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The effective stress concept in the cyclic mechanical behavior of a natural compacted sand

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ABSTRACT

Road pavement structures are generally composed of granular materials. The influence of the unsaturated state, or suction, on the mechanical behavior of unbound granular materials in roads during a large number of cycles has not been given sufficient attention and is not generally considered in models used for these materials.

This article presents an experimental study on compacted natural sand in Missillac, France that used the direct shear test and the soil water retention curve (SWRC) to measure the effective stress, and repeated load triaxial tests to determine the material's resilient behavior.

The effective stress concept was used in a nonlinear elasticity model to predict the material's resilient behavior under unfavorable moisture conditions, which are one of the most common mechanisms of deterioration in low-traffic pavements.

1. Introduction

Recent studies concerning the improvement of flexible pavement design methods have noted that, in most cases, when water content increases in the unbound layers or soil on a permanent basis, the decrease in bearing capacity of these layers leads to rutting. This distress occurs mainly in the granular base and subbase layers. Despite this knowledge, the rutting of unbound materials is still poorly understood and is not accounted for in most pavement analysis and design methods.

The repeated load triaxial test (RLTT) is commonly used to establish the mechanical characteristics of granular materials and describe their resilient behavior (Drumm et al., 1997; Gomes Correia, 1999; Yuan and Nazarian, 2003; Khoury and Zaman, 2004; Rababah, 2007; Cary and Zapata, 2011; Khoury et al., 2011; Bilodeau and Doré, 2012) or permanent deformation behavior (Barksdale, 1972; Sweere, 1990; Hornych et al., 1993). The behavior of unbound granular materials in roads is generally studied in the unsaturated state, but the modeling of this behavior is usually based on total stresses. Nevertheless, a complete description of the material behavior necessitates an effective stress approach that controls or monitors the pore pressures (or pore suctions) separately from the applied pressures. Because most road materials are coarse-grained and partially saturated and/or above the water table, it is usually impossible to monitor the pore suctions during each transient pulse when a RLTT is performed. For this reason, all testing programs determine the parameter values for resilient and incrementally developed plastic strain models in terms of the total (rather than the effective) stresses. This last point has been recently underlined in a synthesis of the various modeling approaches developed for unbound granular materials in roads (Dawson, 2008). One of the main conclusions made for future work was to improve these models by accounting for the unsaturated state of the material and its influence on mechanical behavior. Experimental work shows that variation of the water content in granular materials has a significant influence on their mechanical behavior, especially on their resilient modulus, as reported by Li and Selig (1994), Drumm et al. (1997), Yuan and Nazarian (2003), Khoury and Zaman (2004), Rababah (2007).

Our study considered a clayey sand (Missillac sand from France), and we studied its resilient behavior with repeated load triaxial tests, its maximum strength line or critical state line with direct shear tests and its hydric characteristics with a water characteristic curve. Modeling of the resilient behavior was then carried out with the Uzan model (Uzan, 1985) and expressed in terms of effective stresses.

2. Experimental program

This section presents the physical, hydric and mechanical tests performed on the Missillac sand. Missillac is a clayey sand that has been used as subgrade soil in the accelerated pavement testing facility at LCPC (Laboratoire Central des Ponts et Chaussées) in Nantes, France for full-scale pavement tests.

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2.1. Study material

Missillac sand is a typical subgrade soil found in a low-traffic pavement. It is sensitive to moisture and its in situ elastic modulus typically varies between 50 and 100 MPa when previously measured by field tests. This soil is classified A3 based on AASHTO.

The particle size distribution of Missillac sand, shown in Fig. 1, is continuous ($d_{60}=1.10$ mm; $d_{30}=0.48$ mm; $d_{10}=0.01$ mm), and it has a maximum particle size of approximately 10 mm. The material was prepared in the laboratory in a Proctor mold at specified water contents and compacted using the normal Proctor test procedure.

The compaction curve and the CBR curve of Missillac sand are shown in Fig. 2. The optimum of the normal Proctor compaction is $w_{opt}=9\%$ and $\gamma_d=20.6$ kN/m^3. The CBR curve normally shows a different optimum point of $w_{opt}=8\%$ and $I_{CBR}=46\%$. This CBR curve indicates a material that is sensitive to moisture, with an important loss of CBR between w = 8% and w = 11%.

The specimens were compacted at 8 different water contents: 7, 8, 9.6, 10, 11, 12.3, 13 and 14%, and at a constant density of approximately 20 kN/m^3. Table 2 presents the initial states of all specimens in the study.

To find the variation in suction with soil water content, laboratory tests to measure suction were performed using two methods, the filter paper method (ASTM, 1995) and the tensiometer method (Konrad and Ayad, 1997; Tarantino and Mongiovi, 2001; Rahardjo et al., 2005).

