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Potential Collapse for Sandy Compacted Soil during Inundation

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Abstract
Collapsible soils show relatively high apparent strength in their dry state, but have low density, porous structure. One of the most important problems concerning collapsible soils is instability and considerable settlement due to minor changes in the water content which can cause remarkable damages to overlying structures. Therefore, evaluation of collapsibility potential through defining many empirical criteria is especially important. Experimental work program was developed to investigate the effect of relative compaction and amount of initial water content on collapsibility potential. This paper includes results of experimental work conducted to study the performance of collapsible soil improved by pre-construction wetting and compaction energy. The study showed that increase of both relative compaction energy and degree of saturation minimize the risk of collapsibility potential.

Keywords: *Collapsible soil, Residual soil, Collapsibility, Soil inundation.*

1. Introduction

Collapsible soils are found throughout the world in recent soil deposits in arid and semi-arid environments that are eolian, loessial, subaerial, colluvial, mudflow, alluvial, residual, or man made fills. Man made fills which were compacted at the optimum water content, may also develop a collapsible or metastable structure at low density.

Collapsible soils are defined as any unsaturated soil that goes through a radical rearrangement of particles and greatly decreases in volume upon wetting, additional loading, or both. These soils have a loose soil structure, i.e. a large void ratio and a water content far less than saturation. Collapsible soils show relatively high apparent strength in their dry state, but have a low density, porous structure and are susceptible to a large settlements upon wetting. Typically the structure of these low-unit weight, unconsolidated sediments consists of coarser particles bonded at their contact points by the finer silt and/or clay fraction, or possibly by surface tension in the water at the air-water interfaces. Some soils under constant applied load show a volume decrease related to an increase in moisture content. This wetting induced or collapse strain is a typical feature of the so-called collapsible soils, which are usually non saturated, low dry density, and met stable structured soils (Feda 1966 [1]; Dudley 1970 [2]; Jennings and Knight 1975 [3]; Vilar et al. 1981 [4]).

According to (Day, 2001 [5]) collapse behavior could happen in fill material as a result of decrease in negative pore water pressure (capillary tension), when the fill becomes wet. Common causes of the wetting can be either natural, such as rainfall and fluctuation in ground water table, or man-made, such as excessive irrigation and leakage from water and sewer lines. Collapsible soil as defined by Day (2001) [5] ; is a soil that is susceptible to a large and sudden reduction in volume upon wetting. Collapsible soil deposits share two main features, they are loose, cemented deposits, and they are naturally quite dry.

The dry density and water content of soil specimens at the time of compaction are generally considered as the primary soil properties that control the amount of collapse.

Several researchers have reported that soils exhibit collapse if the dry density of the soil specimen is less than 1.6 KN/m^3. Jennings and Knight (1975) [3]; reported that the above conclusion is a misconception and should be dispelled.

This study presents the effect of compaction on the geotechnical properties of collapsible soils. The effect of moulding water content, and dry density on the collapse potential, and compressibility of compacted silty sand soils was investigated. Tests performed include oedometer, and California bearing ratio.

It is emphasized that, samples for oedometer, and CBR tests were taken from the same patch of soil at desired moisture content. The CBR test was employed in this experimental program for its simplicity and wide use in highway design. The CBR test provides the stress-penetration data for a small bearing test; both deformation and strength data can be obtained. All tests were conducted in accordance with ASTM D-1883-73.

In this study regarding site investigation, soil sampling and many laboratory tests, the possibility of collapse phenomena was investigated.

The main aim of this study is to examine the collapsibility rate of residual soil at sixth of October city, Giza governorate, Egypt

2. Overview of collapsible soils

Several collapse criteria based on some parameters such as dry density, Atterberg limits, moisture content, void ratio, clay content, and prosity have been proposed in the literature, (Tadepalli and Fredlund, 1991 [6] in Ayadat, 2007 [7]). Several authors (Al-Rawas, 2000 [8] and Ali M.M, 2011 [9]) have studied the soil collapse and listed the factors contributing to the occurrence of this phenomenon. The main factors are summarized as follows:

• An open unstable structure and partially saturated.
• A high total stress is applied.
• The presences of cementing agent in the soil.

