EFFECT OF GRAIN SIZE ON COMPACTION TEST RESULTS

M.F.Ghanem, K.A.Abou-Ahmed and A.Z.El-Hakim
Transportation Department,Fuculty of Engineering,
Alexandria University, Alexandria,Egypt.

ABSTRACT

Compaction test of soil and soil aggregates is considered one of the main control tests during the construction of highways. The maximum grain size of the aggregates used in road construction is one of the most important factors that affect the compaction test results. Sometimes, test results could not represent the actual behaviour of the compacted material in the field, since the specifications permit using materials in highway construction having larger grain sizes than those recommended for performing the compaction tests. In the course of this investigation, a detailed study of the effect of using larger grain sizes than the specific one, on the compaction characteristics is presented. Three different locally available materials commonly used in road construction in Alexandria and surrounding areas containing large grain sizes were employed, along with three different mould sizes. The compaction test results were analysed and compared with the standard results. The effect of maximum grain size as well as mould diameter on test results was discussed and analysed. A comparison between the experimental results of the dry density and theoretical values is presented. Mathematical models for predicting both dry density and optimum moisture content have been also presented. The significance of this work is to contribute to the understanding of these variables which affect the compaction characteristics of highway materials.

***Keywords:* compaction test, highway materials, maximum grain size, mold diameter, dry density, optimum moisture content, aggregates.**

1-INTRODUCTION

In 1933, P.R.Proctor devised a laboratory method of testing, commonly known as (Proctor test) or standard AASHO compaction test. The apparatus used consists of a cylindrical mould having a volume of 944 cm^3 (1/30 ft^3) with an internal diameter of 100 mm (4") and a height of 115 mm (4.6"). Prepared soil samples are compacted in the mould using 25 blows of 2.5 kg (5.5 lb.) metal hammer having a 50 mm (2") diameter circular face, dropped from a height of 300 mm (12") on each of the three soil layers of equal thickness.

The soil to be used in the compaction test should be passed through sieve (#3/4") sieve (according to the ASTM) [1,2] or through sieve no 4 according to AASHO [3].

The aim of Proctor test is to determine the maximum dry density and the optimum moisture content of the soil.

The particle size distribution is considered one of the most important factors that influence test results, therefore, it is important to study the effect of such a factor by using materials having larger grain sizes than those specified for the test by AASHO or ASTM.

A detailed study of the effect of using larger grain sizes than those recommended by specifications on the compaction characteristics is presented, since such larger grains are mainly used in highway construction.

In the course of this study, three different locally available materials used in road construction having different maximum grain sizes of 20, 30 and 50mm were employed.

Also, three different mould sizes having 100, 150 and 250 mm diameters were used to suit the larger grain sizes.

2-MATERIALS

Materials used in this investigation represent locally available materials widely used in Alexandria and the surrounding area for highway construction and soil replacement under some civil constructions in case of weak soils.

These materials include the following:-

1- Crushed Lime Stone Aggregate:

This material is commonly used as a base course for high quality roads and as a coarse aggregate in the hot asphaltic concrete mixtures. It was provided from Alam-El-Markeb location.

2-Deposited Lime Stone Aggregate:

This material was secured from the km 26 Alexandria-Marsa Matrouh road. This material is widely used as a base course in road construction in Alexandria and El-Beheira provinces.

3- Natural Sandy-Gravel Material:

The material was delivered from an area located at km 81 Alexandria-Cairo desert road. Such a material is mainly employed for soil replacement purposes .

Table (1) shows the results of some physical tests performed on used materials.

Table 1. Some physical properties for used materials.

Physical proporty	Crushed lime Stone	Deposted lime Stone	Sandy-Gravel Material
Max. dry density kN/m^3)	16.67	18.10	21.39
opt. Moist. content (%)	6	14.1	5
Specific gravity	2.64	2.41	271
Water absorptiion (%)	0.93	8.71	0.16

3- TESTING TECHNIQUES:

In order to investigate the effect of the maximum allowable grain size on the compaction process, many samples of each material having different grain size distribution were prepared. These samples have different maximum grain sizes of 20, 30 and 50 mm. Also, three different cylindrical compaction moulds having 100 mm (4"), 150 mm (6") and 250 mm (10") diameters were employed.

The samples were compacted according to the standard compaction procedure (ASTM D 698 - 78, D 1557-78) [1,2].

Modification of the number of blows (N) due to the deviation of the mould diameter and height from the standard dimensions is taken into consideration according to the following formula:

$$N = 25 \frac{D^2}{D_s^2} \cdot \frac{h}{h_s} \rightarrow \qquad (1)$$

Where

D Diameter of the used mould.
h height of the used mould.
D_s Diameter of the standard mould .
h_s height of the standard mould .

4. TEST RESULTS AND DISCUSSION

4.1 *Dry Density and Optimum Moisture Content*

Figure (1) shows the results of the compaction tests on the three investigated materials using the 100 mm (4") diameter mould (standard mould). The maximum allowable grain size for each material is 20 mm. It is apparent from the results that the sandy-gravel material has the highest maximum dry density (21.4 kN/m^3) corresponding to the lowest optimum moisture content (5%).

