The Effect of Temperature and Ageing on the Behaviour of Self-compacting Concrete Containing Supplementary Cementitious Materials

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Abstract. Self-compacting concrete (SCC) is increasingly replacing conventional vibrated concrete due to its high flowability and low energy demand during construction. The substantial proportion of paste found in SCC yields a different microstructure to conventional concrete, and thus, when subjected to different curing temperatures, it exhibits distinctive mechanical behaviour. However, the effect of curing temperature on SCC containing supplementary cementitious materials (SCMs) as partial cement replacements is yet to be thoroughly investigated. This paper aims to assess the behaviour of SCC with various SCMs cured at different temperatures to estimate the robustness and applicability of these mixes in concrete structures. For this study, certain percentage volume fractions of the cement in the SCC mixes were replaced by silica fume (SF), fly ash (FA), or ground granulated blast-furnace slag (GGBS). Tests were conducted on the fresh concrete to verify that the prepared mixes complied with the criteria for self-compacting concrete. Thereafter, cubes were made from the SCC mixes and cured at different temperatures (10, 20, 35, and 50 °C). Cubic compressive strength tests were conducted at 1, 3, 7, 14, 28, 56 and 90 days. The results demonstrated that the strength gain tends to be slower at low curing temperatures (<20 °C). In contrast, high curing temperatures (>20 °C) could accelerate the strength gain in concrete but could also cause retardation of the strength development at a later age. However, using SCMs can make SCC more resistant to the detrimental effects of high curing temperatures.

Keywords: Self-compacting concrete · Supplementary cementitious materials · Curing temperature · Strength development · Fresh properties

1 Introduction

Self-compacting concrete (SCC) is one of the significant advancements in concrete technology [1]. It is highly workable, easily placed, compacts and flows under its own weight without needing external vibration, and can pass through narrow areas between

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heavy reinforcement bars [2]. SCC was developed in Japan in the late 1980s due to the shortage of skilled labourers in construction industries [2]. The interest in using SCC in construction has recently increased worldwide due to its meritorious structural properties. It is predicted that, over time, it will replace conventional concrete in many applications [1].

Considerable research has been conducted on the use of supplementary cementitious materials (SCM) as a partial replacement of cement to enhance the fresh and hardened properties of SCC, which would contribute towards a more sustainable SCC [3]. The compressive strength of concrete is generally regarded as a determination of concrete performance and is mainly attributed to the hydrated cement paste [4]. The reactivity of each pozzolanic material in the cement paste varies due to its specific chemical composition and physical properties [5]. Khan et al. [6] stated that mineral admixtures could be classified into two categories: (a) highly reactive pozzolans, such as silica fume, and (b) low to moderately reactive pozzolans, such as fly ash and GGBS. This difference in reactivity can be more extensive when the mixes are subject to different curing temperatures [7, 8].

As concrete ages, it is subjected to varying internal temperatures induced by the hydration reactions and by variations in the ambient temperature, particularly when it is cast on-site [9]. In general, the use of higher curing temperatures causes an acceleration in the early strength gain of concrete. However, this can detrimentally affect strength development at a later age. In contrast, a low curing temperature slows the strength gain of the mixes at an early age but can result in a higher long-term strength [10].

Although abundant experimental investigations deal with the effect of curing temperature on the hardened properties of traditional concrete, there is a lack in the literature focusing on the effect of curing temperature on SCC with supplementary cementitious materials.

SCC is designed with similar composition materials to conventional concrete but with different mix proportions [2]. These proportions, together with the absence of vibration during concrete casting, result in distinctive effects on the hydration characteristics due to the curing temperature, which subsequently affects the hardened concrete properties [11]. Bearing in mind the increasing interest in using SCC over the last few years, combining high-strength properties with SCC offers benefits to the construction industry and could conceivably be one of its future targets [1].

A study was implemented by [12] to assess the influence of temperature on SCC properties due to the lack of an applicable guideline assessment. It was reported that the pores in SCC tended to be coarser when the concrete was exposed to heat treatment. Soutsos et al. [11] studied the resultant compressive strength of self-compacting concrete under different curing temperatures for curing durations of up to 28 days. They concluded that the higher curing temperature improved the compressive strength at an early age while negatively affecting the long-term strength. Further, SCC with GGBS was less negatively affected over time by the curing temperature. Similar outcomes were found in the studies conducted by [13], which indicated the beneficial use of SCMs in SCC to mitigate the adverse effects of high curing temperatures with time. It can thus be seen that the earlier research focussed on the early-age strength behaviour of SCC.

