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SHEARING RATE EFFECT ON MECHANICAL BEHAVIOR OF MSW MATERIALS

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ABSTRACT

Recent catastrophic failure in different regions of the world is an indication on the poor level of engineering knowledge on the mechanical behavior of MSW materials which are the main materials in the landfill body.
However extensive researches have been made to represent a clear frame work to describe the behavior of these materials but clearly all of these attempts had not been enough. In the region with high seismic activity, mechanical response of MSW materials under quick and dynamic loading condition is one of the issues which should be addressed however there are some evidences concerning the higher resistance of MSW materials under dynamic loading condition. As a part of an extensive research, using large triaxial apparatus and large direct shear box, the effect of shearing rate on the mechanical response of these materials were evaluated. Effect of this factor also estimated on the pore water pressure generation pattern using large triaxial tests performed in un-drained condition. The results confirmed the achievement of Augello et al. (1995, 1998), Zekkos (2005) and Zekkos et al. (2007) regarding higher level of shear resistance of MSW materials under dynamic loading condition. The results also showed that however the rate of pore water pressure generation decreases with increasing the loading rate but final level of pore water pressure is independent of loading rate.

INTRODUCTION

In the regions with high seismic activity, the stability issues during strong ground motions is a matter of concern and because of this reason the mechanical response of MSW materials under dynamic loading condition should be considered. Especially in the cases which the leachate collection system is not included in the landfill construction, the MSW materials will be saturated and therefore pore water pressure generation during quick loading is one of the issues which should be considered due to its effect on the stability of the waste mass.

Augello et al. (1995) using Kavazanjian et al. (1995) recommendations for estimation of unit weight and shear strength, evaluated the seismic performance of landfills during the 1994 Northridge earthquake. They also employed the average shear modulus reduction and material damping curves recommended by Kavazanjian and Matasovic (1995) and those by Vucetic and Dobry (1991). According to their achievements static and dynamic friction angles for a factor of safety equal to 1.2 to range between 19 and 35 degrees and 30 and 40 degrees, respectively. They concluded that the dynamic strength of the waste fill is higher than the shear strength of MSW materials in static condition.

Choosing a more conservative level of stability in static condition (FS=1.3), Augello et al. (1998) estimated static and dynamic values of internal friction angle from 25 to 41 and 27 to 45 degrees, respectively. These findings indicated that the dynamic strength of waste fill is higher than the conservative estimates of static strength. The authors suggested the middle values of this range, 33 degrees to 38 degrees, to be appropriate for use in design and analysis.

Zekkos (2005) stated that the strain rate of strong earthquake ground motions from numerical analysis is estimated to be approximately 2000%/hr or 33%/min. According to these values this researcher performed several large scale triaxial tests on MSW samples with different fiber content under various strain rate changing from 0.5%/min to 50%/min. The results suggested that as the strain rate increases the material becomes stiffer. The increase of shear strength level of MSW materials depending on the fiber content changed from 25% to 32% for a 100-fold strain rate increase (Fig. 1).

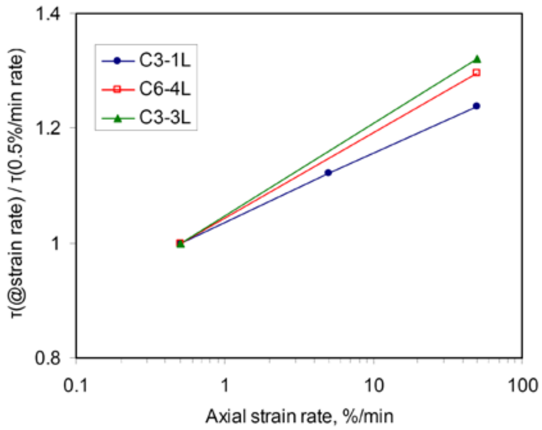

Fig. 1. Shear rate effects on the mechanical response of MSW materials with different fiber content (Zekkos, 2005)

Based on the results of these investigations this researcher concluded that the dynamic shear strength of MSW is larger than the static shear strength by a factor of 1.25 to 1.3 which due to the scarcity of the data a factor of 1.2 was suggested to estimate a conservative level of dynamic shear strength from static shear strength.

