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Strengthening of Soil by Using Artificial Fibers - A Review

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Abstract—*The inflation in the value of land and the limited availability of sites for construction is greatly encouraging engineers to consider in situ soil improvement of loose and weak/expansive soil deposits. Hence, strengthening of soil is primary need of geotechnical engineers for construction of high rise buildings over it, which is especially required in the age of smart cities. Recent researchers have significantly improved the engineering behavior of expansive soil using different techniques such as an addition of salt solution, sand, fiber etc. Among all of these, fiber is one of the best materials to solve the soft and expansive soil problems. Therefore, soil reinforcement is required which is defined as a technique to improve the engineering characteristics of soil in order to develop the parameters such as shear strength, compressibility, density and hydraulic conductivity by using various natural and artificial fibers. However, natural fiber is a prehistoric idea which is improved now by using artificial fibers for soil reinforcement. The main aim of this paper is to analyse history, benefits, applications and possible executive problems of using different types of short and/or long fibers in the improvement of basic characteristics of the soil. In this study, it has been observed that relative strength improvement reaches around 290% (approximately 3 times of natural soil) along with achieving various milestones such as up to 90% improvement in crack reduction, 25% improvement in confining pressure and 21% reduction in confining pressure etc. by fiber inclusion. This paper tends to present a review of existing experimental and analytical work in this field and identifies other areas needing attention too.*

1. INTRODUCTION

1.1 Requirement of soil strengthening

The rapid growth of the town and cities of India causing excessive load on its infrastructure and also causing an inflation in its substitute, land, which have inherently limited supply. The building industry has been forced to look for cheaper land for construction.As a result construction is now carried out on sites which, due to poor ground conditions, would not previously have been considered suitable for development. The soil at a construction site or part thereof is not always totally suitable as a structural support. This greatly encourages engineers to considered *in situ* soil improvement of weak soil deposits. Improvement of desirable properties of soil like compaction, CBR, unconfined compression, shear strength and swelling characteristics can be undertaken by a variety of soil improvement techniques. There are many soil improvement techniques either chemical or mechanical. These may be classified as ground reinforcement, ground improvement and ground treatment (Maheshwari and Solanki, 2000). Some soils have excessive volume change during wetting and drying cycles (i.e. swell-shrink). It is found more in soils containing of montmorillonite which is commonly known as expansive soil, black cotton soil and bentonite clay. However, prewetting methods, replacing expansive soil by non-expansive soil, stabilizing with lime, cement etc., dewatering, and preloading currently used to stabilize the swelling soil (Puppala and Musenda 2000).Now a day, fibers are used to reinforce the expansive soil for its better strength and reducing the settlement. Basically, natural and synthetic fibers are the most common types of fiber used for this purpose. Most common types of natural fibers are coir, flax, barely straw, sisal, bamboo, cane and jute whereas; the synthetic fibers are polypropylene, polyester, polyethylene and glass fibers (Hejazi et al., 2011). Fiber-reinforced soil has some advantages such as low cost, light weight, capability of maintaining strength isotropy within soil mass. Its application in construction is also not significantly affected by weather conditions (Patel and Singh, 2016).

1.2 Various methods of strengthening of soil

In modern era, there are numerous techniques and methods to solve the problem of week soil. Strengthening of soil, an important abstract of geotechnical engineering, helps to improve its strength and consolidation behaviour. Classification of the soil reinforcement methods is entitled in figure-1 showing its various aspects of approach. The up–down arrows in this figure illustrate some unconventional methods of soil reinforcement achieved by the combination of randomly distributed fiber with chemical admixtures such as cement, lime and/or chemical resins. Some of the methods appeared in Fig. 1 may have the disadvantages of being ineffective and/or expensive. So, new methods are still being researched to increase the strength properties and to reduce the swell behaviors of problematic soils (Puppala and Musenda, 2000). It is emphasized that short fiber soil composites have recently attracted increasing attention in geotechnical engineering for the second time. This concept will be followed by this paper in the following. Consequently, studies on mechanical behavior of short fiber soil composite are comparatively new when compared to other research fields (Hejaji et al., 2000).

