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Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete

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Abstract

The influence of moisture states of natural and recycled aggregates on the properties of fresh and hardened concretes was investigated. Concrete mixes were prepared with natural and recycled aggregates at different proportions. The moisture states of the aggregates were controlled at air-dried (AD), oven-dried (OD) and saturated surface-dried (SSD) states prior to use. The ratio of cement to free water was kept constant for all of the mixes. At the fresh state, the slump loss for various concrete mixtures was determined, while the compressive strength was determined after curing for 3, 7 and 28 days. The test results showed that the initial slump values of the concrete mixtures were dependent on the initial free water contents, and the slump loss values of the mixtures were related to the moisture states of the aggregates. Slump loss was significant when 100% AD or OD recycled aggregate was used. The effect of the moisture states of the aggregates on the strength of the concretes prepared with OD and SSD state aggregates at early age (i.e., 3 and 7 days) was noticeable. The concrete prepared with the AD aggregates achieved the highest average strength values at 3, 7 and 28 days. However, at 28 days, the concrete strengths prepared with different types of aggregates were similar. The results suggested that an AD aggregate that contains not more than 50% recycled aggregate is optimum for producing normal strength recycled aggregate concrete.

Keywords: Recycled aggregates; Moisture state; Strength development; Concrete

1. Introduction

In Hong Kong, the construction industry produces about 37,000 tonnes of construction and demolition (C&D) waste everyday, which is roughly four times higher than that of municipal solid waste. But the shortage of land for new landfills and the end of major land reclamation projects in the near future have setup alarm in Hong Kong to find alternative uses of the C&D waste [1]. The government has adopted a policy to support innovative programmes that will promote the reuse of recycled aggregates. Recently, a few open storage sites have been set up for temporary storing C&D waste and producing recycled aggregates, such as in Tseung Kwan O and at the old Kai Tak airport site. A development is being made to produce bricks and blocks with recycled C&D wastes [2]. To further develop the use of recycled aggregates in concrete production in Hong Kong, a systematic research programme is being carrying out at the Hong Kong Polytechnic University.

A number of past research has studied the properties of concrete made with recycled aggregates [3–5]. Hendriks and Pietersen [6] and Hendriks and Nijkerk [7] outlined the application issues of recycled aggregates in Europe and described the main processes and equipment. Travakoli and Soroushian [8] highlighted the key factors that influence the strength characteristics of recycled aggregate concrete, such as the strength, size distribution and water absorption of the original concrete. Larbi et al. [9] tried a thermal treatment method to improve the quality of recycled aggregate, and they found that after thermal treatment at 800 °C, the recycled aggregate was reasonably comparable to conventionally used river-dredged aggregates.

Due to the high water absorption capacity of recycled concrete aggregates, the influence of the moisture states of the recycled aggregates on the properties of the fresh and hardened concrete prepared with recycled aggregates has received some research interest. Prewetted and saturated recycled aggregates were used in several studies [3,10] in order to prevent a rapid decrease in concrete workability. These studies concluded that there was no obvious impact of the prewetted recycled aggregates on the mechanical prop-

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erties of concrete. In addition, this prewetting method has been recommended by several researchers [3]. However, Fleisher and Ruby [11] indicated that wet processing (i.e., prespraying) is not necessary for technological reasons as long as the natural moisture of the aggregates is taken into account during the mix design. Also, it is suggested that it is hardly possible to prespray the recycled aggregate uniformly at a level of work that can still be justified. Oliveira and Vazquz [12] found that the compressive strength of the concrete made from dry and saturated recycled aggregates was slightly lower than the reference concrete. The decrease was especially noticeable in flexural strength of the concrete prepared with the saturated aggregates. In addition, the concrete prepared with saturated and dry recycled aggregates exhibited poorer freeze–thaw resistance, whereas better results were obtained from the concrete made with the semisaturated aggregates.

This study aims to increase the insight of the effects of the moisture states of the recycled aggregates on fresh and hardened concrete properties so as to promote the practical application of recycled aggregates in concrete production. A test program was carried out to determine the properties of the fresh and hardened concretes prepared with natural and recycled aggregates with different initial moisture states. The workability of the fresh concretes was measured by means of slump, while the compressive strength test was conducted on the hardened concretes.

