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Effect of wetting-drying cycles on physical and mechanical properties of a recycled construction and demolition material

Effet des cycles de mouillage-séchage sur les propriétés physiques et mécaniques d'un matériau de construction et de démolition recyclé

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ABSTRACT: Recycled Construction and Demolition (C&D) materials are progressively being used in civil engineering applications, such as base and sub-base layers of transport infrastructures. However, the knowledge related to the long-term behaviour of recycled aggregates in geotechnical and pavement applications is very scarce. The breakage of the particles, particularly when the recycled aggregate has clay masonries, is commonly pointed out as an issue for the usage of these recycled materials. A laboratory study was undertaken to investigate the effect of wetting-drying (W-D) cycles on geometrical, physical and mechanical properties of a mixed recycled aggregate coming from C&D waste. The effects of the number of cycles (10 and 20 W-D cycles) on particle size distribution, shape and flakiness indexes, particles density, water absorption, sand equivalent, methylene blue, water-soluble sulphate content, Los Angeles abrasion and aggregate crushing value were assessed. This study shows that W-D cycles have caused a slight degradation of the recycled aggregate, even if the effect of the number of cycles (above 10) is not quite relevant. LA abrasion loss of this mixed recycled aggregate is high, making its application as unbound material in pavement layers impracticable without additional measures.

RÉSUMÉ : Les matériaux recyclés de construction et de démolition (C&D) sont progressivement utilisés dans des applications de génie civil, telles que les couches de base et de sous-base des infrastructures de transport. Cependant, les connaissances en matière de comportement à long terme des granulats recyclés dans les constructions géotechniques et les chaussées sont très limitées. La fragmentation des particules, en particulier lorsque le granulat recyclé contient des maçonneries en argile, est généralement considérée comme un problème majeur pour l'utilisation de ces matériaux recyclés. Une étude de laboratoire a été réalisée pour étudier l'effet des cycles mouillé-séché (M-S) sur les propriétés géométriques, physiques et mécaniques d'un granulat recyclé mixte provenant de résidus de C&D. Les effets du nombre de cycles (10 et 20 cycles M-S) sur la distribution granulométrique, les indices de forme et d'aplatissement, la densité des particules, l'absorption d'eau, l'équivalent de sable, le bleu de méthylène, la teneur en sulfate hydrosoluble, l'abrasion de Los Angeles et l'écrasement de l'agrégat recyclé ont été évalués. Cette étude montre que les cycles M-S ont provoqué une légère dégradation du granulat recyclé, même si l'effet du nombre de cycles (supérieur à 10) n'est pas très important. Le coefficient de Los Angeles de cet agrégat recyclé est élevé, ce qui rend son application comme matériau non lié dans les couches de la chaussée impraticable sans mesures supplémentaires.

KEYWORDS: sustainable geotechnics, recycled aggregates, construction and demolition waste, wetting-drying cycles

1 INTRODUCTION

Large amounts of wastes are currently being generated from human activities. One of those activities is the construction industry, responsible for the production of around 35% of the European Union´s total waste and consumption of about 50% of all extracted material (European Commission 2021). Over recent years, the recycling of Construction and Demolition (C&D) wastes in construction applications, such as base and sub-base layers of transport infrastructures, has been a priority area at a global level. However, the knowledge related to the long-term behaviour of recycled aggregates coming from C&D waste in geotechnical and pavement applications is very scarce.

In many European countries, such as Portugal and Spain, the generation of mixed recycled aggregates (comprising concrete, mortars, ceramics, etc.) is much higher than the production of recycled concrete aggregates (RCA). Nevertheless, most of the studies found in the literature have been carried out on selected recycled aggregates: RCA, crushed bricks, reclaimed asphalt pavement (Arulrajah et al. 2013, Rahman et al. 2014, Freire et al. 2019). Thus, it is of great importance to carry out research studies with these mixed recycled aggregates, which are much less studied than RCA or other selected aggregates.

