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Compaction behavior of fine-grained soils, lateritic soils and crushed rocks

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Abstract

This paper studies compaction characteristics and California Bearing Ratio, *CBR* values of fine-grained soils, lateritic soils and crushed rocks. All test data were collated from the Bureau of Rural Road 6, the Department of Rural Roads, Thailand. The Ohio's and the modified Ohio's curves can predict satisfactorily the compaction curves of the fine-grained soils, and lateritic soils and crushed rocks consistent with the grade B of the American Association of State Highway and Transportation Officials (AASHTO) requirement. The *CBR* value of a specific soil is directly related to the relative dry unit weight (the ratio of dry unit weight to maximum dry unit weight, $\gamma_d/\gamma_{d,\max}$). The field compaction result of a fine-grained soil at the optimum water content, *OWC*, shows that initially the dry unit weight increases rapidly with the number of roller passes and the relationship between dry unit weight and number of roller passes is represented by the logarithm function. Finally, the dry unit weight reaches a constant value, which is close to the laboratory maximum dry unit weight. Even with a large number of roller passes (compaction energy), the dry unit weight cannot be enhanced further because the soil state approaches the zero air void state. In practice, the excess roller pass is thus not economic. Based on the analysis of the test data, the field compaction procedure for road embankment and pavement constructions, which includes the material selection and the construction control, is suggested. It is useful in terms of both engineering and economic viewpoints.

Keywords: Compaction; California Bearing Ratio (*CBR*); Fine-grained soils; Lateritic soils; Crushed rocks

1. Introduction

Soils are materials that are not "made to order" and thus do not always exhibit the properties desired for constructing earth systems. Therefore, modification of soils at the site to improve their engineering properties becomes necessary. Soil compaction is one of the most extensively used techniques to achieve this due to its cost-effectiveness. The aim of compacting earth fills is to reduce settlement and permeability and to increase shear strength. Compaction is essential in many geotechnical applications such as railway subgrades, airfield pavements and earth retaining structures. The laboratory and field California Bearing Ratio, *CBR* values of the compacted soils are generally used for pavement design.

Attempts to model soil compaction have been made since the early 1940s. Most of these modeling attempts included correlation equations for estimating the compaction characteristics (optimum water content, *OWC*, and

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maximum dry unit weight, $\gamma_{d,\max}$) of soil in terms of soil index properties and grain size distribution (Davidson and Gardiner, 1949). Ramiah et al. (1970) correlated both OWC and $\gamma_{d,\max}$ solely to liquid limit. Jeng and Strohm (1976) correlated the standard energy Proctor OWC and $\gamma_{d,\max}$ to index properties of 85 soils. Blotz et al (1998) used Proctor compaction data from 22 fine-grained soils to correlate OWC and $\gamma_{d,\max}$ with liquid limit and compaction energy. Gurtug and Sridharan (2002 and 2004) correlated OWC and $\gamma_{d,\max}$ of fine-grained soils compacted by various compaction energies to plastic limit.

An early study by Joslin (1959) on a large number of compaction curves yielded 26 typical standard Proctor curves (named the Ohio's curves) that are presumed to approximately resemble most of the soil encountered in earth construction. These curves provide a quick method for identifying an approximate compaction curve of a given soil using one water content–bulk density data point determined from the standard Proctor penetration needle. Pandian et al. (1997) and Nagaraj et al. (2006) developed a model that enables the determination of the density and water content relationship of fine-grained soils separately for the dry and the wet sides of optimum based on liquid limit and specific gravity. The study gave a set of curves, which closely approximated the results of Joslin (1959). However, this model can be applied only to fine-grained soil compacted under the standard Proctor energy.

Recently, Horpibulsuk et al. (2008 and 2009) have proposed a phenomenological model to describe the compaction curves of fine- and coarse-grained soils under different compaction energies. The model predicts satisfactorily the entire compaction curves. They also introduced the modified Ohio's compaction curves for the other energies of 296.3, 1346.6 and 2693.3 (modified Proctor) kJ/m^3. These curves are very useful for quick determination of compaction curves using a single trial test result. The prediction of the CBR values of the compacted soils is also vital for pavement engineers. It would be advantage if the CBR values can be approximated from dry unit weight, which is simply obtained from the Ohio's and the modified Ohio's curves. For economic and energy saving, the optimal number of roller passes to attain the target dry unit weight and CBR values is required for the field compaction.