2. Experiments

2.1. Materials

2.1.1. Cement and fine aggregate

The cement used in this study was a locally produced ordinary Portland cement equivalent to ASTM Type I Portland cement. The density of the cement was 3.16 g/cm^3 and the specific surface was 3.5 cm^2/g. The chemical composition of the cement is shown in Table 1. No chemical and mineral admixture was used in this study. The fine aggregate used was natural river sand with a fineness modulus of 2.11.

2.1.2. Coarse aggregates

Both natural and recycled aggregates were used in this study. The natural aggregate was a crushed granite with nominal sizes of 10 and 20 mm. The recycled aggregate was a crushed and graded unwashed recycled concrete aggregate obtained from a single source at the old Kai Tak airport in Hong Kong. The recycled aggregate was generated by the demolition activity of a number of reinforced concrete buildings and the concrete runway. The recycled aggregate was divided into two types in terms of their maximum nominal sizes, i.e., 10 and 20 mm. The physical and mechanical properties of the recycled aggregate are shown in Table 2, where the porosity of the aggregates was determined using mercury intrusion porosimetry (MIP). In the concrete mixtures, the 10 and 20 mm coarse aggregates were used in a proportion of 1:2.

Table 1
Chemical compositions of cement (%)

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	L.O.I.
63.15	19.61	7.32	3.32	2.54	2.13	2.97

Table 2
Properties of natural and recycled coarse aggregates

Type	Nominal size (mm)	Density (kg/m^3)	Water absorption (%)	Strength (10% fine value) KN	Porosity (%)
Crushed granite	10	2620	1.25	159	1.60
	20	2620	1.24		
Recycled aggregate	10	2330	7.56	117	10.45
	20	2370	6.28		

2.2. Preparation of concrete mixtures

The concrete mixes were prepared with the use of natural and recycled coarse aggregates in four combinations; i.e., 100% natural, 80% natural + 20% recycled, 50% natural + 50% recycled and 100% recycled. These proportions of the concrete mixes were designed using the absolute volume method by assuming the aggregates were at a saturated surface-dried (SSD) condition. Adjustments were sequentially made according to the moisture contents and water absorption capacity of the respective aggregates. All the mixes had a free water content of 205 kg/m^3, a free water-to-cement (w/c) ratio of 0.57 and a fine aggregate to total aggregate ratio of 0.375. As the densities of the natural and recycled coarse aggregates were different, the actual amounts of fine and coarse aggregates in the mixes were slightly different.

In the study, the moisture states of the natural or recycled coarse aggregates were controlled at three states, i.e., air-dried (AD), oven-dried (OD) and SSD, while the fine aggregate was used at the as-received moisture state. Thus, in total, 12 concrete mixes were prepared with different combinations of natural and recycled aggregates in different moisture states. The OD aggregates were prepared by drying them in a 105 °C oven for 24 h, and they were cooled down to room temperature prior to mixing in the mixer. SSD aggregates were prepared by removing the surface moisture from the aggregates with a moistened cloth after immersing the aggregates in water for 24 h. The detached cement mortar during the soaking process was carefully collected and returned into the mixture.

To maintain the designed mix proportioning unchanged, the amounts of water and aggregates used in mixing were adjusted according to the actual moisture contents of the aggregates. When the AD and the OD aggregates were used, an additional amount of water was needed to saturate the aggregates. Also, as the recycled aggregate had a higher water absorption capacity, the amount of water added to the mix increased as the percentage of recycled aggregate increased

Table 3
Actual mass of water and materials used in different mixes

Mix	Combination of coarse aggregate	Moisture state of coarse aggregate	Proportions (kg/m^3)						
			Water	Cement	Sand	Crushed granite		Recycled aggregate	
						10 mm	20 mm	10 mm	20 mm
AD1	100% crushed granite	AD	214	353	667	362	724		
OD1		OD	221	353	667	360	720		
SSD1		SSD	209	353	666	364	729		
AD2	80% crushed granite + 20%	AD	217	353	660	287	574	70	139
OD2	recycled concrete	OD	230	353	661	284	569	67	135
SSD2		SSD	206	353	661	288	576	72	144
AD3	50% crushed granite + 50%	AD	229	353	647	176	351	170	343
OD3	recycled concrete	OD	247	353	647	175	349	164	332
SSD3		SSD	207	353	649	177	354	177	354
AD4	100% recycled concrete	AD	241	353	625			330	663
OD4		OD	271	353	625			317	642
SSD4		SSD	209	353	625			342	684

when they were used in the AD and OD states. The actual amounts of water and materials used in these 12 mixes are given in Table 3, and the moisture contents of the aggregates used in these mixes are given in Table 4. All the concrete mixtures were mixed for about 5 min in a Croker concrete mixer before casting into moulds and compaction on a vibrating table.

