DESCRIPTION OF COMPACTED SAND/CLAY MIXTURES : COMPACTION PROCESS AND CLASSIFICATIONS OF SOILS

V. FERBER, H. HAVARD, J.C. AURIOL & K. BOUSSAID
Laboratoire Central des Ponts et Chaussées, Bouguenais, France
Valery.Ferber@lcpc.fr, Herve.Havard@lcpc.fr, Jean-Claude.Auriol@lcpc.fr, Khaled.Boussaid@lcpc.fr

ABSTRACT

In earthworks field, soils classifications are partly based on granulometric criteria, and in particular on the fines proportion. Current thresholds have been determined more or less empirically but the influence of the fines on the compaction process has rarely been quantitatively described. In order to palliate this lack of comprehension, compaction tests were carried out on various sand/clay mixtures. At the optimum Proctor, the apparent dry density of the fines and the apparent density of the sand fraction were calculated. The evolution of these parameters with the fines proportion shows that between 0 and 10-20 % of fines, the fines are loose and even don't fill in the voids between sand particles. In this range, the behaviour of the coarse part of the mixture depends on its particle size distribution. Between 10-20 and 35-50 % of fines, voids between sand particles are filled in by the fines and the dry density of the fine fraction increases steadily with its proportion in the mixture. At the opposite, the apparent density of the sand part of the mixture decreases. Moreover, the mixture reaches its highest optimum dry density for 20 to 30 % of fines, this value depending probably on the compaction energy. Between 35-50 and 100 % of fines, the compacity of the fines seems to be little dependent of its proportion. In this case, the mixture behaviour is controled by the fines behaviour. Thus, although sand/clay mixtures can not rigorously represent natural soils, this approach shows that, at the optimum proctor, the dry density of the fines increases with its proportion in three stages. This could explain why many classifications take two thresholds into account for the fines proportion. It also appears that these thresholds depend on the grain size distribution of the sand fraction and on the compaction energy. The comparison between these observations and the thresholds of the current classifications underlines the variety of choices in the definition of soils families.

KEY WORDS

COMPACTION / OPTIMUM PROCTOR / CLAY / SAND / CLASSIFICATION / THRESHOLDS

1. INTRODUCTION

Soils classifications aim to gather together, under a common name, soils presenting similar behaviours. In earthworks field, the compaction behaviour is a well adapted criterium to determine the limits between soils families. Numerous parameters influence the compaction of a soil, and current classifications take them into account by the mean of identification tests. Basically, for natural materials, tests describing the distribution of particles size and the physico-chemical properties of the clay fraction are of main interest for classifications.

Among classification criteria, the fines proportion, also called 80 µm passing (or 63 or 75 micrometers depending on countries), is an old but universally used parameter. It enables to distinguish fine soils from coarse soils.

In order to bring new comprehension elements of phenomena relating soils nature and their compaction behaviour, Proctor tests were carried out on sand/clay mixtures and similar bibliographic data were used (Mvondo-Ondoa, 1979). The results of these tests at various fines proportion were interpreted to describe the physical state of each fraction of the mixture when compacted at the optimum Proctor. After a presentation of the characteristics of the materials and the experimental procedure, the results will be exposed and interpreted. On the base of these results, a discussion on the current thresholds will then be proposed.

2. MATERIALS CHARACTERISTICS

In this study, numerous experimental data comes from the thesis of Mvondo-Ondoa (1979) who studied mixtures of Leucate sand with Provins and Aix clays. Complementary compaction tests were performed with Speswhite kaolin (fine fraction) and Missillac and Fontainebleau sands (sand fraction).

On the whole, all clays used in this study are constituted of particles smaller than 80 µ and all sands used are constitued of particles larger than 80 µ. Other characteristics of the clays are reported on table 1. The grain size distributions of all materials are presented on figure 1.

Table 1 – Main characteristics of clays

	% < 2 µ	Specific density (g/cm^3)	Methylen blue value, VBS (g/100g)	Wp (%)	Wl (%)	Ip
Aix clay	53	2,65	10,2	27,5	70,3	42,8
Provins clay	74	2,65	2,5	26	51,9	25,9
Speswhite Kaolin	78	2,65	1,4	32,3	55,1	22,8

The Missillac sand is an alluvial sand from which fines particles were extracted by sieving. Its grain size distribution is similar to the Leucate sand one which was studied by Mvondo-Ondoa (1979). The Fontainebleau sand is characterized by a very bad gradued grain size distribution, with more than 90 % of particles between 80 and 300 µ.