The durability of an aggregates can be commonly associated with physical and chemical issues. The physical problems are more relevant in aggregates that are susceptible to freezing- thawing or wetting-drying and physical wear, while the chemical problems are concerned with cement-aggregate reactions.

RCA generally exhibit good durability with good resistance to weathering and erosion. However, mixed recycled aggregate with significant content of clay masonries and mortars may exhibit less suitable behaviour in the long-term. The breakage of particles is commonly pointed out as a relevant issue for the use of these recycled materials.

The study herein presented follows an earlier investigation (Pereira et al. 2019) and is part of a broader research study focused on the long-term behaviour of recycled C&D materials. The effects of several wetting-drying (W-D) cycles under controlled conditions on geometrical, physical, mechanical and chemical properties of a mixed recycled aggregate coming from C&D waste are presented and discussed.

2 MATERIALS AND METHODS

2.1 *Recycled aggregate*

The recycled aggregate used in this study is produced in a stationary C&D recycling plant, where the C&D wastes undergo a mechanical and manual sorting process. It is a coarse aggregate, with particle size distribution between 10 and 30 millimetres (Figure 1), being one of the granulometric fractions generated during the recycling process.

Like most recycled aggregates produced in Portuguese recycling plants, this aggregate comes from non-selected C&D wastes, resulting mainly from the demolition or rehabilitation of housing buildings. Figure 1 illustrates a sample of this recycled aggregate. Its constituents will be described in Section 3.

Figure 1. Sample of the recycled aggregate used (ruler in centimetres).

2.2 *Test procedures*

Considering that this recycled aggregate has in their composition high amounts of ceramic masonries (Figure 1), potentially more sensitive to climatic variations and particle breakage, it was decided to evaluate the effect of several wetting-drying (W-D) cycles on its geometrical, physical, mechanical and chemical properties.

Each W-D cycle consisted of placing the aggregate samples into an electric oven under a temperature (T) of 60ºC for 7 days, and then putting the samples in a humidity chamber (T = 20ºC and relative humidity close to 100%) for another 7 days period (Figure 2). So one each W-D cycle lasts 2 weeks.

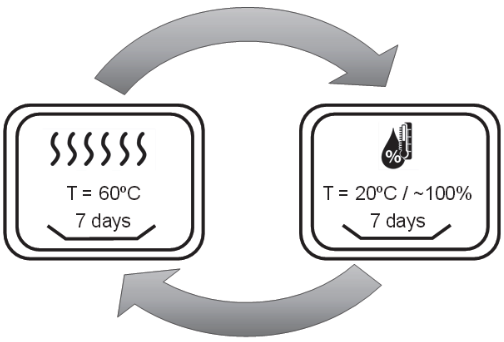

Figure 2. Schematic representation of a wetting-drying (W-D) cycle.

In order to evaluate the effect of W-D cycles on the recycled aggregate properties, its characterisation was carried out after 10 and 20 cycles. The assessed properties and the related testing methods are summarized in Table 1.

3 RESULTS AND DISCUSSION

3.1 *Geometrical properties*

In order to simplify the discussion of the results, the constituents of this recycled aggregate are presented firstly. The particles of the recycled aggregate were separated by hand sorting and classified, following the standard EN 933-11 (2009), as concrete, concrete products, mortar, concrete masonry units (Rc); unbound aggregate, natural stone, hydraulically bound aggregate (Ru); clay masonry units, calcium silicate masonry units (Rb); bituminous materials (Ra); glass (Rg); soils (Rs); and, other materials, such as, gypsum drywall particles or woods (X).

Table 1. Laboratory testing methods.

