- Technical Paper -

INFLUENCE OF EXPANSIVE ADMIXTURE ON LAP SPLICE PERFORMANCE OF REBAR IN SHCCs UNDER CYCLIC LOADING

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ABSTRACT

Compared to plain concrete, fiber-reinforced strain-hardening cement-based composites (SHCCs) show a significant improvement in ductility and cracking behavior. But rich mixtures in the SHCC materials reduce these performances due to initial shrinkage. Expansive admixture (EXA) was used for controlling initial shrinkage of SHCCs. This paper describes the test results on the lap splice performance of rebar in the SHCCs with different compressive strength and mixture. The test results show that the replacement of 10% cement at the volume fraction by EXA in the SHCC mixture can improve the tensile and cracking behavior of lap spliced rebar in monotonic and cyclic loading.

Keywords: lap splice, strain-hardening cement-based composites (SHCCs), expansive admixture (EXA), cracking behavior

1. INTRODUCTION

In the last decades, fiber reinforced cement based composites have advanced and gained enormous momentum. Especially, strain-hardening cement-based composite (SHCC) is a ductile cement-based composite, which exhibits a pronounced strain-hardening behavior due to bridging of fine multiple cracks by short, well distributed fibers. On the other hand, SHCC mixture exhibits huge shrinkage strain, due to higher cement content and absence of coarse aggregates [1]. Today, several methods are available to limit shrinkage of cement-based composites: (1) expanding and non-shrinking cements, (2) surface treatments, (3) shrinkage reducing admixtures (SRA) and (4) expansive admixtures (EXA). Authors have tried to control the initial shrinkage of SHCC materials with replacement of a part of Portland cement by calcium sulfoaluminate (CSA) admixture. In the previous studies [2], authors investigated the effect of the replacement level of EXA in the SHCC material with the compressive strength of 70MPa on the mechanical properties, such as compressive, tensile, and flexural behavior. Their test results showed that the replacement of 10% cement at the volume fraction by EXA would significantly reduce the initial shrinkage and improve the mechanical properties of SHCC material made with 1.5% of polyethylene (PE) and low water-to-binder (W/B) ratio of 0.30.

Recently, SHCC material has been used for the critical members, repair and retrofit of existing members, and the joining of pre-cast components made with normal concrete. Bonding behavior between steel and SHCC material is one of the keys of the resisting mechanisms of reinforced SHCC members. Fischer and Li reported the ductility property of engineered cementitious composites (ECC) affects the tension stiffening effect of the cementitious composites [3]. It suggests that in the same context, SHCC can enhance the bond property between steel and SHCC matrix and the possibility of reducing the requirement of steel [4]. Taking advantage of the excellent bond capacity between steel bar and SHCC, a much shorter joint, i.e. less lap splice length, can be made [5]. In addition, no transverse reinforcements need to be incorporated.

This study aims to evaluate the lap splice performance of steel bar embedded in conventional SHCC and expansive SHCC with different compressive strength (30 and 100MPa).

2. EXPERIMENTAL INVESTIGATION

2.1. Mixture Proportion and Materials

The experimental program included six cement-based composite mixtures, as shown in Table 1. The mixture proportions were different according to specified compressive strength and cement-based composite's type. The difference between SHCC with the same compressive strength is the replacement or not of CSA expansive admixture (EXA).

The main components of the dry mixes used in this study were cement, silica sand, silica fume, and Calcium Sulfoaluminate (CSA) expansive admixture. Type I Portland cement, conforming to ASTM C 150, was used to produce the SHCC mixtures. Silica sand, with a specific gravity of 2.61 and grain sizes ranging from 105 to 120 μm, was used in the study. Silica fume (Elkem Microsilica, grade 940). A CSA-based expansive admixture (Denka) was used to reduce autogenous shrinkage and internal tensile stress in the cement-based matrix. Properties of steel and PE fibers are shown in the Table 2. The steel fiber used in this

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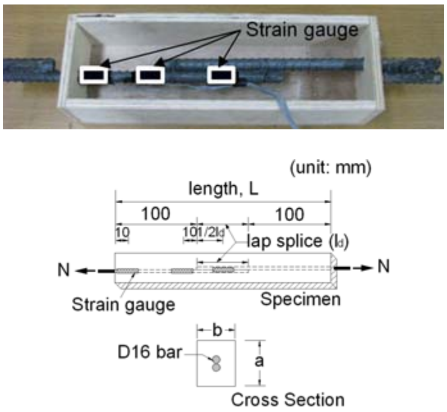


