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Experimental analysis of the effect of some compaction methods on mechanical properties and durability of cement stabilized soil

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Abstract Cement stabilized soil is usually compacted by different mechanical methods to increase its strength and durability. This paper summarizes the results of an experimental study on the effect of different compaction methods on the performance of stabilized soil. The compaction methods investigated were either static compaction by applying a static pressure using an universal compression testing machine, dynamic compaction by a drop weight method, or static compaction coupled with vibration. All methods were applied on unstabilized soil or cement stabilized soil. The effect of each method of stabilization on compressive strength, shrinkage and water resistance are reported. Dynamic compaction with about 8% of cement content seems to give the best performance for the soil investigated.

Introduction

Earth construction is the most used type of building throughout the long history of Algeria. Because of its low cost and because of the important needs in housing estimated at more than two millions units, local authorities are encouraging research in this field.

Different techniques are used in earth construction [1–3]. The oldest technique used is dammed earth or pisé which consists of pouring earth stabilized by natural fibres or a binder in a pre-prepared formwork for wall construction with manual compaction in layers of about 1 m height. Another technique is the adobe, where blocks are manually prepared in wooden moulds and dried in the open air. Straw is sometimes used to reduce cracking. This technique is mostly used in rural areas and in self-built housing projects. However, the quality of the blocks is usually unsatisfactory due to surface cracking.

The main drawback of earth construction buildings is the need for continuous maintenance to improve water resistance and durability. Many failures have been reported after seasonal flooding in some cities in Algeria, which undermined the use of earth blocks. In addition, with the recent developments of masonry and reinforced concrete, soil based constructions are regarded as designed for the poor people and hence of lower quality.

The most recent and promising technique is chemical and/or mechanical stabilized soil. A clay sandy soil is usually used after being mixed with some cement or lime in the moulds, hydraulically compacted and then cured. Hence, higher compressive and tensile strengths, better cohesion and better water resistance are obtained thus improving its stability. Some hydraulic machines were developed to ease compaction and to get blocks similar to concrete blocks. Reinforcement with natural fibres is sometimes used and found to give a better performance with regard to compressive and flexural strengths as well as shrinkage [4].

In Algeria, most of the research work was done on cement stabilization and mechanical properties. In order to improve the performance of this material, investigations are needed on the effect of compaction methods on the durability of local soils.

This paper summarizes an experimental investigation on the effect of compaction and chemical stabilization by

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ordinary Portland cement on the performance of earth blocks. Particular attention is given to the effect of different methods of compaction on the mechanical properties and water resistance.

Materials used and test methods

Materials used

Typical clay sandy soil from the mountainous region of Tizi-Ouzou which is known for its earth construction and local traditional pottery industry was used. Soil was first passed in a 5 mm sieve before being characterized for its grading curve, consistency limits and chemical composition. Ordinary Portland cement type CEMI 32.5 was used for the chemical stabilization. Chemical stabilization was investigated by adding 0, 4, 6, 8, 10, 12, 15 or 20% of cement by weight of dry soil and its effect on compressive and splitting tensile strength at different curing times was analysed. The sand used in combination with cement to study its effect on shrinkage was fine river sand passing a 0.63 mm sieve.

Compaction methods

In order to reduce the soil porosity and to increase its durability and water resistance, three different methods of compaction: dynamic, static and vibro-static were studied and their effect on the soil characteristics and performance investigated.

Static compaction

Static compaction is obtained by applying a static pressure using an universal compression testing machine on stabilized soil put in a cylindrical mould 100 mm diameter and 165 mm height at a strain rate of 1.27 mm/min until the desired compaction stress was obtained (Fig. 1). After demoulding, the height and the density of the specimen were measured and the specimens left in the air laboratory condition until testing at the age of 28 days.

Vibro-static compaction

In order to enhance the performance of stabilized soil, specimens were first vibrated on a laboratory-shaking table for one minute before being subjected to a static compaction force.

Dynamic compaction

A modified Proctor test was used in order to overcome the drawbacks of static compaction which could not lead to a perfect grain arrangement whatever the static pressure applied. The mould was filled by the mix and the dynamic compaction was obtained by dropping a 12.5 kg falling-weight from a height of 820 mm on a cylindrical specimen 120 mm in diameter and 180 mm in height and the number of drops increased until the desired compaction energy per unit volume of the soil was reached (Fig. 2). Four levels of compaction energy by unit volume of soil (E_v) were fixed: 3.0, 5.5, 8.3 and 10.3 joule/cm^3.

