1. Introduction

Construction and demolition waste is generated in large amounts in medium and large-sized cities in Brazil. According to Schneider [1], in the year 2003 about 16,000 tons of solid wastes from civil construction were produced daily in São Paulo – the largest Brazilian city – representing 50% of the overall solid waste. Furthermore, only about one third of this material was delivered to the public landfills, while the rest was disposed of illegally.

Researches confirm that construction and demolition waste has a great potential to be reused as aggregate in road construction [2–5]. The aggregate from recycled construction and demolition waste (RCDW) is an attractive alternative material for bases and sub-bases due to its high resistance and its non-expansive behavior [6,7]. However, the quality of the recycled materials varies considerably and is quite difficult to control [8]: some proper guidelines on the production and application of these aggregates are needed [9–11].

The purpose of this paper is to evaluate the feasible use of RCDW aggregate in pavement applications, mainly as base and sub-base material in low-volume roads. The recycled material is characterized under standard laboratory tests and evaluated by repeated load triaxial tests. Besides, the effect of the compactive effort on its physical and mechanical properties is analyzed. The following tests were carried out: water absorption, grain-size distribution, grain shape, California bearing ratio (CBR), resilient modulus and permanent deformation. The conclusions and some recommendations about the use of RCDW aggregates in road construction are presented.

2. RCDW as pavement aggregate

Demolition debris has been significantly recycled since the end of the Second World War [12]. However, studies about its physical properties, mechanical behavior and durability are quite recent.

In Britain, O’Mahony and Milligan [9] studied the possibility of using crushed concrete and demolition debris as sub-base coarse aggregate. CBR experiments were conducted and the behavior of the recycled materials was compared with the behavior of limestone. The results showed that CBR of crushed concrete was similar to that of natural aggregate. Conversely, demolition debris presented a fairly decrease in its CBR. Bennert et al. [3] analyzed the performance of recycled concrete aggregate in base and sub-base applications. The authors concluded that a blended mixture of 25% of recycled concrete aggregate with 75% of natural aggregate would obtain the same resilient response and permanent deformation properties as a dense-graded aggregate base coarse, currently used in base and sub-base layers.

Molenaar and van Niekerk [8] studied the influence of composition, gradation and degree of compaction on mechanical characteristics of crushed concrete and crushed masonry in the Netherlands.
The results demonstrated that although the composition and gradation have an influence on the mechanical characteristics of the recycled materials, the degree of compaction is clearly the most important factor.

Motta [4] studied the mechanical behavior of RCDW aggregates from São Paulo. The results indicated an increase in the resilient modulus over time. In order to verify the pozzolanic activity of this recycled material, the modified Chapelle test was carried out. The results demonstrated the existence of non-inert cement particles in the RCDW aggregate, which improved the performance of the recycled material.

In 2004, the first Brazilian standard procedure about the RCDW aggregate application in pavements was published (NBR 15115 [13]). This standard proposes the use of this recycled material as base and sub-base layers for low-volume roads and considers the CBR as the main parameter to design. A summary of suggested limits for the selection of RCDW aggregates is presented in Table 1.

3. Material

A typical Brazilian construction and demolition waste is a mixture of ceramic, concrete blocks, mortar, reinforced concrete, steel, plastic, asbestos cement and wood [14]. Recycling this material so as to obtain the RCDW aggregate requires a well planned production procedure, in which sorting, separation, size reduction, and sieving are important steps in the complete process.

The recycled material investigated in this research derives from a recycling plant located in the São Paulo metropolitan region. This recycling plant uses a hammer crusher to produce RCDW aggregates particularly and its nominal capacity is about 80 tons/h. There is no systematic control of the arriving material, that consists mainly of construction and demolition waste. However, visual inspection, manual pre-sorting and magnetic separator are used so as to remove the undesirable materials (such as asbestos cement, wood, plastic, paper and metals). For this study, a representative sample of about 2 tons of RCDW aggregate was used for the laboratory evaluation.

