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Effects of organic matter on mechanical properties of dredged sediments for beneficial use in road construction

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In France, the road construction sector is the greatest consumer of granular materials, with a yearly consumption of about 200 million tons. With the shortage of standard materials, the valorisation of dredged sediments for road construction could constitute an interesting solution. Dredged sediments generally consist of a mineral phase, an organic phase (in various forms) and a liquid phase (water). The presence of organic matter (OM) in sediments, even in small amounts, affects their engineering properties. The main objective of this study is to investigate the effects of organic matter content on the engineering properties of dredged sediments. For this purpose, a specific methodology to reconstitute samples with different amounts of organic matter contents is proposed. The evaluation of the effects of organic matter content in term of compressibility, shear strength, compaction and bearing capacity show that even for high amount of organic matter the performances of the studied samples are compatible with the use in road construction sector.

1. Introduction

The increase in the demand of granular materials combined with the environmental constraints for opening new quarries impose better management of natural resources. Each year in France, the field of civil engineering uses more than 400 million tons of materials of which 96% are of natural origin [1]. In this context, the valorisation of waste such as dredged sediments could constitute an alternative sustainable material [1–11].

In France, the road construction sector is the greatest consumer of granular materials, with a yearly consumption of about 200 million tons. Hence, the valorisation of dredged sediments for road construction could constitute an interesting solution. However, in the road construction sector, the material engineering characteristics needed vary and depend on the road category, the layer of the road structure and the type and amount of binders used.

However, the dredged sediment generally consists of a mineral phase, an organic phase (in various forms) and a liquid phase (water). It generally agreed that the presence of organic matter (OM) in sediment, even in small amounts, affects their engineering properties [3–6,10–17]

In road applications, under different practice guidelines developed in different countries, the use of organic materials is limited to organic matter content between 2% and 4% for road pavement material and between 5% and 7% for use as embankment materials [18]. The argument used for the limitation of the amount of organic materials is generally linked to the evolution of organic matter with time, which was supposed to increase the void ratio and hence the compressibility of the material. In this context, as a first step in the valuation of dredged sediments in road construction, it was considered important to explore to what extent

organic matter affects the mechanical parameters and how these parameters will evolve with the evolution of the organic matter content.

Previous studies have been conducted about the effects of organic matter on soil properties. Organic matters have been reported to have significant effects on mechanical properties of soil such as decreasing shear strength or soil resistance [10–14,16,19–22]. Much of conducted researches had been done on the engineering behaviour of highly organic soils. However, relatively little is known about the engineering behaviour of dredged marine sediment with an amount of organic matter just higher and lower than the prescribed values for use in road construction. Therefore, the aim of the present study in addition to explore the effects of organic matters on the mechanical properties is to investigate the veracity of prescribed limits in relation with the evolution of these properties. The relationship between the measured properties, in the range of organic matter contents investigated, will be also studied.

2. Materials and methods

2.1. Materials

The sediments (S) are dredged from Dunkirk Harbour, which is the third most important French harbour. By its location, it is ranked as the seventh port on the northern European side, extending from Le Havre to Hamburg.

The dredged sediments were stored in barrels at the laboratory after a period of natural dewatering on site (Figure 1(a)). In the laboratory, samples from different barrels are mixed to constitute a representative sample.

The organic material used for specimen enrichment was an industrial compost (C) with high organic matter content (Figure 1(b)). Prior to mixing with sediments for enrichment, a specific procedure of preparation was developed in order to ease the mixes.

2.2. Samples preparation

Prior to the preparation of the different samples, marine sediments and the compost (organic material) were first oven dried at low temperature to reduce the water in the materials. The organic material was pulverised in a blender to reduce the size of its constituents, and then the obtained material was sieved at 400 μm to remove coarse particles (Figure 1(b)).

The sediments with an initial organic matter content of 5.6% was mixed with the compost (with an organic matter content of 42%) in the required proportions to prepare samples with organic matter content ranging from 7.5% to 15%, with a step of 2.5% (Figure 2). The choice of these ranges of values will also make it possible to analyse whether the limits set in terms of organic matter content in road works material is correlated to a significant change in the engineering properties.

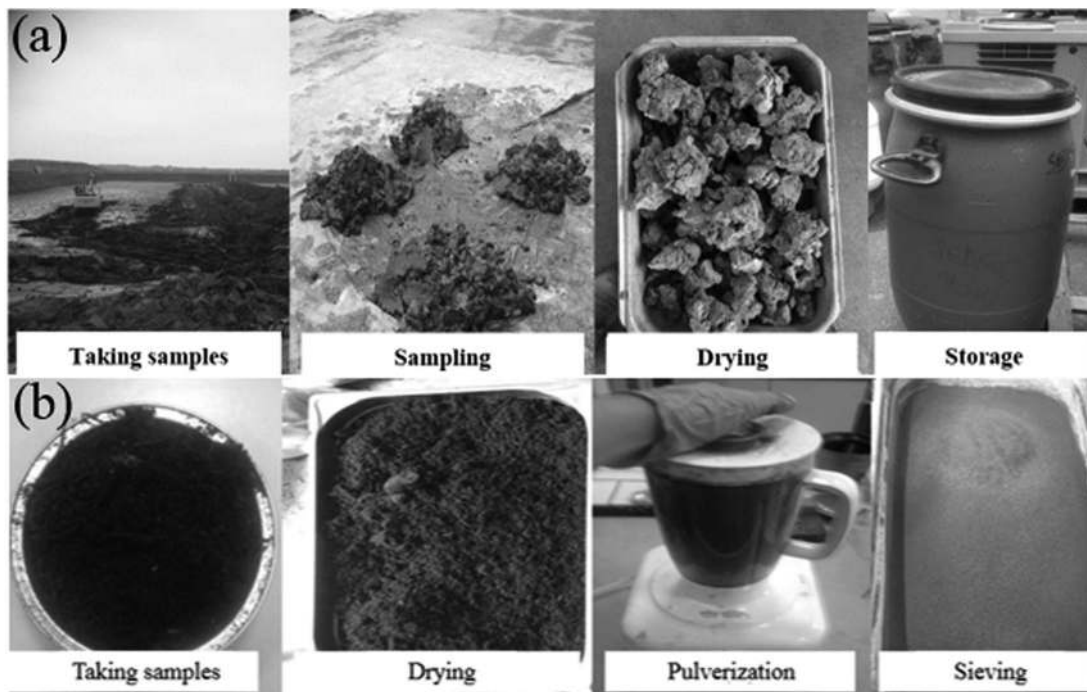


Figure 1. (a) Sample preparation of the dredged sediment; (b) sample preparation of the organic material.

