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Interaction between loading, freeze–thaw cycles, and chloride salt attack of concrete with and without steel fiber reinforcement

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Abstract

In this paper, the deterioration of concrete subjected to the combined action of four-point bending—loading, freeze–thaw cycles, and chloride salt attack—is discussed. Test results show that concrete tested in chloride salt solution scaled much more severely than in fresh water, and its weight loss in chloride salt solution was twice that in water. However, dynamic modulus of elasticity (DME) of concrete in chloride salt solution dropped more slowly than that in water due to supercooling resulting from chloride salt. It is also shown that the degradation process of concrete simultaneously exposed to loading, freeze–thaw cycles, and chloride salt attack was significantly accelerated. The higher the stress ratio exerted, the lesser the freeze–thaw cycles that concrete could resist and, consequently, the shorter the service life. When a relatively high steel fiber content is introduced (1.5 vol.%), the deterioration process of concrete subjected to the three damaging processes is considerably reduced. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Chloride; Durability; Fiber reinforcement; Freezing and thawing

1. Introduction

The evaluation of durability and service life is often important and complicated in concrete applications. The deterioration of concrete resulting from a single damaging process (such as freeze–thaw cycles) does not seem to be consistent with the actual environment where concrete structures are exposed. It has been noted that the deterioration of concrete is accelerated when it is exposed to both loading and freeze–thaw cycles [1–3]. Moreover, the situation get worse if concrete is subjected to multiple damaging processes such as loading, freeze–thaw cycles, and chloride or sulfate attack, where the damage can be combined because of mutual interaction. In this paper, the deterioration of concrete with different strength grades when exposed to loading, freeze–thaw cycles, and chloride salt attack is investigated. The favorable effect of steel fiber on reducing the degradation of concrete is discussed as well.

2. Materials and test methods

2.1. Materials and mix proportions

A Chinese standard 525# R(II) Portland cement (which has standard compressive strength of 52.5 MPa at the age of 28 days according to GB175-92), river sand with fineness modulus of 2.36, and coarse aggregate of crushed basalt stone with maximum size of 10 mm were used in the test. A naphthalene-type superplasticizer was used, and the dosage was adjusted to keep the slump of fresh mixed plain concrete in the range of 70–150 mm. A straight low-carbon steel fiber with a rectangular cross section, an aspect ratio of 40, and a length of 20 mm was adopted to prepare the steel fiber reinforced concrete (SFRC).

A series of non-air-entrained plain concrete (PC) and SFRC with water–cement ratio of 0.44, 0.32, and 0.26 were prepared (denoted as PC-0.44, PC-0.32, PC-0.26, SFRC-0.44, SFRC-0.32, and SFRC-0.26, respectively). The proportions and basic characteristics of concrete mixes are given in Table 1. The air content of fresh mixed concrete was measured according to ASTM C231. All specimens were demolded after 24 h of casting and cured in a condition of 20 ± 3 °C and 95% relative humidity. At the age of 24 days,

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Table 1
Proportions of concrete mixes

Series	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Steel fiber (kg/m^3)	Air content (vol.%)	Compressive strength at 28 days (MPa)
PC-0.44	409	180	657	1169	0	2.8	56.0
PC-0.32	440	142	665	1236	0	2.7	76.2
PC-0.26	477	124	621	1262	0	2.5	89.0
SFRC-0.44	409	180	854	926	117	2.2	60.8
SFRC-0.32	440	142	816	1039	117	2.3	89.7
SFRC-0.26	477	124	749	1124	117	2.6	95.0

some of the specimens were immersed at a 3.5 mass% sodium chloride solution, and the remaining were immersed in water for 4 days.

2.2. Test methods

At the age of 28 days, testing of concrete exposed to freeze–thaw cycles under loading in fresh water or in a NaCl solution (3.5 mass%) was carried out in accordance with ASTM C666A. The specimens (40 × 40 × 160 mm beams) were subjected to three-point bending. The stress ratios, i.e. the ratios of flexural loading externally applied to the ultimate flexural loading, were controlled by a specially designed loading system[2]. Preloading specimens were put into a freeze–thaw test chamber as schematically illustrated in Fig. 1. Then the freeze–thaw tests were performed. The loss of the dynamic modulus of elasticity (DME) and of the weight of concrete specimens were monitored and recorded. The relative dynamic modulus of elasticity (RDME) is the ratio of the DME value measured after a certain number of freeze–thaw cycles to that before the cycling. According to the test procedure, the specimen was considered failure if its RDME dropped to 60% or less, or if its weight loss exceeded 5.0%. The ultimate number of freeze–thaw cycles up to failure (N_f) was also monitored. Three specimens were measured for each concrete mix.