Zekkos et al. (2007) reported the results of staged direct shear tests on MSW materials with different fiber content and fiber orientation and under different values of displacement rate. Tests were performed at displacement rates of 0.1 mm/min and 5 mm/min. The stress-displacement response suggests that as the displacement rate increases, the mobilized shear stress increases. The results of this research are illustrated in Fig. 2. The displacement rate effects for the specimens with horizontally oriented fibers were similar and the specimen with vertically oriented fibers yielded more pronounced displacement rate effects.

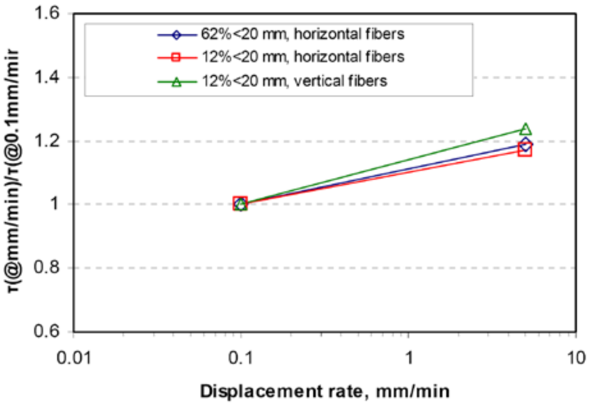

Fig. 2. Shear rate effects on the mechanical response of MSW materials with different fiber content and fiber orientation (Zekkos et al., 2007)

EXPRIMENTAL PROGRAMME

To address the effect of shearing rate on the mechanical response of MSW materials two type of tests were employed: large undrained triaxial tests and large Direct Shear tests. The triaxial tests were performed in Federal University of Bahia (UFBA), Salvador, Brazil and the direct shear tests were conducted in Iran University of Science and Technology (IUST), Tehran, Iran.

Large Triaxial Tests in UFBA

The large triaxial apparatus includes a loading frame with a capacity up to 300 kN manufactured by EMIC company which was capable to apply load with a wide range of rates changing 1 to 1000 mm/min. The loading frame also had a load cell with precision of 1 N. Software named VEGA controls the different aspects of triaxial test approach like applying confining pressure, back pressure in conventional manner and different stress paths as well using a servo control system.

The average density of samples was around 9 kN/m3 and the average water content of samples was 115%. The fiber content of the samples was about 10% and since they were collected before landfilling procedure, the collected samples did not contain soil fragments.

To compact the sample the loading frame of triaxial apparatus was used and all samples compressed up to 8 kN for 2 hours. The sample's height was limited to 30 cm during compaction stage but because of rebound tendency of sample the average height of samples was around 35 cm.

After preparation of sample and filling the chamber, with a low value of back and cell pressures, leading to a confining pressure of 10 kPa, a flow was applied to sample for at least 2 hour. The target value of the Skempton coefficient, B, used to check the sample's saturation was chosen 0.95. In the case of lower values of B, the saturation was continued by parallel increasing of the back and cell pressure with increments of 50 kPa.

After saturation stage, the samples were consolidated. The consolidation period was up to 24. This phase was ended after the volume of samples become virtually constant.

The base value for the loading rate in the shearing stage was evaluated using the equation suggested by Head (1984). According to this approach the loading rate was chosen 0.8 mm/min. This value is compatible with the loading rate reported by Carvalho (1999), 0.7 mm/min, and Jessberger & Kockel (1993), 1 mm/min.

To evaluate the effect of loading rate two other loading rates were chosen 2.5 and 7.5 mm/min. According to average height of samples before shearing stage, these two values are 1 and 3%/min which are lower than upper bond values reported by Zekkos (2005). The reason of choosing such a relatively low value of loading rate comparing strain rate imposed to soil in strong motion are, (1) loading rate limitation in the case of CU tests and (2) the buckling of samples during shearing phase especially in higher values of loading. The list of performed tests is summarized in Table 1.

Table 1. List of performed tests in UFBA

No.	Confining pressure (kPa)	Loading rate (mm/min)	Remarks
1	50	0.8	-
2	150	0.8	-
3	300	0.8	-
4	50	0.8	Repeat
5	150	0.8	Repeat
6	300	0.8	Repeat
7	50	2.5	-
8	150	2.5	-
9	300	2.5	-
10	50	7.5	-
11	150	7.5	-
12	300	7.5	-

Large Direct Shear Tests in IUST

A large direct shear apparatus was used for performing the direct shear tests. The device has the capability of applying a shearing force up to 100 kN whereas the maximum vertical load that can be applied to the specimen (with dimensions of 300 mm x 300 mm x 150 mm) is 50 kN.

