Journal of Asian Concrete Federation
Vol. 11, No. 4, pp. 15-22, December 2025
ISSN 2465-7964/ eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2025.11.4.15

Technical Paper

Evaluation of restraint method and seawater resistance of reinforced concrete with expansive additive

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(Received: 25-Aug-2025; Revised: 03-Oct-2025; Accepted: 09-Nov-2025; Published online: 25-Dec-2025)

Abstract: Reinforced concrete with expansive additive introduces shrinkage-compensated strain under the constrained conditions of the reinforcement, which reduces cracking and improves durability. However, there is not a few methods for evaluating the performance of concrete with expansive additive in restraints, and there is not enough data available. Therefore, this paper proposes a method for evaluating the durability of reinforced concrete with expansive additive by Cage-shaped restraining steel bars with four longitudinal steels and stirrups installed at both ends. Furthermore, to investigate seawater resistance, a three-year exposure test was conducted in an environment simulating the submerged zone, tidal and splash zone.

As a result, the use of restraining steel bars has made it possible to numerically evaluate the expansion and contraction behavior of concrete with expansive additive. The behavior of concrete with expansive additive was confirmed under exposure conditions. Under the exposure environment, the submerged zone showed expansion behavior and the tidal and splash zone showed shrinkage behavior. The pore structure of concrete with expansive additive depended on the exposure conditions, although densification occurred in reinforcing steel bar restraints. The chloride ion penetration depth of concrete with expansive additive in a marine environment under restraining conditions was almost the same as that of concrete without expansive additive. The seawater resistance of concrete with expansive additive is not considered to be particularly poor, judging from the distribution of concentrations of the major elements.

Keywords: Expansive additive, Restraining steel bar, Seawater resistance, Durability

1. Introduction

Since Japan is surrounded by the sea on all sides, the effective utilization of ocean space is an important issue in the future. Recently, technologies to make highly effective use of ocean energy such as waves and offshore wind have been advancing, and wave power generation and offshore wind power generation, for example, are currently being considered worldwide as energy sources for the next generation. Furthermore, the use of water space with floating structures is also being promoted, and various mega-float concepts are being considered for airports and parks. Against this background, it is necessary to design materials to be used in these structures on the assumption that they will be subjected to seawater action in the future.

Under these circumstances, the choice of materials to be used is important to improve the durability of these structures. For example, cracks in concrete structures are believed to reduce the ability of deteriorating factors to penetrate and infiltrate, thereby compromising durability. One material that can control this cracking is an expansive additive. This is because concrete with expansive additive has excellent crack resistance and water tightness, and is expected to be used in marine

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structures [1][2].

On the other hand, the properties of concrete with expansive additive cannot ignore the influence of restraint conditions by steel bars. This is because concrete with expansive additive is not used in practice because of its ineffectiveness under unconstrained conditions [3]. Therefore, kokufu reported that curing with steel bar restraint is important in evaluating the freeze-thaw resistance of expanded concrete [4]. Focusing on the continuous void volume of the expanded mortar, Li et al. reported that the continuous void volume of the expanded mortar decreased under restrained conditions, and that this effect improved the mass transfer resistance. Thus, it has been pointed out that in evaluating concrete with expansive additive, it is necessary to provide appropriate restraint conditions [5].

Table 1 Materials used

Material	Abbreviation	Remarks
Water	W	Tap water, 1.00g/cm^3
Cement	OPC	Ordinary portland cement, 3.16g/cm^3
Expansive additive	EX	Lime-based expansive additive, 3.16g/cm^3
Fine aggregate	S	Water absorption rate 2.20%, 2.56g/cm^3
Coarse aggregate	G	Water absorption rate 0.67%, 2.65g/cm^3

Therefore, in this paper, the authors examined the properties of concrete with expansive additive in a marine environment, using the method currently being developed by the authors for imposing restraint conditions. The parameter of the expansive additive and the degree of the constrained reinforcement ratio were evaluated by exposure tests over a period of three years.

2. Materials and Methods

2.1 Materials

The list of materials used in the test is shown in Table 1, mix proportion of concretes is shown in Table 2, and ordinary portland cement and lime-based expansive additive with the chemical composition is shown in Table 3.

