Procedia Engineering
Volume 143, 2016, Pages 323–330
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

# Impact of Compaction Methods on Resilient Response of Unsaturated Granular Pavement Material

Ehsan Yaghoubi[1*], Mahdi M Disfani[2], Arul Arulrajah[3] and Jayantha Kodikara[4]
[1&3]*Swinburne University of Technology, Hawthorn, Australia.*
[2]*The University of Melbourne, Parkville, Australia.*
[4]*Monash University, Clayton, Australia.*

**Abstract**
Compaction of aggregates is an important part of the design, construction and research of pavement geotechnics projects. An important application of compaction is sample preparation for pavement design studies. Conventionally, the impact method of compaction is used for studies on pavement materials. However, recently, some researchers have been using other methods of compaction, such as static compaction, specifically for studying the unsaturated behavior of pavement materials. The objective of this study is to investigate the effect of compaction techniques on resilient behavior of compacted laboratory specimens. Studies show that the resilient behavior of unsaturated compacted road pavement materials is influenced by suction. In this regard, two types of recycled Construction and Demolition (C&D) material were selected and static and impact compaction methods were utilized for sample preparation. Further, accuracy of four predictive resilient modulus models with or without incorporation of suction was investigated. Test results show the impact of compaction method on particle breakage, matric suction and accordingly resilient behavior of C&D granular material.

*Keywords:* Matric Suction, Static Compaction, Impact Compaction, Recycled Material, Resilient Modulus

# 1 Introduction

Pavement materials are normally compacted in unsaturated conditions and remain unsaturated during most of their service life. In the unsaturated condition, matric suction, which is the result of the tension generated at the air water interface in the soil structure, affects the mechanical behavior of the pavement material (Craciun and Lo, 2010). Matric suction (hereafter referred to as suction) acts as an internal normal stress that adds to the stiffness of soil against external loading (Alonso et al., 1990). Suction values can be related to moisture contents using the Soil Water Characteristic Curve (SWCC). Values of suction in granular materials are significantly lower than those of fine materials; however,

* Corresponding author. Tel: +61392144666 E-mail: eyaghoubi@swin.edu.au

Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016


doi:10.1016/j.proeng.2016.06.041

studies such as Ba et al. (2013), Azam et al. (2013), and Rahardjo et al. (2013), among others, claim noticeable influence of suction in mechanical behavior of granular pavement material. An important mechanical property of pavement material is the resilient modulus ($M_r$), which is a key parameter in many pavement thickness design procedures (Azam et al., 2013). Earlier predictive resilient modulus models do not account for suction, such as May and Witczak (1981) and modified universal model (AASHTO, 2002), whereas more recently developed models do consider the impact of suction (Azam et al., 2013; Cary and Zapata, 2011; Craciun and Lo, 2010; Liang et al., 2008; Yang et al., 2005).

Impact (modified Proctor) and static compaction procedures are the two most widely used techniques (Kouassi et al., 2000). The impact of compaction method on soil mechanical properties has been supported by the difference in unconfined compressive strengths of samples of same density prepared through static and impact procedures (Crispim et al., 2011). This can be attributed to differences in the formation of pores by these compaction techniques. Micrographs taken from the compacted samples have highlighted differences in generated particle structures. A similar conclusion was made by Doris Asmani et al. (2011) through analyzing X-ray test results on samples compacted using static and impact methods. Compaction can cause aggregate breakage, and create changes in pore size and distribution, which can affect the SWCC of the samples (Zhang and Buscarnera, 2015). This aspect of the impact of compaction has had limited investigation and is the focus of this paper.

The extent of induced changes in SWCC can differ during static and impact compaction procedures, even in samples achieving similar densities and compacted under the same moisture content. The main objective of this study is to investigate the influence of method of compaction on the hydro-mechanical behavior of compacted samples of pavement granular material, and the consequent impact on their resilient modulus. Four resilient modulus prediction models were selected to evaluate the data obtained from laboratory tests. These models include: modified universal model of AASHTO (2002), Yang et al. (2005), Liang et al. (2008), and Azam et al. (2013). While there are many other methods available, these models were selected since their input data was available for this research program. These models are presented through Equations 1 to 4, respectively:

$$M_r = k_1 p_a \left(\frac{\sigma_b}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad (1)$$

$$M_r = k_1 (\sigma_d + X_w \psi_m)^{k_2} \quad (2)$$

$$M_r = k_1 p_a \left(\frac{\sigma_b + X_w \psi_m}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad (3)$$

$$M_r = k_0 \left(\frac{\sigma_b}{3p_a}\right)^{k_1} \left(\frac{\tau_{oct}}{\tau_{ref}}\right)^{k_2} \left(\frac{\psi_m}{p_a}\right)^{k_3} \left[\left(\frac{\text{P-MDD}(1 - k_4 \text{P-CB}/100)}{100}\right)\right]^{k_5} \quad (4)$$

