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Strength of a clay soil and soil–cement mixture with resin

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A series of laboratory experiments were carried out to investigate the effect of resin on the strength of a clay soil and soil–cement mixtures. One group of tests were carried out on samples of the clay soil that were prepared with different resin contents. Another group of tests were conducted on mixtures of soil–cement and soil–cement–resin with specified resin contents. The results show that adding more than 10% resin increases the strength of the soil, whereas at resin contents below 10% no significant effect was observed. The strengths of the samples of soil, soil–cement mixture and soil–cement–resin mixture increased with increasing percentages of cement and resin. The results also show that the increase in strength is a function of percentage of agents and curing time.

1. Introduction

Problematic soils can generally be characterised as poor-quality materials. They usually have the potential to show undesirable engineering behaviour, such as high swell potential and shrinkage, high moisture susceptibility and low bearing capacity. Geotechnical engineers often have the choice of replacing the problematic soils with better-quality soils for construction or attempting to improve the engineering properties of the soils through a suitable soil stabilisation technique. Due to problems with the availability of good-quality materials, haul distance and economic considerations, stabilisation of the existing soils is often the preferred option for construction.

Stabilisation is commonly used to improve the mechanical properties (e.g. strength and stiffness) of soils. The improvement is effected by controlling the void ratio of soil by introducing a cementing agent or by injecting a substance to fill the pore volume. Chemical stabilisers are divided into two groups: traditional agents and non-traditional agents. Traditional chemical stabilisers such as lime, cement, fly ash or bituminous material have such effects as developing a cementitious bond between the particles or increasing the water resistance of the soil. Recently researchers have found that concentrated liquid agents such as petroleum-based emulsions and polymers can be used as materials for stabilisation. These are classed as non-traditional chemical stabilisers.

Soil stabilisation using traditional agents such as lime and cement is a topic that has been extensively researched and the number of publications dealing with lime and cement stabilisation is vast. Ingles and Metcalf (1972) explained the processes involved in treating soil with lime and indicated that adding lime to clay increases the strength and decreases the plasticity index of clay and that there is no significant decrease in the swell potential of active clays and the linear shrinkage values.

The cement agent developed as a result of mixing a small quality of cement with soil is identical to the cementation product developed by addition of lime. Cement stabilisation increases the compressive, tensile and flexural strength, durability and stiffness properties of soil (Al-Rawas *et al.*, 2005; Bahar *et al.*, 2004; Broms and Boman, 1978; Croft, 1967; Khair *et al.*, 1991; Miller and Azad, 2000; Mitchell, 1976; Sezer *et al.*, 2006; Tang *et al.*, 2007).

A number of researchers such as Ajayi-Mejebi *et al.* (1991), Bolander (1999) and Tingle and Santoni (2003) used non-traditional agents as an alternative method for soil stabilisation. Scholen (1992) categorised non-traditional stabilisers into five groups and attempted to describe the reinforcement mechanisms for some of them. Ajayi-Mejebi *et al.* (1991) examined the mechanism of stabilisation of clay-silt soils with combination of an epoxy resin and a polyamide hardener. They found that the value of California bearing ratio (CBR) for a mixture of clay and silt increased when treated with 4% epoxy resin agent. Katz *et al.* (2001) and Rauch *et al.* (2002) investigated the effect of three non-traditional agents on treatment of a clay soil. Rauch *et al.* (2002) indicated that there was no significant improving effect of agents (enzymes) on the Atterberg limits, compacted density, shear strength or swell potential, while Katz *et al.* (2001) reported only minor changes in the mechanical behaviour of the soil.

Some researchers such as Afridi *et al.* (1994) and Gao *et al.* (2002) focused on certain aspects of mechanical behaviour such as strength and durability of resin-modified cement mortars and resin-modified concrete. In addition, a number of studies have been carried out on the effects of resin on soil–cement mixtures. Anagnostopoulos and Hadjispyrou (2004), Anagnostopoulos (2007) and Estabragh *et al.* (2011) suggested that acrylic resin can increase the strength of soil–cement mixture.

