Impact of compaction method on mechanical characteristics of unbound granular recycled materials
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Laboratory testing methods are constantly being developed to simulate true field conditions in controlled laboratory environment. The aim of laboratory testing methods is to reproduce specimens which accurately replicate field performance in terms of mechanical behaviour of pavement materials under applied loads. Compaction is the most common soil stabilisation technique in ground improvement and pavement construction works. Among the available laboratory compaction methods, the impact method followed by the static method are the most commonly used procedures. Since the nature and approach of these two compaction methods are fundamentally different, an investigation on the effect of using these techniques on the mechanical performance of pavement materials prepared by each of these methods is essential, so as to better understand both these compaction methods. In this regard, two types of recycled construction and demolition (C&D) materials suitable for pavement applications, namely crushed brick (CB) and recycled concrete aggregate (RCA) were selected. Laboratory specimens were prepared using the above-mentioned procedures. Different aspects of geotechnical characteristics of the specimens, including aggregate breakage, changes in soil–water characteristics, stiffness, and resilient characteristics, were investigated. The outcomes of this research indicate that the influence of method of compaction must be considered when interpreting the laboratory test results for field design purposes.

Keywords: static compaction; impact compaction; aggregate breakage; recycled material; unbound granular materials; resilient modulus

Introduction
Compaction is a soil stabilisation technique for increasing the strength characteristics of soils and aggregates and also to reduce their deformation potential. This is achieved by applying mechanical energy to lower voids from the soil matrix. Compaction in the field is achieved using a variety of methods. The four most common techniques for field compaction are: dynamic (e.g. dropping weights), kneading (e.g. applying sheep foot/rubber-tyred rollers), vibration (e.g. vibratory rollers), and static compaction (e.g. smooth-wheeled rollers) (Browne, 2006). Accordingly, laboratory testing methods have been developed for simulating the field condition in order to prepare test specimens to evaluate the properties of pavement materials.

The current laboratory compaction techniques are used to determine two important pavement and geotechnical design and construction parameters: optimum moisture content (OMC) and
maximum dry density (MDD). These two parameters are then used to control field compaction and to achieve certain performance. However, OMC and MDD in the laboratory are obtained by applying specific compaction energy. Therefore, these parameters can vary depending on the magnitude and nature of compaction energy (Reddy & Jagadish, 1993). Figure 1, as an instance, shows how increasing the energy of compaction results in the decrease in OMC and increase in MDD of the same material. In this case, the energy of compaction is increased by adding to the number of drops of compaction hammer per layer of the material.

The most widely used laboratory compaction techniques are impact and static compaction methods (Kouassi, Breysse, Girard, & Poulain, 2000). Normally, the impact method is used for field compaction control and sample preparation, whereas the static method is used for sample preparation in research projects using the compaction parameters obtained from the impact method.

The standard and modified Proctor tests are the most common impact compaction methods. The standard Proctor test was first developed in the 1930s, but due to technological advancements in heavy rollers, it was often deemed to be unable to represent true field conditions. Accordingly, the modified Proctor compaction technique was developed in the 1940s. In the modified method, compaction energy was increased from 594 to 2700 kN/m$^3$ (Das, 2010). While the impact compaction involves repeated dropping of a hammer of specific weight from a determined height for a defined number of blows, in the static compaction approach, pressure is applied on the surface of each layer in the compaction mould and maintained long enough until the change in axial displacement reaches zero or until the required density (or void ratio) is achieved.

Field compaction is normally performed using compaction machinery which applies static pressure solely or together with such actions as vibration and kneading. To simulate this
compaction process in the laboratory, the determination of energy input per unit volume of the soil in field and laboratory is essential. This causes two problems in using the impact method. First, the nature of laboratory compaction is different to the static or kneading method implemented in the field. Second, the impact compaction method applies a defined energy input, whereas in the field, different types of compaction machinery are used applying different compaction energies to the soil (Reddy & Jagadish, 1993). Therefore, the OMC obtained from impact methods cannot necessarily be suitable for field compaction. Another drawback of the impact method observed during compaction procedure of granular material is that aggregates escape from underneath the hammer contact surface. On the other hand, in static compaction the main drawback is that the displacement of the aggregates under compaction pressures is limited, since continuous loading and aggregate interlock during static compaction prevent particles from slipping over each other freely. This may cause stress concentration in some parts of the specimen, and accordingly some higher local density in some parts and larger macro pores in others (Holtz, Kovacs, & Sheahan, 1981). Additionally, in this method, under higher compaction pressures, the void ratio of the samples is decreased to the extent that it gets close to saturation condition. At this stage not only air, but also water is forced out of the sample. This is also the case at higher water contents, even at lower compaction pressures. This may result in lower obtained water content, compared to what is required in the field to achieve the target density.

This paper presents and discusses a suite of experimental results to investigate the influence of compaction method on hydraulic and mechanical characteristics of two types of construction and demolition (C&D) materials commonly used in pavement applications, being crushed brick (CB) and recycled concrete aggregate (RCA). Insufficient knowledge and uncertainties on field performance of recycled materials through interpretation of laboratory test results remain a prime reason delaying the widespread application of these materials in pavement construction (Arulrajah, Piratheepan, Disfani, & Bo, 2013).

Literature Review
In spite of developing many laboratory compaction procedures, the impact and static methods are the most accepted laboratory compaction procedures. However, the mechanism of these methods differs from the way soil and aggregates are compacted in the field. Field compaction is the result of one or more of the following actions: static force, vibration, kneading, tamping, and impact blows (Browne, 2006). As a result, researchers have investigated laboratory techniques which can better simulate the field compaction, by including actions such as kneading (Kouassi et al., 2000) or utilising gyratory compactors originally used for compacting bound material (Browne, 2006). However, the difficulties and complexities of applying these compaction techniques are the prime reasons that the impact and static methods have remained as the most commonly used methods. Static compaction is known to be a faster, simpler, and easier method of compaction compared to the impact method (Asmani, Hafez, & Shakri, 2013). Therefore, in recent years, static compaction has been the more common specimen preparation technique used for C&D material (Azam & Cameron, 2013; Azam, Cameron, & Rahman, 2013).

