lifting part.
2. Vertical guide pipe.
3. Release mechanism.
4. Part to prevent the second impact.
5. Holder.
6. Lifting pallet.
7. Lifting hand wheel.
8. Lead screw.
9. Optical signal tube.
10. Specimen.
11. Drop weight hammer.

Figure 2: The drop hammer impact testing machine.

$$E_d = \frac{W_i t_i^2}{W_1 t_1^2} \times 100, \quad (4)$$

where E_d is relative dynamic modulus of elasticity, W_1 is the initial weight of the specimen (kg), and W_i is the weight of a specimen after i times freeze-thaw cycles (kg). t_1 is the initial ultrasonic time of a specimen (s), and t_i is the ultrasonic time of a specimen after i times freeze-thaw cycles (s).

2.2.5. Flexural Impact Test. Figure 2 shows the drop hammer impact testing machine. It consists of two stiff constraints, which restrain the specimen from moving. It is capable of dropping a mass of 1.0–10.0 kg from height of up to 2.0 m above the target specimen. 3 kg and 0.3 m were used in this study. A steel cylindrical projectile with a 40 mm diameter is the head of the drop hammer. One part is designed to prevent the second impact. For each specimen, the side surface (2 mm from the top surface) and the bottom surface are bonded with a strain gauge, respectively. The strain was monitored by a high-speed data acquisition system. The impact energy is a constant value during the impact test. SZ120-100AA strain gauges were used to measure the strain [15, 16].

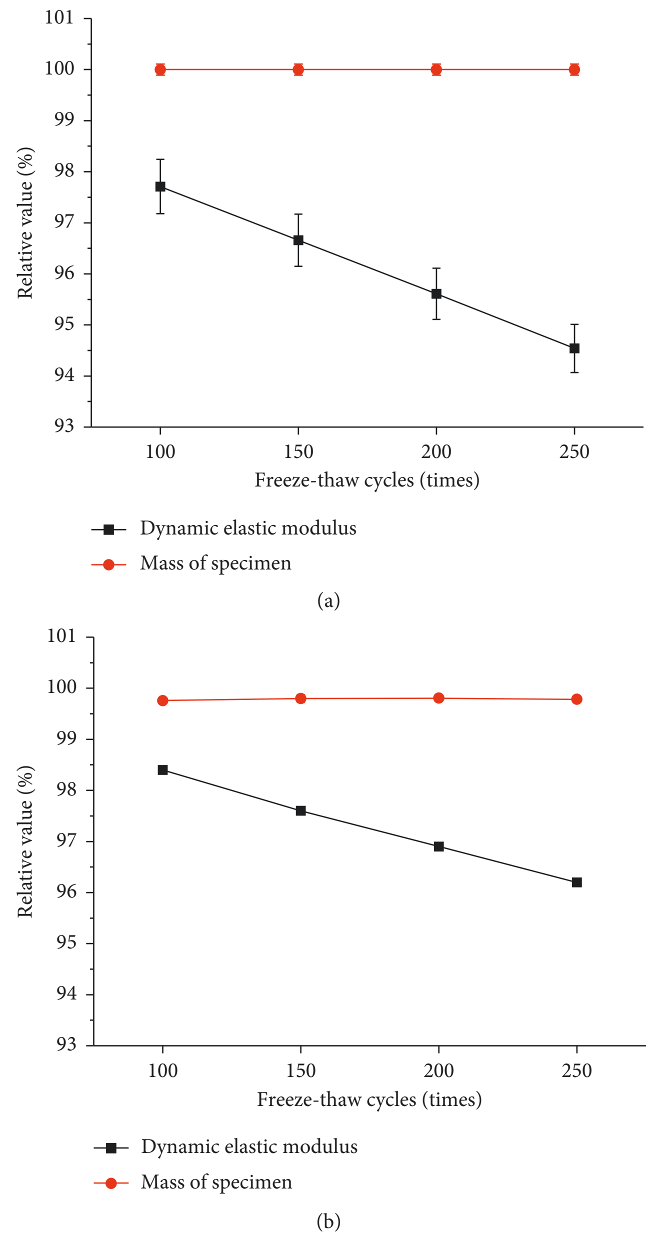
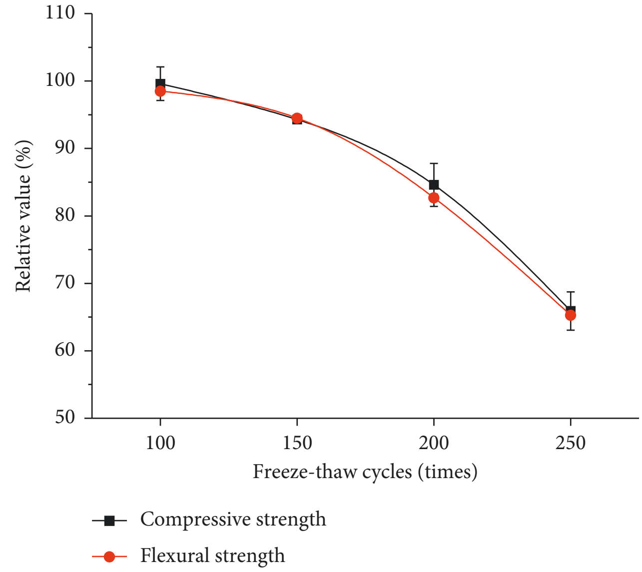