Assessed properties	Standard
Geometrical properties:	
Particle size distribution	EN 933-1: 2012
Flakiness index	EN 933-3: 2012
Shape index	EN 933-4: 2008
Sand equivalent – Assessment of fines	EN 933-8: 2012
Methylene blue – Assessment of fines	EN 933-9: 2009
Constituents	EN 933-11: 2009
Physical and mechanical properties:	
Particle density and water absorption*	EN 1097-6: 2013
Resistance to fragmentation (Los Angeles)	EN 1097-2: 2010
Aggregate crushing value	BS 812-110: 1990
Chemical properties:	
Water soluble sulphates	EN 1744-1: 2009

* for different particle size fractions

Figure 3 illustrates some constituents of the recycled material after manual sorting, ready for weighing. Based on the weight of each constituent its proportion is calculated (Figure 4).

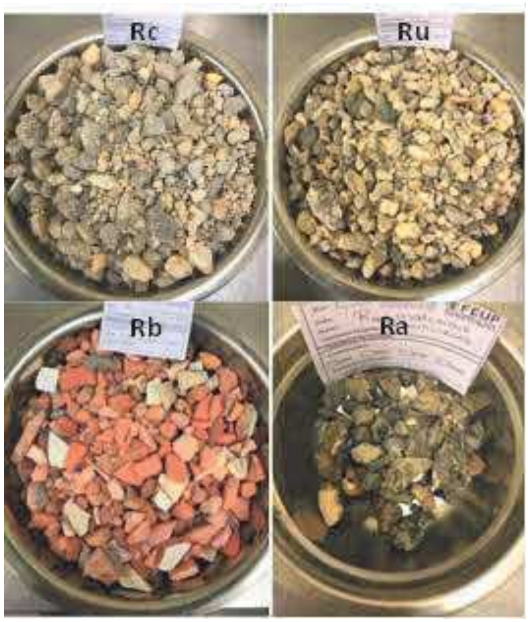

Figure 3. Constituents of the recycled aggregate after manual sorting.

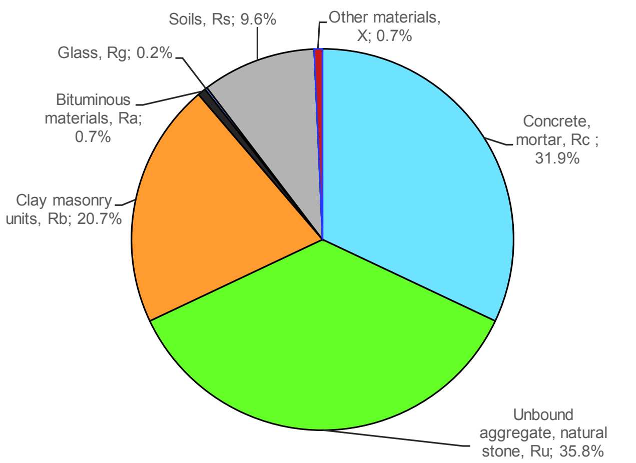

Figure 4. Constituents of the recycled aggregate following the standard EN 933-11.

As shown in Figure 4, this recycled aggregate is composed mainly of unbound aggregates, crushed concrete (concrete products, mortar, concrete masonry units), and masonries (clay masonry units, calcium silicate masonry units, aerated non-floating concrete). A significant proportion of soils was also noticed, resulting mostly from powder particles bonded to larger particles, which separate during the washing process.

The grain size distributions of the recycled aggregate before and after 10 and 20 W-D cycles are presented in Figure 5. Each curve represents the mean curve of 3 tested samples.

Figure 5 shows that the variation of temperature and humidity has reduced influence on particles with dimensions larger than 14mm. In general, the aggregate has become finer, ie, with higher content of fine particles, after W-D cycles however, the increase in the number of cycles did not cause further degradation. The reason why the effects on the particle size distribution are more relevant for 10 cycles than for 20 W-D cycles can only be attributed to the heterogeneity of the recycled material.

After the W-D cycles the recycled aggregate presents a higher percentage of particles with dimensions lower than 14 mm. For example, the percentage of particles lower than 2 mm increased from 12% to 19% after the 10 W-D cycles, but only to 17% after 20 cycles. The percentage of particles below 0.063mm was not significantly affected by W-D cycles, ranging from 4% to 7%.