An electrical motor apply the horizontal displacement to the lower part of the shear box at a constant rate. The displacement rate of this apparatus changes from 0.001 to 19.99 mm per minute. The shear displacement and vertical deformation of the specimen is measured by two LVDT with traveling course of 10 and 3 cm respectively. The shear load is measured by a proving ring, equipped with a digital dial gauge, connected to the upper part of the shear box.

The density of samples was around 12 kN/m3 and the water content of samples was 70%. Also the fiber content of materials was less that 7% by weight and just like the samples used in UFBA research the samples did not contain soil fragments.

The samples compacted by hand to reach the target density and then for a period of 24 hour consolidated under target normal stresses.

Landva and Clark (1990) used the shearing rate of 1.5 mm/min in their research. Jones et al. (1997) chose this value 0.5 mm/min and Thomas et al. (1999) applied 3 mm/min rate to shear samples. Zekkos (2005) reported the results of direct shear tests performed in University of Patras, Greece which samples were sheared at 1 mm/min. Zekkos et al. (2007) represented the results of direct shear tests at 0.1 and 5 mm/min.

In this research there level of shearing rates was chosen, 0.8, 8 and 19 mm/min which the base value is compatible with value chosen by Jones (1997) and Zekkos (2005).

It is also should be mentioned that in this research the samples were sheared at their natural water content and without saturation. In Table 2 the list of direct shear tests performed in IUST has been summarized.

Table 2. List of performed tests in IUST

No.	Normal Stress (kPa)	Shear rate (mm/min)
1	50	0.8
2	150	0.8
3	300	0.8
4	50	8
5	150	8
6	300	8
7	50	19
8	150	19
9	300	19

TEST RESULTS

Triaxial tests

The results of Consolidated-Undtained triaxial (CU) tests on the samples with loading rate of 0.8 mm/min are illustrated in Fig. 3. The main characteristics of the MSW mechanical behavior can be observed in this graph: the upward concave in deviatoric stress - axial strain curve and the pronounced increase of the pore water pressure during the shearing phase. The strain hardening in mechanical response of MSW materials in triaxial tests has been reported by researchers such as Jessberger & Kockel (1993), Grisolia & Napoleoni (1995), Carvalho (1999), Machado et al. (2002, 2008), Towhata et al. (2004), Zekkos (2005) and Nascimento (2007).

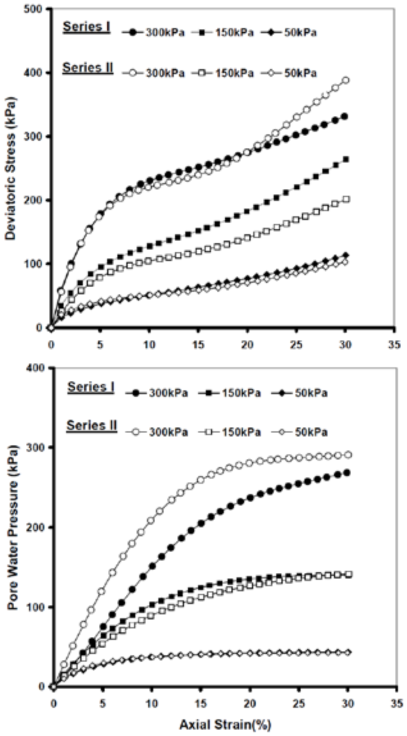

Fig. 3. Results of triaxial tests on saturated samples sheared at 0.8 mm/min

Researchers like Vilar & Carvalho (2002) and Towhata et al. (2004) believed that the existence of the fibrous material in waste (papers and plastics) is the source of such a pronounced strain hardening. Zekkos (2005) stated that during triaxial compression, under the increasing vertical load and the increasing anisotropic conditions, the initial horizontal structure of the specimen will become even more pronounced and this could lead to a further increase in strength.