Figure 3: Relative weight loss and dynamic modulus of elasticity: (a) in water; (b) in KAc solution.

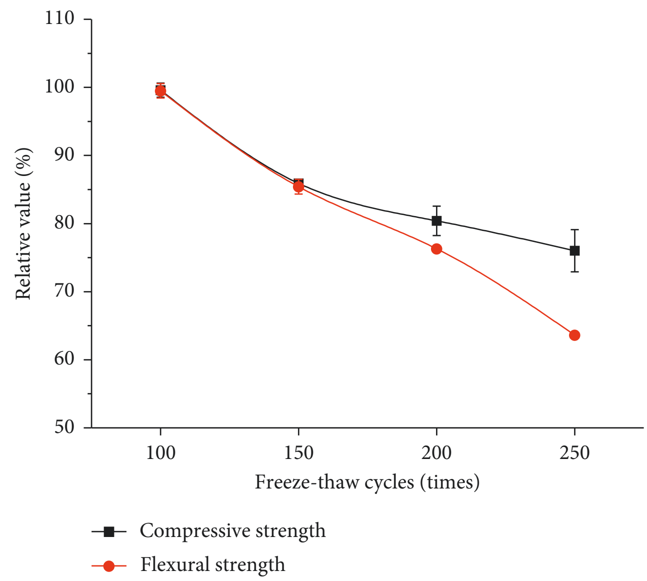
2.2.6. Microstructure and Element Content Analysis. The field emission scanning electron microscope (SEM, JSM-7500F) with energy dispersive X-ray analysis (EDX) was used to investigate the microstructures of the specimens. The samples for SEM analysis were soaked in anhydrous ethanol to stop hydration and dried at 60°C for 4 hours. The samples were coated with 20 nm gold before testing. The EDX was used to measure the element content of


(a) (b) (c) (d)

Figure 4: Surface of the specimens subject to the F-T cycles in KAc solution: (a) 100; (b) 150; (c) 200; (d) 250.



(a)



(b)

Figure 5: Relative compressive strength and flexural strength of RCC: (a) in water; (b) in KAc solution.

samples. The resolution was 129.92 eV, and the measurement time was 50 s.

3. Results and Discussion

3.1. Freeze-Thaw Cycle Test

3.1.1. Weight Loss and Dynamic Modulus of Elasticity. The relative weight loss and the relative dynamic modulus of elasticity (E_d) of RCC with F-T cycles in water and KAc solution are shown in Figure 3. It clearly indicates that there is little change in weight of RCC with F-T cycles in water. Pigeon and Marchand [7], Andersson [17], and Marchand et al. [18] also obtained the similar results. The surface of the specimens with F-T cycles in KAc solution is shown in Figure 4. Based on Figures 3(b) and 4, the KAc deicer also caused no scaling or insignificant scaling in RCC. In the study from Wang et al. [19] and also Nanni [20], it was stated that KAc minor scaling might be related to alkali carbonation of concrete surface. However, Piggott [5] reported that the overall quality and properties of concrete and internal structure of concrete surface have an effect on the surface scaling. The preparation process of RCC may be another reason that the mass loss is not remarkable.