Where $p_a$ is atmospheric pressure, $\sigma_b$ is bulk stress, $\tau_{oct}$ is octahedral shear stress, $\tau_{ref}$ is reference shear stress ($\frac{\sqrt{2}}{3} \times$ peak shear strength), $\psi_m$ is matric suction, *P-MDD* is the percentage of Maximum Dry Density, *P-CB* is the percentage of Crushed Brick in the blend and $k_0$ to $k_5$ are regression coefficients. $X_w$ is Bishop's effective stress parameter ($=(\psi_{aev}/\psi_m)^{0.55}$), where $\psi_{aev}$ is air-entry value.

# 2 Experimental Plan

Granular materials used in this study were Crushed Brick (CB) and Recycled Concrete Aggregate (RCA) with a maximum particle size of 19 mm. These were collected from a recycling facility in Melbourne, Australia. Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) obtained from modified Proctor compaction method (ASTM D1557-12 (2012)) for CB and RCA were 1990 kg/m$^3$ and 10.8%, and 1960 kg/m$^3$ and 11.0% respectively.

Two methods of compaction: static and modified Proctor methods (ASTM D1557-12 (2012)) were used to observe the alteration in the Particle Size Distribution (PSD) of the specimens after the compaction procedure. A series of trial and error compaction tests (4000 kPa to 12000 kPa static pressures) showed that static compaction under a pressure of 12000 kPa results in specimens with density close to that of a specimen prepared using modified Proctor procedure. In both methods, materials were compacted in 5 layers inside a 105 mm diameter mold. In the static method, after applying the pressure on each layer, pressure was kept constant until no further deformation was recorded. Post-compaction specimens were then oven-dried for 24 hours and sieve analysis was then performed. For each of the 4 types of specimens, being CB-Static, CB-Modified, RCA-Static and RCA-Modified, 2 replicate specimens were compacted and analyzed after compaction. Figure 1 shows average PSD of CB and RCA pre-compaction and post-compaction specimens. Larger gap between pre- and post-compaction PSD of CB suggests greater amount of aggregate breakage in CB.

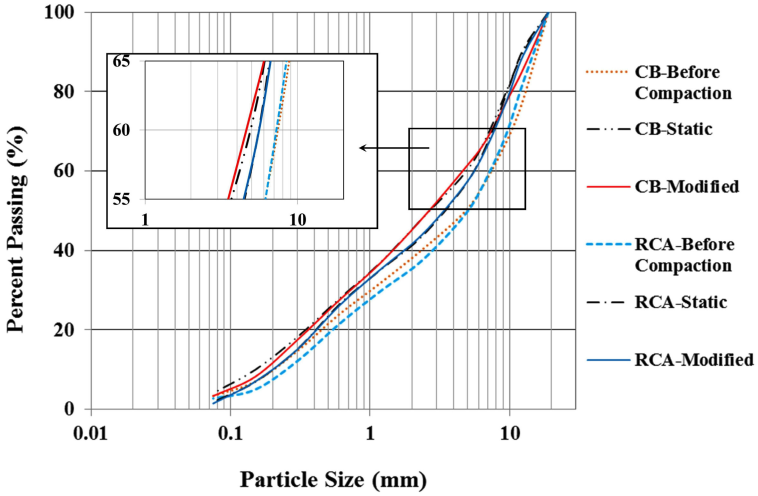


**Figure 1:** Alteration in PSD of CB and RCA after compaction

To determine the resilient modulus of the compacted specimens, Repeated Load Triaxial (RLT) tests were conducted on specimens. AASHTO-T307-99 (2007) procedure was followed and a triaxial cell under a loading frame capable of applying a haversine-shaped pulse with loading periods of 0.1 s and resting periods of 0.9 s was used. Samples were compacted in 8 layers using a 100 mm diameter mold with the height of 202mm, aiming to reach similar densities in each blend.

