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Mechanical fatigue behavior in treated/stabilized soils subjected to a uniaxial flexural test

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ABSTRACT

The use of in situ fine-grained soils treated with lime and/or hydraulic binders as subgrade in common civil engineering infrastructures is a sustainable upgrading process for natural materials with low mechanical performances. In the case of land transport projects, the lack of knowledge on mechanical fatigue behavior in these materials leads either to empirical oversized design of the layers made with these materials or to their rejection. However, the development of a relevant test now enables us to accurately measure the mechanical fatigue performances of treated soils. First, sample preparation appears to explain most fatigue performances, not sample mineralogy. Second, based on original results on three treated soils and previous results from the literature, it seems that a behavior law governs these performances. Finally, a simple classification tool shows that these materials can be considered within the entirety of transport infrastructures from subgrade layers to subbase layers.

1. Introduction

In situ soils present in right-of-way of civil engineering projects generally have mechanical characteristics inconsistent with stress rates generated by civil engineering infrastructures. To enhance their engineering and mechanical properties for a use in subgrade layers, it is common to mix them with a few percent of hydraulic binders [16,22,36]. This process has the advantage of minimizing environmental impact and reducing the cost of the infrastructures [43,49,30,44,45,35,32].

This approach is widely used in numerous civil engineering applications, for instance, embankments, foundations, slabs and pile and pavement construction. It is based on the measurement of monotonic mechanical performances [51,14,13,29]. However, for transport structures, the service life of infrastructures leads to a number of loadings superior to 10^7 cycles for pavements and 10^8 for high speed rail lines. The result is that, for these infrastructures, fatigue is one of the main failure modes [26,39,57].

Currently, difficulties in measuring mechanical fatigue performances of treated/stabilized natural soils with a high number of cycles at the laboratory scale has led to empirical design of pavement layers made with these materials [51,36,33]. Consequently, those layers are oversized and these materials are restricted to subgrade layers. They are seldom used in pavement subbase layers in which standardized materials treated with hydraulic binders, such as lightly cemented granular mixtures [9,10,11,12], are preferred [50,6]. In the railway sector, in classic High Speed Rail (HSR) projects, this lack of knowledge has purely and solely led to them not being used. The in situ materials that do not have sufficient characteristics are stripped, landfilled and substituted by materials from quarries [47].

Therefore, to rationalize the costs of the 25-million kilometers of new transport infrastructures anticipated by 2050 [28,38], understanding mechanical fatigue mechanisms for stabilized/treated natural soils and defining design rules in relation to these mechanisms are major technical, economic and environmental challenges.

Two kinds of tests are used to study the fatigue behavior of hydraulically bound materials. Large scale tests aim to reproduce a part of the structure [34,31] or even the whole structure [40] in a tank. These tests are generally costly and need a complicated procedure that does not allow parametric studies. Consequently, smaller-scale tests must first be carried out. These are more practical for taking into account scattered results of fatigue tests.

This second category of tests simulates the repetition of stress states due to traffic loadings into a specimen. The main tests used are flexural beam tests with three existing different configurations. Three- and four-point bending test configurations subject a beam resting on two support brackets to a compressive load with one or two points of load application [32,46]. The compressive load

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Nomenclature

Fatigue parameters
σ_f maximum bending stress (MPa)
$N_{fail.}$ number of loadings leading to failure
$\sigma_{\log10(Nfail.)}$ tensile stress that leads to rupture after $N_{fail.}$ cycles (MPa)
σ_6 tensile stress that leads to rupture after $N_{fail.} = 10^6$ cycles (MPa)
$S = \sigma_{\log10(Nfail.)}/\sigma_f$ stress ratio
$e = \sigma_6/\sigma_f$ endurance
β slope of the fatigue curve
ΔS uncertainty on the measurement of the stress ratio S (MPa)
$\Delta\log_{10}(N_{fail.})$ uncertainty on the measurement of the number of cycles that leads to failure $N_{fail.}$