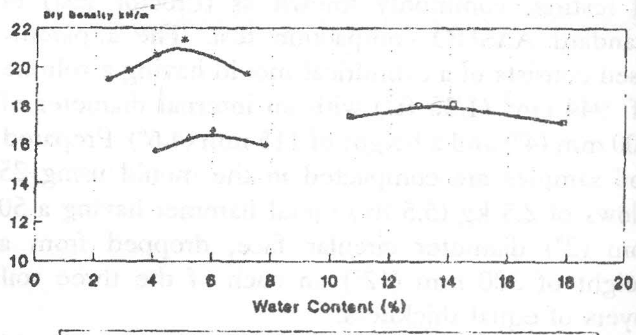

Figure 1. Relationship between dry bensity and moisture content for different materials used.

The crushed lime stone and deposited lime stone

The crushed lime stone and deposited lime stone aggregates have a maximum dry density of 16.67 and 18.1 kN/m3 corresponding to an optimum moisture content of 6 and 14% respectively.

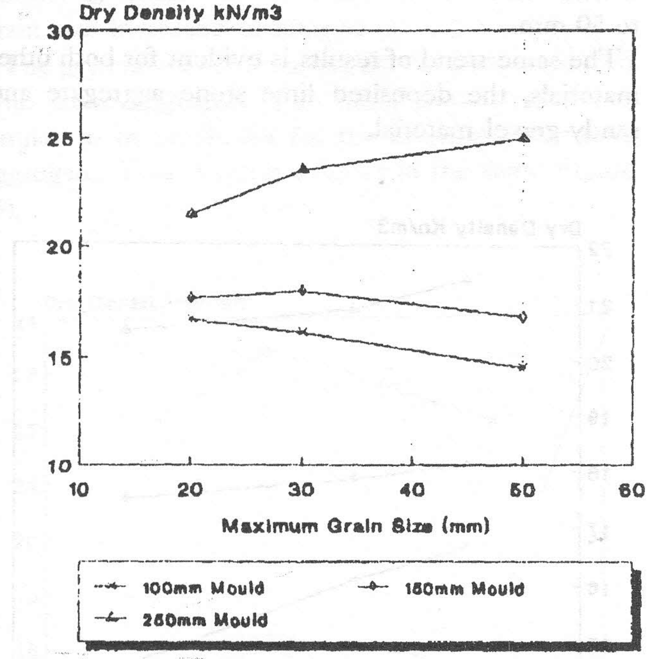

Figure 2. Compaction test for Crushed lime stone aggregate

4.2 *Effect of Mould Diameter on Compaction Test Results*

4.2.1 Crushed Lime Stone Aggregate

The relationship between the different maximum allowable grain-sizes used and the maximum dry density using the different compaction mould diameters of the crushed lime stone aggregate is demonstrated in Figure (2). It is clear that for the same maximum grain size, the dry density increases with the increase of the mould diameter. For example, at a maximum grain size of 20 mm, the dry density increased from 16.67 to 17.62 kN/m^3 by increasing the mould diameter from 100 to 150 mm and it increased to 21.44 kN/m^3 by using 250 mm mould diameter. This may be expressed as a percentage. The dry density of the crushed lime stone aggregate with a maximum grain size of 20 mm could be increased by 28.6% by increasing the mould diameter from its standard value of 100 mm (4") to 250 mm (10"). Also, it may be increased by 71.6% for the case of using a maximum grain size of 50 mm.

4.2.2 *Deposited Lime Stone Aggregate*

Figure (3) represents the dry density versus the maximum grain size of the deposited lime stone aggregate using the different compaction moulds. The general trend of the results in this figure is similar to that shown for the crushed lime stone aggregate in Figure (2). The dry density generally increases as the mould diameter increases for the same maximum grain size.

The increase in dry density may reach up to 22.3% with the increase of the mould diameter from 100 to 250 mm.