# 3 SWCC Prediction

Determination of SWCC in the laboratory or field is time consuming and costly (Aubertin et al., 2003). Hence, predictive models that use basic geotechnical properties are developed for estimation of SWCC. In this research, SWCC of the compacted specimens was determined using two predictive models, being Aubertin et al. (2003) and Perera et al. (2005). Both of these methods are applicable for granular materials. Input parameters of these models include: $D_i$, the particle size corresponding to *i*-percent passing (in mm), where *i*=10, 20, 30, 60, and 90, *P200*, the percentage of the sample particles smaller than 75 μm (in decimals), $C_u$, the coefficient of uniformity, and *e*, the void ratio of the compacted samples. These are presented in Table 1, and show that for each material, the difference in breakage through modified Proctor and static compaction under 12000 kPa is not significant. For a more accurate comparison, relative breakage index ($B_r$) was calculated using Hardin (1985) method to quantify the amount of particle breakage (Table 1). $B_r$ is the ratio of $B_t$ (total breakage) to $B_p$

(breakage potential). These are obtained using the PSD curve. $B_p$ is the area enclosed by pre-compaction gradation curve, particle size=75 μm line and percent passing=100% line. $B_t$ is the area enclosed by pre-compaction, and post-compaction gradation curves. The estimated SWCCs, together with air-entry values ($\psi_{aev}$) and suction values ($\psi_m$) corresponding to the OMC are shown in Figure 2. Both predictive models result in greater suction values for CB compared to RCA. However, while Aubertin et al. (2003) model predicts greater $\psi_m$ for samples compacted through modified Proctor procedure, converse outcomes are obtained from Perera et al. (2005) model.

| Types of Specimens | $B_r$ | $D_{10}$ | $D_{20}$ | $D_{30}$ | $D_{60}$ | $D_{90}$ | P200 | Cu | e |
|---|---|---|---|---|---|---|---|---|---|
| CB- Modified | 0.083 | 0.16 | 0.36 | 0.72 | 4.52 | 14.28 | 0.041 | 28.5 | 0.322 |
| CB- Static | 0.092 | 0.16 | 0.34 | 0.70 | 4.87 | 12.57 | 0.034 | 31.3 | 0.355 |
| RCA- Modified | 0.069 | 0.20 | 0.41 | 0.80 | 5.56 | 12.94 | 0.015 | 28.4 | 0.373 |
| RCA- Static | 0.058 | 0.20 | 0.40 | 0.80 | 5.58 | 12.24 | 0.019 | 28.2 | 0.394 |