Table 2 Mix proportion of concretes

	W/P	s/a	unit weight (kg/m^3)				
	(%)	(%)	W	OPC	EX	S	G
PL50	50	46	168	336	0	805	974
EX50				316	20		

Table 3 OPC and EX with the chemical composition

	Chemical composition (%)						
	Ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
OPC	1.7	21.4	5.3	3.1	63.4	1.0	2.0
EX	0.9	4.8	1.2	0.8	76.3	0.6	15.4

2.2 Test parameters

The test parameters were presence or absence expansive additive and restraint steel bar ratio. The method for installing reinforcing bars in concrete is specified in JIS A 6202 “Expansive Additive for Concrete” [6]. However, in this method, since the reinforcing bar is confined from the outside of the concrete, rusting of the reinforcing bar cannot be prevented. Therefore, as shown in Figure 1 and Photo 1, the authors designed the reinforcing bar confinement to inside the concrete test specimen of 100×100×400 mm, which is the size used to evaluate durability. Furthermore, considering the actual structure, the design for the pull-out performance and bond performance of the reinforcing bars was addressed by installing transverse reinforcing bars at the 30mm positions on both ends of the main reinforcing bars. This restraining steel bar was devised and compared with three different ratios of restraint rebar. The restrained main bars are 4.0(Abbreviation: S), 6.0(Abbreviation: M), and 8.0(Abbreviation: L) (mm) in diameter, and the restrained bar ratios are 0.5, 1.1, and 2.0 (%), respectively. Photo 1 shows the appearance of a Cage-shaped restraining steel bars.

2.3. Exposure environment

Photo 2 shows the exposure conditions of the various specimens. For the submerged zone, the exposure was conducted at a facility that can store natural seawater. For the tidal and splash zone, exposure was conducted at a site where a cycle of spraying seawater for about 4 hours and drying for about 8 hours was possible [7].

Table 4 Evaluation and Test methods

Evaluation method		Test method	Summary
Physical properties	Compressive Strength	JIS A 1108	·φ10×20cm (N=3) ·Measured at 28 days old (before exposure), 1 year, and 3 years
	Length change	JIS A 1129-2	·10×10×40cm (N=3) ·Measured at 28 days (base length), 1 year, and 3 years of age after curing in water
Micro Perspectives	Pore structure and generated hydrates	Mercury pressure-injection porosimeter Hydration product identification by XRD	·Samples were taken from the center of the test specimen, and two cross sections were used as the measurement area. ·The specimens were immersed in acetone to stop hydration, and then dried in D-dry before being used as specimens. ·The measurement range of pore size distribution was 0.003 to 30 µm
	Chloride ion penetration resistance and concentration distribution of major elements	EPMA Method for Surface Analysis of Elements in Concrete Samples used (PL50,EX50M)	·A sample is taken from the center of the specimen and coated with methacrylic resin. ·After that, the cut surface is polished to make it an analytical surface.

2.4 Evaluation and Testing Methods

The evaluation and test methods are shown in Table 4. First, for the compressive strength, a test in water at 20°C was also conducted for comparison. Next, for free expansion and contraction strain, a contact gage method was used, which allows the measurement terminals to be embedded inside the test specimen, in consideration of the exposure environment. Finally, the specimens used for the evaluation of pore structure, hydration products, chloride ion penetration resistance, and concentration distribution of major elements were 10 × 10 × 40 cm in size, sealed on four sides (casting surface, casting bottom surface, and both ends), and exposed so that the two sides (test body frame surface) would be under open conditions. Figure 2 shows the details of the analysis sample collection method.

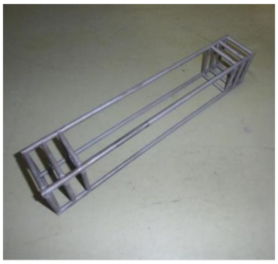

Photo 1 Appearance of a Cage-shaped restraining steel bars

Photo 2 Exposure conditions of the various specimens (Submerged zone and Tidal and splash zone)