This paper attempts to examine the applicability of the Ohio's and the modified Ohio's curves to different soils, to develop a generalized relationship between CBR and dry unit weight and to suggest the optimal number of roller passes. The laboratory compaction and CBR results of different fine-grained soils, lateritic soils and crushed rocks were collated from the Bureau of Rural Road 2, the Department of Rural Roads, Thailand. The lateritic soils and crushed rocks are consistent with the requirement of the American Association of State Highway and Transportation Officials (AASHTO) for subbase materials, base courses and surface courses. A step-wise procedure for field compaction is finally suggested based on the critical analysis of the test data. It facilities the material selection and field compaction control. The suggested procedure is applicable to road embankment and pavement constructions.

2. Materials and methods

The compaction and CBR test results of the fine-grained soils, lateritic soils and crushed rocks were collated from the Bureau of Rural Road 6, the Department of Rural Roads, Thailand. The test results of 61 fine-grained soils, 68 lateritic soils and 64 crushed rocks were analyzed in this study. Tables 1 and 2 summarize the range of the gradation of the lateritic soils and crushed rocks compared with the requirement of the American Association of State Highway and Transportation Officials (AASHTO) for subbase materials, base courses and surface courses. Both the lateritic soils and the crushed rocks are consistent with the requirement and classified as Grade B. The liquid limits and plasticity indexes for the lateritic soils are between 22% and 24%, and 4.7% and 7.6%, respectively. The crushed rocks are non-plasticity (NP). The compaction and CBR tests were performed under the standard Proctor energy for the fine-grained soils and the modified Proctor energy for the lateritic soils and the crushed rocks. Only these three soil types are considered in this study because they are abundant and commonly used for pavement application in Thailand. The fine-grained soils are used for subgrade and the lateritic soils and the crushed rocks are used for subbase and base, respectively. The field compaction data from a road construction project in Pathumthani province,

Table 1
Gradation requirements for soils used as subbase materials, base courses and surface courses (AASHTO M147).

Opening size (mm)	Percent finer					
	Grade A	Grade B	Grade C	Grade D	Grade E	Grade F
50.8	100	100	–	–	–	–
25.0	–	79–95	100	100	100	100
9.5	30–65	40–75	50–85	60–100	–	–
4.75	25–55	30–60	35–65	50–85	55–100	70–100
2.0	15–40	20–45	25–50	40–70	40–100	55–100
0.425	8–20	15–30	15–30	25–45	20–50	30–70
0.075	2–8	5–20	5–15	5–20	6–20	8–25

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Table 2
Gradation range of the crushed rocks and the lateritic soils.

Opening size (mm)	Crushed rocks (64 samples) Percent finer	Lateritic soils (68 samples) Percent finer
50.8	100	100
25.0	88.3–92.7	87.8–91.2
9.5	57.6–63.0	60.5–65.0
4.75	36.3–44.1	41.8–55.5
2.0	23.1–26.0	22.4–27.8
0.425	14.2–17.3	15.0–17.2
0.075	5.7–7.4	5.3–7.8

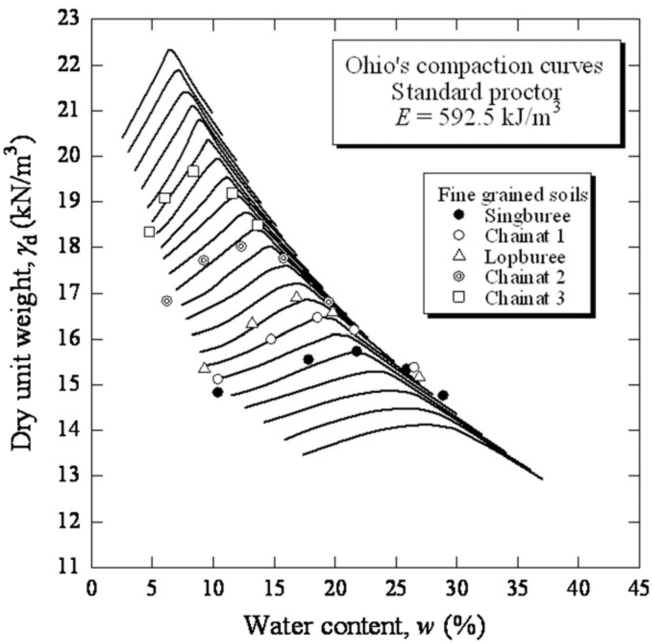

Fig. 1. Compaction curves of fine-grained soils under standard Proctor energy.