**Table 1:** Input parameters for SWCC prediction of compacted samples

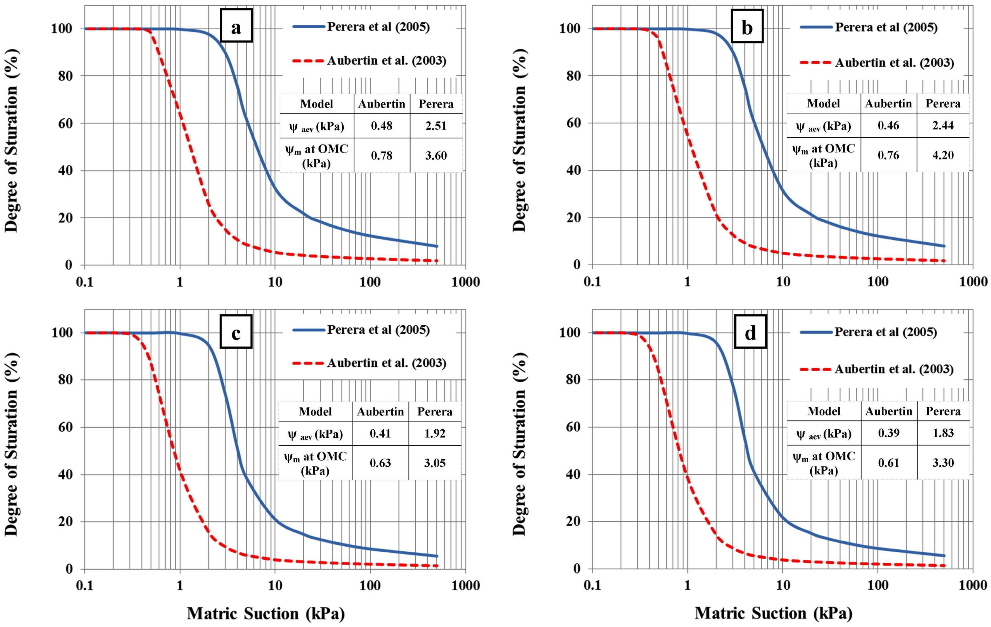


**Figure 2:** Predicted SWCC for (a) CB-modified, (b) CB-Static, (c) RCA-Modified, (d) RCA-Static

The predicted data were fitted to Fredlund and Xing (1994) model. Curve-fitting parameters of this model ($a$, $n$, $m$, and $\psi_r$) are presented in Table 2. Perera model predicts higher values of the parameter "$a$" (related to the $\psi_{aev}$). While the slope of SWCC (parameter "$n$") of each specimen is almost similar in both predictive models, higher values of parameter "$m$" in Aubertin model causes a flatter slope at the dry side of the SWCC. Residual suction ($\psi_r$) was assumed to be 100 kPa as recommended by Perera et al. (2005) for non-cohesive materials. Greater density combined with higher breakage during compaction of CB resulted in formation of smaller pore sizes. This resulted in higher suction values for CB specimens compared to RCA specimens at any specific degree of saturation. Figure 1 shows that modified Proctor method results in greater breakage and dry density in both CB and RCA samples (although the difference is not significant). Therefore, higher suction values were expected from specimens prepared by the impact compaction method. Based on the results shown in Figure 2, outcomes of Aubertin et al. (2003) method follow the above-mentioned justification, while this is not the case for outcomes of Perera et al. (2005) model. The reason can be the fact that Perera model only takes PSD parameters into account, whereas Aubertin model considers both PSD and void ratio. Accordingly, in this research, SWCC obtained from Aubertin model were used. Further justification of this can be achieved through validation of the predicted SWCC by experiments, planned for next stage of this research. Laboratory measurements also reveal possible errors in the estimated SWCC, as model uncertainty can be important in this case where there is insignificant difference between post-compaction PSD of static and impact specimens.

| Model | Aubertin et al. (2003) | | | | Perera et al. (2005) | | | |
|---|---|---|---|---|---|---|---|---|
| Model parameters | a | n | m | $\psi_r$ | a | n | m | $\psi_r$ |
| CB-Modified | 0.90 | 4.10 | 1.22 | 100.0 | 3.66 | 3.32 | 0.79 | 100.0 |
| CB-Static | 0.83 | 4.30 | 1.20 | 100.0 | 3.63 | 3.51 | 0.77 | 100.0 |
| RCA-Modified | 0.69 | 3.83 | 1.34 | 100.0 | 2.77 | 4.18 | 0.83 | 100.0 |
| RCA-Static | 0.66 | 3.72 | 1.38 | 100.0 | 2.91 | 4.24 | 0.83 | 100.0 |

**Table 2:** Fredlund and Xing (1994) parameters using outcomes of Aubertin and Perera models

# 4 Evaluation of Resilient Modulus Models

The combination of a range of repeated vertical stress and static confinements through 15 sequences of RLT tests according to AASHTO T-307 procedure resulted in a total of 60 data sets for $M_r$ values. Average measured $M_r$ values were 242 and 132 MPa for CB-Modified and CB-Static and 256 and 197 MPa for RCA-Modified and RCA-Static, respectively. Obviously, for both materials, specimens compacted using modified Proctor method have greater $M_r$ values. Influence of suction on resilient behavior of compacted CB and RCA was studied by fitting the dataset from the RLT tests to the four models discussed in section 1. All models except the modified universal model incorporate suction. Figure 3 shows the predicted vs. measured resilient modulus using these predictive models.

