Effect of using cemented sand as a replacement layer beneath a strip footing.

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\section*{ABSTRACT}
Soil replacement is an effective technique used in construction practices. Hence, several studies have considered the mechanisms to remove and replace mitigation in the past. This research represents an analysis of the efficiency of cemented stabilized soil replacement for improving the behaviour of weak soil. On the other hand, the optimum design for foundation depends on the soil properties beneath these foundations. One of the best solutions for this challenge is to increase the shear parameters and reduce the compressibility for the foundation soil using cemented sand mixture technique. An experimental program was conducted to study the impact of cement stabilization on the geotechnical characteristics of sandy soils, furthermore, five cement ratios (3\%, 5\%, 7\%, 10\% and 15\% by dry weight of sand) have been mixed with sandy soil and tested under compaction and shearing. The results illustrated that the maximum dry unit weight of sand increases with the increase in cement content whereas the optimum moisture content decreases marginally with the increase in the cement content. In addition, increasing cement content leads to an increase of cohesion, friction angle and Young’s modulus. This paper is considered a serious attempt to estimate the optimum cement ratio required to improve the mechanical properties of soil replacement under a strip footing. Numerical modelling for this footing was done by Plaxis software. The results illustrated that adding the cement mixture improves the behaviour of footing. The effect of the replacement extension on the strip footing is also analyzed, where; the results indicated that the optimum replacement extension is equal to the thickness of replacement. This study is based on the limitation of the herein proposed numerical model and its properties.

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\section*{Introduction}
Cement is considered the oldest additives since starting of soil stabilization technology Sherwood [1] and Euro Soil Stab [2] Soil treatment with cement additives (e.g. lime, gypsum, cement, and fly ash) has been a ground
improvement technique in foundation engineering, road construction, and geo-
technical engineering for many years (Choobbasti et al. [3], Choobbasti et al. [4],
Sarokolayi et al. [5,6], Tavakoli and Kutanaei [7], Mashhadban et al. [8]).
Cementation of sandy soil leads to increases the stiffness, shear strength, com-
pressive strength, brittle behavior, and decrease compressibility and permeability
of the material (Kutanaei and Choobbasti [9]; Mashhadban et al. [10]). Sherwood
[1] mentioned that mixing of cement may be considered as an essential stabiliz-
ing agent since it can be used alone to bring almost the stabilizing action
required. Euro Soil Stab [2] sates that the cement response is not dependent on
soil minerals, and the key part is its reaction with water that will be accessible in
any soil. This could be the reason why cement is utilized to stabilize in a wide
extend of soils. Al-Tabbaa and Evans [11] reported that the calcium silicates, C₃
S and C₂S are the two main cementitious components of ordinary portland
cement responsible for strength development. Das [12] reported that the usage
of cement stabilization improves the shear strength of sand. Oyediran et al. [13]
studied the impact of termite activities of clay with higher cement content and
showed that it behaves like a soft rock. The results also showed that, when
cement comes to some lateritic soils, the termite reworked soils and showed
remarkable improvement in shear strength, CBR, plasticity index and specific
gravity.

Lee et al. [14] improved that the behaviour of the cement-clay with lower
cement content is comparative to an over-consolidated soil. They also intro-
duced a constitutive model for cement-clay with a new parameter (bonding
stress ratio) to estimate the effect of cementation within the framework of the
critical state concept. Asskar et al. [15] investigated the combined effect of
cement and nanosilica on the engineering properties of sand. Three different
cement ratios (5%, 9% and 14% by weight of dry sand) and four different
nanosilica ratios (0%, 5%, 10% and 15% by weight of cement) were considered.
The results showed that the maximum dry density of sand increased with the
increase of the cement content. (INDOT) [16] showed the applicability of cement
to stabilize calcareous soils. Mohamed et al. [17] concluded that the presence of
sulfates in soil–cement mixtures is attributable to the formation of expansive
stringier and traumatize minerals. Also, they concluded that increasing of cement
content leads to an increase in the strength of cement-treated soil. The rate of
improvement decreases with an increasing plasticity index of soils. Ali and
Youssef [18] reported that the cement used as a subgrade material in Saudi
Arabia is intended to stabilize sandy silt.