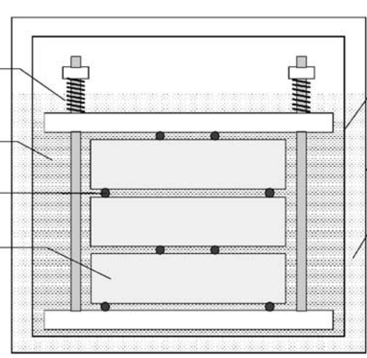

Fig. 1. Sketch of the preloading concrete subjected to freeze–thaw cycles and chloride salt attack.

3. Test results and discussion

3.1. Effect of NaCl solution on the deterioration of concrete exposed to freeze–thaw cycles

Concrete with good frost resistance often severely scaled in a NaCl solution when subjected to freeze–thaw cycles, and the weight loss of concrete specimens in a NaCl solution reaching failure threshold earlier than that in water.

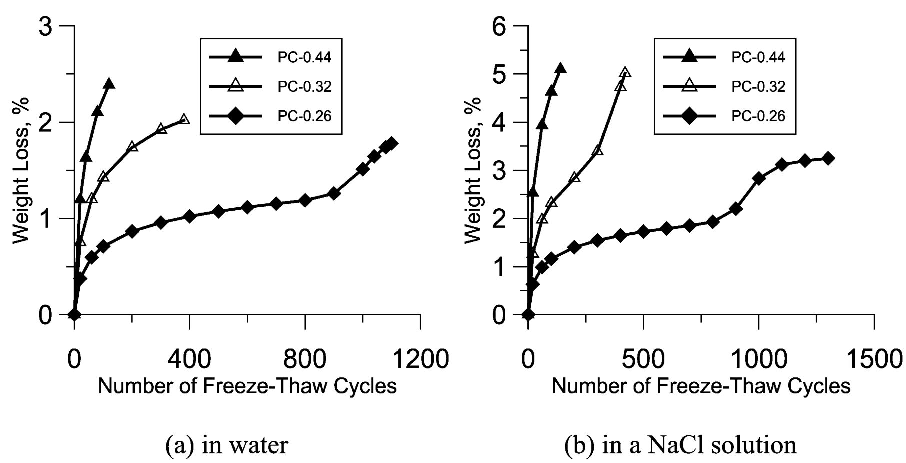

Fig. 2. Weight loss of plain concrete subjected to freeze–thaw cycles in water and in a NaCl solution.

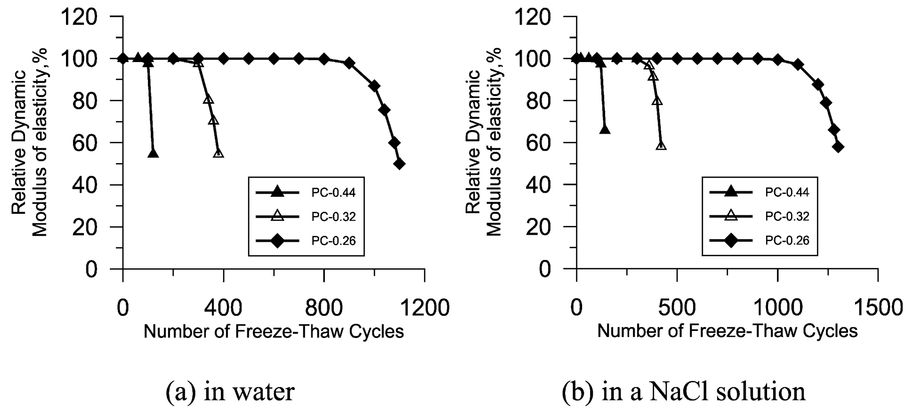

Fig. 3. Change of the RDME of concrete subjected to freeze–thaw cycles in water and in a NaCl solution.

