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Hydro-Mechanical Behavior of a Tuff and Calcareous Sand Mixture for Use in Pavement in Arid Region

I. Goual, M. S. Goual, M. K. Gueddouda, Taïbi Saïd, Abou-Bekr Nabil, A. Ferhat

***Abstract*—**The aim of the paper is to study the hydro-mechanical behavior of a tuff and calcareous sand mixture. A first experimental phase was carried out in order to find the optimal mixture. This showed that the material composed of 80% tuff and 20% calcareous sand provides the maximum mechanical strength. The second experimental phase concerns the study of the drying-wetting behavior of the optimal mixture was carried out on slurry samples and compacted samples at the MPO. Experimental results let to deduce the parameters necessary for the prediction of the hydro-mechanical behavior of pavement formulated from tuff and calcareous sand mixtures, related to moisture. This optimal mixture satisfies the regulation rules and hence constitutes a good local eco-material, abundantly available, for the conception of pavements.

***Keywords*—**Tuff, sandy calcareous, road engineering, hydro mechanical behaviour, suction.

I. INTRODUCTION

IN some desert regions, classic materials ("good quality" aggregates) are scarce or even inexistent. The necessity to build roads with optimized cost has prompted engineers and technical experts to adapt local materials. Lot of these materials proved to be very interesting in road design, as tuff, volcanic materials, sands, lateritic, etc.

The valorization of local materials for road engineering is topical; the aim is to better harness their behaviour under different climatic situations, their implementation, and to achieve a characterization that would enhance easy their classification and their use by road engineers and experts.

In Algeria, the tuffs approximately cover an area of about 300,000 km2. Their use in road construction is considerably developed. They are usually used in the construction of road pavements (base and foundation layers) for low or average traffic [1].

After wet compacting and desiccation, tuff acquires cohesion that long lasts. This cohesion disappears almost completely after complete saturation [1]-[2].

A first part of this work was conducted to valorization of local materials, namely the tuff of Laghouat region (south of Algeria), by addition of wastes of crushing stations (calcareous sand), for the purpose of their use in road engineering [3]. This part was concerned the effect of calcareous sand addition on the engineering properties of tuff. The results have permitted to select the formulation 80% tuff + 20% calcareous sand, which present the best mechanical strength. The weak point of this formulation is the poor water resistance, when after immersion a total collapse of the specimens was observed after a few tens of minutes.

This fall of resistance is characteristic of the non-cohesive granular materials, which owe their cohesion to the presence of the capillary forces during compaction. These forces disappear starting from a certain threshold, the presence of water becoming harmful for cohesion [4].

This paper presents the study of hydro mechanical behavior of this optimal mixture. The aim is dual: (i) to study the suction effect on behavior of the optimal formulation, (ii) to determine the parameters of the constitutive laws, necessary for modeling the unsaturated behaviour of road pavements taking into account the moisture fluctuations.

II. MATERIALS AND METHODS

A. Materials

The optimal mixture tuff-calcareous sand (TSCopt) used in the study was formed by two soils (80% tuff and 20% calcareous sand) from Laghouat region located 400 km South of Algiers. The first material is the tuff a material available within the Laghouat region. It is used often in road construction of low traffic. The second material is the calcareous sand, which is a residue of the crushing stations.

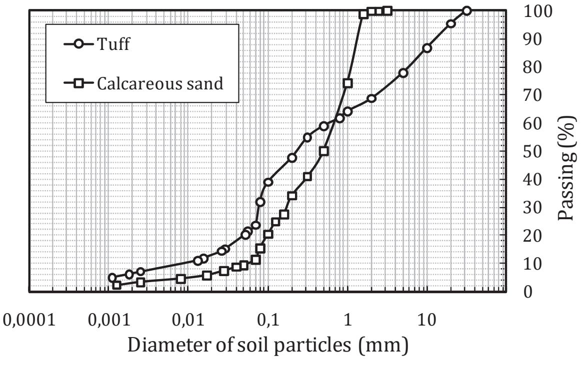

Fig. 1 Grading curves of the two used materials

F. I. Goual is with the Laboratory of Research in Civil Engineering, University of Laghouat, Algeria (corresponding author to provide phone: +213-665916610; fax: +213-29920067; e-mail: goualid@yahoo.fr).