A moistening the soil will reduce the suction and destroy the liaison officers.

Jennings and Knight (1975) [3] in AI-Rawas, 2000 [8], suggested a classification (see table 1) after determining collapse potential CP, which is defined as:

$$CP\ (\%) = \Delta H/H0 = \Delta e_c/1+e_0$$

ΔH :Change in height of the specimen upon flooding.

H_O : Original height of the specimen.

.Δe_c: Change in void ratio upon flooding.

e_0 : Void ratio before flooding.

Holtz and Hilf (1961) [10] described the mechanism of collapse accompanying wetting as the result of capillary pressures approaching zero and the degree of saturation increasing to 100 %. The mechanism for cohesion less soils was explained on the basis of the "reduction of shear factor" (i.e., shear strength - shear stress) against collapse. It was postulated that during inundation, the Mohr circle translates horizontally by an amount equal to the negative pore-water pressure existing in the soil before inundation. Due to this transition, the effective stress path intersects the Mohr-Coulomb failure envelope, resulting in a general shear failure and associated settlement.

Burland (1965) [11] explained the collapse mechanism in terms of the stability at the interparticle contact points. Due to inundation, the negative pore-water pressure at the contact points decreases, giving rise to grain slippage and distortion.

Larinov (1965) [12], Dudley (1970) [2], and Barden et al. (1973) [13]; described the collapse phenomena in terms of the bonding materials present at the contact points. It was suggested that in the case of silt bonds (i.e., bonding material is of silt- sized particles) the temporary strength was mainly due to capilllary tension. In this case, the temporary strength would be lost during inundation, resulting in a decrease in volume. However, it was suggested that, in general, the bonding material for collapsible soils was clay. Dudley (1970) [2] postulated that the capillary forces provided temporary strength to the clay bonds when in a dry state.

The underlying principles associated with all postulated mechanisms are that (i) the soil must be unsaturated and (ii) the pore-water pressures must be negative. The fact that soils must be unsaturated to exhibit collapse encourages the consideration of the unsaturated soil mechanics principles.

(Fedo, 1988 [14]) proposed an equation for assessment of soil collapsibility potential as follow: $i_c = \frac{\frac{m}{Sr} - PL}{PI}\ \%$

where: m and Sr are the natural water content and soil saturation ratio respectively. The PL and PI are plastic limit and plasticity index of soil.

Based on the above criterion, if the collapsibility index, i_c is less than 1, it means that soil is susceptible to collapse.

Based on (Denisov, 1964 [15]) proposed criterion, if $\frac{e}{e_{LL}} > 1$ then the soil is collapse susceptibly where: e and e_{LL} are the soil void ratio in natural and liquid limit water content respectively.

Proposed criterion of (Clevenger, 1985 [16]) for collapsibility evaluation is based on the soil dry density. He declares if the soil dry density is lesser than 12.8 KN/m^3 then the soil will collapse after minor water content changes. On the other hand, if the soil density is more than 14.4 KN/m^3 then the lesser collapse settlement could be expected. For medium range of soil density, the medium collapse settlement could be evaluated.

According to (Lin and Wang, 1988 [17]) criterion, the collapsibility index of soil in self weight condition is defined as follow: $i_{cz} = \frac{h_z - h_{zs}}{h_1}$

Where: h_z and h_{zs} are the soil sample thickness in odometer test regarding overburden pressure in natural and saturation conditions respectively and h_1 is initial soil sample thickness.

The soil condition and tendency to be collapsed are summarized in Table1, after Jennings and Knight (1975) [3].

Table 1. Potential severity of collapse (Jennings and Knight 1975 [3]).

Collapse Intensity	*Collapsibility Index (%)*
No Collapsibility	0-1
Medium Collapsibility	1-5
High Collapsibility	5-10
Very High Collapsibility	10-20
Extremely Collapsible	>20

To evaluate soil collapsibility, various criteria has been defined by many researchers. Reviewing the existing literature of collapsible soil, the works of Abelev [18] Clevenger [10], Denisov [15], Fedo [14] , Lin and Wang [17] could be mentioned.