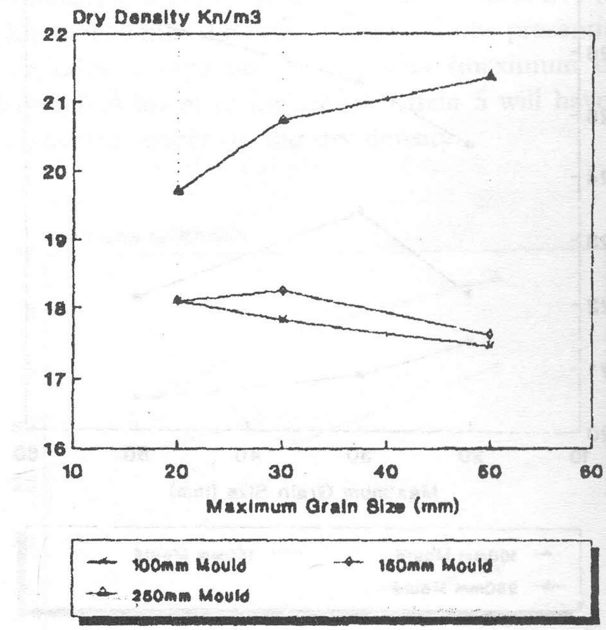

Figure 3. Compaction test for Crushed lime stone aggregate

4.2.3 *Sandy-Gravel Material*

The results of compaction tests on the sandy-gravel material with different maximum grain sizes of 20, 30 and 50 mm along with different mould diameters of 100, 150 and 250 mm are presented in Figure (4). It is clear that the general trend of the results for both crushed and deposited lime stone aggregates still holds true. The dry density of the sandy-gravel material increases as the mould diameter increases for the same maximum grain size (for a 20 mm maximum grain size, the dry density is 21.39, 22.12 and 24.5 kN/m^3 with the use of compaction mould diameters of 100, 150 and 250 mm respectively). The increase in dry density is approximately 29.3% when a 250 mm mould diameter is used with a maximum grain size of 50 mm.

In general, it can be stated that for a specific maximum grain size, the dry density of the materials used in this study, increases with the increase of the mould diameter. This increase may reach up to 71.6, 22.3 and 29.3% for the crushed lime stone aggregate, deposited lime stone aggregate and sandy-gravel material respectively.

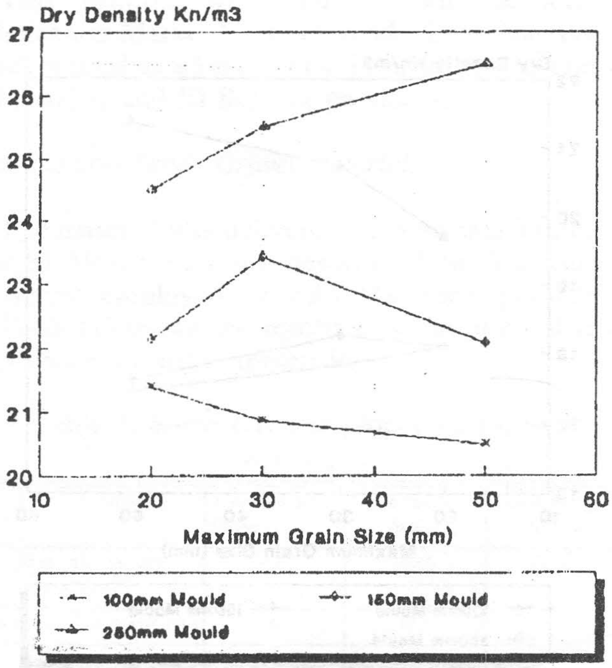

Figure 4. Compaction test for sandy-Cravel material.

4.3 *Effect of Maximum Grain Size on Compaction Test Results*

4.3.1 The Standard Mould

The effect of maximum grain size on the dry density using the standard 100 mm mould diameter for the three materials used in the course of this study is illustrated in Figure (5) , which shows that the dry density decreases with the increase of maximum grain size. This is clear for the three materials. For the crushed lime stone aggregate, the dry density decreased from 16.67 to 16.07 kN/m^3 as the maximum grain size increased from 20 to 30 mm. Again, the dry density decreased to 14.53 kN/m3 with the increase of the maximum grain size to 50 mm.

The same trend of results is evident for both other materials, the deposited lime stone aggregate and sandy-gravel material.

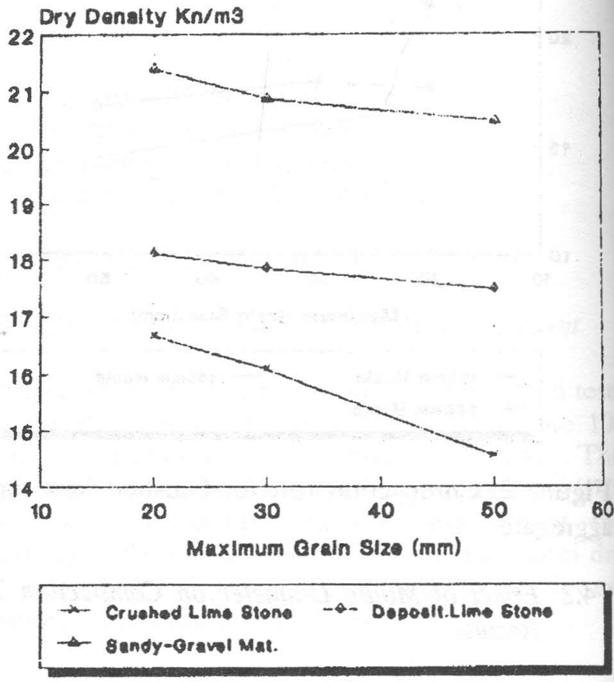

Figure 5. Compaction test using mould dlameter 100mm.