4. Physical characteristics

4.1. Composition

In order to determine the composition of the RCDW used in this study, the coarse aggregate – fraction retained on the 4.75 mm sieve – was examined by visual analysis. The RCDW aggregate was separated into four main groups: (i) cementitious materials (the major component of the RCDW aggregate, comprised mainly of concrete and mortar), (ii) highly porous ceramic materials (bricks and roof tiles), (iii) less porous ceramic materials (ceramic tiles), and (iv) crushed rocks, as indicated in Table 2, and illustrated in Fig. 1. The undesirable materials occur in very small proportions, in accordance with the Brazilian standard as presented in Table 1, and were negligible in this work.

4.2. Water absorption

The coarse aggregates were separated into groups in accordance with its composition in order to determine the water absorption. The test procedure followed the American specification ASTM C127 and the results are presented in Table 2.

According to the Federal Highway Administration (FHWA) [15] recycled concrete materials have rougher surface texture, lower specific gravity, and higher water absorption when compared with virgin aggregates of the same size, enhancing the adhesion of mortar to the aggregates incorporated in the concrete. The group of cementitious materials used in this research followed the same trend as reported by FHWA and also presented high value of water absorption. The same was observed in the less porous ceramic materials. The highly porous ceramic group showed the highest value when compared to the other studied groups. By a weighted average, it was verified that the water absorption of the RCDW aggregate was 12.2%, mostly dependent on the occurrence of highly porous ceramic materials.

4.3. Grain shape

This test was carried out according to the Brazilian standard NBR 6954 in order to determine the percentage of cubic, flat or elongated particles. The aggregate fractions retained in the 4.75 mm sieve were divided into groups by visual characterization according to their nature. A digital slide calliper was used for measuring thickness, width and length of each particle. The classification of grain shape was made using the relations among three measurements (length, width, and height). The results are summarized in Table 2.

Fig. 1. Illustration of the four main groups of the RCDW aggregate evaluated: (a) cementitious materials, (b) highly porous ceramic material, (c) less porous ceramic material, and (d) crushed rocks.
5. Compaction tests and particles breakage

5.1. Compaction tests (proctor)

To evaluate the effect of compaction effort on the RCDW aggregate properties, two distinct proctor energies were applied: intermediate and modified. The intermediate effort corresponds approximately to 50% of the modified effort and is widely used for sub-bases in the Brazilian specifications. The laboratory compaction tests were carried out based on the American standard procedure (ASTM D1557).

The literature reveals the difficulty in obtaining a compaction curve for recycled materials [8,9]. The RCDW sample was well split and the distribution of grains, according to the dimension and nature, was kept similar for each specimen, allowing the obtaining of typical compaction curves at both compaction efforts (Fig. 3). The values of optimum moisture content and maximum dry density indentified were 13.5% and 18.2 kN/m² for modified effort, and 14.6% and 17.6 kN/m² for intermediate effort.

5.2. Particles breakage

The RCDW aggregate evaluated in this study presents abrasion of 51.5%, according to the Los Angeles test method (ASTM C 535-09). In order to evaluate its breakage process, the grains shape of specimens compacted with intermediate and modified efforts were compared with the grains shape before compaction. A tripartite-cylinder with 150 mm diameter and a 300 mm height was used (Fig. 4). Table 3 presents the percentages of each grain shape classification before compaction and after intermediate and modified efforts.

The cubic grains represented the majority in the three cases evaluated, due to the high occurrence of cementitious materials. Moreover, it is clear that after compaction, the percentage of cubic grains increases. By analogy, flat and elongated grains decrease. Although the small number of elongated particles, the reduction of this shape group was remarkable after compaction. No significant changes in shape were observed between intermediate and modified effort and one can conclude that most of the breakages occur at the beginning of compaction, when the material is not yet densified and the mobility of the particles is facilitated.