Fig. 1 Configuration and dimension of rebar lap splice specimen

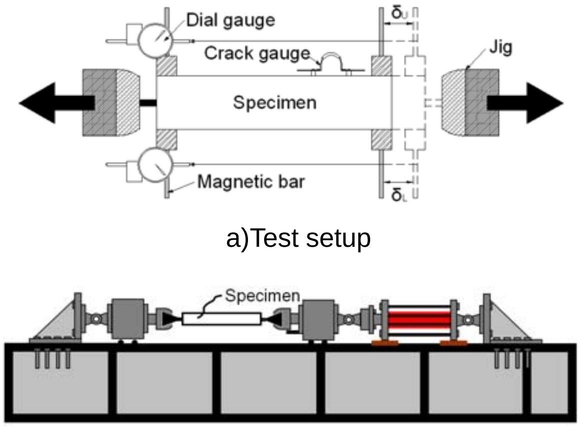


Fig. 2 Test setup of rebar lap splice specimens

study was hooked and of circular cross section. The cement-based batches were mixed in a laboratory mixer. All dry components (without fiber) were homogenized in the mixer. Then, the water was added and mixed until a low-viscous, fluid consistency was achieved. Subsequently the fiber was added gradually during continuous mixing. Afterwards the composition was mixed intensively until a uniform fiber distribution was reached.

2.2. Specimen Preparation

The test specimens consisted of cement-based prisms with centrally placed reinforcing bars for pullout tests. Dimensions of the specimens, reinforcing bar layout, and other details relevant to the experiment are shown in Fig. 1 and Table 3. All of the specimens had a cross sectional dimension of 100×80 mm and were cast in the same way.

The lap splice length (l_d) in the specimens was determined by ACI 318 Building Code. 100% and 60% of lap splice length calculated by the ACI 318 Building Code were used for concrete and SHCC specimens, respectively.

2.3. Test Procedure

The test setup is shown in Fig. 2. All specimens were slowly in direct tension through the free ends of the embedded rebar using friction grips. The direct tensile test was conducted using 1,000 kN capacity hydraulic testing machine. The test sequence consisted of submitting the specimens to a displacement controlled constant axial extension rate of 0.05 mm/min. The deformation rate of specimens was measured using

Table 1 Mixture proportion of cement-based composites

Cement-based composite type	W/B	Specific compressive strength, MPa	Fibers, %		Unit weight, kg/m³							
			PE	SF	Cement	Water	Silica fume	EXA	S	G	AE	T
Con_30	0.50	30	-	-	350	175	-	-	770	981	-	-
Con_100	0.18	100	-	-	800	160	89	-	546	835	-	-
SHCC30_00*	0.45	30	0.75	0.75	1,075	484	-	-	430	-	-	-
SHCC30_10	0.45	30	0.75	0.75	968	489	-	108	430	-	-	-
SHCC100_00	0.19	100	0.75	0.75	1,409	319	245	-	163	-	33	7
SHCC100_10	0.19	100	0.75	0.75	1,268	319	247	141	165	-	33	7

*SHCC30_00: cementitious composite type; design strength; EXA replacement level,
Note: PE, Polyethylene fiber; SF, Steel fiber; EXA, expansive admixture; AE, air-entraining agent; T, antifoaming agent.

Table 2 Mechanical properties of fibers

Fibers	Specific gravity,	Length, l	Diameter, d	Aspect ratio	Tensile strength,	Young's modulus,
	kg/m³	mm	μm	l/d*	MPa	GPa
PE	0.97	12	12	1,000	2,500	75
SF	7.85	32	405	79	2,300	206

*Note: l, length; d, diameter.