In the current research, an experimental investigation was carried out using
five different cement ratios (3%, 5%, 7%, 10% and 15%) as an admixture for
stabilization of sand for using as foundation soil. Then, the improved properties of
cemented sand were used in a numerical model to determine the optimum ratio
for improvement of replacement sandy layer under foundations. In the numerical model, four different depths (D) of mixed sandy soil layer (0.50, 1.0, 1.50 and 2.0 m.) were considered under a footing with width (B) equal 3.0 m and has a concentrated load of 300 kPa.

**Materials**

**Sand**

In the current study, the used sand is air-dried clean siliceous yellow sand collected from local sand of Egypt, which is typically used as a construction material in concrete, mortar and soil replacement in Egypt. Grain-size analysis was performed on the sand sample according to ASTM D421 [19], the results are illustrated in the following Figure 1.

The plot shows that the sand is poorly graded with medium to fine sand, according to the unified soil classification system [USCS]. Table 1 indicates the index properties of the tested sand (the water content and dry unit weight are estimated from the modified Proctor test).

**Cement**

The cement used in the present study was produced by a local cement factory in Egypt (Suez Cement Factory) of Ordinary Portland Cement type. Cement sample was analyzed to get chemical properties. Table 2 indicates the chemical analysis results of a cement sample.

![Figure 1. Grain-size distribution analysis.](image)
Laboratory testing program and results

Compaction analysis

Stabilizer (cement) was added in amounts of 3%, 5%, 7%, 10% and 15% by dry weight of the soil. The required amount of stabilizer was added to a dry soil sample passing sieve No. 4 (4.75 mm). The soil and stabilizer were mixed together until reaching a uniform colour. The modified compaction test (ASTM D1557) [20] is applied to account the maximum dry density for each mixture. The compaction curves for natural soil and the five mixtures were outlined in Table 3 and plotted in Figure 2. The natural soil has the maximum dry density of 17.55 kN/m$^3$ at optimum water content (OWC) of 12.35%.

It is clear that, with increasing cement percentage, the optimum water content decreases and the maximum dry unit weight increases as shown in Figure 2. Changes in compaction parameters (y dry and OWC) are affected by higher specific gravity value of cement than sand, alterations in the grain-size

### Table 1. Summary of geotechnical properties of the used sand.

| Property          | Value | Property          | Value |
|-------------------|-------|-------------------|-------|
| Specific gravity (Gs) | 2.64  | Maximum Dry unit weight (yd) (kN/m$^3$) | 17.55 |
| % of Clay         | 0.00  | Optimum Water content (Wc) (%)      | 12.35 |
| % of Silt         | 0.00  | Angle of internal friction ($^\circ$) | 37.52 |
| % of fine Sand    | 67.86 | Effective diameter (D10) mm         | 0.151 |
| % of medium Sand  | 32.14 | 30% passing diameter (D30) mm       | 0.208 |
| % of coarse Sand  | 0.00  | 60% passing diameter (D60) mm       | 0.354 |
| % of fine Gravel  | 0.00  | Coefficient of uniformity(Cu)       | 2.34  |
| Unit weight (yb)  | 17.92 | Coefficient of gradation(Cc)        | 0.809 |

### Table 2. Chemical analysis results of cement.

| Sample      | TDS (ppm) | pH  | SiO2 (%) | R2O3 (%) | CaO % | MgO % | SO3 % |
|-------------|-----------|-----|----------|----------|-------|-------|-------|
| Cement      | 6180      | 12.06 | 18.5     | 8        | 65    | 1.7   | 1.85  |

TDS: Total Dissolved Sulfates, SiO2: Silica, R2O3 = (Al2 o3 + Fe2O3), CaO: Lime, MgO: Magnesia, SO3: Sulfates.

### Table 3. Maximum dry unit weight and corresponding O.W.C%.

| Group No. | Group Name         | Maximum dry unit weight (Yd max)(kN/m$^3$) | Corresponding O.W.C % |
|-----------|--------------------|-------------------------------------------|------------------------|
| G1        | Sandy Soil only    | 17.55                                     | 12.35                  |
| G2        | Sand +3% Cement    | 17.86                                     | 11.45                  |
| G3        | Sand +5% Cement    | 18.08                                     | 11.12                  |
| G4        | Sand +7% Cement    | 18.79                                     | 10.43                  |
| G5        | Sand +10% Cement   | 19.02                                     | 10.08                  |
| G6        | Sand +15% Cement   | 19.40                                     | 9.41                   |
direct optimum applied chosen The presented sand and Groups 23)
Direct distribution of the mixture and reduction in moisture content (Al-Aghbari et al. [21], Zabielska [22]).