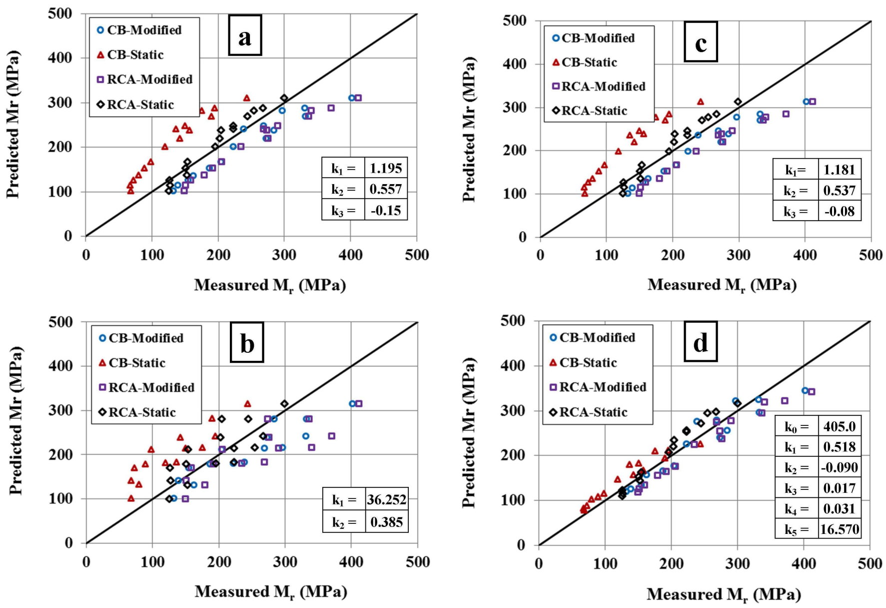


**Figure 3:** Predicted vs. measured resilient modulus for all specimens using (a) AASHTO (2002), (b) Yang et al. (2005), (c) Liang et al. (2008), and (d) Azam and Cameron (2013) models

For evaluation of the goodness of fit, 3 statistical measurements were used: standard accuracy ($S_e/S_y$), coefficient of determination ($R^2$), and Root Mean Square Deviation (*RMSD*), where $S_e$ is standard error of estimate and $S_y$ is the standard deviation (Azam et al., 2013; Witczak et al., 2002). Witczak et al. (2002) criteria was used for evaluation of goodness of fit (Table 3). In this subjective criteria, $S_e/S_y \leq 0.35$ and $R^2 \geq 90$, $0.36 \leq S_e/S_y \leq 0.55$ and $0.70 \leq R^2 \leq 0.89$, $0.56 \leq S_e/S_y \leq 0.75$ and $0.40 \leq R^2 \leq 0.69$, and $0.76 \leq S_e/S_y \leq 0.90$ and $0.20 \leq R^2 \leq 0.39$, represent Excellent, Good, Fair, and Poor fit, respectively. Table 3 shows that Yang et al. (2005) model didn't present a good fit and Liang et al. (2008) model did not show much improvement compared to the modified universal model, despite taking suction into account. This can be because both Yang et al. (2005) and Liang et al. (2008) used fine materials for the development of their models. Nevertheless, these models were selected due to lack of models on granular materials in which the required input parameters were obtainable in this research program. Azam et al. (2013) model, is generated using data obtained from granular material and shows an excellent fit to the data obtained in this research. The role of suction in prediction of $M_r$ values, was investigated through sensitivity analysis of data predicted by Liang et al. (2008) and Azam et al. (2013) models. In this regards, the range of model parameters (minimum and maximum values) were determined. $M_r$ values corresponding to minimum/maximum ranges of each parameter were calculated, while using average values for the other parameters. The range of model parameters in this research is reported in Table 4. Range of changes in $M_r$ values within Liang et al. (2008) and Azam et al. (2013) model parameters' changes are plotted in form of tornado plots (Figure 4).

| Model | Inclusion of Suction | *RMSD* (%) | $S_e/S_y$ | $R^2$ | Rating (Witczak et al., 2002) |
|---|---|---|---|---|---|
| AASHTO (2002) | NO | 34.1 | 0.64 | 0.60 | Fair |
| Yang et al. (2005) | YES | 41.1 | 0.73 | 0.48 | Fair |
| Liang et al. (2008) | YES | 33.8 | 0.64 | 0.61 | Fair |
| Azam et al. (2013) | YES | 13.7 | 0.33 | 0.90 | Excellent |

**Table 3:** Evaluation of goodness of fit of measured and predicted data

| Parameters | $\sigma_b$ (kPa) | $\psi_m$ (kPa) | $\psi_{aev}$ (kPa) | $\tau_{ref}$ (kPa) | *P-MDD* (%) | *P-CB* (%) |
|---|---|---|---|---|---|---|
| Min | 75.80 | 0.61 | 0.39 | 23.15 | 98.00 | 0.00 |
| Average | 324.73 | 0.70 | 0.44 | 89.38 | 99.00 | 50.00 |
| Max | 689.60 | 0.78 | 0.48 | 179.52 | 100.00 | 100.00 |

**Table 4:** Range of model parameters applied in this research

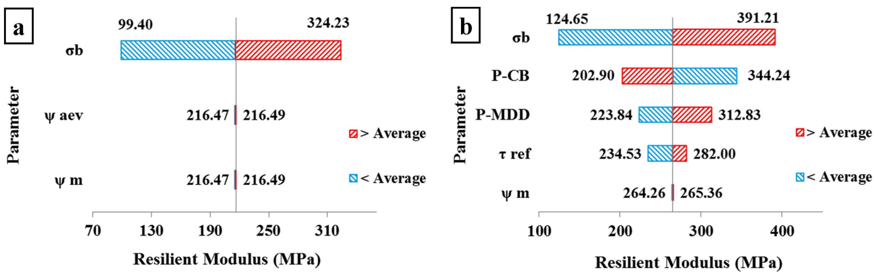


**Figure 4:** Tornado plots presenting sensitivity analysis of model parameters of (a) Liang et al. (2008) and (b) Azam et al. (2013) models