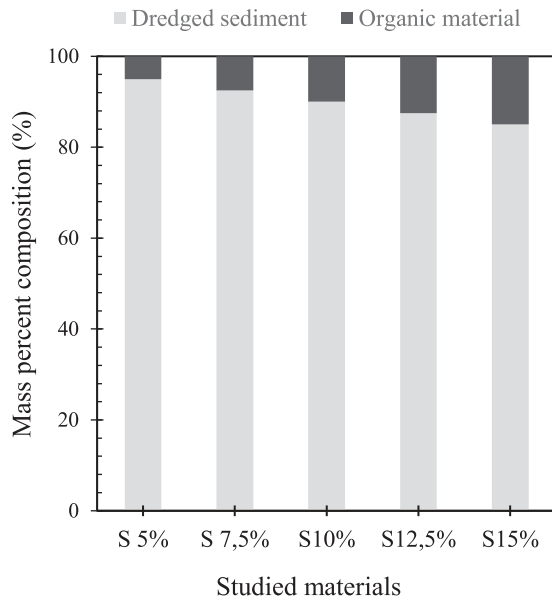


Figure 2. The composition of the reconstituted samples.

2.3. Experimental program and test procedures

The experimental program undertaken in the framework of this research enclose the determination of the physical properties of the raw materials as the reconstituted samples used in the study. The physical properties measured consist in the determination of grain size distribution curves, the initial water content, the organic matter content, the consistency limits, the methylene blue value, the specific gravity, the specific surface area using BET theory for each material. The tests are undertaken according respectively to the test standards (ISO 13320 [23]; NF P94-050 [24]; XP P94-047 [25]; NF P94-051 [26]; NF P94-068 [27]; EN ISO 18753 [28]; ISO 9277 [29]).

To assess the impacts of organic matter content on few mechanical properties, the experimental program enclose compaction tests according to test standard NF P94-093 [30] and the measurement of Immediate Bearing Index (IBI) following to test standard NF P94-078 [31]. The compressibility test is performed according to test standard XP P 94-090-1 [32]. Finally, the measurement of shearing resistance is assessed according to test standard NF P94-071 [33].

For compaction aptitude of the samples, the optimum water content, the maximum dry density and the immediate bearing index are evaluated successively using Normal Proctor tests and Modified Proctor tests.

For the compressibility study, the tests are conducted on reconstituted samples with the compaction method (Normal Proctor energy). The samples are prepared with a dry density equal to 95% of the optimal dry density and a water content on the wet side of the

compaction curves. This procedure was setup after various tests to reconstitute homogenous samples with a controlled void ratio and a high saturation degree. The loading and unloading procedures of the samples used during the tests are as follows:

- A first loading phase with pressure increments fixed at each step twice the previous pressure to finally reach a pressure value equal to 600 kPa. It is to know that this static loading is supposed to correspond to the pressure induced in the material by the Normal Proctor energy NF P94-093 [30].
- Unloading phase, up to 150 kPa following the same pressure increments than the loading phase.
- Reloading, with the same pressure increments, up to 1200 kPa.
- Finally unloading up to 150 kPa by following the same pressure increments than the first loading pressures.

For the shearing resistance, the samples are prepared with a dry density equal to 95% of the optimal dry density and a water content on the wet side of the compaction curves using a Normal Proctor energy (as in the compressibility test). Direct shear tests were conducted under three different normal stresses for each material ($\sigma_1 = 150$ kPa, $\sigma_2 = 300$ kPa, $\sigma_3 = 600$ kPa).

3. Results and discussion

3.1. Physical properties

Prior to the study of organic matter content on the mechanical properties of the dredged sediments, the physical properties of the raw materials are evaluated (Table 1). From the obtained results, the material classification according to the French soil classification system dedicated to road works [18], classify the sediment as an F_1A_1 type materials. The raw sediment is considered as 'Low plasticity silty loam with a low organic matter content'.

The compost exhibits a high amount of organic matter and a grain distribution curve coarser than the dredged sediments. The methylene blue values are comparable to that of dredged sediments. The specific gravity, as expected, is lower to that of the dredged sediments. This low value is probably due to the presence of organic matter.

The measurement of the physical properties on the reconstituted samples with increasing amount of organic matter content is addressed in Table 2 and Figure 3 for grain size distribution curves. From the obtained results, it can be shown that the organic matter content affects in the same way the liquid limit values and the plastic limit values. The plastic index

Table 1. The engineering properties of the raw sediment and the organic material.

Parameters	Raw sediment (S)	Organic material (C)
Grains size < 2 μm (%)	18.87	2.07
2μm < grains size < 63 μm (%)	56.74	29.35
63 μm < grains (%)	24.39	68.58
Water content (%)	20.19	23.02
Organic matter content «OM» (%)	5.67	42.24
Liquid limit «W _L » (%)	29	–
Plastic limit «W _p » (%)	17	–
Plasticity index «I _p » (%)	12	–
Methylene blue value «MBV» (g/cm ³)	0.93	1.03
BET specific surface area (m ² /g)	6.84	0.94
Specific gravity	2.57	1.92
Maximum dry density «MDD» (g/cm ³)	1.6	–
Optimum water content «OWC» (%)	18.62	–
Immediate Bearing Index «IBI» (%)	17	–
Compression index (Cc)	0.16	–
Recompression index (Cr)	0.017	–
Initial void ratio (e ₀)	0.83	–
Preconsolidation pressure «σ'c» (kPa)	93	–
Angle of internal friction «φ» (degrees)	24.27	–

values are almost unchanged. The specific gravity as discussed above, is decreased by increasing the amount of organic matter, and the methylene blue value is almost unchanged. In terms of samples classification, the reconstituted samples with increasing amount of organic matter content are almost within the same class of material classification than the dredged sediments (Table 1, fascicule 1 [18]).

3.2. Compaction characteristics

Figure 4(a) and (b) show the compaction curves of the studied samples with different amount of organic matter following the Normal Proctor test and Modified Proctor test, respectively. Comparing the shape of compaction curves, these later are shifted to the right and down with the increasing amounts of organic matter in the samples. This result is valid for both types of Proctor tests (Normal and Modified).

Table 2. Physical properties of the reconstituted samples.

Parameters	Raw sediment (S)	S 7.5%	S 10%	S 12.5%	S 15%
Grains size < 2 μm (%)	18.87	19.38	17.59	16.38	15.20
2 μm < grains size < 63 μm (%)	56.74	56.60	53.79	51.88	50.03
63 μm < grains (%)	24.39	24.02	28.62	31.74	34.77
Passing at the 80 μm sieve (%)	79.11	79.03	73.51	69.54	66.43
Liquid limit «W _L » (%)	29	–	48	52	62
Plastic limit «W _p » (%)	17	–	34	40	50
Plasticity index «I _p » (%)	12	–	43	14	12
Methylene blue value «MBV» (g/cm ³)	0.93	–	32	1.39	1.38
Specific gravity	2.57	–	11	2.51	2.45
SETRA class	F ₁₁	–	1.09	F ₁₁	F ₁₂
Type behaviour	A ₁ F ₁₁	–	2.55	A ₁ F ₁₁	A ₁ F ₁₂
		–	F ₁₁	A ₁ F ₁₂	A ₁ F ₁₂
		–	A ₁ F ₁₁		

