Groutability and effectiveness of microfine cement grouts

Injectabilite et efficacité des injections des ciments très fins

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ABSTRACT
A laboratory investigation was conducted in order to evaluate the properties, the groutability and the effectiveness of microfine cements. Four gradations from CEM II/B-M (according to EN 197-1) type of cement were used having nominal maximum grain sizes of 100 μm, 40 μm, 20 μm and 10 μm. The properties of suspensions, with water to cement ratios of 1:1, 2:1 and 3:1 by weight, were determined in terms of viscosity, bleeding, setting times and unconfined compression strength. Groutability and effectiveness were evaluated by conducting one-dimensional injections into five different, clean sands using three specially constructed devices. The effectiveness of cement suspensions was quantified by conducting unconfined compression, triaxial compression and permeability tests on grouted sand specimens. Groutability of cement suspensions increases with increasing cement fineness and water to cement ratio. Microfine cement suspensions with water to cement ratios of 2:1 and 3:1 can penetrate into medium to fine sands. Groutability predictions by conventional criteria are not always confirmed by laboratory injections. Sands grouted with microfine cements obtained unconfined compression strength values of up to 3 MPa and, in terms of the Mohr-Coulomb failure criterion, exhibited significant cohesion (up to 1360 kPa). The permeability coefficient of the sands was reduced by up to 5 orders of magnitude.

RÉSUMÉ
Une étude en laboratoire a été conduite pour évaluer les propriétés, l'injectabilite et l'efficacité des ciments très fins. Quatre différentes courbes de gradation de CEM II/B-M (selon EN 197-1), ont été utilisées avec des dimensions maximales des grains a 100, 40, 20 et 10 μm. Les propriétés des suspensions, avec un rapport de poids entre eau et ciment de l'ordre de: 1:1, 2:1 et 3:1, ont été déterminées en termes de viscosité, évapotranspiration, temps de solidification et compression simple. Injectabilite et efficacité ont été évaluées au moyen des injections unidimensionnelles, dans cinq différents sables purs, en utilisant trois dispositifs expérimentaux, spécialement fabriques à ce propos. L'efficacité des suspensions de ciment a été quantifiée par des essais de compression simple, des essais de compression triaxiale et des essais de perméabilité, sur des échantillons de sable injecte. L' injectabilite des suspensions en ciment augmente avec leur finesse, aussi bien qu'avec le rapport eau – ciment. Les suspensions en ciment très fin ayant des rapports d'eau sur ciment de l'ordre de 2:1 et 3:1, peut pénétrer dans des sables fins ou moyennement fins. Les prédictions d' injectabilite par des critères conventionnels ne sont pas toujours confirmes par les essais d'injection en laboratoire. Des sables injectes par des ciments très fins ont obtenu des valeurs de compression simple 3 MPa au maximum, alors que, en termes du critère de rupture de Mohr-Coulomb, présentent des valeurs de cohésion significatives (jusqu' a 1360 kPa). Le coefficient de perméabilité des sables est réduit de 5 ordres de magnitude au maximum.

Keywords : grouting, suspensions, microfine cements, laboratory investigation, grouted sand, groutability, permeability, strength

1 INTRODUCTION

The safe construction and operation of many structures frequently requires improvement of the mechanical properties and behavior of soils by permeation grouting using either suspensions or chemical solutions. The former have lower cost and are harmless to the environment but can not be injected into soils with gradations finer than coarse sands. The latter can be injected in fine sands or coarse silts but are more expensive and, some of them pose a health and environmental hazard. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradations. As a result, a number of fine-grained cements, called microfine or ultrafine cements, has been developed and manufactured. The behavior of microfine cements in permeation grouting is the objective of many ongoing research efforts.

Presented in this paper are preliminary results obtained and observations made during an extensive laboratory investigation conducted in order: (a) to develop a series of new microfine cements and (b) to investigate the behavior and performance of microfine cements in permeation grouting by documenting suspension properties and evaluating groutability of suspensions and effectiveness of grouting with these materials.

