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Contribution of the fiber reinforcement on the fatigue behavior of two cement-modified soils

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ABSTRACT

Soil modification with cement is a well-established practice in the field of geotechnical engineering. The addition of cement is an eco-friendly process to increase mechanical performances of fine grained soils. This practice is commonly used to rationalize the cost of land transport infrastructures.

The mechanical fatigue, which results from repeated loadings, is one of the main failure modes of these layered structures. These repeated loadings generate repeated tensile stresses at the bottom of the layers. To overcome these stresses on cement-modified soils, it seems relevant to add fibers in the materials as it is usually used in the field of concrete.

The objectives of the study are to investigate the influence of the reinforcement with a small amount of natural fibers on the fatigue behavior of two cement-modified soils. The first soil can be defined as a sandy clay material, while the second can be defined as a coarse grained material with a small clay content.

Fatigue performances of the two cement-modified soils without fibers and reinforced with several amount of fibers are measured using the two-point bending test. Results highlight that the reinforcement has positive effects on the stabilized sandy clay material while the fibers addition seems to slightly decrease the performances of the stabilized coarse grained material.

Microscopic observations coupled with a statistical analysis on gammadensimetry measurements show in both cases that a fiber-balls phenomenon limits the homogenous distribution of the fibers in the soils. In the first case, this phenomenon is not detrimental. The natural matrix is intimately related with the fibers, and fibers prevent microcracking process. In the second case, because of the size of the grains, the links between the matrix and the fibers are isolated and fibers are not stressed during microcracking process.

This study highlights that the failure processes of cement-modified soils are clearly related to the mineralogical nature of the matrixes. It also highlights that the failure processes for those materials are different than for highly cemented materials.

1. Introduction

In situ soils present in the right-of way of civil engineering projects generally have mechanical characteristics inconsistent with stress rates generated by civil engineering infrastructures. The addition of few percent of hydraulic binders significantly increases their engineering and mechanical properties [1–4]. This process has the advantage of minimizing environmental impact and reducing the cost of the infrastructures [5–10].

This practice is well established among geotechnical engineers [1,11] and is used in numerous civil engineering applications such as embankments, foundations, slabs and pile and pavement construction [12–14]. It was recently proposed for the capping layers of high speed rails infrastructures [15–18] and road foundation layers [19]. These last studies have reminded that fatigue is one of the main failure modes of land transport infrastructures [20,21].

Fatigue is defined as a process of progressive, permanent internal changes in a material subjected to repeated loadings [22]. For hydraulic materials used in the layers of transport infrastructures, these repeated loadings generate a repeated tensile stresses at the bottom of the layers [15,16,23]. In order to enhance the tensile strength and fatigue performances of cement-modified soils, it seems relevant to add fibers in the materials as it is usually used in the field of concrete [1,4,24]. This addition produces bonding and friction between the cemented matrix and the fibers [25]. It could allow decreasing the micro cracking process [22,26] on the

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one hand, and on the other hand, sustaining mechanical performances even after failure [25].

Synthetic or natural fibers can be used. A substantial literature can be found on the effect of synthetic fibers on the behavior of soils-cement (5–15% of hydraulic binders by weight of dry soil) and cement-modified soils (5% or less) also known as stabilized soils [1,24]. This literature is fundamentally based on the results of unconfined compressive strength tests [24]. Some results can also be found about tensile stress. Especially, the addition of glass fibers in soil-cement mixtures improves the tensile strength of the mixtures [26,27]. It has also been highlighted that the addition of polypropylene fibers increases the indirect tensile strength of soils-cement [23,24,26,28]. A null effect was also observed and depends on the amount of fibers and on the soil-type [26]. The tensile performances of cement-treated (10%) clayey gravel and cement-treated (10%) high clayey soil seem to be improved with the addition of synthetic fibers, while the tensile performances of silty soils-cement are not affected by the reinforcement. On the borderline of soil-cement definition, it also has to be noticed that a small increase on the flexural strength of soft clay treated with 20% of cement and reinforced with 0.5–1% of steel and polypropylene fibers has been observed [29]. Recently [30], for a clayey soil stabilized with a high amount of hydraulic binders (8% of cement and 30% of fly ash), an increase of the tensile stress has been reported. Similar tendencies have been observed [24] for a clayey-silt organic soil treated with a high amount of cement (54%) and reinforced with a high amount of fibers (3.6–14.3%): an increase on both indirect tensile strength and flexural strength and a decrease on direct tensile strength have been reported.