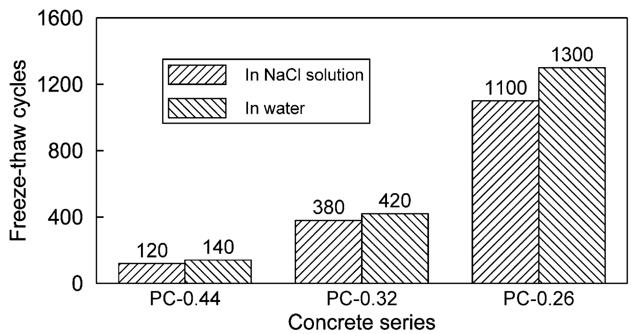

Fig. 4. Number of freeze–thaw cycles at failure in water and in a NaCl solution.

Fig. 2(a) and (b) gives the weight loss of plain concrete (PC-0.44, PC-0.32, and PC-0.26) when subjected to freeze–thaw cycles in water or in a NaCl solution. In Fig. 2(a), the weight loss rate decreased and the ultimate freeze–thaw cycles of the concrete increased for a higher-grade concrete mix. Fig. 2(b) refers to the tests in a NaCl solution. It should be noted that the concrete mixes with higher water–cement ratios (PC-0.44, PC-0.32) could not bear more than 500 freeze–thaw cycles and failed due to the weight loss over 5% given by the criteria of ASTM C666A.

The weight loss of concrete specimens is caused by the scaling of concrete surface. In actual concrete applications, concrete surface scaled markedly when exposed to deicing

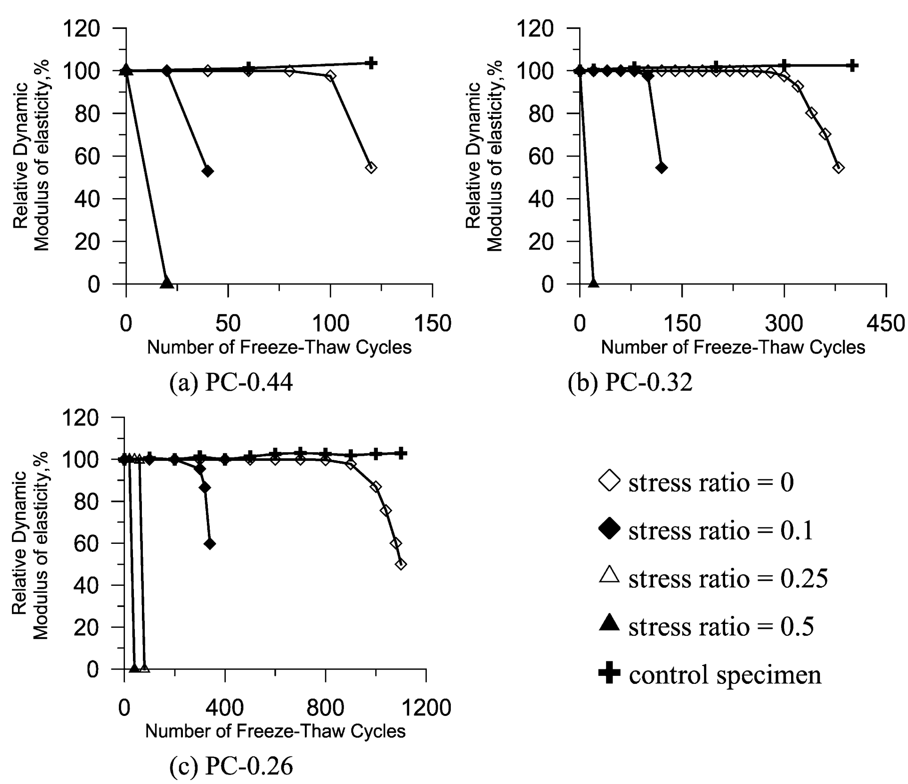

Fig. 5. Effect of stress ratio on the RDME of concrete subjected to the freeze–thaw cycles.