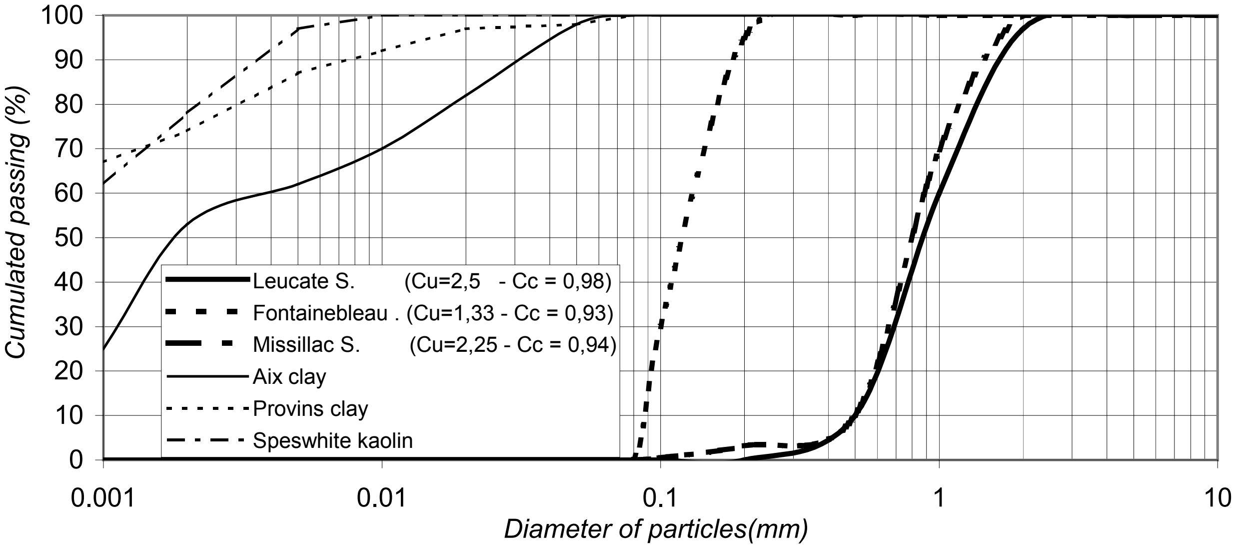


Figure 1 – Grain size distribution of sands and clays

As an example, the calculated grain size distribution of Speswhite kaolin/ Missillac sand mixtures are presented on figure 2.

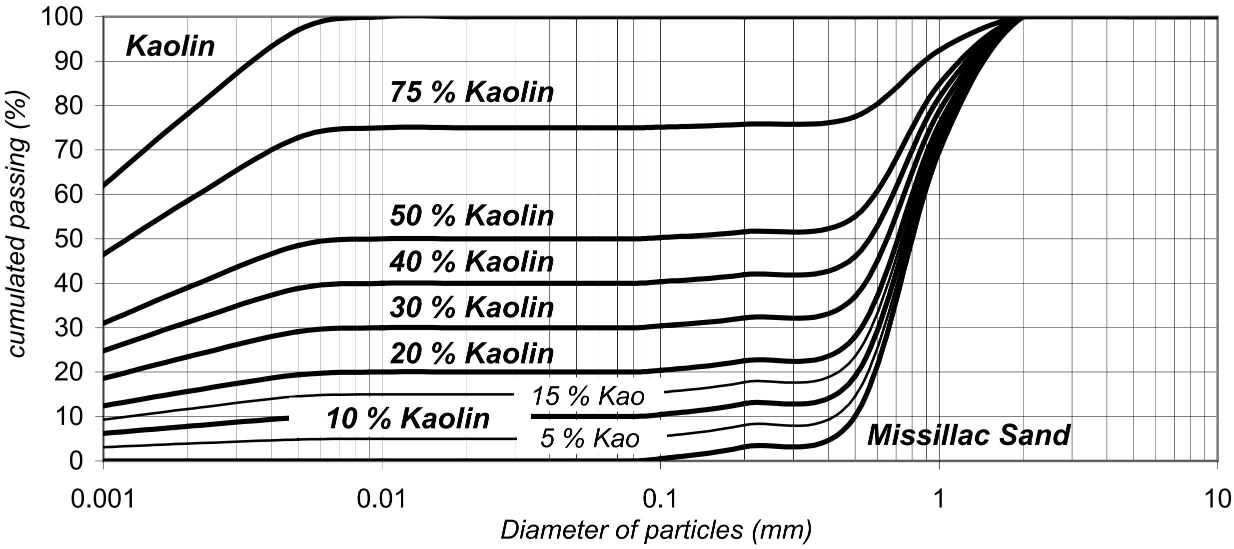


Figure 2 – Grain size distribution of Speswhite kaolin / Missillac sand mixtures.

It can also be noted that the methylen blue value of all mixtures (equation (1)) and the pasticity index of mixtures containing more than 20 % of fines (equation (2)) can be deduced from the characteristics of the fine fraction and its proportion in the mixture (Al-Shayea, 2001).

$$VBS_{mixture} = VBS_{fines}.P_f \tag{1}$$

$$Ip_{mixture} = Ip_{fines}.P_f \tag{2}$$

where P_f is the proportion of fines in the mixture, $VBS_{mixture}$ and $Ip_{mixture}$ respectively the blue methylen value and the plasticity index of the mixture, VBS_{fines} and Ip_{fines} respectively the blue methylen value and the plasticity index of the fines.

3. EXPERIMENTAL PROCEDURE

3.1. Preparation of the mixtures

The mixtures were prepared by a simple addition of dry masses of each constitutive material. It must be pointed out that mixtures containing Fontainebleau sand were prepared with a Speswhite kaolin which will be called « new kaolin », in opposition to the mixtures prepared with the Missillac sand, for which the Speswhite kaolin had been subjected to a wetting/drying cycle and will then be called « old kaolin ». It's a non negligible fact since it was observed that the optimum Proctor of the « new » kaolin (W_{opn} = 29 %, ρ_{dopn} = 1,44 t/m^3) is quite different from the « old » kaolin one (W_{opn} = 33 %, ρ_{dopn} = 1,35 t/m^3).