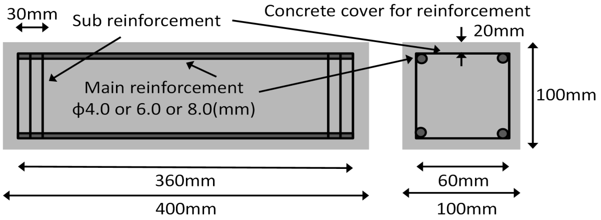

Figure 1 Cage-shaped restraining steel bars

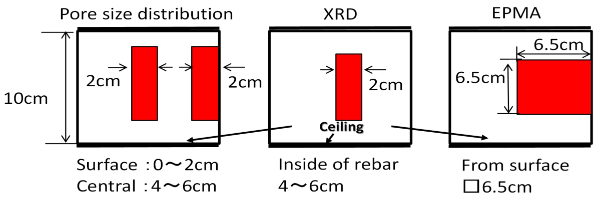

Figure 2 Details of analysis sample

3. Results and Discussion

3.1 Compressive Strength

Figure 3 shows the change in compressive strength over time. The figure shows that the compressive strength properties at each parameters are almost the same as those obtained after 3 years of curing in 20°C water, and no differences in compressive strength properties were observed due to differences in exposure environments. No significant differences were observed between PL50 and EX50. Therefore, the strength properties of the concrete with expansive additive were almost the same as those of the concrete without expansive additive, and no effect of the marine environment was observed.

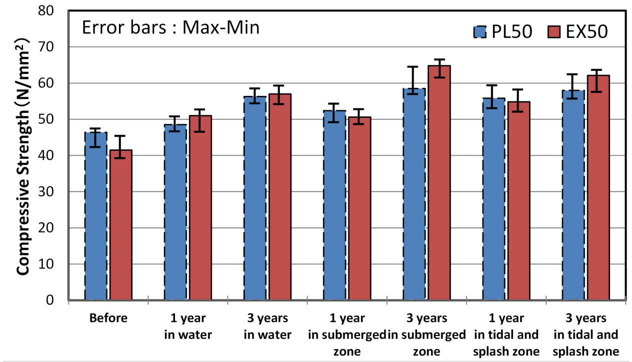

Figure 3 Compressive Strength

3.2 Length change

Figure 4 shows the length change over time in various exposure environments. Figures 5 shows the rate of mass change over time. From the figure, first, in the submerged zone, expansion behavior was observedat all parameters, with values ranging from +50 to around $+100x10^{-6}$. The rate of mass change was also found to show an increasing trend at all parameters, similar to the trend for free expansion/shrinkage strain. If magnesium sulfate from seawater component scauses erosion, it reacts with calcium hydroxide in the concrete, producing dihydrate gypsum and magnesium hydroxide (an expansive component) [8]. Furthermore, C_3A in concrete reacts with dihydrate gypsum to form ettringite (an expansive component) [8]. This mechanism causes concrete expansion, leading to sulfate deterioration in seawater. Therefore, since the concrete with or without expansive additive exhibits similar expansion behavior and mass change rate, no deterioration due to seawater action can be observed in concrete with expansive additive. On the other hand, comparing the EX50 parameters regarding the effect of reinforcing bar confinement, a slight tendency was observed where both free expansion strain and mass change rate decreased as the confinement ratio increased. This suggests that the reinforcing bar confinement in concrete with expansive additive in the submerged zone affects the length change property and mass change rate.

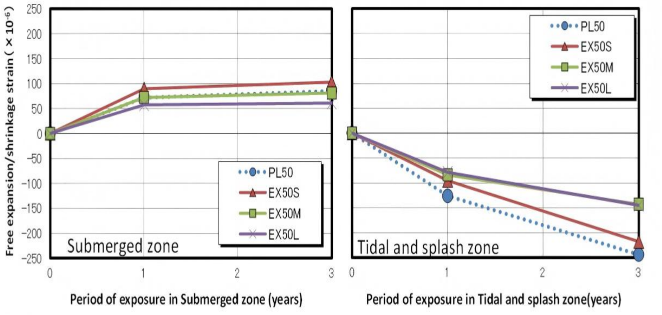

Figure 4 Length change (Submerged zone and Tidal and splash zone)