Therefore, the present study aims to extend this concept and investigate the strength-gain behaviour of high-strength SCC blended with pozzolanic materials when cured at different temperatures for curing durations up to 90 days, as well as applying the maturity method to predict strength development. This will provide a greater understanding of reliability for utilising SCC in the construction industry.

1.1 Research Significance

In recent years, SCC has been more widely used due to its numerous advantages, such as applications involving congested reinforced concrete members. Therefore, SCC is expected to be increasingly used in high-rise buildings in the future. However, the increased structural demand for concrete in high- and low-rise structures could result in insufficient normal-strength SCC to satisfy the needs. Furthermore, the behaviour of fly ash, GGBS, and silica fume in high-strength SCC mixes have yet to be sufficiently studied to permit SCC's use in various temperature environments. The current research results will serve as a guide to ensure the safety of structures built from SCC using SCMs. They will assess the robustness of the studied mixes, thus encouraging the use of environmentally friendly, sustainable SCC in construction.

2 Materials and Methods

2.1 Materials

Portland cement (PC), with a compressive strength grade of 52.5 MPa (CEM I 52.5 N) in accordance with the requirements of (EN 197–1) [14], fly ash (FA), ground granulated blast-furnace slag (GGBS), and silica fume (SF) with specific gravities of 3.15, 2.4, 2.4, and 2.2, respectively, were used. The chemical composition of the PC and supplementary materials are provided in Table 1. Coarse crushed limestone aggregate with a maximum size of 10 mm and specific gravity of 2.65 was used, whilst natural river sand with particle sizes less than 2 mm and a specific gravity of 2.55 constituted the fine aggregate. Limestone dust with similar particle sizes to the river sand, and a specific gravity of 2.6, replaced approximately 30% of the river sand. Potable tap water was used for the SCC. The low water contents need a water reducer to supply the required workability of SCC mixes; therefore, a new generation of superplasticiser (SP) of the Poly-Aryl-Ether-based type with a specific gravity of 1.07 was incorporated.

All the mixes used in this study had a water-cement (W/C) ratio of 0.40, selected to achieve the target compressive strength of 70 MPa at 28 days. FA, GGBS, and SF were used in the study mixes as partial replacements for PC at rates of 40, 40, and 10% by mass, respectively. Since SF blends require a high volume of water due to the SF fineness, the SP volume of the SF-blended mixes was adjusted to maintain their self-compaction properties. The mix proportions are given in Table 2. The SCC mixtures were labelled in the format of SCC-X-Y, where X stands for the blended material in the cement paste and Y represents the percentage of pozzolanic materials used as cement substitution.

Table 1. The chemical composition of the cementitious binder materials.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	TiO_2
OPC	19.69	4.32	2.85	63.04	0.74	0.16	2.17	3.12	0.33
SF	85	–	–	1	–	4	–	2	–
GGBS	34.34	12.25	0.32	39.90	0.45	0.41	7.70	0.23	0.65
FA	53.10	20.64	8.93	6.12	2.17	1.68	1.79	1.93	0.90

Table 2. The mix proportions of the experimental SCC mixes.

Mix label	Mix ingredients (kg/m^3)								
	Cementitious materials				Aggregate			Water	SP
	PC	FA	GGBS	SF	Fine		Coarse		
					Sand	Limestone			
SCC-PC-100	514.1	–	–	–	525.00	225.00	833.0	205.6	3.3
SCC-FA-40	308.4	205.6	–	–	515.27	220.83	796.9	205.6	3
SCC-GGBS-40	308.4	–	205.6	–	515.27	220.83	796.9	205.6	3
SCC-SF-10	462.6	–	–	51.4	525.00	225.00	820.5	205.6	5.4