2 MATERIALS AND PROCEDURES

For the purposes of this investigation, a cement of type CEM II/B-M, according to EN 197-1, was used. The ordinary cement (designated as F0) was pulverized in order to produce three additional cements with nominal maximum grain sizes of 40 μm, 20 μm and 10 μm, which are designated as F1, F2 and F3, respectively. The grain size distributions of all cements are shown in Figure 1. All suspensions were prepared using potable water since it is considered appropriate for preparing cement–based grouts. A dosage of superplasticizer equal to 1.4% by weight of dry cement was added to F1, F2 and F3 cement suspensions for viscosity reduction. The water/cement (W/C) ratios of all suspensions used, was equal to 1:1, 2:1 and 3:1 by weight. The properties of suspensions were evaluated in terms of bleeding capacity, viscosity, setting times and strength. The values of suspension properties presented in Table 1 indicate that fine (F1) and microfine (F2 and F3) cement suspensions enhanced with superplasticizer can be used in permeation grouting for soil improvement.

The grouted soils were clean, uniform sands with angular grains. Five different sand gradations were used with grain sizes limited between sieve sizes (ASTM E11) Nos. 5 and 10, 10 and

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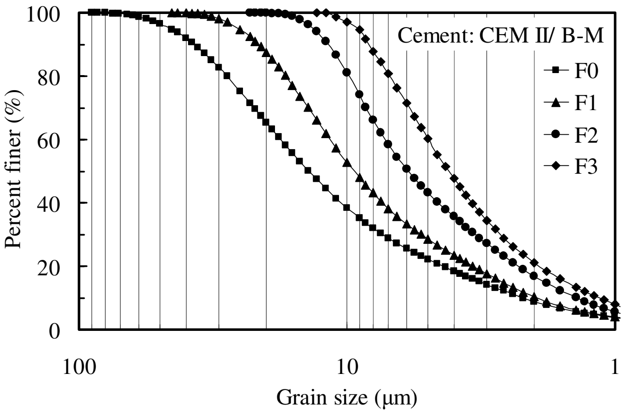


Figure 1. Grain size distributions of cements.

Table 1. Cement suspension properties.

Cement	W/C ratio	Apparent viscosity, cP		Bleeding capacity, %	Setting times, hours		Unconfined compression strength, MPa	
		60 rpm*	3 rpm*		Initial	Final	7 days	28 days
F0	1:1	193	2123	16	9	14	4.4	9.0
	2:1	26	265	50	9	18	2.5	3.9
	3:1	10	23	64	10	37	1.4	2.7
F1	1:1	7	14	29	7	10	10.3	12.7
	2:1	2	2	47	7	11	1.9	3.3
	3:1	1.5	2	67	8	12	1.0	1.9
F2	1:1	30	416	2	5	8	6.9	10.6
	2:1	8	40	35	7	12	2.3	2.8
	3:1	2	4	49	8	19	1.1	1.6
F3	1:1	111	1885	2	4	6	8.3	9.7
	2:1	17	226	19	5	8	3.2	3.6
	3:1	3	15	38	6	8	1.3	1.5

* Viscometer rotation speed, Viscosity values obtained at t = 0 min

Table 2. Sand properties.

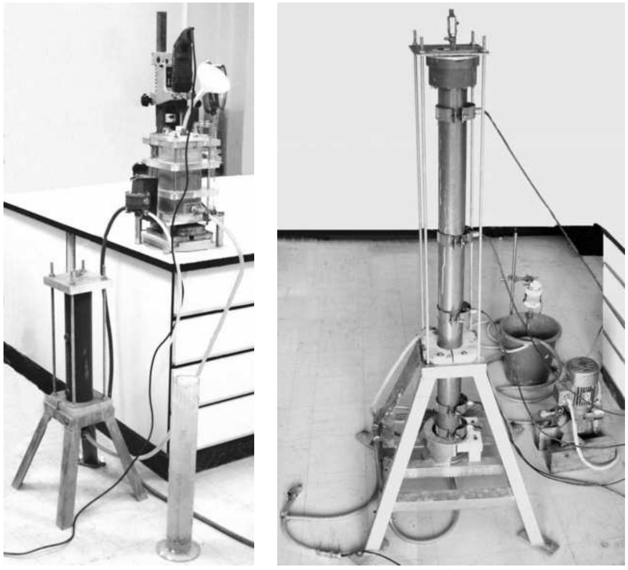
Sand	Specific gravity, Gs	Void ratios		Permeability coefficient, * k_{20}, cm/sec
		Minimum, e_{min}	Maximum, e_{max}	
S1	2.71	0.66	1.06	2.31
S2	2.72	0.68	1.03	0.80
S3	2.72	0.69	1.07	0.22
S4	2.70	0.70	1.06	0.04
S5	2.72	0.72	1.12	0.013

