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# Use of recycled Construction and Demolition Materials in geotechnical applications: A review

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**ABSTRACT**

The proper use of natural resources is one of the fundamental pillars of sustainable development imposed on modern societies. A more effective and efficient use of natural resources, as well as the mitigation of environmental impacts induced by their extraction could be achieved if proper management and recycling policies of Construction and Demolition (C&D) wastes were implemented. The valorisation of wastes in the construction industry is needed and is a way toward sustainability. This paper provides a literature review on studies related to the valorisation of Construction and Demolition (C&D) materials in geotechnical engineering applications, with an emphasis on their use as recycled aggregates in base layers of roadway infrastructures and as filling material for geosynthetic reinforced structures. Specifications that should be followed when these materials are used in such projects are also summarised. With this review it is intended to promote the use of recycled C&D materials, showing that research carried out all over the world has demonstrated their good performance in general.

KEYWORDS: Construction and Demolition materials; Recycled aggregates; Recycled filling materials; Sustainable Construction

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## Contents



## 1 INTRODUCTION

The reduction of non-renewable natural resource extraction is a constant concern relating to the preservation of the environment, and encourages the use of recycled materials. In recent years environmental sustainability has demanded a decrease in the exploitation of non-renewable resources and a progressive increase in waste valorisation in diverse areas. The valorisation of wastes in the construction industry is, therefore, a need and one way forward for sustainability.

After the Industrial Revolution, rapid population growth, economic development, mismanagement of the use of natural resources and a lack of environmental consciousness served to make waste management an important issue for society. Nowadays, problems arising from the concentration of wastes from industrial activities and urban expansion have gained great social and environmental importance.

Waste management is discussed at the International level, in particular by the United Nations (UN), who hold conferences and summits and created the "World Commission on Environment and Development (WCED-UN)" driven by an official report in 1987 entitled "Our Common Future" (WCED, 1987). This report traces the panorama of waste and its impact on the environment, proposing strategies to approach the problem, which are still perfectly valid for the management of waste. *Our Common Future*, also known as the Brundtland Report, defined the concept of sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987).

Meetings involving many countries, such as occurred in Stockholm in 1972 and in Rio de Janeiro 20 years later, allowed the institutionalization of issues relating to the environmental theme. The Rio +10 meeting, held in Johannesburg in 2002, and the Rio +20, held once more in Rio de Janeiro in 2012, continued this movement which seeks to regulate human action on an international scale by forming international environmental policies.

The construction industry is responsible for 50% of the consumption of natural resources (European Commission, 2001). Construction and demolition (C&D) materials have been identified by the European Commission as a priority stream because of the large amounts of wastes that are generated and their high potential for re-use and recycling. An effective and efficient usage of natural resources, as well as a mitigation of the environmental impacts induced by their extraction, could be achieved if proper management and recycling policies of C&D materials were implemented.

The importance of recycling C&D material has been raised due to the scarcity of natural aggregates, the large volumes of landfills, as well as other environmental concerns. The increased growth of construction worldwide has resulted in the

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consumption of vast amounts of virgin (natural) aggregates. With the increasing demands of global population more and more land has been acquired for residential, commercial, agricultural and infrastructure purposes, and this leads to difficulties in finding suitable landfill areas. Moreover, environmental considerations play a major role because recycling waste materials saves energy, reduces greenhouse emissions and delivers a more sustainable future. Although there are some measures taken by governments at national and/or regional levels to recover the C&D materials to a certain extent, plenty of room still exists to extend the recovery of C&D wastes. Without proposing sustainable alternatives for recycled C&D materials, it will be difficult to encourage or enforce the recovery of C&D materials (Arulrajah et al., 2011).

This paper presents a state-of-the-art review on the research and usage of different types of recycled C&D materials in geotechnical engineering projects, with an emphasis mainly on their application as filling material for embankment construction and as base layers for transportation infrastructures. Their geotechnical and geo-environmental properties have been analysed by researchers all over the world, and are described and discussed here. The review also summarizes some standards and specifications that should be followed when selecting the backfill material for the construction of embankments stabilized by reinforcement elements and for usage as base layers of roadways.