Similarly to the grain shape, the gradation was analyzed for the RCDW aggregates in three different stages: before compaction and after intermediate and modified efforts. As illustrated in Fig. 2, the compaction process broke partially the particles, resulting in finer size-distribution curves. The change in gradation was more pronounced at the beginning of the compaction process, mostly on the coarse fraction, such as 38 and 25 mm. When the modified effort was applied, the breakage continued, but less intensively because of an increase in the interlocking degree. The increase in the amount of fine particles was produced by the breakage of coarse grains and by the friction between particles during the compaction process.

This result indicates the importance of an adjusted compactive effort so that the particle breakage happens during the construction and not along the pavement life. It is important to point out that in the field this breakage process would probably be larger compared to laboratory, since the use of cylinder causes a restriction in the particles mobility. The change in the grain-size distribution contributes to a better densification of the RCDW aggregate that will probably imply in less permanent deformation. Hence, the moisture content must be rigorously controlled in the field, with the possible need to be increased during the compaction process.

### Table 1
Summary of the Brazilian standard for the selection of RCDW aggregates for pavement application.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Specified limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undesirable materials</td>
<td></td>
</tr>
<tr>
<td>Same origin</td>
<td>≤2.0%</td>
</tr>
<tr>
<td>Different origin</td>
<td>≤3.0%</td>
</tr>
<tr>
<td>Grain shape</td>
<td></td>
</tr>
<tr>
<td>% Flat grains</td>
<td>≤30%</td>
</tr>
<tr>
<td>Gradation</td>
<td></td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>63.5 mm</td>
</tr>
<tr>
<td>Cu (uniformity coefficient)</td>
<td>≥10</td>
</tr>
<tr>
<td>% passing on sieve 0.42 mm</td>
<td>100 ≦ x ≦ 40%</td>
</tr>
<tr>
<td>CBR</td>
<td></td>
</tr>
<tr>
<td>According to the layer</td>
<td></td>
</tr>
<tr>
<td>Base: ≥60%⁵</td>
<td></td>
</tr>
<tr>
<td>Sub-base: ≥20%</td>
<td></td>
</tr>
<tr>
<td>Swelling</td>
<td></td>
</tr>
<tr>
<td>According to the layer</td>
<td></td>
</tr>
<tr>
<td>Base: &lt;0.5%⁵</td>
<td></td>
</tr>
<tr>
<td>Sub-base: &lt;1.0%</td>
<td></td>
</tr>
</tbody>
</table>

⁵ Only for low-volume roads (N < 10⁶).

### Table 2
Physical characteristics of RCDW aggregates.

<table>
<thead>
<tr>
<th>Group material</th>
<th>Occurrence by weight (%)</th>
<th>Water absorption (%)</th>
<th>Grain shape</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cubic (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flat (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Elongated (%)</td>
</tr>
<tr>
<td>Cementitious materials</td>
<td>55</td>
<td>11.5</td>
<td>83.5</td>
</tr>
<tr>
<td>Highly porous ceramic materials</td>
<td>16</td>
<td>20.7</td>
<td>37.0</td>
</tr>
<tr>
<td>Less porous ceramic materials</td>
<td>14</td>
<td>11.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Crushed rocks</td>
<td>12</td>
<td>3.8</td>
<td>82.1</td>
</tr>
<tr>
<td>Undesirable materials</td>
<td>3</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 3
Changes in shape of RCDW aggregates.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Before compaction (%)</th>
<th>After intermediate effort (%)</th>
<th>After modified effort (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic</td>
<td>55.7</td>
<td>68.0</td>
<td>69.0</td>
</tr>
<tr>
<td>Flat</td>
<td>38.8</td>
<td>29.0</td>
<td>29.0</td>
</tr>
<tr>
<td>Elongated</td>
<td>5.5</td>
<td>3.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
6. Mechanical properties

6.1. California bearing ratio

The CBR was conducted according to ASTM D1883. Eight specimens of RCDW aggregate were compacted using the moisture contents defined previously (four at intermediate effort and four at modified effort).

