The Effect of Polymers on Soil Properties

Effet des polymères sur les propriétés des sols

by T. W. LAMBE, Associate Professor of Soil Mechanics and Director of the Soil Stabilization Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., U.S.A.

Summary

This paper discusses the use of synthetic polymers as soil stabilizers. The stabilization can be effected either by monomer addition followed by in situ polymerization or by polymer addition followed by a polymer reaction or a soil-polymer reaction. The theory of each approach is discussed.

Laboratory test data are presented which illustrate the pronounced effect polymers can have on soil properties. Plasticity, permeability, strength, and density can be either increased with some polymers or decreased with others. The frost heaving in a soil can be reduced.

A coarse soil can be completely impermeabilized by the in situ polymerization of a co-monomer solution of calcium acrylate and N-methylolacrylamide.

Physicochemical reactions between polymers and soil can cause significant changes in soil properties in concentrations as low as 0.01% of the soil dry weight.

A coordinated research effort of soil and chemical specialists will result in considerable progress in the use of polymers for soil stabilization. The incorporation of chemicals with fine grained soils is a problem yet to be satisfactorily overcome. There is no reason to expect a magic chemical which will stabilize all soils under all conditions.

Sommaire

Cette communication étudie l'emploi des polymères synthétiques comme stabilisateurs du sol. La stabilisation peut être effectuée soit par addition d'un monomère suivie d'une polymérisation in situ, soit par addition d'un polymère suivie d'une réaction de polymérisation ou par une réaction de polymérisation dans le sol. La théorie de chaque procédé est discutée.

Des résultats d'essais de laboratoire illustrant l'effet prononcé que peuvent avoir les polymères sur les propriétés du sol sont présentés. La plasticité, la perméabilité, la compressibilité et la densité peuvent être soit augmentées, avec certains polymères, soit diminuées avec d'autres. Le gonflement par le gel peut être réduit.

Un sol grossier peut être complètement imperméabilisé par la polymérisation, sur place, d'une solution d'un co-monomère d'acrylate de calcium et de N-méthylolacrylamide.

Des réactions physico-chimiques entre des polymères et un sol peuvent causer des changements importants dans les propriétés du sol à des concentrations aussi faibles que 0,01% du poids du sol sec.

Un considérable progrès dans l'emploi des polymères pour la stabilisation des sols résultera d'un effort coordonné de recherches entre les spécialistes du sol et les chimistes. L'adjonction de produits chimiques à des sols de fine granulométrie est un problème non encore résolu. Il n'y a aucune raison d'attendre qu'un produit chimique magique stabilise tous les sols dans toutes les conditions.

Introduction

For many centuries man has attempted to alter or control the properties of soil. The advancement of civilization, especially the development of modern transportation, has greatly intensified the need for the engineer to change the characteristics of a soil or to maintain the optimum natural properties of the soil under all water conditions (i.e., "soil stabilization"). Most of the known ways of altering soil behavior were discussed and summarized at the Conference on Soil Stabilization held June 18, 19 and 20 at M.I.T., Cambridge, Massachusetts.

Soil stabilization by means of chemicals, aided by mechanical treatment, offers more promise for significant accomplishments than do other methods. The stabilizers recently developed, along with the increasing aid of the chemical industry, which is noted for its vigorous and very successful research, assure the soil engineer of interesting soil additives to come. Progress in chemical stabilization is, however, dependent on the elucidation of such soil fundamentals as soil-water relationships and the forces acting between soil particles.

A type of chemical that has proved a worthy soil stabilizer, and that will probably become much more useful, is the polymer. A polymer is an organic macromolecule formed by the combination of single molecules called monomers. While natural polymers like rubber have had an important influence on mankind for many years, the development of synthetic polymers like nylon has occurred within the last twenty-five years. Polymer structure and properties can be widely varied by the chemist; therefore, he can synthesize almost any type of stabilizer the soil engineer wants. The following paper briefly describes the effects of several synthetic polymers on soil properties.

Chemical incorporation in polymer stabilization can be accomplished in one of two ways. In the first method, the monomer (or monomers) is incorporated along with a catalyst system which causes polymerization concurrently with physical and/or chemical reactions between the soil and the monomer or polymer. In the second method, the preformed polymer, in the form of a solid, a solution, or an emulsion, is added to the soil. Reactions may then occur between the polymer and the soil after any necessary preliminary steps, such as solution of the polymer or breaking of the polymer emulsion.