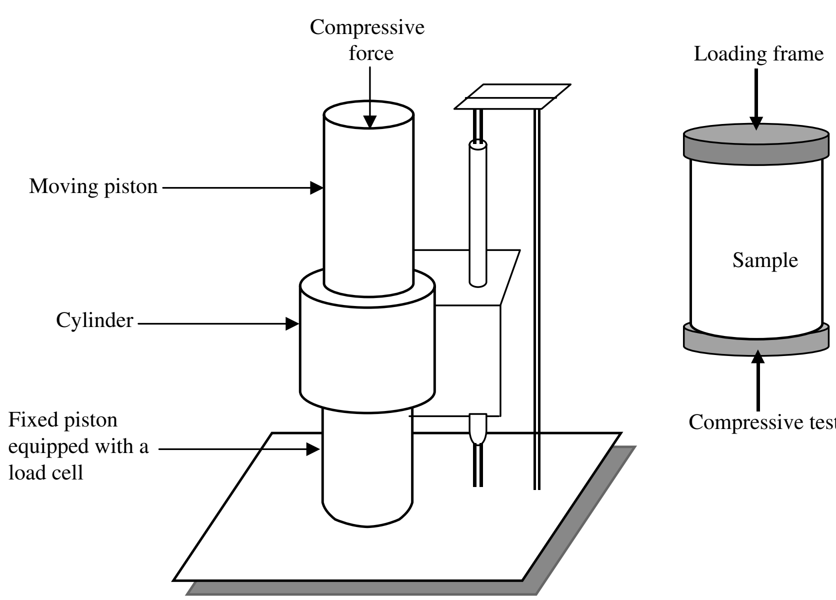

Fig. 1 Setup-up of the static compaction

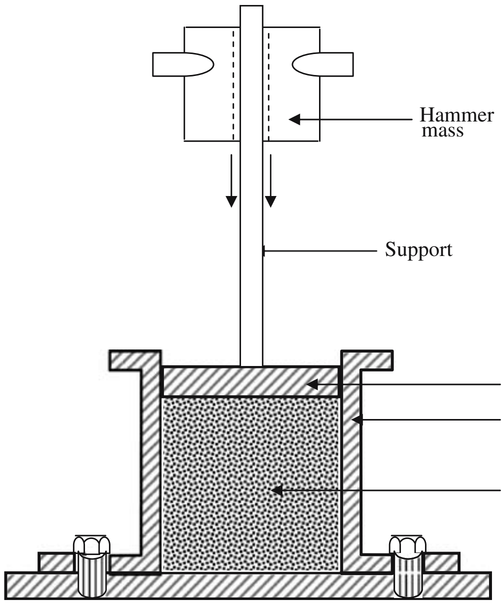

Fig. 2 Experimental set-up of the dynamic compaction

Testing program and testing methods

Samples for testing are prepared by first oven drying the soil, and homogeinizing the mixture obtained by blending the required amount of cement with the dry soil in a mechanical mixer before adding water followed by a new mixing. The mixture was put in a normalized Proctor mould, and then left to cure until the age of testing. Tests were conducted according to the local and to the RILEM TC 153 recommendations [5–7].

Compressive strength was determined on samples prepared in compaction moulds under standard Proctor conditions. The effect of stabilization of a mixture of cement and sand on shrinkage, water permeability and electrical conductivity was also investigated. Linear shrinkage was measured on 100 mm cylindrical samples compacted as Proctor and stabilized with cement, sand or a mixture of cement and sand. A falling head permeability apparatus was used for water permeability tests on cylindrical specimens of 50 mm diameter and 100 mm height. Cylindrical specimens were also used for the conductivity tests. An electrical current was passed through the specimen and the electrical intensity and the potential difference were measured between two points and hence conductivity calculated. Thermal conductivity and thermal properties were measured using the Vernotte's method [8] with the experimental set up shown in Fig. 3. The method consists of applying a heating sheet on one face of the material and recording the temperature evolution on the opposite face. The effusivity ($b = \sqrt{\lambda \rho_c}$) is obtained from the evolution of the temperature on the unheated face, and by comparison of the temperatures of the two faces of the material, its conductivity (λ), volumetric heat (ρ_c) and diffusivity ($a = \lambda / \rho_c$).

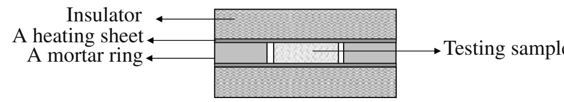

Fig. 3 Thermo-physical properties experimental set-up

The effect of a combined chemical stabilization by cement and mechanical stabilization by static, vibro-static and dynamic compaction on the mechanical properties were studied. Durability tests by water capillary action were also investigated. Five samples were tested for each level of cement stabilization and for each variable studied.