Next, in the tidal and splash zone, contrary to the results for the submerged zone, shrinkage behavior was observed for all parameters, and a similar decreasing trend was observed for the rate of mass change. This is thought to be largely due to the addition of dry conditions in the tidal and splash zone. As for the trend of each parameter, EX50S with a restrained rebar ratio of 0.5% tended to show larger shrinkage strain and mass loss rate due to drying, similar to PL50. However, EX50M and EX50L, which have constrained rebar ratios of 1.0% and 2.0%, showed smaller shrinkage strain and mass loss rate due to drying compared to PL50. This may be due to the effect of restraint by the steel bars. As the ratio of restrained steel bars increased, the shrinkage restraint stress increased and the drying shrinkage strain decreased. In this paper, the effect of the ratio of restrained steel bars and the shrinkage reduction effect of the expansion material were also confirmed in EX5OM and EX50L, where the effect of restraint was relatively large.

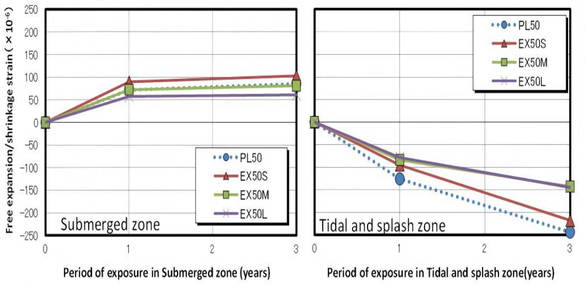

Figure 5 Rate of mass change (Submerged zone and Tidal and splash zone)

3.3 Pore structure

Figure 6 shows the relationship between cumulative pore volume and pore diameter in the submerged zone. Figure 7 shows the relationship between cumulative pore volume and pore diameter in the tidal and splash zone. For the pore size classification, a threshold of 0.1μm was used, which is considered to change air and water permeability, a threshold of 0.05μm, which is considered to change chloride ion permeability, and a threshold of 0.01μm or less, which is considered to increase fine porosity and change the degree of flexure.

The figure shows that regardless of the exposure conditions, the cumulative pore volume of concrete with expansive additive tended to be smaller than that of PL50. The effect of the constrained rebar ratio was also significant, and it was found that the larger the constrained rebar ratio, the smaller the cumulative pore volume. Comparing the results by exposure condition, first, in the submerged zone, the pore volume of 0.1 to 30μm decreased while the pore volume of 0.01 to 0.05μm increased for the concrete with expansive additive compared to PL50. It has been reported that the use of an expansive additive causes the formation of hydrates in the 1μm voids and the formation and growth of crystals while holding a large amount of capillary-level voids between the hydrates, resulting in the decrease of 1μm voids and the increase of 0.02 to 0.1μm capillary-level voids. The results of this test are similar, and are considered to be a phenomenon peculiar to concrete with expansive additive [9]. In the tidal and splash zone, on the other hand, the tendency observed in the submarine zone is smaller, indicating that the pore volumes of 0.01 to 0.05 μm and 0.1 to 1 μm of EX50 are comparable to those of PL50. This is presumably due to the heterogeneity of the concrete microstructure caused by drying. It is said that the the amount of pores smaller than 0.05μm decreases andthe amount of pores between 0.05 and 0.1μm increases due to the heterogeneity of the concrete structure caused by drying [10]. In this report, such a tendencywas confirmed in the tidal and splash zone, and it was seen to be strongly affected especially in the surface layer.to be strongly affected especially in the surface layer.

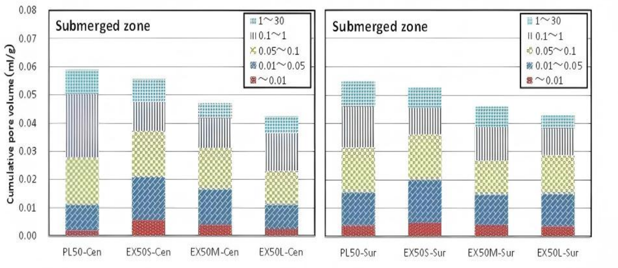

Figure 6 Relationship between cumulative pore volume and pore diameter
(Submerged zone, abbreviate Center as Cen and Surface as Sur)