The F-T cycles in water or in KAc solution also have an insubstantial effect on E_d of RCC. E_d of RCC with 250 F-T cycles decreases by 5.5% and 3.8%, respectively. The loss of the elastic modulus of the RCC is less than that of normal concrete in the freeze-thaw test [21, 22]. This is probably due to the layering and the vibrating during the RCC specimen preparation which results in a higher surface strength.

3.1.2. Mechanical Properties of RCC. The compressive strength and the flexural strength of RCC cured for 28 days are 47.7 MPa and 9.0 MPa, respectively. Figure 5 shows the relative compressive strength and flexural strength of RCC subjected to F-T cycles in water and KAc solution. It can be seen that the F-T cycles in water or in KAc solution decrease both the compressive strength and the flexural strength of RCC. The compressive strength and the flexural strength are decreased by 33% when the RCC specimens are subjected to 250 F-T cycles in water. The results can be explained by the internal cracking caused by the expansion of water in concrete during F-T cycles.

250 F-T cycles in KAc solution decreases the compressive strength and the flexural strength of RCC by 23% and 36%, respectively. The strength loss can be explained by the traditional deterioration mechanism due to frost. In addition,

Table 2: The content of K^+ (by weight).

F-T cycles	100	150	200	250
Content of K^+ (%)	0.5	2.73	2.83	3.93

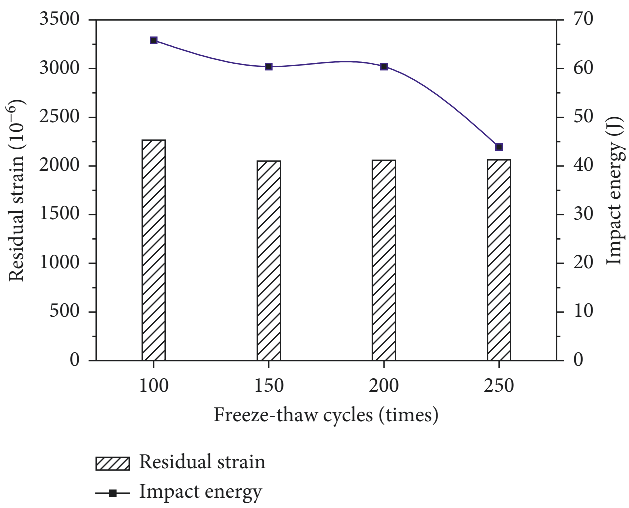
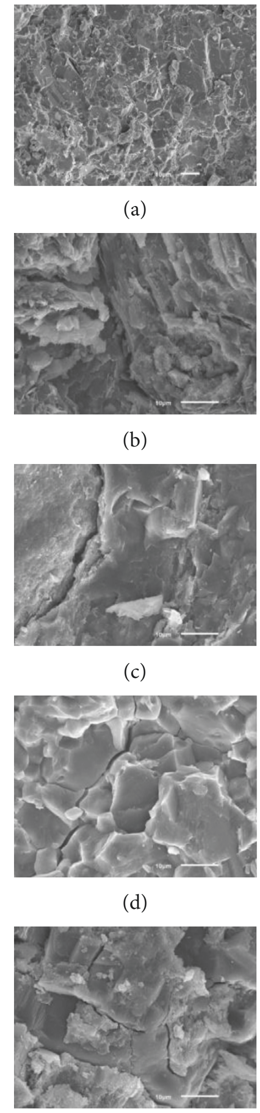


Figure 6: Residual strain and impact energy of RCC subjected to the F-T cycles in KAc solution.

it is postulated that KAc increases the level of saturation in concrete, possibly due to changes in surface tension and viscosity of pore water [13]. However, the decreasing trend in the compressive strength slowed. This is mainly attributed to the more penetration of KAc and the formation of an ettringite-like needle structure when the KAc deicer is used [19, 23]. The content (by weight) of K^+ at the same depth of the RCC specimens with the F-T cycles in KAc solution is shown in Table 2.

The deposition of ettringite seems to follow the appearance of cracks when F-T deterioration occurs. In the early stage, ettringite does not promote the propagation of existing cracks and cause new cracking in concrete. Cracks caused by frost damage will also give space for the crystallization of ettringite [24]. The filling and covering effect of ettringite on concrete crack could improve the compressive strength of concrete in early stage [25]. However, this filling action has slight effect on the flexural strength.