Results and discussion

Physical and chemical characteristics of the soil used

Table 1 summarizes the characteristics of the soil used. The grading curve of the soil used was within the limits for a well-graded soil but with a small excess of 0.1 mm particles. The soil has a liquid limit of 39% and a plasticity index of 15% and hence could be classified as moderately plastic clay type A6 according to the American Association of State Highway Transportation Officials (AASHTO) system. The chemical composition showed that harmful substances such as sulphate, chloride and organic matters are negligible and that this clay is rich in carbonate.

Effect of cement stabilization on soil properties

Compressive strength

The optimum water content for the soil without stabilization was obtained using a normalized Proctor mould and was 10% by weight of dry soil for a maximum dry specific

Table 1 Identification and characteristics of the soil used

Property		
Atterbeg limits	Liquid limit w_L	39
	Plasticity index I_p	15
Grain size distribution	Gravel (>4.75 mm) (%)	7.7
	Sand (0.074–4.75 mm) (%)	30.3
	Clay and silt (< 0.074 mm) (%)	62.0
Chemical characteristics	Iron oxide–Alumina (%) (Fe_2O_3–Al_2O_3)	15.8
	Carbonate $CaCO_3$ (%)	34.0
	Chloride NaCl (%)	0.17
	Sulphate $CaSO_4$ (%)	0.0
	Insoluble residue I.R. (%)	45.5
Proctor standard test	Optimum water content (%)	11
	Maximum dry density (kN/m^3)	17.6
Sand equivalent	By piston test (%)	15.60
	By sight (%)	28.57

density of 17.5 kN/m^3. Compressive strength at the dry state and compressive strength after immersion in water for 48 h at the age of 28 days are given in Table 2. It can be seen that the increase of the cement content increases the compressive strength because the hydration products of the cement fill in the pores of the matrix and enhance the rigidity of its structure by forming a large number of rigid bonds in the soil. These bonds which links the clay particles together could be attributed to the cementitious reaction products such as calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH) and calcium aluminosilicate hydrates (CASH) [9].

The immersion in water for 48 h reduced the compressive strength up to 60% for cement-stabilized samples and complete disintegration of unstabilized specimens was observed in few minutes. The reduction in strength was lower with higher cement content up to an optimum level of 10%, which gives the lowest reduction in strength of about 50%. Higher increase in cement content does not give any positive effect.

Splitting tensile strength and modulus of elasticity at the dry state were also found to increase with the increasing of cement content in a similar trend to that observed with the compressive strength [10]. The splitting tensile strength increased from 0.25 to 0.80 and 1.2 MPa when cement content increases from 0 to 10% and 22%, respectively. However, after water immersion, the splitting tensile strength was very low.

The development of dry compressive strength with age of air curing is shown in Fig. 4. It can be clearly seen that the relative compressive strength obtained after 7 days of curing was about 70% of that obtained after 21 or 28 days of curing for up to 10% of cement content. However, for 12%, 15% and 20% of cement content, the relative compressive strength at 7 days as compared to that of 21 and 28 days was only about 50%. This shows that mixes with higher than 10% cement content need a period of curing of 21–28 days for the complete strength development.

Shrinkage

The effect of mixing water content on final shrinkage at 28 days is shown in Fig. 5. This figure shows the importance of reducing the mixing water content to that of optimum Proctor.