2.2 Mixing and Test Procedures

A pan laboratory mixer was used to prepare the SCC mixes. The components of SCC were added in the following order: coarse aggregate, PC, fine aggregate, supplementary cementitious material, water, and superplasticisers. Both coarse and fine aggregates were dried in the oven. Coarse aggregate was added to the mixer first and mixed for 1 min. PC was added and combined with the coarse aggregate for 1 min. Next, the fine aggregate and limestone dust were added simultaneously and mixed for approximately 2 min to ensure the homogeneity of the mixes. The supplementary cementitious material was then added and mixed for 1 min. One-third of the superplasticiser amount was dissolved in the water and added to the mix in two parts, after which the remaining superplasticiser was added to the mix. The mixing process continued for a further 6 min, resulting in a total mixing time of 11 min. Before casting the concrete cubes, the mixes were tested to measure the self-compaction properties [15]. A slump flow test was used to assess the flowability and a J-ring test to assess the passing ability; all the tests were video-recorded in the fresh state. By visual inspection, the mixes showed no signs of segregation.

After ensuring that the experimental mixes met the SCC criteria, the concrete was cast into 100 mm cube moulds. Compaction occurred due to the specimens' self-weight; no use was made of a vibration table. The moulded cubes were covered and wrapped with a plastic sheet (polyethene) and placed into water tanks with curing temperatures of 10, 20, 35, and 50 °C to evaluate the effects of curing temperature on the strength gain. After 24 h, the specimens were demoulded and placed back in the curing tanks.

The compressive strength tests were conducted at 1, 3, 7, 14, 28, 56 and 90 days from the day of the casting. The reported test results were obtained from the average value of three tests. Where the standard deviation of the results exceeded 10%, an additional cube specimen was tested to provide greater certainty in the calculated average value.

3 Results and Discussion

3.1 Fresh Properties

Concrete can be categorised as SCC if the mix complies with three essential parameters in the fresh state: (1) filling ability, (2) passing ability, and (3) segregation resistance [15]. To confirm the SCC properties of the mixes, various tests were conducted as prescribed in EFNARC, namely slump flow, slump flow time (t_{50}), and J-ring tests. The test results are summarised in Table 3.

In terms of slump flow diameter (D_{slump}), it was observed that all the mixes fell in a satisfactory range of flow spread diameter (550–800 mm) and slump flow time (t_{50}). The J-ring test was used to verify the ability of the SCC mixes to pass through reinforcement bars. It was noted from the results that no blockage occurred in the studied mixes, and the results complied with [15]. Furthermore, thorough visual inspections confirmed that the studied mixes revealed no sign of segregation. These observations concur with the literature [16]-[18].

Table 3. Test results of the studied mixes.

Mix label	D_{slump} (mm)	t_{50} (s)	D_{slump}–$D_{J\text{-}ring}$ (mm)	The difference in height of the concrete inside and outside of the ring (mm)
SCC-PC-100	645	1.78	45	10
SCC-SF-10	660	2	50	10
SCC-FA-40	720	1	15	2.5
SCC-GGBS-40	740	1.7	50	4

3.2 Development in Compressive Strength

Figure 1 shows the compressive strength development results of the SCC specimens with varying quantities of SCM at different curing temperatures, plotted with error bars related to the average replicate specimens. It can be observed that the rate of strength development relied on (a) the chemical process driven by the hydration and pozzolanic reactions [5], (b) the physical process referring to particle size and the filling effects of the particles [19], and (c) the curing temperature of the specimens [20]. The curing temperatures modified the properties of each constituent material differently. At a standard curing temperature (20 °C), the PC concrete gained strength more rapidly than the other mixes, except SF concrete. This can be ascribed to the slow pozzolanic reactions of FA and GGBS, which mainly react with excess calcium hydroxide (CH) after hydration. In contrast, SF is highly pozzolanic owing to its high silicate composition and large surface area, and thus the pozzolanic reactions increase the concrete strength at an early age.