3. Identification of collapsible soil

The dry density and liquid limit graph (Gibbs and Bara, 1962 [19]) are recommended as quick identification methods for collapsible soils. Soil of sufficiently low natural density, which has sufficient void space to hold its

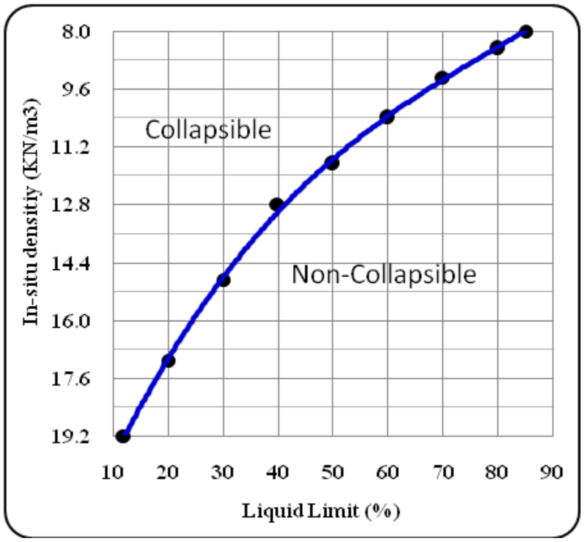

Fig. 1. Identification of collapsible plastic soils (After Gibbs and Bara, 1962 [19]).

liquid limit moisture at saturation, is susceptible to collapse upon wetting, Fig. 1.

4. Estimation of collapse settlement

The characterization of soil collapse is traditionally performed using a conventional oedometric test in which a specimen, under a constant load and at a certain moisture content, is flooded. This procedure, albeit valid, does not consider some issues related to the problem especially the soil suction due to the limitations of the experimental technique. Field evidence indicates that strain due to collapse may occur due to the gradual increase in moisture content or, in other words, due to the gradual reduction in soil suction. In this case, volumetric variations can occur without saturation, but with the soil still presenting significant soil suction, as shown by Tadepalli et al. (1992) [20], Vilar (1995) [21], Machado and Vilar (1997) [22], and others, when using controlled soil suction tests.

The quantification of volume change occurs when soil undergoes collapse is obtained from oedometer test. It is believed that single and double oedometer test is reasonably adequate tools to investigate behavior of collapsible residual soil.

4.1 Single oedometer collapse test

The single oedometer method consists of one sample. The undisturbed soil specimen at natural moisture content loaded in the conventional oedometer to a stress level ranging between 200 and 400 KPa and then inundation by distilled water is applied to induce collapse, after 24 hours, the oedometer test is carried out by increasing load to its maximum loading.

(Abelev, 1948 [18]) defined the collapse potential (Ie) as:

$Ie=\frac{\Delta e_c}{1+e_1}$ where:

Δe_c : Change in void ratio resulting from saturation.

e_1 : Void ratio just before saturation.

While, (Jennings and Knight, 1975 [3]) , recommended the using of stress level of 200 KPa , and calculate the collapse potential according to the following equation:

$Ie = \frac{\Delta e_c}{1+e_0}$ where:

Δe_c : Change in void ratio resulting from saturation.

e_0 : Natural void ratio.

The stress level of 200 KPa was adapted by (ASTM D 5333-96, 2000) to classify the severity of the collapse problem (Day, 2001 [5]). A typical result obtained from this test is shown in Fig. 2.