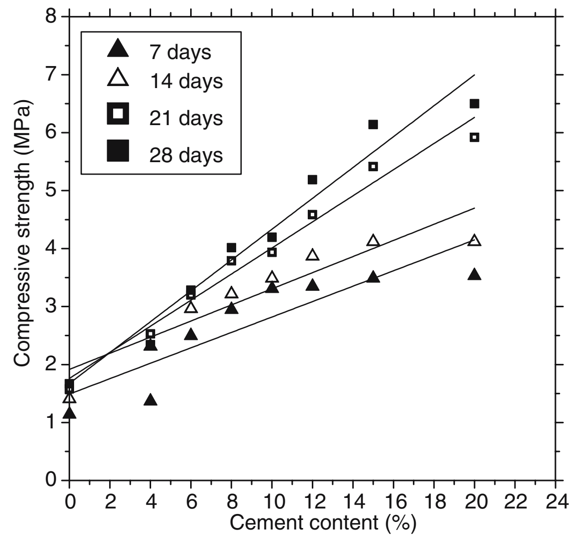

Fig. 4 Development of dry compressive strength for different cement content

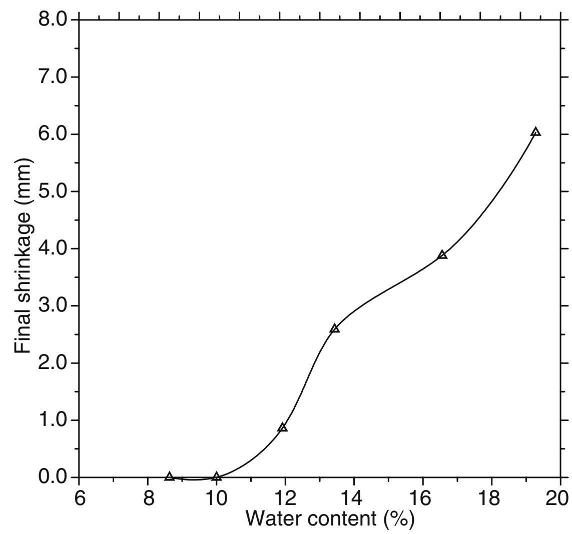

Fig. 5 Variation of the final shrinkage with mixing water content

Figure 6 shows the effect of cement, sand and a mixture of cement and sand stabilization on the variation of final linear shrinkage. The shrinkage of cement stabilized soil at 28 days of age as compared to that of unstabilized soil was reduced by about 20% and 44% for 6% and 10% of cement content, respectively. The addition of sand reduces the shrinkage as sand particles oppose to shrinkage movement.

Table 2 Dry and immersed compressive strength

Cement content (%)	0	4	6	8	10	12	15	20
Dry compressive strength (MPa)	1.67	2.34	3.28	4.02	4.20	5.19	6.14	6.5
Immersed compressive strength (MPa)	0	1.22	1.80	2.03	2.12	2.21	2.43	2.66
Relative residual compressive strength (%)	0	52.06	54.79	50.54	50.52	40.58	39.55	40.92

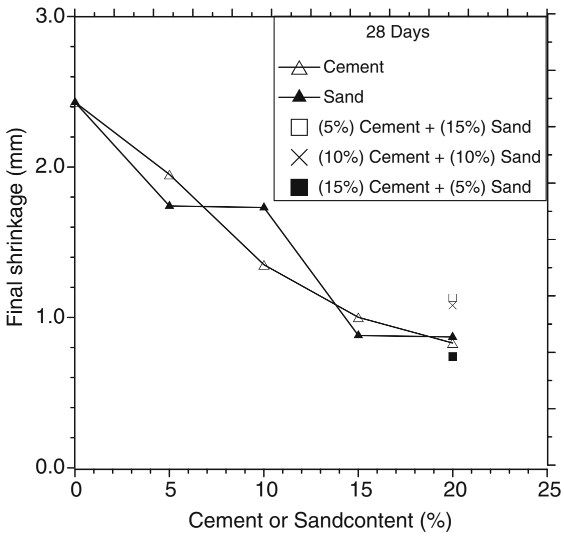

Fig. 6 Effect of cement and sand content on the final shrinkage

The reduction in shrinkage was about 29% and 64% for 10% and 15% of sand content, respectively. Further increase of sand content did not affect the shrinkage. The combination of cement and sand reduces the shrinkage slightly better than when only cement is added. A mixture of 5% sand and 15% of cement seems to give the lowest shrinkage.

Permeability and electrical conductivity

As expected the addition of cement reduces water permeability. The water permeability coefficient decreases from 14×10^{-8} m/s to 0.27×10^{-8} m/s when cement content increases from 5% to 20% [10]. The reduction in permeability could be attributed to the reduction of large pores by the cement particles and cement hydration products. This shows that stabilization of the soil with cement could lead to a better mechanical strength, lower permeability and hence better durability. Electrical conductivity increases with mixing water content and then decreases up to the optimal water content and seems to stabilize for higher water content [10]. The effect of increase in cement content and sand content on the electrical conductivity was not significant probably due to the conflicting effect of both void ratio and water content.

Thermo-physical properties

Thermal conductivity is usually controlled by the material constituents, water content and the void ratio. Although the effect of increasing cement and/or lime content does not follow a fixed trend for both soils investigated (Table 3), thermal conductivity varied from 0.84 to 1.25 W/m K. This variation may be attributed to the variation in density and water content of the specimen. Water and air have a thermal conductivity of, respectively, 0.60 and 0.024 W/m K and, hence, a wet specimen has a higher thermal conductivity than a dry specimen. Thermal conductivity of soil A was lower than that of soil B because of the differences between them in density, gradation and compaction water content. It should be noted that the thermal conductivity values are lower than those of a standard cement mortar (1.15), concrete (1.75) or fired clay brick which are, respectively, 1.15, 1.75 and 1.2 W/m K [11] and hence a better thermal insulation is obtained especially in hot climate regions. Good correlation is obtained between the measured and calculated values of the effusivity showing the adequacy of the simple experimental apparatus used.

Effect of compaction methods on soil properties

Static compaction

As expected, the dry density increases with the applied compressive stress. The optimal water content was about 10–13% (Fig. 7). The effect of static compaction on the dry density is more pronounced when the water content is on the dry side of the curve. This might be due to the high resistance to the rearrangement of soil particles which are flocculated. For higher water contents, particle groups are weaker.