S. M.S. Goual, T. M.K. Gueddouda and S. A. Ferhat are with the Laboratory of Research in Civil Engineering, University of Laghouat, Algeria (e-mail: Gueddouda_mk@yahoo.fr, msgoualid@yahoo.fr, ferhatah@yahoo.fr).

F. S. Taïbi, was with Laboratory Waves and Complex Media, FRE CNRS 3102, Le Havre University, Le Havre, France (e-mail: taibis@univ-lehavre.fr).

F. N. Abou-bekr is with the Water and Structures Laboratory in Their Environment, University of Tlemcen, Algeria (e-mail: aboubekrnabil@yahoo.fr).

B. Methods

The experimental work is based on the drying-wetting tests.

On drying-wetting paths, in the absence of external stress, the only varying parameter is suction. Drying–wetting cycle is obtained by controlling matric suction in the TSCopt sample. These tests consist in imposing to the samples a series of increasing suctions up to total drying, then rewet them by imposing successive decreasing suctions (wetting). Three methods were used to control the matric suction: [6]-[11] .

TABLE I
PHYSICO-MECHANICAL AND CHEMICAL PROPERTIES OF THE OPTIMAL MIXTURE TSCOPT [3]

Symbol	TSCopt	TSR*	Standards [5]
%<80 µm	26	< 30	NFP94-056 et 057
LL (%)	34	/	NFP94-051
PI (%)	-	< 13	
w_{MPO} *(%)*	10.4	14	NFP94-093
γ_{dMPO} *(g/cm$^{3)}$)*	2	1.8	
ICBR (unsoaked)	32	> 40	NFP94-078
ICBR (soaked)	19	/	
Rc28 (MPa)	4.2	> 2	-
CaCO3 (%)	57	/	-

* Thresholds imposed by the Technical Saharan Road (TSR). LL=liquidity limit, PI=plasticity limit; w_{MPO}=optimal water content, γ_{dMPO}=maximum dry weight, Rc28 = unconfined compressive strength at 28 days.

Tensiometric plates were used to achieve low suction values, between 0.001 to 0.02 MPa; the specimens were placed on sintered glass filters, and a negative pressure was applied to the water, the air pressure being atmospheric.

Osmosis was used to achieve intermediate soil suctions, between 0.05 and 8 MPa. In the osmotic technique, dialysis membranes with very small pores (5 nm) are placed between the TSCopt sample and a solution of polyethylene glycol (PEG 20000 and PEG 6000 are used for suctions ranging respectively between 0.05 to 1.5 MPa and 3 to 8 MPa) to prevent the passage of macromolecules. As the macromolecules tend to hydrate and attract water from the soil, the specimen was subjected to suction, which depended on the PEG concentration in the solution.

To achieve high suctions, between 3 and 1000 MPa, the transfer of water occurs in vapour phase. Several salt solutions were used to control the relative humidity of the atmosphere in the desiccators containing the samples, and hence the matric suction in the samples.

Once the capillary equilibrium was reached (generally after one or two weeks for suctions lower than 1.5 MPa and two months for larger values of suction [12]) the final properties of the specimens were measured. The specimens were weighed, then immersed in a non-wetting oil of known density; their external volume was derived from the difference between the initial weight in air and the apparent weight when immersed in oil. Finally, their dry weight was measured after the evaporation of both water and oil in an oven at 105°C for 24 h and used to calculate the water content, void ratio, and degree of saturation.

In order to achieve the drying-wetting tests, three initial moisture conditions were imposed:

- Saturated slurry: the samples are prepared with initial water content equal to 30%.
- Dry pastes: the samples are dried at 105°C during 24 hours in an oven.
- Compacted sample according to the MPO.