The water content was obtained by adding to the dry mixture the appropriate amount of tap water on a thin layer of soil spread out on a plate. After having been manually mixed for an initial homogeneization, the mixture was conditionned in an hermetic box for two days at least, in order to let it reach an hydric equilibrium. After a manual breaking up leading to a 0/5 mm grinding, the mixture was ready for the compaction test.

3.2. Compaction

Mixtures studied by Mvondo-Ondoa (1979) and Leucate sand with Aix and Provins clays were compacted in a conventional Protor mould (diameter : 101,6 mm) with the modified Proctor hammer (volumic energy of 2679 kJ/m^3).

Mixtures of Speswhite kaolin with Fontainebleau and Missillac sands were compacted with a miniature device. This compaction device enables the compaction of fine soils (particles smaller than 2 mm) in a 70 mm diameter oedometric mould, with a small size hammer designed in order to reproduce the volumic energy of the standard Proctor test (french NF P 94 093 standard, volumic energy of 593 kJ/m^3). Its characteristics are presented on figure 3.

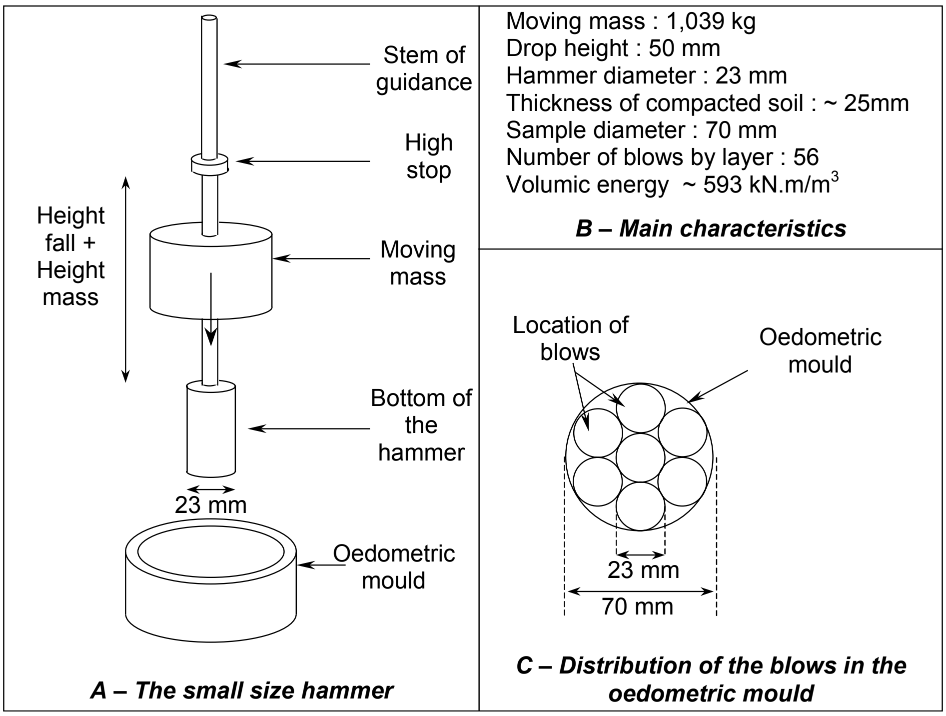


Figure 3 – Characteristics of the compaction device for oedometric mould.

With this device, soils are compacted in two 13 mm thick layers with a distribution of blows similar to the standard Proctor test in a CBR mould (diameter 152 mm). After the compaction, the sample is leveled to obtain a final thickness of 25 mm. Comparisons had been carried out first to get sure this process and the conventional Protor test conduct to the same results (figure 4).

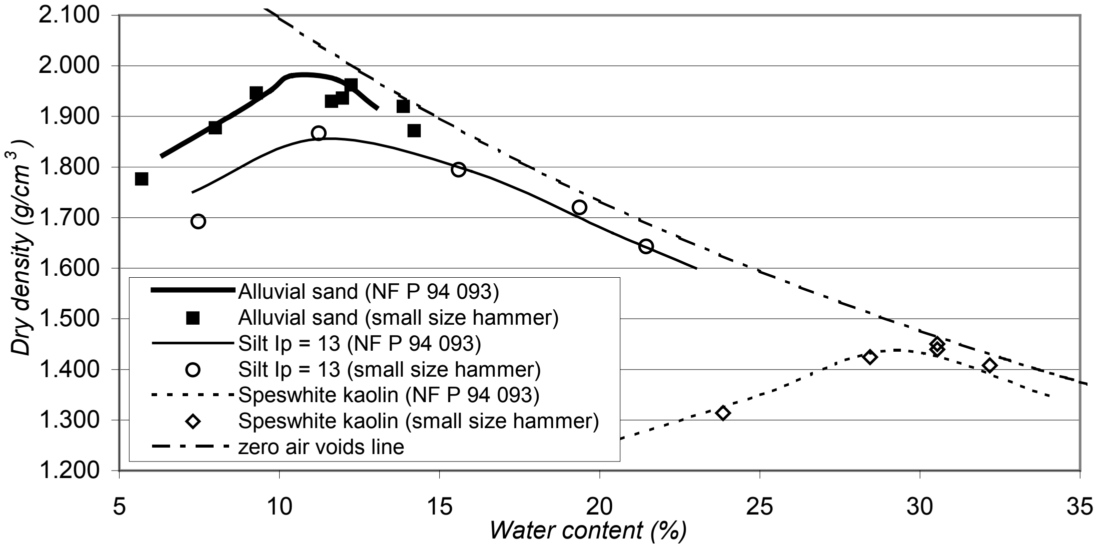


Figure 4 – Compaction curves obtained for various soils with the conventional Proctor test and the small size compaction test (small hammer in oedometric mould).