The results indicated average CBR of 73% and 117% for intermediate effort and modified effort, respectively. The bearing capacity of the RCDW aggregate gets higher, when the compactive effort increases. CBR is usually a dispersive test with a fairly difficult
repeatability, but despite the variation in the results (coefficient of variation of 19% and 22% for intermediate effort and modified effort, respectively), the CBR for the modified effort was approximately 60% higher compared to the intermediate effort. The average result obtained for the RCDW aggregate compacted at the modified effort is comparable to a high quality well-graded crushed stone material.

According to the Federal Highway Administration [15] typical CBR values for recycled concrete aggregates are between 94% and 148%. As specified by the Brazilian standard procedure [13], the RCDW aggregate must reach a CBR value of at least 60%, and the swelling is limited to 0.5%, in order to be used as a base layer for low-volume roads. The swelling measured was null after soaking in tap water for 4 days for all specimens of RCDW aggregate investigated. Thus, the studied material fully complies with the Brazilian standard, for both compactive efforts. However, it is also important to analyze the response of the RCDW aggregate under repeated loading.

6.2. Resilient modulus

The resilient behavior was determined by a repeated load test, based on the AASHTO TP46 specification for soils and aggregate materials. The AASHTO bulk stress model is expressed as follows:

\[ M_R = k_1 \theta^k_2 \]  
\[ \theta = \sigma_d + 3 \sigma_3 \]

where \( M_R \) is the resilient modulus (MPa); \( k_1, k_2 \) the material parameters based on laboratory results; \( \theta \) the bulk stress (MPa); \( \sigma_d \) the deviatoric stress (MPa); \( \sigma_3 \) is the confining stress (MPa). For the resilient modulus tests, two specimens were compacted at intermediate effort and two at modified effort. The RCDW aggregate was compacted using the optimum moisture contents and the samples obtained were 150 mm in diameter and 300 mm in height. After compaction, the specimens were allowed to cure for a period of four days before testing so as to homogenize its moisture content and avoid the loss of water. The equipment used for this experiment is illustrated in Fig. 5.

As illustrated in Fig. 6, the resilient modulus of the RCDW aggregate increases with the increment of the proctor energy. For the intermediate effort, the resilient moduli vary between 160 and 440 MPa, and for the modified effort between 200 and 500 MPa, depending on the bulk stress. Consequently, using a more intensive compaction effort, the resilient displacement of the RCDW aggregate can be reduced from 10% to 20%. The increment observed in the resilient modulus was not expressive as that in the CBR test. Although the same compaction energy was used in both experiments, some facts may have contributed to the different increment observed, as follows: (i) the CBR specimens may not be sufficiently representative of the original material as the resilient modulus specimens. The CBR standard procedure limits the maximum aggregate size, while the resilient modulus allows the use of the same gradation used in the field; (ii) the confinement stress in the CBR test is not representative of the confinement stress observed in the field as the one applied in the resilient modulus, and (iii) the displacements measured in the resilient modulus test are in the elastic region, but the same is not observed in the CBR.

The resilient behavior of the recycled material was also compared to standard road aggregates. The well-graded crushed stone regression model obtained by Rada and Witczak [16] presented resilient modulus between 165 and 420 MPa (with the bulk stress varying from 0.1 MPa to 0.8 MPa). Nataatmadja and Tan [17] presented the regression models for recycled concrete aggregate. The resilient modulus varied between of 160 and 550 MPa, for the same bulk stress condition previously mentioned. Based on these results, it is possible to conclude that the resilient modulus of RCDW aggregate and of recycled concrete aggregate obtained in laboratory are similar to that expected for crushed stone. According to Bennert et al. [3], recycled materials can present higher values of resilient modulus than natural material currently used in pavement construction. This is probably explained by the higher angle of internal friction in this type of material, which contributes to improve the shear resistance. Molenaar and van Niekerk [8] observed angle of internal friction around 40° for recycled unbound materials, what contributes to the improvement of the shear resistance.