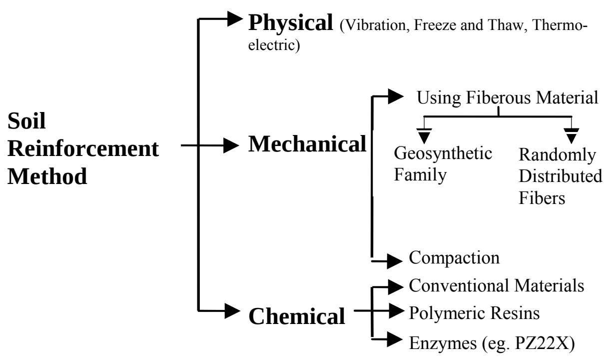


Figure 1: Different methods of Strengthening of Soil.

1.3 Other methods

Out of these methods, reinforcement by man-made randomly distributed fiber or artificial fiber is discussed and studied in this paper. Another categorization of methods which is basically used for expensive soils having excessive swelling and shrinkage behavior on wetting and drying respectively (i.e. Black-cotton soil, Bentonite) could be done as mentioned in table-1. Generally, expansive soil which has very low strength has excessive volume change (i.e. swell-shrink) during wetting and drying cycles. However, prewetting methods, replacing expansive soil by non-expansive soil, stabilizing with lime, cement etc., dewatering, and preloading currently used to stabilize the swelling soil.

Table 1: Succinct introduction of strengthening methods.

Sr. no.	Method of strengthening	Basic Procedure
1.	Prewetting	Cyclic wetting-drying and compaction.
2.	Replacement	Site soil is replaced with offsite soil.
3.	Stabilization	Mixing some fibers/chemicals in soil.
4.	Dewatering	Reduction in water by mechanical machines.
5.	Preloading	Soil is loaded with equivalent structural load for some duration.

In prewetting, the soil is subjected to moisture and compacted properly. This cycle is repeated many times resulting in advanced preconstruction settlement of soil causing reduction in possible future settlement value and damages as well. This is one of the most popular methods. But it requires depth of impact and time cycle and hence fiber methods are preferred.

Here in Table-2, Characteristics of commonly used fibers is discussed.

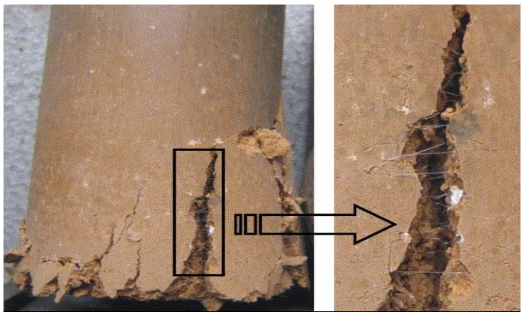
Table 2: Characteristics of commonly used fibers

Type of reinforced soil	Type of reinforcement	Stress-strain behaviour	Role and function of reinforcement
Reinforced earth	Ideally inextensible inclusions (metal strips, bars, etc). $E_r/E_s>3000$	Inclusions may have rupture strains which are less than the maximum tensile strain in the soil without inclusions,under the same operating stress conditions	Strengthen soil (increases apparent shear resistance) and inhibits both internal and external deformations. Catastrophic failure and collapse of soil can occur.
Ply soil	Ideally extensible inclusion (natural and synthetic fibers, roots fabrics and geotextiles) $E_r / E_s> 3000$	Inclusions may have rupture strains which are greater than the maximum tensile strain in the soil without inclusions. These inclusions cannot rupture.	Some strengthening. Greater extensibility. Smaller loss of post peak strength.