Conventionally, compaction is known to be influenced by three factors, being water content, soil type, and compaction effort (Das, 2010). Surprisingly, in sample preparation, the effect of the nature of compaction method is ignored with the aim being to prepare specimens with consistent dry density. A pioneering research comparing static and impact compaction procedures was carried out by Reddy and Jagadish (1993), who focused on making the static method more representative of the true field conditions. The OMC and MDD values obtained from this method were believed to correlate well with field compaction operations. Hafez, Asmani, and Nurbaya
(2010) chose five different types of soils and compared the OMC and MDD values obtained from the static and impact methods with field results and suggested that the static method provides a more sensible representation of field conditions compared to the impact method. Asmani, Hafez, and Nurbaya (2011) investigated the uniformity of specimens prepared using the impact and static compaction methods based on the density and water content of the top and bottom layers of the specimens. They concluded that impact compaction results in non-uniformity across the specimen height. Asmani et al. (2011) supported their conclusion by using X-ray tests on specimens prepared by static and impact compaction, and concluded that the static procedure resulted in more uniform specimens.

A common approach in using static compaction for pavement material specimen preparation is to obtain OMC and MDD from the impact method, and use these values to compact samples. Crispim et al. (2011) prepared specimens with insignificant density difference (1–3%) using the static and impact methods and conducted unconfined compressive strength (UCS) tests on the specimens. In spite of achieving almost the same densities, UCS values for statically prepared specimens were found to be 20% lower for clay of high plasticity and 37% higher for clayey sand. In order to conduct more investigations, Crispim et al. (2011) took photomicrographs of the specimens prepared by the two methods and observed that unlike specimens prepared with the impact method, statically prepared specimens presented a fairly uniform distribution of porosity. They suggested that this may be the reason for different mechanical strengths in the specimens.

In materials with a significant coarse fraction, the structure of aggregates changes during compaction. This alteration of particle size is due to breakage of the particles, especially the coarse fraction of a blend. Studies show that aggregate breakage changes the hydraulic states of soil, and accordingly affects the unsaturated behaviour of soils (Zhang & Buscarnera, 2015). Since pavement material tends to be unsaturated during their service life, these changes in unsaturated behaviour of compacted material (in subgrade, sub-base, or base) should be taken into account. The capillary potential of soil results in an inter-particle normal force that contributes to the stiffness of soil against external loading (Alonso, Gens, & Josa, 1990). This inter-particle pull is matric suction (hereafter referred to as suction) and is increased by reduction in size of soil pores (i.e. reduction in equivalent radius of a capillary tube). Compaction alters the particle size distribution (PSD) of a blend due to breakage resulting in larger values of suction (Zhang & Buscarnera, 2015). This is because breakage causes increase in the percentage of the smaller sized particles, resulting in smaller pore sizes, and accordingly higher values of suction at a specific degree of saturation. Soil–water characteristic curve (SWCC) relates the moisture content of soil to its suction. PSD affects SWCC, since it influences formation of the network of capillary pores inside a block of soil.

Compared to cohesive soils, suction is rather small in unbound granular pavement materials due to the larger size of pores in their structure. As a result, few studies have been done on the unsaturated behaviour of the unbound granular materials compared to many studies on unsaturated behaviour of fine soils. However, there are some recent studies on the influence of suction on unbound granular materials’ mechanical performance with the understanding that the effect of suction forces cannot be ignored (Azam et al., 2013; Azam & Cameron, 2013; Ba, Nokkaew, Fall, & Tinjum, 2013; Cameron, 2014; Rahardjo, Satyanaga, Leong, & Wang, 2013; Yang, Lin, Kung, & Huang, 2008). Nevertheless, in these research works the effect of compaction method and the resulting alteration in PSD have not been considered. To the best of authors’ knowledge, this is the first time that the changes in soil–water characteristics of unbound granular materials due to changes in the PSD as a result of compaction are investigated.

The few above-mentioned studies show that the difference in the nature of the impact method of compaction and static method of compaction can result in specimens with different behaviours and characteristics. However, this important factor (method of compaction) has normally been
ignored in research conducted on pavement granular materials. Hence, a detailed investigation on the influence of these laboratory compaction procedures on mechanical performance of the specimens prepared using these techniques is required. The primary objective of this research is to propose, for the first time, a testing approach to compare the impact method of compaction with static method of compaction. Further, the two compaction methods are evaluated and compared by considering a series of tests to study the influence of compaction technique on a range of mechanical performance characteristics, including soil–water, stiffness, and resilient characteristics of the laboratory specimens.

Materials and methods

Two types of C&D materials, namely CB, and RCA, suitable for pavement sub-base applications were used in this research (Arulrajah, Disfani, Horpibulsuk, Sukrisiripattanapong, & Prongmanee, 2014). The materials were collected from a major recycling facility in Melbourne, Australia. Table 1 presents the geotechnical properties of CB and RCA material used in this research as evaluated in the laboratory. Previous research, such as Arulrajah et al. (2014) and Arulrajah et al. (2013), among others, show that CB and RCA have physical properties comparable to typical quarry materials. In particular, Los Angeles abrasion value of both CB and RCA is lower than the maximum limit of this property for conventional unbound granular materials used in pavements (Arulrajah et al., 2014). As a result, the amount of aggregate breakage during the compaction for CB and RCA is expected to be similar to that of typical base/sub-base granular materials.