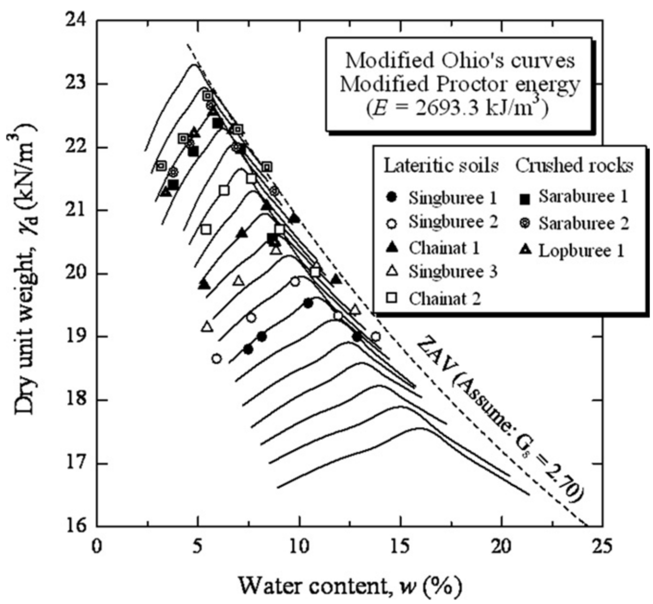

Fig. 2. Compaction curves of lateritic soils and crushed rocks under modified Proctor energy.

Thailand were taken to study the development in unit weight with number of roller passes. The dry unit weight for each roller pass was measured by the nuclear method. Finally, the field compaction procedure is suggested based on the analysis of the test data.

3. Results

The optimum water content, OWC and maximum dry unit weight, $\gamma_{d,\max}$ values range from 11% to 23% and 15 to 20 kN/m^3 for the fine-grained soils, from 7% to 12% and 19.5 to 21.5 kN/m^3 for the lateritic soils and from 6% to 7% and 22.2 to 22.8 kN/m^3 for the crushed rocks. Figs. 1 and 2 show the compaction curves of the fine-grained soils, and the lateritic soils and the crushed rocks, respectively. It is of interest to mention that all the fine-grained soils (under standard Proctor energy) follow the Ohio's compaction curves (Joslin, 1959) and all the lateritic soils and the crushed rocks follow the modified Ohio's compaction curves (Horpibulsuk et al., 2008 and 2009). In other words, the Ohio's and the modified Ohio's curves predict satisfactorily the compaction behavior of the fine-grained soils, and lateritic soils and crushed rocks, which are consistent with the grade B of the AASHTO requirement.

Fig. 3 shows typical compaction and CBR test results of a lateritic soil. The left Fig. 3a shows the compaction curve under the modified Proctor energy and the right Fig. 3a shows the CBR values at the optimum water content (which is generally specified in the field compaction) under different compaction energies. The three data points cover the range of the field compaction that the relative compaction (the ratio of the field dry unit weight to the laboratory maximum dry unit weight) must be higher than 90%. The number of blows shown in the figure is recommended by the American Society of Testing and Materials, ASTM. The CBR value increases linearly with increasing γ_d for the relative dry unit weight ($\gamma_d/\gamma_{d,\max}$) ranging from 90% to 100%. Fig. 3b shows the effect of the compaction energy on the development in dry unit weight, γ_d and CBR at OWC. The γ_d and CBR values increase with the logarithm of compaction energy, E. This finding is in agreement with the previous studies (Boutwell, 1961; Blotz et al., 1998; Gurtug and Sridharan, 2004; Horpibulsuk et al., 2008 and 2009). Because the CBR value of a given soil is essentially controlled by the densification (the CBR development is