This confirms that the dry density of all investigated materials using the standard mould, decreased with the increase of the maximum allowable grain size. This phenomena may occur since the larger grain sizes are not well arranged which may prevent the good orientation of soil particles to take place with the minimum air voids.

4.3.2 150 mm Mould Diameter

Figure (6) shows the dry density values using the 150 mm mould diameter in the compaction procedure for the three different materials employed in this study. The dry density for the crushed lime stone aggregate increased from 17.62 kN/m^3 to 17.96 kN/m3 as the maximum grain size increased from 20 to 30 mm, then the effect was reversed, and the dry density decreased to 16.76 kN/m^3 as the maximum grain size increased to 50 mm.

The general trend of the results for both deposited lime stone aggregate and sandy-gravel material is similar to those shown for the crushed lime stone aggregate. This is quite evident in the same Figure (6).

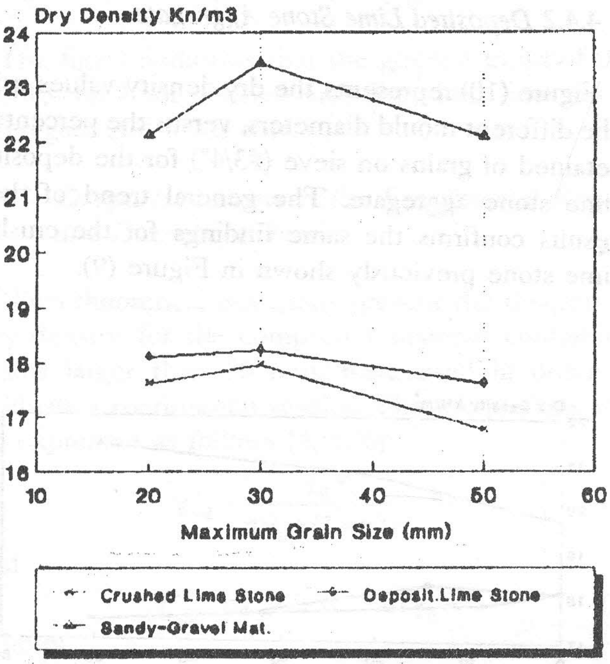

Figure 6. Compaction test using mould diameter 150mm.

4.3.3 250 mm Mould Diameter

In contrast with the results shown in Figure (5) which indicated that the dry density using the standard 100 mm mould diameter, decreases with the increase of maximum grain size, Figure (7) indicates that using the 250 mm mould will lead to an increase in the dry density as the maximum grain size increases. For example, the dry density of the crushed lime stone aggregate of 20 mm maximum grain size is 21.44 kN/m^3 compared with 23.47 kN/m3 and 24.94 kN/m^3 for crushed lime stone with maximum grain sizes of 30 and 50 mm respectively.

Similar results could be observed on the same graph for both deposited lime stone aggregate and sandy-gravel material.

Figure (8) summarizes the previous results for all investigated materials. It shows the relationship between the dry density of the compacted material and the ratio between mould diameter and maximum allowable grain size, (D_{mould}/d_{agg}). It is evident that the dry density of all investigated materials increases with the increase in diameters' ratio, (D_m/d_{ag}), up to a certain value, this value is called here a critical ratio, at which the dry density of all investigated materials reach a maximum value and any deviation from this value causes a reduction in the dry density. According to the used mould diameters and grain sizes, this critical ratio is five (5). This means that the critical ratio ensures presenting acceptable compaction test results (maximum dry density). A lower or higher ratio than 5 will have a detrimental effect on the dry density.

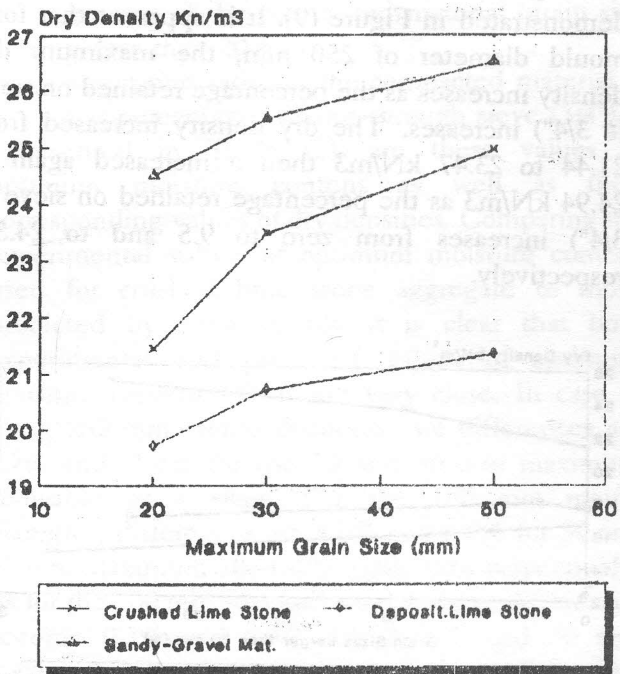

Figure 7. Compaction test using mould diameter 250mm.