Table 3 Thermo-physical properties test results

Sample	Height	Cement (C) or lime (L) content (%)	Water content (%)	Conductivity λ (W/m K)	Diffusivity a (m^2/s)	Volumetric heat ρ_c (J/m^3 K)	Effusivity $b = \sqrt{\lambda \rho_c}$(W $s^{1/2}$/m^2 K)	Effusivity b (direct measurement)
1A	6.8	5C	0.96	12	4.8×10^{-7}	2.00×10^6	1,390	1,370
3A	6.8	15C	0.84	13	4.1×10^{-7}	2.07×10^6	1,320	1,270
5A	6.6	10L	0.88	12	4.5×10^{-7}	1.97×10^6	1,320	1,310
6A	7.8	10C + 2L	0.98	12	4.7×10^{-7}	2.09×10^6	1,430	1,430
1B	7.8	5C	1.15	9	5.7×10^{-7}	2.00×10^6	1,520	1,600
4B	7.8	15C	1.22	12	6.9×10^{-7}	1.78×10^6	1,470	1,360
5B	7.0	10L	1.25	12	7.1×10^{-7}	1.77×10^6	1,490	1,490
6B	7.0	10C + 2L	0.87	12	4.7×10^{-7}	1.83×10^6	1,260	1,230

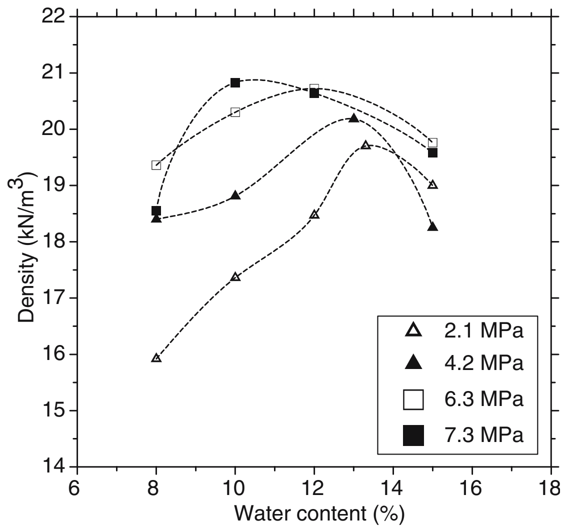

Fig. 7 Variation of dry density with static compaction stress

The increase in static compaction stress lowers the water content for the optimal dry density. The dry compressive strength also increases with the static applied stress (Fig. 8). About 60% increasing of the dry compressive strength was obtained when the applied static stress increased from 2.1 to 7.3 MPa. However, the effect of applied static stress is negligible at high water content.

Vibro-static compaction

Figure 9 shows the variation of dry density with the vibro-static compression stress. Vibration seems to enhance the dry density only when the static compaction stress is low. For the optimum water content, slightly higher dry and humid compressive strengths were obtained as compared to

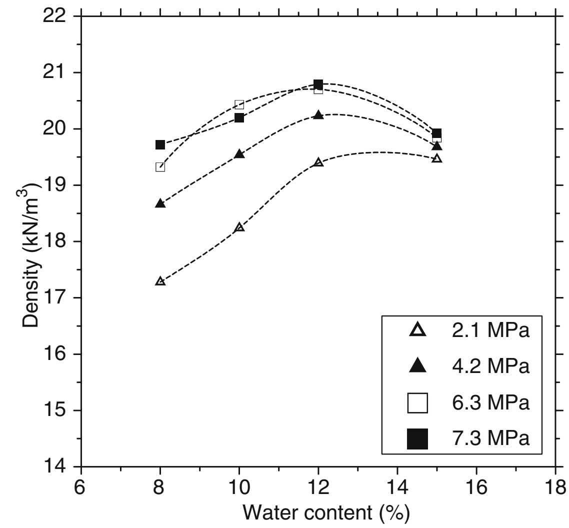

Fig. 9 Variation of dry density with vibro-static compaction stress

static compaction. The average increase in strength was about 5% (Fig. 10). Vibro-compaction does not seem to enhance the performance of the soil when lower water content is used and in this case static or dynamic compaction are better. However, for higher water content than the optimal values, vibro-compaction seems to be the best compaction method probably due to of the low friction forces.