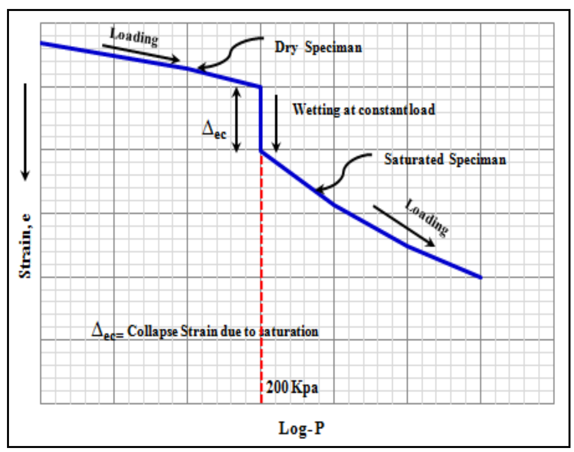

Fig. 2. Schematic diagram of single oedometer collapse test.

4.2 Double oedometer collapse test

(Jennings and Knight, 1975 [3]) proposed a method for calculating collapse settlement of as soil for design purposes using the results of a double oedometer. Two identical samples are placed in oedometers, one tested at in-site natural moisture content and the other is fully saturated before the test begins, and then subjected to identical loading. Two stresses versus strain curves are generated. The difference between the compression curves

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is the amount of deformation that would occur at any stress level at which the soil get saturated. Results from double oedometer test are shown in Fig. 3.
The collapse potential can be determined at any required stress level. Critical stress (σ'_{cr}) represents the stress level at which the dry sample loose structure breaks down and beyond it the two curves converge. This behavior could be explained also by that at a high stress level, the limiting

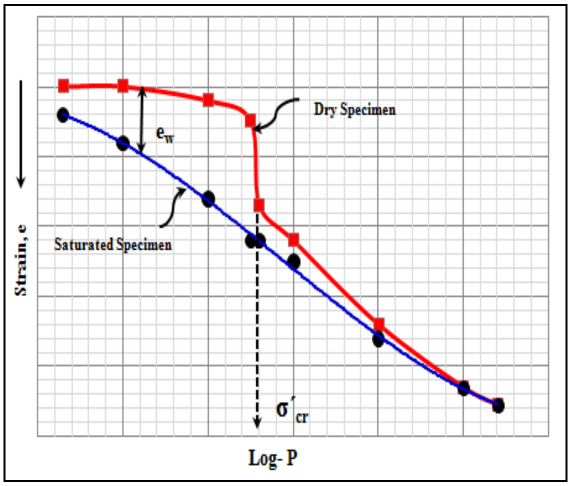

Fig. 3. Schematic diagram of double oedometer test.

void ratio for saturated sample is approached for particles packing (Lutenegger and Saber, 1988 [23]).

5. Materials and methods

5.1. Basic properties of the soil

The collapsible soil used in this experimental program were collected from a trial test pits in a newly developing district in the northern extension of Sixth of October City , Giza governorate, Egypt, where the presence of collapsible soil layers was detected near the ground surface by site investigations. Laboratory tests were performed on good quality samples trimmed from a block that was manually extracted at a depth of 2.0 m from ground surface. The tested engineering properties are listed in Table 2.

5. 2 Collapsibility evaluation of tested soil

Based on preliminary extracted parameters from site investigation in conjunction with laboratory tests, the basis engineering judgments concerning soil collapsibility have been summarized in Table 3. The possibility of collapse phenomena was investigated and confirmed for sixth of October site through the previous mentioned theories and empirical equations.

5.3. Preparation of compacted soil samples

The air dried representative soil sample passing the 2 mm sieve was completely hand-blended at the designed water content. The mixture was permitted to achieve equilibrium for 24 hours in a sealed plastic bags. The required mass of prepared wet soil samples was compacted statically into the oedometer ring to different dry densities

Table 2. Engineering properties of soils.