The pattern of pore water pressure generation is compatible with the reported results by Carvalho (1999) and Nascimento (2007). The pattern of pore water pressure generation is similar to that observed in peat materials, as reported by Oikawa & Miyakawa (1980), Yamaguchi et al. (1985), Cola & Cortellaszzo (2005) and Mesri & Ajlouni (2007).

It is believed that the waste particles compressibility plays a very important role in this behavior which during the shearing phase the waste particles were squeezed leading a decrease in voids intra and inter particles and cause accumulation of water in the space between sample boundaries and membrane. (Karimpour Fard, 2009 and Shariatmadari et al., 2009)

In Fig. 4 the results of triaxal tests on samples sheared at different loading rate are presented. According to these graphs, increasing the loading rate leads to increase in the shear strength of samples and stiffness of sample which is compatible with Zekkos (2005) achievements.

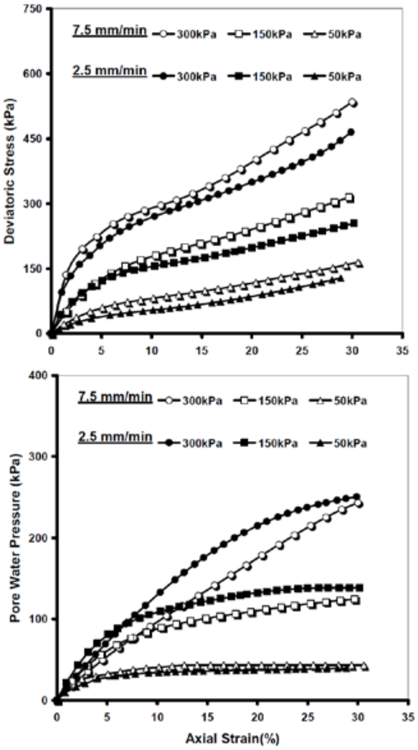

Fig. 4. Results of triaxial tests on samples sheared at 2.5 and 7.5 mm/min

The final level of pore water pressure generated in tested samples under higher level of loading rate is the same as samples tested at 0.8 mm/min, however the rate of pore water pressure generation decreases with the loading rate. The reason of lower rate of pore water pressure generation under higher loading rate could be due to time which the pore water needs to be stabilized.

As illustrated in Fig. 4, however in higher levels of confining pressure the rate of pore water pressure decreases with increasing the loading rate, but the final level of pore water pressure is independent of loading rate.

Direct shear tests

The results of first set of direct shear tests performed with shearing rate of 0.8 mm/min are depicted in Fig. 5.

No upward concave could be observed in the mechanical response of MSW materials which indicates the tensile strength of fibers insides the samples is not mobilized. It is because the shearing plane in direct shear apparatus is parallel to the orientation of fibers which during samples preparation are forced to the horizontal direction. This is the main difference between mechanical response of MSW materials which are tested in triaxial and direct shear tests.

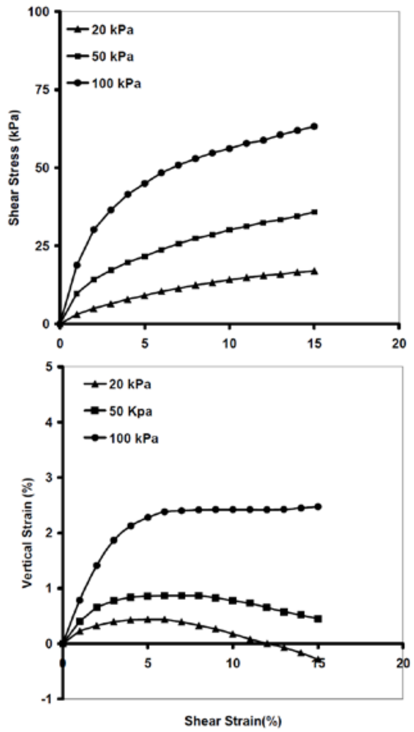

Fig. 5. Results of direct shear tests performed at 0.8 mm/min shearing rate

Since the failure mechanism in the landfills is mainly in the form of instability in the slopes and with a failure plane, the tensile strength of fibers and mainly plastics are mobilized during failure, therefore the response of MSW materials in triaxial tests could be more reliable comparing direct shear test results.