In Situ Polymerization of Calcium Acrylate

A. Theory of Treatment

Calcium acrylate, having the formula shown in Fig. 1, is added to the soil along with a redox catalyst system. Poly-

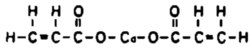

Fig. 1 Graphic Formula of Calcium Acrylate
Formule graphique de l'acrylate de calcium

merization occurs to give a product consisting of soil particles interwoven in and attached to strong, flexible polymer chains. Fig. 2 illustrates the soil-polymer system for a sodium clay treated with calcium acrylate.

The properties of the polymer can be markedly changed by copolymerizing calcium acrylate with other monomers. For example, the strength of the polymer can be increased and flexibility decreased by copolymerizing the calcium acrylate with zinc acrylate. Changes in the swelling properties of the polymer through copolymerization are described later in this section.

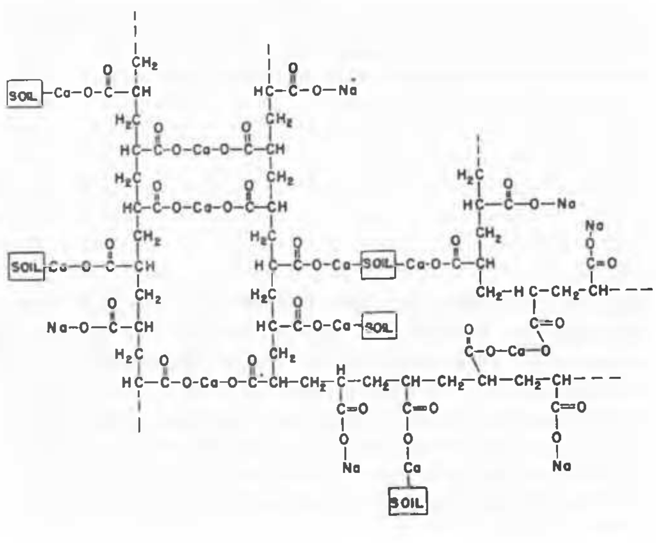

Fig. 2 Calcium Acrylate—Soil Polymer
Acrylate de calcium – polymère du sol

B. Alteration of Soil Properties

Monomer: Calcium acrylate monomer acts as a dispersing or fluidizing agent in a soil-water system. Evidence of this effect is given in Table 1, which lists the liquid limit of ten soils with and without 10% calcium acrylate monomer. In all cases the liquid limit has been reduced considerably. This reduction means that, as far as fluidity is concerned, the acrylate has the effect of replacing water in the system; in other words, the acrylate monomer weakens the soil.

Fig. 3 shows that the presence of calcium acrylate reduces the power required to obtain a given degree of mixing of soil and chemicals. Similarly, soil treated with the acrylate monomer can be compacted to a higher density at a lower water content by a given compactive energy than can soil alone. For example, 7½% acrylate monomer raises the maximum Proctor

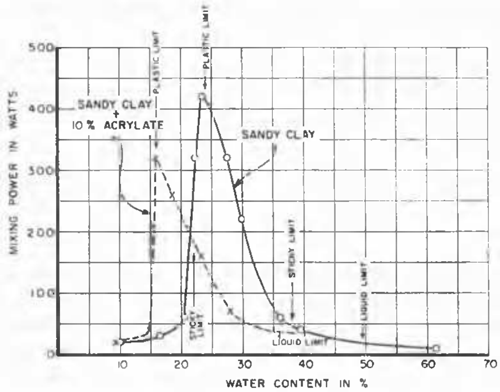

Fig. 3 Mixing Data for Fort Belvoir Sandy Clay
Données sur le mélange du sol de Fort Belvoir

Table 1 Effect of Calcium Acrylate Monomer on Liquid Limit
Influence d'un monomère d'acrylate decalcium sur la limite de liquidité