In this research, two compaction procedures were applied for sample preparation: static compaction using several constant pressures and impact compaction using the modified Proctor effort (ASTM-D1557, 2012). To assure maximum consistency, as well as repeatability, prior to compaction, materials were split in three portions of particle size range. Then these three portions, namely particles smaller than 2.36 mm, those between 2.36 and 9.5 mm, and those larger than 9.5 mm were mixed in specific percentages to reconstitute samples with consistent PSD. In order to verify this, three trial samples were prepared by mixing the above-mentioned portions and were then re-sieved. Then the standard deviation of the %passing each sieve size was calculated for the three obtained PSDs. Standard deviations of between 0.3% and 1.8% for CB and 0.2% and 1.5% for RCA show negligible difference in PSD of the samples prepared using the above-mentioned procedure. For checking the repeatability, three CB samples were prepared using the control sieves and wetted to OMC of CB. These were then separately compacted under static pressure of 4000 kPa for comparing their post-compaction dry densities. Obtained dry densities were 1845, 1851, and 1849 kg/m³. Since the PSDs and dry densities obtained are very close, and testing procedure is done using automatic/programmable equipment with high precision and control over testing procedure, test results are expected to be repeatable.

| Material | \(D_{\text{max}}\) (mm) | \(C_e\) | \(C_u\) | Coarse fraction | Fine fraction | MDD (kg/m³) | OMC (%) |
|----------|----------------|--------|--------|----------------|---------------|-------------|---------|
| CB       | 19             | 0.9    | 34.6   | 2.66           | 2.61          | 1990        | 10.8    |
| RCA      | 19             | 0.7    | 28.8   | 2.66           | 2.71          | 1960        | 11.0    |
Experimental plans are explained in the following sections. In this research, besides recognised pavement material tests, a testing procedure is proposed to relate impact and static methods of compaction.

**Determination of dry densities**

In both compaction procedures, moulds with diameter of 105 mm and height of 115.5 mm were used and materials were compacted in five layers. The samples were compacted with OMC obtained from the modified Proctor method. In the static method, targeted pressure was constantly applied on the sample until no further or negligible displacement was observed. Similar to the impact method, in the static procedure, drainage was allowed from the top of the mould. This resulted in the reduction in the final moisture content of the specimens prepared under higher compaction pressures or those with the moisture content greater than OMC. Attention was paid to place the same amount of material in the mould for each layer, so that the only variables were the compaction effort and compaction method. Care was taken to avoid segregation while placing the loose material inside the mould. Static compaction was done using a Universal Testing Machine (UTM-100) capable of applying 130 kN of compression axial load. Impact compaction was done using an automatic Proctor compactor set to the modified mode.

**Proposed constrained modulus testing approach**

A procedure similar to ASTM D2435 (2011), with slight modifications, was used to generate the compression curves of void ratio–vertical stress for specimens prepared following an adaptation of the modified Proctor compaction method. The objective of this proposed procedure was to determine the yield stress of the specimens prepared by the modified Proctor method by generating the compression curves under several stress levels and applying the Casagrande (1936) method for determination of pre-consolidation stress. Sample preparation was done using moulds with a diameter of 105 mm and a height of 115.5 mm. The compaction procedures (static and impact) mentioned in the previous section were followed; however, in order to maintain the minimum specimen diameter-to-height ratio (according to ASTM D2435-11), samples were compacted in two layers, each with a final thickness of approximately 21 mm, following an adaptation of the modified Proctor method. Loading was applied using a UTM-100 machine with a capacity of 130 kN of compression axial loading. Figure 2 shows a schematic of the constrained modulus test set-up. Two-way drainage was provided for the samples according to ASTM D2435-11. Test data were collected using a data logger for both load and deformation measurements. The compacted samples were subjected to incrementally applied controlled-stress loading. The standard loading schedule consisted of a load increment ratio of 2, starting from 25 kPa, that is, 25, 50, 100, 200, and finally 12,800 kPa. Each test specimen was kept under each constant loading stage until no or very minor deformation was recorded.

**Stiffness and resilient characteristics testing and calculations**

The sample preparation for stiffness and resilient characteristics testing was done using a split compaction mould with a diameter of 100 mm and a height of 202 mm. Specimens prepared with the impact method were compacted in eight layers, following the procedure described in ASTM-D1557 (2012). For the top layers a collar was used to ensure that aggregates remain inside the mould during compaction. Statically prepared specimens were compacted with a similar procedure, but under static compression instead of drops of hammer. Specimens were aimed to have similar densities in order to investigate the influence of the method of compaction.
Resilient characteristics of the compacted samples were determined using repeated load triaxial (RLT) tests. The RLT test is meant to simulate the pavement layer’s condition under repeated traffic loads. For conducting RLT tests, a haversine-shaped loading pulse with 0.1 s loading period and 0.9 s resting period was applied (AASHTO-T307, 2007). A triaxial cell was used with the UTM to carry out the RLT tests. During the tests, specimens were protected from the moisture change using a latex membrane. Resilient modulus ($M_R$) is the ratio of a repeated axial stress ($p_{rep}$) to the recoverable axial strain ($\varepsilon_r$) caused by the repeated load (Equation (1)):

$$M_R = \frac{p_{rep}}{\varepsilon_r} = \frac{p_{max} - p_{con}}{\varepsilon_r},$$  

where $p_{max}$ is the maximum applied vertical stress, and $p_{con}$ is the contact stress which is the vertical stress applied on the RLT specimen in order to keep the contact between the loading cap and the specimen.

Stiffness characteristics of the compacted samples were determined using the UCS test. Since the RLT test is a non-destructive test, same specimens were used for UCS tests. Conventionally, in the UCS test, only the ultimate strength is measured. In this research, however, the obtained results were used for the determination of other stiffness characteristics of the specimens, being Young’s modulus ($E$) and secant modulus ($E_{50}$). $E$ is the ratio of stress to strain on the strain curve at the elastic zone where the strains are recoverable. $E_{50}$ is the slope of the line drawn from the origin to stress that equals half of the UCS peak value on the stress–strain curve. These parameters are presented in Figure 3.

