Compressive Strength of Soil Improved with Cement

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ABSTRACT

The soil type can affect significantly the effect of cement stabilisation. In order to investigate this, five types of soils were mixed with cement at various cement proportions in order to obtain a large variation of compressive strength values. The compressive strength of the cement treated soils was determined for a curing period of the cement equal to 7 and 28 days. It was obvious that the soil type is a controlling factor on the rate of increase of compressive strength with increasing cement content. Other factors affecting strength are the curing time of cement and the optimum water content.

1. INTRODUCTION

The use of cement as an improving agent in various applications in ground engineering is quite common. The improvement is achieved through a mixing procedure with the soil (and other additives). Soil - cement mixing has been increasingly used in the past in a number of applications. Primarily, it has been used as an improvement material for the stabilisation of sub-bases in road foundations (Marsellos et al., 1986). Additionally, in some developing countries, it has been extensively used for the production of compacted soil-cement blocks, which are used for the construction of masonry buildings (Venkatarama Reddy et. al., 2007). Cement (and lime) is also used for the stabilisation and solidification for the remediation of contaminated sites. Soil improvement by the use of cement can also be achieved by means of other techniques, e.g. deep soil mixing, jet grouting and construction of lime or cement-stabilised soil columns.

The parameters which influence significantly the strength of a cement-stabilised soil are the water content, the sand and fines content, the liquid limit, the amount of added cement and curing time (Anagnostopoulos & Chatziangelou, 2008). In the present study, different soil types were mixed with cement at various cement proportions and compacted using the standard Proctor test at the maximum dry density. The compressive strength of the cement treated soils was determined for a curing period of the cement equal to 7 and 28 days. It was obvious that the soil type is a controlling factor on the rate of increase of compressive strength with increasing cement content. Additionally, the compressive strength of soil-cement mixtures for a curing period of 28 days is significantly higher than those for a curing period of 7 days. Similar studies on sandy soils (Consoli et al., 1998), have proved that cement addition to soil increases stiffness, brittleness and peak strength.

2. LABORATORY TESTING

2.1. Treated Soil Types

The soil samples used in the present study are classified, according to the Unified Soil Classification System as: a) two non-plastic silty sands (SM), b) two non-plastic, poorly graded silty gravels (GP-GM), c) a plastic clayey gravel (GC), d) a clay and a silt of low plasticity (CL, ML). The grain size distribution of each soil type as well as their plasticity index (PI) and specific gravity of solids (G_s) is given in Table 1.

Table 1. Grain size distribution for tested soils

Material - Designation	Gravel (%)	Sand (%)	Fines (%)	Plasticity Index (PI)	Specific gravity (kN/m^3)
CL	10.1	18.4	71.5	22	2.75
ML	0.7	69.7	29.6	N.P.	2.73
SM (1)	40.8	41	18.2	N.P.	2.66
SM (2)	2.9	81.4	15.7	N.P.	2.71
GP-GM (1)	65.5	28.4	6.1	N.P.	2.74
GP-GM (2)	49.6	42.1	8.3	N.P.	2.73
GC	51.3	34.1	14.6	15	2.72

2.2. Testing Procedure

Cemented specimens were prepared with cement contents of 3%, 5% and 7% by weight of dry soil and cured for seven and twenty eight days. The samples were prepared by mixing soil and water, with the addition of Portland cement (CEMII/ B-M (P-L) 32.5 N).

Samples with cement content of 5% were initially compacted in three equal layers into a 101 mm diameter and 130 mm high cylindrical mold for each increment of water added, so as to determine the water content, w, of the compacted soil-cement mixture. The soil preparation procedures specified in ASTM D558-04, Method B were followed in order to calculate the relation of the moisture and dry density of the soil-cement mixtures. According to this method the soil that passes a ¾ inch (19.0 mm) sieve, corresponding to size smaller than fine gravel, is mixed with cement. Most soil-cement construction specifications cover soil gradation limit maximum size to 3 in. (coarse gravel) or less. The values of maximum dry density and optimum moisture content for the soil-cement mixtures are listed in Table 2.