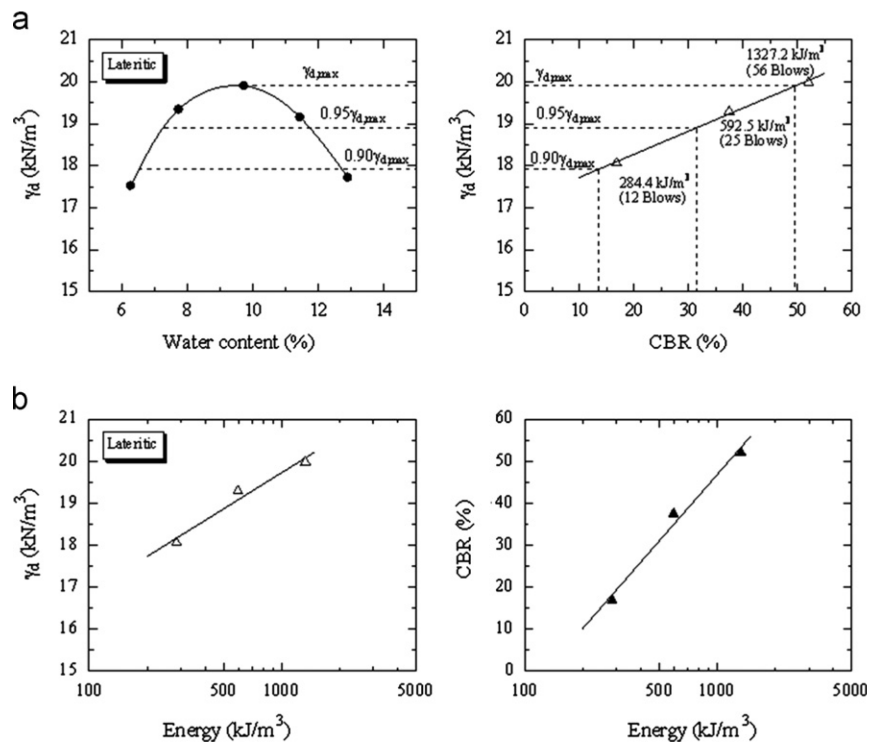

Fig. 3. Compaction and CBR test results of a lateritic soil. (a) water content and CBR versus unit weight and (b) dry unit weight and CBR versus compaction energy.

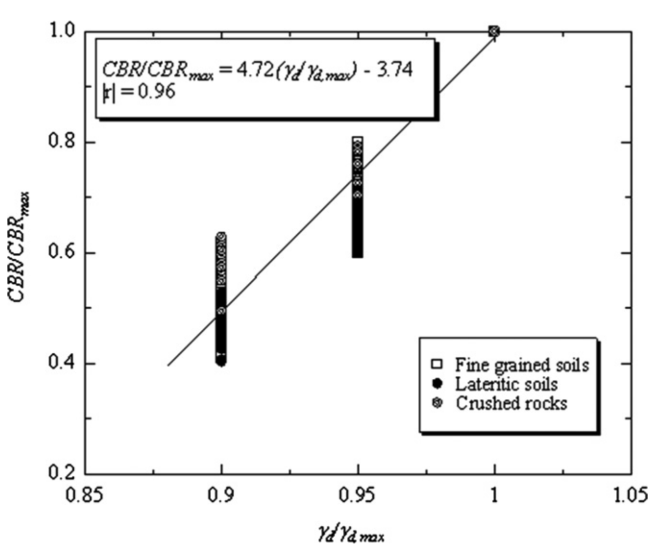

Fig. 4. Regression analysis of the normalized CBR and relative dry unit weight for the tested soils.

dependent upon the relative dry unit weight), it is logical to develop a generalized relationship between the *CBR* and the relative dry unit weight for different soils (*vide* Fig. 4). A regression analysis of the three soils yields the following equation with a high degree of correlation of 0.940:

$$\frac{CBR}{CBR_{\max}} = 4.95\frac{\gamma_d}{\gamma_{d,\max}} - 3.96 \text{ for } 90\% < \gamma_d/\gamma_{d,\max} < 100\% \quad (1)$$

where $CBR_{\max}$ is the CBR value corresponding to the maximum dry unit weight. From Eq. (1), the CBR value at the relative dry unit weight between 90% and 100% can be approximated once the $CBR_{\max}$ is known.

Because the physical properties control the engineering properties of compacted soils (Nagaraj et al., 2006; Gurtug and Sridharan, 2002; and Horpibulsuk et al., 2008 and 2009), a relationship between $CBR_{\max}$ and $\gamma_{d,\max}$ for a given type of soil is possibly developed. Fig. 5 shows the relationship between $CBR_{\max}$ and $\gamma_{d,\max}$ of the 61 fine-grained soils, the 68 lateritic soils and the 64 crushed rocks. The linear regression analyses of the three soil types yield the following equations with the degrees of correlation greater than 0.850.