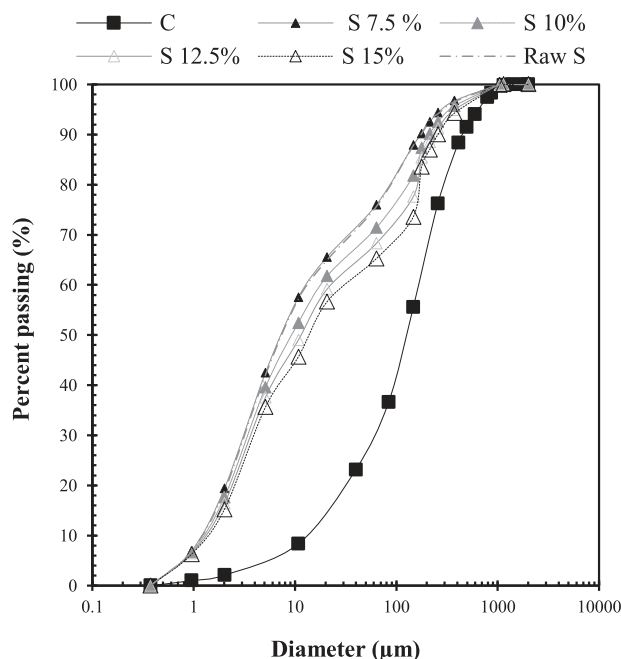


Figure 3. Grains size distribution of the reconstituted samples.

In terms of the change in dry density with the water content, the same curve shape is recorded independently of the amount of organic matter content in the studied samples. All the curves, on the wet side, are parallel to the saturation curves and a substantial effect of water content on the dry density is recorded on the dry side of the curves for all the studied samples. The susceptibility to compaction decreased proportionally to the rate of organic matter added. Malkawi et al. [34] also observed that the organic matter added (peat) to inorganic illitic clayey soil at eight levels (0%, 5%, 10%, 12.5%, 15%, 17.5%, 20% and 30% by weight) increases the critical water content for compaction and decreases the maximum bulk density. A similar trend was observed by Ekwue [20] on other type of soil (sandy loam and clay) at four levels of organic matter content (0%, 4%, 8% and 12% by mass). On the inorganic silty clay soil, Al-Kifae and Hamad [19] also observed a similar trend.

3.2.1. Effect of the organic matter on maximum dry density and optimum water content

The results of maximal dry density and optimum water content evolution with organic matter content for both types of Proctor test is reported in Figure 5(a) and (b). It can be seen that the maximal dry density decreases with increasing organic matter content whereas the optimum water content increases with increasing organic matter content. It can be also noticed that the evolution of the Proctor test characteristics is almost linear in the range of organic matter content explored in this study. The effects of energy compaction on the

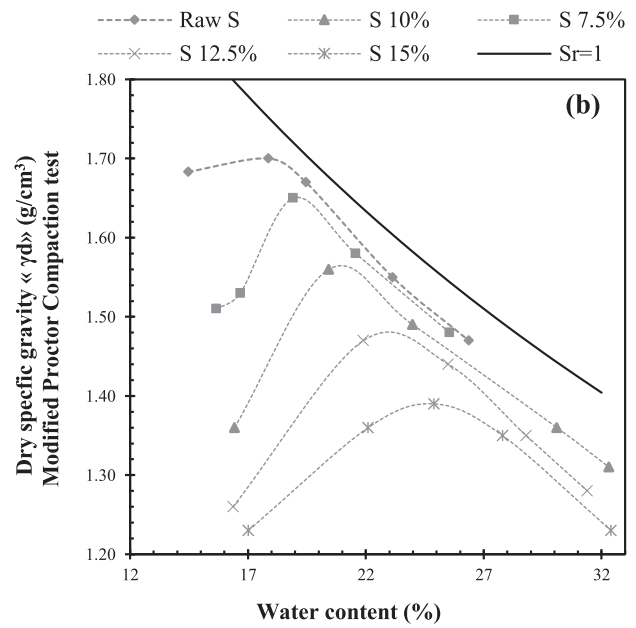
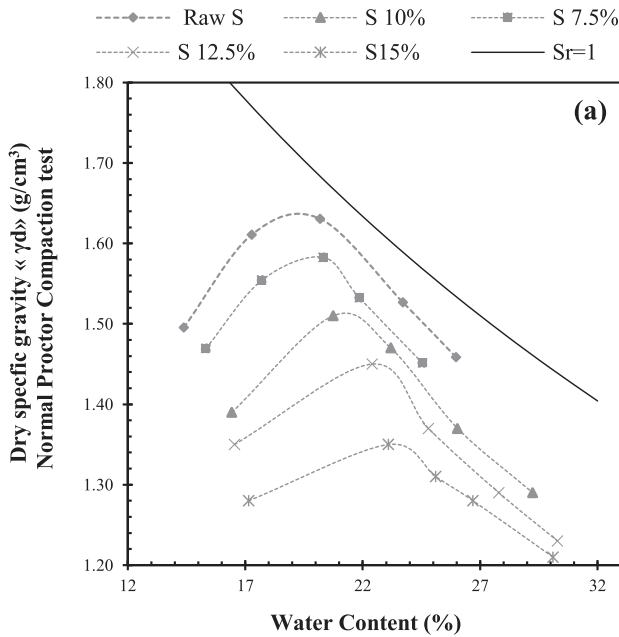


Figure 4. (a) Normal Proctor compaction curves of the reconstituted samples; (b) modified Proctor compaction curves of the reconstituted samples.

Table 3. Studied materials classification according to SETRA [18].

Classification parameters	Raw sediment (S)	S 7.5%	S 10%	S 12.5%	S 15%
Organic matter content (%)	F ₁₁	F ₁₁	F ₁₁	F ₁₂	F ₁₂
Passing at the 80 μm sieve (%)	A	A	A	A	A
Plasticity index «p» (%)	A ₁	A ₁	A ₁	A ₁	A ₁
Methylene blue value «MBV» (g/cm ³)	A ₁	A ₁	A ₁	A ₁	A ₁
Immediate bearing index «IBi» (%)	A _{1m}	A _{1m}	A _{1m}	A _{1m}	A _{1h}
SETRA class	F ₁₁ A _{1m}	F ₁₁ A _{1m}	F ₁₁ A _{1m}	F ₁₂ A _{1m}	F ₁₂ A _{1h}

evolution of the Proctor characteristics are not constant with increasing amount of organic matter content. From the results of Figure 5(a) and (b), we can notice that for a moderate amount of organic matter content (till 8%), the effects of the energy of compaction induces almost a constant decrease of the optimal dry density and an increase of the optimum water content. However, for a high amount of organic matter content, the effects of the energy on the Proctor test characteristics seems to be reduced. This last result is probably due to the fact that the organic matter in excess in the samples, absorb partly the energy transmitted during compaction which limit the impact of compaction energy on the density of the samples. From Figure 6, it can be seen that there exists a linear relationship between the void ratio and the optimum water content. The obtained results above for dredged sediments could be supported by different research works on other types of material. Malkawi et al. [34] have concluded that the organic particles are stiff

when compressed, but when they absorb water are soft and sponge-like, which explains the shapes of compaction curves on the high organic ranges. Ekwue [20] observed that the addition of organic matter to a sandy loam and a clay soil reduced the maximum dry density and increased the optimum moisture content and that the compaction curves of the clay soil presented lower values of bulk density at higher corresponding optimum moisture content than the sandy loam. Zhang et al. [35] observed, after the addition of peat to three soils of different texture (sandy, silt-loam, and clay), that the susceptibility to compaction decreased proportionally to the rate of organic matter added.