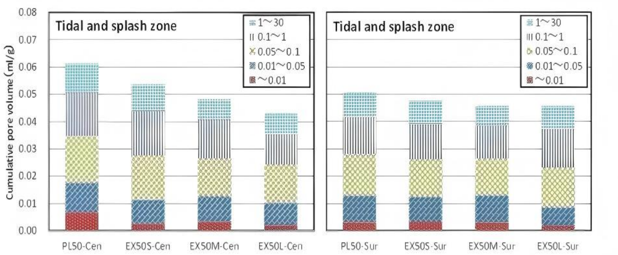

Figure 7 Relationship between cumulative pore volume and pore diameter
(Tidal and splash zone, abbreviate Center as Cen and Surface as Sur)

3.4 Hydration product

Figures 8 and 9 show the identification of the hydrates formed by X-ray diffraction (XRD). The figure shows that there was no significant difference in the hydrates produced by the concrete with the expansive additive compared to PL50. Furthermore, no difference was observed in the hydrates produced as a result of the restraint conditions.

3.5 Chloride ion penetration resistance

Figure 10 shows the sample preparation method of the specimen for the electron beam icroanalyzer (EPMA). Figures 11 and 12 show the results of surface analysis tests of chloride ions in concrete by EPMA method for PL50 and EX50M by exposure conditions.

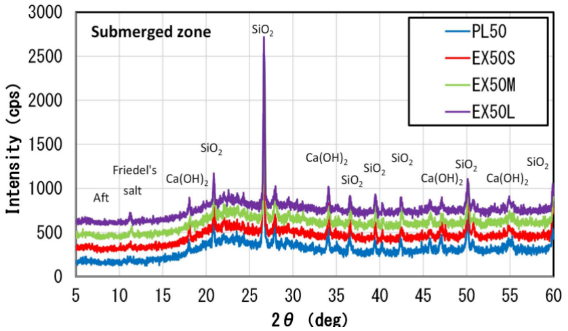

Figure 8 Hydration product (Submerged zone)

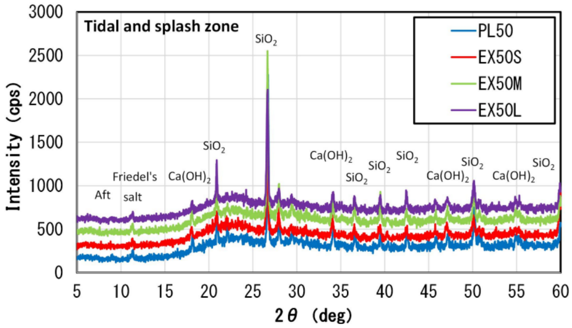

Figure 9 Hydration product (Tidal and splash zone)

Here, the white dotted lines shown in the figure indicate the average depth of corrosion at a chloride ion limit concentration of 0.3%, based on ACI 318-89. Based on the test results to date, EX50M and EX50L have suppressed drying shrinkage strain compared to PL50.Since a rebar ratio of 0.95% is standard in the constrained expansion test specified in JIS A 6202 [6], EX50M with a constrained main rebar of 6.0 mm dia (rebar ratio 1.1%) was selected for evaluation. However, it is clear that the reinforcement ratio is important for fully realizing the effects of concrete with expansive additive. Therefore, further investigation into the optimal reinforcement ratio, which could not be clarified in this paper, remains a future task.

Comparison of PL50 and EX50M shows that the chloride ion penetration depths are almost the same regardless of the exposure conditions. Therefore, the chloride ion penetration depth of concrete with expansive additive in a marine environment under restraining conditions was almost the same as that of concrete without expansive additive.

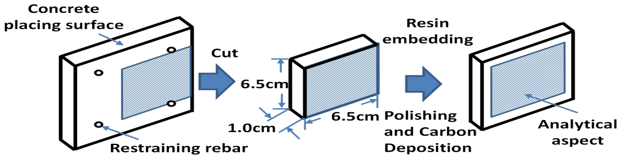

Figure 10 EPMA sample preparation method

3.6 Concentration distribution of major elements

The concentration distributions of CaO, MgO, and SO_3, the major elements that change as degradation indicators when exposed to the marine environment, are shown in Figures 13 and 14. The concentration distribution in the submerged zone is omitted here because the results were similar to those in the tidal and splash zone.