Lateral displacement was also measured to determine Poisson’s ratio ($\nu$) and to calculate constrained modulus (oedometric modulus ($E_{oed}$)). For this purpose, three linear variable differential transformers (LVDT) were installed laterally pointing at the mid-height of the specimen forming 120-degree angles. Poisson’s ratio controls the extent to which a sample can be compressed (Thom, 2008). It is defined as the ratio of lateral strain to axial strain under axial loading in the elastic zone of the axial stress–strain curve (Equation (2)).

$$\nu = \frac{\varepsilon_1}{\varepsilon_a},$$  

where $\varepsilon_l$ is the lateral strain and $\varepsilon_a$ is the axial strain. Lateral strain values used to calculate the Poisson’s ratio were obtained using the average values measured by the three lateral LVDTs. Poisson’s ratio relates the Young’s modulus to constrained modulus ($E_{oed}$). According to Hooke’s law $E_{oed}$ can be obtained using Equation (3):

$$E_{oed} = \frac{(1 - \nu)E}{(1 - 2\nu)(1 + \nu)}, \quad (3)$$

where $E$ is the Young’s modulus, and $\nu$ is the Poisson’s ratio. Values of $E_{oed}$ obtained from Equation (3) and those obtained from outcomes of the proposed constrained modulus approach are compared in the next section.

**Results and discussion**

**Yield stress of compacted samples**

The proposed constrained modulus testing approach aimed to determine yield stress of a specimen compacted through the modified Proctor method as the maximum stress that the specimen has experienced in the past. The obtained yield stress was then applied to compact a sample of the same material with the same moisture content, but using the static method. The aim was to investigate whether applying the obtained yield stress using the static method would result in a specimen with the MDD of modified Proctor procedure.

To verify the reliability of the above-mentioned approach, three samples were compacted under specific pressures of 2500, 3000 and 4000 kPa. These pressures were obviously the maximum stress the samples had experienced. In the next step the yield stress of these specimens was estimated using void ratio–pressure curves obtained from the constrained modulus testing approach. Figure 4 shows the void ratio–pressure curves obtained by conducting the proposed testing procedure on the compacted specimens.

Following the Casagrande (1936) method, the compression curves for CB and RCA presented in Figure 4 were analysed to obtain the yield stress values presented in Table 2. The table also shows the dry densities, as well as the percentage of difference between the compaction pressure and the calculated yield stress.
Figure 4. Void ratio versus vertical stress curves for samples compacted using static and modified Proctor methods.

Table 2. Densities and obtained yield pressures of CB and RCA compacted under specific static pressures.

| Material                  | Crushed brick | Recycled concrete aggregate |
|---------------------------|---------------|----------------------------|
| Compaction pressure (kPa) | 2500          | 2500                       |
|                           | 3000          | 3000                       |
|                           | 4000          | 4000                       |
| Obtained dry density (kg/m³) | 1772.9       | 1661.5                     |
|                           | 1837.4        | 1683.0                     |
|                           | 1850.2        | 1729.0                     |
| Obtained yield pressure (kPa) | 3583         | 3485                       |
|                           | 4398          | 3992                       |
|                           | 5508          | 5610                       |
| Percentage of difference from compaction pressure (%) | 43.3          | 39.4                       |
|                           | 46.6          | 33.1                       |
|                           | 37.7          | 40.3                       |

Results presented in Table 2 show that for the statically compacted samples, the yield stresses obtained are about 40% greater than the maximum pressure applied during compaction. Figure 4 also shows the compression curves for CB and RCA samples compacted using the modified Proctor method. Using the Casagrande (1936) method and the e-logp curves corresponding to impact compaction presented in Figure 4, the yield stresses for these specimens were determined to be 3140 and 3374 kPa for CB and RCA, respectively. Results presented in Table 2 suggest that the obtained yield stresses are about 40% greater than the maximum pressure experienced by specimens. For example, the RCA sample compacted under 2500 kPa static pressure resulted in a yield pressure of 3485 kPa (39.4% greater than 2500 kPa) following a one-dimensional compression and Casagrande (1936) procedure. Therefore, it is expected that the maximum equivalent static pressure that CB and RCA specimens, compacted with the modified Proctor compactor, experienced was 2243 and 2410 kPa, respectively. This is because yield pressures of 3140 kPa (40% greater than 2243 kPa) and 3374 kPa (40% greater than 2410 kPa) were obtained from Figure 4. Accordingly, it is expected that static pressures of 2243 and 2410 kPa result in the same dry density as MDD of modified Proctor compaction for CB and RCA, respectively. However, this conclusion is not supported by the experimental results. Static compaction of CB samples under 2250 kPa and RCA under 2400 kPa pressures results in dry densities less than 90% of their corresponding modified Proctor MDD. This suggests that the method of compaction impacts the mechanical properties of the compacted materials. Furthermore, the proposed procedure cannot predict the static pressure required for preparing a specimen with a dry density identical to MDD of modified Proctor method. In order to develop a better understanding, possible reasons such as differences in gradation curves caused by aggregate breakage during the compaction and consequent changes in suction forces were investigated. Then, stiffness and resilient characteristics
of specimens with the same dry density, but prepared using different compaction methods were compared.

**Constrained modulus of the compacted samples**

Constrained modulus or oedometric modulus \( (E_{\text{oed}}) \) is a parameter obtained from oedometer test. It is defined as the slope of stress–strain curve in geostatic condition (Feeser & Bruckmann, 1995) and is one of the input parameters for describing soil stiffness when the lateral strain is zero. Figure 5 shows the strain versus stress curves obtained from the incremental loading approach for samples compacted by the modified Proctor method and also under static pressures of 2500 and 4000 kPa.

It is apparent from Figure 5 that with changing stress level there is a stronger change in \( E_{\text{oed}} \) of modified Proctor specimen compared to those compacted under static pressure. In contrast to higher density of modified Proctor (impact) specimen, its \( E_{\text{oed}} \) is significantly lower at lower stress intervals, but gradually increases and becomes greater at higher stress intervals (3200–6400 kPa and 6400–12,800 kPa). Same pattern exists for both CB and RCA. This can be related to the different packing and structures developed in the specimens during static and impact compaction. Static specimens tend to have honeycomb structures in their body due to limited freedom of particle displacement during static loading, which is not the case in impact compaction procedure. This causes the formation of local particle arches with higher densities that show higher strength against static loading (i.e. oedometer loading), even though this type of structure tends to collapse easier under dynamic loads (Holtz et al., 1981). This is further supported by results of stiffness and resilient characteristics tests presented in the following sections. Values of \( E_{\text{oed}} \) are determined and presented in Table 3.