## 2 PRODUCTION AND RECYCLING OF C&D WASTES

The act of recycling is almost as old as humanity itself. (Schulz and Hendricks, 1992) cite records of use of crushed masonry by the Romans, in the production of a mixture of lime, water and sand for the construction of their buildings. More recently, demolition debris has been significantly recycled since the end of the Second World War with the use of crushed brick as aggregates in concrete for the reconstruction of buildings.

Construction and Demolition (C&D) wastes are usually defined as the residues from the operations of construction, reconstruction, extension, alteration, maintenance and demolition of buildings and other infrastructures. These wastes consist of distinct types of materials, and are a heterogeneous residue that can contain any material that is part of a building or infrastructure as well as any other materials used during construction work. According to the European Waste Catalogue (Commission Decision 2000/532/EC), C&D wastes can be composed of:

- Concrete, bricks, tiles and ceramics;
- Wood, glass and plastic;
- Bituminous mixtures, coal tar and tarred products;
- Metals;
- Soil (including soil excavated from contaminated sites), stones and dredging spoil;
- Insulation materials and asbestos-containing construction materials;
- Gypsum-based construction material;
- Other construction and demolition materials.

In Europe, particularly in Portugal, the construction industry presents unique aspects involving traditional methods, which lead to the production of high amounts of waste. As mentioned previously, the construction industry is responsible for the consumption of 50% of natural resources and the production of around 50% of the waste (European Commission, 2001).

The C&D wastes are therefore likely to range between a total of 310 and 700 million tonnes per year in the European Union, representing 0.63 to 1.42 tonnes per capita per year. The systematic inclusion of wastes coming from excavations could significantly increase these amounts, ranging from a total of 1,350 to 2,900 million tonnes of waste per year (2.74 to 5.9 tonnes per capita per year) (EC DG ENV, 2011).

Table 1 shows the amounts of C&D wastes produced in different countries of the EU and their rates of reuse and recycling.

The reuse or valorisation of C&D materials on the one hand reduces the use of natural resources (non-renewable), and on the other hand avoids the landfill of inert materials coming from the construction industry. Despite these main advantages of C&D wastes recycling, some member states of the European Union have low recycling rates, including Portugal, which has a recycling rate of about 5%. This rate is below the EU average (46%) (EC DG ENV, 2011) and far below the minimum of 70% stipulated by the Waste Framework Directive of the European Parliament, to be achieved in 2020 (UE Directive 2008/98/EC).

In fact, in the European Union there are major differences in terms of management of C&D wastes in different countries. There are countries where the recycling of C&D materials has become a common practice, and elsewhere, where this practice is now at the beginning or practically non-existent (EC DG ENV, 2011). Table 1 shows that there are 6 countries in the European Union (Denmark, Estonia, Germany, Ireland, United Kingdom and Netherlands), which have already achieved the objectives proposed by the European Directive. The truth is that in these countries there are three main factors that have accelerated waste recycling: shortage of raw materials; difficulty in finding places for landfills and legal and economic measures that promote recycling. However, there are some countries with a less than 40% rate of C&D waste recycling (Czech Republic, Poland, Finland, Greece, Hungary, Cyprus, Spain and Portugal). The low recycling rates in Portugal are mainly due to the abundance of natural aggregates of very good quality and the lack of technical regulations for the use of recycled aggregates.

It should be noted that, the average recycling rate of 46% for the EU-27 (Table 1) is a rough estimate with a high degree of uncertainty (EC DG ENV, 2011).

Some European Directives were prepared with the intention of safeguarding the environment from negative impacts. Directive 2008/98/EC, replacing older directives, aims to promote reducing the correlation between economic growth and waste production. Principles were established for the treatment of wastes, promoting the prevention of negative impacts on the production and management of waste and primarily protecting the environment and human health. Directive 2008/98/EC also states that member states have to take measures regarding the treatment of waste in accordance with the hierarchical priorities described as follows:

- Prevention
- Preparation for reuse
- Recycling
- Other recovery, for example energy
- Elimination.

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# 3 MATERIALS REQUIREMENTS

## 3.1 Standards related to aggregates for base layers of roadways

In general, every country has its own standards and technical specifications for aggregates suitable for roadway construction. As it is impossible to include all of them and their territorial application in this review, only American Standards (ASTM) are briefly mentioned here.