Soil	*Liquid Limit of Soil, in %*	*Liquid Limit of Soil + 10% Calcium Acrylate, in %*
Buckshot Clay Vicksburg, Miss.	67.0	46.3
Loess Vicksburg, Miss.	27.0	22.4
Clayey Silt Vicksburg, Miss.	35.0	27.8
Buggs Island Reservoir Norfolk, Va.	52.3	30.8
Grey-tan Silt Paducah, Ky.	28.3	20.2
Silt Covington, Ky.	34.3	26.4
Sandy Silt Cagles Mill Reservoir, Ind.	21.7	18.4
Red Clayey Silt Camp Cambell, Ky.	45.2	22.6
Tan Silt Cagles Mill Reservoir, Ind.	29.2	15.8
Sandy Clay Fort Belvoir, Va.	49.0	36.0

Table 2 Soils treated with 10% Calcium Acrylate
Sols traités avec 10% d'acrylate de calcium

Soil	*Water Content in %*	*Tensile Strength in psi*	*Elongation at Rupture in %*
Silt Paducah, Ky.	25	38	43
Silt Manchester, N.H.	30	33	103
Sandy Silt Shreveport, La.	35	17	87
Clayey Sandy Silt Newport, Ark.	35	25	64
Clayey Sandy Silt Blytheville, Ark.	30	36	53
Silty Sandy Clay Camp Hulen, Tex.	35	28	106
Clayey Silt Vicksburg, Miss.	30	39	96
Loess Vicksburg, Miss.	25	28	73
Silty Clay Stuttgart, Ark.	35	43	16
Buckshot Clay Vicksburg, Miss.	45	14	34
Sandy Clay Fort Belvoir, Va.	35	40	16

dry density of Fort Belvoir sandy clay from 107 to 119 lbs./cu.ft. and lowers the optimum water content from 20 to 13½%.

Polymer: In situ polymerization has a remarkable effect on most of the soil properties. Some of these effects are described below.

(*a*) Strength: The most important effect of the acrylate polymer is the very large increase of strength that can be obtained. Table 2 shows the tensile strength and water content of eleven soils treated with an amount of calcium acrylate equal to 10% of the dry soil weight. Before treatment all of the soils had a zero tensile strength at the water content equal to that in Table 2.

Increases in compressive strength, while not as spectacular as those in tensile strength, can be obtained from calcium acrylate treatment. For example, the compressive strength of Fort Belvoir sandy clay at 16% water content is increased from 30 to 600 pounds per square inch by a 10% acrylate treatment.

(*b*) Flexibility: Soil can be made rubbery by the calcium acrylate treatment. The amount of flexibility imparted depends on the soil, water content, and amount and type of treatment. The elongation of a treated sample of the Fort Belvoir sandy clay at rupture in a tensile test can be made to vary from less than 1 to over 100%.

(*c*) Permeability: The polymer with its entrapped water can effectively block the flow passages in a soil and, therefore, can reduce the permeability of the soil to essentially zero. This reduction of permeability is discussed in the next part of this paper, where it is shown that a sand was made completely impermeable by a less than two per cent treatment of polymer.

(*d*) Compressibility: Since the acrylate polymer fills the soil voids and reduces the permeability of the soil, the polymer reduces both the rate and amount of compression.

(*e*) Freeze-Thaw Resistance: The sandy clay from Fort Belvoir, Virginia, is the only soil on which freeze-thaw studies have been made. Tests showed that a calcium acrylate treatment raised the freeze-thaw resistance of this soil from negligible to significant values. As one would expect, the samples prepared at low water contents and high acrylate contents had the most resistance to deterioration from freeze-thaw cycles. The resistance of samples prepared with 10% acrylate was comparable to the resistance of samples treated with 10% Portland cement or 20% road oil.[1]

(*f*) Frost Heave: Two soils that are highly susceptible to frost were treated with calcium acrylate and then subjected to freezing tests by the Frost Effects Laboratory, Corps of Engineers, Boston, Massachusetts. The test results, presented in Table 3, show that calcium acrylate is very effective in preventing ice segregation in the Fort Belvoir clay, and produces a marked reduction in ice segregation in the New Hampshire silt.