4. RESULTS AND INTERPRETATION

4.1. Compaction curves

The compaction curves of Speswhite kaolin / Missillac sand are reported on figure 5. For the other mixtures, the results were similar and not presented here in order to simplify the presentation. Between 0 and 15 % of kaolin, the maximum dry density increases with the proportion of kaolin. This value of 15-20 % seems to be a kind of optimum of fines proportion at the Proctor normal energy. But, if the mixture is on the whole at its optimum, what can be said about its fines fraction ? How the sand particles are prevented from compaction by the presence of a fine fraction ? In order to answer to such questions in a quantitatively way, we propose here to describe the physcical state of each fraction.

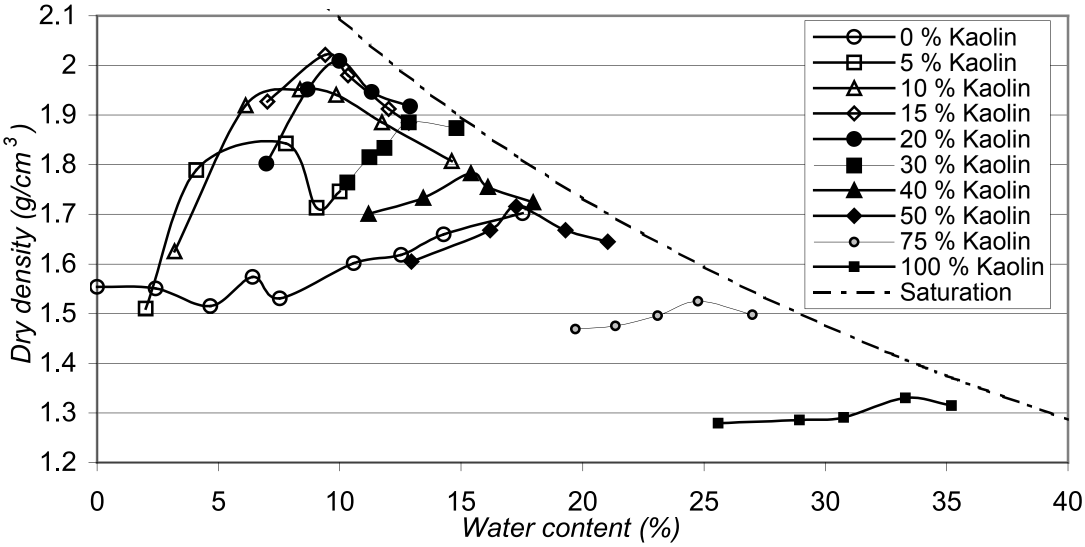


Figure 5 – Compaction curves for « old » Speswhite kaolin / Missillac sand.

4.2. Fines and sand fraction description

If it is assumed that, in a fines / sand mixture, all the water is contained in the fine fraction, for each value of the water content and dry density, three parameters can be calculated in order to describe the physical state of the fines and the sand fraction :

- the apparent dry density of the fines fraction, ρ^*_f, which corresponds to the mass of the fines divided by the volume of the voids between sand particles :

$$\rho^*_f = \frac{\textit{fines dry mass}}{\textit{sample volume} - \textit{sand volume}} = \frac{\rho_d \cdot \rho_s . P_f}{\rho_s - \rho_d .(1 - P_f)} \quad (3)$$

- the water content of the fines fraction, W^*_f, which corresponds to the water mass divided by the fines mass :