The (ASTM D 1241 – 07, 2007) standard covers the quality and grading of sand-clay mixtures, gravel, stone or slag screenings, sand, crusher-run coarse aggregate consisting of gravel, crushed stone or slag combined with soil mortar or other combinations of these materials for use in the construction of the sub-base, base and surface courses. Two types of mixtures are specified in this standard: Type I, mixtures consisting of stone, gravel or slag with natural or crushed sand and fine mineral particles passing a 75µm sieve; and Type II, mixtures consisting of natural or crushed sand with fine mineral particles passing a 75µm sieve, with or without stone, gravel, or slag. The composite soil-aggregate material of Type I and II shall conform to the gradation requirements reproduced in Table 4 and be free of vegetable matter and lumps or balls of clay.

A coarse aggregate (retained on a 2.00 mm sieve) for use in Type I and Type II mixtures shall consist of hard, durable particles or fragments of stone, gravel, sand or slag and shall have a percentage of wear of not more than 50 (by the Los Angeles abrasion test). A fine aggregate (passing a 2.00 mm sieve) shall consist of natural or crushed sand and fine mineral particles. The fraction passing a 75µm sieve shall not be greater than 2/3 of the fraction passing a 425µm sieve. The fraction passing a 425µm sieve shall have a liquid limit and a plasticity index not greater than 25 and 6, respectively.

Table 5 summarizes the gradations and type of mixtures for use in the construction of sub-base, base and surface courses.

### 3.2 Standards and specifications for fills used in geosynthetic reinforced structures

Soil reinforcement is a common design alternative for the construction of retaining walls and steep slopes (Vieira et al., 2013). This results mostly from its reduced costs and excellent long-term behaviour when compared to long-term behaviour of conventional retaining structures.

The behaviour of reinforced soil structures depends on the physical and mechanical properties of the reinforcement elements, on geotechnical characteristics of the backfill material and on the soil/reinforcement interaction. High shear strength and adequate drainage capacity are the typical requirements expected from soil selected as backfill for reinforced soil structures. The need of good drainage capacity results from the fact that backfill materials must be able to quickly dissipate any water pressure that may be developed both during construction and throughout the lifetime of the structure. Granular soils generally meet these two design requirements regarding strength and drainage.

Nowadays the use of geosynthetics with high tensile strength and drainage capacity allows the use of low quality soil as backfill material in geosynthetic stabilised structures. According to Kutara (1990), it is possible to build geosynthetic reinforced structures with any type of soil, even with materials coming from wastes. However, the authors of this review believe that this statement must be taken with some caution. Good performance of embankments or retaining structures constructed with non-traditional filling materials must be proven, and that work is not yet entirely complete.

Regarding the requirements of filling materials for construction of geosynthetic reinforced structures, it is possible to adopt the recommendations from British Standards (BS 8006, 2010), from the *German Geotechnical Society* (EBGEO, 2011), from the *Federal Highway Administration* (FHWA, 2010), from the *American Association of State*

*Highway and Transportation Officials* (AASHTO, 2012) and from the *National Concrete Masonry Association* (NCMA, 2010). Some details about these requirements will be presented in the following sections.

### 3.2.1 British Standard – BS 8006

Some international standards, like BS 8006 (2010), do not allow the use of purely cohesive soils in the construction of reinforced soil structures in permanent works. The reasons for that are their low strength, high moisture content, high creep and low bond strength between the soil and the reinforcement. In spite of that, the use of cohesive-frictional fills is allowed.

The recommendations of BS 8006 (2010) consider the mechanical, chemical and electrochemical criteria of materials that will be used as backfill for reinforced soil structures. The filling material for walls and abutments should be from classes 6I/6J or from classes 7C/7D, established by the *Specification for Highway Works* (Department of Transport, 1993). However, besides these classes, for steep slopes (face angle between 45º and 70°) and shallow slopes (face angle smaller than 45°), BS 8006 allows the classes 1 and 2 established by the above-mentioned *Specification for Highway Works*.

Table 2 presents a summary of the permitted constituents that should be acceptable for each class of filling material. The grading requirements allowed in the different classes of filling material are presented in Table 3.

### 3.2.2 German guidelines

The stipulated soil properties of filling materials depends on the demands of the structure, where bearing capacity, deformation behaviour, frost hazard, drainage behaviour and the actions on the structure are important (EBGEO, 2011). The German guidelines differentiate the demands on the filling soil for structures subjected to predominantly static loads and those subjected to predominantly dynamic loads.