Acrylic resins have many advantages in comparison with other non-traditional chemical agents such as lignin (natural resin), phosphorus pentoxide and phosphoric acid. Acrylic resins are usually prepared in emulsion form with 40–60% solids; they are non-toxic and non-flammable. After curing they are not water soluble. Lignin has been used as an additive to soils for many years. It is available in powder form and in the form of sulfite liquid. It is used in both forms as an additive to soils. Lignin is water-soluble, hence its stabilising effects are not permanent. Phosphorus pentoxide is another agent that works extremely quickly – too quickly to allow for adequate mixing and compaction. One of the problems of this agent is its extremely toxic nature and the neutralising effect of trace amounts of calcium carbonate. Phosphoric acid is an effective agent for stabilising soil but it is extremely hazardous. Sodium hydroxide has been considered as an additive to cement as a stabiliser but it is caustic, being a strong alkali, and extremely corrosive to many materials and human tissues. As a result of these considerations, acrylic resins are preferable to other agents for soil stabilisation.

Review of the literature shows that a large amount of research has been carried out on the application of traditional stabilising agents. However, in spite of rapid development of existing non-traditional agents and introduction of new stabilisers, little research has been directed towards the use of non-traditional agents.

The aim of this work was to design and carry out a programme of experiments to study the effects of a non-traditional (resin) and traditional (cement) agents on the mechanical behaviour of a clay soil and also on the properties of soil–cement mixtures.

2. Materials used and testing programme

2.1 Properties of materials

The main materials that were used in this work were soil, cement, resin and water. The soil used in this experimental work was clay, consisting of 8% sand, 55% silt and 37% clay. The grain size distribution of the soil is shown in Figure 1. The physical and chemical properties of the soil are presented in Tables 1 and 2. The standard compaction test showed that the optimum water content of the soil was 17·5%, corresponding to a maximum dry unit weight of 17·2 kN/m^3. The soil is classified as clay with low plasticity (i.e. CL according to the Unified Soil Classification System (USCS)).

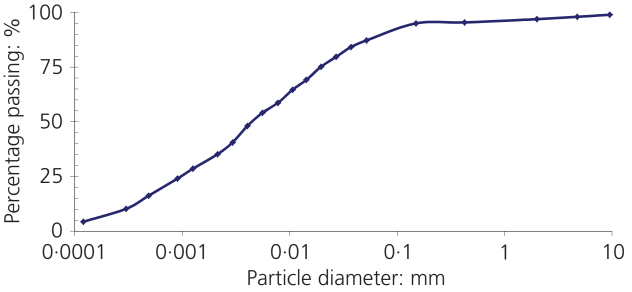

Figure 1. Grain size distribution curve

Property	Value
Liquid limit: %	46·0
Plastic limit: %	23·0
Plasticity index PI: %	23·0
Specific gravity, G_s	2·7
Optimum water content: %	17·5
Maximum dry unit weight: kN/m^3	17·2
Compression index, C_c	0·7
Swelling index, C_s	0·08

Table 1. Physical properties of the soil

Chemical component	Amount
SO_4^{2-}: meq/L	83·00
HCO_3^-: meq/L	4·00
CO_3^{2-}: meq/L	0·60
Mg^{2+}: meq/L	10·00
Ca^{2+}: meq/L	24·00
K^+: meq/L	0·33
$CaCO_3$: %	10·2
OC[a]: %	0·10
pH	8·00
Electrical conductivity: μmoh/cm	10·74

[a] Organic content

Table 2. Chemical composition of the soil

The cement used was Portland type 1 with specific gravity of 3·15 g/cm^3 and Blaine fineness of 4200 cm^2/g. The physical and mechanical properties of the cement are shown in Table 3.

The commercial name of the resin that was used is Tarabeton. The resin is a non-cross-linking acrylic emulsion of a thermoplastic chemical substance with good binding properties. Typical properties of the resin used are presented in Table 4.

Drinking water was used for compaction, preparation of samples and hydration of cement. It had a pH of 7·76, chloride content of 17 meq/l and calcium + magnesium content of 9·1 meq/L.