Specific gravity	2.67
Liquid limit , WL (%)	32
Plasticity Index ,IP (%)	17
Natural water content ,w (%)	4.0 average
Natural Dry density (KN/m^3)	13.6
Natural degree of saturation, S_r (%)	11
Initial Natural void ratio , e_0	0.963
Maximum Modified Proctor test, KN/m^3	18.6
Optimum Moisture content, %	11.5
Clay fraction (% < 2 μm)	14
Silt fraction (%)	27
Sand fraction (%)	59
Soil type (USCS)	ML

Table 3. The basic engineering judgment for job site collapsibility

Proposed criterion	***Collapsibility coefficient formula***	***Collapsibility coefficient range***	***Collapse intendancy***
Abelev (1948)	$S_s = \frac{e_0 - e_1}{1+e_0} = \frac{0.875-0.73}{1+0.875} * 100 =$ 7.73 %	7.73>2	High collapsibility
Denisov (1964)	$\frac{e}{e_{cr}} = \frac{0.875}{0.73} = 1.2$	1.2>1	Medium collapsibility
Clevenger (1985)	$\gamma_d = 13.8$ KN/m^3	1.28<1.36<1.44	High collapsibility
Feda (1988)	$L_{cr} = (m/sr - PL) / P.I = (\frac{8}{0.333} - 15) / 16 = 1.137$	1.137>1	High collapsibility

Table 4. Properties of prepared compacted samples

<table>
<tr><th colspan="12">Initial dry density, KN/m³</th></tr>
<tr><td colspan="2">1.4</td><td colspan="2">1.5</td><td colspan="2">1.6</td><td colspan="2">1.7</td><td colspan="2">1.8</td><td colspan="2">1.86</td></tr>
<tr><th colspan="12">Initial void ratio, e₀</th></tr>
<tr><td colspan="2">0.907</td><td colspan="2">0.780</td><td colspan="2">0.669</td><td colspan="2">0.571</td><td colspan="2">0.483</td><td colspan="2">0.435</td></tr>
<tr><th colspan="12">Initial water content, w (%)</th></tr>
<tr><td colspan="3">5.0</td><td colspan="3">8.0</td><td colspan="3">12.0</td><td colspan="3">16.0</td></tr>
</table>

using the mold shown in figure 4. After compaction, the soil specimen and the ring were weighed to obtain the initial density of the specimen. Characteristics of tested soil samples are summarized in Table 4.

5.4 Test performance

This experimental study consisted of a series of single oedometer tests conducted on soil specimens under various values of water content at different initial dry densities. Specimens were statically compacted into an oedometer ring using the compaction mold shown in Fig.4.

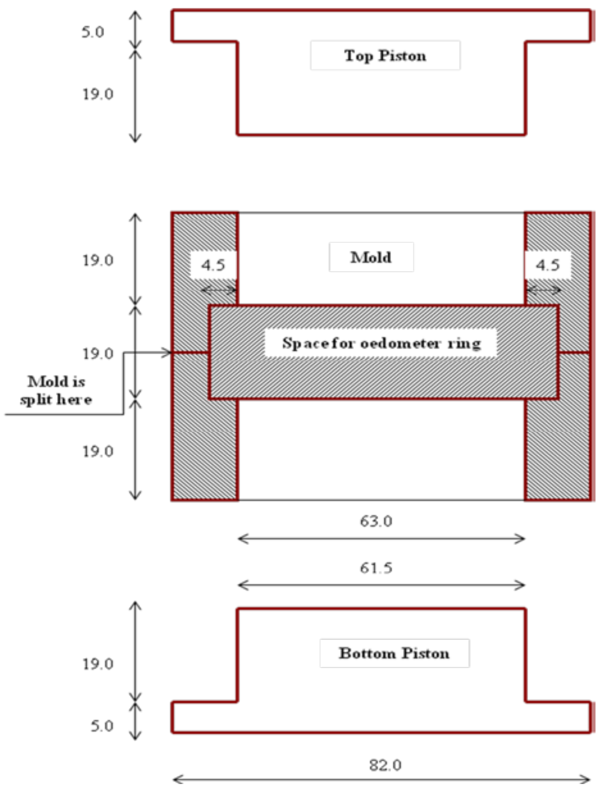

Fig. 4. Compaction mold. Dimensions in millimeters.

The mold is similar to that used by Booth (1977) [24] and Maswoswe (1985) [25]. The dimensions of the ring were 19.0 mm in height and 63.0 mm in diameter.