2.3. Tests

2.3.1. Slump

The slump of the fresh concrete prepared was measured using the standard slump test apparatus. When a fresh concrete mixture was first prepared, about 20 l (3 times the quantity required for the slump test) of the fresh concrete was taken aside on a steel plate. The first (initial) slump was measured. Afterward, slump values were regularly measured at intervals of 15 min. The concrete mixtures were covered by plastic films between the test intervals. The total testing period lasted for 165 min. The room temperature during testing was 21 ± 2 °C.

Table 4
Moisture contents of aggregates for mix preparation

Mix	Moisture content (%)				
	Sand	Crushed granite		Recycled aggregate	
		10 mm	20 mm	10 mm	20 mm
AD1	0.61	0.70	0.66	3.70	2.90
OD1	0.61	0.00	0.00	0.00	0.00
SSD1	0.40	1.25	1.24	7.16	6.14
AD2	0.76	0.78	0.85	3.84	3.22
OD2	0.82	0.00	0.00	0.00	0.00
SSD2	0.82	1.25	1.24	7.16	6.14
AD3	0.45	0.72	0.42	3.28	3.15
OD3	0.45	0.00	0.00	0.00	0.00
SSD3	0.76	1.25	1.24	7.16	6.14
AD4	0.40	0.65	0.48	3.65	3.02
OD4	0.42	0.00	0.00	0.00	0.00
SSD4	0.42	1.25	1.24	7.16	6.14

2.3.2. Compressive strength

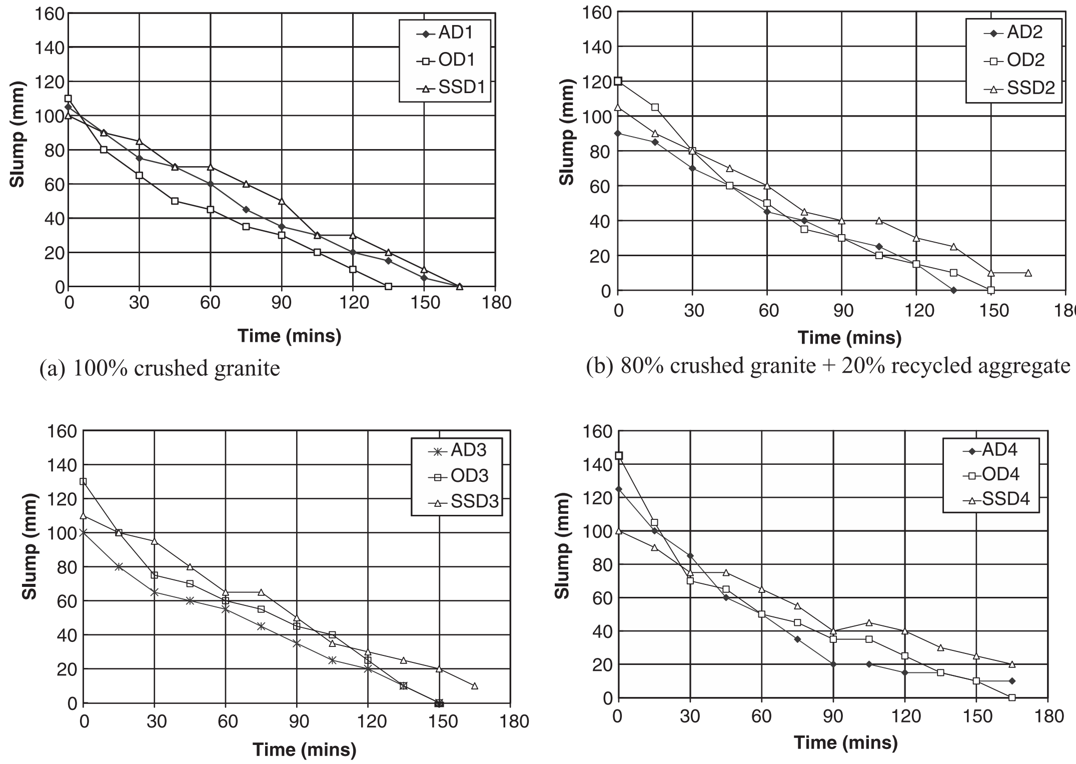
The compressive strength of the hardened concrete was determined at the ages of 3, 7 and 28 days on 100 mm cubes. These cubes were removed from the moulds after 1 day and were cured in water at 27 °C before testing.