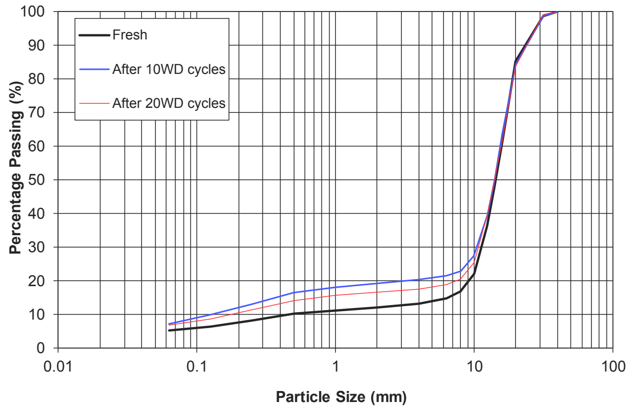

Figure 5. Effects of W-D cycles on the particle size distribution.

The presence of flaky and long particles is detrimental in pavements construction, particularly in surface courses, since they may break more easily under traffic loads. Furthermore, unpaved roads constructed with aggregates exhibiting high flakiness and shape indexes tend to present lower resistance to rutting. So, the Flakiness index (FI) and Shape index (SI) were evaluated.

FI denotes the mass percentage of flat particles (with smaller dimension lower than half of the major dimension), while SI represents the mass of particles having a ratio between the particle maximum dimension (L) and minimum dimension (E) greater than 3. It is worth mentioning that a lower value of these indexes means that the mass of flat (not spherical or non-cubical) particles is lower.

As an example, Figure 6 shows the particles considered cubic and non-cubic according to the test procedure to quantify SI.

Figure 7 shows the values of FI and SI for fresh samples and for samples subjected to 10 and 20 W-D cycles. After exposure to W-D cycles, the shape index decreased from 27% to 20 % and this decrease was not influenced by the number of cycles. As a matter of fact, there is a slight decrease from 20.2% for 10 W-D cycles to 19.8% for 20 W-D cycles.

Regarding the FI index, the effect of the cycles was inconclusive. A decrease occurred when the aggregate was subjected to 10 W-D cycles, but for 20 W-D cycles the FI value has exceeded the value for fresh samples. However, these results should be critically analysed since the classification of particles, following the standard EN 933-3 (2012), is carried out only for particles retained in the sieve 4 mm. This implies that the mass of material analysed for the sample submitted to 10 W-D cycles is lower than the masses for fresh and 20 W-D samples. It should be noted that this evidence is in agreement with the results of the particle size distribution (Figure 5). In addition to this particularity of the testing methodology, the heterogeneity of the material (in particular the particle content of clay masonries) should also be considered.

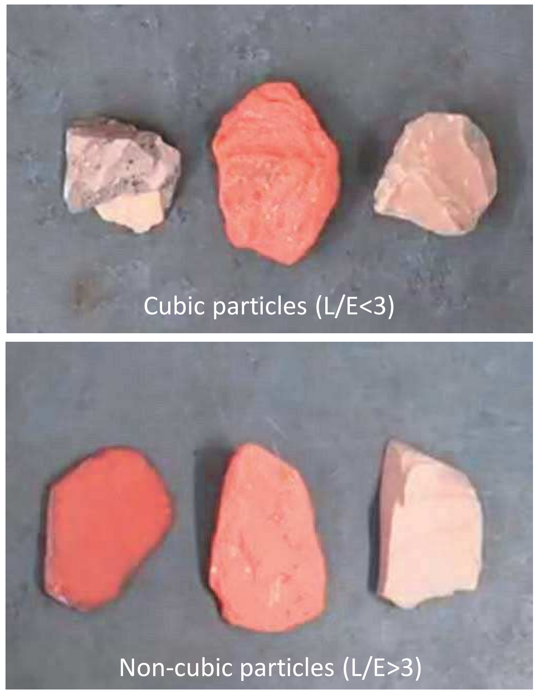

Figure 6. Example of particle selection for SI determination.