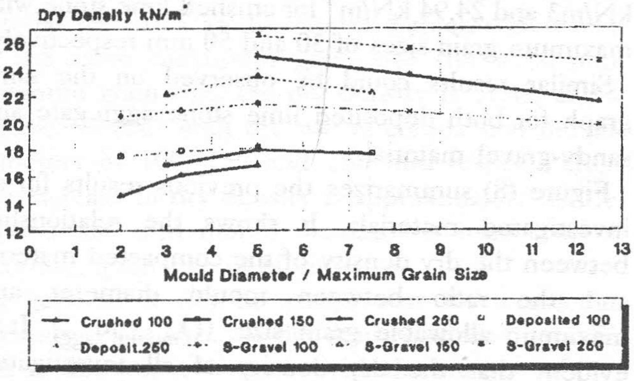

Figure 8. Relationship between dry density and (D_m/d_g) for all investigated materials using different moulds.

4.4 *Effect of Grain Sizes Larger than 20 mm on Compaction Test Results*

4.4.1 *Crushed Lime Stone Aggregate*

The relationship between the percentage of grains larger than 20 mm and the maximum dry density of these grains for crushed lime stone aggregate is demonstrated in Figure (9). It is apparent that for a mould diameter of 250 mm, the maximum dry density increases as the percentage retained on sieve (# 3/4") increases. The dry density increased from 21.44 to 23.47 kN/m3 then it increased again to 24.94 kN/m3 as the percentage retained on sieve (# 3/4") increases from zero to 9.5 and to 24.3% respectively.

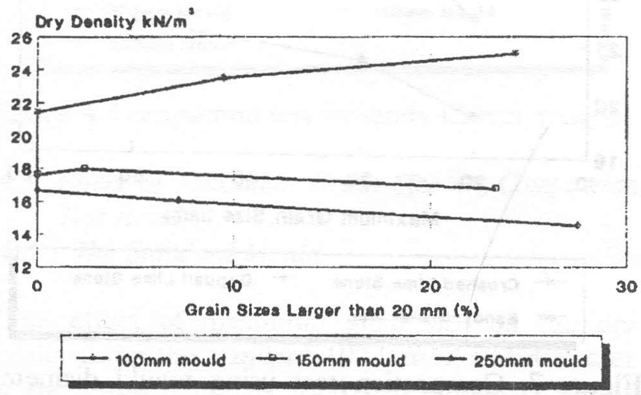

Figure 9. Effect of grain sizes larger than 20mm on compaction test results for crushed lime stone aggregate.

When a mould diameter of 150 mm was used, the maximum dry density increased first, then it started to decrease. It increased from 17.62 to 17.96 kN/m^3 as the percentage retained increased from zero to 2.4% then, the dry density decreased to 16.76 kN/m^3 as the percentage retained increased to 23.28%.

As for a mould diameter of 100 mm (standard), it is evident that the maximum dry density decreases as the percentage retained on sieve # 3/4" increases. It decreased from 16.67 to 16.07 and 14.53 kN/m3 as the percentage retained increased from zero to 7.25 and 27.5% respectively.

4.4.2 *Deposited Lime Stone Aggregate*

Figure (10) represents the dry density values using the different mould diameters, versus the percentage retained of grains on sieve (#3/4") for the deposited lime stone aggregate. The general trend of these results confirms the same findings for the crushed lime stone previously shown in Figure (9).

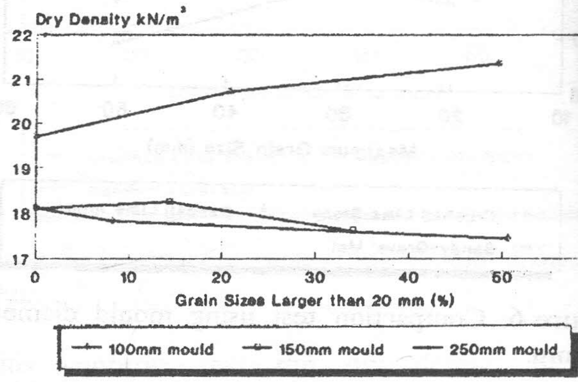

Figure 10. Effect of grain sizes larger than 20mm on compaction test results for deposited lime stone aggregate.

4.4.3 *Sandy-Gravel Material*

Figure (11) shows the maximum dry density versus the percentage retained on sieve # 3/4" using mould diameters of 100, 150 and 250 mm for the sandy-gravel material.

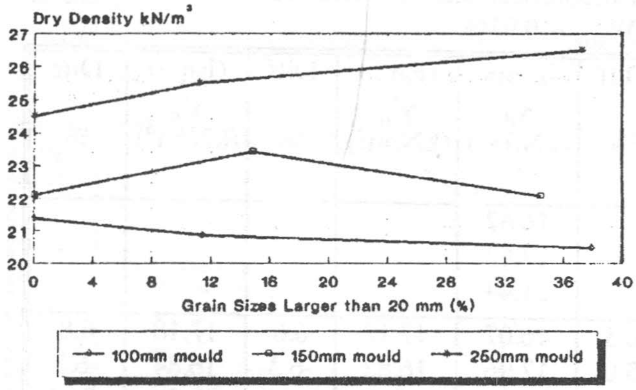

Figure 11. Effect of grain sizes larger than 20mm on compaction test results for sandy-gravel material.