Table 3 Summaries of lap splice specimens

Specimens ID	Cross sectional dimension; a×b*, mm²	Length; L*, mm	Splice length, mm
LS_Con30	100×80	640	440
LS_Con100	100×80	440	240
LS_SHCC30_00	100×80	460	260
LS_SHCC30_10	100×80	460	260
LS_SHCC100_00	100×80	340	140
LS_SHCC100_10	100×80	340	140

*See Fig. 1

Table 4 Summaries of material properties*

Cement-based composite type	Shrinkage during 1 day, μ	Compressive strength, MPa	Young's modulus, GPa	Tensile strength, MPa	Tensile strain capacity**, %
Con30	132	32.9	22.5	-	-
Con100	443	84.7	35.4	-	-
SHCC30-00	261	40.1	16.5	4.47	1.25
SHCC30-10	0	44.2	16.0	4.59	0.35
SHCC10-00	414	89.9	29.1	6.54	0 09
SHCC100-10	322	91.8	28.8	6.57	0.02

*Compressive and tensile strength results are the average of three and five specimens, respectively.
**Tensile strain at the peak tensile stress

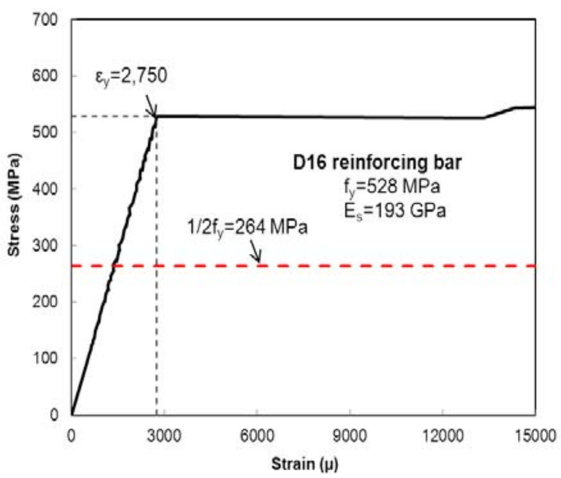


Fig. 3 Stress-strain relationship of reinforcing bar

dial gauge and the crack gauge installed to measure the crack width of the specimen surface of rebar lap splice region. The positions of dial gauge and crack gauge are shown in Fig. 2(a).

3. MATERIAL PROPERTIES

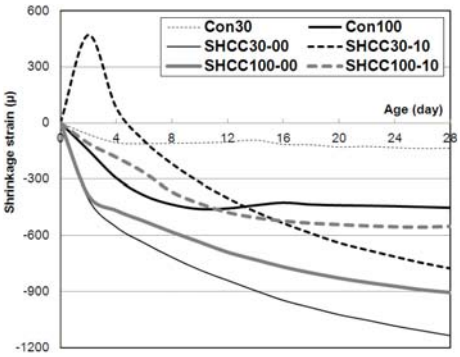
3.1. Stress-Strain Relationship of Reinforcing Bar

The tensile stress-strain behavior of the steel bar No. 5 (16 mm diameter) is shown in Fig. 3. The bar has an elastic modulus of elasticity of 193 GPa and the yield strength and strain of the bar are 528 MPa and 2,750 micro strain, respectively.

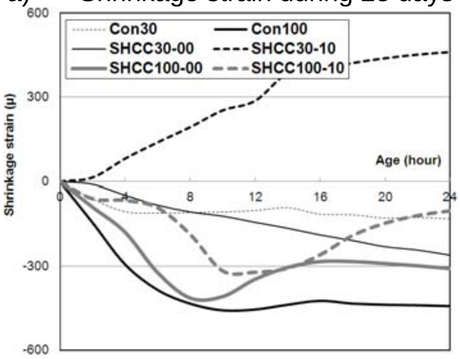
3.2. Mechanical Properties of SHCCs

To characterize the mechanical behavior of SHCC materials, the free shrinkage test, compressive and direct tensile tests were conducted on the four SHCC and two concrete mixtures. The free shrinkage specimens were stored and tested in a standard environment (20±1℃ and 60±1% RH). Autogenous strains and self-induced stressed measurements were performed continuously on each specimen. Moreover, compressive test was performed at the age of 28 day on three cylindrical specimens with the dimension of 100×200 mm. To evaluate the tensile and cracking behavior of SHCC materials under direct tension, five dumbbell-shaped specimens with a thickness of 30 mm and a measuring length of 200mm were made and tested for each mixture. Table 4 shows summaries of test results such as shrinkage strain, compressive, and tensile strengths.