**Direct shear test**

Groups of direct shear tests were performed to understand the behaviour of sand during shear resistance with and without adding different cement ratios. All samples were prepared by casting in a mold with dimension (60 mm × 60 mm × 34 mm). After the soil and cement were mixed together until a uniform colour was observed; then, the water was added to the soil-cement mixture. All specimens were prepared at their maximum dry unit weight and optimum moisture content as obtained from the standard Proctor compaction tests conducted on both cemented and natural soils (ASTM D-698 2010) [23]. The time used for the setting of specimens is 4 days. The normal stresses were chosen as 50, 78 and 106 kPa for all the specimens. The shear loading was applied at a rate of 0.12 mm/min. Figure 3 shows the sample in the mold of the direct shear device, while, Table 4 shows the results of direct shear tests.

The effect of cement content on the shear strength parameters (c and φ) is presented in Figure 4(a, b). The data indicate that the stabilized sand possesses cohesion and angle of internal friction, which confirms the earlier findings of other researchers. The shear strength parameters, the cohesion and angle of internal friction increase significantly with increasing cement content. This effect is attributed to increasing the stiffness of soil as a result of increasing the cement stabilizer. It is obvious that the friction angle increases with the increase of cement ratio till reaching 5%, and then it decreases as shown in Figure 4(b). This result can be attributed to adding water to sample, the mixture of cemented sand produced viscous gel under low cement content. Then, the cement matrix and viscous gel have a combined effect on mechanical

![Figure 2](image-url)
properties of the cemented sand sample. The higher cement content than 5% has a negative effect on cement matrix which can reduce the angle of internal friction. Therefore, the optimum-required cement content with highly ponded grains and angle of internal friction is 5% cement ratio.

Figure 3. Sample shape in the mold of direct shear device.

Table 4. Summary of results for direct shear tests.

| Group No. | Group Name          | Cohesion (C) (kN/m²) | Angle of internal friction (ϕ)º | Young’s modulus (E) (kN/m²) |
|-----------|---------------------|----------------------|---------------------------------|----------------------------|
| G1        | Sandy Soil only     | 0.00                 | 37.52                           | 30,000                     |
| G2        | Sand +3% Cement     | 65.80                | 44.37                           | 32,461.53                  |
| G3        | Sand +5% Cement     | 170.4                | 47.50                           | 35,322.19                  |
| G4        | Sand +7% Cement     | 384.8                | 44.82                           | 46,824.37                  |
| G5        | Sand +10% Cement    | 1787.8               | 44.29                           | 61,567.95                  |
| G6        | Sand +15% Cement    | 2253.9               | 44.05                           | 128,765.70                 |

Figure 4. Effect of cement content on: (a) Cohesion and (b) Angle of internal friction.
In addition, the effect of cement content on Young’s modulus (E) is presented in Figure 5. When the cement content is higher than 5%, the rate of increase in Young’s modulus increases significantly.

**Numerical analysis for case study**

A numerical analysis based on the finite element method (FEM) is used to investigate the behaviour of strip footing founded on the suggested stabilized cement sand. This analysis aims to estimate the optimum cement content required to be added to the replacement of sandy soil under the footing. The geometry model used in Plaxis (8.2 professional version [24]) and the soil properties are shown in Figure 6. A nonlinear

![Figure 6](image)
elasto-plastic, Hardening Model, is adopted in the analysis. The footing exerts a stress of 100 kPa (assumed value) at the foundation level. The following Table 5 shows the soil properties used in the analysis considering different cement ratios, in addition, the footing properties are outlined in Table 6.

### Results and discussions

Running the model using original soil (without adding soil replacement) shows that the maximum vertical deformation, the bending moment of the footing and the general factor of safety for shear strength (based on phi/c reduction analysis) are 81.44 mm, 111.84 kN.m/m and 1.174; respectively. Noted that the acceptable value for the factor of safety is 2.0 according to Egyptian code for foundation, part-3 (202/3), item (3/3/6) [25].