The preparation of the compacted specimen is carried out in three steps as follows:

In the first step, natural soils were air-dried; the tuff was passed through a 4 mm sieve to eliminate the biggest particles. We take a mass proportion of 80% tuff and 20% calcareous sand, and then both the aggregates are mixed up before adding water.

In the second step, the required quantity of water corresponding water content of MPO was added to the TSCopt and both were carefully mixed by hand. The mixing is done by sieving several times in order to avoid the formation of clumps and to have a homogeneous mixture. The TSCopt-water mixture was kept in a sealed plastic bag for at least 24 h to achieve uniform moisture conditions.

In the third step, the materials were statically compacted to the corresponding dry density of MPO in mould with double piston at a rate of 1.14 mm/min. This compaction method leads to a homogeneous repartition of the compaction stress [10], [13], [14].

The initial parameters (e, w, Sr ...) of samples are measured immediately before tests. The compacted specimen was cut into smaller specimens (2-3 cm3).

III. RESULTS AND DISCUSSION

Fig. 2 presents the drying path followed by the saturated slurry and the wetting path followed by the dry slurry. The three right-hand side curves present the void ratio (Fig. 2 (b)), the saturation degree (Fig. 2 (d)) and the water content (Fig. 2 (f)) versus suction. On the two left-hand side curves, the void ratio (Fig. 2 (a)) and the saturation degree (Fig. 2 (c)) are plotted versus water content.

In the [w, e] plane (Fig. 2 (a)), on the drying path, the samples prepared from a slurry leave rapidly the saturation line defined by: e = w.Gs. After that, when the water content decreases, the void ratio tends towards a constant value. The shrinkage limit w_{SL} is about 20% corresponding to a void ratio e_{SL} equal to 0.54.

The [log(s), e] plane (Fig. 2 (b)), represents the compressibility behaviour of the soil under the effect of suction. The elbow of the curve where the plateau of shrinkage starts permits to determine the shrinkage limit suction « s_{SL} » which is about 0.8 MPa. This pressure plays an important part in modeling the behaviour of the soil as it corresponds to a drastic change in its properties [12], [15], [16].

The [log(s), Sr] plane (Fig. 2 (d)), represents the change in degree of saturation versus suction. The soil remains quasi saturated on a drying path up to a suction of 0.02 MPa, called suction of desaturation s_d or otherwise termed the air entry value, determined from the [w, Sr] plane (Fig. 2 (c)) by the intersect of the drying line plotted for Sr<50% with the horizontal axis corresponding to Sr=100%. After desaturation, the degree of saturation decreases progressively down to 6%, corresponding to suction of about 160 MPa. The suction of desaturation s_d is small compared to the suction of shrinkage limit s_{SL}. This is a characteristic of clay slurries on drying paths [17]. This decrease in the degree of saturation is described by a decrease in water content in the last plane [log(s), w] (Fig. 2 (e)).

If we consider the wetting path of the sample initially dried in the oven corresponding to a conventional suction of 1000 MPa, we note that the hysteresis of the drying-wetting cycle depends on the suction range: for 13MPa<s<160MPa, the water content and the void ratio vary slightly, the degree of saturation varies from 10 to 20%. The hysteresis between the drying and the wetting is negligible, and we note reversibility between the drying and the wetting paths.

For 0.5 MPa<s<13 MPa, the increase in the degree of saturation and the water content is more important, while the void ratio remains quasi-constant. In this range, the hysteresis appears between the drying and wetting paths in the [log(s), Sr] plan (Fig. 2 (d)) and [log(s), w] plan (Fig. 2 €). This could correspond to an intermediate phase of saturation where largest pores of the TSCopt are first saturated. The behaviour of the largest pores is governed by the effect of menisci, and is mainly due to the “ink bottle effect” [12], [18], [19]. For s<0.5MPa, the soil tends to be progressively saturated to reach values of Sr > 80% for suctions near 0, without reaching the total saturation of the material. In the [log(s), e] plane (Fig. 2 (b)), the wetting path follows a straight line with a smaller slope compared to that of the drying path. This can be explained by the fact that the drying path is a plastic compressibility behaviour, whereas the wetting path is a « hydric unloading » and follows an elastic path.