3.2.2. Effect of organic matter content on the immediate bearing index

In addition to the compaction tests, the Immediate Bearing Index (IBI) can be measured on the compacted specimens using the normal Proctor test or the modified Proctor test (Figure 7(a) and (b)). The IBI is conventionally defined to evaluate the suitability of a soil or a man-made material to withstand heavy machinery moving over it. Figure 8(a) shows the IBI results at optimum Proctor compaction for the studied samples, it can be seen that when the organic matter content increase from 5% to 15%, the highest organic matter sample loses about 60% of its bearing capacity relative to that of the raw specimen. For the specimens compacted in the CBR mould, according to the Modified Proctor test, a dramatic decrease of the bearing capacity

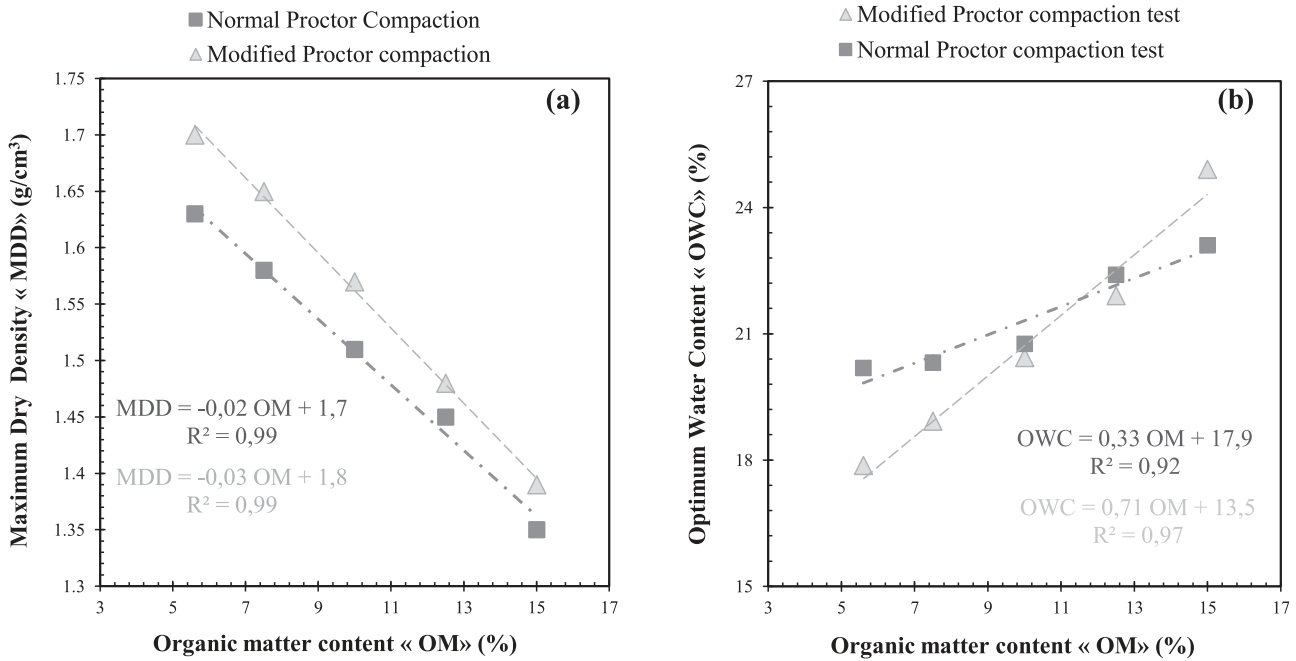


Figure 5. (a) Effect of organic matter on the maximum dry density according to the normal and modified Proctor tests; (b) effect of organic matter on the optimum moisture content according to the normal and modified Proctor tests.

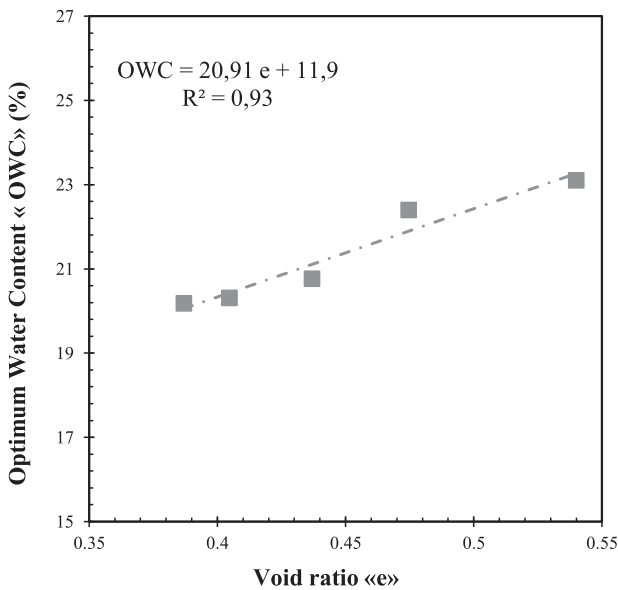


Figure 6. Relationship between the optimum water content and the void ratio.

(around 80%) of the highest organic matter sample compared to that of the raw dredged sediment. In fact, from the observation of the Figure 8(b), it can be said that there exists a strong relationship between the IBI and the maximum dry density. The linear relationship between IBI and maximum dry density could also explain the decrease in the IBI with the amount of organic matter in the samples.

3.2.3. Effect of organic matter content on road material classification

Following the analysis of the effects of organic matter content on the physical as the mechanical behaviour of the studied materials, in this section the effects on materials classification are discussed. On the basis of the French soil classification system dedicated to road works [18], aside from the differences in the organic character of the samples, the material classification based on grain size distribution, consistency limits and MB value was presented in Table 2. It seems that the classification according to the physical parameters stay within the same class of materials (Table 3). The studied materials are classified in group A₁ (Low-plasticity loams, alluvial silts, fine clean sands, low-plasticity). Based on hydric condition, it is possible to classify the studied materials based on their sensitivity to water. Thus, four samples have a moderate hydric condition (with m prefix), one material with a hydric condition (prefix h). From the classification [18], it can be observed that the classification according to the hydric condition stay within the same class of materials even with an organic matter content exceeding 10%.

3.3. Compressibility behaviour

The relation between the effective vertical stress (σ'_v) and the void ratio (e) at the end of the primary consolidation was plotted during the loading and unloading stages for the sediment samples studied (Figure 9).