The figure indicates that the general trend of the results for both crushed and deposited lime stone aggregate still holds true.

4.5 *Comparison Between the Experimental Results and Theoretical Ones*

Two theoretical equations present the theoretical dry density for the compacted material containing grains larger than 20 mm, were used in order to evaluate experimental results. These equations can be expressed as follows [4, 5, 6]:

$$\gamma'_d = \frac{\gamma_d \gamma_s}{u\gamma_s + (1+u)\gamma_d} \rightarrow \quad (2)$$

and

$$\gamma'_d = u\gamma_d + 0.9(1-u)\gamma_d \rightarrow \quad (3)$$

Where:

γ'_d the theoretical dry density of the compacted material which contains grain sizes larger than 20 mm,

γd the experimental standard dry density of the compacted material (grain size is less than 20 mm),

u the percentage passing through sieve (3/4"),

γ_s the specific weight of the compacted material which contains grain sizes larger than 20 mm.

4.5.1 *Crushed Lime Stone Aggregate*

Table (2) shows a comparison between the experimental and theoretical dry densities of the crushed lime stone aggregate using the three different moulds. It can be seen that for a mould diameter of 250 mm, the theoretical values of the dry density underestimate the experimental results using both equations (2) and (3). The differences are [26.5% (equation 2), 26.2% (equation 3)], and [26.4%, 26.1%] for the 50 and 30 mm maximum allowable grain size respectively. For the 150 mm mould diameter, a good agreement between the theoretical and experimental results is clear. Differences are [8.8%, 9.3%] and [-6.3%, -6.2%] for the 50 and 30 mm maximum allowable grain size respectively. As for the 100 mm standard mould, the theoretical values overestimate the experimental results by [27.7%, 28.1%] and [6.6% , 6.8%] for the 50 and 30 mm maximum allowable grain size respectively.

According to the data given in the same Table (2), the optimum moisture content for crushed lime stone aggregate can be predicted by using the following equation [4,5,6] :

$$w'_{opt} = u\, w_{opt} + (1-u)\, w_{abs} \quad (4)$$

in which

w'_{opt} the theoretical optimum moisture content of the compacted material which contains grain sizes larger than 20 mm,

w_{opt} the experimental standard optimum moisture content of the compacted material (grain size is less than 20 mm),

w_{abs} absorption ratio for the compacted material,

u the percentage passing through sieve (3/4").

Presented in Table (2), are these values of optimum moisture content as well as their corresponding values of dry densities. Comparing the experimental values of optimum moisture content used for crushed lime stone aggregate to those predicted by equation (4), it is clear that both experimental and predicted values of optimum moisture content values are very close. In case of using 250 mm mould diameter, the differences are 3.7% and -1.4% for the 50 and 30 mm maximum allowable grain sizes. For the 150 mm mould diameter, differences are 4.8% and 5.0% for 50 and 30 mm maximum allowable grain sizes respectively. As for the 100 mm standard mould, these differences become 0.2% and 0.5% for the 50 and 30 mm maximum allowable grain size. This confirms that the optimum moisture content for the crushed lime stone aggregate can be predicted successfully by using the previous equation (4).

Table 2. Comparison between experimental results and theoretical ones for crushed lime stone aggregate

$\gamma_s = 2.637\ W_{opt(st)}\ W_{abs} = 0.93\%$

d_{ag} (mm)	D_{mould} (mm)	Pass (u)	Retained (1-u)	Tests W_{opt} %	(Eq.4) W_{opt} %	Diff %	Tests γ_d (kN/m³)	(Eq.2) γ'_d (kN/m³)	Diff %	(Eq.3) γ'_d (kN/m³)	Diff %
20	100	1	--	6			16.67				
	150	1	--	6			17.62				
	250	1	--	6			21.44				
30	100	0.928	0.072	5.6	5.63	0.5	16.07	17.12	6.6	17.18	6.8
	150	0.976	0.024	5.6	5.88	5.0	17.96	16.82	-6.3	16.84	-6.2
	250	0.905	0.095	5.6	5.52	-1.4	23.47	17.27	-26.4	17.34	-26.1
50	100	0.725	0.275	4.6	4.61	0.2	14.53	18.55	27.7	18.61	28.1
	150	0.767	0.233	4.6	4.82	4.8	16.66	18.23	8.8	18.32	9.3
	250	0.757	0.243	4.6	4.77	3.7	24.94	18.31	-26.5	18.39	-26.2

4.5.2 Deposited Lime Stone Aggregate

Table (3) shows the calculated values of the dry density for the deposited lime stone aggregate using the three different moulds along with the experimental results. It is evident that for the mould diameter of 250 mm, there is a good agreement between the theoretical and experimental results. The differences are [-3.3%,-6.9%] and [-7.9%, -9.1%] for both 50 and 30 mm maximum allowable grain size respectively. When a mould diameter of 150 mm was used, differences of [12.2%, 9.7%] and [3%, 2.1%] are evident for maximum grain sizes of 50 and 30 mm respectively. Differences of [18.7%, 14.1%] and [3.7%, 3.2%] for the same maximum allowable grain sizes of 50 and 30 mm, between the theoretical and experimental results are apparent using the standard 100 mm mould diameter.