3. Results and discussions

3.1. Initial slump

The changes of the concrete slump with time are shown in Fig. 1. For the mixes prepared with only crushed granite as the coarse aggregate, the initial slump values of the three mixes were about 100–110 mm (Fig. 1a). The difference in the moisture states of the coarse aggregate did not appear to affect the initial slump significantly when crushed granite was used only, although the concrete with OD coarse aggregate showed a slightly higher initial slump. The slump values of these mixes decreased to zero at 135 min for mix OD1 and at 165 min for mixes AD1 and SD1 after initial mixing. The higher initial slump for the concrete with the OD aggregate was due to the higher initial free water content in the mix (see Table 3). However, as the absorption capacity of the crushed granite was only around 1%, the amount of water involved in the adjustment was small. For example, the actual amounts of water added to the mixes were 209 kg/m^3 for the mix prepared with the SSD coarse aggregate and 221 kg/m^3 for the mix prepared with the OD coarse aggregates. Such a small change in the amount of added water resulted in only a small change in the initial slump value.

Shown in Fig. 1b and c is the changes in slump of the concrete mixes prepared with 20% and 50% recycled aggregates, respectively. When the coarse aggregates were used in the OD state, the initial slump of the mixes reached 120 mm for a 20% replacement and 130 mm for a 50% replacement, although the initial slump values of the mixes prepared with the AD and the SSD aggregates still main-



(a) 100% crushed granite

(b) 80% crushed granite + 20% recycled aggregate

(c) 50% crushed granite + 50% recycled aggregate

(d) 100% recycled aggregate

Fig. 1. Changes of slump of concrete mixes with different types of coarse aggregates and at different moisture states.

tained at about 100 mm. The increase in the initial slump with an increasing amount of recycled aggregate is due to the higher water absorption capacity of the recycled aggregate leading to a larger amount of initial free water used in the mix (Table 3).

For the mixes with the all the coarse aggregates being replaced by the recycled aggregate, the effect of the moisture state of the coarse aggregate became significant (Fig. 1d). When the coarse aggregate was used in the OD state, the actual amount of water added to the mix was 271 kg/m^3 as a result of water adjustment. This amount of water was much higher than that was added to the mix prepared with the SSD coarse aggregate. Also, the amount of water involved in the adjustment of the mix with the AD coarse aggregate was also increased (see Table 3). The initial slumps of the mix with OD coarse aggregates reached 145 mm and that of the mix with AD coarse aggregate reached 125 mm, which was similar to the mix prepared with 50% recycled aggregates at the OD state. In contrast, the mix with SSD coarse aggregates still maintained an initial slump of 100 mm.

Overall, it is clear that if the recycled aggregates are used in the SSD state, the replacement of natural aggregates by recycled aggregates at any percentage results only in a small change in the initial slump of the concrete. Despite the occasional discrepancies noted for the samples AD2 and AD3, it can be observed from Fig. 2 that if the recycled aggregates are used in the AD and the OD states and at high percentage replacement levels, the initial slump will increase as a result of the higher amount of water added to the mix for saturating the aggregates. This is because the initial slump of concrete is strongly dependent on the initial free water content.