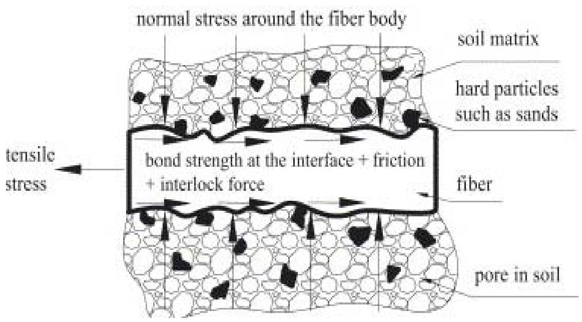
2. FIBER MECHANISM

2.1 Behaviour of fiber under reinforcement

The soil is found weak in shear and tension and hence needed to be reinforced with some material having good shear and tension properties. Fibers have sufficiently acceptable required soil characteristics and hence adequate to use as reinforcing material. The bond is formed between soil and fiber causes increment in cohesion leading to increased shear characteristics as well as reducing possible settlement in soil-fiber composite. Because of the interfacial force, the fibers in the matrix are difficult to slide and they can bear tensile stress, as the sketch drawing shown in Fig. 2(a). When the specimens are under load, the 'bridge' effect of fiber can efficiently impede the further development of tension cracks and the deformation of the soil Fig.2 (b). As a result, the fiber-reinforced soil demonstrated a somewhat ductile behavior resulting in better shear strength than previous cases of unreinforced soil continuum. The mechanical interlock effect of the fibers provides increased tensile strength and cohesion to the soil matrix.



(a)



(b)

Fig. 2: (a) The 'bridge' effect of fiber reinforcement in soil impedes development of tension cracks.
(b) Sketch of mechanical behavior at the interface between fiber surface and soil matrix(C. Tang et al).

Several researchers pointed out that the fiber sliding resistance was strongly dependent on the fiber surface roughness (Shah, 1991; Tagnit-Hamou et al., 2005; Frost and Han, 1999). As the fibers were mixed or samples were compacted, the hard particles (such as sands) of mixtures impacted and abraded the fiber surface, causing

2.2 Shear Mechanism

Several investigators have reported the results of triaxial and plane strain compression tests on cylindrical samples of dry sand containing thin, horizontal layers of tensile reinforcing material. The results of these triaxial tests on fabric-reinforced sand have been interpreted in two different, yet refined ways.

Equivalent confining stress concept - Yang (1972) hypothesized on the basis of his tests that tensile restraint in the reinforcement induced an "equivalent confining stress" increase. Accordingly, from the Mohr Coulomb formulation for the strength of a cohesionless material, if follows that

$$(\sigma_{1f})R = (\sigma_3 + \Delta\, \sigma_{1f})\, k_P \quad (1)$$

In which

(σ_{1f}) R= major principal stress at failure in reinforced sand;

σ_3= applied confining stress on the sample;

k_p = tan2 (45 + ϕ/2);

ϕ = friction angle of the unreinforced sand

Pseudo-cohesion concept - Schlosser and Long (1974) proposed that the reinforcements induced an anisotropic or pseudo cohesion that was a function of their spacing and tensile strength. Thus, the strength of the reinforced composite is given by

$$(\sigma_{1f})\, R = \sigma_3\, k_P + 2c_R\sqrt{k_P} \quad (2)$$

The anisotropic pseudo cohesion was computed from a force equilibrium analysis of a reinforced composite. The expressions can be derived by solving above two and reinforcement could be computed.

3. STUDY OF SOIL-FIBER COMPOSITES

3.1 Classification

Reinforcements used in geotechnical applications can be classified as ideally inextensible inclusions and extensible inclusions (Mc Gown et al. 1978). The comparative behaviour of reinforcement in the case of inextensible and extensible inclusions is shown in Table 4.1. The stress-strain behaviour of the reinforcement is quite different in these two cases. The inextensible inclusions may rupture at strains less than the maximum tensile strain in unreinforced soil and may result in catastrophic failure; whereas the extensible inclusions can take larger strains and never rupture. The extensible inclusions provide greater extensibility (ductility) and smaller loss of post-peak strength as compared to soil alone or soil reinforced with inextensible inclusions. Fiber reinforcement comes in the category of extensible inclusions (i.e., ply soil). The concept of fiber reinforcement is analogous to the reinforcement of soils with plant roots. The influence of root reinforcement on the shear strength and the stability of natural slopes have been reported by several investigators (Gray 1986). It was reported that plant roots particularly live roots significantly improve the shear strength of soils and the stability of natural slopes. The extent of increase in shear strength of root-reinforced soils was found to depend upon the concentration and properties of roots. The relative increase in strength, i.e., percentage gain in strength over 3X unreinforced soil was observed to be 98 % to 290 % with varying concentration of roots from 0.2 % to 1.0 % for different types of plant roots.

3.2 Literature Synthesis

Synthesized polymers are main resource of synthetic fibers which belongs from raw materials such as petroleum based chemicals or petrochemicals. Generally, this fiber is used to improvement of soil.