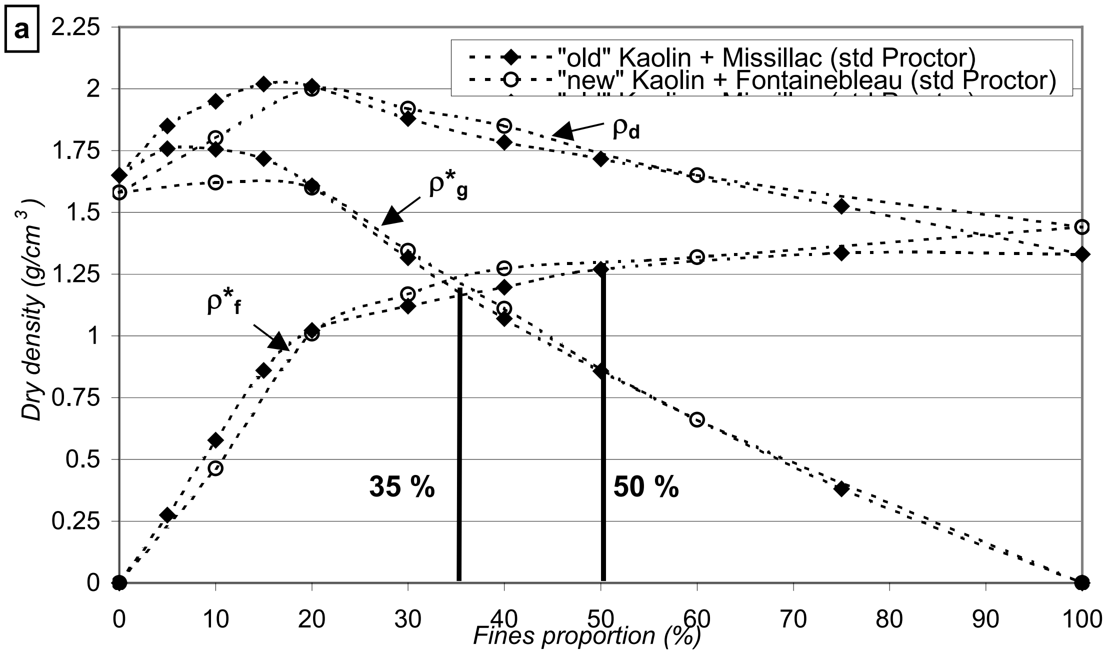
$$W^*_f = \frac{\textit{water mass}}{\textit{fines dry mass}} = \frac{W}{P_f} \quad (4)$$

- the apparent dry density of the sand fraction, ρ^*_g, which corresponds to the dry mass of the sand divided by the total volume of the compacted sample :

$$\rho^*_g = \frac{\textit{sand mass}}{\textit{sample volume}} = \rho_d .\left(1 - P_f\right) \quad (5)$$

with ρ_d the gobal dry density of the sample, ρ_s the average density of the particles, W the global water content of the mixture and P_f the proportion of fines in the mixture. It can be noted that such calculations had already been used in order to study coarse fractions in earth dams (Post , 1953).

On figure 6 are reported ρ^*_f et ρ^*_g parameters versus the fines proportion at the optimum Proctor. Mixtures compacted at the standard Proctor energy (figure 6-a) are distinguished from those compacted at the modified Proctor energy (figure 6-b). On figure 7, the W^*_f parameter, calculated at the optimum Proctor water content is reported versus the fines proportion for the four families of mixtures studied here.



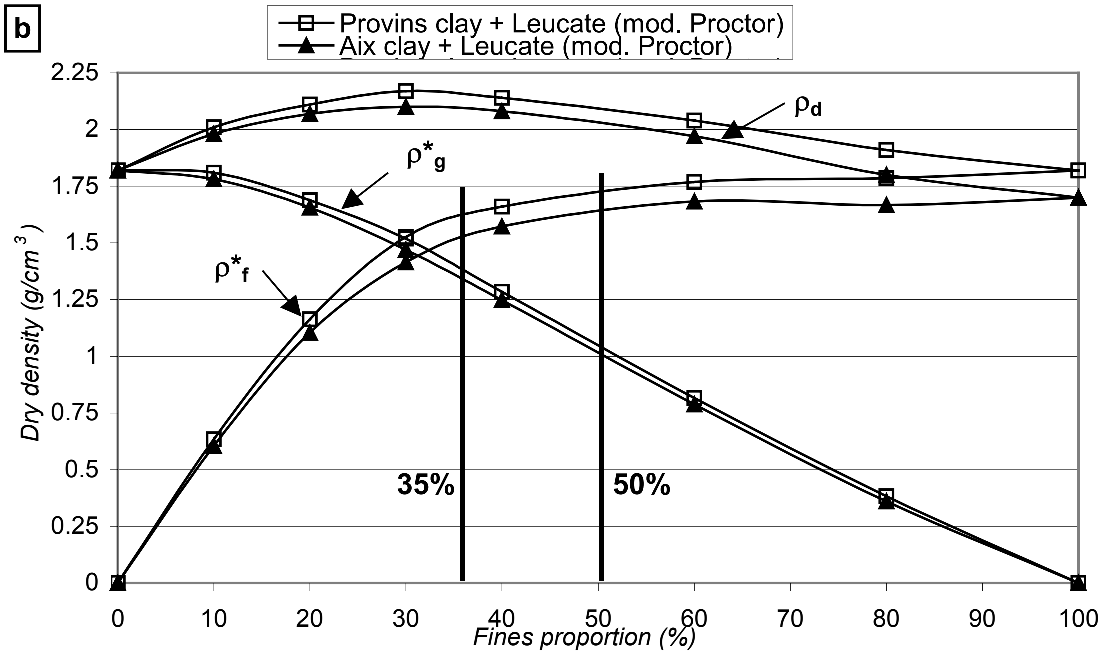


Figure 6 – Influence of the fines proportion on the global dry density (ρ_d), the dry density of the fines fraction (ρ^*_f) and the apparent dry density of the sand fraction (ρ^*_g) at the standard (a) and modified (b) Proctor.