6.3. Permanent deformation

Repeated load triaxial tests are often used to predict the permanent deformation of soils and granular materials [18]. These
experiments allow the analysis of the relationship between the number of loading cycles and the accumulated permanent strain in the specimen.

Repeated load triaxial tests were conducted in cylindrical specimens (150 mm in diameter and 300 mm in height) to evaluate the influence of compaction energy on the permanent deformation of the RCDW aggregate specimens (compacted at intermediate and modified efforts). The tests were conducted up to 180,000 cycles and submitted to a deviatoric stress of 300 kPa and a confining stress of 50 kPa, \( \frac{\sigma_d}{\sigma_3} = 6.0 \) (this ratio is usually smaller than 10.0 [8]). This stress level was obtained by backcalculation of a pavement structure and it simulates the response of the base and sub-base layers.

As can be seen in Fig. 7, for the same stress level \( \frac{\sigma_d}{\sigma_3} = 6.0 \), the RCDW aggregate compacted at the modified effort presented, after 180,000 cycles, presented permanent deformation approximately 10% smaller than at the intermediate effort (3.867 \( \times \) \( 10^{-3} \) mm/mm and 4.283 \( \times \) \( 10^{-3} \) mm/mm, respectively). The results corroborate the importance of compacting the RCDW aggregate at higher energy, in order to improve its mechanical response.

The exponential model reported by Monismith et al. [19] was used to predict permanent deformation:

\[
\varepsilon_p = aN^b
\]  

where \( \varepsilon_p \) is the accumulated permanent strain \( (10^{-3} \text{ mm/mm}) \); \( a \) the permanent deformation of the first cycle \( (10^{-3} \text{ mm/mm}) \); \( N \) the number of loading cycles; \( b \) is the slope of the least-square regression analysis. The exponential model presented coefficients of determination above 97\% (Table 4).

Further tests were conducted using specimens of RCDW aggregate compacted with modified effort, in order to evaluate potential gain in resistance. The specimens were subjected to four test conditions: (i) deviatoric stress of 100 kPa and confining stress of 50 kPa, \( \frac{\sigma_d}{\sigma_3} = 2.0 \); (ii) deviatoric stress of 200 kPa and confining stress of 50 kPa \( (\sigma_d/\sigma_3 = 4.0) \); (iii) deviatoric stress of 300 kPa and confining stress of 50 kPa \( (\sigma_d/\sigma_3 = 6.0) \); (iv) deviatoric stress of 500 kPa and confining stress of 75 kPa \( (\sigma_d/\sigma_3 = 6.7) \). The tests were again carried out up to 180,000 cycles and the results were analyzed using the shakedown concept applied to pavements defined by Sharp and Booker [20]. The shakedown consists in a process of adjustment, where after a certain number of load cycles no further permanent strains develop and the material responds elastically. Werkmeister et al. [21] observed three types of permanent strain accumulation using the shakedown concept:

- Range A (plastic shakedown range): the material has a plastic response for a finite number of load applications, but after the postcompaction period, the response becomes resilient and no further permanent deformation occurs.

\[Fig. 6. \text{Resilient modulus results for the RCDW aggregate.}\]  

\[Fig. 7. \text{Permanent deformation results for the RCDW aggregate.}\]
– Range C (incremental collapse): the material has a continuing incremental plastic deformation with each load cycle, and at high load levels, the response is always plastic in a progressive increment of the permanent deformation. This behavior can result in the failure of the pavement structure.

– Range B (intermediate response – plastic creep): the material presents an intermediate response between ranges A and C. During the first load cycles, the material reaches high levels of plastic deformation, but after this period, the level of plastic deformation decreases and becomes close to a constant level.

In order to analyze these ranges of behavior, Werkmeister et al. [21] suggested the permanent deformation results to be plotted as permanent vertical strain rate versus permanent vertical cumulative strain.