Setty and Murthy (1987)examined to study the effect of PP fiber on black cotton soil. Test result showed that cohesion intercept increased with fiber inclusion and slightly decreased with frictional angle.

Maher and Ho (1994)studied the behavior of kaolinite–fiber (PP and glass fibers) composites, and found that the increase in the UCS was more pronounced in the glass fiber-reinforced specimens.

Puppala and Musenda (2000) examined to investigate the influence of discrete and randomly oriented polypropylene fiber on expansive soil. Two types and four fiber dosage (0, 0.3, 0.6, and 0.9 percentage by dry weight of soil) had used to stabilize the expansive soil. Result showed that UCS was increased by addition of fiber and decreased both volumetric shrinkage strains and swell pressure of the expansive clays. The fiber treatment also enhanced the free swell potential of the soil. It was reported that shear strength was attributed to the tensile strength of fibers in the soil-fiber mix.

Santoni and Webster (2001) described laboratory and field tests conducted using a new fiber stabilization technique for sands. Laboratory unconfined compression tests using 51 mm long monofilament polypropylene fibers to stabilize a poorly graded (SP) sand showed an optimum fiber content of 1% (by dry weight). Field test sections were constructed and traffic tested using simulated C-130 aircraft traffic with a 13,608 kg tire load at 690 kPa tire pressure and a 4,536 kg military cargo truck loaded to a gross weight of 18,870 kg. Test results showed that sand-fiber stabilization over a sand subgrade supported over 1,000 passes of a C-130 tire load with less than 51 mm of rutting. The top 102 mm of the sand-fiber layer was lightly stabilized with tree resin to provide a wearing surface. Based on limited truck traffic tests, 203 mm thick sand-fiber layer, surfaced with a spray application of tree resin, would support substantial amounts of military truck traffic.

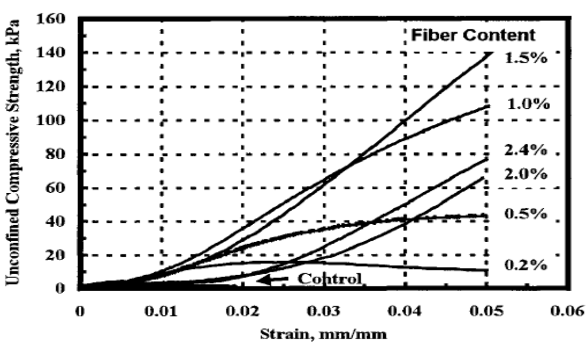


Fig. 3: Relationship between Percent of Fiber and Permanent Deformation (Santoni and Webster, 2001).

Millar and Rifai (2004) studded on the impact of fiber reinforcement on the development of desiccation crack in compacted clay samples, as well as the impact of the fiber additives on soil workability, compaction characteristics and hydraulic conductivity. Four dosage of Polypropylene fiber (0.2, 1.0, 1.5, and 2%) was used to this present investigation. It was reported that the optimum fiber content necessary to achieve maximum crack reduction and maximum dry density, while maintain acceptable hydraulic conductivity, is between 0.4 and 0.5%. For this range of fiber content, the crack reduction observed approximately 50%, as compared to the unamended soil sample. The maximum crack reduction was observed approximately 90%, for a content of 0.8%. Hydraulic conductivity was increased significantly for fiber content exceeding 1%.

Consali et al., (2004)Saturated drained triaxial compression tests with local strain measurement were carried out to evaluate the effects of using three different randomly distributed fibers (polyester, polypropylene and glass fibers) and rapid hardening Portland cement to improve the engineering behaviour of a uniform fine sand. In addition to the nature of the fibers also analysed have been the separate and combined effect of fiber content (up to 0.5% by weight), fiber length (up to36 mm), cement content (from 0% to 7% by weight) and initial mean effective stress (20, 60 and 100 kN/m2) on the deformation and strength characteristics of the soil. The present work searches for the establishment of a relation between the properties of the fibers and the mechanical behaviour of the composite material, originated from their combination with soil and cement. The cementation itself notably increased modulus, peak cohesive intercept, peak friction angle and brittleness of the sand. Inclusion of polyester and glass fibers (both relatively stiff) slightly reduced the stiffness and increased the peak friction angle of both the cemented and uncemented sand, and also slightly reduced the peak cohesive intercept and brittleness of the cemented composite. On the other hand, relatively flexible polypropylene fiber reinforcement dramatically reduced the brittleness (changing the mode of failure of the cemented sand from brittle to ductile for longer fibers) and stiffness, while increasing the ultimate strength of the cemented composite.