3.1.3. Impact Properties of RCC. Figure 6 shows the residual strain and impact energy of RCC subjected to the F-T cycles in KAc solution. It is clearly seen that the effect of the F-T cycles in KAc solution on the residual strain is slight. This is probably due to the damage of RCC under the impact loading is still a brittle fracture. In addition, the strain gauge bonded on the bottom surface of the specimen cannot record the strain when the specimen is broken into two sections. However, there is a decreasing trend in the impact energy of RCC, especially for the specimens subjected to 250 F-T cycles in KAc solution, and the impact energy decreases by nearly 30%. This result can be due to the decreasing action of the F-T cycles on the flexural strength of RCC.



(a)
(b)
(c)
(d)
(e)

Figure 7: Microstructures of RCC without and with the F-T cycles in KAc solution: (a) 0; (b) 100; (c) 150; (d) 200; (e) 250.

3.1.4. Microstructures of RCC. In order to better understand the effect of the F-T cycles on the impact properties of RCC, the microstructures are observed and shown in Figure 7. Almost no microcrack occurs in the RCC matrix without the F-T cycles (Figure 7(a)). The F-T cycles will cause expansive pressure and osmotic pressure in concrete [26]. The surface spalling and internal cracking occur when the tensile stress produced by the two pressures exceeds the tensile strength of concrete. Therefore, microcracks occur and increase with the increase of the F-T cycles (Figures 7(b)–7(e)), which is consistent with the development of the strength of the specimens subjected to the F-T cycles in KAc solution.

3.2. Properties of RCC Immerged in KAc Solution. In order to determine whether the deicing fluid has a corrosive effect on the concrete, the specimens without the freeze-thaw cycles

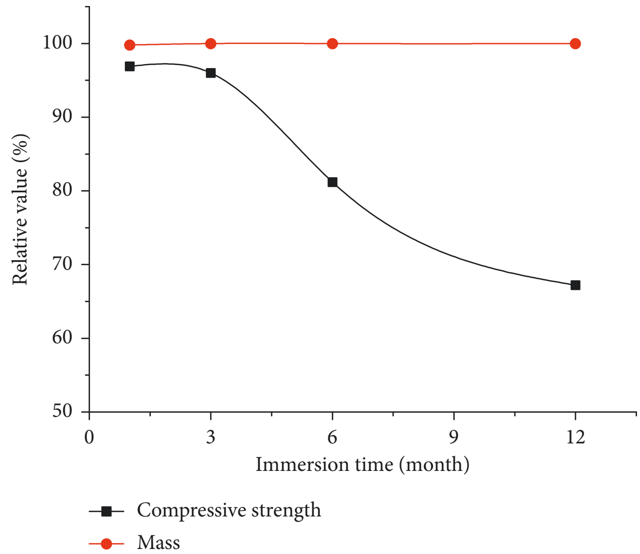
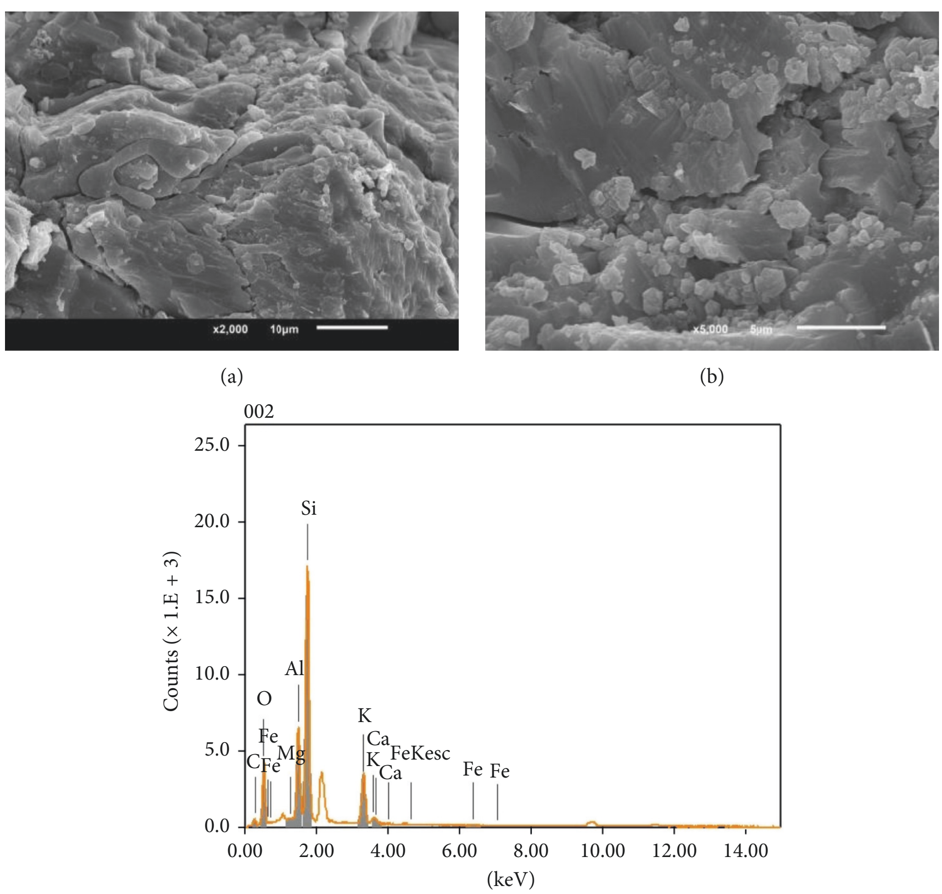