![Figure 5. Strain versus stress curves obtained from the proposed testing approach for (a) CB and (b) RCA.](image-url)
Table 3. Oedometric modulus of the compacted samples for different stress levels.

| Stress interval (kPa) | E<sub>oed</sub> for material and compaction types (kPa): |
|-----------------------|-------------------------------------------------------|
|                       | Static under 2500 kPa | Static under 4000 kPa | Modified Proctor |
|                       | CB | RCA | CB | RCA | CB | RCA |
| 25–50                 | 11,629 | 38,280 | 19,661 | 45,650 | 7575 | 5981 |
| 50–100                | 18,897 | 50,243 | 22,938 | 39,129 | 11,363 | 9570 |
| 100–200               | 33,594 | 48,680 | 39,321 | 49,800 | 18,180 | 16,888 |
| 200–400               | 54,973 | 63,222 | 61,167 | 73,040 | 27,270 | 25,520 |
| 400–800               | 100,783 | 105,332 | 100,091 | 121,733 | 36,976 | 45,936 |
| 800–1600              | 151,175 | 142,605 | 169,385 | 190,539 | 65,122 | 68,561 |
| 1600–3200             | 130,746 | 112,730 | 214,829 | 265,600 | 106,420 | 119,314 |
| 3200–6400             | 89,172 | 83,914 | 166,189 | 192,633 | 161,600 | 180,141 |
| 6400–12,800           | 138,217 | 127,696 | 156,587 | 134,326 | 239,079 | 240,188 |

Densities of the compacted samples

Samples compacted under a static pressure equal to yield stress of modified Proctor specimens (obtained from the proposed constrained modulus testing approach) do not achieve the MDD of modified Proctor procedure. Accordingly, a series of static compaction tests under several pressures were conducted in order to determine the pressure that results in the same density as the MDD of modified Proctor compaction. Densities of the samples compacted under several pressures, as well as those compacted using impact method, are presented in Tables 4 and 5, for CB and RCA, respectively.

Table 4. Results of series of compaction tests on CB.

| Compaction pressure (kPa) | 3000 | 4000 | 6000 | 8000 | 10,000 | 12,000 | Modified Proctor |
|--------------------------|------|------|------|------|--------|--------|------------------|
| Target moisture content (%) | 10.8 | 10.8 | 10.8 | 10.8 | 10.8   | 10.8   | 10.8             |
| Obtained moisture content (%) | 10.7 | 10.7 | 10.5 | 10.2 | 10.0   | 9.7    | 10.4            |
| MDD (kg/m³)              | 1817.3 | 1850.9 | 1911.2 | 1924.3 | 1933.5 | 1941.3 | 1989.9         |
| Void ratio               | 0.447 | 0.421 | 0.376 | 0.367 | 0.36   | 0.355  | 0.322          |
| Percentage of achieved MDD to Modified Proctor MDD (%) | 91% | 93% | 96% | 97% | 97% | 98% | 100% |

Table 5. Results of series of compaction tests on RCA.

| Compaction pressure (kPa) | 3000 | 4000 | 6000 | 8000 | 10,000 | 12,000 | Modified Proctor |
|--------------------------|------|------|------|------|--------|--------|------------------|
| Target moisture content (%) | 11.0 | 11.0 | 11.0 | 11.0 | 11.0   | 11.0   | 11.0             |
| Obtained moisture content (%) | 11.0 | 11.0 | 11.0 | 11.0 | 10.9   | 10.9   | 10.6            |
| MDD (kg/m³)              | 1733.1 | 1766.0 | 1801.3 | 1840.8 | 1879.5 | 1929.7 | 1959.6         |
| Void ratio               | 0.552 | 0.523 | 0.493 | 0.461 | 0.431  | 0.394  | 0.373          |
| Percentage of achieved MDD to modified Proctor MDD (%) | 88% | 90% | 92% | 94% | 96% | 98% | 100% |
The obtained densities/void ratios indicate that under the same compaction pressure, CB samples reach a higher density compared to RCA samples, as is the case in impact compaction. Tables 4 and 5 also show the percentage of MDD of samples compacted under different static pressures to modified Proctor MDD. Changes in relative densities by increasing the compaction pressure from 3000 to 12,000 kPa appear to be uniform for RCA (i.e. a 2% increase at each stress level). This change for CB specimens increases up to 3% at lower pressure levels (3000, 4000, and 6000 kPa) and increases up to 1% increase at higher pressure levels (8000, 1000, and 12,000 kPa).

Another observation is that with an increasing static compaction pressure, there is a decrease in the post-compaction moisture content of the statically prepared CB specimens. This occurs in the CB specimens that reach a degree of saturation of about 80% or more if they are wetted to the OMC of the modified Proctor method and compacted under static pressure (i.e. 6000 kPa and higher pressures). Under compaction pressure, the aggregates that are non-compressible cannot move; therefore, as the void ratio decreases, not only air, but also water is forced out of the sample. This results in a lower obtained water content in CB specimens, after static compaction, as the compaction pressure increases. However, this is not the case for RCA specimens. This can be attributed to the existence of cement particles in RCA blends that increases the water absorption, as well as the existence of fused particles in CB blends that tends to absorb less water. This can clearly be seen by observing the surfaces of CB and RCA particles using micrographs provided in the following sections. Interestingly water absorption of RCA has been reported to be 10% greater than that of CB (Arulrajah et al., 2013).

**Aggregate breakage during compaction**

A sieve analysis was conducted on CB and RCA samples before and after compaction. Figure 6 illustrates the changes in gradation curves before and after applying different compaction pressures, as well as impact compaction. The gradation curves show that aggregate breakage occurs even under lower compaction pressures, that is, 3000 or 4000 kPa. Figure 6 also shows that PSD of post-compaction static specimens under 12,000 kPa pressure almost coincides with that of modified Proctor specimens with slight differences.

Breakage results in changes in gradation curves and consequently pore network of material. Tables 6 and 7 show changes in gradation parameters, such as $C_u$ and mean aggregate size ($D_{50}$), before and after compaction for CB and RCA, respectively.