In all the cases, the stabilized replacements beneath the footing with different thicknesses (D) 0.50, 1.0, 1.50 and 2.0 m are utilized in the analysis, accordingly, changing in replacement extension (L) relative to its thickness, L/D, varies within zero to 4.0. However, in the case of zero cement, the replacement soil beneath the footing was sandy soil only overlaying the original soil. The properties of the used replacement sandy soil indicated in Tables 4 and Tables 5 where the angle of internal friction \( (\phi)^o = 37.52^o \), Young’s modulus \( (E) = 30,000 \text{ kN/m}^2 \) and \( (Yb) = 17.92 \text{ kN/m}^3 \). Also, the properties of the original soil is the angle of internal friction \( (\phi)^o = 20.0^o \), Young’s modulus \( (E) = 15,000 \text{ kN/m}^2 \) and cohesion = 3.0 kN/m^2 as shown in Figure 6(b).

### Table 5. Soil properties used in the model.

| Group Name       | Cohesion (C) (kN/m^2) | Angle of internal friction (\( \phi \))^o | Young’s modulus (E) (kN/m^2) | Unit weight Yb (kN/m^3) |
|------------------|-----------------------|------------------------------------------|-----------------------------|-------------------------|
| Sand only        | 0.00                  | 37.52                                    | 30000                       | 17.92                   |
| Sand +3% Cement  | 65.80                 | 44.37                                    | 32461.53                    | 18.61                   |
| Sand +5% Cement  | 170.4                 | 47.50                                    | 35322.19                    | 18.88                   |
| Sand +7% Cement  | 384.8                 | 44.82                                    | 46824.37                    | 19.09                   |
| Sand +10% Cement | 1787.8                | 44.29                                    | 61567.95                    | 19.52                   |
| Sand +15% Cement | 2253.9                | 44.05                                    | 128765.70                   | 19.87                   |

### Table 6. Footing properties used in the model.

| Parameters                          | Values         |
|-------------------------------------|----------------|
| Axial Stiffness (EA) (kN/m)         | 1.107 E+07     |
| Flexural Rigidity (EI) (kN.m^2/m)   | 2.306 E+05     |
| Equivalent Plate Thickness (m)      | 0.50           |
| Poisson’s Ratio (u)                 | 0.15           |
| Specific Weight (kN/m/m)            | 1.000 E-03     |
Effect of the stabilized depth (D) on various straining actions

The numerical models were analyzed for different thicknesses of stabilized replacements (D = 0.50, 1.0, 1.50 and 2.0 m). The effect of cement content on vertical displacement, bending moment and general factor of safety are outlined in Figures 7–9; respectively.

The vertical deformation significantly decreases with increasing each of the cement ratio and mixed depths. It is noticed that at 15% cement ratio, the vertical displacements decrease by ratios of 15.41%, 25.58%, 31.86% and 26.35% for mixed depths 0.50, 1.0, 1.50 and 2.0 m, respectively as shown in Figure 7.

The bending moment on footing increases with increasing the mixed depth under foundation until reaching replacement thickness 1.0 m which corresponding to (1/3) of footing width (B); then, the moment is going almost constant. Moreover, the bending moment increases with increasing of the cement content as shown in Figure 8, this is attributed to that the increase in bending moment due to the hydration process of the cement binds with soil particles which interact together and makes the compacted matrix, causing an increase in stiffness for the composite soil under the footing.

As illustrated in Figure 9, the general factor of safety for shear strength increases with increasing the mixed depth under foundation, noted that the acceptable value for the factor of safety is 2.0 according to Egyptian code for foundation, part-3 (202/3), item (3/3/6) [25] as shown in Figure 9. Also, it is noted that the factor of safety increases with increasing of the cement content.

Figure 7. Effect of cement content on vertical deformation behaviour.
The factor of safety almost has an insignificant change after the cement content reaching 7%.

**Figure 8.** Effect of cement content on bending moment behaviour.

**Figure 9.** Effect of cement content on factor of safety.
**Effect of ratio (L/D) on various straining actions**

The effect of the ratio between replacement extension distance (L) and replacement mixed depth (D) versus the vertical deformation, footing bending moment and factor of safety were investigated for cement contents of zero%, 3%, 5%, 7%, 10% and 15%. Figure 10 reveals that the rate of decreasing in the vertical displacement is high with the increase in ratio (L/D) until reaching L/D = 1; then, the displacement becomes almost constant. Also, it is noticed that the vertical displacement at cement cases 3%, 5%, 7%, 10% and 15% almost is close for L/D = 0, this leads to conclude that there is no effect for increasing the amount of cementation on the vertical displacement at L = 0.