Both models show very low sensitivity to suction. Azam et al. (2013) model contains 6 variables. However, since both $\tau_{oct}$ and $\sigma_b$ are obtained from major and minor principal stresses, only $\sigma_b$ was considered in the sensitivity analysis. Since CB and RCA were not blended, a modification was applied to Azam et al. (2013) model by omitting the *P-CB* parameter and fitting CB and RCA data separately, by assuming $k_4$ equal to zero. Figure 5 shows the predicted vs. obtained resilient modulus, together with $S_e/S_y$ and $R^2$ values, using the modified model. In both CB and RCA, "Excellent" fit to this model is observed. Sensitivity analysis showed that this model has low sensitivity to suction, as well. However, it should be noted that in this research, range of changes of suction is significantly lower compared to other parameters such as $\sigma_b$, as the RLT samples were compacted using their estimated OMC (i.e., degree of saturation of 70 to 80%), which leads to low suction values. Significance of effect of changes in suction on resilient modulus of specimens was further recognized by calculating ratio of range of changes in $M_r$ values, by taking maximum/minimum of one parameter and taking average value of other parameters, to the range of each parameter (Table 5).

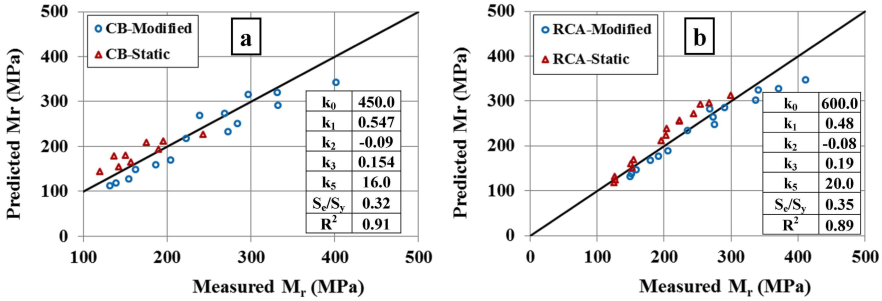


**Figure 5:** Predicted vs. obtained resilient modulus using modified Azam and Cameron (2013) model for CB samples (a), and RCA samples (b)

| Material | $\Delta M_r/\Delta\sigma_b$ | $\Delta M_r/\Delta\psi_m$ | $\Delta M_r/\Delta\tau_{ref}$ | $\Delta M_r/\Delta P\text{-}MDD$ |
|---|---|---|---|---|
| CB | 0.33 | 37.93 | 0.22 | 30.91 |
| RCA | 0.36 | 72.13 | 0.24 | 47.20 |

**Table 5:** Ratio of $M_r$ changes to each parameter's changes using modified model of Azam et al. (2013)

# 5 Conclusions

In this research, two types of widely used compaction techniques were applied for the compaction and sample preparation CB and RCA. The specimens prepared using these procedures were then studied in terms of difference in SWCC and resilient behavior. Based on the results, obtained through testing within a limited range of suction, the following points are concluded:

1. Greater aggregate breakage in CB samples, resulted in smaller pore sizes, and accordingly, higher suction values at similar degrees of saturations, compared to RCA samples.
2. Minor difference was observed in aggregate breakage of each material during impact and static methods. However, estimated SWCCs of the impact and static specimens were different, despite the specimens being densified to almost the same degree.
3. Even though predictive models did not show a significant sensitivity to the changes in suction within suction ranges of this research, ratio of range of changes in resilient modulus to range of suction was greater than that of other parameters. This suggests that influence of suction cannot be ignored in assessing the resilient modulus response of granular materials.
4. Overall, it was observed that in specimens with identical dry densities and moisture contents, method of compaction resulted in different suctions. This difference, despite being minimal (suction < 1 kPa), can in some cases influence the resilient modulus of specimens along with different coarse particle structure caused by different methods of compaction. Consequently, it is important that for simulating field conditions for practical purposes, influence of the compaction procedure in the outcomes of laboratory tests be taken into account.

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