As evident from Tables 6 and 7, the extent of breakage is different under different static pressure levels. Even though, it can be observed from Figure 6 that the difference in fine contents, before and after compaction, is not significant. Breakage due to compaction turns gravel particles into sand particles, but it does not increase the percentage of particles smaller than 75 μm. The extent of breakage also slightly differs between specimens prepared by static (under 12,000 kPa pressure) and impact methods. These differences may be one of the reasons responsible for the different characteristics of samples compacted with different compaction methods.

**Changes in soil–water characteristics**

Since the determination of SWCC in the laboratory or field is challenging and often expensive, predictive models, such as Arya and Paris (1981), Aubertin, Mbonimpa, Bussières, and Chapuis (2003), and Likos and Jaafar (2013) among others, are developed to estimate the SWCC using basic geotechnical properties of a material. In order to investigate the effect of type of compaction and the resulted breakage on SWCC, the predictive model of Aubertin et al. (2003) was implemented using the PSD of post-compaction material. This model was selected since its input data
Figure 6. Changes in gradation curves, before and after the compaction for (a) CB and (b) RCA.

were available for the present study. Aubertin et al.’s (2003) model predicts SWCC of materials using the basic and easy-to-obtain geotechnical properties. This model is applicable for both fine-grained and granular materials. In case of granular materials, the model requires void ratio, $D_{10}$, $D_{60}$, and $C_u$. These parameters were presented in Tables 6 and 7 for CB and RCA, respectively. Then the link between degree of saturation and suction (SWCC) is obtained through Equations (4–6):

$$S_r = S_c + S_a^a(1 - S_c),$$

where $S_c$ is a function of equivalent capillary rise ($h_{co}$), coefficient of uniformity ($C_u$), and suction ($\psi$), and $S_a^a$ is a function of adhesion coefficient ($a_c = 0.01$ for granular materials), void ratio ($e$), residual suction ($\psi_r$), suction in complete dryness ($\psi_0 \approx 10^6$ kPa), $\psi$ and $h_{co}$. Values of $h_{co}$ and
Table 6. Changes in gradation parameters before and after compaction for CB.

| Compaction type | Before compaction | Static compaction under: | Modified Proctor |
|-----------------|-------------------|---------------------------|------------------|
|                 |                   | 3000 kPa  | 4000 kPa  | 6000 kPa  | 8000 kPa  | 10,000 kPa | 12,000 kPa |
| $D_{10}$ (mm)   | 0.20              | 0.16       | 0.17       | 0.15       | 0.17       | 0.16       | 0.15       | 0.18       |
| $D_{50}$ (mm)   | 4.47              | 3.87       | 3.37       | 3.23       | 3.15       | 2.89       | 2.67       | 2.65       |
| $D_{60}$ (mm)   | 6.90              | 6.47       | 5.60       | 5.38       | 5.56       | 5.17       | 4.92       | 4.62       |
| $C_u = $        | 34.60             | 39.90      | 33.70      | 35.70      | 33.50      | 32.10      | 32.70      | 26.30      |
| Change in $D_{50}$ (%) | - | 13.5% | 24.6% | 27.8% | 29.6% | 35.3% | 40.3% | 40.7% |

Table 7. Changes in gradation parameters before and after compaction for RCA.

| Compaction type | Before compaction | Static compaction under: | Modified Proctor |
|-----------------|-------------------|---------------------------|------------------|
|                 |                   | 3000 kPa  | 4000 kPa  | 6000 kPa  | 8000 kPa  | 10,000 kPa | 12,000 kPa |
| $D_{10}$ (mm)   | 0.25              | 0.20       | 0.22       | 0.22       | 0.21       | 0.22       | 0.20       | 0.20       |
| $D_{50}$ (mm)   | 5.02              | 4.15       | 3.76       | 3.51       | 3.45       | 3.45       | 3.43       | 3.36       |
| $D_{60}$ (mm)   | 7.25              | 6.33       | 5.84       | 5.75       | 5.63       | 5.60       | 5.58       | 5.57       |
| $C_u = $        | 28.80             | 31.00      | 26.80      | 25.80      | 27.30      | 25.10      | 28.20      | 28.40      |
| Change in $D_{50}$ (%) | - | 17.2% | 25.1% | 30.1% | 31.2% | 31.3% | 31.6% | 33.0% |
\( \psi_r \) for granular materials are obtained from Equations (5) and (6), respectively.

\[
h_{co} = \frac{0.75}{eD_10(1.17 \log(C_u) + 1)}, \quad (5)\]

\[
\psi_r = 0.86h_{co}^{1.2}. \quad (6)
\]

Figure 7 shows the SWCCs of the CB and RCA specimens obtained from the Aubertin et al.'s (2003) model. SWCCs of CB and RCA show that generally increasing the compaction pressure results in higher values of suction for an equal degree of saturation. This occurs due to the formation of smaller pore sizes which is the result of breakage and/or higher compaction energy that generates denser specimens (i.e. smaller pores). Also, generally in both CB and RCA, for a specific degree of saturation, the amount of suction in modified Proctor specimens was greater than that of static specimens.

The section of the curves between 90% and 100% saturation is magnified in Figure 7 for a clearer observation of the influence of compaction approach on the SWCC. This section of the curves, close to the fully saturated condition, is used for determination of the air entry value (AEV). The AEV is the suction value that must be reached before air is introduced into the soil.
pores (Fredlund & Xing, 1994). This is the point where desaturation begins and the behaviour of the soil should be investigated in the unsaturated context. The AEV of CB samples compacted under 3000 kPa, 12,000 kPa pressure and modified Proctor effort were 0.30, 0.46, and 0.48 kPa, respectively. These values for RCA were 0.25, 0.39, and 0.41 kPa, respectively.