Figure 11 presents the results of the effect of (L/D) on the footing bending moment. Generally, there is an increase in the bending moment with increasing L/D. However, after L/D = 1, the increase in the bending moment is negligible. Also, it is noticed that the moment at cement cases 3%, 5%, 7%, 10% and 15% almost is same for L/D = 0; therefore, it is deduced that there is no effect for increasing the amount of cementation on the bending moment at L = 0.

As can be seen in Figure 12 the factor of safety for shear strength increases with the increase in L/D noted that the acceptable value for the factor of safety is 2.0 according to Egyptian code for foundation, part-3 (202/3), item (3/3/6) [25] as shown in Figure 12. This behaviour does not show a significant increase within interval L/D = 1 to 2. It is noticed that the factor of safety at cement cases 3%, 5%,
Figure 11. Effect of improvement distance with cement on bending moment.

Figure 12. Effect of improvement distance with cement on factor of safety.

7%, 10% and 15% almost is same for L/D = 0, this leads to conclude that there is no effect for increasing the amount of cementation on the safety factor at L = 0.
The effect of the ratio between replacement-mixed depth (D) and the width of footing (B) versus the vertical deformation, the bending moment exerted on the footing and the general factor of safety were investigated for cement contents of zero%, 3%, 5%, 7%, 10% and 15% at replacement extension distance \( L = 1.0 \) m. Figure 13 illustrates that there is a significant effect of increasing ratio \( D/B \) on decreasing the vertical displacement. This effect is because increasing \( D/B \) leads to increasing the stiffness of the soil beneath the footing. Also, it is noticed that there is a small effect for cement contents of 3%, 5%, 7%, 10% and 15% on decreasing the vertical displacement versus \( D/B \).

Figure 14 presents the results for the effect of \( D/B \) ratio on the bending moment exerted on the footing. It can be noted that the peak bending moment occurred within the interval \( (D/B = 0.30 \text{ to } 0.50) \), where this interval ratio leads, then, it decreased by increasing \( D/B \). After \( D/B = 1 \), the rate of the bending moment is going steady. It is deduced that the value of \( L/D = 1 \) will lead the corresponding \( D/B = 1/3 \). For \( D/B = 1.50 \), this cement ratio gives minimum-exerted bending moment, where the increase in cement ratio more than 10% leads to make the soil behave as a rigid continuum under the footing.

Figure 15 presents the results for the effect of \( (D/B) \) ratio on the general factor of safety for shear strength, noted that the acceptable value for the factor of safety is 2.0 according to Egyptian code for foundation, part-3 (202/3), item
as shown in Figure 15. It can be noted that the factor of safety increases almost linearly with increasing the ratio (D/B) in all cement ratios.

**Figure 14.** Effect of ratio (D/B) on bending moment at L = 1 m.

**Figure 15.** Effect of ratio (D/B) on factor of safety at L = 1 m.
Conclusions

The current study was carried out to clarify the effect of adding different cement ratios 3%, 5, 7, 10% and 15% to stabilize replacement of sandy soil under a strip footing. The following conclusions are outlined:

(1) Generally, increasing the cement ratio mixed with sandy soil leads to an increase in shear strength parameters and maximum dry unit weight. However, the optimum water content decreases.

(2) The cement stabilization leads to a decrease in vertical deformation with increasing each of the cement ratio and mixed depths.

(3) The increase in ratio (L/D) leads to a decrease in the vertical deformation and increase in bending moment until reaching (L/D) = 1. Then, the behaviour goes to be steady.

(4) At zero replacement extension, there is no effect of increasing the amount of cement stabilization on vertical deformation, the general factor of safety and bending moment.

(5) The increase in ratio (D/B) leads to decrease in the vertical deformation and increase the general factor of safety. Furthermore, the peak bending moment occurred within the interval D/B = 0.30 to 0.50; then, it decreased by increasing (D/B).

(6) The maximum-exerted bending moment occurred at the cement ratio of 15%. Meanwhile, at D/B = 1.50, this cement ratio gives minimum exerted bending moment.

(7) The optimum cement content is 7% since increasing after that leads to an insignificant change in various straining actions and factor of safety for shear strength.

(8) The ratio (L/D), is (L/D) = 1 since increasing after that leads to an insignificant change in various straining actions and factor of safety for shear strength.

(9) The ratio (D/B), is (D/B) = 0.33 at L = 1 m. since increasing after that leads to an insignificant change in various straining actions and factor of safety for shear strength.

Disclosure statement

No, potential conflict of interest was reported by the authors.

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