As comparison, a saturated oedometric test carried out on the same slurry is plotted in Fig. 2 (b). Moreover, a normally consolidated (NC) line deduced from the correlation with the relative density (e_{max} and e_{min}) [20] is added. It is noted, that the NC oedometric path coincides with the correlation line. However, this correlation does not describe well the drying path of the slurry, contrary to the case of clays where the correlation is formulated according to the liquid limit [17].

Concerning samples compacted at MPO, corresponding to a suction s_{MPO} of approximately 0.65 MPa determined by the filter paper method [21], Fig. 3 shows the drying- wetting paths. The points corresponding to larger values of s_{MPO} belong to the drying path and those corresponding to smaller values of s_{MPO} belong to the wetting path. The drying–wetting cycle of the slurry specimens has also been reported in this figure, and is represented as a dashed line.

In the [log(s), Sr] plane (Fig. 3 (d)), the degree of saturation decreases rapidly from 80% (corresponding to Sr_{MPO}) to reach 10% for a suction value of about 105 MPa. This decrease is also noted in the [log(s), w] plane (Fig. 3 €).

Fig. 4 (b) shows that the void ratio at MPO e_{MPO} is close to the void ratio of shrinkage limit e_{SL} of compacted samples. The location of this shrinkage limit is lower than that of the slurry. This confirms the assumption that the shrinkage limit is not an intrinsic parameter of the material, but that it depends on the initial state [21]. However, in the quasi-saturated domain (Sr>80%), the slope of the wetting path of the compacted samples at MPO is slightly more important than that of the slurry. Indeed, the wetting path is a hydric unloading, which causes large strains (swelling) in the case of the compacted soils, due to a microstructure tighter than that of the slurry [14].

Table II summarizes the different parameters derived from the different planes. As a comparison, Fleureau et al. [12], proposed relations between optimum water content, maximum unit weight and suction at MPO and the liquid limit of material:

$$w_{MPO} = 4.55 + 0.32 \cdot LL - 0.0013 \cdot LL^2 \tag{1}$$

$$s_{MPO} = 1.72 \cdot LL^{1.64} \tag{2}$$

$$\gamma_{dMPO} = 20.56 - 0.086 \cdot LL + 0.00037 \cdot LL^2 \tag{3}$$

TABLE II
DIFFERENT PARAMETERS DERIVED FROM THE DIFFERENT PLANES FOR THE DRYING–WETTING TESTS

Parameters	Slurry samples	Compacted samples
s_d(MPa)	0.02	-
w_d (%)	22	-
s_{SL} (MPa)	0.8	0.9
w_{SL} (%)	20	18
e_{SL}	0.54	0.51
s_{MPO}	-	0.65

s_d: suction of desaturation; w_d:desaturation water content; s_{SL}: suction of shrinkage limit; w_S: shrinkage limit; e_{SL}: Void ratio at the shrinkage limit; s_{MPO}: suction at MPO.

TABLE III
COMPARISON BETWEEN MEASURED AND PREDICTED PARAMETERS

Parameters	Measured	Predicted [12]
s_{MPO} (MPa)	0.65	0.65
$\gamma_{d\,MPO}$ (g/cm$^{3)}$)	02	1.8
w_{MPO} (%)	10.4	14

IV. CONCLUSION

The paper highlights the possibility of the valorisation of local and economic tuff material with addition of quarry waste, as the calcareous sand, for the design of pavements in the arid regions, which do not possess high quality materials.