Results presented in Tables 4 and 5 show that the pressures from 3000 to 12,000 kPa result in relative densities between 91% and 98% for CB and 88% and 98% for RCA, by taking the MDD modified Proctor method as reference. However, the relative AEV of the CB specimens prepared using static method was between 62% and 96% by taking the AEV of the specimen compacted using modified Proctor method as reference. The relative AEV for RCA specimens was in the range of 62–95%. This shows that for a relatively small variation in density (about 10%) there is a quite significant change in the AEV of specimens (more than 30%). Also, for modified specimens and static specimens compacted under 12,000 kPa which are almost identical in density and have very similar PSD curves, the AEV was found to be different. This implies that in C&D material, in addition to density (void ratio) and aggregate breakage, different packing structures caused by different compaction methods influence the formation and size of the pores and consequently suction forces. This in fact contributes to changes in the AEV (and generally, changes in suction values) and for studying the influence of compaction on SWCC of soils, as well as the subsequent field behaviour under environmental and external loadings, this factor should be taken into account.

Nevertheless, this should be noted that possible errors in the estimation of SWCC due to model uncertainty can occur. This is important in this case where there is not a significant difference between post-compaction PSD of modified specimens and static specimens compacted under 12,000 kPa pressure. Hence, further justification of this through validation of the predicted SWCC by experiments is planned for next stage of this research work.

**Stiffness characteristics**

UCS test is the most common test for determining the pavement design parameters, due to its simplicity and the fact that it needs minimum laboratory facilities to be carried out (Piratheepan, Gnanendran, & Lo, 2010). Figure 8 illustrates the stress–strain curves obtained from the UCS tests. Generally, RCA specimens show greater UCS compared to CB specimens. The interesting point is that even though specimens of each type of C&D material have the same densities, those prepared by static compaction result in greater UCS peak values. This indicates that the type of
compaction influences the stiffness of compacted samples with the same density. This can be related to the fact that each compaction method results in development of different structures in the specimens. In unbound granular materials, the packing arrangement which is to a great extent controlled by the PSD influences the mechanical behaviour of granular materials (Santamarina & Cho, 2004). Effect of aggregate packing on potential for permanent deformation (Yideti, Birgisson, Jelagin, & Guarin, 2013), resilient behaviour (Yideti, Birgisson, Jelagin, & Guarin, 2014), and California bearing ratio (Yideti, Birgisson, & Jelagin, 2014) are approved through theoretical and experimental research and analysis.

In the static procedure, compaction energy is uniformly distributed on top of each layer resulting in specimens with more uniform structures. However, limited feasibility of particle displacement and slipping under constant static pressure during compaction causes stress concentration in some parts of the specimens. This results in the formation of honeycomb-like structures in the specimens compacted with the static method. In this case, even though, the overall density of static specimens is identical to that of impact specimens, local high density and local low density parts form in the body of the static specimens. Figure 9(a) and (b) shows a schematic of compacted specimen structures inspired by the simple procedure mentioned in Holtz et al. (1981). In both Figures 9(a) and 7(b), three particles sizes, each with equal numbers in both frames are drawn and arranged. This means that both soil specimens shown in Figure 9(a) and (b) are identical in PSD (i.e. identical density), but different in the arrangement of particles (i.e. different aggregate packing).

As evident from Figure 9(b), in static specimens a denser arch-like skeleton is formed that can show higher strength against static loads in one direction. This type of structure is stable under static loads (Holtz et al., 1981). In this case, due to higher local density around these arch-like structures that carry the majority of the applied load, higher UCS values were expected (Table 8). This is illustrated in Figure 9 by including the potential force chains, in which thickness of the lines represents the magnitude of the force. More uniform distribution of density in Figure 9(a) results in more particles contributing to distributing the loads, and accordingly thinner chain force lines. Greater force chain means higher aggregate interlock, which results in higher strength in the direction of static loading, as is the case for static specimens in UCS testing. The response of impact and static specimens under dynamic loads is reported and discussed in the next section.

Values of $E$, $E_{50}$ and Poisson’s ratio for the compacted samples are presented in Table 8. Using Equation (1) and applying the values of $E$ and $v$, values of $E_{oed}$ are calculated and presented in Table 8.
Table 8. Stiffness characteristics derived from UCS tests for CB and RCA.

| Material | CB | RCA |
|----------|----|-----|
|          | Modified Proctor | Static under 12,000 kPa | Modified Proctor | Static under 12,000 kPa |
| Specimen dry density (kg/m³) | 1967.3 | 1952.8 | 1934.7 | 1928.1 |
| Specimen moisture content (%) | 10.3 | 10 | 10.4 | 10.5 |
| UCS peak value (kPa) | 309.5 | 358.5 | 441.0 | 539.7 |
| $E$ modulus (kPa) | 38,866 | 29,401 | 58,147 | 50,621 |
| $E_{50}$ modulus (kPa) | 32,896 | 20,425 | 50,425 | 49,491 |
| Poisson’s ratio | 0.37 | 0.39 | 0.26 | 0.30 |
| $E_{oed}$ modulus (kPa) | 8895 | 6406 | 17,075 | 13,509 |

Values of $E_{oed}$ were earlier calculated using the void ratio versus vertical pressure curves and presented for several stress levels in Table 3. A comparison between the $E_{oed}$ of Table 3 and the values presented in Table 8 shows that they are very similar at stress levels of 100–200 kPa, and 200–400 kPa. Interestingly, these are approximately the stress levels at which Poisson’s ratios were calculated and used in Equation (1) to calculate the $E_{oed}$. This suggests a correlation between the proposed testing approach and the UCS test for the determination of the $E_{oed}$.

Table 8 also presents the variation of stiffness parameters for specimens compacted by static and impact methods, even though the dry densities of the specimens were the same. This observation further illustrates the impact of the compaction method on stiffness characteristics of compacted granular C&D specimens.

**Resilient characteristics**

Resilient modulus ($M_R$) is one of the basic stress–strain relationships required for structural analysis and design of pavement layers subjected to moving wheel loads. However, in none of the research works carried out in this area the influence of compaction method on this characteristic of granular pavement materials has been considered. In this research, specimens of CB and RCA were compacted to their corresponding modified Proctor MDD, using static and modified Proctor methods and undergone RLT tests in accordance with the AASHTO-T307 (2007) procedure.