According to Table (3), the optimum moisture content could not be predicted by using the previous equation (4). A modification in this equation should be taken into consideration, and the equation may be written as:

$$w'_{opt} = u\ w_{opt} + (1-u)\ w_{abs} - c \qquad (5)$$

in which, c = a reduction factor equal to 2 to 4 % depending on the percentage of the material larger than 20 mm.

This is due to the high absorption ability of the deposited lime stone by immersion in water for a long time, whereas the duration of mixing with water for compaction takes a very short time.

4.5.3 *Sandy-gravel material*

The data in Table (4) represent a comparison between the experimental and theoretical results of the dry density of the sandy gravel material. It can be seen that for a mould diameter of 250 mm the theoretical values underestimate the experimental results by [12.4%, 15.1%] and [14.1%, 14.8%] for both 50 and 30 mm maximum allowable grain size. A very good agreement between test results and theoretical values is clear in case of using a mould diameter of 150 mm. The differences are [4.4%, 1.5%] and [-5.7%, -6.8%] for 50 and 30 mm maximum grain size respectively.

As for the standard mould, the theoretical values overestimate test results by [13.4%, 9.9%] and [5.0%, 4.1%] for a maximum grain size of 50 and 30 mm respectively.

The optimum moisture content can be predicted also by using equation (4) without any modifications. Table (4) shows an excellent agreement between the experimental values of optimum moisture content and predicted ones for the sandy-gravel material. The difference does not exceed 2% in any case.

Table 3. Comparison between experimental results and theoretical ones for deposited lime stone
$\gamma_s = 2.41$ $W_{opt} = 14\%$ $W_{abs} = 8.71\%$.

d_{ag} (mm)	D_{mould} (mm)	Pass (u)	Retained (1-u)	Tests W_{opt} %	(Eq.4) W_{opt} %	Diff %	Tests γ_d (kN/m^3)	(Eq.2) γ'_d (kN/m^3)	Diff %	(Eq.3) γ'_d (kN/m^3)	Diff %	(Eq.5) (Eq.4-c) (c)
20	100	1	--	14			18.10					
	150	1	--	14			18.10					
	250	1	--	14			19.70					
30	100	0.917	0.083	11	13.56	23.3	17.82	18.48	3.7	18.4	3.2	2.6
	150	0.856	0.144	11	13.24	20.4	18.23	18.77	3.0	18.62	2.1	2.2
	250	0.791	0.209	11	12.89	17.2	20.73	19.09	-7.9	18.85	-9.1	1.9
50	100	0.494	0.506	8	11.32	41.5	17.54	20.71	18.7	19.92	14.1	3.3
	150	0.660	0.340	8	12.20	52.5	17.61	19.77	12.2	19.32	9.7	4.2
	250	0.505	0.495	8	11.38	42.3	21.35	20.64	20.64	19.88	-6.9	3.4

Table 4. Comparison between experimental results and theoretical ones for sandy-gravel
$\gamma_s = 2.708$ $W_{opt} = 5\%$ $W_{abs} = 0.16\%$

d_{ag} (mm)	D_{mould} (mm)	Pass (u)	Retained (1-u)	Tests W_{opt} %	(Eq.4) W_{opt} %	Diff %	Tests γ_d (kN/m^3)	(Eq.2) γ'_d (kN/m^3)	Diff %	(Eq.3) γ'_d (kN/m^3)	Diff %
20	100	1	--	5			21.39				
	150	1	--	5			22.12				
	250	1	--	5			24.50				
30	100	0.886	0.114	4.4	4.45	1.1	20.87	21.91	5.0	21.73	4.1
	150	0.852	0.148	4.4	4.28	-2.7	23.42	22.07	-5.7	21.83	-6.8
	250	0.888	0.112	4.4	4.46	1.3	25.50	21.90	-14.1	21.72	-14.8
50	100	0.621	0.379	3.3	3.17	-3.9	20.49	23.24	13.4	22.52	9.9
	150	0.656	0.344	3.3	3.34	1.2	22.08	23.06	4.4	22.42	1.5
	250	0.628	0.372	3.3	3.20	-3.0	26.50	23.20	-12.4	22.50	-15.1

In general, for all investigated materials in the course of this study, using a 150 mm mould diameter leads to a reasonable agreement between the experimental results and theoretical values of the dry density with both 50 and 30 mm maximum allowable grain size. However, for a mould diameter of 250 mm, the theoretical values underestimate the experimental results. As for the standard mould , the theoretical values of the dry density overestimate the experimental results.