$$CBR_{\max} = \gamma_{d,\max} - 9.63 \quad \text{for the fine-grained soils}$$
$$15\text{kN/m}^3 < \gamma_{d,\max} < 20\text{kN/m}^3 \quad (2)$$

$$CBR_{\max} = 2.95\gamma_{d,\max} - 9.08 \quad \text{for the lateritic soils}$$
$$19.5\text{kN/m}^3 < \gamma_{d,\max} < 21.5\text{kN/m}^3 \quad (3)$$

$$CBR_{\max} = 17.44\gamma_{d,\max} - 276.76 \quad \text{for the crushed rocks}$$
$$22.2\text{kN/m}^3 < \gamma_{d,\max} < 22.8\text{kN/m}^3. \quad (4)$$

where the $\gamma_{d,\max}$ is expressed in kN/m^3. Using Eqs. (2)–(4), the $CBR_{\max}$ value can be approximated from $\gamma_{d,\max}$. The $\gamma_{d,\max}$ value is simply obtained from the Ohio's and the modified Ohio's compaction curves. Hence, the CBR values at different relative dry unit weights between 90% and 100% can be approximated using Eq. (1).

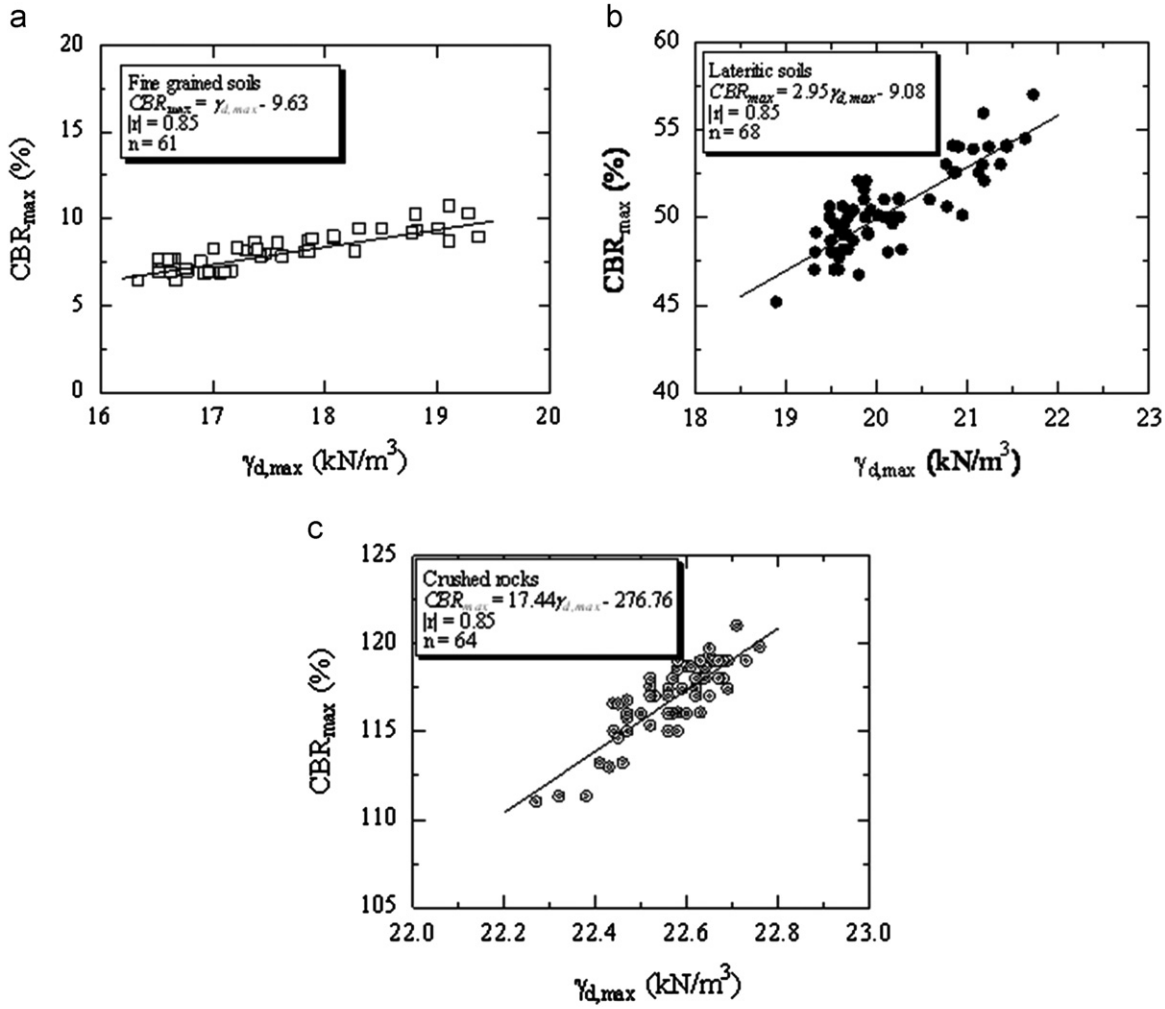

Fig. 5. Relationships between CBR and maximum dry unit weight of the studied soils. (a) Fine-grained soils, (b) Lateritic soils and (c) Crushed soils.

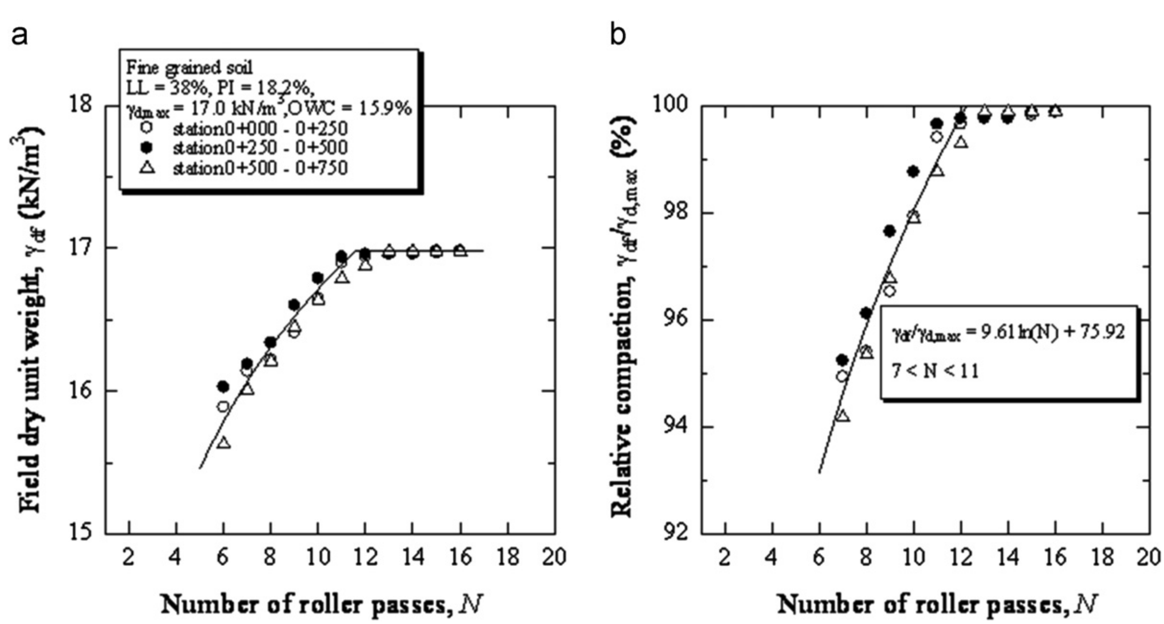

Fig. 6. Field compaction test result of a fine-grained soil.

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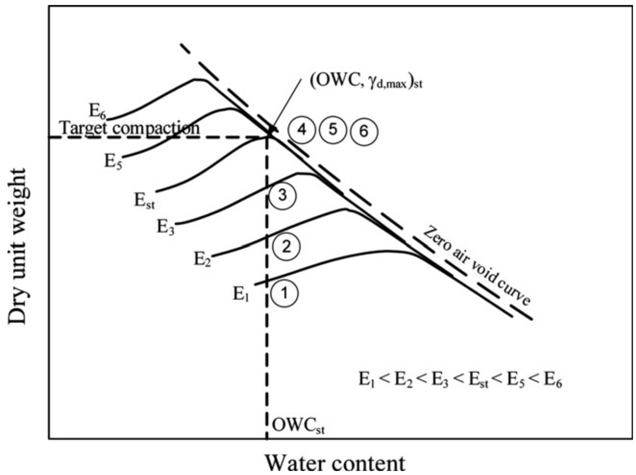

Fig.7. Schematic diagram showing the development in dry unit weight with compaction energy.