Figure 8: Relative mass and compressive strength of RCC immerged in KAc solution.



(a) (b)

(c)

Figure 9: (a, b) Microstructures and (c) EDS of RCC immerged in KAc solution for 12 months.

are immersed in the KAc solution. The mass loss, the strength, and the microstructure of the specimens are measured. Figure 8 shows the mass and compressive strength of RCC immerged in KAc solution. It can be seen that the mass is almost unchanged after the RCC specimens are immersed in KAc solution for 12 months, which indicates that the complete immersion of the KAc solution does not cause the surface spalling. The compressive strength has a smaller drop after 3 months of immersion. However, the compressive strength decreased by 18.8 and 32.8% after 6 and 12 months of complete immersion in KAc solution. The decrease of the compressive strength (32.8%) caused by 12-month immersion in KAc solution is very close to that (33%) of samples subjected to 250 F-T cycles in water. However, the decrease value is greater than that (23%) of samples subjected to 250 F-T cycles in KAc solution.

The microstructures and the energy dispersive spectrum (EDS) of RCC immerged in KAc solution for 12 months are shown in Figure 9. Comparing to the RCC matrix without the F-T cycles (Figure 7(a)), the microcracks were observed in the microstructure picture. In addition, the mass percentage of the K element in the new crystal is 5.58%, which indicates that more KAc solution has penetrated into the specimens subjected to 12 months of complete immersion in KAc solution. The osmosis pressure and the crystallization pressure of KAc solution may cause expansion and cracks in the RCC matrix, which decreases the compressive strength of specimens after a long-term contact with KAc solution.

3.3. Degradation Mechanism. The degradation mechanism of RCC subjected to the F-T cycles in KAc solution can be explained by the traditional theory due to frost. In addition to the pressure generated by osmosis and crystallization, KAc generally increases the saturation of the concrete and keeps concrete pores at or near the maximum fluid saturation, thereby increasing the risk of frost damage [13, 19].

Furthermore, KAc may induce alkali-silica reaction in the concrete-containing reactive aggregate, which causes expansion and cracks after a long-term contact. These cracks create channels for water and other solutions to penetrate into concrete and reduce freeze-thaw durability.

4. Conclusions

For the materials used and test methods applied, the following conclusions can be drawn:

(1) The effect of freeze-thaw cycles in KAc solution on the weight loss and the elastic modulus of RCC is slight. The elastic modulus of RCC with 250 freeze-thaw cycles decreases by 3.8%.

(2) 250 freeze-thaw cycles in KAc solution decrease the compressive strength and the flexural strength by 23% and 36%, respectively. The content (by weight) of K^+ at the same depth of RCC specimens increases with the increase of freeze-thaw cycles, which reduces the decreasing trend of the compressive strength caused by freeze-thaw cycles in KAc solution.

(3) The impact energy of RCC specimens subjected to 250 freeze-thaw cycles in KAc solution decreases by nearly 30%.

(4) Microcracks occur and increase with the increase of freeze-thaw cycles in KAc solution.

(5) The compressive strength of RCC without freeze-thaw cycles decreased by 18.8 and 32.8% after 6 and 12 months of complete immersion in KAc solution. The decrease of the compressive strength (32.8%) caused by 12 months immersion in KAc solution is greater than that (23%) of samples subjected to 250 F-T cycles in KAc solution.

