Mechanical properties and microstructure of soils treated with a vinyl-based copolymer

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Abstract. In soil stabilisation, the use of alternative products to lime or cement has been proposed. However, the effects of these additives, of various origins, on soil behaviour and stabilizing mechanisms are not well understood. Thus, the aim of this paper is to characterize the modification of the mechanical behaviour and microstructure of two soils after treatment with one of those product, a vinyl based copolymer. After treatment, both materials were compacted up to their maximum dry density. The mechanical behaviour of the materials as a function of the curing conditions, suction and water content was first determined. In a second step, the alteration of the microstructure by the treatment product was assessed. The results showed that the treatment permitted to significantly improve the strength of the tested soils. Moreover, the efficiency of the product increases when the soil is dried. However, the Young modulus is not significantly modified by the treatment. Microstructural reorganization after co-polymer addition has been detected by SEM technique for kaolin samples, whereas no modification have been observed for silt samples.

1. Introduction

In earthworks, sustainable development will play a larger role in future project design and the assessment of technical solutions by contractors. Currently, the reduction of the environmental impact of earthworks is a growing issue. One of the major challenges facing earthworks companies is the need to use a majority of natural materials extracted within the construction site, including materials with very low geotechnical characteristics. The common industry solution is to use lime, cement or fly ash to improve the soil geotechnical properties; however, sustainable development principles also require a reduction in the consumption of water and non-renewable energies as a way to limit greenhouse gas emissions. In this context, soil treatment with various non-traditional additives has been tested.

Seven non-traditional stabilizers categories can be defined, based on the major active component [1]–[3]. Those are salts, acids, enzymes, lignosulfonates, petroleum emulsions, polymers and tree resins. Acids are low pH aqueous solutions containing sulfonated molecules such as naphthalene or limonene [4]. The presence of proteins in enzymatic solutions was confirmed by some authors [5]. Lignosulfonates are organic polymers derived from lignin extracted by the sulfite processing of cellulose in the wood-pulp and paper industries. Petroleum emulsions contain asphalt or synthetic iso-alkane fluids suspended in emulsions by a surfactant, polymer emulsions contain vinyl acetates or

acrylic copolymers and tree resins are diverse emulsified by-products of the timber and paper industries [6]. Nevertheless, many of these products also include secondary additives such as surfactants or ultraviolet inhibitors, which may react with the soil minerals or modify the soil water properties and thus influence the mechanical behaviour of the treated soils.

In this context, the study was focused on the hydro-mechanical properties and microstructure of a kaolin and of a silty soil treated with vinyl-based copolymer since only very few studies on the use of such material are available in the literature [7]–[9]. The impact of the treatment on the strength of the two soils is first presented. Then, the action of the treatment on the microstructure of the soil was conducted by performing SEM tests to identify the mechanisms involved by the treatment products, and as a function of the curing conditions.

2. Materials and Methods

2.1 Tested soils and treatment product

A commercial type of kaolin and a natural silty soil were used. Firstly, index properties and optimum water content were determined (Table 1). The main purpose was to highlight the impact of the clay fraction on the effects of the treatment product.

A vinyl based co-polymer was employed in the framework of this study. The amount of co-polymer was

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comprised between 0 and 10%, on a dry weight basis. It was supplied as a dry powder.

2.2 Samples preparation

The compaction characteristics of the two soils were determined under Standard Proctor effort. The optimum water content of the pure kaolin of was 30.0% and the maximum dry density was 1.30 Mg.m^{-3} . The optimum water content of the silty soil of was 16.0% and the maximum dry density was 1.81 Mg.m^{-3} .

The amount of co-polymer was determined according to the dry weight of the soil used in the mixture. Water and copolymer were mixed for 2 minutes by using a mechanical stirrer to prepare the liquid mixture. Then, liquid mixture was poured into the mechanical mixer containing the soil, and mixed for several minutes until a homogenous mixture was obtained.

The mixture was placed in a mould with 50 mm diameter and 100 mm height. The samples were then statically compacted. All the samples were compacted at the optimum water content and the maximum dry density of the untreated soil. Indeed, both parameters are known to impact significantly the hydromechanical properties of treated soils.

Table 1. Index properties of both tested soils.

Value (%)	Silt	Kaolin
Liquid limit	20.6	56
Plastic limit	27.3	30
Plasticity index	6.7	26

3. Impact of curing conditions

The impact of the curing conditions was first assessed by conducting two distinct test series with different curing conditions. Those experiments were performed only with the silty soil.

3.1 Curing time and temperature

Several tests were performed to assess the impact of the curing time and of the curing temperature. Different curing conditions were considered, with two possible temperatures: 20 or 40°C. The compacted samples were introduced in an individual plastic container to avoid any exchange of water. After the curing period, the samples were tested immediately to determine their strength. Prior testing, samples cured at 40°C were equilibrated at a temperature of 20°C, to avoid effect of temperature on the mechanical behaviour.

The results showed that the curing temperature and the curing time have not significant impact on the strength of the tested soil (**Table 2**). The scatter in the results can be attributed to the small dispersion of the samples final water content.