The oedometer ring containing the soil specimen was then firmly held between two porous stones. The specimen was held in this configuration to avoid disturbance.

The procedure used to conduct collapse tests is that recommended by the standard ASTM D5333-1992 (Standard Test Method for Measurement of Collapse Potential of Soils [26]) which is a standard for the study of the collapsible soils.

The single oedometer test procedure employ one oedometer test loaded initially dry up to a prescribed pressure, 200 KPa , then soaked , and the collapse magnitudes were observed. Loads were applied in cumulative increments prescribed as following, 5, 10, 25, 50, 200, 1000 KPa. During each load stage, the cumulative load was maintained for at least 24 hours and until the rate of deformation reaches less than 0.001 mm/min. Collapse potential (CP) is defined as the collapse strain due to wetting at applied pressure of 200 KPa (Jennings and Knight, 1975) [3].

6. Results and Discussion

A 24 experimental tests carried out on compacted sandy soils at different dry densities (1.86, 1.8, 1.7, 1.6, 1.5, and 1.4 KN/m^3) and different water contents (5, 8, 12 and 16 %) were done. A sample of these results reported in Fig. 5.

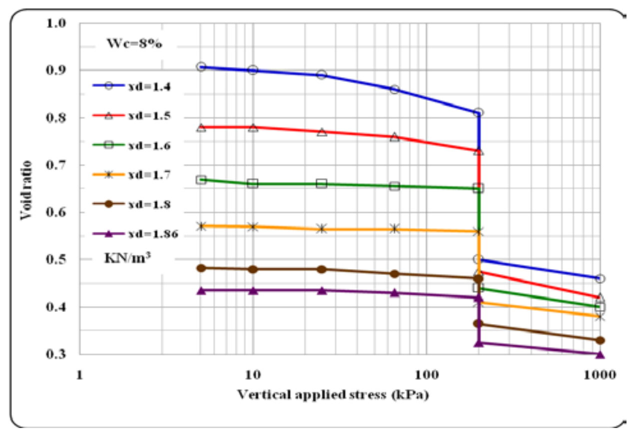

Fig. 5 Results of collapse tests for various compacted density at Wc=8%

Fig. 5 depicts the results of single oedometer tests performed on compacted soil samples at 8% water content for various studied dry density.

At the Modified Proctor Optimum conditions of dry density and water content respectively 18.6 KN/m^3 and 11.5 %, the recorded Collapse Potential (CP %) is less than 2 %, Fig. 5, so under these conditions the soil is not collapsible.

With the same water content (12%), and decreasing the initial density of 18.6 to 18, 17, 16,15 and 14 KN/m^3, higher potentials of collapse are obtained as shown in Fig. 6.

In order to establish the influence of dry density and water content on collapse potential of the studied soil, Fig. 6 and 7 were plotted. From the study of the results plotted in Fig. 6, the highest rate of collapse potential is obtained for a density of 14 KN/m^3 (it's represent 75% of the density at the optimum). This is explained by the fact that the soil structure is open: it has an important initial void ratio of about 0.91.

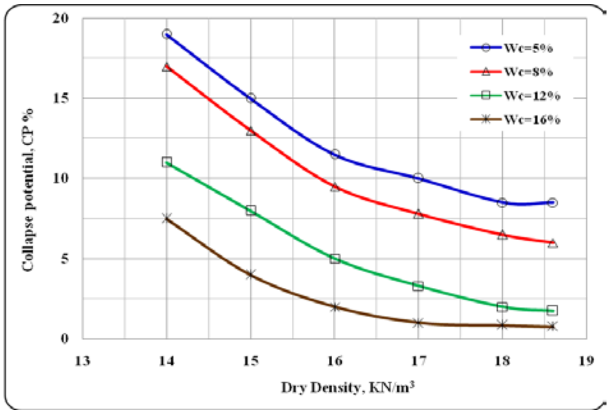

Fig. 6 Variation of collapse potential, with dry density

We can explain this phenomenon by the mechanism that occurs after flooding (at load of 200 kPa), the suction became zero therefore the apparent cohesion disappeared thus reducing shear forces.