Fig. 6 shows the development in the field dry unit weight with the number of roller passes of a fine-grained soil at three measurement points (250 m apart). The field compacted water content was fixed at about the laboratory optimum water content under the standard Proctor test. The field compaction was performed layer by layer until the final thickness was reached. The final thickness was about 20 cm. The soil was compacted by a vibratory sheepsfoot roller, going back and forth. The vibratory sheepsfoot roller is drums with a large number of projections. The area of each projection is about 50 cm^2. The contact pressure under the projections is about 4200 kPa. The vibratory supplies frequency of 25 cycles per minute. The thickness for each layer was 3–4 cm and the final layer was attained at the sixth roller pass. The dry unit weight was recorded for each roller pass after the sixth roller pass. Initially, the dry unit weight increases rapidly (*vide* Fig. 6a). Beyond 11th roller pass, the dry unit weight seems to be constant even with the increase in the number of roller passes. Fig. 6b shows that the relative compaction (the ratio of the field dry unit weight to the laboratory maximum dry unit weight) reached almost 100% at the eleventh roller pass. Even with the significant increase in the compaction energy through the roller pass, the dry unit weight cannot be enhanced further because the dry unit weight of the soil in this state is close to that in the zero air void state (ideal state). In practice, the excess roller pass is thus not economic. Fig. 7 shows a schematic diagram depicting the development in the dry unit weight with the compaction energy (roller pass). The soil is compacted at *OWC* under various compaction energies (number of roller passes). The soil states are in the dry side of optimum when compaction energies are lower than the standard Proctor energy (points 1, 2 and 3). The soil states move from points 1 to 3 and approach the optimum state (point 4). When the compaction energy is greater than the standard Proctor energy, the soil states (points 5 and 6) are on the wet side of optimum. At this state, the dry unit weights of the compacted soil are essentially the same even with a large compaction energy applied. Because the γ_d and compaction energy relationship is represented by the logarithm function (Fig. 3b), the relationship between the relative compaction and the number of roller passes is proposed:

$$\frac{\gamma_{df}}{\gamma_{d,\max}} = a + b\ln N \quad (5)$$

where γ_{df} is the field dry unit weight, and a and b are constant, which depend on the soil type. Once the constants a and b for a compacted soil is determined from a back-calculation of two field measuring data, the required number of roller passes to attain the target relative compaction can be approximated. The optimal number of roller passes that the dry unit weight is insignificantly enhanced is approximated by taking the $\gamma_d/\gamma_{d,\max}$ in Eq. (5) as 100%.

4. Suggested field compaction execution

From the analysis of the test data, the field compaction procedure for road embankment and rural and highway pavements is suggested and presented by the following steps:

Material selection:

1. Determine the index properties of the soils from different borrow pits.
2. For the soils consistent with the AASHTO requirement, estimate the compaction curves and $\gamma_{d,\max}$. This task can simply done using the Ohio's and the modified Ohio's curves.
3. From the obtained $\gamma_{d,\max}$, determine the $CBR_{\max}$ using Eqs. (2) to (4).
4. Approximate the *CBR* value for the relative compaction ranging from 90 to 100% using Eq. (1).

4.1 If the approximated *CBR* value is lower than the design value, select other soils.

4.2 If the approximated *CBR* value is higher than the design value, conduct the compaction and *CBR* tests on the selected soil to determine the actual value.

Field execution and compaction controls:

5. Perform the field compaction of the selected backfill. The water content must be within 2% of *OWC*.
6. Record the dry unit weight and the number of roller passes and determine the a and b values of Eq. (5); hence the optimal number of roller passes.
7. When the optimal number of roller passes is reached, check the field dry unit weight. The relative compaction must be greater than 95% for the compaction specification in Thailand.

5. Conclusions

This paper deals with the characteristics of compaction and *CBR* of the three soil types (fine-grained soils, lateritic soils and crushed rocks). These soils are generally used as subgrade, subbase and base, respectively. The Ohio's and the modified Ohio's curves predict satisfactorily the compaction behavior of the compacted soils. From the predicted curves and Eqs. (1)–(4), the *CBR* values at different relative dry unit weights between 90% and 100% can be approximated. The laboratory and field compaction data show that the relationship between the relative compaction and the number of roller passes is represented by the logarithm function. From the analysis of the test data, the field compaction procedure for road embankment and rural and highway pavements, which includes the material selection and the field compaction control, is suggested. It is useful in terms of engineering and economical viewpoints.

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