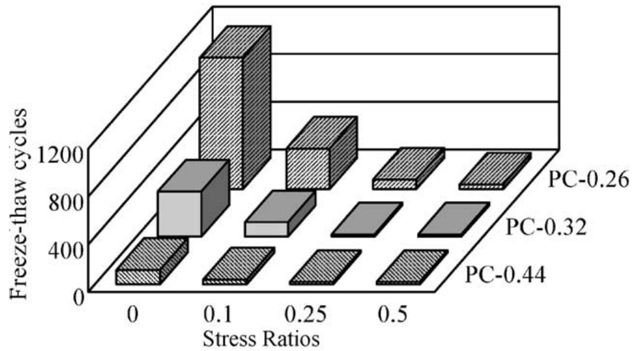

Fig. 6. Number of freeze–thaw cycles of concrete at failure under loading.

salt and freeze–thaw cycles caused by the change of climate. The cycling rate in the laboratory conditions was much higher than that in the natural environment. Thus, it is reasonable that the scaling observed during the tests was more severe and the scaling depth of concrete specimens being over 5 mm. Besides, the weight loss in a NaCl solution was twice as large as that in water.

Changes in the RDME of the concrete specimens exposed to freeze–thaw cycles in water or in NaCl solution is given in Fig. 3. Although severely scaled in concrete surfaces, the DME loss of concrete immersed in a NaCl solution is less than in the water. NaCl lowers the freezing point (for example, the freezing point of a 3.5% NaCl solution is -2.03 °C [4,5]). Moreover, the smaller the pore size, the lower the freezing point of the salt solution in pores, which is favorable to the improvement of the frost resistance of concrete. As shown in Fig. 4, the number of freeze–thaw cycles at failure in a NaCl solution was roughly 20% higher than those in fresh water.

3.2. Effect of flexural stress on frost resistance of concrete

Fig. 5 shows the RDME of concrete subjected to different stress ratios (0, 0.1, 0.25, 0.5) at different numbers of freeze–thaw cycles. The control specimens were cured in 20 ± 5 °C, RH > 90% as reference. External loading accelerated the degradation process of concrete exposed to freeze–thaw cycles. The higher the stress ratio exerted, the faster the RDME dropped and the lesser the cycles at failure. With a stress ratio of 0.5, PC-0.26 failed in a brittle manner after 40 cycles, with RDME dropping to zero. It is noticeable that the stress ratios had little effect on the weight loss of the concrete subjected to the freeze–thaw cycles. The reason is that the external loading merely accelerated the initiation and propagation of cracking, by increasing the amount and the size of cracks and not the scaling of concrete surface.

As shown in Fig. 6, external loading has evident effect on the maximum number of cycles. When the stress ratio was 0.5, all the concrete mixes failed at about 20–40 cycles;