* Sands in dense condition

14, 14 and 25, 25 and 50, and 50 and 100, and designated as S1, S2, S3, S4 and S5, respectively. The sands were grouted in dense condition (mean value of relative density, D_r, 98±1%) and were dry prior to grouting. The angles of internal friction, φ, for all sands range from 44° to 45°, as obtained from UU triaxial compression tests in dense, dry specimens. The values of other properties of sands are presented in Table 2.

The groutability of suspensions was evaluated by performing injections into sand columns of a diameter equal to 7.5 cm and a length equal to 36.5 cm. The special device (Figure 2a) consisting of a pressurized feed tank with a stirring shaft, an air pressure regulator and a line to the PVC grouting column, was used. Injection was stopped when either the volume of the injected grout was equal to two void volumes of the sand in the column or when the injection pressure became equal to 200 kPa.

The special apparatus shown in Figure 2b was used for injecting sand columns with cement suspensions. It allows for adequate laboratory simulation of the injection process and investigation of the influence of the distance from injection point on the properties of grouted sand. The grouting column was made of PVC tube with an internal diameter of 7.5 cm and a height of 144 cm. Injection was stopped when either the volume of the injected grout was equal to two void volumes of the sand in the column or when the injection pressure became equal to 700 kPa. After curing for 28 days, the grouted columns were cut in alternating lengths of 16 cm and 9 cm. The resulting specimens with a length of 16 cm were tested in unconfined compression at an axial strain rate equal to 0.05 %/min. The specimens with a length of 9 cm were utilized for constant head permeability testing under water pressures ranging from 10 kPa to 200 kPa, using a specially constructed apparatus which allowed for testing of the grouted specimens in the PVC tube.



(a) (b)

Figure 2. Laboratory equipment (a) for groutability evaluation and, (b) for grouting sand columns.

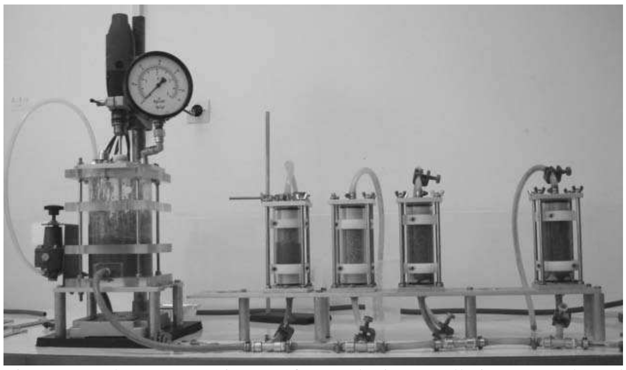


Figure 3. Laboratory equipment for producing small-size grouted sand specimens.

The laboratory equipment shown in Figure 3 was used to produce small-size grouted sand specimens, with a height of 11.2 cm and a diameter of 5.0 cm, ready for testing. This system consists of a pressurized feed tank with a stirring shaft, a pressure regulator and grouting manifolds with a line to each of four specimen molds. Unconsolidated – undrained triaxial compression tests were conducted on both grouted and ungrouted dense sand specimens at an axial strain rate equal to 0.2 %/min and confining pressures of 100, 200 and 400 kPa.

3 GROUTABILITY

For the purposes of the experimental investigation reported herein, groutability was evaluated by conducting injection tests with the apparatus shown in Figure 2a. Groutability was characterized as "satisfactory" when the predetermined quantity of grout (two void volumes of the sand column) could be injected, as "moderate" when the volume of injected grout was approximately equal to one void volume of the sand column, and as "impossible" when the quantity of the injected grout was very small. From the results of the injection tests presented in Table 3, it can be observed that groutability was "satisfactory" in S1 and S2 (Nos. 5-10 and 10-14) sands for all combinations of suspension composition. Groutability in S3 (Nos. 14-25) sand was "moderate" or "impossible" for F0 (ordinary) cement suspensions and "satisfactory" for the finer cement suspensions. The S4 (Nos. 25-50) sand was grouted "satisfactorily" only with microfine cement F2 suspensions having W/C ratio equal to 3:1 and microfine cement F3 suspensions having W/C ratios of 2:1 and 3:1. Groutability of all suspensions with W/C ratio equal to 1:1 was "impossible" in S4 sand. Penetration in S5 (Nos. 50-100) sand was negligible for any cement suspension used. Accordingly, it can be stated that the increase of cement fineness and/or W/C ratio significantly improves the groutability of cement suspensions. On a quantitative basis, microfine cement suspensions with W/C ratios of 2:1 and 3:1 can be injected in medium to fine sands.