(6) More attention should be paid to using KAc in practical engineering because both the freeze-thaw cycles and the complete immersion in KAc solution damage the mechanical properties of RCC. The decrease of mechanical properties of RCC used in airport runway will have serious effect on the flight safety. KAc solution should be replaced with a new type of harmless deicing fluid.

Data Availability

The datasets used during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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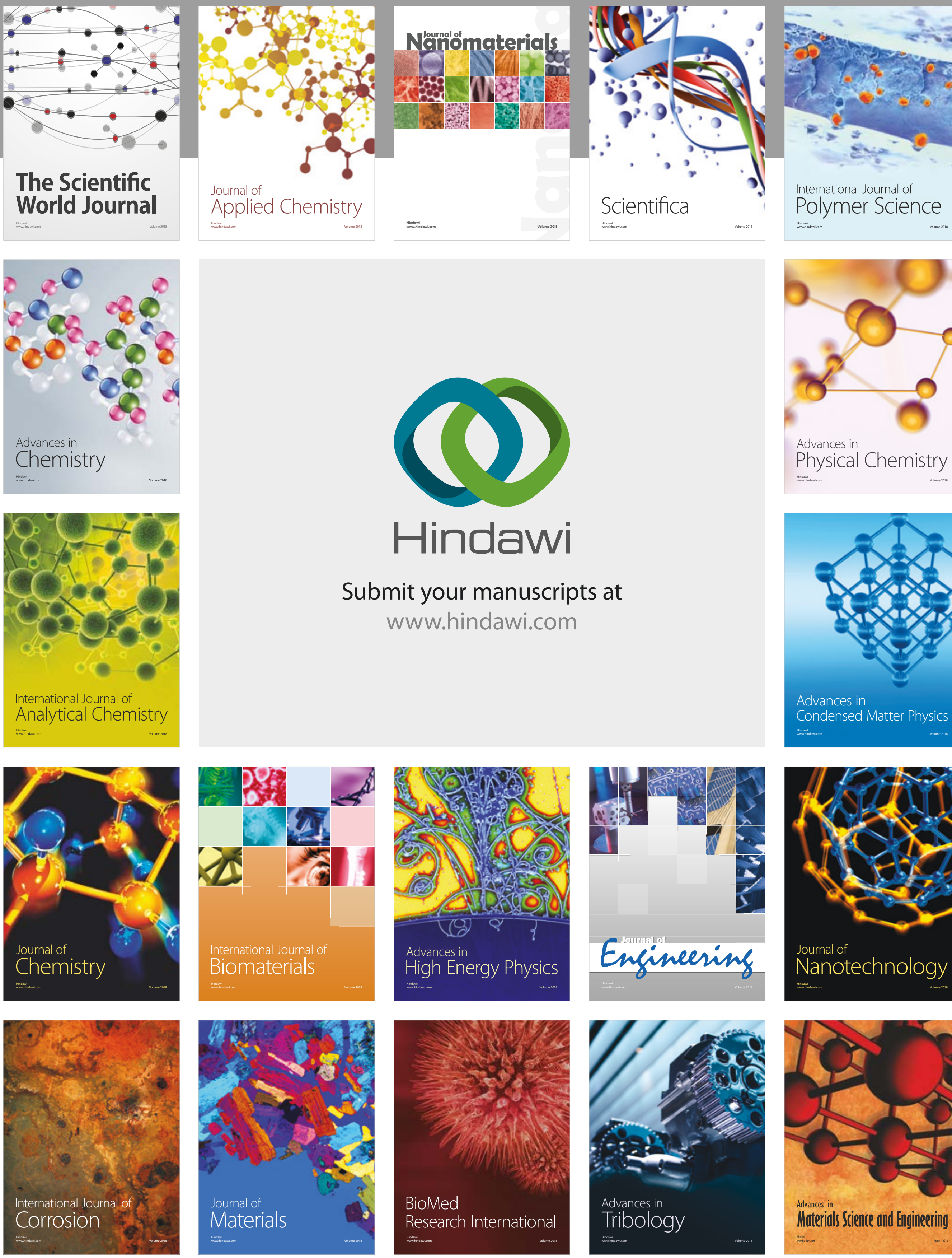
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