Also, the optimum moisture content for all investigated materials can be predicted generally by equation (5), taking into consideration that the term c, will be zero in case of crushed lime stone aggregate and sandy- gravel material. It becomes 2 or 4% for deposited lime stone aggregate.

4.6 *Dry Density Curve Fitting*

An important practical objective of this study is to try to determine the pattern of the dry density as a function of grain sizes larger than 20 mm in order to predict the dry density.

The curves presented in Figures (9), (10) and (11) showing the effect of large grain size for the three different moulds have been replotted in Figure (12) as a semi-logarithmic relationship. This was valid only for the 250 mm mould diameter. This resulted in a linear relationship between the dry density and the logarithm of the grain size larger than 20 mm .

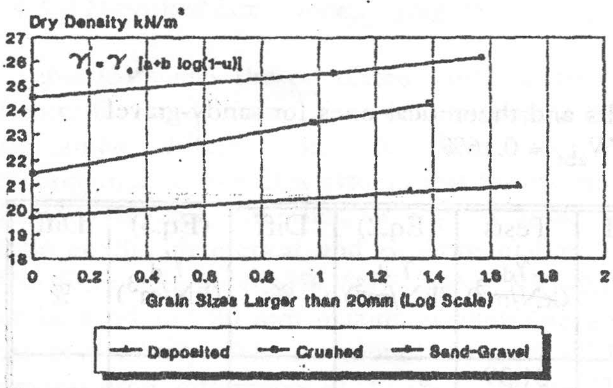

Figure 12. Curve fitting for dry density and larger grain sizes than 3/4 using mould diamter 250 mm.

For the three investigated materials, the maximum dry density using the 250 mm mould can be mathematically modelled by the function:

$$\gamma'_d = \gamma_{d\,(standard)}\ [a + b \log (1\text{-}u)] \rightarrow \qquad (6)$$

in which,

γ'_d the maximum dry density of the compacted material using 250mm mould diameter,

$\gamma_{d\,(standard)}$ the maximum dry density of the compacted material in the standard mould,

(1-u) the percenatge retained on sieve (3/4") (large grain sizes),

a, b constants depending on the compacted material.

With the constants a and b established, the equations can be rewritten as follows:-

For the crushed lime stone aggregate

$$\gamma'_d = \gamma d\ [1.29 + 0.150 \log (1\text{-}u)] \rightarrow \qquad (7)$$

For the deposited lime stone aggregate

$$\gamma'_d = \gamma d\ [1.09 + 0.044 \log (1\text{-}u)] \rightarrow \qquad (8)$$

For the sandy gravel material

$$\gamma'_d = \gamma d\ [1.15 + 0.053 \log (1\text{-}u)] \rightarrow \qquad (9)$$

CONCLUSION

The principal findings and conclusions of this investigation have been summarized as follows:-

1- The dry density of all investigated materials using the standard mould, decreases with the increase of maximum allowable grain size.

2- For a specific maximum grain size, the dry density of the used materials increases with the increase of the mould diameter. This increase may reach up to 71.6, 22.3 and 29.3% for the crushed lime stone aggregate, deposited lime stone aggregate and sandy- gravel material respectively.

3- For a specific mould diameter, the dry density of all investigated materials increases as the ratio between mould diameter and maximum allowable grain size, (D_m/d_{ag}), increases up to a certain value (critical ratio) then decreases thereafter.

4- For all investigated materials, this critical ratio is equal to five (5). This ratio ensures presenting acceptable compaction test results. A lower or higher ratio than 5 has a detrimental effect on the dry density.

5- For all investigated materials, test results of dry density were evaluated using some known theoretical formulae. This was successful for the 150 mm mould diameter. However, the theoretical values underestimate the experimental results for the 250 mm mould diameter and overestimate these results for the standard mould.

6- The response of all investigated materials to the compaction test using the 250 mm mould diameter, indicates a linear relationship of dry density (compared with the standard dry density) with the logarithm of grain sizes larger than 20 mm .

7- The dry density of the investigated materials using the 250 mm mould diameter can be predicted using the following mathematical model of the form:-

$$\gamma'_d = \gamma_d \, [a + b \log (1-u)]$$

where, a, b are constants depending on the type of compacted material.

8- The optimum moisture content can be successfully predicted by using the following equation:

$$w'_{opt} = u \, w_{opt} + (1-u) \, w_{abs} - c$$

where, c = 2 to 4% for deposited lime stone aggregate and zero for crushed lime stone aggregate and sandy- gravel material.

Acknowledgement

The authors would like to thank Mr. G.A. EL Mahdy, Mr. V.F. Hanna and Mr. A.A. Abdu for their cooperation during the laboratory work. Their efforts are very appreciated.

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