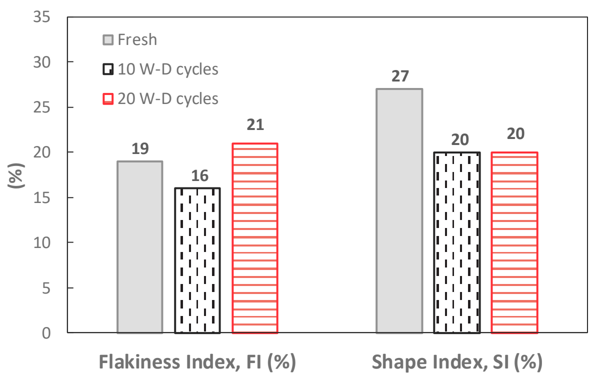

Figure 7. Influence of the W-D cycles on the flakiness and shape indexes.

As mentioned in 2.2, the assessment of fines was performed through the sand equivalent and the methylene blue tests performed on the particle size fraction 0/2 mm. Figure 8 presents the sand equivalent value (SE) and the value of the methylene blue (MB) for fresh samples and for samples subjected to 10 and 20 W-D cycles. The values of the parameter $MB_{0/D}$ (stipulated in the Portuguese specifications) are also shown in Figure 8. $MB_{0/D}$ is the value of MB multiplied by the percentage of material passing the 2 mm sieve.

The value of MB tended to increase with the number of W-D cycles, probably resulting from the disintegration of coarse clay masonry particles. It should be recalled that the value of MB reflects the amount and characteristics of clay minerals, which can be potentially harmful, for example, to the performance of the pavement layers. The MB value of an aggregate increases when materials of clay origin are present in greater quantities.

It is worth mentioning that, according to the Portuguese specifications, the $MB_{0/D}$ should be lower than 2% to be allowed the use of the recycled aggregates in less demanding layers of embankment and capping layers of transport infrastructures (LNEC E474 2009) or rural and forest roads (LNEC E484 2016). For unbound pavement layers the threshold is reduced to 1%.

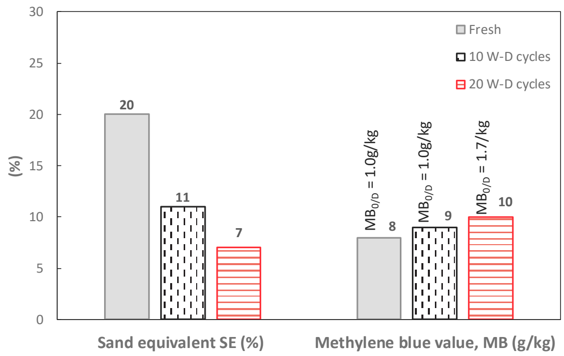

Figure 8. Results of the assessment of fines.

Most fine aggregates are mixtures of coarse particles (e.g., sand) and undesirable clay-like materials and fine dust. The term "sand equivalent" expresses the relative proportions of fine dust or clay-like materials in fine aggregates (or granular soils). A higher sand equivalent value indicates a "cleaner" aggregate, i.e. containing less fine dust or clay-like materials.

As expected, the exposure of the aggregate to W-D cycles led to the decrease in SE value, i.e., the presence of undesirable fine particles increased. Although the SE value decreased with the number of cycles, the decrease was more pronounced for the first 10 W-D cycles.

The decrease of the SE value with the number of W-D cycles is not in fully agreement with the particle size distributions presented in Figure 5. However, it should be noted that the content of fine particles (<0.063mm) is almost equal in the samples subjected to 10 or 20 W-D cycles.

3.2 *Physical and mechanical properties*

As is well-known, the particle density of an aggregates is the ratio of the mass of a given volume of material to the mass of the same volume of water. However, different values are obtained depending on the allowance made for pores, resulting three types of value: oven dried, saturated surface-dried and apparent particle densities.