At the second stage, samples with different cement contents were compacted into a 101.6 mm diameter and 116.4 mm high cylindrical mold and prepared at the optimum moisture content, as determined by the compaction tests. During the preparation of the stabilized soil specimens, cement content between 3% and 7% by weight of dry soil was used.

The specimens were then subjected to unconfined compression tests. The compressive strength of the soil-cement mixtures was determined according to ASTM D1633-00 Method A. This test method is used only on soils with 30% or less retained on the ¾ inch (19.0 mm) sieve. The tests were performed under a constant stress rate.

Table 2. Compaction characteristics of soil-cement mixtures

Material - Designation	Optimum Moisture Content, OMC (%)	Dry density, ρ_d (Mg/m^3)
CL*	17.6	1.71
ML	13.1	1.90
SM (1)	8.4	2.09
SM (2)	14.6	1.76
GP-GM (1)	6.7	2.28
GP-GM (2)	5.2	2.29
GC	7.6	2.12

* Optimum moisture content of the sample was determined for cement content equal to 6%.

3. RESULTS

3.1. Compaction Characteristics

The moisture-density (compaction) curves for the cement treated soils were determined using the method described in ASTM D558-04, Method B. The cement content was equal to 5%. Figure 1 shows the variation of the dry density with the moisture content for the tested samples, while their values are summarised in Table 2. The maximum dry density decreases with the optimum water content, as it can be seen by the best-fit line for all tested samples.

Silty gravel (GP-GM) and clayey gravel (GC) have higher dry density values, while clays (CL) and silts (ML) have lower values. The difference of the maximum dry density of the two sands stems from the higher percentage of gravel of the sample SM(1), thus its compaction characteristics are closer to the gravel soils mixtures.

The effect of the cement content on the compaction curves was not investigated in the present study. Aiban et al. (1998) concluded that there is no fundamental difference in the dry density between the untreated soil and cement-marl mixtures, by conducting test with cement content between 3% and 7%.

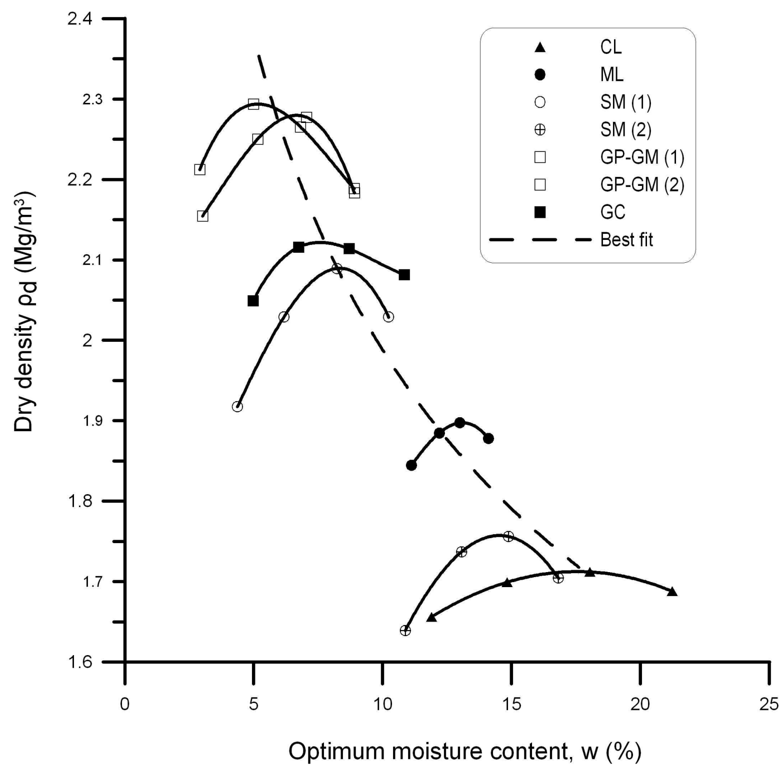

FIG 1. Compaction curves for tested soils (Dry density- moisture content)