But, in the field of subgrade layers for transport infrastructures, the used materials exhibit generally a low economic cost. Therefore, the addition of manufactured products such as synthetic fibers does not seem to be a viable technical and economic solution. Natural fibers are known to have a low cost and a high availability [31–34]. Hence, the use of this kind of material to enhance cemented "earthworks-material" performances appears to be a relevant and eco-friendly solution.

Several recent works were performed to study the effect of the addition of fibers on the tensile properties of cement-treated soil. In the first one [26], the reinforcement with cellulose fibers of cement-treated (10%) soils is a bit effective with clayey gravel and high clayey soils but not with silty soils. An optimum fibers amount depending on the soil granulometry was also proposed. A part of these results was confirmed in a second study [28]. The tensile performances of a high clayey matrix treated with 10 and 15% of cement are slightly increased when the cement-matrix is reinforced with less than 1% of carpet fibers. In a more recent study [35], authors have shown that beyond the addition of 1% of coir fibers, the tensile performances of a lime treated (5%) clay soil tend to decrease.

Now, for a new material such as reinforced soil-cement, to be accepted by the engineering community of land transport infrastructures, the measurements of sizing empirical parameters such as indirect tensile stresses are not enough. The characterization of the mechanical behavior related to the structures is needed and therefore, the understanding of fatigue failure is an essential step.

The aims of this paper are:

- Firstly, to investigate at the laboratory scale on the effect of the addition of natural fibers on the high-cycle fatigue properties [22] of two cement-modified soils. Results are discussed with regards to the geotechnical nature of matrixes.
- Secondly, to understand the mechanisms of the fiber reinforcement on the two cemented matrixes. To achieve this goal, visual and microscopic observations were performed and were confirmed and quantified using a statistical approach on density measurements.
- Finally, the material quality indexes (QI) are determined [19] to quantify the improvements in terms of pavement design.

2. Materials and methods

2.1. Soils

For this study, two soils (AD and SB) were sampled in the French region "Bretagne – Pays de Loire" from two different construction sites during earthwork operations. Both times, they were considered for a use in subgrade after cement stabilization.

- Soil no. 1: AD

The first soil AD was taken near the city of Le Mans. The sampling was performed with an excavator equipped with a ditch bucket at a depth between 1.5 m and 3 m.

From the geological point of view, it belongs to the western margin of the Parisian Basin bordering the Armorican Massif. It was deposited during the Albian and Cenomanian stages (Cretaceous period) at the end of a marine regression (Early Cretaceous) followed by a transgression period (Cenomanian). This detritic formation is therefore composed of marine sediments and terrigenous materials. Since the land emerged at the end of Cretaceous era, the formation has been altered by climatic conditions such as Quaternary glaciations [36].

The maximum diameter of larger elements in this material is less than 50 mm. It can be classified as fine grained soil [37]. Through a 2-mm sieve, the cumulated undersize is 94%. The cumulated undersize less than 80 μm is 49%, which means that its mechanical behavior is controlled through its fine fraction. It is made up of less than 5% silt and has $C_{2\mu m}$ = 32% clays (Fig. 1). Therefore it is a sandy clay material [38].

The Liquid limit W_L is 43% and Plastic limit W_P is 25% [39]. The plasticity index I_P (=$W_L - W_P$) is 18. The soil is classified A-7-5 following the AASHTO Soil Classification System.

The clay activity is thus $A = I_P/C_{2\mu m} = 0.56$. These results mean that the clays may be inactive and should have a low impact on the soil behavior when soil is wetted or dried.

- Soil no. 2: SB

The second soil SB was taken near the city of Nantes with shovels at a depth between 1 m and 1.5 m.

From the geological point of view, it is located in the south of the Armorican Massif. This siliceous detrical formation was deposited during the gradual withdrawal of the Atlantic ocean during the Pliocene stage (Neogene period). During the quaternary period and its periglacial phenomena, this loose formation suffered of eolisation. It results nowadays fine grained sand with poor clay content [40].

The maximum diameter of larger elements in this material is less than 50 mm. It can be classified as fine grained soil [37]. Through a 2-mm sieve, the cumulated undersize is 99%. The cumulated undersize less than 80 μm is 28%, which means that it is a sandy soil with a medium amount of fines. It is made up of less than 10% silt and has $C_{2\mu m}$ = 10% clays (Fig. 1). Therefore these observations confirm that this material can be considered as sand made of fine to coarse grains with small clay content [38].

The Liquid limit W_L is 31% and the Plastic limit W_P is 17%. The plasticity index I_P is 14. The soil is classified A-2-6 following the AASHTO Soil Classification System.

The clay activity is $A = I_P/C_{2\mu m} = 1.4$. These results highlight that clay's activity can be considered as high and that it should have an impact on the soil behavior when soil is wetted or dried.