Casagranda et al. (2006) evaluated at large shear displacements by a series of ring shear test to study the effect of polypropylene fiber on bentonite clay. Normal stress was being varied between 20 and 400 kPa. Bentonite /polypropylene fiber composite were mixed with fiber length of 12 or 24 mm. Thickness of the fiber was 0.023mm and fiber content was either 1.5 or 3% by dry weight. Bentonite/fiber composites show peak strengths that are significantly higher than the nonreinforced specimen's at all confining pressure but the effect, was not as large as, has been observed in some other soil (using the same type of fiber, amount of fiber, and fiber thickness). Perhaps, the most important observations were that lower shearing resistance between the fiber surface and the surrounding soil. However, It has also observed that post peak strain softening was greater than nonreinforced specimens at all confining pressure. 25% improvement was observed for bentonite by inclusion of fiber at the same normal stress.

Abdi et al. (2008**)** examined the impact of random fiber (1, 2, 4, & 8% fiber as dry weight of soil with 5, 10 and 15 mm length) inclusion on consolidation settlement, swelling, hydraulic conductivity, shrinkage limit and the development of desiccation crack in compacted clays. It was observed that consolidation settlement and swelling of fiber reinforced samples reduced significantly whereas hydraulic conductivity increased slightly by increasing fiber content and length. Furthermore, shrinkage limit also increased with increasing fiber content and length. Indeed, consolidation settlement was more when fiber length increased from 5 to 10 mm. Hydraulic conductivity increased for fiber contents exceeding 1%. It can be happened that if fiber were longer, they would have provided longer paths for water to drain quicker, thus increasing the hydraulic conductivity of the samples. Random fiber inclusion improved the soil tensile strength very effectively and it gives greater contact surface area. As a result, fiber resists shrinkage on desiccation.

Akhras et al. (2008) investigated to study the effect of fiber (natural and synthetic) on the swelling properties of clayey soils. Nylon and Palmyra fibers (1, 2, 3, 4 and 5% with different aspect ratio 25, 50, 75, and 100) used to evaluate the swelling pressure and swelling potential of three types of expansive soil for each combination. Minimum swelling potentialwas noticed for all soil when clayey soil was mixed with 5% fibers (Nylon and Palmyra).It was reported that swelling pressure decreased from 21% for the control clayey soil to an average of 5.25% and 4.62% for clayey soil mixed with nylon and Palmyra fibers respectively. Maximum swelling pressure was observed to be 410, 310, and 190 kPa for clay soil-1, soil-2 and soil-3. However, the minimum swelling pressures were noticed to be 120 and 82.5 kPa, 120 and 97.5 kPa, and 78 and 74 kPa, for soil-1, soil-2 and soil-3 containing nylon and Palmyra fibers, respectively. It was reported that decreasing reduction in the swelling pressure with increasing aspect ratio of the fibers was believed to be result of a greater amount of fibers available when fibers with low aspect ratio are used. Therefore the probability of fibers to cross potential failure plain was much higher for mixture with low aspect ratio fiber content. It was observed that the impact of the inclusion of fibers in clayey soils increased with increasing clay fraction of the clayey soil.

Moayed and Izadi (2011) described treatment of saline soil in Iran with lime resin-epoxy polymer and polypropylene fiber. Fiber dosage (0.1%, 0.2%, 0.3% and 0.4% by dry weight) had been used to reinforce the saline soil. It was reported that maximum dry density decreased and optimum moisture content increased (Cai et al., 2006) with inclusion of fiber. It was observed that 0.2% fiber dosage was the most optimum rather than other dosage. Compression index of soil with adding 0.1, 0.2, 0.3 and 0.4% of polypropylene fiber has been increased 1.23, 1.06, 1.19, and 1.24 time with respect to non-stabilize state respectively.