Such mechanical responses have been reported by researchers like Mazzucato et al. (1999), Mahler and De Lamare Netto (2003), Langer (2005), Zekkos (2005) and Zekkos et al. (2007) which indicate the shape of mechanical response graph in direct shear test apparatus is in the form of hyperbolic.

Some researchers like Singh (2008) have suggested a hyperbolic stress-strain model to predict the mechanical response of MSW materials which contains five different factors based on the relationship proposed by Kondener (1963).

The results of direct shear tests performed at 8 and 19 mm/min shearing rate are illustrated in Fig. 6. The effect of shearing rate on the level of mobilized shear strength is pronounced. Since under short-term loading conditions less creep and relative displacement of the waste constituents will occur in the refuse larger short-term stiffness and resistance to loading will be resulted (Anderson and Kavazanjian, 1995).

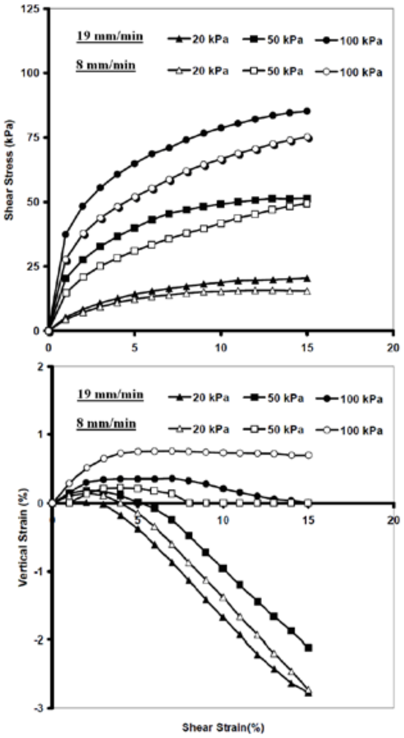

Fig. 6. Results of direct shear tests performed at 8 and 19 mm/min shearing rate

In Fig. 7 a comparison among contraction-dilation behavior of MSW materials sheared at different shear rate are presented.

As could be observed in this graph, however in the shearing rate of 0.8 mm/min, except in the low level of normal strains, no dilation occurs, with increasing the loading rate; even in the high levels of normal stress, samples exhibit dilation during shearing.

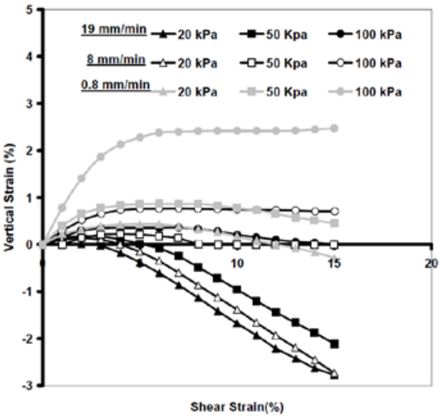

Fig. 7. Contraction-Dilation behavior of MSW materials sheared at different shearing rate in direct shear apparatus

ANALYSIS AND DISCUSSION

Interpretation of triaxial and direct shear tests performed on MSW materials based on the Mohr-Coulomb constitutive model is very common in the literature; however compressibility of MSW materials components and also existing foil like reinforcing element leads to the situation which these types of materials do not follow the frame work represented by this model.

Because of upward concave in the mechanical response of MSW materials under triuaxial loading condition, all of the researchers are agree that a MSW failure criterion should be strain dependent, but the level of shear strain which should be considered is still the source of debates.

Figure 8 shows the results of performed triaxial and direct shear test in the form if shear strength parameter, internal friction angle and intercept cohesion. Clearly with increasing of axial or shear strain level, both of the shear strength factor increase.