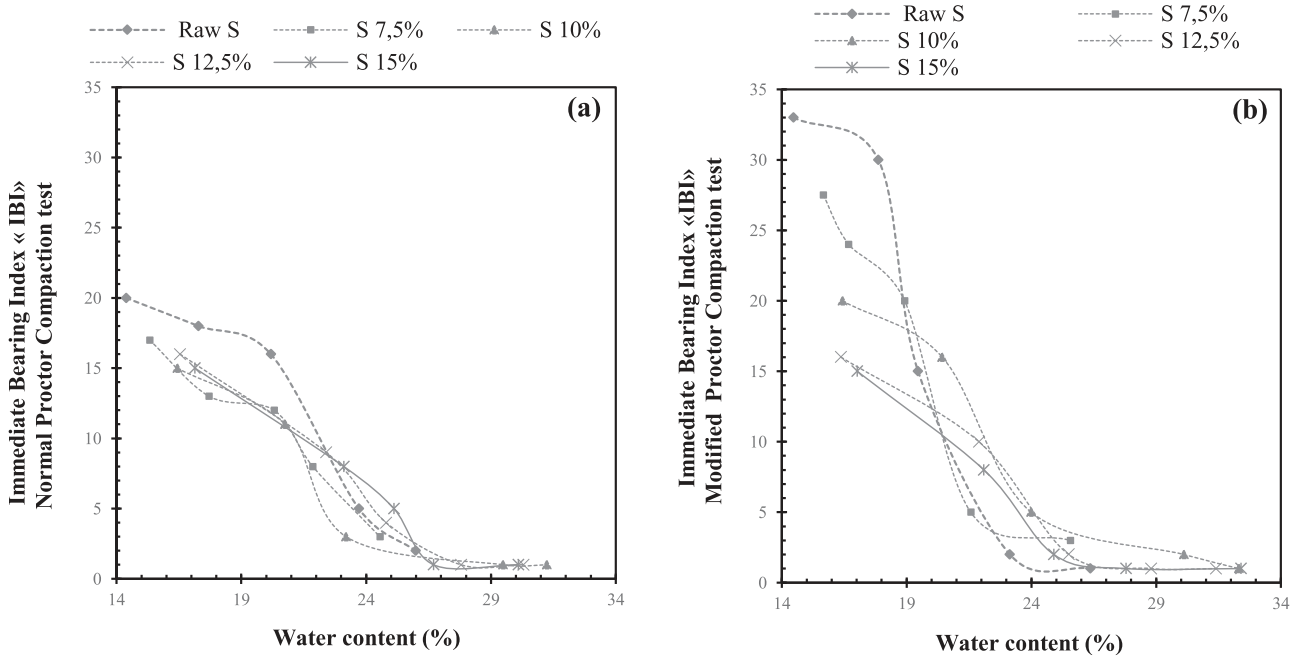


Figure 7. (a) IBI curves of the reconstituted samples using the normal Proctor test; (b) IBI curves of the reconstituted samples using the modified Proctor test.

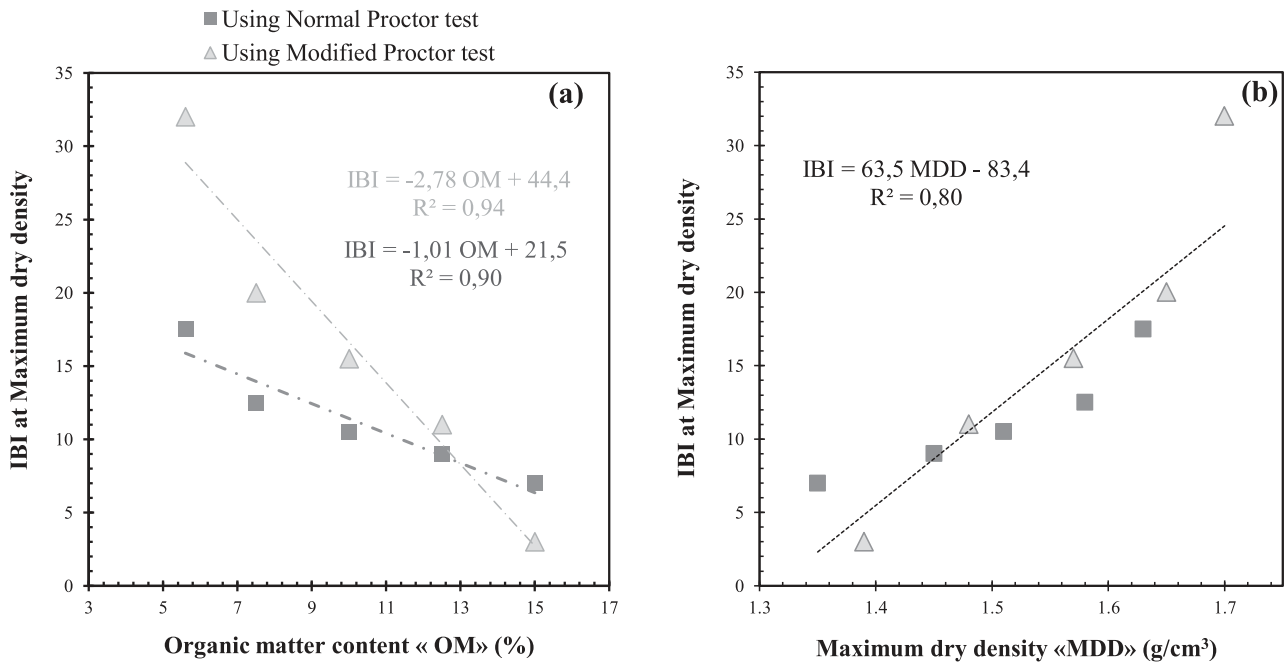


Figure 8. (a) Variation of IBI with organic matter content; (b) Relationship between the IBI and the maximum dry density.

From Figure 9, it can be seen that the organic material added to the raw dredged sediment shift the compressibility curves to higher void ratio values. More over, from Figure 9, it can be seen that with higher amount of organic matter, the slope in the overconsolidated domain as in the normally consolidated domain increase with increasing values of organic matter contents.

3.3.1. Effect of organic matter content on the void ratio

In terms of void ratio evolution with organic matter content, In Figure 10, the initial void ratio versus the organic matter content of the sample studied for compressibility are reported. It can be seen that the void ratio increases with increasing organic matter content.

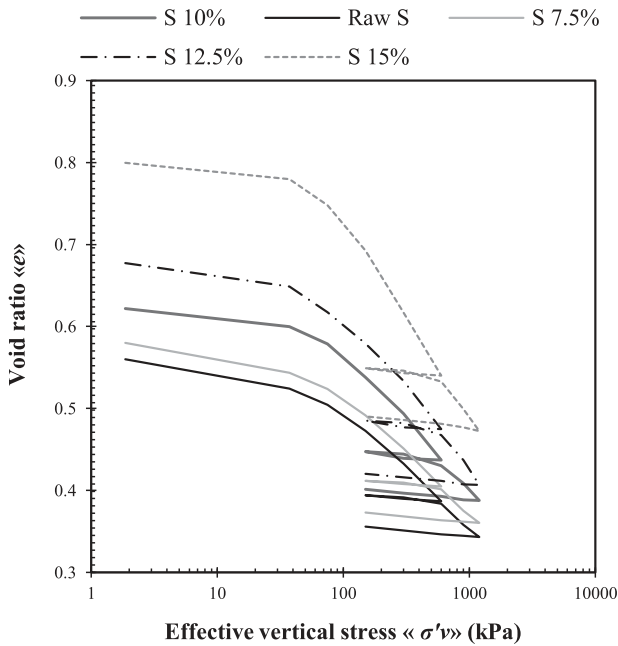


Figure 9. Void ratio versus the effective vertical stress.