Table 2 presents the mean values of the particle densities and water absorption obtained on fresh samples and on samples subjected to 10 and 20 W-D cycles. These tests were carried out on two different particle size fractions (4.0/31.5 mm and 0.063/4.0 mm) and for three specimens for each condition.

From Table 2 it can be concluded that fine aggregates (passing 4 mm sieve) show slightly higher particles density than coarse aggregates (retained on 4 mm sieve) and this trend remains after the W-D cycles. As expected the effects of W-D cycles on the particle density of the aggregate is negligible.

It is also worth mentioning that, even though it is a mixed recycled aggregate, the values for particle density are in accordance with those usually obtained for normal weight natural aggregates.

The water absorption for the coarse aggregate (particles retained on 4 mm sieve) was not affected by the W-D cycles. The values obtained for this recycled material are higher than those of natural materials (generally in the range 0.5% to 1.5%), but close to the values obtained by Arulrajah et al. 2011 for recycled crushed brick.

The fine aggregate (particles passing 4 mm sieve) presented water absorption values significantly lower than those of the coarse aggregate. However, as reported by Pereira et al. 2019, for this particle size fraction the coefficients of variation of this parameter tend to be very high, meaning that these values may be erroneous.

During the test procedures, the finest particles (below 0.063 mm) are removed by washing. Nevertheless, the porous nature of the recycled aggregate and the disaggregation of the larger particles during washing may allow some fine particles remaining in the samples. If these particles are clay-like nature, their cohesive characteristics may distort the results.

In the samples subjected to 10 W-D cycles the use of a dispersant (sodium hexametaphosphate) was also tested and, as can be perceived from Table 2, the water absorption values were very close to those for coarse aggregates.

Figure 9 presents the effects of W-D cycles on the Los Angeles (LA) abrasion coefficient and on the aggregate crushing value. Regarding LA abrasion resistance, carried out on the particle size fraction 16/31.5 mm, the effect of W-D cycles can be considered negligible, as the increase is very small. First of all, it should be noted that the LA value of this mixed recycled aggregate is very high, which would make unfeasible its application in unbounded pavement layers without any kind of treatment or mixture with another aggregate. Indeed, as can be seen in Figure 10, this aggregate experiences a significant degradation in the LA chamber. Figure 10 shows the aggregate degradation at the end of the test (Figure 10b) and after washing (Figure 10c).

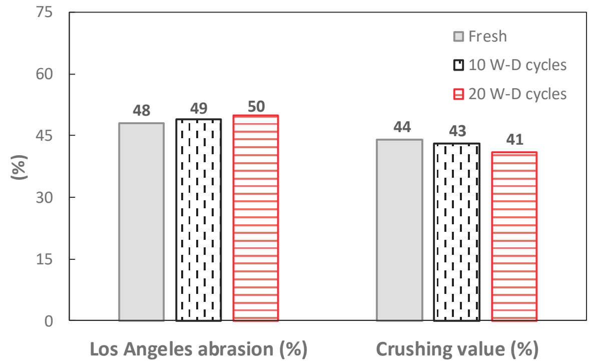

Figure 9. Effects of W-D cycles on resistance to fragmentation and crushing.

Figure 10. Fresh sample appearance in LA abrasion test: (a) before going into the testing machine; (b) after getting off the testing machine; (c) after washing.

High Los Angeles (LA) abrasion values in mixed C&D recycled aggregates have been identified in the literature. Jiménez et al. 2012 reported a LA abrasion value of 31% for a mixed recycled aggregate with 21% of ceramics and 53% of natural aggregates without cement mortar attached, while Agrela et al. 2012 presented LA values around 38% for mixed recycled aggregates with crushed ceramic particles in the range 15-22%. Bassani and Tefa 2018 achieved a LA value of 50% for crushed bricks and tiles, whereas Arulrajah et al. 2013 presented LA loss of 36% for a crushed brick aggregate.

Table 2. Test results of particles density and water absorption of the recycled aggregate for different particle size fractions.