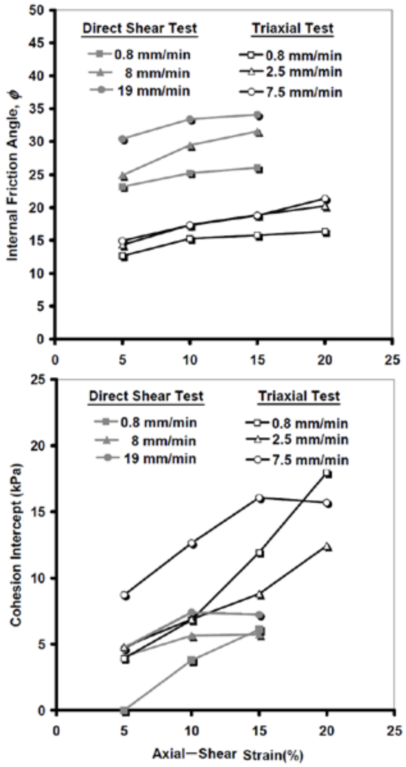

Fig. 8. Variation of shear strength parameter of MSW materials with loading rate

According to these graphs, increasing the loading or shearing rate leads to higher values of both the shear strength parameter, however in the case of internal friction angle achieved from triaxial test results, this increase in higher values of loading rate is not pronounced.

In the same loading or shearing rates, the shear strength parameter achieved from direct shear tests and triaxial tests are not the same. However the internal friction angle estimated from direct shear tests is higher that values achieved from triaxial tests but in the case of cohesion intercept the, direct shear tests yield lower values.

Fig. 9, the shear strength envelope of MSW materials represented based on the triaxial and direct shear tests.

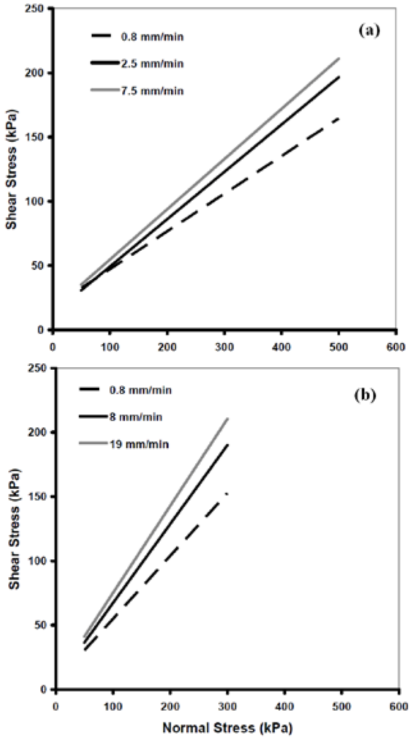

Fig. 9. Shear strength envelope of MSW materials achieved from (a) triaxial tests, (b) direct shear teats

The failure criteria in triaxial and direct shear tests to develop these envelopes were chosen 20% of axial strain and 15% shear strain respectively.

Clearly could be observed that with increasing the loading and shearing rate the mobilized shear strength increases. This increase in the case of triaxial test results, by changing loading rate from 0.8 to 7.5 mm/min is averagely 15%.

In the case of direct shear test, increasing shearing rate from 0.8 to 19 mm/min leads to an increase in the shear strength level up to 35%.

CONCLUSIONS

The mechanical response of MSW materials under quick loading condition during ground motions is one of the issues which has not addressed properly yet especially in the case of saturated samples that pore water pressure generation could affect stability issues.

As a part of a comprehensive research on the mechanical response of MSW materials under different condition, the effect of loading and shearing rate on the mechanical response of these materials using large triaxial and direct shear tests were evaluated.

The results emphasized that with increasing the loading and shearing rate the level of shear strength will increase which is compatible with Augello et al. (1995, 1998), Zekkos (2005) and Zekkos et al. (2007) findings.

According the performed analyses with increasing the loading rate from a base value of 0.8 mm/min achieved by head (1985) approach to 7.5 mm/min, the level of shear strength will increase up to 15%.

In the case of direct shear test results this increase is up to 35% by changing the shearing rate from 0.8 to 19 mm/min.

The rate of pore water pressure generation decreased by increasing the loading rate however that final value of pore water pressure was the same in all saturated samples and equal almost to confining pressure. It seems that lower rate of pore water pressure generation in the case of higher loading could be attributed to time which water needs for pressure stabilization, however because of stress dependency of MSW materials hydraulic conductivity, the permeability of MSW materials at higher loading rate which higher level of mean pressure is applied on the sample will be lower.

The direct shear tests results also showed that with increasing the shearing rate, the dilation tendency of material increases.

With increasing the loading rate, the level of internal friction angle and cohesion intercept factor increase.

According to the results of this research it could be concluded that stability of waste fills which are stable at static loading condition even in the saturated condition, could not be a matter of concern however more sophisticated laboratory and field tests should be performed to address this issue.

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