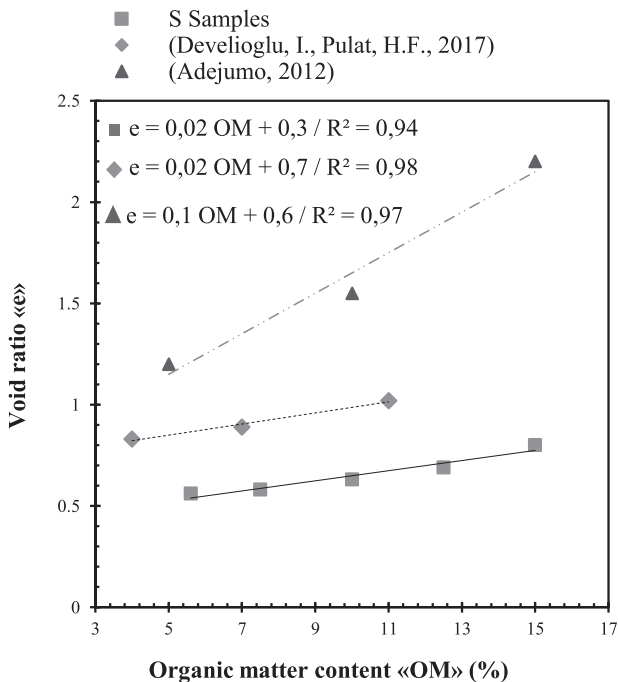


Figure 10. Void ratio versus the organic matter content.

The obtained trend is well-supported by the finding of previous studies. Adejumo [36] has observed that the initial void ratio of organic clay soils increased with increase in organic matter content. A similar trend was observed by Develioglu and Pulat [13] on another type of soil (organic dredged soils) at four levels of organic matter content (0%, 4%, 7% and 11% by mass).

3.3.2. Effect of organic matter content on the preconsolidation pressure

In Figure 11, the preconsolidation pressure estimated from compressibility tests reported in Figure 9 is plotted versus the organic matter content. As it can be seen, the preconsolidation pressure decrease with the increase in organic matter content. It is to know that the measured preconsolidation pressure in the compressibility test performed in this study is the result of the sample preparation.

As discussed previously, the Proctor compaction test, is supposed to induce an equivalent static load of 600 kPa. Comparison of the results obtained from Figure 11 in terms of preconsolidation pressure is far from the expected results. This difference was already mentioned and discussed in previous study on other type of materials [37]. The decrease of the preconsolidation pressure with the increase of the organic matter content could be explained partly by the efficiency of compaction on organic material. The energy transmitted to the sample is partly absorbed by the recoverable deformation of the organic matter which will induce a decrease in the efficiency of the compaction process.

3.3.3. Effect of organic matter content on the compression index (Cc) and the recompression index (Cr)

The compression index (Cc) for each sample was measured on the linear part of the compressibility curve in the normally consolidated domain. The recompression index (Cr) is measured on the linear part of

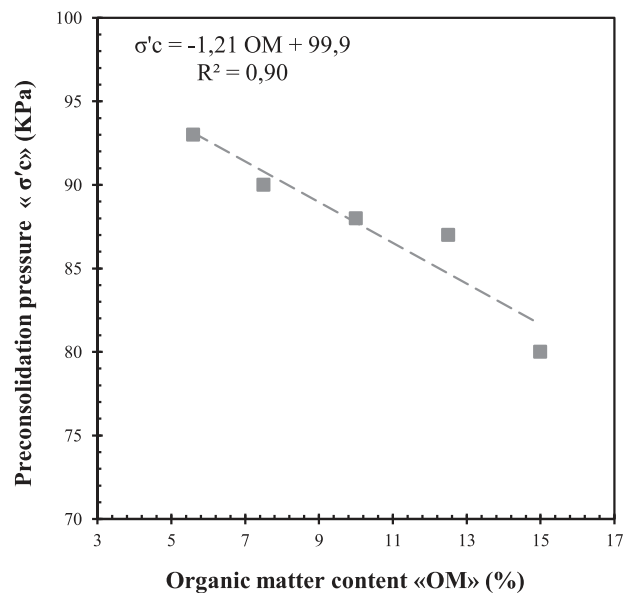


Figure 11. Preconsolidation values versus the organic matter content of the reconstituted samples.

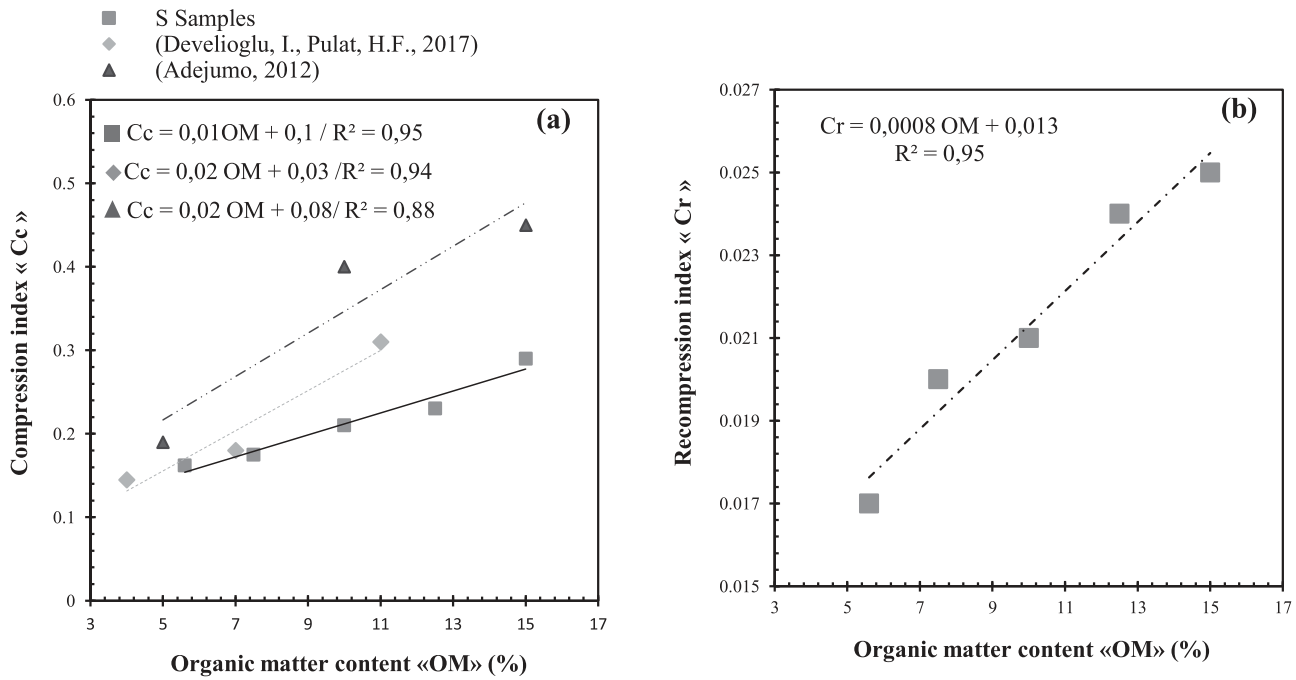


Figure 12. (a) Compression index values versus the organic matter content of different specimens; (b) recompression index values versus the organic matter content of different specimens.