A preliminary evaluation of groutability can be made using available criteria, such as the "groutability ratios" (Mitchell 1981; Verfel 1989) which are defined as $N_1=(D_{15})_{soil}:(D_{85})_{grout}$ and $N_2=(D_{10})_{soil}:(D_{95})_{grout}$. D_{10}, D_{15}, D_{85}, and D_{95} are characteristic grain sizes of soil and grout. Grouting is considered possible for $N_1>25$ or $N_2>11$ and not possible for $N_1<11$ or $N_2<6$. $N_1>20$ is considered the minimum condition necessary for penetration and, if $N_1\geq 50$, satisfactory permeation should be achieved. Values of N_1 and N_2 for the materials used in this investigation are presented in Table 3. A comparison between predictions and laboratory observations indicates that conventional criteria, such as the groutability ratios, may yield relatively optimistic predictions which are not always confirmed experimentally. This is attributed to the fact that groutability ratios are based solely on characteristic grain sizes of grout and soil and do not take into consideration factors, such as W/C ratio, which have an effect on groutability. The inadequacy of groutability ratios to predict correctly the groutability of cement based suspensions has also been verified by others (Zebovitz et al. 1989; De Paoli et al. 1992; Akbulut & Saglamer 2002).

Groutability can also be estimated using the empirical formula presented by Akbulut & Saglamer (2002):

Table 3. Groutability predictions and experimental results.

Cement	Sand	N_1	N_2	W/C ratio	N	Injection result *
F0	S1	70	47	1:1–3:1	58	S
	S2	46	32	1:1–3:1	39	S
	S3	25	17	1:1	23	I
				2:1	23	M
				3:1	23	M
	S4	11	7	1:1–3:1	12	I
	S5	5	3	1:1–3:1	7	I
F1	S1	119	85	1:1–3:1	101	S
	S2	78	57	1:1–3:1	68	S
	S3	42	30	1:1–3:1	36	S
	S4	19	13	1:1	19	I
				2:1	19	I
				3:1	20	I
	S5	9	6	1:1–3:1	10	I
F2	S1	210	161	1:1–3:1	183	S
	S2	138	108	1:1–3:1	123	S
	S3	75	58	1:1–3:1	66	S
	S4	34	25	1:1	32	I
				2:1	32	M
				3:1	31	S
	S5	15	12	1:1–3:1	16	I
F3	S1	297	236	1:1–3:1	260	S
	S2	195	159	1:1–3:1	175	S
	S3	106	85	1:1–3:1	93	S
	S4	47	37	1:1	44	I
				2:1	43	S
				3:1	43	S
	S5	22	18	1:1–3:1	23	I

* S: satisfactory, M: moderate, I: impossible

$$N=\frac{D_{10}(soil)}{d_{90}(grout)}+k_1\frac{w/c}{FC}+k_2\frac{P}{D_r} \qquad (1)$$

where N is groutability (if N>28 soil can be grouted sufficiently by cement-based grouts), D_{10} and d_{90} are characteristic grain sizes of soil and grout, w/c is water to cement ratio of grout, FC is the finer content of soil passing through a 0.6 mm sieve, P is the grouting pressure, D_r is relative density of soil and k_1, k_2 are constants. Although the values used, were not always between the limits given by Akbulut & Saglamer (2002), groutability N was computed by applying Equation 1 for the injection tests conducted in this investigation and the results obtained, are shown in Table 3. It can be observed that, predictions of groutability using Equation 1 are closer to the experimental results than the predictions based on groutability ratios, due to the fact that a larger number of factors affecting groutability is taken into consideration in this Equation.