Sabat (2012) investigated to study the effect of randomly distributed polypropylene fibers, rice husk and lime on expansive soil. UCS increased from 60 kPa to 72 kPa at 10% addition of rice husk ash. Strength increased due to contribution of frictional resistance from RH (rice husk) along with cohesion from expansive soil and strength decreased because of the reduction of cohesion component. Maximum value of UCS was observed to be 174 kPa when %RH and %lime were 10% and 4%. MDD of rice husk ash-lime stabilized expansive soil goes on decreasing. It was found to be observed as13.3 kN/m³ for 2% fiber inclusion.

Mukharji and Mishra (2016) studied on the absence of impermeable natural soils, compacted sand–bentonite mixture along with a layer of geosynthetic clay liner (GCL). It was found that due to desiccation, the bentonite present in the liner shrinks resulting in an increase in the hydraulic conductivity of the liner. To prevent the desiccation cracking of bentonite, glass fiber was added to the mixture as a reinforcing material. However, the addition of the fiber can influence the geotechnical properties of liner material. To study the effect of the fiber on the geotechnical properties of the sand–bentonite mixtures with one layer of GCL, glass fiber of 10 mm length was added in the proportion of 0.5% and 1.0% to different sand–bentonite mixtures. Result shows that the swelling pressure and swelling potential of the soil–bentonite mixture with a layer of GCL decreased significantly with the increase in the glass fiber content in the mixture. The hydraulic conductivity of the mixtures was decreased with the inclusion of the GCL to mixtures; however, it increased considerably when glass fiber was added to the mixture.

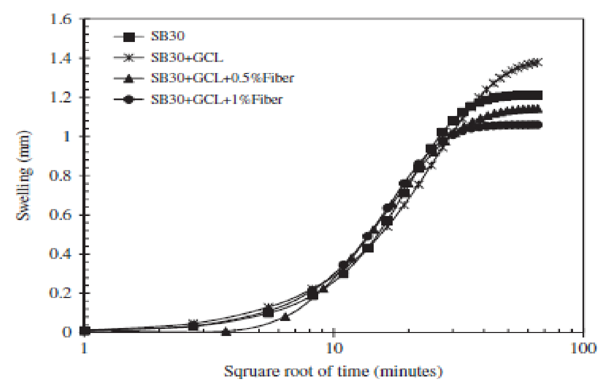


Fig. 4: Swelling-time plot for mixture (Mukharji and Mishra, 2016)

Patel and Singh (2016) did an experimental study to investigate the application suitability of randomly distributed glass fiber-reinforced cohesive soil as subgrade material. Glass fiber of 20 mm length with varying fiber contents (fc = 0.25, 0.5, 0.75 and 1% by dry weight of soil) was used as reinforcement. The effects of fiber content variation on compaction parameters of soil, and the effect of fiber content and soaking time variation on CBR strength were investigated. The soaking time was varied from 4 to 40 days. The CBR and secant modulus were calculated at different penetration depths ranging from 2.54 to 12.7 mm. Test results have shown that the glass fiber content has insignificant effect on the OMC and MDD of the soil. The CBR strength is found to increase with penetration depth up to 7.62 mm penetration and thereafter remains almost constant at all fiber contents. The CBR strength and secant modulus of soil have improved significantly with fiber content up to an optimum fiber content value of 0.75%, and decrease with increase in soaking time at any fiber content. The maximum improvement in CBR strength is found out as 2.48, 2 and 1.5 times for 4, 20 and 40 days soaking for 0.75% fiber inclusion. It has been found that the glass fiber-reinforced soil can be extensively used as subgrade material.

4. CONCLUSION

The screened literature has generally explained that material property is found to be improved by inclusion of fiber. Swelling and shrinkage has to be controlled in fiber soil matrix by inclusion of fiber. Cohesion value increased but internal friction angle increased up certain limit after that value is approximately constant. Ductile nature of material is more prominent by inclusion of fiber.In this study, it has been observed that various milestones were achieved such as upto 90% improvement in crack reduction, 25% improvement in confining pressure and 21% reduction in confining pressure etc. by fiber inclusion. Along with this, relative strength improvement is also observed around 290%.

However, in fiber-reinforced cemented soil, the interactions between the fiber surface and the hydrated products make main contribution to the strength at the interface. The micromechanical behavior of the fiber/matrix interface depends on binding material properties in the soil, normal stress around the fiber body, effective contact area and fiber surface roughness.

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