Table 4. Compressibility of soils [39].

Term	Compression index
Slight or low compressibility	0–0.19
Moderate or intermediate	0.20–0.39
High compressibility	0.40 and over

Table 5. Effect of organic material on compressibility behaviour of studied samples.

Name	Compression index	Term
Raw S	0.162	Slight or low compressibility
S 7.5%	0.175	Slight or low compressibility
S 10%	0.21	Moderate or intermediate
S 12.5%	0.23	Moderate or intermediate
S 15%	0.29	Moderate or intermediate

the compressibility curve in the over consolidated domain. The evolution of the obtained values versus the amount of organic matter is shown on Figure 12(a) and (b) respectively for the compression index and the recompression index. From the obtained results, it can be seen that both parameters increase with the increase of the organic matter content. This result is in agreement with research results of several authors [13,35]. McDonald [38] explains this relationship by the increased thickness of the adsorbed water layer associated with the addition of organic matter which increases the compressibility by allowing greater sediment particle mobility, especially regarding to the clay mineral platelets.

In terms of the amplitude of evolution of the parameters with the amount of organic matter, it can be seen that a 100% increase is recorded for an increase of organic matter content from 5% to 15%. In terms of the ratio of the compression index over the recompression index, it seems that this ratio is almost unchanged.

In terms of absolute values interpretations of the obtained results, Sowers [39] has classed the compressibility behaviour of soils according to the compression index on three categories (Table 4). From the Table 5 and Figure 12(a), it seems that the studied samples range on two categories, from 5% to 7.5% of organic matter, the samples are considered as lower compressibility soils, and from 10% to 15% organic matter range, the samples are considered as moderate compressibility soils.

The Figure 13(a) and (b) indicate that there is a significant level of correlation between the compression index and the consistency limits (liquid limit, plastic limit). It is clear that the liquid limit and the plastic limit increased with an increase in compression index for the reconstituted dredged sediments. Some researchers also observed a similar trend: Skempton and Jones [40] conducted consolidation test on a number of clays collected from different locations and gave a linear equation for the compression index for a remoulded sample and Jain et al. [41] on a Weathered Birimian Phyllites (Table 6). However, the plasticity index for the reconstituted

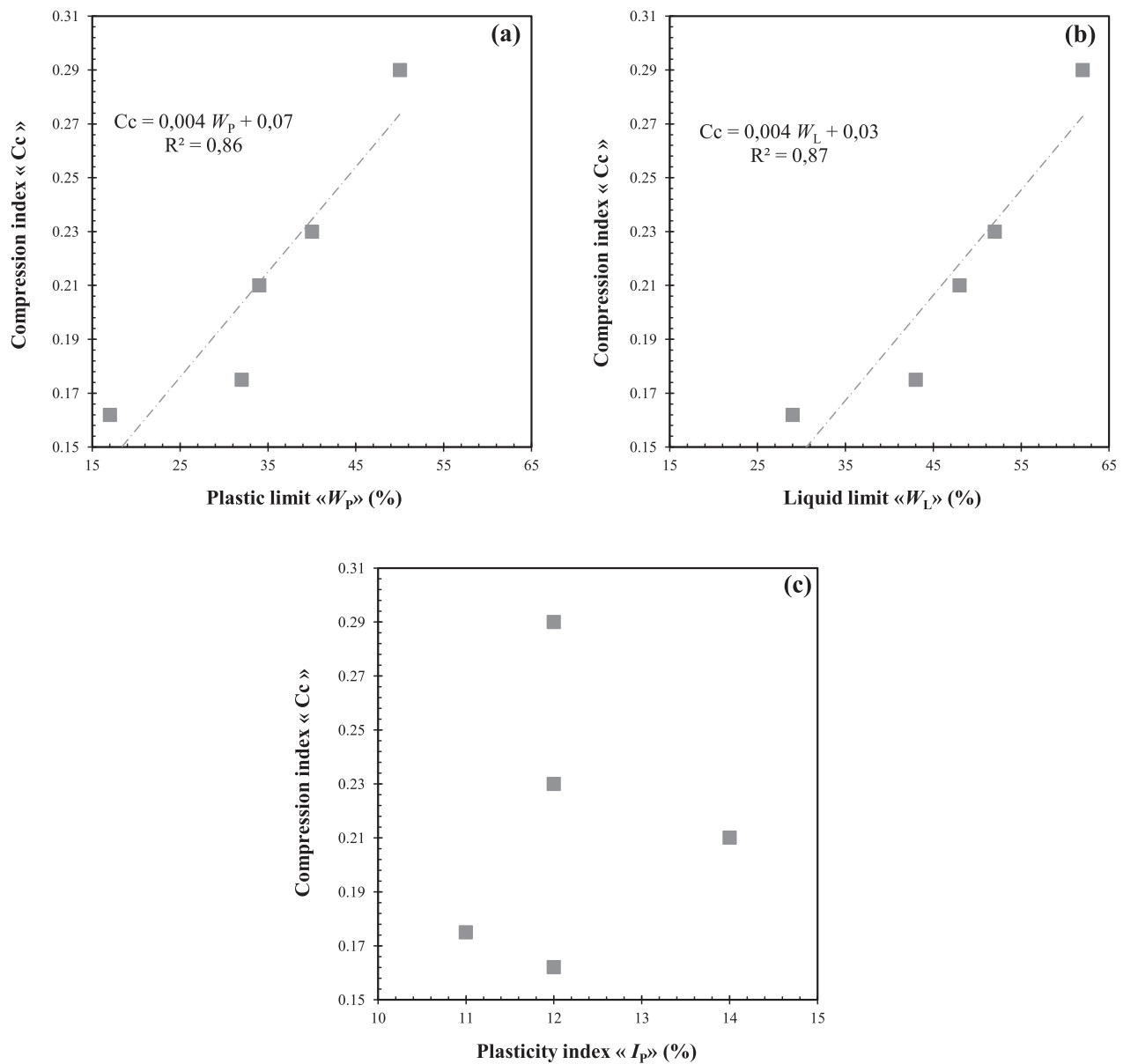


Figure 13. (a) Correlation between the compression index and the plastic limit; (b) correlation between the compression index and the liquid limit; (c) correlation between the compression index and the plasticity index.

Table 6. Relationship between the consistency limits and the compression index.