4 EFFECTIVENESS

Results of permeability and unconfined compression tests conducted on specimens obtained from microfine cement grouted sand columns, after curing for 28 days, are presented in Figure 4. The permeability of the grouted sand specimens

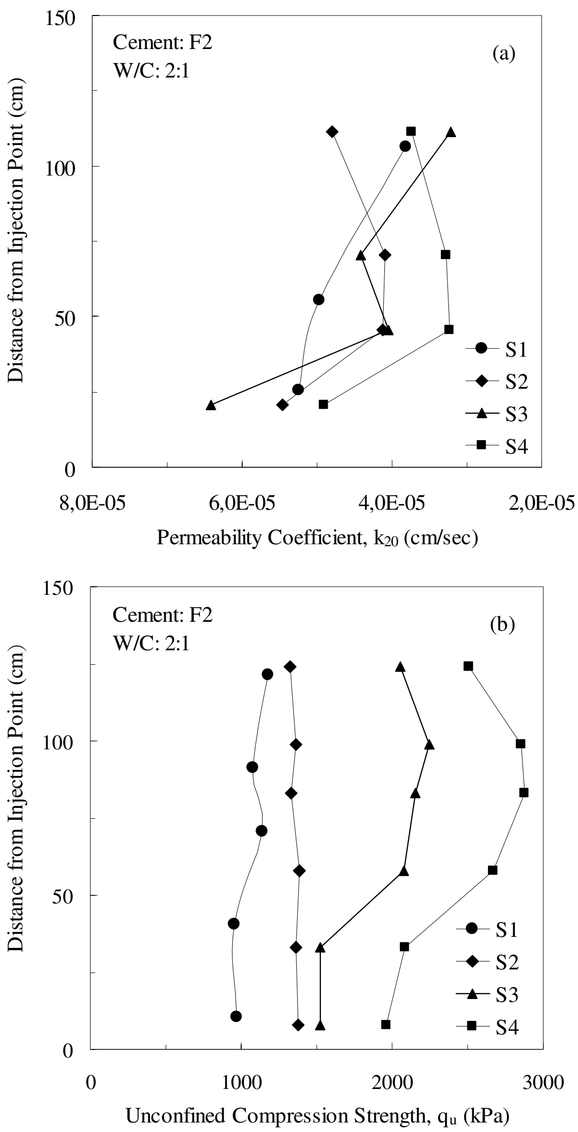


Figure 4. Permeability (a) and unconfined compression strength (b) of specimens from grouted sand columns.

(Figure 4a) ranged from $3.2 \cdot 10^{-5}$ cm/sec to $6.4 \cdot 10^{-5}$ cm/sec indicating an improvement (reduction) of sand permeability by 3 to 5 orders of magnitude and the unconfined compression strength of the grouted sand specimens (Figure 4b) ranged from 1 MPa to 3 MPa. Permeability reduction increases with increasing grain size of the sand and is not substantially affected (remains significant) by the distance from injection point. On the contrary, unconfined compression strength increases with decreasing sand grain size due to the increase of the number of grain-to-grain contact points as the grain size of sand decreases (Zebovitz et al. 1989) and, either is unaffected by the distance from injection point (S1 and S2 sands), or is lower near the injection point (S3 and S4 sands), observation that needs further documentation. Sands with permeability ranging between $2 \cdot 10^{-2}$ and $2 \cdot 10^{-3}$ cm/sec have been grouted with various microfine cements (Legendre et al. 1987; Zebovitz et al. 1989; De Paoli et al. 1992) and the permeability of the grouted sands had values ranging from 10^{-3} cm/sec to 10^{-7} cm/sec (a reduction of sand permeability by 1 to 5 orders of magnitude). Accordingly, the end effect of grouting with the suspensions used in this investigation on sand permeability is comparable to that obtained by grouting with other microfine cement suspensions.

The results obtained from all triaxial compression tests indicate a significant strength increase due to grouting which can be quantified in terms of the strength ratio, defined as the ratio of the deviatoric stress at failure of grouted and ungrouted sand specimens, tested under the same confining stress. The effects of confining stress, cement gradation and grout water to cement ratio are shown in Figure 5 for specimens prepared with S3 sand. It can be observed that the strength ratio values decrease with increasing confining stresses and with increasing water to cement ratio of the grouts, while they increase with increasing cement fineness. The effect of sand grain size on strength ratio values is shown in Figure 6 for specimens grouted with very fine cement (F3) at water to cement ratio of 2:1. It can be observed that the strength ratio values decrease with increasing sand grain size and this effect is more pronounced at low confining stresses.