At a later age, concrete with pozzolanic materials developed a higher strength due to an increased formation of calcium silicate hydrate (C-S-H) gel, which is mainly responsible for strength gain in concrete and fills the voids in the matrix, thus refining the microstructure [21]. The higher curing temperatures (35 and 50 °C) tended to accelerate the hydration and pozzolanic reactions of the clinker, leading to an increase in the early-age concrete strength. However, this could adversely affect and decrease the strength of concrete at a later age. A high curing temperature can cause accelerated hydration and non-uniformly distributed hydration products, resulting in a large pore structure [22]; this is known as the crossover effect. This overall trend remained the same for all SCC mixes in this study. However, it was observed that the material with lower pozzolanic reaction tended to be less vulnerable to the detrimental effect of higher temperature curing. For example, the crossover threshold between 20 and 50 °C occurred at 14 days with the PC mixes, which was earlier than the other SCM mixes. This concurs with observations in the literature [7, 23]. The dense C-S-H gel generated at an early age due to the high curing temperature caused a loosening of the microstructure of the PC concrete [24]. The limited quantity of hydration products generated at a later age would be unable to fill the pores sufficiently. Hence, low-strength development in PC concrete occurred at high temperatures in the long term [24]. Despite the higher pozzolanic reaction of SF concrete than of PC concrete, the effect of the curing temperature was less detrimental to the SF concrete at a later age, owing to SF's small particles, which could fill the voids and enhance the packing properties (micro-aggregate effects) [7]. Due to the slow pozzolanic reaction in FA and GGBS concrete, the produced C-S-H gel can effectively block the pores in the long term at high temperatures [21]. This suggests that blending mineral admixtures with cement can enhance the microstructure of the concrete and thus protect against the adverse effect of the temperature on pore formation.

With low-temperature curing (10 °C), all the specimens showed a lower early-age strength than those cured at higher temperatures, although the strength gradually developed over time. For example, the compressive strength of PC concrete exceeded that of concrete cured at a higher temperature (50 °C) from 14 days onward. The slow strength-gain reaction tended to form a more homogeneous distribution of the hydration products [25]. Compared with PC concrete, SF concrete showed a slower strength gain for low curing temperatures for the first seven days. From day seven onward, the SF concrete strength gain rate increased. It was noted that the concrete mixes with the inclusion of GGBS and FA showed slower strength gains and no strength enhancement at a later age, in contrast to the PC concrete. Thus, it can be confirmed that SCM specimens cured at low temperatures require longer for strength gain than PC specimens, which is undesirable when used in fast-track construction. However, SCC without SCM shows a faster strength gain than vibrated concrete specimens when cured at low temperatures [23]. Although the heat of hydration in both concrete types is initially low, the reaction develops faster in SCC due to the lower volume of course aggregate, which acts as an obstacle to retard the reaction. Further, the large proportion of paste evident in SCC accelerates strength development [26].

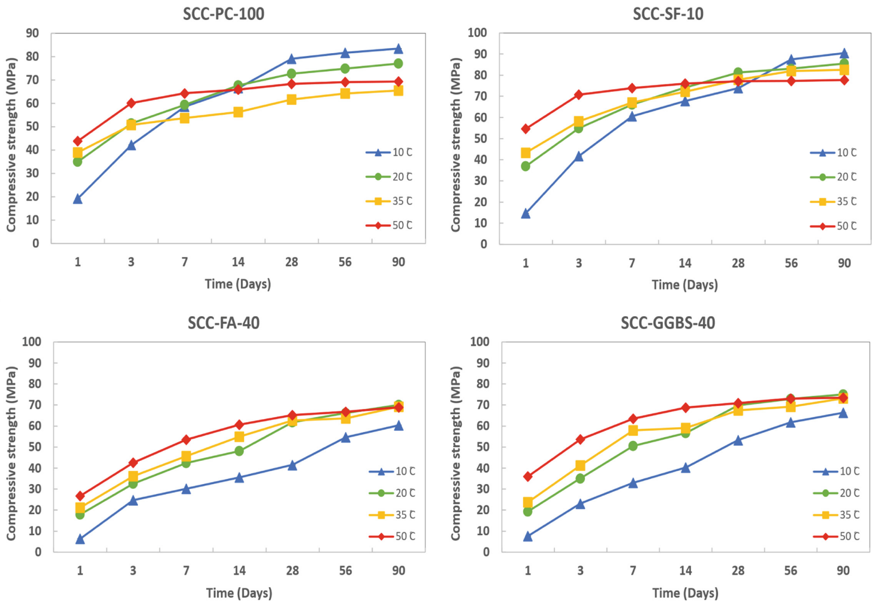

Fig. 1. Compressive strength development of the studied SCC mixes according to the curing temperature.