Fig. 4 shows the shrinkage of concrete and SHCC mixtures obtained from free shrinkage tests during 90 days. It can be seen that the normal strength (30MPa) SHCC mixture with 10% replacement of EXA had highest shrinkage strain value, due to higher water content and hydration reaction. The high strength (100MPa) SHCC mixture with 10% replacement of EXA had low expansive strain value because of high cement content. Also, this high cement content of high strength SHCC mixtures leads to huge shrinkage strain.

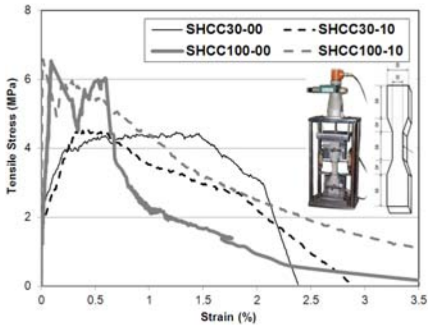


a) Shrinkage strain during 28 days

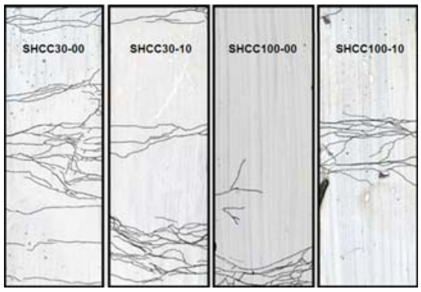


b) Shrinkage strain during 24 hours

Fig. 4 Shrinkage strain of cement-based composites



a) Average tensile responses of SHCCs



b) Typical crack patterns of SHCCs

Fig. 5 Average tensile responses of SHCCs

Average tensile responses of each SHCC material obtained from five dumbbell-shaped specimens at 28 days are shown in Fig. 5(a). The replacement of 10% cement content by CSA EXA increased slightly the maximum stress, and pattern of strain softening is similar to each other. Fig. 5(b) shows the typical crack patterns of tensile specimens after test.

4. LAP SPLICE BEHAVIOR OF REBAR IN SHCC MATERIALS

The test results of the lap splice specimens are summarized in Table 5. Table 5 shows strength and strain at initial crack and maximum. Tensile stress carried by cement-based composite in lap splice of rebar is also provided.

4.1. Direct Tensile Response of Rebar Lap Splices

The tensile responses of lap splice specimens under cyclic loading are shown in Fig. 6. The tensile strain is calculated from the displacement measured by dial gauges [Fig. 2(a)] equipped on the either sides of the specimens. From the comparison of tensile responses between LS_SHCC30_00 and LS_SHCC100_00 specimen in Fig. 6, it can be seen that LS_SHCC30_00 shows 20% more than tensile strength and strain capacity compared to LS_SHCC100_00. However, the stiffness of the LS_SHCC100_00 shows stiffer than that of LS_SHCC30_00. However, the tensile behaviors of lap splice specimens (LS_SHCC30_10 and LS_SHCC100_10) using expansive SHCC materials are similar to each other and are improved compared to lap splice specimens with conventional SHCC materials.

Table 5 Test results of lap splice specimens

Specimen ID	Initial crack		Tensile strength, MPa	Tensile strain, %	Average crack width at 0.1% (tensile strain) , μm	Tensile strength of cement matrix, MPa
	Strength, MPa	Strain, %				
LS_CON30	95	0.008	316	0.06	89	0.45
LS_CON100	149	0.002	168	0.06	214	1.60
LS_SHCC30_00	65	0.001	474	0.23	46	3.12
LS_SHCC30_10	114	0.005	515	0.15	64	3.82
LS_SHCC100_00	100	0.013	420	0.15	36	2.21
LS_SHCC100_10	249	0.002	439	0.12	38	3.72