Mechanical considerations
$\bar{\varepsilon}$ strain tensor
$\bar{\sigma}$ stress tensor
E Young's modulus of materials (MPa)
G shear modulus of materials (MPa)
ν Poisson's ratio of materials
F_e applied load (N)
$A(z)$ area of the specimen (m)
h height of the specimen (m)
$I_y(z)$ moment of inertia (m^4)
$\upsilon(z)$ distance from neutral axis (m)
g gap between the top of the specimen and the point of the load application
$M_{fy}(z)$ bending moment (N m)
$u(z)$ displacement of the specimen along the x-axis (m)

Geotechnical considerations
$C_{2\mu m}$ cumulated undersize for particles with a diameter less than 2 μm (%)
W_L Liquid limit of materials (%)
W_P Plastic limit of materials (%)
$I_p = W_L - W_P$ plasticity index of materials
$A = I_p/C_{2\mu m}$ clay activity of materials

generates a tensile stress in the lower part of the beam. The four-point bending test is most commonly used because between the two loading points, the specimen is subjected to pure bending. This test is largely used to evaluate the fatigue behavior of stabilized recycled aggregates [53,59,27] and has also been somewhat used to characterize the fatigue behavior of treated soils [18,52,55,17]. The third configuration is the two-point bending test. It consists in applying an alternative load to the top surface of a trapezoidal specimen embedded at its base. This test was also used to evaluate the fatigue behavior of cement-treated aggregates or sands [2,3,29]. For the same maximum tensile stress, this test has several advantages compared to the common four-point configuration test on a 400 × 100 × 100 mm beam:

- the requisite load is about four times lower;
- the deflexion is about four times higher.

As a result, for the modulus measurement, two-point bending is more appropriate. But in the field of treated/stabilized soils, the difficulties in preparing laboratory samples with the same dimensions as for cement-treated aggregates has led to testing materials on smaller samples with non-relevant dimensions for soils with aggregates larger than 2 mm [25].

Based on an analytical approach, numerical calculations and experimental results on three natural fine-grained soils treated with hydraulic binders, the aims of this paper are to:

- Demonstrate that the mechanical fatigue behavior of common treated soils can be accurately measured at the laboratory scale with the two-point bending test;
- discuss the resulting performances;
- show that these performances are relevant for structure design compared to other usual hydraulically bound materials.

First, we present the fatigue test that we used. Experimental results on a reference polyvinyl chloride (PVC) specimen were compared with analytical and numerical calculations to validate the test configuration. Second, three natural soils treated with hydraulic binders were tested. Results are first discussed with regards to the geological nature of matrixes and to sample preparation, then compared with data from the literature to propose a general behavior law, and finally implemented on a simple bilayer structure so that the material quality indexes (QI) could be determined. The three indexes were finally compared with the indexes of classic hydraulically bound materials.

2. Materials and methods

2.1. Fatigue test

2.1.1. Principle

For the design of land transport infrastructures, the sizing criterion for layers made with hydraulically bound materials is the maximum tensile stress σ_{max} resulting from the loading on the whole structure [50]. This worst tensile stress is located at the bottom of the stabilized layers [24,54,47]. To be suitable, the material must have a fatigue strength, $\sigma_{\log10(N)}$, defined as its cyclic tensile stress that can be withstood for N loadings, superior to σ_{max}. [37,48,25,42,50,51,58]. The number of loadings N is determined in relation with the expected traffic and the service life of the structure.

The fatigue test is a two-step procedure applied on pseudo-trapezoidal specimens clamped at their base (Fig. 1). First, the monotonic flexural test consists in applying a steadily increasing load to the top surface of the specimen to measure the maximum

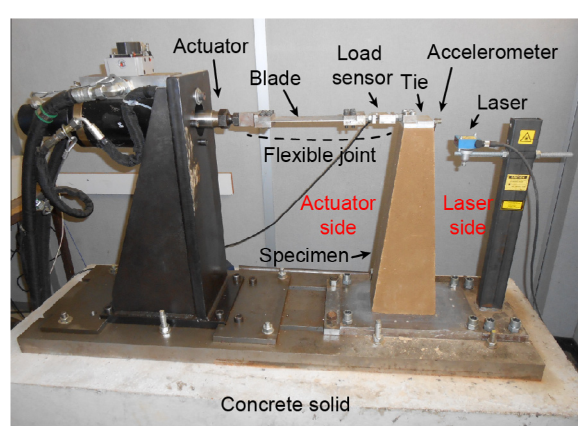

Fig. 1. Picture of experimental device.