2.2 Sample preparation and testing

Standard compaction tests were conducted on the natural soil and mixtures of soil–cement and resin–soil. The samples for the main tests were prepared by static compaction according to the optimum water content and maximum dry unit weight that were obtained from the standard compaction tests. To prepare soil–cement samples, natural soil, cement and water were weighted with an accuracy of 0·1 g. They were mixed in a container and water was added up to the optimum water content. The mixture was kept in a sealed container for about 30 min for uniform distribution of moisture. The samples were prepared in a cylindrical mould by static compaction in three layers. Each layer was compacted at rate of 1 mm/min until maximum dry density (according to the compaction test) was achieved. The length and diameter of the samples were 100 mm and 50 mm, respectively. They were stored in a special cabinet at 25°C temperature and 95% relative humidity. For preparation of soil–resin and soil–cement–resin samples the specified amount of resin was dissolved in water and added to the soil or soil–cement mixture to the optimum water content. The same procedure as used for preparing soil–cement samples was used for preparing soil–resin and soil–cement–resin samples.

Physical property	Amount
Normal consistency: %	24·4
Initial setting time: min	21·0
Final setting time: min	145·0
Compressive strength, 7 days: kPa	30 000·0
Compressive strength, 28 days: kPa	43 000·0

Table 3. Properties of cement

Property	Value
Solid content:%	50·00
pH	7·50 ± 0·5
Density: g/cm^3	1·04
Mean particle size: µm	0·10
Surface tension: mN/m	42·00
Tensile strength: N/mm^2	4·00
Mechanical stability	Excellent
Appearance	Milky white liquid
Type	Non-cross-linking
Emulsifying system	Non-ionic

Table 4. Typical properties of Tarabeton resin

2.3 Compressive strength

The unconfined compressive strength test is the most commonly used test for determination of mechanical properties of soil–cement. The value of unconfined compressive strength is an indicator of the degree of reaction of the mixture (soil–cement, soil–resin and soil–cement–resin) and the rate of hardening. This kind of test provides a convenient basis for testing and is a quick and simple procedure for comparative analysis. Compressive strength serves as a criterion for determining minimum cement requirements for proportioning soil and cement. Because strength is directly related to density, this property is affected in the same manner as density by degree of compaction and water content. Unconfined compression tests were conducted on the samples of soil–resin, soil–cement and soil–cement–resin after curing times of 3, 7 and 28 days according to the ASTM D1633 standard (ASTM, 1983).

3. Results and discussion

The results of standard compaction tests for soil with 5%, 8% and 10% resin show that the optimum water content and maximum dry density are nearly the same as those of the natural soil. The maximum dry density for a soil–cement mixture increased and the optimum water content decreased with increasing cement content. These variations can be attributed to the change in the clay's behaviour due to hydration resulting from the reaction of cement with soil moisture and exchange of ions. These results are consistent with those reported by Croft (1967).

Figures 2 and 3 present typical results of mixtures of soil and resin after curing times of 3, 7 and 28 days for resin contents of 8% and 10%, respectively. Figure 2 shows that the peak strength of the natural soil is about 280 kPa at 3·2% axial strain, but the

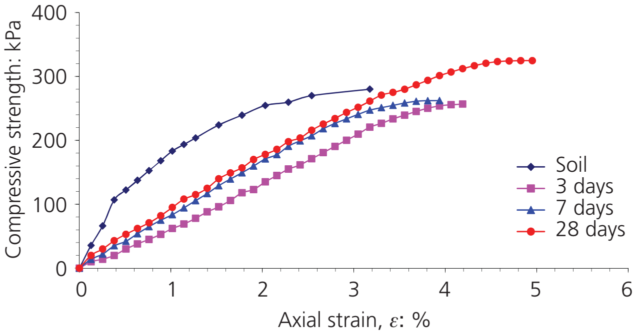

Figure 2. Stress–strain curves for a mixture of soil with 8% resin for different curing times

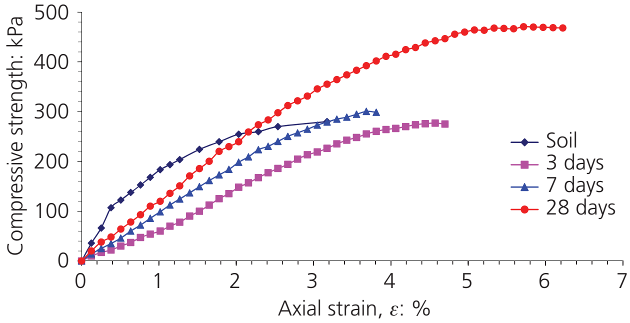

Figure 3. Stress–strain curves for a mixture of soil with 10% resin for different curing times