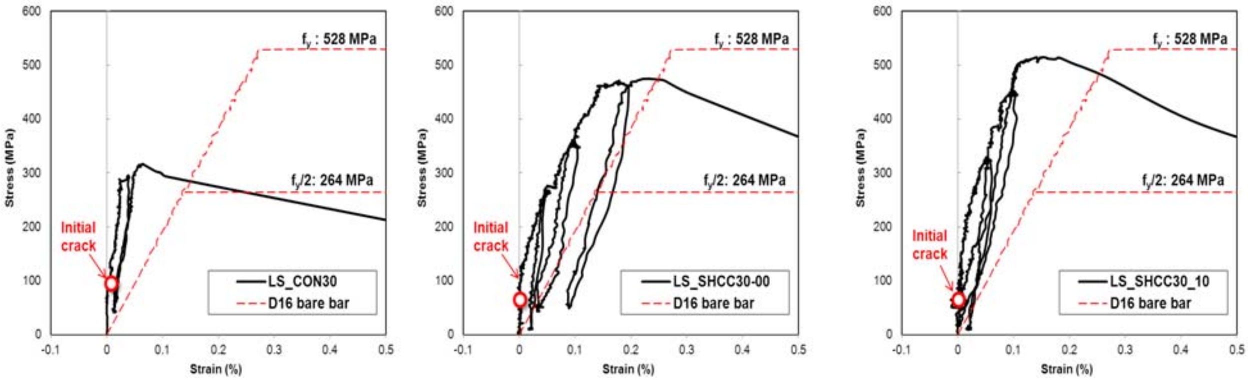
All lap splice specimens made with SHCC materials (with 60% of rebar lap splice length calculated by ACI 318 Building Code[6] present tensile strength more than the half of yield stress of bare bar. The tensile strengths of lap splice specimens with 30MPa SHCC show 50 – 63% higher strength than those of lap splice specimens with conventional concrete. This phenomenon is remarkable for lap splice specimens with 100MPa SHCC materials.

4.2. Tensile Stress of Cement-based Matrix in Lap Splice Specimens

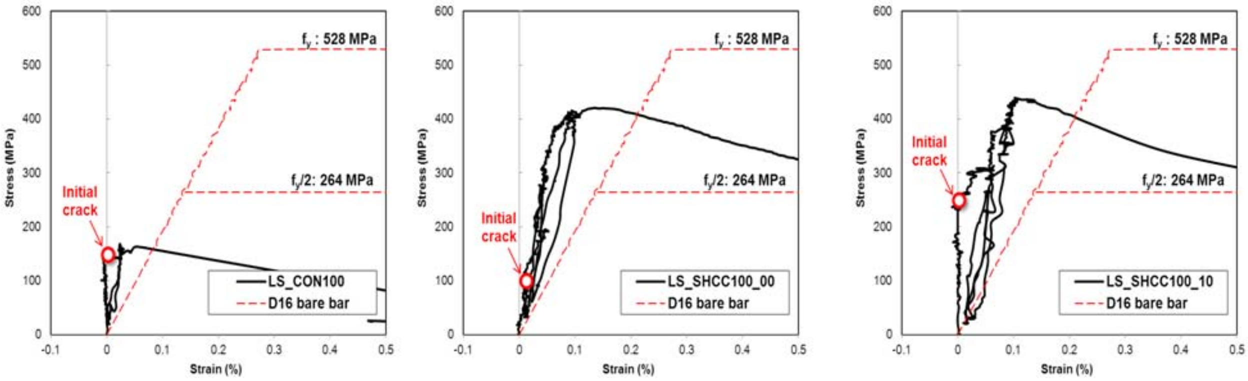
The tensile stress carried by SHCC materials in the lap splice specimens was calculated by the following equation:

$$\sigma_c=(F-E_s\varepsilon_s)/(A_t-A_s) \quad (1)$$

Where σ_c is the tensile stress carried by SHCC material (MPa); F is the total force measured by load