Parameters	Fresh	10 W-D cycles	20 W-D cycles
Particle size fraction 4/31.5 mm			
Oven-dried particle density (Mg/m^3)	2.205	2.205	2.190
Saturated and surface dried particle density (Mg/m^3)	2.348	2.349	2.333
Apparent particle density (Mg/m^3)	2.573	2.575	2.559
Water absorption (%)	6.5	6.5	6.6
Particle size fraction 0.063/4 mm			
Oven-dried particle density (Mg/m^3)	2.506	2.441	2.486
Saturated and surface dried particle density (Mg/m^3)	2.575	2.547	2.546
Apparent particle density (Mg/m^3)	2.693	2.731	2.646
Water absorption (%)	2.8	4.4/6.4#	2.4

Using sodium hexametaphosphate dispersant

The W-D cycles had an unexpected effect on the aggregate crushing value (ACV). The W-D cycles provoked the ACV decrease, meaning that crushing was lower. However, the variations are quite small (in particular for the 10 W-D cycles), which can only be attributed to the heterogeneity of the material.

The water-soluble sulphates contents for fresh samples and for samples subjected to 10 and 20 W-D cycles are presented in **Error! Not a valid bookmark self-reference.**. The W-D cycles caused a slight increase in the water-soluble sulphates content (%SO_3). Although it is hard to argue that this increase is directly due to the W-D cycles, i.e. due to the variation in water-content and temperature, it can be explained by the particle size variations caused by the cycles.

It is commonly assumed that water-soluble sulphates content is strongly influenced by the amount of gypsum (Vegas et al. 2011; Jang and Townsend 2001). Other researchers consider that the high sulphates content of the recycles aggregates results from the cement of attached mortar (Juan and Gutiérrez 2009) or from the crushed clay bricks in the recycled aggregates (Barbudo et al. 2012).

As the determination of the water-soluble sulphates content is carried out on the 0/4mm particle size fraction and the W-D cycles caused the disaggregation of the particles, the cement and clay content in this fine fraction is potentially higher in the samples subjected to the W-D cycles and, therefore, higher water-soluble sulphates contents are detected.

It is also worth pointing out that the water-soluble sulphates contents are well below the limit of 0.7% recommended by Portuguese specifications for use of recycled aggregates in roadway layers.

Table 3. Effect of W-D cycles on water-soluble sulphates content.

	Water-soluble sulphates content (%)
Fresh	0.115
10 W-D cycles	0.135
20 W-D cycles	0.190

4 CONCLUSIONS

A mixed recycled aggregate coming from C&D waste was exposed to successive wet/dry cycles in their natural state and under controlled conditions, in order to investigate the potential degradation induced by temperature and humidity changes on its geometrical, physical, mechanical and chemical properties. This particular recycled aggregate was selected due to its high content of clay masonries particles.

On the basis of the results presented the following main conclusions can be drawn:

- The W-D cycles under controlled conditions seem to have reduced influence on size particles of the coarse aggregate (particles > 14 mm).
- In general, the content of fine particles after W-D cycles increased. However, the increase in the number of cycles did not cause further degradation.
- The effects of the W-D cycles on the flakiness and shape indexes are not relevant.
- The value of MB tended to increase with the number of W-D cycles, probably resulting from the disintegration of coarse clay masonry particles. W-D cycles led to the decrease in SE value, however, the decrease was more pronounced for the first 10 W-D cycles.
- The LA abrasion loss of this mixed recycled aggregate is very high, which would make unfeasible its application in unbounded pavement layers without any kind of treatment or mixture with another aggregate. The effect of W-D cycles on LA value can be considered negligible.
- The W-D cycles caused a slight increase in the water-soluble sulphates content due to the increase of the cement and clay content in the fine fraction.

The results presented herein are part of a broader research project aiming to study the long-term behaviour of recycled C&D materials. The content of ceramic materials mixed with concrete and mortar has some influence on the performance of these recycles aggregates. Therefore, promoting the selective demolition is essential towards a more sustainable construction industry.

5 ACKNOWLEDGEMENTS

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