Table 3 Effect of Calcium Acrylate on Frost Heave
Influence de l'acrylate de calcium sur le gonflement par le gel

Calcium Acrylate in %	*Heave in %*	
	New Hampshire Silt	*Fort Belvoir Clay*
0.0	235.3	188.4
5.0	43.8	0.0
7.5	12.8	1.2
10.0	7.3	2.7

C. *The Impermeabilization of Cohesionless Soils by in situ Polymerization*[2]

There are a number of materials (for example, clay, Portland cement, bitumen and sodium silicate) that are used to render pervious soils impervious by a process of injection. Each of these available materials has certain limitations. There is need for a low-viscosity liquid which can be injected to form, in a short period of time, a treated soil that is completely impermeable but can withstand deformation. Research at M.I.T. showed that a water solution of calcium acrylate and a redox catalyst system had considerable promise of meeting the requirements of a desirable injection material. Attempts to reduce the amount of chemical required to less than five per cent of the soil dry weight were not entirely successful.

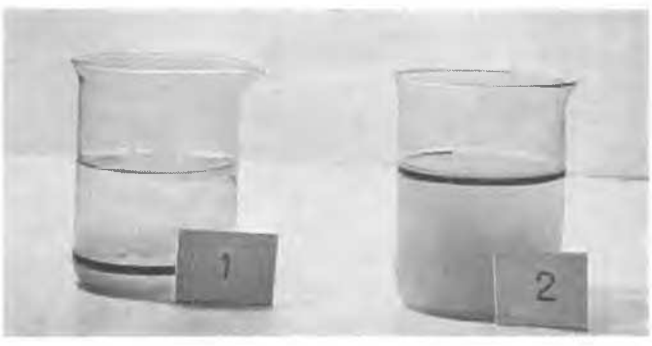

Fig. 4 Swelling Polymer
Gonflement du polymère

[1]) 60% oil and 40% water emulsion.
[2]) See *Jansen* and *Supplee*, 1952.

It was found that a 1 : 1 copolymer of calcium acrylate and N-methylolacrylamide would swell considerably in water. The extent of swell is illustrated in Fig. 4, where it can be seen that the copolymer (2 in Fig. 4) has a volume six times as great as an equal weight of calcium polyacrylate. The copolymer was successfully used to make soils ranging from a pea gravel to a silty sand completely impermeable.

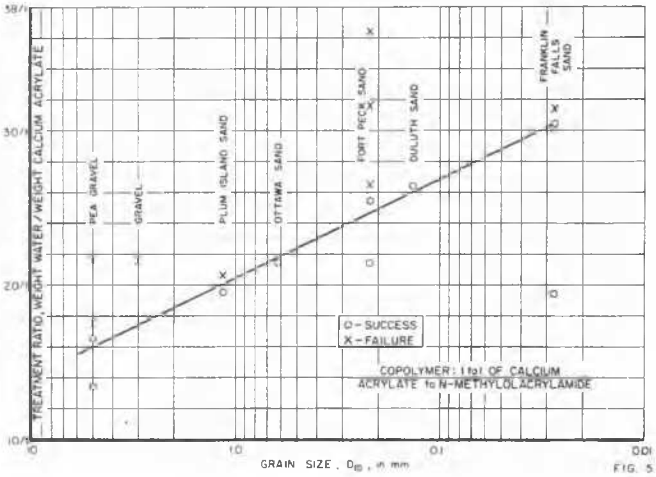

Fig. 5 Amount of Copolymer Required for Impermeabilization
Quantité de copolymère nécessaire pour l'imperméabilisation

Fig. 5 shows that there is an approximate relationship between the treatment ratio (expressed as the weight of water divided by the weight of calcium acrylate) and the grain size of which 10% of the soil weight is finer. Fig. 6 shows how the permeabilities of two soils are reduced as the treatment ratio is decreased, that is, as the amount of chemicals is increased. Fig. 6 shows that a treatment ratio of about 25 : 1 was required to make the Fort Peck sand completely impermeable. This 25 : 1 treatment amounts to about 2% chemicals based on the dry weight of the soil. In other words, for every cubic foot of the soil, about two pounds of chemical would be required. The soils treated with the copolymer were subjected to a hydraulic head in excess of one hundred feet of water without a detectable increase in permeability.