From the figure, the decrease in CaO, the increase in MgO, and the increase in SO_3, which are indicators of sulfate degradation of concrete, were all within 1.0 to 2.0 mm of the specimen depth for all parameters, and no significant differences in depth were observed when comparing each parameter. It is reported that there is a correlation between the depth of penetration of magnesium ions (The EPMA measurements were performed on MgO) [11], a degradation factor in seawater, and the depth of degradation due to seawater. Therefore, it is not recognized that concrete with expansive additive has particularly poor resistance to seawater.

4. Conclusion

In this paper, three-year exposure tests were conducted using the restraint conditions proposed by the authors, presence or absence of the expansive additive and different restraint rebar ratios as parameters, to evaluate the properties of concrete with expansion material in a marine environment. As a result, the following conclusions were obtained.

(1) The strength property of concrete with expansive additive was nearly equal to that of concrete without expansive additive, and no effect from the marine environment was observed.

(2) The length change property of concrete with expansive additive showed a similar trend to concrete without it. However, the influence of reinforcing bar

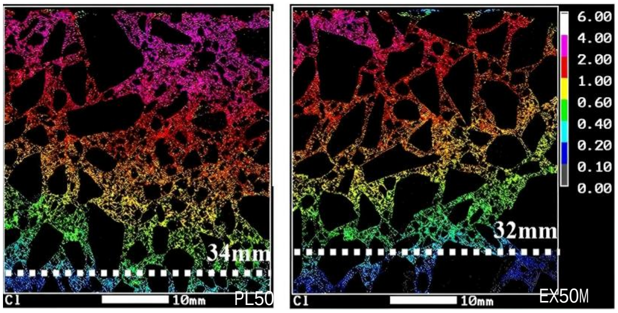

Figure 11 Distribution of permeated chloride ions by EPMA(Submerged zone)

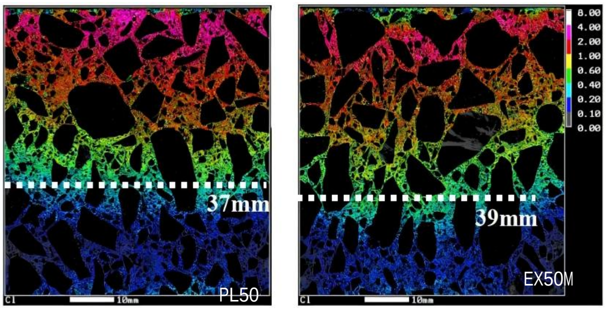

Figure 12 Distribution of permeated chloride ions by EPMA (Tidal and splash zone)

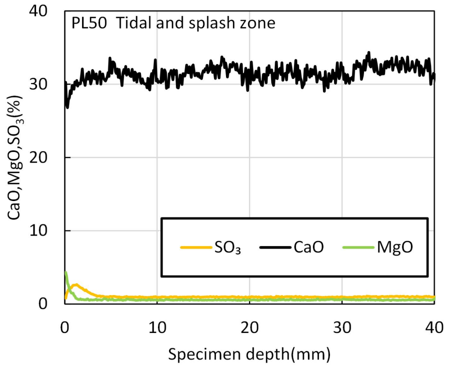

Figure 13 Concentration distribution of CaO, MgO, SO_3 (PL50)

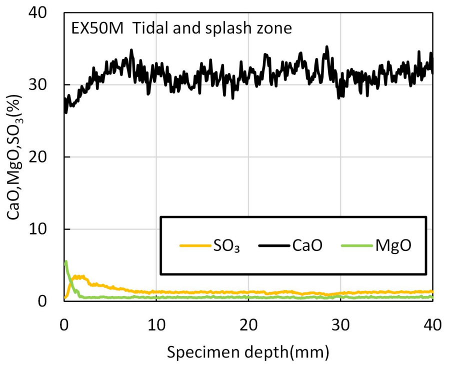

Figure 14 Concentration distribution of CaO, MgO, SO_3 (EX50M)

confinement was observed particularly noticeable in the tidal and splash zone.

(3) The pore structure of concrete with expansive additive depended on the exposure conditions, although densification occurred in reinforcing steel bar restraints.

(4) The chloride ion penetration depth of concrete with expansive additive in a marine environment under restraining conditions was almost the same as that of concrete without expansive additive.

(5)The seawater resistance of concrete with expansive additive is not considered to be particularly poor, judging from the distribution of concentrations of the major elements.

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