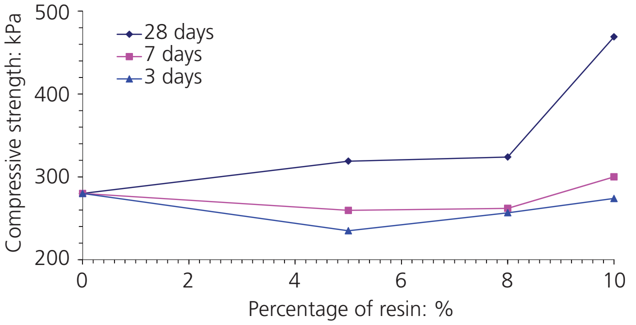

Figure 5. Variations of compressive strength with different percentages of resin for soil-resin mixture with various curing times

samples of soil and 8% resin after 3 and 7 days have strengths of 256 and 262 kPa at strains of 4·2% and 4%, respectively. It is seen that the strength of soil–resin mixture is decreased slightly in comparison with the strength of the natural soil (280 kPa). The peak strength for curing time of 28 days is about 324 kPa, which shows an increase of about 16% compared with the natural soil. The peak strength values of soil–cement with 10% resin after curing times of 3, 7 and 28 days are 274, 300 and 467 kPa at strains of 5%, 3·7% and 3·4%, respectively. It is seen that for curing times of 3 and 7 days the variation of strength is insignificant in comparison with the natural soil, but after 28 days curing time the strength increases by about 67%. It can be concluded from Figures 2 and 3 that the ductility of soil–resin samples is increased by the addition of resin. Figure 4 shows the effect of 5%, 8% and 10% resin on the behaviour of the soil after curing time of 28 days. The strength of the mixture increases with increasing resin content. The variations of compressive strength with different percentage of resin content for soil-resin mixture with different curing times (3, 7 and 28 days) are shown in Figure 5. The increase in strength is more obvious after 28 days. It can be concluded that the percentage of resin and curing time play important roles in increasing the strength of the soil–resin mixtures.

Typical stress–strain curves for mixtures of soil–cement and soil–cement–resin with 8% and 12% cement and 0%, 5%, 8% and 10% resin are shown in Figures 6 and 7 after curing times of 7 and 28 days, respectively. Figure 6 shows that the peak strengths of soil–cement and soil–cement with 5% resin after 7 days of curing are nearly the same (1950–2000 kPa). The strength of mixtures of soil–cement with 8% and 10% resin is increased to 2250 and 2650 kPa (Figure 6), respectively. Therefore, for a given curing time, the strength is increased with increase in the resin content. Figure 7 shows similar results for the mixtures of soil–cement and soil–cement–resin after 28 days of curing time. It is clear that the stress–strain curves are changed by increasing the resin content. Figure 7 shows that the strength of the soil–cement mixture is about 3160 kPa, but for the mixtures of soil–cement with 8% and 10% resin the strength is increased to 4090 and 4560 kPa, respectively. This shows the role of resin in increasing the strength of the mixture. These results are consistent with the findings reported by Anagnostopoulos *et al.* (2003) and Estabragh *et al.* (2011). It is observed from this figure that the initial slope of the stress–strain curves is increased by increasing the resin content. The variations of compressive strength of mixtures of soil–cement–resin with different resin contents, after curing times of 3, 7 and 28 days,

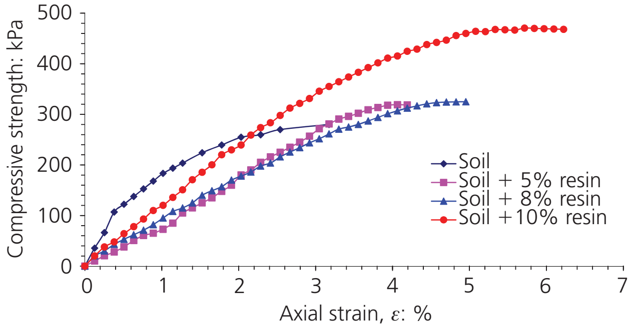

Figure 4. Stress–strain curves for soil and mixtures of soil with different percentages of resin after 28 days' curing time