The effect of the initial molding water content on the amount of collapse for various values of initial dry density is shown in Fig. 7. The outputs shown in Fig. 7 elucidated an inverse relation between the initial molding water content and collapse potential at a constant dry initial density. At lower density and water content we found the highest potential of collapse (19%) for the studied soil.

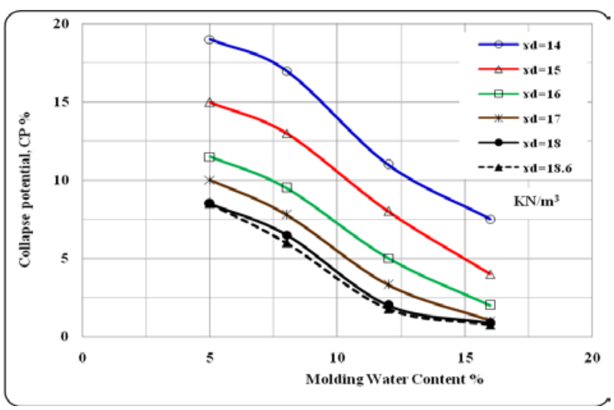

Fig. 7 Variation of collapse potential, with molding water content.

The meditation of the results shown in Figure 6 clearly that there is an inverse relation between the collapse potential (CP) and dry density. The same think is observed for the relation between CP and water content, figure 7. At higher value of water content, we obtain a lowest potential of collapse.

The approximate linear relationships between the amount of collapse and the initial properties are in agreement with the observations made by (Popescu, 1986 [27]) and Foss, 1973 [28]) .

The CBR tests results are presented in Fig. 8 which shows CBR values as a function of moisture content, for different soil density. The general pattern of the curves was roughly the same irrespective of the soil density showing that the CBR value decreased to small values as the water content increased, regardless of the corresponding value of dry density. The CBR values are higher in the dry side of optimum moisture content due to strong cementation bonds and surface tension forces. Whereas, the CBR values are lower in the wet side optimum moisture content which is mainly caused by the presence of water that may weaker the inter particles forces and results in higher lubrication which reduced the strength and increased compressibility.

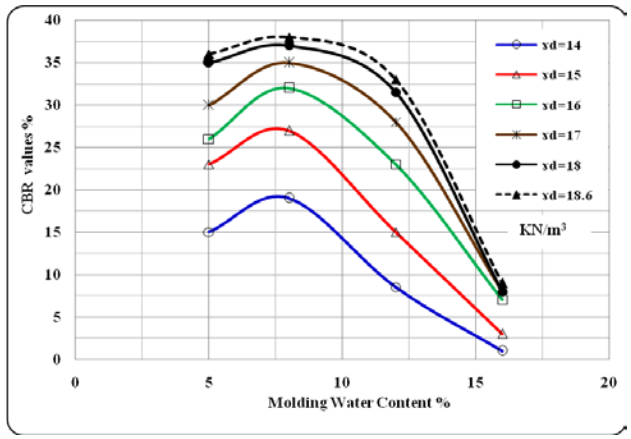

Fig. 8 Variation of CBR with molding water content.

Samples compacted at water content higher than O.M.C give a small rate in increase of CBR values. So it is recommended to compact the collapsible soil at water content equal to O.M.C to achieve the minimum values of collapse potential.

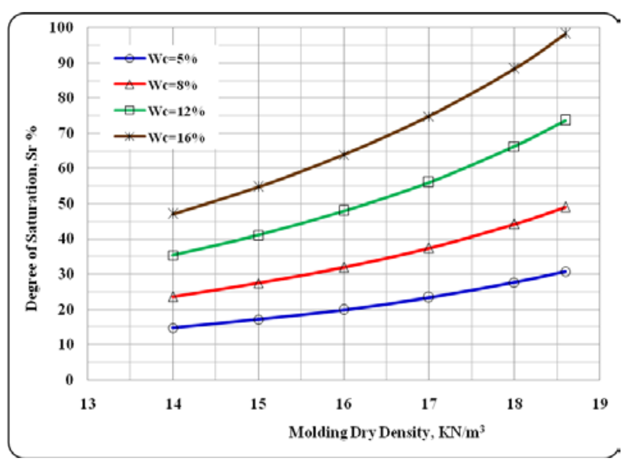

Fig. 9 Variation of degree of saturation, versus dry density.