As shown in Figs. 8 and 9, the permanent deformation of the RCDW aggregate is widely influenced by the stress levels. For the relation $\sigma_d/\sigma_3 = 2.0$ the material presents the lowest permanent deformation value at 180,000 cycles. Moreover, the RCDW aggregate presented permanent deformation in the beginning of the experiment, but after 80,000 cycles the response becomes resilient, reaching the elastic shakedown (Range A). Conversely, at higher stress levels, such as $\sigma_d/\sigma_3 = 4.0$ and $\sigma_d/\sigma_3 = 6.0$, there is an increase in the permanent deformation; during the experiment, the strain decreases after 50,000 cycles, and the permanent deformation continues in a low constant level. In this condition, the material has an intermediate response (Range B). For the relation $\sigma_d/\sigma_3 = 6.7$, the permanent deformation increases progressively with cycles, and at the end of the experiment it is still higher (Range C). The test was conducted up to 180,000 cycles, but if its duration was extended, the strain would progress up to the specimen collapse. The stress level is particularly important when studying the use of RCDW aggregate in base layers, because thin asphalt surfaces are commonly used in low-volume roads, resulting in high stress levels in base layers. In these conditions, rutting is a distress that should be considered.

### Table 4
Permanent deformation model obtained for the RCDW aggregate.

<table>
<thead>
<tr>
<th>Proctor effort</th>
<th>Exponential model</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate</td>
<td>$\varepsilon_0 = 1.1754 N^{0.1027}$</td>
<td>0.9736</td>
</tr>
<tr>
<td>Modified</td>
<td>$\varepsilon_0 = 1.1215 N^{0.1024}$</td>
<td>0.9828</td>
</tr>
</tbody>
</table>

![Fig. 8. Permanent deformation results for the RCDW aggregate for different stress levels.](image1)

![Fig. 9. Permanent vertical strain of RCDW aggregates using the shakedown concept.](image2)
7. Conclusions

Based on the laboratory study performed on the RCDW aggregate, the following conclusions can be drawn:

(1) The water absorption varies greatly according to the nature of the materials. For large occurrence of highly porous ceramic materials, such as bricks and roof tiles, the water absorption of the RCDW increases significantly. It is also possible to infer the grain shape based on the composition. The results show that cementitious materials have predominantly cubic grains, whereas less porous ceramic materials have mostly flat grains.

(2) The grain-size distribution is fairly changed by the compaction process. The particles of RCDW aggregate present some breakage during compaction, which is more intensive when the energy increases. In the same way, the compaction process modifies the grain shape classification, increasing the percentage of cubic grains. However, the effect of modified effort does not differ significantly from intermediate effort. It is recommended to use proper compaction energy and to control the RCDW aggregate after the compaction process, in order to verify its breakage potential.

(3) The use of modified effort implies a substantial increase in the bearing capacity of the RCDW aggregate, compared to the CBR values obtained with intermediate effort.

(4) Comparing the resilient modulus results obtained for the RCDW aggregate with a standard well-graded crushed stone, it is observed that both materials present similar behavior. The use of higher compactive effort reduces the resilient displacement of the RCDW aggregate in only 10–20%.

(5) The compactive effort also influences the resistance to permanent deformation of the RCDW aggregate. For the same stress level, a slightly reduction in permanent deformation is observed, when the material is compacted at higher energy. Moreover, the permanent deformation of the RCDW aggregate also depends on the stress levels. This fact must be seriously considered in the case of base layer application, especially when a thin asphalt surfacing layer is selected, due to the commonly high stress levels transferred to the base. The use of shakedown concept contributes to the understanding of the material response under the traffic loading and to avoid of pavement distresses.

In summary, it can be concluded that the composition and the compaction effort are important factors in the physical and mechanical behavior of the RCDW aggregates. Recycled material must be rigorously controlled, before and after its application. The results obtained in this research encourage the use of RCDW aggregates as a viable alternative for road construction.

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References

[4] Motta RS. Laboratory study of recycled aggregate from construction and demolition waste to be used as a pavement material in a low volume road. MSc thesis, University of São Paulo; 2005 [in Portuguese].