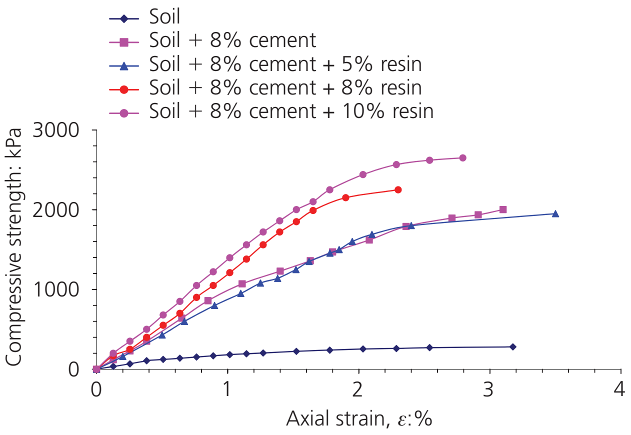

Figure 6. Stress–strain curves for soil and mixtures of soil–cement with different percentages of resin after 7 days' curing time

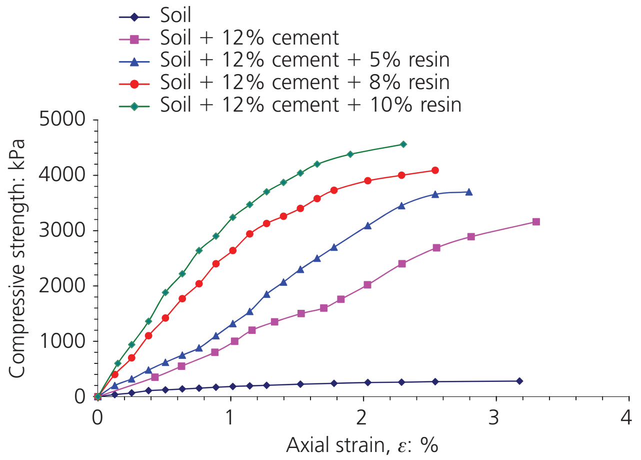

Figure 7. Stress–strain curves for soil and mixtures of soil–cement with different percentages of resin after 28 days' curing time

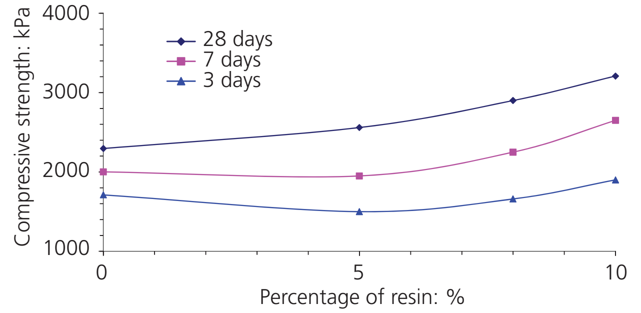

Figure 8. Variations of compressive strength with different percentages of resin for soil with 8% cement during various curing times

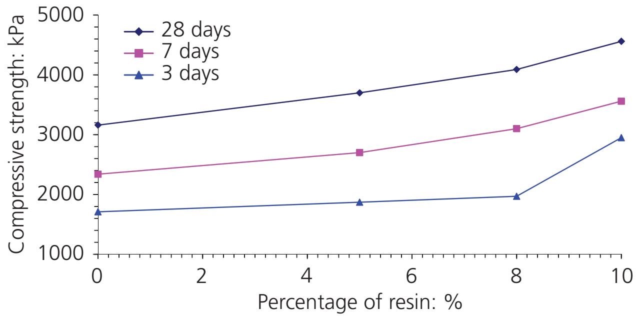

Figure 9. Variations of compressive strength with different percentages of resin for soil with 12% cement during various curing times

are shown in Figures 8 and 9 for 8% and 12% cement, respectively. These figures indicate that besides the cement content, the percentage of resin and curing time are important factors in achieving the strength of the mixture. Figure 10 shows the

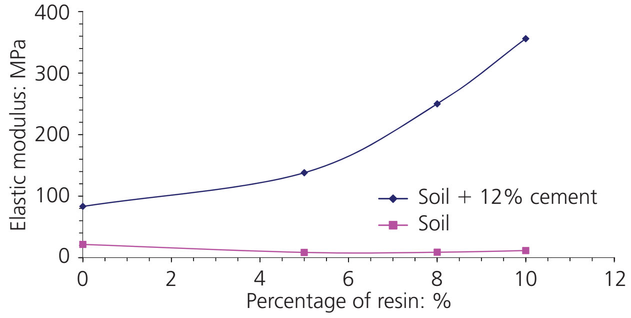

Figure 10. Variations of elastic modulus with different percentages of resin for soil and soil with 12% cement

variation of elastic modulus with different percentages of resin for the soil and mixture of soil with 12% cement. The elastic modulus was calculated on the basis of the 50% strength from the stress–strain curves. This figure shows that the value of elastic modulus for soil–cement increases with increasing percentage of resin; however, for the soil with resin, the variation of elastic modulus with resin content is insignificant.