3.2. Slump loss

The present study shows that when the natural coarse aggregate was used in the AD and the SSD states, the slump of the mixes decreased to zero at 165 min after mixing. The use of the natural aggregate in the OD state resulted in a quicker loss of slump of the mix with time, particularly

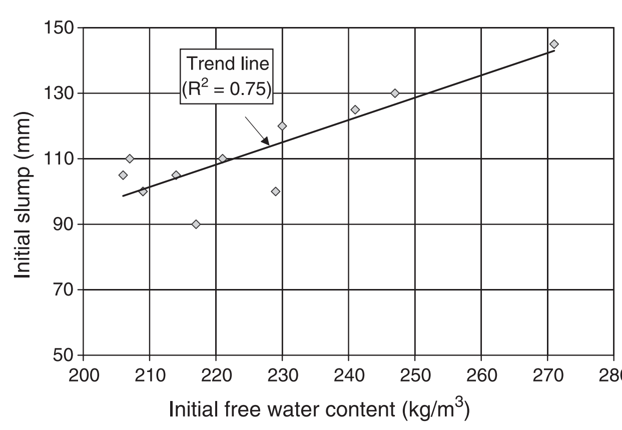


Fig. 2. Effect of initial free water content on initial slump of concrete mixes.

during the initial first hour. This is due the absorption of water by the dry aggregate, which reduced quickly the amount of free water in the mixture. The slump of this mix decreased to zero at 135 min after mixing (Fig. 1a). The use of the recycled aggregate, as a replacement of the crushed granite, prolonged the process of slump loss. The mixes prepared with 20–100% recycled aggregates in the SSD state showed a slower process of slump loss and the slump did not reach zero during the test period of 165 min. In comparison, the mixes prepared with 20–100% recycled aggregates in the OD state showed a faster loss of slump than the mixes prepared with recycled aggregates in the SSD state. The former reached the zero slump at 150 min (with 20% and 50% recycled aggregate) and at 165 min (with 100% recycled aggregate) (see Fig. 1b–d).

3.3. Compressive strength

The compressive strengths of the concrete mixes are shown in Table 5. It can be observed that all the concrete mixes achieved the target compressive strength of 35 MPa at the age of 28 days. However, the effects of the moisture states of the coarse aggregates on the compressive strength of the concrete were quite different for different combinations of coarse aggregates. When only crushed granite was used as the coarse aggregate, the mixes prepared with the coarse aggregate in the AD and SSD states had similar compressive strength values at all tested ages, while the strength of the mix prepared with the coarse aggregate in the OD state was much lower. The use of recycled aggregate as a replacement of the crushed granite seemed to have a positive effect on the mixes prepared with the coarse aggregates in the OD state but a negative effect on those prepared with the coarse aggregates in the SSD state. Fig. 3 shows that while the strength of the AD mixes almost maintained unchanged as the percentage of recycled aggregate increased, the strength of the OD mixes increased but the strength of the SSD mixes decreased. As a result, the OD mix showed a higher compressive strength than the SSD mix at all tested ages when all the crushed granite was replaced by the recycled aggregate.

Table 5
Compressive strength of concrete

Mix	Compressive strength (MPa)		
	3 days	7 days	28 days
AD1	25.0	34.9	48.3
OD1	18.2	27.9	40.2
SSD1	25.2	33.1	46.0
AD2	23.3	34.8	44.9
OD2	19.4	29.2	43.2
SSD2	20.4	30.3	43.0
AD3	22.9	32.2	44.7
OD3	21.0	29.2	39.7
SSD3	17.7	27.0	38.1
AD4	24.4	33.9	46.8
OD4	21.7	32.1	43.3
SSD4	17.5	28.5	39.1

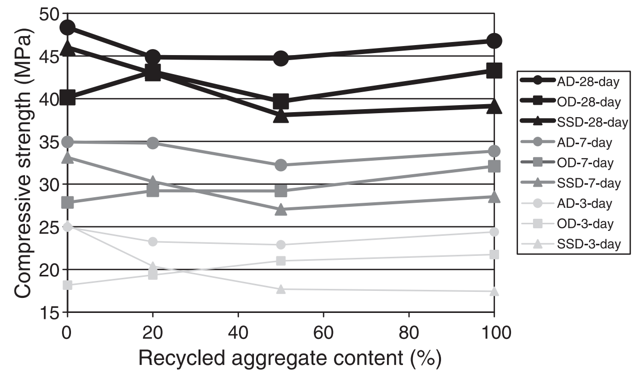


Fig. 3. Effect of recycled aggregate content on compressive strength.