To gain perspective into this effect, the compressive strengths of the concrete cured at 10, 35, and 50 °C were compared with that cured at a standard temperature of 20 °C. Figure 2 depicts the sensitivity of the studied specimens to the curing temperature. Overall, the strength ratio decreased with age at higher curing temperatures (35 and 50 °C). It approached the strength ratio of specimens cured at a standard temperature due to the crossover effect mentioned previously. This decreasing trend was more delayed with FA, GGBS, SF, and PC concrete. In contrast, the trend was the opposite at a low curing temperature (10 °C). The strength ratio at 10 °C curing gradually increased with age and took a while to overtake the strength of specimens cured at a standard temperature. This extended time was more pronounced with FA, GGBS, SF, and PC concrete.

To determine the activation energy value of the samples, the calculation procedures followed the analysis method described in ASTM [27]. This is by fitting Eqs. (1) with the strength development test results for each curing temperature to find the required constants for determining the apparent activation energy.

$$S = \frac{S_u k(t - t_0)}{1 + k(t - t_0)} \quad (1)$$

In Eq. (1), S_u is the ultimate compressive strength of the SCC samples (MPa), k is the rate constant (1/days), t is the test age of the concrete (days), and t_0 is the age

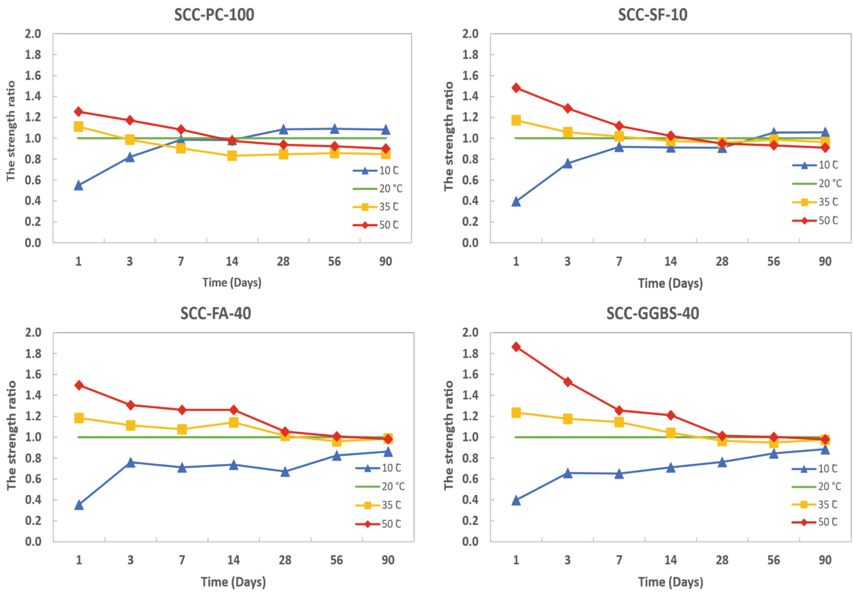

Fig. 2. The ratio of the strength development between the mixes cured according to curing temperature and cures at standard temperature.

at which the strength development of concrete is assumed to start (days). The negative slope of the fitted line between $\ln(k)$ and $\frac{1}{T}$, where the temperature is given in Kelvin, is the apparent activation energy divided by the gas constant. The apparent activation energy values are listed in Table 4.

Table 4. The apparent activation energy values of the studied samples.

Mix label	SCC-PC-100	SCC-SF-10	SCC-FA-40	SCC-GGBS-40
activation energy (KJ/mol)	37.3	45.6	25.6	36.5

To estimate the strength development of the concrete, it is necessary to determine the equivalent age t_e from Eqs.

$$t_e = \Sigma e^{-\frac{E_a}{R}\left(\frac{1}{T}+\frac{1}{T_r}\right)}\Delta t \tag{2}$$

where E_a is the apparent activation energy (J/mol), R is the gas constant (J/°K.mol), T and T_r are the temperatures of the concrete and reference temperature, respectively (Kelvin), and Δt is the curing period (days).