The surfaces of clay particles carry negative charges, mainly as a result of isomorphous substitution or due to dissociation of hydroxyl. The negative charges result in cations present in the water in the void space being attracted to the particles. The cations are not held strongly and if the nature of the water changes they can be replaced by other cations, a phenomenon referred to as cation exchange. When they are mixed with resin, organic molecules undergo polymerisation reactions around the clay particles that bind the soil particles together. The process of attachment of clay particles to the polymer is caused by ion exchange reaction (Scholen, 1995). The results of tests on soil-cement show that adding cement to soil produces a relatively high strength mixture. The strength of soil is increased by increasing the percentage of cement and the curing time. This can be attributed to the cementation between soil particles. During compaction of the soil–cement mixture, chemical bonds develop between adjacent cement grain surfaces and between cement and soil particle interfaces. In clay soils, the hydration of cement creates strong linkages between minerals and the aggregates to form a new fabric so that the particles cannot slide over one another (Estabragh *et al.*, 2011). These linkages between soil and cement develop and complete in time. The final reaction between soil and cement causes the strength to increase and plasticity and water-holding capacity of clay soil to decrease (Al-Rawas *et al.*, 2005).

The resins that were used in this study are from the acrylic family. The most numerous class of monomers are the acrylics, such as esters of acrylic acid and methacrylic acid. These acids are both crystalline solids at low ambient temperature, becoming liquid at slightly higher temperatures. They polymerise and copolymerise extremely rapidly and hence are frequently employed in copolymers to obtain alkali-soluble polymers. While both acids are water soluble, methacrylic acids, as might be expected because of its angular methyl group, is more soluble in ester monomers (Warson and Finch, 2001).

When water is added to the mixture of soil–cement and resin, the reaction of soil and cement occurs as described above. However, resin usually has a large amount of COO^-, so it can react with Ca^{2+} because of hydrolysis in alkaline solution and produce $RCOO^-$. The final reaction is as shown in Equation 1.

$$1.\quad 2RCOO^- + Ca^{2+} \rightarrow [RCOO]^-\ Ca^{2+}\ [OOCR]^-$$

The $[RCOO]^-\ Ca^{2+}\ [OOCR]^-$ is formed on the surface of CSH (calcium silicate hydrate) gel or $Ca(OH)_2$ crystals. The interwoven network structure consists of ion-bonded large molecular systems which bridge by means of Ca^{2+} (Gao *et al.*, 2002).

It is concluded from these experimental results that non-traditional chemical agents (resin) can increase the strength of soil and soil–cement mixtures. The resin reacts with soil and hydration products of cement and increases the strength through binding the particles and forming a rigid structure in the mixture. These agents can be used for treatment of cohesive soils for construction works such as subgrade and to provide material for erosion resistance where the existing soil is cohesive and limitations such as haulage distance of other soils and economic and environmental restrictions make the use of existing soil the preferred option. Durability tests should be carried out to study the long-term effects of resins and the environmental effects should be evaluated by considering the possible pollution caused by these agents under actual field conditions.

4. Conclusion

The aim of this research was to study the effects of resin in improving the mechanical behaviour of clay soil and soil–cement mixtures consisting of a clay soil with cement. The following conclusions can be drawn from the results of this work.

- Both resin and cement, as non-traditional and traditional chemical agents, improve the strength of a clay soil. The effect of cement is greater than that of resin, but besides increasing the strength the resin also improves the ductility of the soil. The amount of improvement is a function of the proportions of the agents and the curing time.
- Addition of resin to a soil–cement mixture improves the properties of the mixture. For a given cement content this improvement is a function of percentage of resin and curing time. The initial slope of the stress–strain curves (stiffness) is increased by increasing the percentage of resin.

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