It is well known that the strength of concrete depends on the strength of the cement matrix, the aggregates and the interfacial bond between the cement matrix and the aggregates. For concrete prepared with crushed granite, the difference in strength development between the OD mix and the SSD mix might be related to the development of the interfacial bond strength. Wong et al. [13] found that SSD granite had a better bond with cement than the dried one in the initial period of curing. This may account for the lower strength of the concrete prepared with the OD granite than that with the SSD granite, although the high initial w/c ratio in the OD mix may also reduce the strength of the cement matrix.

The situation in the concrete prepared with recycled aggregates is different. The results of the present study reveal that compared with the crushed granite, the moisture states of the recycled aggregate had an opposite effect on the strength development of the concrete, and the use of the recycled aggregate in the SSD state is not preferred. The lower compressive strength of the concrete prepared with the SSD recycled aggregate may be attributed to the bleeding of concrete, which was observed during compaction of the concrete cubes on the vibrating table. During vibration, the water inside the recycled aggregate particles may move toward the cement matrix, creating a relatively high local w/c in the vicinity of the particles. This process can weaken the bond between the recycled aggregate and the cement matrix. On the contrary, when the recycled aggregate is used in the OD state, water may move from the bulk cement matrix toward the recycled aggregate particles and cement particles may accumulate around the recycled aggregate particles. As a result, a stronger bond may be formed between the cement matrix and the aggregate particles particularly at the early age.

3.4. Additional discussion

The results presented above have shown that when recycled aggregate was used as a replacement of natural aggregate in the AD state (a moderate case), the workability of the fresh concrete and the compressive strength of hardened concrete were almost unchanged when compared with concrete prepared with natural aggregate. However, when the recycled concrete was used in the OD or SSD states (the extreme cases), both the workability and the compressive strength of the concrete were significantly affected due to the high water absorption capacity of the recycled aggregate.

In the case of using recycled aggregates in the OD state, the initial slump of concrete was increased as a result of the increased amount of initial free water added to the mix. This high initial slump is undesirable in practice because it can lead to the segregation of concrete during casting, although the slump may decrease more quickly due to the absorption of water by the recycled aggregate.

In the case of using the recycled aggregate in the SSD state, the high water content inside the aggregate particles may result in "bleeding" during casting. Consequently, the compressive strength of the concrete would be reduced. In practice, the use of SSD or over wetted recycled concrete should be avoided; otherwise, the w/c ratio of the mix should be adjusted, taking into account the possible reduction in concrete compressive strength.

One important point to note is that when recycled aggregate is used at high percentages (e.g., 50% or higher), the concrete mixtures would be less cohesive (based on observations during mixing and casting) than those prepared with natural aggregates. The lack of cohesiveness of the concrete also affect the integrity and homogeneity of the fresh concrete during casting, which in turn would affect the mechanical and durability properties of the hardened concrete.

It is clear that the moisture states of the aggregates can change the workability and the uniformity of the concrete mixes and hence would affect the properties of the hardened concrete. In the production of recycled aggregate concrete, the moisture states of the recycled aggregates should be taken into account not only for determining the water requirement, but also for adjusting other technical parameters (such as mixing time, compacting time) during concrete production. Generally, for large-scale production of normal strength recycled aggregate concrete, the optimal moisture condition is the AD (as-received) moisture state. The wet (SSD) recycled aggregates should only be used in special situations.

4. Conclusions

1. The moisture states of the aggregates affected the change of slump of the fresh concretes. OD aggregates led to a higher initial slump and quicker slump loss, while SSD and AD aggregates had normal initial slumps and slump losses. The initial slump of concrete was strongly dependent on the initial free water content of the concrete mixes.
2. For the concrete mixtures prepared with the incorporation of recycled aggregates, the AD aggregate concretes exhibited the highest compressive strength. The SSD recycled aggregates seemed to impose the largest negative effect on the concrete strength, which might be attributed to "bleeding" of excess water in the prewetted aggregates in the fresh concrete.
3. Based on the results of this study, aggregates in the AD (as received) state and contain not more than 50% recycled aggregate should be optimum for normal strength recycled aggregate concrete production.

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