Dynamic compaction

The effect of dynamic compaction on dry density is shown on Fig. 11. The optimal water content is about 9.5–11.0% and the maximum dry density about 20.0 kN/m^3 for all energy compaction levels. The increase of the energy compaction increases the dry compressive strength by

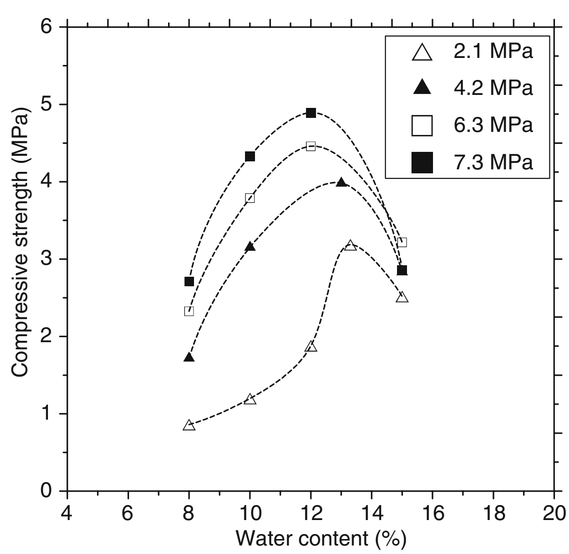

Fig. 8 Compressive strength under static compaction

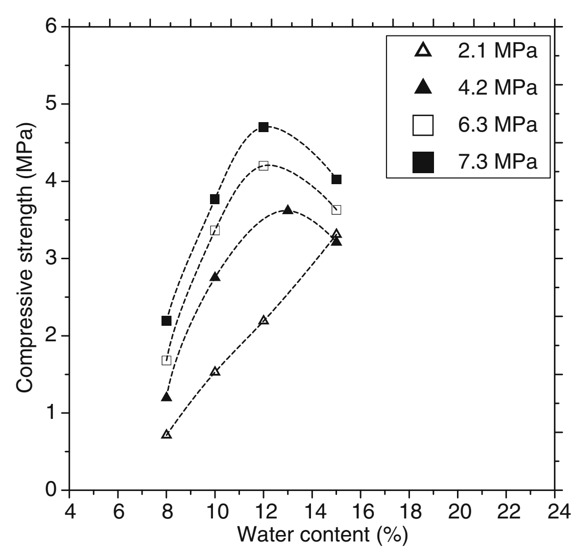

Fig. 10 Compressive strength under vibro-static compaction

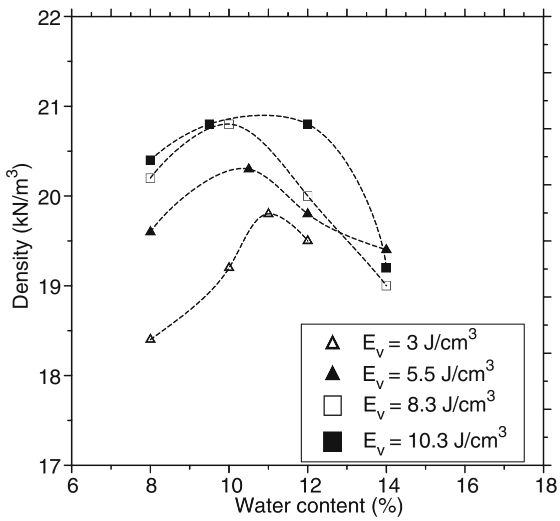

Fig. 11 Variation of dry density with dynamic compaction stress

more than 50% but reduces the optimum water content from 12% to about 10% (Fig. 12). The increasing in compressive strength and dry density with the increasing in compaction energy was more pronounced when specimens were moulded on the dry side than on the wet side of the optimum moisture content. After immersion in water, higher dynamic compaction energy gave a residual compressive strength of about 2 MPa as compared to a complete disintegration for unstabilized specimen.

The effect of cement content was studied for compaction energy of 8.3 joule/cm^3. The compressive strength was almost doubled when cement content increases from 2% to 12%. However, after 48 h immersion in water, the compressive strength was only about 20–25% of the dry compressive strength for all cement content levels as dynamic compaction did not improve the compressive strength after immersion. However, the residual compressive strength for cement content higher than 6% was higher than the 2 MPa required usually for concrete blocks.

Comparison of different compaction methods

Dry density

The three different methods of compaction used in this investigation did not affect significantly the dry density of the soil. Figure 13 summarizes the variation of the dry density with water content and method of compaction. It can be clearly observed that the highest dry density was obtained with the dynamic method when water content is on the dry side of the curve and with the vibro-compaction method when the water content is on the wetter side.

Compressive strength

Figure 14 gives the compressive strength under different compaction methods and with different cement content in the dry state. It can be seen that dynamic compaction allows the highest compressive strength at all level of cement stabilization. Higher dynamic compaction gave a compressive strength in excess of 10 MPa as compared to a maximum of 8 MPa for static compaction. At 12% of water content, the increasing of cement content from 2% to 15% increased the compressive strength from 4.25 MPa to 8.2 MPa, for static compaction and from 5.9 MPa to 10.5 MPa for dynamic compaction.