3.2. Strength Improvement

Considering the results from tests on all soil types, it is evident that the compressive strength of the cement treated soil increases with the increase of cement content in the soil-cement mixture. The data in Figure 2a clearly indicate that there is an increase, almost described by a power curve, in the compressive strength with the cement content for cutting time of 7 days. The increase is more pronounced for samples that have higher percentage of gravel (GP-GM and GC samples). On the contrary, fine soil-cement mixtures (CL or ML) show a slight increase in compressive strength with increasing cement content. The laboratory results from the unconfined compression tests are presented in Table 3.

Additionally, the compressive strength of the mixtures is always higher for the samples cured for 28 days in comparison to those cured for 7 days. Figure 2b shows the compressive strength of the soil-cement mixtures after a curing period of 28 days.

Table 3. Unconfined compressive strength of soil-cement mixtures

Material Designation	Unconfined Compressive strength, q_u (MPa) Curing time 7 days (28 days)		
Cement content	3%	5%	7%
CL*	0,69 (0,96)	1,05 (1,39)	2,08 (2,67)
ML	1,04 (1,68)	1,57 (2,51)	2,35 (3,54)
SM (1)	2,00 (2,42)	2,69 (3,29)	3,29 (3,99)
SM (2)	0,52 (0,70)	0,78 (1,22)	1,04 (1,46)
GP-GM (1)	0,52 (1,05)	3,91 (4,57)	4,85 (6,68)
GP-GM (2)	0,17 (1,39)	0,78 (1,90)	6,69 (4,51)
GC	1,39 (2,34)	2,61 (2,60)	3,12 (3,06)

* The soil-cement mixture was prepared at 4%, 6% and 8%.

Based on the strength tests executed in the sandy soil–cement mixtures, with increasing cement/soil ratios, it was obvious that the compressive strength increases more persistently with cement content for soils having a lower percentage of sand and that the slope of the increase in strength is higher as the dry density of the mixture increases or the OMC decreases. The strength increase for the sand sample SM(1) is given by equation $q_u = 1.045\ C^{0.589}$ (r^2=0.99) and $q_u = 1.267\ C^{0.590}$ (r^2=0.99) for curing period of 7 and 28 days respectively.