Once the equivalent age t_e has been determined, this can be substituted into Eqs. (1), with the applicable constants. Figure 3 shows the strength estimation of the studied mixes from these calculations. It appears that the strength estimation is affected by the curing temperature and SCM in the blended cement mixes. At low curing temperatures, the strength of (SCC-PC-100) and (SCC-SF-10) mixes were overestimated at an early age and underestimated with increasing age. In contrast, the strength of (SCC-FA-40) and (SCC-GGBS-10) was overestimated due to the slow pozzolanic reaction of FA and GGBS [21]. At higher curing temperatures, the strength of SCC with PC appeared to have a greater overestimation than the other samples, as seen by the early crossover effects.

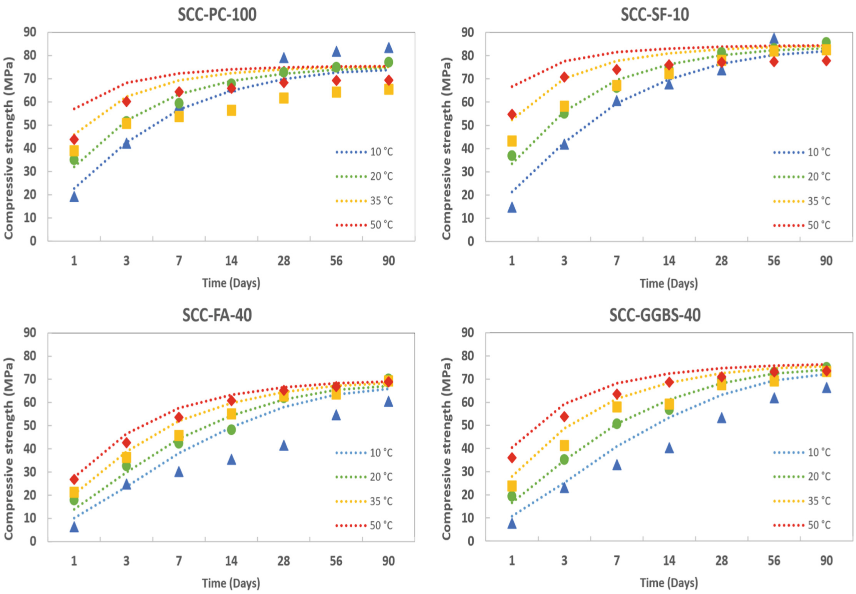

Fig. 3. Prediction of developing compressive strength of the studied SCC mixes

4 Conclusion

In this study, the influence of curing temperature and time on the compressive strength behaviour of high-strength SCC with different SCM was investigated, and conclusions were drawn as follows:

- At a standard curing temperature, SF tended to accelerate the strength development of the concrete, whereas FA and GGBS tended to slow the strength gain at an early age but provided higher strength at a later age.
- Compared to standard temperature curing, high curing temperatures (>20 °C) could accelerate the strength gain in concrete but simultaneously could cause the retardation of the strength gain in the long term. In addition, the rapid early strength gain in concrete resulted in heterogeneous hydration products, which, with time, adversely affected the strength development.

- It is possible that including the pozzolanic materials in concrete could mitigate the detrimental effects of the rapid strength development induced by high curing temperatures in the long term. The crossover effect was more delayed when FA, GGBS, or SF were included in the mixes, respectively.
- At low-temperature curing (< 20 °C), the concrete gained strength slower, increasing in strength with age. The PC concrete was expected to have a higher compressive strength than FA and GGBS concrete. Although the addition of SF could improve the compressive strength of the concrete from 7 days onward, the slow initial strength gain is undesirable in fast-track construction.
- Although the strength development of the studied mixes at low temperatures was low during the initial stages, this work indicates that high-strength SCC with no replacement of cement can show good performance at cold temperatures owing to its low proportion of coarse aggregate. In contrast, SCC with SCM can be used in fast-track construction when the ambient temperature is high without significant adverse effects on its performance at a later age. However, it is preferable to avoid using SCM with SCC when the ambient temperature is cold. Based on these results, this work would help assess the safety of structures built from high-strength SCC with SCMs which could increase its applicability in real-life scenarios.
- The strength was overestimated for the samples containing FA or GGBS at low curing temperatures. In contrast, the strength was overestimated at high curing temperatures for the control and SF samples.
- This work will be continued with the objective of developing a new approach for determining the activation energy based on the modification of the maturity function to yield accurate predictions of SCC strength development.

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