On figure 6, it can be seen that mixtures of Leucate sand compacted at the modified Proctor energy reach a maximum dry density at the optimum for a fines proportion of approximately 30 %, whatever is the nature of the fine fraction. Although the Missillac and the Leucate sands show similar grain size distributions, mixtures of Missillac sand with Sopeswhite kaolin, compacted at the standard Proctor energy, reach their maximum dry density with only 15-20 % of fines. At the standard Proctor energy, the mixtures of Speswhite kaolin with Missillac sand and Fontainebleau sand reach this maximum dry density at the optimum for respectively 15-20 and 20 % of fines. Thus, the fines proportion conducting to highest dry density at the optimum Proctor seems to depend mainly on two parameters : the compaction energy and the gradation of the sand fraction (although it was not studied here, the characteristics of the fine fraction is also supposed to have an influence). The higher is the compaction energy and/or the badest graded is the sand fraction, the more the maximum dry density is obtained for high fines proportions.

The evolution of ρ^*_f with the fines proportion presents three distinct stages. Between 0 and approximately 20-30 % of fines de fines, this parameter increases linearly and sharply with the fines proportion and then, beyond 20-30 % of fines, the slope of the cruve decreases clearly. A difference can be noted here between the two compaction energy. As a matter of fact, ρ^*_f reaches a value of 90 % of the optimum Proctor dry density of the fines (namely the dry density for 100 % of fines) for approximately 35-40 % of fines under a modified Proctor energy (figure 6-b) and only 45-50 % of fines under a standard Proctor energy (figure 6-a). Thus, at the modified Proctor energy, the fine fraction behaviour would become dominating on the sand behaviour as soon as its proportion in the mixture exceeds 35-40 %, while at the standard Protcor energy it would become dominating only beyond a proportion of 45-50 %.

About the evolution of ρ^*_g with the fines proportion, it is seen that between 0 and 10-20 % of fines, the apparent dry density of the sand stagnates and can even increase in a first stage. Beyond, it decreases steadily with the fines proportion. The evolution of this parameter between 0 and 10-20 % underlines the influence of a slight amount of fines in a sandy soil. As a matter of fact, it can be commonly observed how difficult it is to compact pure sands containing very low rates of fines. This obervation is illustrated here by the increase of ρ^*_g between 0 % of and low proportion of fines. It can also be noted that, between 0 and 10-20 % of fines, the presence of fines don't disturb the compaction of the sand fraction since ρ^*_g doesn't decrease in this span. Thus, between 0 and 10-20 % of fines, the fine fraction fills in the voids between sand particles and doesn't disturb the compaction of this latter fraction. But in fact, it seems that this 10-20 % threshold could depend on the nature of the sand fraction. Thus, for a bad graded sand like the Fontainebleau sand, 20 % of fines approximately are necessary to cause the decrease of ρ^*_g , i.e. to conduct the mixture from a sandy mixture to an intermediate mixture. For better graded sands, like Leucate or Missillac sands, only 10 % of fines seem to be enough.

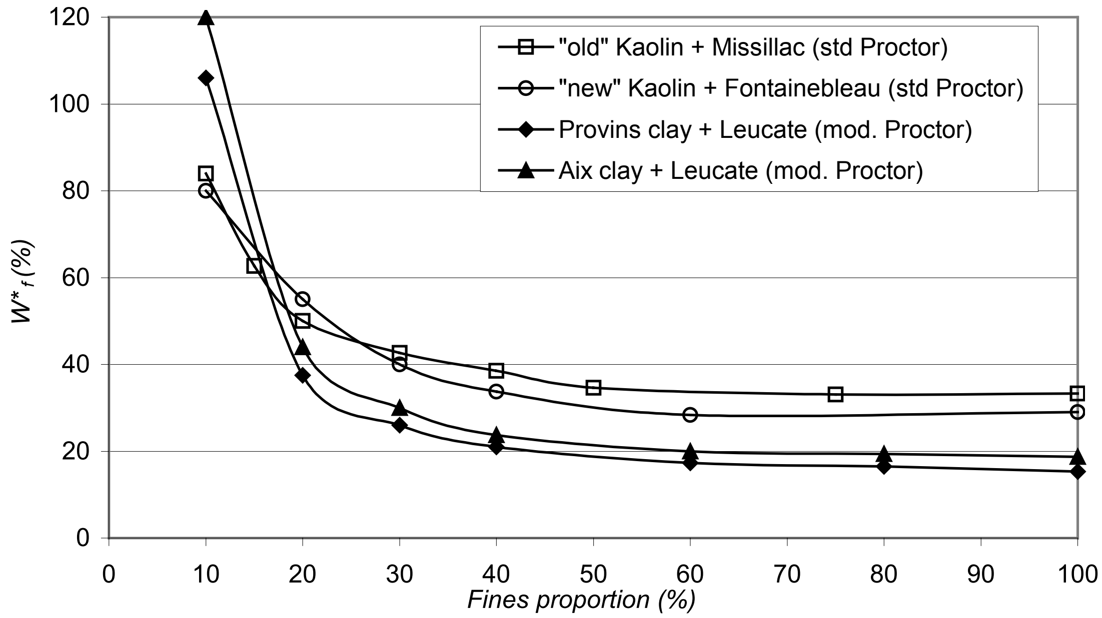


Figure 7 – Influence of the fines proportion on the water content of the fine fraction W^*_f.