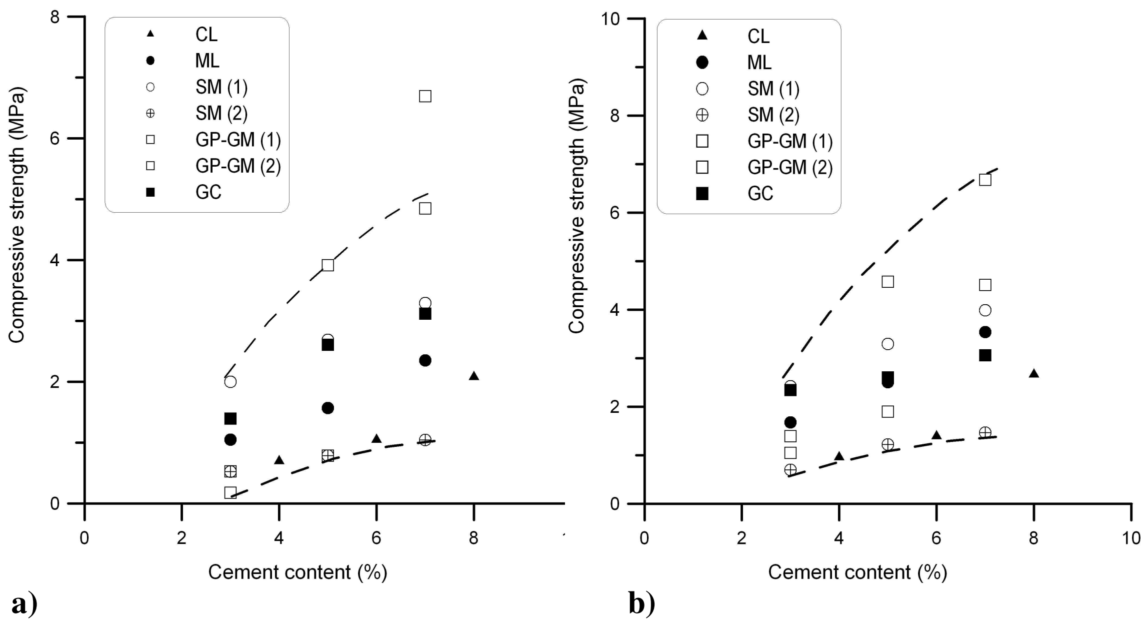

FIG 2. Plot of compressive strength with cement content for treated soils, a) curing time 7 days, b) curing time 28 days.

Based on the strength tests executed in the gravely soil–cement mixtures, it is obvious that the increase in compressive strength of the clayey gravel sample (GC) is much lower than this of the silty gravel sample (GP-GM), due to the higher content of fines in the first one.

The data in Figure 2a and 2b indicate that there is a power increase in the compressive strength of the treated soils with cement content, both for curing time of 7 and 28 days. Aiban et al. (1998) performed tests on a stabilised marl road base and concluded that beyond a cement content of 5% the increase in unconfined compressive strength is only marginal. This limit was not determined in the present study.

The change in compressive strength of the soil-cement mixtures is dependant upon the percentage of the soil particles. The strength decreases with the percentage of fines and sand for all cement contents, but this decrease is more evident for cement contents equal to 5% and 7%. This behaviour is independent from the curing time of the cement. Figure 3 presents the decrease of compressive strength in relation to the fines percentage of the tested samples. The best-fit equation of the compressive strength with fines content (F) for cement proportion equal to 7% is $q_u = -1.54 \ln(F) + 7.72$ (r^2=0.44) and $q_u = -1.24 \ln(F) + 7.22$ (r^2=0.37) for curing periods of 7 and 28 days respectively. The compressive strength of the mixtures increases with the percentage of gravel.

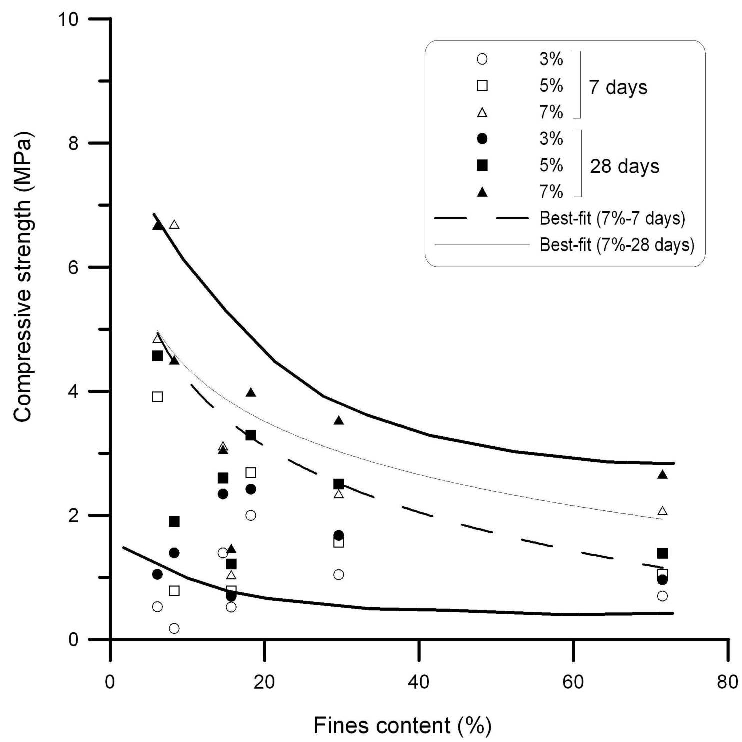

FIG 3. Influence of fines content (F) on compressive strength for different cement contents and curing periods.