The matrix (or matric) and total suction of all the samples, which were all statically compacted at the same initial dry density of 20 kN/m^3, were measured for different water contents using the filter paper technique. Whatman No. 42 filter paper was enclosed with a soil specimen (without being in contact) in an airtight container for a period of two weeks, until the soil reached a state of equilibrium with the relative humidity (amount of water vapor that exists in a gaseous mixture of air and water vapor) in the measuring chamber, thus allowing measurement of the total suction. For matrix suction measurements, the soil samples were compacted in two 1-cm layers. A filter paper was inserted between two pieces of protective filter paper with a larger diameter. The filter paper sandwich was placed between the two soil layers. This test method accounted for the variability of the filter paper's water content when in direct contact with the soil.

The tensiometer technique allowed for measurement of the matrix suction between 0 and 100 kPa. The samples were compacted at the same initial dry density of 20 kN/m^3 and at different water contents, with a height of 2 cm and a diameter of 7 cm. Porous ceramic cups for soaking up the water were carefully put into contact with the samples. The measurements took a few hours to reach an equilibrium state after installation.

Fig. 3 compares the experimental results obtained by the tensiometer method and the filter paper method (Nowamooz et al., 2010, 2011). To adapt the formula of Brooks and Corey (1964) to bimodal SWRCs, the original function is replaced by the following three-part equation:

$$w = \begin{cases} w_s & \psi<\psi_d \\ w_{rM} + (w_s - w_{rM})\left(\dfrac{\psi_{bM}}{\psi}\right)^{-\lambda_M} & \psi_{bM}<\psi<\psi_{bm} \\ w_{rm} + (w_{rM} - w_{rm})\left(\dfrac{\psi_{bm}}{\psi}\right)^{-\lambda_m} & \psi_{bm}<\psi \end{cases} \quad (1)$$

where w_s, w_{rM}, w_{rm}, ψ_{bM} and ψ_{bm} are the saturated water content, the residual water content of the macro-pores (saturated volumetric water content of the micro-pores), the residual water content of the micro-pores, the bubbling pressure of the macro-pores and the bubbling pressure of the micro-pores, respectively. All of these parameters are reported in Table 1, which shows good agreement between the model calculated from Eq. (2) and most of the experimental data.

2.2. Shear tests

Critical state theory (Roscoe et al., 1958) has been used extensively to establish models for simulating the elastic–plastic behavior of unsaturated soils (Alonso, et al., 1990; Toll, 1990; Modaressi and Abou-Bekr, 1994; Alonso, et al., 1999; Loret and Khalili, 2002; Wheeler et al., 2003; Russell and Khalili, 2006; Sheng et al., 2008).

Eighteen direct shear tests were performed in saturated and unsaturated conditions at the same density of approximately 20 kN/m^3. The samples were statically compacted to a size of $6*6*2$ cm^3. The initial states of the performed tests are presented in Table 3. Samples were put in a direct shear box following the preparation phase at the desired water content. Then, different net vertical stresses were applied to the specimens. The shear tests were conducted quickly to maintain the water content at close to its initial value. The water content values of the samples were also checked at the end of the shear phase, and the discrepancy from the initial water content was negligible. The different final suction values summarized in Table 3 can also be estimated from the SWRC (presented in Figure 3) for a given final water content.

The experimental results allow for the determination of the critical state line in the net stress space for different initial water contents under three different vertical stresses of 28, 56 and 112 kPa, as shown in Fig. 4. The internal friction angle and effective cohesion of the material

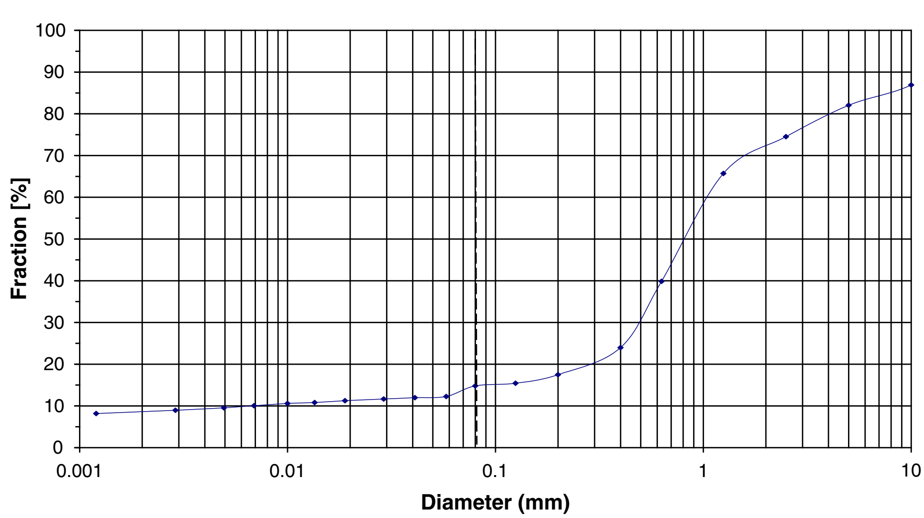

Fig. 1. Particle size distribution curve of the Missillac sand.