Fig. 9 shows that the increase in degree of saturation is another way to increase density of collapsing soil and in turn improve the degree of compaction which leads to a decrease in collapse potential.

To declare the effect of molding water content on collapse potential, the results were plotted as shown in Fig. 10 between molding water content and degree of saturation. The results shown on Fig. 10 indicated that the amount of collapse for compacted specimens varies inversely in a fashion linear relationship with the initial molding water content for a particular dry density and degree of saturation. At lower values of compacted dry density the rate of increase in degree of saturation is small, which means an increase in collapse potential.

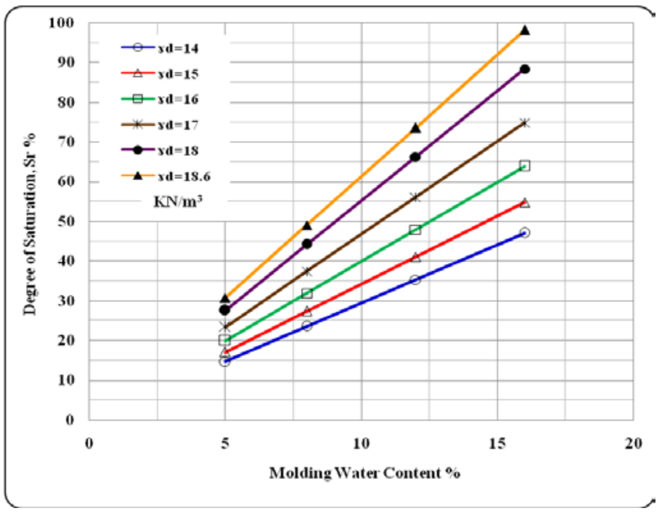

Fig. 10 Variation of degree of saturation, versus molding content.

7. Conclusions

The principal conclusions which we can do in the end of this study are presented as follows:

1- Predicting settlements due to collapsible soil is difficult due to several factors including variability of the sub soils, extent of wetting and variable loading conditions.

2- The tests of collapse carried out, show that for constant water content (constant suction), the potential of collapse increases when the dry density decreases.

3- Collapse criteria based on index parameters such as dry density and degree of saturation were proposed for identification and classification purposes. Such criteria should be used only as indicators since reliance on them can be misleading.

4- Single oedometer test is widely used for estimating the collapse potential, which can be used to calculate soil collapse settlement.

5- Collapsible soils compacted at the Modified Proctor Optimum conditions of dry density and water content is not collapsible.

6- The relationships between the amount of collapse and the initial properties (water content and dry density) are approximately linear.

7- The CBR values decreases with increasing initial water content, regardless of the corresponding value of dry density.

8- Compacting the collapsible soils at water content higher than O.M.C give a small rate in increase of CBR values. So it is recommended to compact the collapsible soil at water content equal to O.M.C to achieve the minimum values of collapse potential.

Notation

The following symbols are used in paper

i_c : Collapsibility index; % (Fedo, 1988) [14]
m: Natural water content ; %
S_r: Soil saturation, %
PL: Plastic limit; %
PI: Plasticity index; %
e: Natural void ratio, %
e_u: Liquid limit void ratio, %
i_{cz}: Collapsibility index (Lin et al., 1988 [10])
h_z: Soil thickness in natural conditions
h_{zs}: Soil thickness in saturation conditions
h_1 : Initial soil sample thickness
I_e : Collapse potential (Jennings et al., 1975 [3])
Δe_c: Change in void ratio resulting from saturation
e_1 : Void ratio just before saturation
e_0 : Natural void ratio
O.M.C: Optimum Moisture Content, %
CBR: California Bearing Ratio, %

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