Finally, the evolution of the water content of the fine fraction with the fines proportion (figure 7) shows a decrease in three stages. Between 0 and 20 % of fines, W*f is extremely high and gets lower than the liquid limit only beyond 15 % of fines. This observation could be a consequence of the hypothesis that all the water is in the fine fraction, which is probably false for such sandy mixtures. Beyond 20 % of fines, the decrease of W^*_f is softer and the curves reach an asymptote for approximately 60 % of fines. Thereby, for mixtures containing between 60 and 100 % of fines, the water content of the mixture at the optimum Proctor can be directly deducted from the water content at the optimum of the fine fraction alone (i.e. for a 100 % of fines mixture) which conducts to the following relation : $W_{opn} \sim P_f \, . \, W_{(opn\ -\ 100\ \%\ fines)}$., where $W_{(opn\ -\ 100\ \%\ fines)}$ is the water content at the optimum Proctor of a 100 % of fines mixture.

It is also observed that, for fines proportion higher than 20 %, W^*_f at the modified Proctor energy is clearly smaller than for the standard Proctor energy. Similarly, at the modified Proctor energy, the constant difference between W^*_f for the Provins clay and Aix clay mixtures could be the result of an influence of the fines physico-chemical properties. It then appears that this influence is not as important as the compaction energy influence.

4.3. Synthesis

The former interpretations can be used to propose a scheme of the fines and coarse fraction organization in the compacted soil (*cf* figure 8).

When the fines represent less than 10 to 20 % of the mixture, they are very wet and part of the water is probably not bond to the fines but located on the sand particles surface. This kind of mixture is represented by the case A on figure 8. Contacts between sand particles are direct and strong. The fines don't even fill in the voids between sand particles and the global behaviour of the mixture is very close to the sand behaviour.

Between 10-20 and 35-50 % of fines, contacts between sand particles are fewer and weaker, because of an increasing presence of clay particles, in the voids and on their surface (figure 8, case B). Nevertheless, sand particles are numerous enough to disturb the compaction of the fine fraction. The fines completely fill in the voids between sand particles and also disturbs their compaction. The mixture behaviour is a complex function of the fines and sand behaviours.

Finally, beyond 35-50 % of fines, sand particles are too few to develop rubbing contacts. They are embedded in the fine fraction and almost don't disturb its compaction. The dry density and the water content of the fine fraction are very close to their values at the optimum Proctor of the 100 % of fines mixture. The global behaviour of these mixtures is controled by the behaviour of the fine fraction.

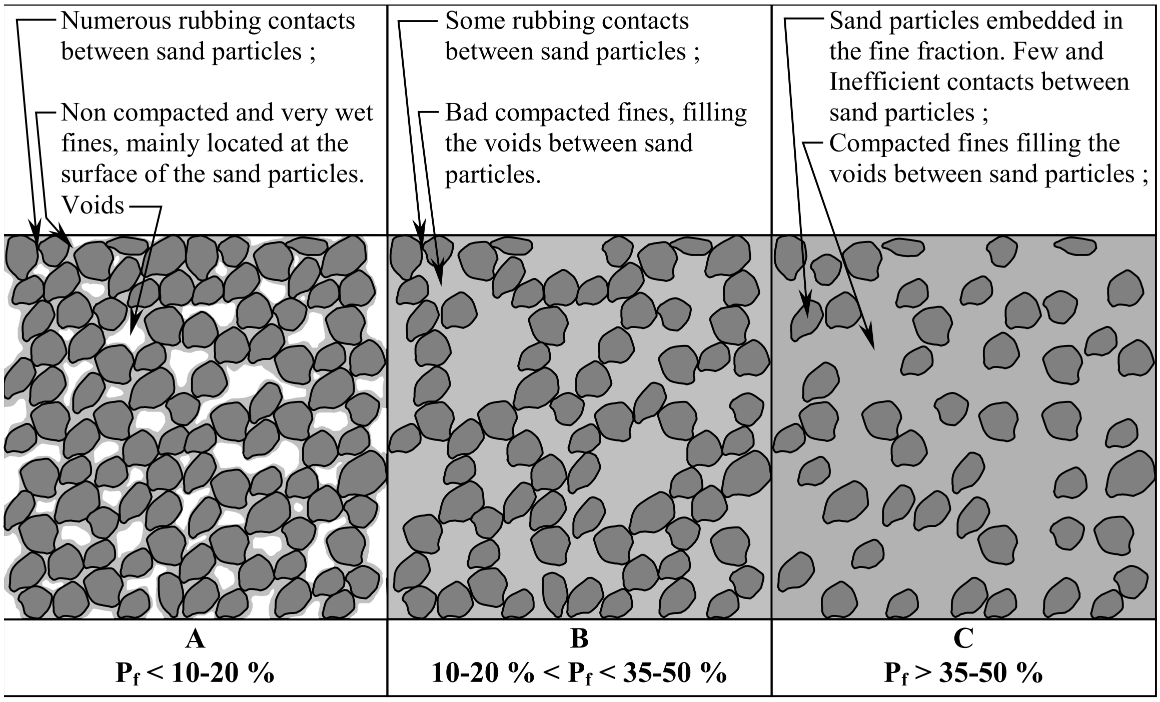


Figure 8 – Schematic organisation of particles depending on the fines proportion.