At optimal water content, it seems that the vibration does not enhance the strength probably because of the low frequency of the laboratory-vibrating table, which is not adequate for a fine material. Dynamic and static compaction

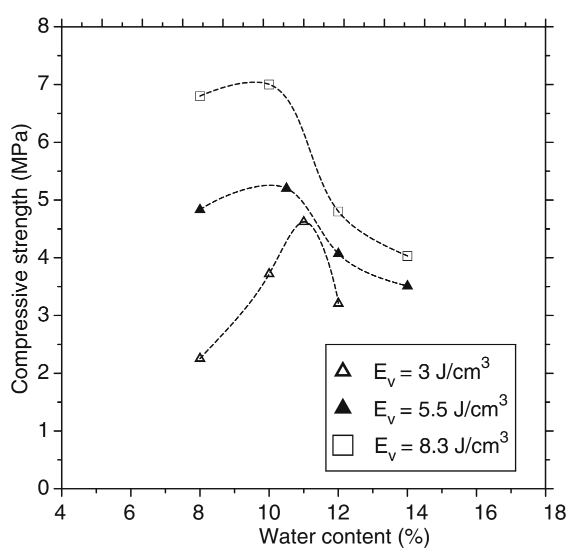

Fig. 12 Variation of the compressive strength under dynamic compaction

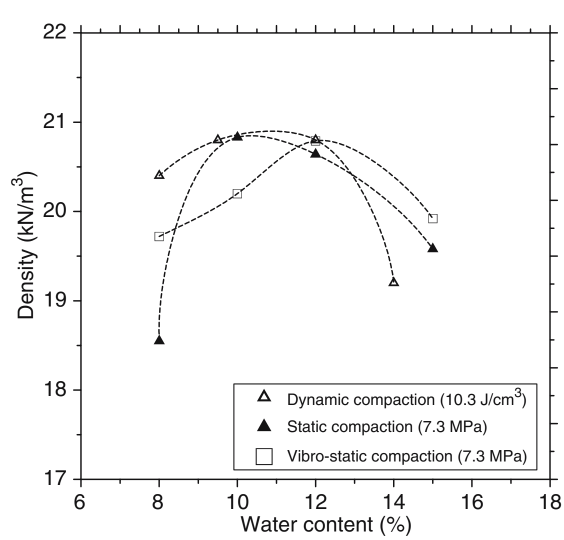

Fig. 13 Effect of the compaction method on the density

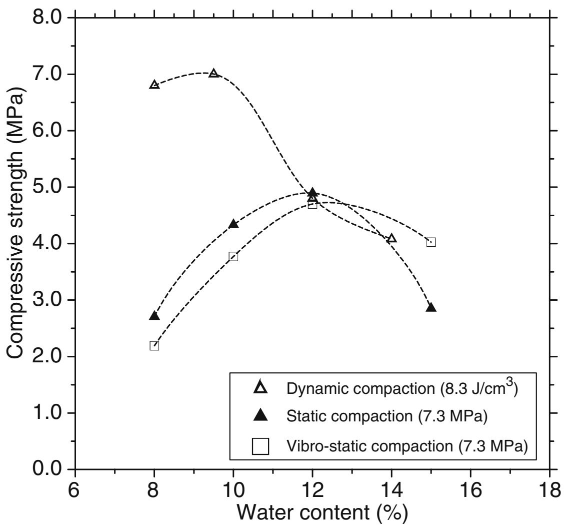

Fig. 14 Effect of the compaction method on the compression strength

with 2–4% cement content gave a similar dry compressive strength as that of vibro-compaction at 6% of cement content.

Residual compressive strength after immersion

Although the static compaction yielded higher dry compressive strength than the vibro-static method, the static compaction was slightly less efficient for the compressive strength after water immersion for 48 h where only 10–19% of the dry compressive strength was obtained for cement content higher than 6% (Fig. 15).

The compressive strength after immersion in water for 2% and 4% cement contents was negligible for all compaction methods and hence the importance of having a higher cement content. It seems that for water resistance, dynamic compaction is the only recommended method of compaction, as it was the only method, which gave higher strength than 2 MPa for more than 6% of cement content.

Water resistance

Water resistance was studied by measuring the height of water penetration by capillary action. Figure 16 shows the effect of static and dynamic compaction on the water absorption by capillary action for cement stabilized soil specimen. Dynamic compaction was fixed at E_v = 8.3 joule/cm^3 and the static compaction at 7.3 MPa stress. The combination of dynamic compaction and chemical stabilization reduces substantially the water absorption by capillary action from 11.9% for 0% cement content to 9.8 and 2.7% when cement content is 5% and 10%, respectively.