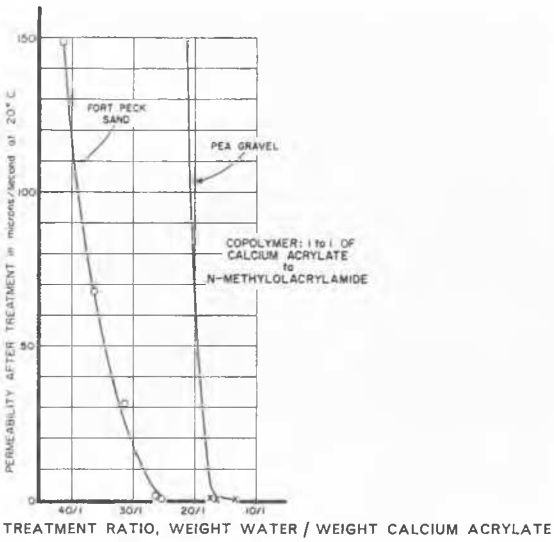

Fig. 6 Variation of Permeability with Copolymer
Variation de la perméabilité en fonction la quantité de copolymère

A comparison between an injection with calcium polyacrylate and the copolymer of calcium acrylate/N-methylolacrylamide is given in Table 4.

Table 4 Injection of Ottawa Sand
Injection de sable d'Ottawa

	Polyacrylate	*Copolymer*
Void Ratio	0.59	0.54
Permeability before treatment in microns per second at 20° C	787.0	542.0
Permeability after treatment in microns per second at 20° C	35.3	0.0
Unconfined compressive strength (lbs./sq.ft.)	135.0	588.0
Calcium acrylate (% dry weight of soil)	3.0	1.01
N-methylolacrylamide (% dry weight of soil)	0.0	1.01
Redox catalyst (mol % of acrylate)	1.0	50.0
Total chemical (% dry weight of soil)	3.08	2.96

This table shows that while a marked reduction in permeability was obtained with the calcium polyacrylate, complete impermeabilization was obtained with the copolymer.

Polymer Addition

A. Theory of Treatment

Of the several methods of stabilization by polymer addition, the use of polymers to alter the surface characteristics of soil particles is the most interesting. The mechanism of soil surface-polymer reactions is not completely understood, because neither the structure of soil[1]) nor the structure of the polymers employed is clearly known.

Inorganic fine grained soil (the soil in which the soil-polymer reactions are most effective) is made of:[2])
(1) aggregates composed of crystals;
(2) crystals composed of sheets or basic units
(3) sheets composed of atoms.
The particle, which is the effective, individual element of the soil can be a sheet, crystal or aggregate. The forces holding the atoms together in a sheet are very strong primary valence bonds; the forces holding the sheets together in a crystal can be strong, as in kaolinite, or weak, as in montmorillonite; the forces holding the crystals together in an aggregate are weak secondary valence linkages. Only the intra-aggregate forces, and intracrystal forces in the case of expanding clays, are weak enough to be broken by chemical additives or engineering applied stresses.

The intra-aggregate forces can be altered in magnitude and even in direction by means of chemicals. *Michaels* (1952) has described the mechanisms by which additives can cause attractive forces between particles, and thereby aggregate the soil, or cause repulsive forces between particles and thereby disperse the soil.

[1]) The author has proposed a theory of soil structure in an unpublished paper entitled "The Structure of Inorganic Soil".
[2]) Natural soils may also contain amorphous material.

Partially hydrolyzed polyacrylonitrile (sodium polyacrylate) is a linear polymer that is a highly effective soil aggregator. In the U.S. it has been marketed under several trade names and sold as a soil conditioner for agricultural purposes. The anionic (acrylate) groups can bond to soil particles through polyvalent cations, acting as bridges, while the individual macromolecules can bond to each other by the occasional highly polar nonionic (amide) groups. The particles can, therefore, be bonded together by a chain aggregate of macromolecules which spans a much greater distance than does a single polymer chain.

Altering the interparticle forces in a soil system can have pronounced effects on the engineering properties of the soil. While the magnitude of property change that can be effected by this type of reaction is considerably less than can be effected by the in situ polymerization of calcium acrylate, the results of the soil surface-polymer reactions are dramatic in view of the small amount of additive required; e.g., calcium acrylate equal to 1% to 10% of the soil dry weight is used, but aggregant concentrations of .01% to .1% are effective.