The compressive strength of the soil-cement mixtures decreases with optimum water content and this is more evident for those with cement contents equal to 5% and 7%. The decrease is described by a power-fit line and given by equation $q_u = 41.2\ OMC^{-1.173}$ (r^2=0.77) for 7% cement and curing period of 7 days, while for a curing period of 28 days it is given by equation $q_u = 18.02\ OMC^{-0.739}$ (r^2=0.50).

3.3. Stress – strain curves

The tangent modulus values of the soil-cement mixtures generally increase with cement content. The modulus of elasticity of sand- and gravel-cement mixtures (samples SM1 and GC) was higher than that of clay- and silt-cement mixtures (samples CL, ML). This is obvious from the slope of the stress – strain curve. Gravel-cement mixtures present the highest values. The stress – strain curves for the different curing periods are similar, apart from the difference in peak stress.

Figure 4 shows the stress – strain curves of the tested soil-cement mixtures for cement content equal to 3% and curing time equal to 28 days. It is clear that the strain at peak stress is larger for clay (CL), silt (ML) and silty sand (SM2). The silty gravel-cement mixtures (GP-GM) showed inconsistent stress – strain plots occasionally.

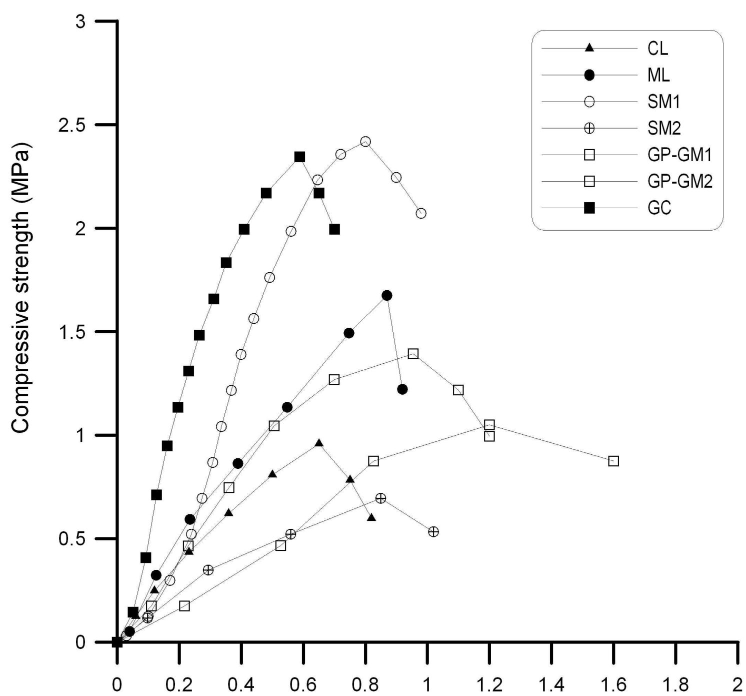

FIG 4. Stress – strain curves for tested soils at cement content 3%.

4. CONCLUSIONS

The test results indicated that the soil type influences significantly the increase of unconfined compressive strength due to cement addition. The addition of cement to all soil types increased the compressive strength and stiffness of the soil-cement mixture.

The increase of compressive strength with cement was more pronounced for samples that have higher percentage of gravel (GP-GM and GC samples) and less for more clayey or silty samples (CL, ML). The increase of strength was described by a power curve depending upon the cement content. The compressive strength of soil-cement mixtures for a curing period of 28 days was significantly higher than those for a curing period of 7 days, usually up to two times.

The change in compressive strength of the soil-cement mixtures is dependant upon the percentage of the soil particles. The strength decreases with the percentage of fines and sand for all cement contents, but this decrease was more evident for cement contents equal to 5% and 7%. Additionally, the strength of the soil-cement mixtures decreases with optimum water content. Concerning the stiffness of the treated soils, the modulus of elasticity of sand- and gravel-cement mixtures (samples SM1, GC) was higher than that of clay- and silt-cement mixtures (samples CL, ML).

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