A similar trend was observed when static compaction was used. Water absorption decreased from 14.3 to 10 and 6.6% for, respectively, 0, 5 and 10% of cement content. However, the static compaction was less efficient than the dynamic compaction in reducing the water absorption.

The positive effect of the combination of chemical and mechanical stabilization seems to have on one hand cemented the soil particles together and filled in the pore space in the soil and on the other hand prevented the reorientation and flocculation of soil particles, which precluded formation of enlarged pores and cracks [12–13].

In order to simulate the effect of hot and humid environment of the region on water intake, water absorption was measured for some specimen tested outside the laboratory either in winter (T = 10 to 25 °C, R.H = 70–90%) or summer (T = 35–45 °C, R.H = 40–60%) (Fig. 17). Water

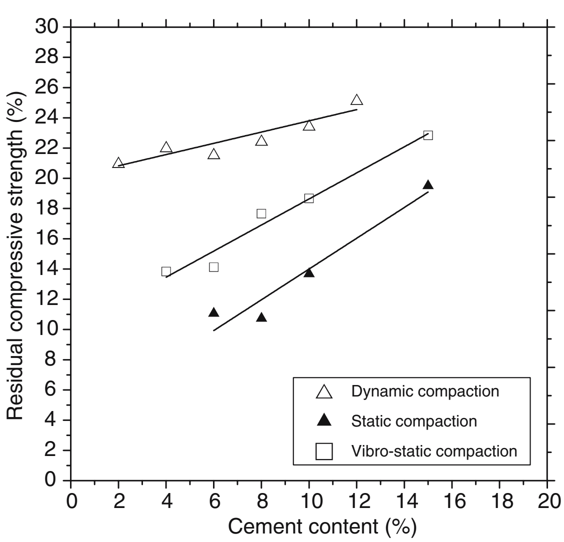

Fig. 15 Relative residual compressive strength after immersion in water

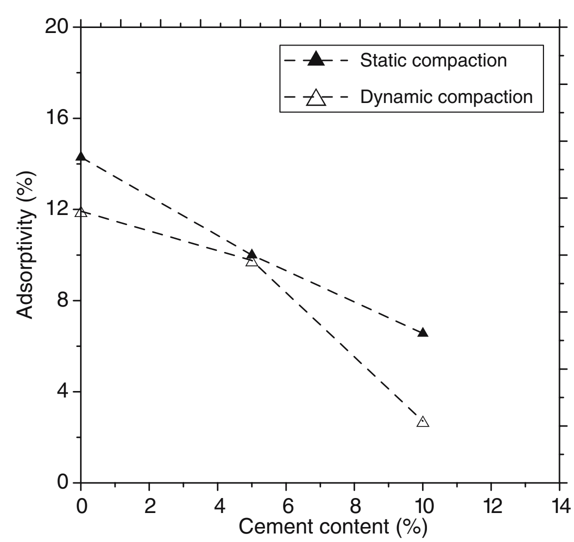

Fig. 16 Comparison of absorption by capillary action obtained with static and dynamic compaction

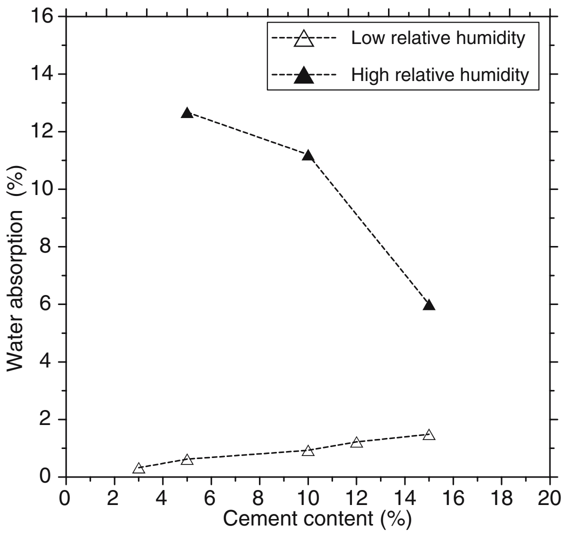

Fig. 17 The effect of relative humidity on water absorption

absorption is very low in dry environment but some care should be taken with humid environments as water absorption is quite high. Although water absorption decreases with the increasing in cement content, surface treatment with cement renders or cement modified polymer renders may be necessary to enhance water resistance.

Conclusion

Mechanical stabilization by dynamic compaction of a local clay sandy soil seems to enhance the mechanical properties and water resistance of the soil as compared to the static or the vibro-static compaction methods. Chemical stabilization with cement content of about 8% seems to be the optimal value for this soil. However, optimal water content should always be sought to get higher strength and higher durability and building design should always avoid a direct contact of stabilized soil blocks with water and rainwater in humid regions.

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