3.2 Role of the water content

The impact of the water content of the samples was also evaluated. The corresponding samples were prepared at the optimum water content and the maximum dry density

of the silt. One quantity of treatment product was selected. The samples were then allowed to dry progressively for different times in a climatic chamber where the relative humidity was set at 50 %, and the temperature was kept constant. After this drying period, the samples were placed in hermetic containers for one week for moisture content homogenisation prior testing their strength.

The results showed that the drying has a major impact on the strength of the treated soil (Fig. 1). The strength increased from about 140 kPa up to a maximum value of 5500 kPa for a water content of 0.5%. As a comparison, the strength of the untreated soil, under the same conditions, increased from about 140 kPa at the initial water content up to 2200 kPa under a water content of 0.5 %. This also demonstrated the positive impact of the treatment product on the strength of the tested silt.

Table 2. Impact of curing conditions on strength.

Curing time (days)	Temperature (°C)	Strength (kPa)	Final water content (%)
1	20	137	15.1
	40	119	15.4
4	20	117	17.2
	40	107	17.1
7	20	147	15.6
	40	155	14.7

Fig. 1. Impact of progressive drying on the strength of the silt treated with 10% by dry mass of vinyl-based co-polymer.

4. Role of the soil nature on strength

Two test series were performed to evaluate the impact of the co-polymer resin as a function of the soil nature. All the samples were dried under a controlled relative humidity of 50% (total suction of about 95 MPa) from

the initial water content corresponding to the optimum water content of each tested soil. The water content of the silt samples was about 1,5% and of the kaolinite samples was about 0,5%, for all the considered treatment product content. The total suction of all samples being equal to about 95 MPa. The differences in behaviour are thus attributable only to the treatment product.

Fig. 2. Mechanical behaviour of the tested soils as a function of the amount of treatment product.

The stress strain curves are plotted on Fig. 2 and on Fig. 3. The main impact of the vinyl co-polymer is an enhancement of the unconfined compressive strength of both soils. The impact of the treatment on the modulus is not significant. Thus, failure occurred at a higher axial deformation of the samples.

The results showed that both soils can be significantly improved by the treatment with the co-polymer. In order to evaluate the impact of the soil type, the unconfined compressive strength was normalised by the strength of the untreated soil (Fig. 4). The UCS of the kaolinite was increased by a factor of about 3.2 compared to the untreated state while the UCS of the silt was increased by a factor of about 2.4. However, the UCS of the kaolinite treated with 5 % of co-polymer was equal to about 500 kPa, approximately ten times lower the strength of the silt under the same conditions.

Fig. 3. UCS as a function of the dosage and of the soil nature.

Fig. 4. Strength normalised by the strength obtained with the untreated soil.

5. Microstructure

The impact of vinyl based co-polymer on the microstructure of both kaolin and silt compacted soils was investigated at the micro scale by SEM technique. The samples tested were dried as described in section 3.2. The aggregate structure induced by compaction is particularly evident for the untreated kaolin sample. Figure 5 shows the macro-aggregates characterised by an intra-aggregate porosity with characteristic size comparable to the size of the kaolin particles, and an inter-aggregate porosity which is at least two orders of magnitude larger. The addition of co-polymer reduces the occurrence of the aggregate structure after compaction, as evidenced by the progressively less defined macro-aggregates as the co-polymer percentage is increased. In particular, for 5% of co-polymer treated kaolin, the matrix-like texture prevails for the observed samples (Fig. 5, nn. 5-6). A completely different initial configuration characterises the untreated compacted silt. Figure 6 shows the microstructure characterized by the presence of large grains, coated by silt and clay particles, reflecting the grain size distribution of the natural soil. Differently to what observed for the treated kaolin samples, the addition of co-polymer does not seem to alter the microstructure of the compacted silt. For each copolymer percentage the arrangement of particles does maintain its peculiar features, irrespective of the percentage of co-polymer added.

Fig. 5. SEM images of untreated kaolin (1, 2), and 1% (3, 4) and 5% (5, 6) copolymer treated kaolin.

Fig. 6. SEM images of untreated silt (1, 2), and 1% (3, 4) and 5% (5, 6) copolymer treated silt.

6. Conclusion

In this study, two types of fine grained soils were stabilized with a vinyl based co-polymer and following conclusions are drawn:

1. Use of copolymer significantly improves the strength of kaolinite and silt, and strength increase is remarkable with increasing copolymer content.
2. Considering increases in strength of kaolin and silt, use of copolymer is more efficient in stabilization of kaolin.
3. Drying significantly influences the strength of soil.
4. Microstructural analyses show that with the increase in co-polymer content, stronger bonding is observed in specimens, which is provided by the interaction among soil, copolymer and water. The relevant improvement of strength induced by co-polymer addition on kaolin is coupled to a significant microstructural reorganization; whereas the relatively lower mechanical improvement induced by co-polymer addition on silt is observed without any significant structural modification of the soil

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