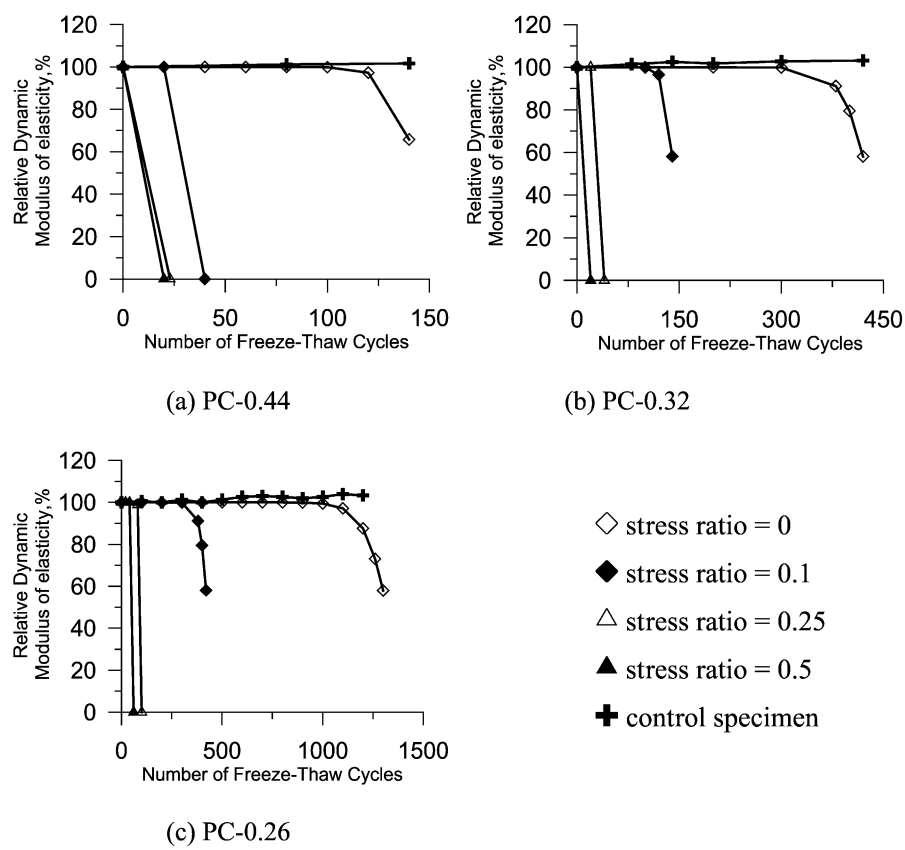

Fig. 7. RDME of concrete subjected to triple damaging.

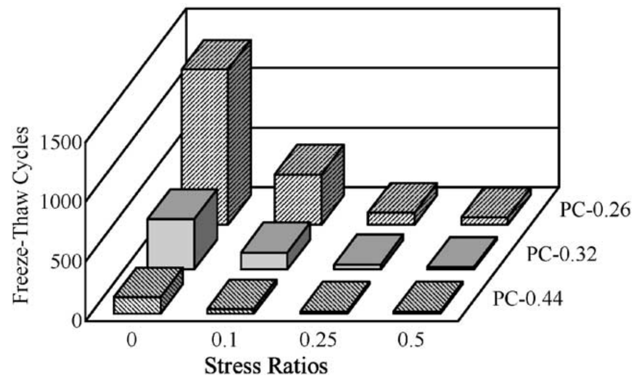

Fig. 8. Number of the ultimate freeze–thaw cycles of the concrete subjected to triple damaging.

when the stress ratio was 0.25, the higher the strength of concrete, the larger the number of cycles at failure and the more resistant to freezing and thawing cycles.

3.3. Deterioration of concrete simultaneously subjected to triple damaging

Fig. 7 showed the RDME loss of concrete subjected to triple damaging (loading, freeze–thaw cycles, and chloride attack). RDME was mainly affected by external loading when concrete was subjected to triple damaging. When stress ratios were equal to 0.25 and 0.5, concrete exhibited a quite brittle failure, with RDME dropping to zero. Therefore, the difference of ultimate freeze–thaw cycles and RDME loss rate between the concrete with different strength grades was unnoticeable (as shown in Fig. 8). For stress ratios of 0.1 and 0, the concrete could bear more freeze–thaw cycles.

For the concrete exposed to triple damaging, external loading could accelerate the DME loss and NaCl solution could speed up the weight loss. Therefore, the deterioration in the concrete was much more severe than under single or double damaging. When the stress ratio was 0.25, the number of freeze–thaw cycles at failure for PC-0.44, PC-0.32, and PC-0.26 was about 10% of the number when those concrete were subjected only to freeze–thaw cycles in water.

It should be noted that the ultimate number of freeze–thaw cycles was considerably reduced with the increase of stress ratios. When the stress ratio was 0.5, all the concrete mixes failed at about 20–40 cycles. The ultimate cycles of freeze–thaw of concrete with a stress ratio of 0.25 was much lower than that of concrete without stress. Therefore, for concrete with stress ratios of 0.5 and 0.25, the dominant damage factor is stress. Similar conclusion can be concluded from the previous section. In order to prevent the degradation of concrete from external stress, steel fiber was introduced.