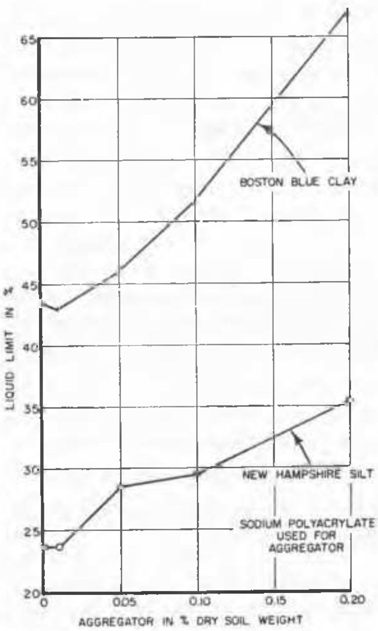

Fig. 7 Effect of Aggregator on Liquid Limit
Effet de l'agrégateur sur la limite de liquidité

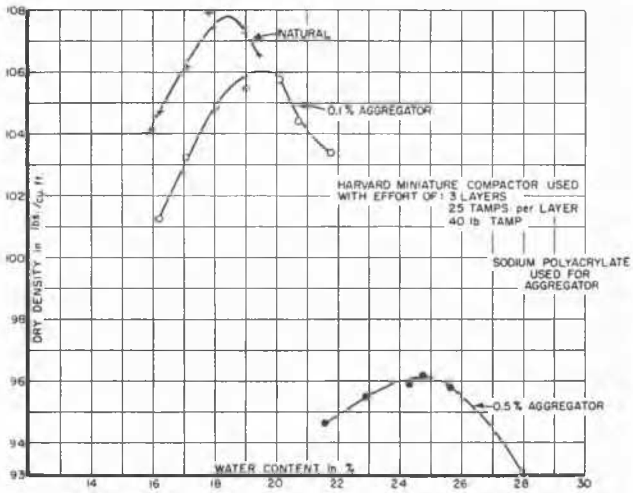

Fig. 8 Effect of Aggregator on Compaction
Effet de l'agrégateur sur la compacité

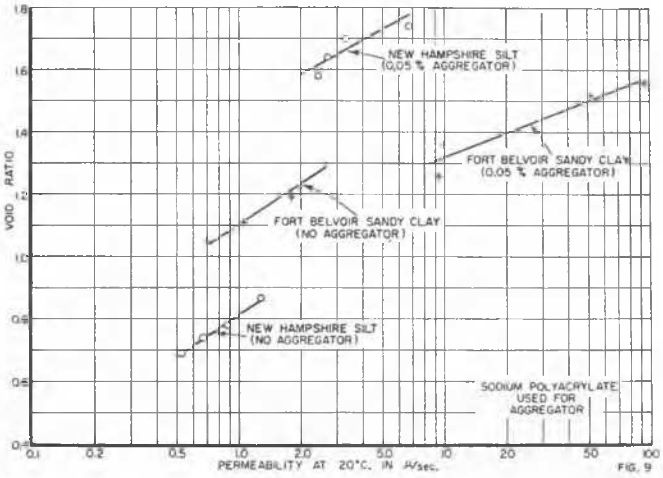

Fig. 9 Effect of Aggregator on Permeability
Effet de l'agrégateur sur la perméabilité

B. Alteration of Soil Properties

Atterberg Limits: Aggregation of a soil increases its void volume and thus increases its water holding capacity. It is logical that, therefore, aggregation increases the liquid limit of soil. Fig. 7 shows the effect of various quantities of partially hydrolyzed polyacrylonitrile on the liquid limits of two soils.

Compaction: Increasing the intra-aggregate forces increases the resistance of a soil to compaction. Fig. 8 shows the effect of various quantities of partially hydrolyzed polyacrylonitrile on the compacted densities of a sandy clay from Fort Belvoir, Virginia.

Permeability: Since soil compacts to a lower density when aggregated than when nonaggregated, it is to be expected that a soil would be more permeable when aggregated. The permeability data on two soils, presented in Fig. 9, bear out this expectation.

Frost Behaviour: Tests performed at the Frost Effects Laboratory, Corps of Engineers, Boston, Massachusetts (1952), showed that 0.05% of sodium polyacrylate reduced the frost heave of a silt from New Hampshire from 150 to 37%.

Conclusions

Even though space limitations in this paper have necessitated a summarizing treatment of the theory and effect of polymer-soil reactions, the promise of polymers as soil stabilizers has been pointed out. One can expect new and better polymer stabilizers to result from the coordinated research efforts of the soil and chemical specialists.

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