5. DISCUSSION ON THRESHOLDS

These observations on the physical state of fine and coarse fractions in compacted mixtures bring some informations on fines proportion thresholds which can conduct to a discussion on their meaning in the current classifications. On the base of an international survey led by Havard (2003) among the members of the AIPCR, a comparison between the chosen thresholds can be done (table 2). Values between 63 and 80 µm are generally chosen to distinguish fine and coarse fraction, depending on the country. We will assume here that this difference has no consequence on our discussion.

Table 2 – Fines proprotion thresholds in the main national classifications (Havard, 2003)

Country (fine/coarse)	Threshold between sand / intermediate soil	Threshold between Intermediate soil / fine soil
Belgium (63 µm)	10 %	-
Germany (63 µm)	5 %	40 %
U.K. (63 µm)	15 %	80 %
Spain (80 µm)	25 %	35 %
France (80 µm)	12 %	35 %
Italy (75 µm)	10-15 %	35 %
Quebec (80 µm)	-	50 %
Cuba (75 µm)	-	50 %
U.S. (75 µm)	-	35 %
Japan (74 µm)	-	50 %
Portugal (75 µm)	-	50 %
Swiss (63 µm)	-	50 %

From table 2, three families of classifications can be distinguished :

- classifications differentiating only fine soils, with one threshold (Quebec, U.S., Japan,…) ;
- two thresholds classifications differentiating sandy soils, intermediate soils and fine soils by the mean of two thresholds (Germany, U.K., Spain, France, Italy) ;
- one classification which differentiates only sandy soils, with one threshold (Belgium).

About the distinction fine soils / intermediate soils, it will be noted that classifications generally use a threshold either of 35 % or of 50 % of fines. According to the experimental results presented here (*cf* figure 6), it's difficult to decide what value is the most relevant since, in both cases, the dry density of the fine fraction in the mixture is lower than its optimum value.

In classifications differentiating sandy soils from intermediate soils, the threshold varies between 5 and 15 % of fines. It has been seen here that, in fact, this value probably depends on the grain size distribution of the sand fraction, and in particular on its good or bad gradation. Thus, a threshold of 5 % could be relevant for a very well graded sand fraction, whereas a threshold of 15 % would be well adapted for a bad graded sand fraction. Moreover, the properties of the fines fraction probably plays a role in this phenomenon.

This little discussion shows that penomena are quite complex and force to arbitrary decisions on thresholds values in order to built relevant but simple classifications.

6. CONCLUSION

The compaction tests carried out on mixtures of various sand and fines fractions, with two different compaction energy, cast new light on the relations between the fines proportion and the compaction behaviour of soils. The description of the physical state of the fine and coarse fractions at the optimum Proctor conducted us to distinguish three main families of mixtures :

- mixtures containing between 0 and 10-20 % of fines, which compaction behaviour is controled by the sand fraction behaviour. It has been seen that in such mixtures, the fine fraction can favour the compaction of the sand fraction. The 10-20 % threshold probably depends on the grain size distribution of the sand fraction ;
- mixtures containing morethan 35-50 % of fines, which behaviour is chiefly controled by the fine fraction . It can be noted that this threshold could depend on the compaction energy ;
-intermediate mixtures, containing between 10-20 an 35-50 % of fines, which compaction behaviour is influenced by both fine and sand fractions, with compex interactions.

It was noted that not all soils classifications adopt this distinction between three families of soils, and that thresholds vary notably from a classification to an other. Given that the nature of the sand fraction, of the fine fraction or the compaction energy can influence the phenomenon, it can easily be understood that a threshold in a classification is the result of an arbitrary choice, which could partly explain the variety observed here.

Moreover, this study also brings elements for thought on the stabilization of soils. As a matter of fact, in a sandy soil (less than 10-20 % of fines), the lime will probably have a limited action because of the small amount of clay particles, while an hydraulic binder will be particularly efficient to bond sand particles. Beyond 10-20 % of fines, the fines fill in the voids between sand particles and limit the action of the hydraulic binder. At the opposite, the increasing amount of clay particles will favour the pouzzolanic reaction and increase its efficiency.

REFERENCES

Al-Shayea, N. A. (2001) The combined effect of clay and moisture content on the behaviour of remoulded unsaturated soils. Bull. Assoc. of Engineering Geology. Vol 62, pp 319-342

Havard, H. (2003) Limites d’emploi des sols naturels, spécifications et contrôles dans les travaux de terrassement. Rapport AIPCR, Comité technique 12, Sujet n°1 : Matériaux naturels hors spécification courante et pertinence du contrôle des travaux de terrassements, 89 p.

Mvondo-Ondoa, J. (1979) Rôle de la granularité et de la composition minéralogique sur la compactabilité et la résistance au cisaillement des mélanges de sable et d’argiles. Thèse 3ème cycle Université P. Et M. Curie - Ecole Nationale Supérieure des Mines de Paris, 149 p.

Norme NF P 94 093 (1999) Détermination des références de compactage d'un matériau - Essai Proctor normal - Essai Proctor modifié. Association Française de Normalisation (AFNOR)

Post G., Londe P. (1953) Les barrages en terre compactée. Pratiques américaines (Earth dams. American practices). Gauthier-Villars Ed.148 pp.