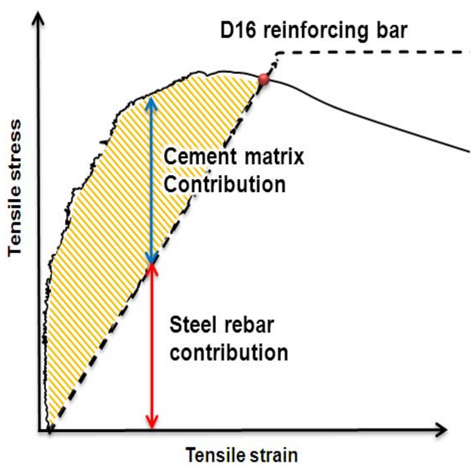


a) LS_CON30 b) LS_SHCC30_00 c) LS_SHCC30_10

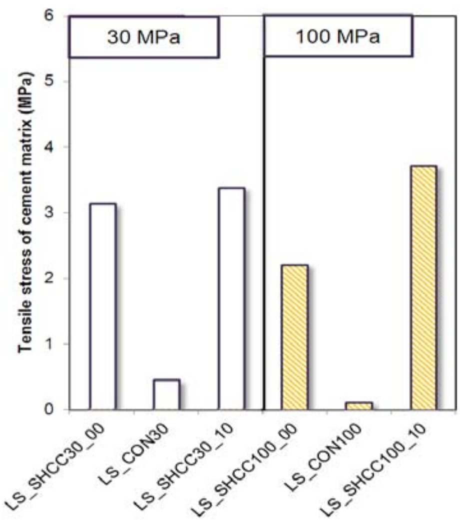


d) LS_CON100 e) LS_SHCC100_00 f) LS_SHCC100_10

Fig. 6 Tensile response of lap splice specimens

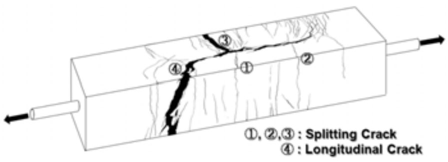


a) The contribution of cement matrix

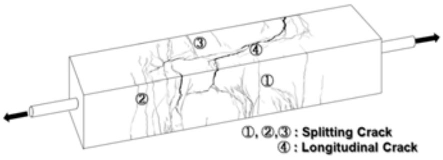


b) Tensile stress of cement matrix

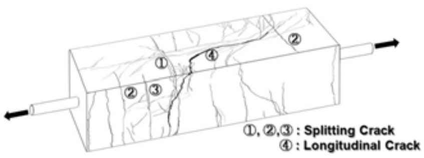
Fig. 7 Tensile stress carried by cement matrix in the lap splice specimen



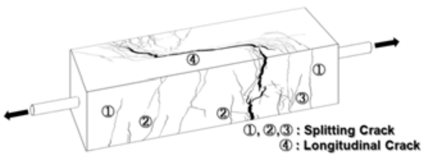
a) LS_SHCC30_00



b) LS_SHCC30_10



c) LS_SHCC100_00



d) LS_SHCC100-10

Fig. 8 Typical crack patterns of lap splice specimens

cell (kN); E_s is the elastic modulus of reinforcing bar (MPa); ε_s is the strain of steel bar measured by strain gauge (mm/mm); A_t is the SHCC cross-sectional area of the specimen (mm^2); A_s is the nominal cross-sectional area of steel bar (mm^2). Fig. 7(a) defines the contribution of cement-based composite in the lap splice specimens. Fig. 7(b) shows the tensile contribution of cement matrix calculated by Eq. (1) and the definition of Fig. 7(a). Fig. 7(b) indicates that the SHCC materials increases the tensile contribution of cement matrix in the lap splice specimens and ultimately can reduce the lap splice length of rebar. Enhancement in this tensile contribution is notable for lap splice specimens made with expansive. As show in Fig.4(a), the expansive SHCC was reduced shrinkage strain around 400µ compared to without EXA SHCC. Eventually, the reduction of shrinkage improved tension effect.

4.3. Cracking Behavior

The final crack patterns obtained from the direct tensile testing of lap splice specimens are shown in Fig. 8. The lap splice specimens made with 30MPa SHCCs show larger width and length in transverse cracks and longitudinal splitting cracks than those with 100MPa SHCC materials. For the specimens with expansive SHCCs, the cracks formed in the lap splice region were small in width and number, whereas the specimens with conventional SHCCs show larger width and number of cracks in the region. The average spacing and width of cracks in the overall length of the specimens were measured with an optical microscope at 60 times magnification.

5. CONCLUSION

Based on the test results on the lap splice in the cyclic loading, the following conclusions are drawn;

1) 30 and 100MPa SHCC materials with 1.5 % volume fraction of hybrid polyethylene and steel fibers considerably increases the tensile strength of rebar lap splice due to the crack-damage mitigation capacity of these SHCC materials.

2) The replacement of 10% cement by CSA expansive admixture has a positive effect on the lap splice performance of steel bar embedded in the SHCC materials with rich mixture. This phenomenon is remarkable for specimens made with higher strength SHCC material.

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