![Resilient modulus results for CB.](image-url)
Figures 10 and 11 illustrate the results of resilient modulus tests, respectively on CB and RCA, in the form of resilient modulus versus maximum axial stress. The average values of $M_R$ for CB specimens prepared by static and modified Proctor methods were 132.0 and 241.7 MPa, respectively. These values for RCA were respectively, 196.5 and 255.8 MPa. This shows up to approximately 80% difference in $M_R$ values obtained for samples compacted using different methods.

It can be observed from Figures 10 and 11 that regardless of type of C&D material, prepared using both compaction methods, greater confinement stress results in higher resilient moduli. Such a behaviour was explained by Puppala, Hoyos, and Potturi (2011) as to be attributed to the increased densification or stiffness of specimens as the confinement increases. However, in this research, specimens have evidently experienced significantly higher pressure, by more than 10 times, during the compaction procedure compared to changes in confining pressure from 20.7 to 103 kPa. Therefore, minor changes in confining stress cannot densify the specimens further significantly. The increasing $M_R$ value may also be related to aggregate interlock. Higher confining pressure brings about greater aggregate interlock, resulting in lower strain under the same axial loading. Figures 10 and 11, also, show that for specimens prepared using both compaction methods, as the deviatoric stress increases in each confinement level $M_R$ values increase. This may be due to stress hardening, which is a phenomenon that makes the materials stronger with each cycle of deviatoric loading (Puppala et al., 2011). However, as Figures 10 and 11 show, changes in deviatoric stress have much less influence on $M_R$ values compared to changes in confining stress, both in impact and static specimens. In other words, the magnitude of deviator stress is less influential on resilient modulus of the specimens compared to confining stress. This was also observed in results reported in Hicks and Monismith (1971) and Lekarp, Isacsson, and Dawson (2000).

More importantly, as shown in Figures 10 and 11, impact compaction results in specimens with greater resilient moduli for each type of material compared to specimens compacted under static pressure. Interestingly, UCS values show that static compaction results in specimens with greater UCS peak values (Table 8). This behaviour may be related to the structure of the specimens after static or impact compactions. As discussed in the previous section, in the static method honeycomb-like structures are formed which show higher strength under static loads, that is, higher UCS peak values. These structures are known to be meta-stable, that is, stable under static loads but susceptible under vibration or dynamic loads (Holtz et al., 1981). Static specimens of this research show higher recoverable strain, and accordingly, lower resilient
modulus. This is supported by the fact that these specimens showed lower Young’s modulus, that is, the slope of the stress–strain curve where the soil is acting elastically and the strains are recoverable (Table 8). This means that at a specific stress, lower recoverable strain occurs for specimens prepared by the impact method, compared to those prepared by the static method. Evidently, the same repeated axial strain that results in lower recoverable strain leads to higher $M_R$ values.

In terms of C&D material type, average values of $M_R$ suggest that generally, for specimens prepared under same compaction method and regime, RCA specimens show greater values of resilient modulus compared to CB specimens. This can be related to the fact that RCA particles have higher roughness compared to CB particles. Aggregates with particles of higher roughness values are known to result in higher resilient modulus (Barksdale & Itani, 1989; Lekarp et al., 2000). Scanning electron microscopy (SEM) was used for a better observation of the RCA and CB particles. Examples of micrographs of CB and RCA particles are shown in Figure 12. Figure 12(a) and (d) shows micrographs of CB and RCA particles, respectively, with magnification of 1000 ×. Figure 12(b) and (c) shows 8000 × magnified micrographs of areas with smooth surface and rough surface on a CB particle, respectively. Figure 12(e) and (f) shows 8000 × magnified micrographs of an RCA particle’s surface, both of which show a rough surface. To ensure that the surface is not covered with dust and loose mortar, both CB and RCA particles were washed and dried before SEM tests. Observing micrographs of CB and RCA particles indicated that RCA particles almost entirely have a rough surface, whereas CB particles have areas with both rough and smooth surfaces. The smooth surface in CB is due to the existence of fused particles of CB. Rougher surface of the RCA particles is in part related to the presence of mortar and finer particles bound to the mortar around RCA granules.

Generally, the above-mentioned resilient behaviours suggest two points. First, specimens with same densities prepared using different compaction methods result in very different resilient characteristics. Second, higher stiffness does not necessarily result in higher $M_R$ when specimens are prepared using different methods of compaction. In other words, the influence of the compaction method needs to be taken into account when the resilient characteristics of granular material are investigated. This is due to the fact that it affects the applicability of mechanical characteristics obtained in laboratory environment for designing and predicting the performance of pavement material compacted in the field using common field compaction machinery.

Figure 12. Micrographs of (a, b, and c) CB particles, and (d, e, and f) RCA particles.
Conclusion

In this research, a testing procedure was proposed to generate a link between two types of popular compaction methods, being static method and impact method (modified Proctor). Since the testing approach did not suggest a correlation between these methods, several physical and mechanical characteristics of specimens prepared by static and impact methods were investigated. The following conclusions can be drawn from this research, for specimens prepared with the same density but using different compaction methods:

(1) At the same dry density, post-compaction PSDs of impact and static specimens were almost identical.

(2) Based on outcomes of the Aubertin et al.’s (2003) model, SWCC of the specimens was not affected significantly by type of compaction, once the same density was achieved. However, small changes in density caused significant changes in suction values.

(3) Stiffness and resilient characteristics of compacted samples are highly influenced by the type of compaction, due to the difference in the formation of specimens’ packing structure during the compaction procedure. When different methods of compaction are applied, higher UCS peak values does not necessarily result in higher resilient modulus. Static specimens showed greater UCS peak values, but lower resilient modulus.

(4) For the same method of compaction, RCA specimens showed greater stiffness and greater resilient modulus, as a result of rougher surface of RCA particles.

(5) The constrained moduli obtained from the proposed testing procedure, showed correlation with those obtained using UCS results.

(6) Nature of the compaction procedure plays an important role on the soil–water, stiffness, and resilient characteristics of the prepared specimens. Different methods of compaction develop specimens with different structures during densification, in spite of identical densities. Hence, taking a target dry density for sample preparation and ignoring the method of compaction is a misleading approach, especially when the simulation of the field condition is intended in laboratory testing.

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