Parameters	Present study	[40]	[41]	[43]
W_L	$Cc = 0.004 W_L + 0.03$	$Cc = 0.007 W_L - 0.049$	–	–
W_p	$Cc = 0.004 W_p + 0.07$	–	–	$Cc = 0.003 W_p + 0.055$
I_p	X	–	$Cc = 0.0082 I_p - 0.047$	–

dredged sediments are not correlated with the compression index (Figure 13(c)).

3.4. Shear strength behaviour

The analysis of the direct shear test results on saturated specimens is shown on the Figure 14. The shape of the direct shear curves is globally the same

for all the tested samples. Again, it is to note that the shape of the shearing curves correspond to the shape of normally consolidated samples rather than over consolidated samples. The samples preparation are made in a same way that that used for the compressibility tests.

To deduce the shearing parameters, a plot of shear stress versus effective normal stress corresponding to

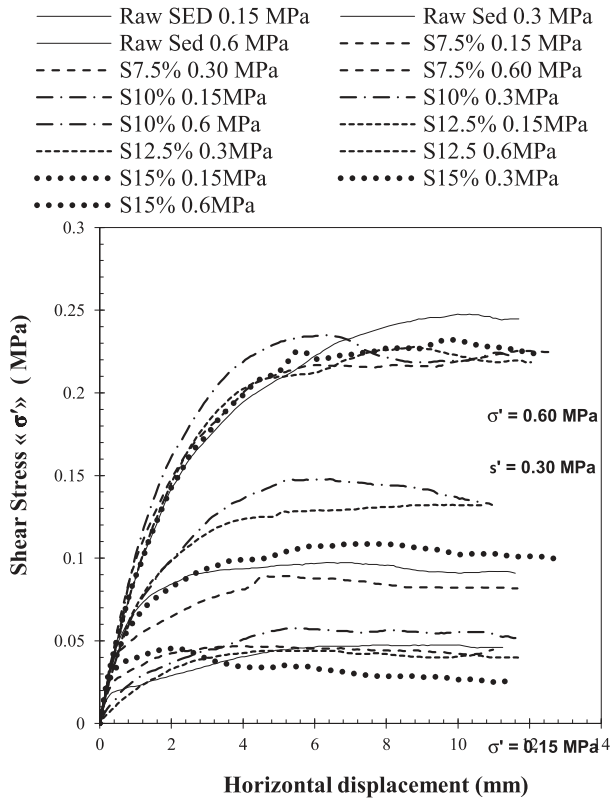


Figure 14. Shear stress versus horizontal displacement.

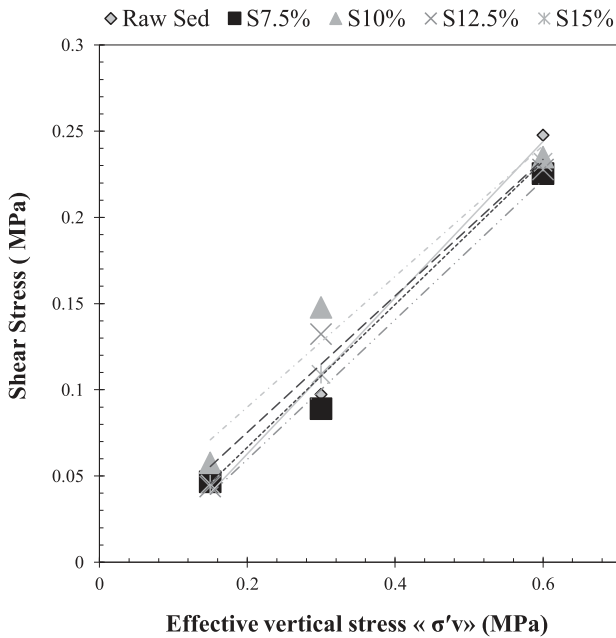


Figure 15. Shear stress versus effective vertical stress.

failure is shown in Figure 15 for the reconstituted samples. From the obtained results, it seems that the effective cohesion is almost equal to zero. The variation of friction angle (ϕ) versus the organic matter content

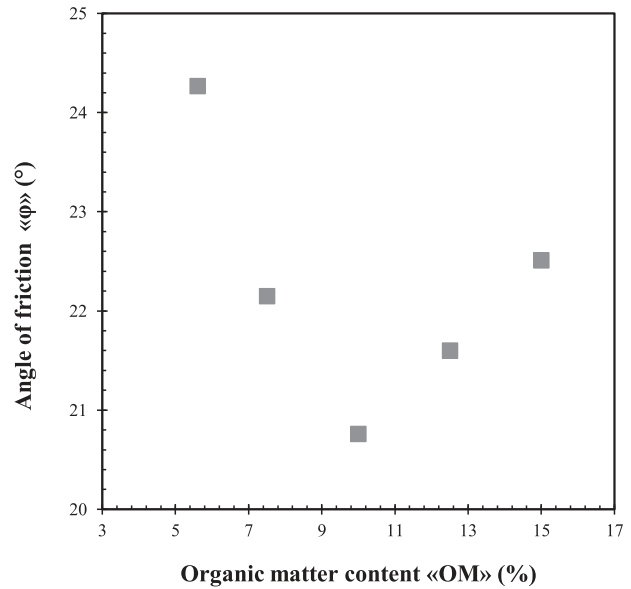


Figure 16. Angle of friction versus organic matter content.

is given in Figure 16. The friction angle decrease with organic contents in the range of 5–10%. From 12.5% of organic matter content we observed an increase of the friction angle. Landva and Pheeny [42] concluded that the fibres in the soil may produce a reinforcing effect on the soil matrix increasing the shear strength of the soil. Similar phenomenon could be the explanation for the increase in the friction angle observed in this study.

4. Conclusions

From the proposed research work, the main finding could be resumed as follows:

- The evolution of the physical properties with the amount of organic matter (between 5% and 15%) was demonstrated. The main effects were recorded on the liquid limit, the plastic limit and the density.
- In the range of organic matter content studied and in the context of French guide in road construction, the material classification on the basis of physical properties is almost unchanged.
- From a point of view of material compaction, the effects of organic matter content on the optimal dry density as the optimum water content is important.
- The recorded effects is consistent independently of the energy used (normal Proctor test or modified Proctor test).
- For a high amount of organic matter content, the effects of the energy on the Proctor test characteristics seems to be reduced.

- The Immediate Bearing Index is moderately affected by the organic matter content in the range of explored range.
- The relationship between the liquid limit and the compression index was confirmed in this study on dredged sediments with organic matter content ranging from 5% to 15%.
- The relationship between the plastic limit and the compression index was confirmed in this study on dredged sediments with organic matter content ranging from 5% to 15%.
- For the materials studied in this present study, we do not find any relationship between plasticity index and compression index.
- The proposed methodology to prepare samples for the odometer tests and the direct shearing tests seems to be adequate.
- The obtained result from the oedometer tests has demonstrated the effects of organic matter content on the compression index as on the recompression index.
- The preconsolidation pressure is slightly affected by the amount of organic matter content.
- The obtained result from the direct shear tests has demonstrated the effects of organic matter content on the friction angle. In fact, the high fibrous content of the organic material causes so-called 'filament effect' produce a reinforcing effect on the soil matrix increasing the shear strength of the dredged sediment.

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