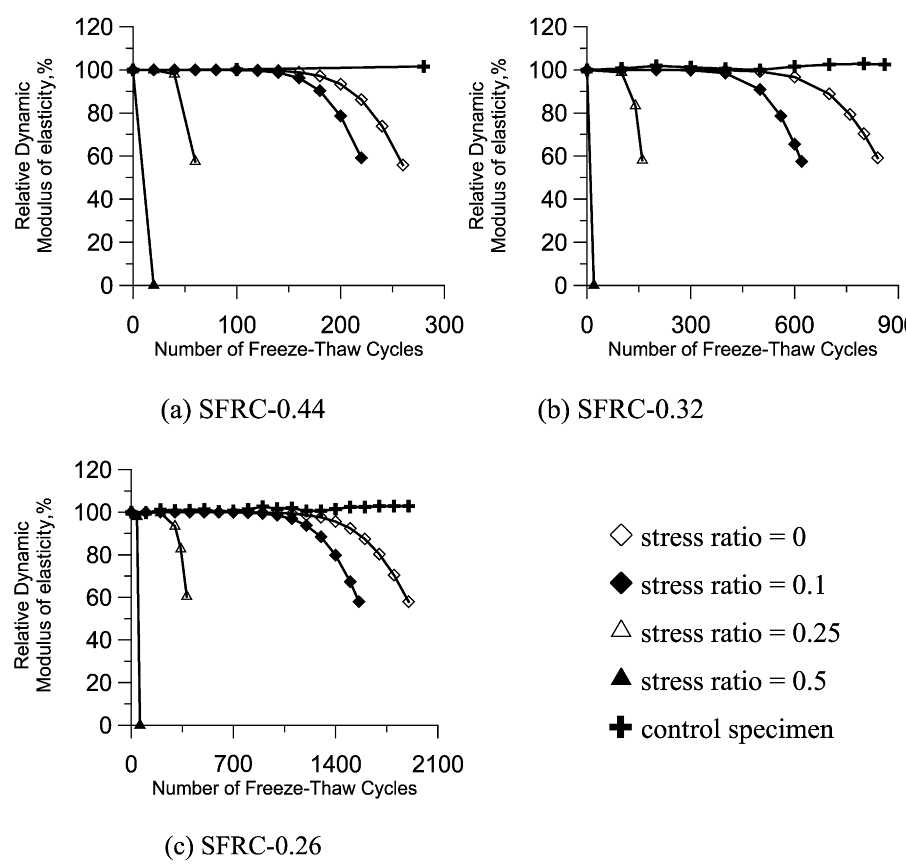

Fig. 9. Effect of steel fiber on the RDME of the concrete subjected to triple damaging.

Table 2
Ultimate number of freeze–thaw cycles of concrete subjected to the combined action of external loading, freeze–thaw cycles, and chloride salt attack

Stress ratios	PC-0.44	SFRC-0.44	PC-0.32	SFRC-0.32	PC-0.26	SFRC-0.26
0.00	140	260	420	780	1300	1900
0.10	40	220	140	620	420	1560
0.25	20	60	40	160	100	380
0.50	20	20	20	20	40	60

The deterioration processes of RDME of the SFRC subjected to triple damaging are shown in Fig. 9. Compared to that of the plain concrete, the RDME loss of the SFRC was more moderate. In some cases, even visible cracks appeared in the surfaces, the SFRC specimens were not failure. For plain concrete, its DME reached the failure threshold as soon as cracks appeared on the concrete surface. As shown in Table 2, the ultimate freeze–thaw cycles of concrete increased significantly when steel fiber was introduced. Therefore, the deterioration of concrete was limited and its resistance against the combined damaging of external loading, freeze–thaw cycles, and chemical attack was improved by the steel fiber.

4. Conclusions

Severe surface scaling occurred when plain concrete was subjected to freeze–thaw cycles in a 3.5% NaCl solution, with weight loss being more than that in water. Due to the decline of the freezing point in the salt solution, the ultimate number of the freeze–thaw cycles of the concrete in a NaCl solution was 20% higher than concrete exposed to the cycles in water, while the DME loss in a NaCl solution was less than that in water. External flexural loading accelerated the deterioration process when concrete was subjected to freeze–thaw cycles. The higher the stress ratio, the faster the DME dropped. However, the loading had little effect on the weight loss of concrete. There was much difference in the failure mode between freeze–thaw cycles and both loading and freeze–thaw cycles. When the stress ratio was high, brittle failure at early cycles occurred. When the plain concrete was subjected to triple damaging, the DME of concrete dropped sharply and the weight loss increased considerably, severe scaling occurring on concrete surface. By incorporating steel fiber, the deterioration of concrete was limited and its resistance against multiple damaging under severe conditions was improved.

Acknowledgments

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