Strength parameter values were also obtained by applying the Mohr-Coulomb failure criterion. The observed significant strength increase (as quantified by the strength ratio values) is attributed primarily to the development of cohesion in the grouted sands, rather than to an increase of the angle of internal friction. A wide range of values was obtained for cohesion, indicating a significant effect of grout composition and sand grain size. Cohesion values ranged between 70 and 260 kPa, 290 to 490 kPa and 620 to 1360 kPa for grout with water to cement ratio of 3:1, 2:1 and 1:1, respectively, increasing with increasing cement fineness. Cohesion values increased with decreasing sand grain size and ranged between 325 to 600 kPa,

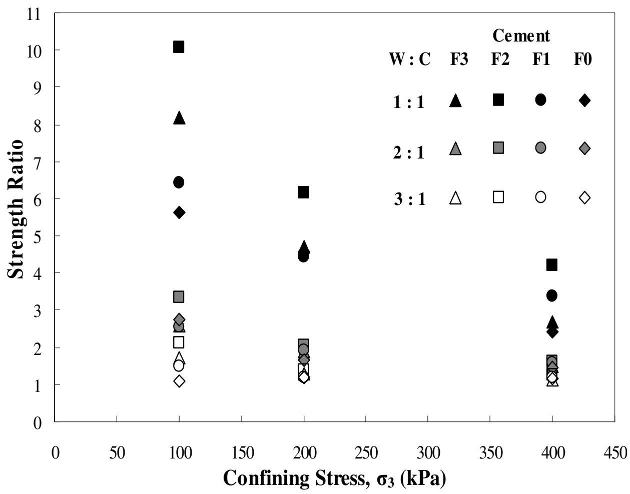


Figure 5. Effect of confining stress and grout composition on strength ratio values.

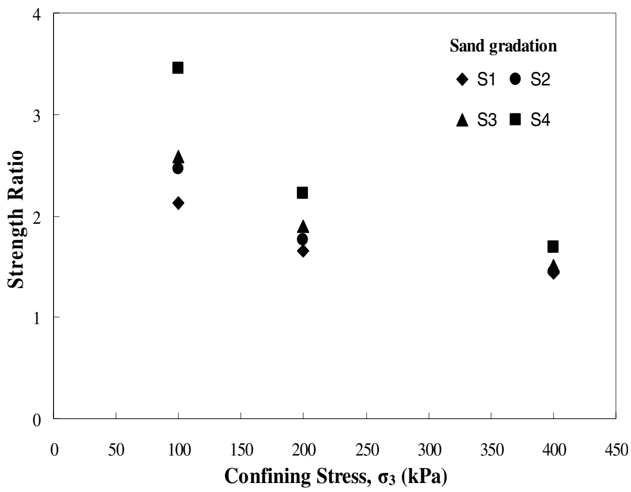


Figure 6. Effect of sand grain size on strength ratio values.

when the sand gradation was varied from limiting sieves Nos. 5–10 to 25–50. The values obtained for the angle of internal friction did not exhibit a consistent trend. Although, a small increase (up to 3^{o} over the value for ungrouted sand) was usually obtained, in some cases the effect of grouting was negligible and even slightly detrimental to the value of the internal friction angle.

5 CONCLUSIONS

Based on the results obtained and the observations made during this investigation, the following conclusions may be advanced:

1. The increase of cement fineness improves the groutability of cement suspensions rendering them effective for grouting of medium to fine sands. Predictions of groutability by groutability ratios are often optimistic, while predictions by an empirical formula were found to be closer to the experimental results.

2. A satisfactory reduction (3 to 5 orders of magnitude) of the permeability of sands can be obtained by grouting with microfine cement suspensions. Permeability reduction increases with increasing grain size of the sand.

3. In terms of strength improvement, grouting with micro- or ultra-fine cements, produced by grinding of common cements, offers a significant advantage over the coarser cements with the same chemical composition.

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