The preliminary tests made it possible to select the optimized mixture with addition of 20% of calcareous sand. This mixture presents better long-term characteristics with an increase of CBR index of about 30% compared to natural tuff.

The drying-wetting paths carried out on this mixture compacted to MPO whose initial suction is about 0.65 MPa, show that on wetting path, this material follows an over consolidated wetting path starting from its initial state, but does not reach total saturation, even for very low values of suction. In addition, on drying path the shrinkage limit plateau is lower than that of the same material prepared initially as slurry. This confirms that the shrinkage limit is not an intrinsic parameter but depends on the initial state.

This study shows that it is possible, at little cost, to valorize a rough and abundant material by the addition of quarry waste, in the spirit of complementarity between the economic constraints and environmental dimension.

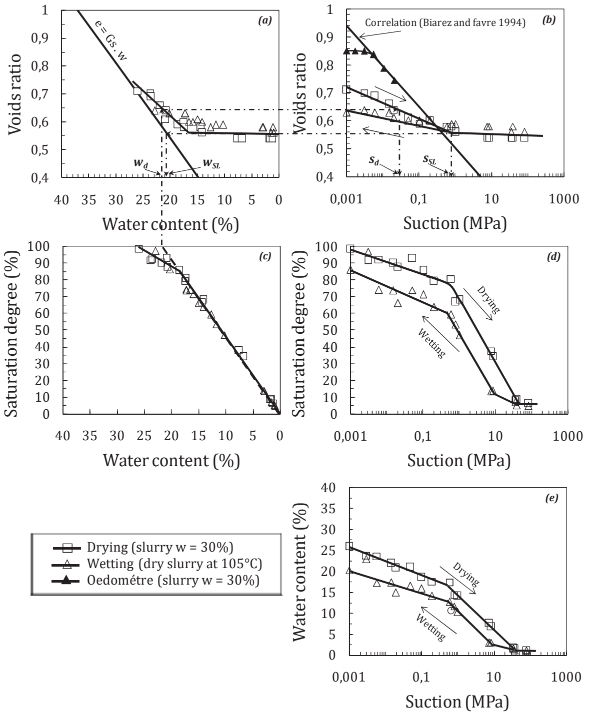

Fig. 2 Drying-wetting paths of the TSCopt (slurry at w= 30% and dry slurry)

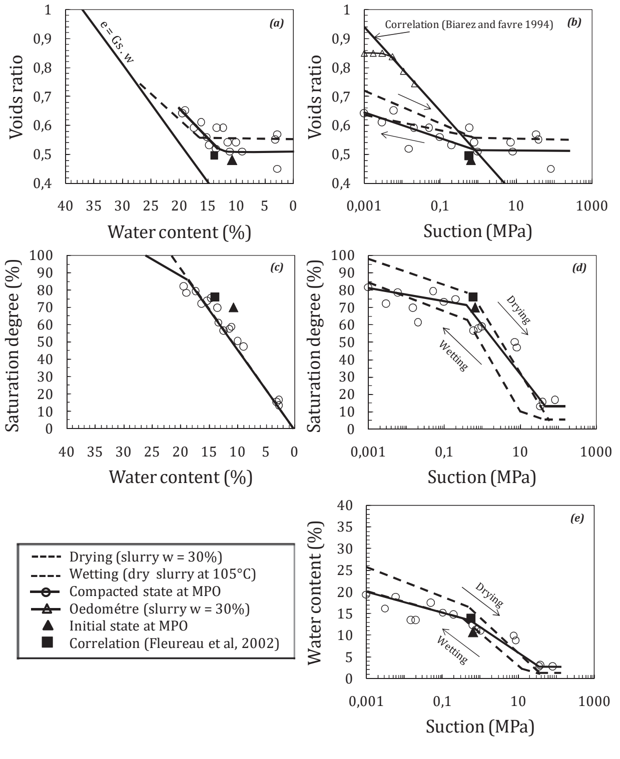

Fig. 3 Drying-wetting paths of compacted TSCopt

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