For predominantly statically loaded structures only the necessary soil mechanics analyses in terms of friction angle, possible cohesion and compactability of the soil are required. Depending on the application and the soil type (mixed and fine-grained soils) it may be necessary to quantify the coefficient of permeability (EBGEO, 2011).

For statically loaded structures the following soil types# (classified in accordance to DIN 18196) could be used:

- coarse-grained soil types of groups SW, SI, SE, GW, GI, GE
- mixed-grain soil types of groups SU, ST, GU, GT
- fine-grained soil types of groups UL, UM, TL, TM

Other soils and materials, including industrial by-products and recycled materials, could be used if their suitability was demonstrated.

The soils shall be of uniform quality and free from harmful constituents. If the soil pH is not within the range $4 < pH < 9$ additional suitable investigations of the compatibility of the fill soil and the reinforcement shall be carried out.

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# Short symbols in accordance with DIN 18196: G – Gravel; S – sand; U – silt; T – Clay; W – wide grading; E – narrow grading; I – gap grading; L – low plasticity; M – medium plasticity.

For predominantly dynamically loaded structures, in addition to the demands previously mentioned, the soil grading should comply with EBGEO (2011):

- Percentage of grain diameter less than 0.063 mm < 7% (by mass)
- Percentage of grain diameter less than 100 mm < 25% (by mass)

- Maximum grain size < 150 mm

### 3.2.3 North American Specifications

In the United States of America the recommendations given by the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO) and National Concrete Masonry Association (NCMA) are followed particularly for works supported by the state. Particularly for mechanically stabilized earth walls and reinforced soil slopes, the North American experience has led to the selection of non-cohesive soils as backfill material.

According to the AASHTO, the backfill material to be used in abutments, piers and retaining walls shall be free-draining material (granular material), with specified grading limits (Figure 1). The backfill shall be considerably free of shale or other soft, poor durability particles, and shall have an organic content not higher than 1%. For permanent applications, the backfill shall have a pH between 4.5 and 9. In case of temporary applications the pH limits may be included in the range 3 - 11.

The NCMA recommendations related to the backfill material are extremely broad. The soil should be inorganic and classified as GP, GW, SW, SP, SM (Unified Soil Classification System), free of debris and meeting specified gradation limits (Figure 1). NCMA also establishes that the pH of the backfill material shall be within the range of 3-9.

For mechanically stabilized earth walls and reinforced soil slopes FHWA recommends a backfill material free from organic or else deleterious materials with the following gradation limits: 100 % passing 102 mm sieve, 0-60% passing No. 40 sieve, and 0-15% passing No. 200 sieve (Figure 1). However, as a result of recent research on construction survivability of geosynthetics and epoxy-coated reinforcements, it is recommended that the maximum particle size for these materials be reduced to 19 mm, unless construction damage assessment tests have been performed on the reinforcement combination with the specific or similarly graded large size granular fill. The backfill material shall be free of shale or other soft, poor durability particles and shall have an organic content of less than 1%. The range of pH values are between 5 and 10.

For the construction of reinforced soil slopes, backfill material with a higher percentage of fines can be used, given that this type of construction has a flexible face and can tolerate some deformation during construction. The specified gradation limits for backfills of reinforced soil slopes are also represented in Figure 1.

## 4 RECYCLED C&D MATERIALS IN GEOTECHNICAL APPLICATIONS

### 4.1 Roadway infrastructures

In engineering, a pavement is a multi-layer system which directly supports traffic and transmits the loads to the base of the infrastructure. It consists of a concrete slab or an asphalt slab resting on a foundation system formed by several overlapping layers of finite thickness (base, sub-base and sub-grade).

Conventionally, crushed aggregates are used in the road base and sub-base. In recent years, in order to provide a viable option for the use of C&D materials, research has been carried out to investigate the possibility of using recycled aggregates in road base or sub-base layers. In some European countries, recycling techniques have being used since the late 1970s. The reuse of aggregates coming from concrete and masonry as a base course for roadways is a common practice in the Netherlands (Herrador et al., 2011). In Australia, it is common to mix recycled concrete aggregate with small amounts of crushed bricks and soil to obtain a recycled product considered suitable for use in pavements (Bakoss and Ravindrarajah, 1999).

Over the past decades, many researchers have developed studies related to the usage of recycled aggregates. O'Mahony and Milligan (1991) studied the option of using crushed concrete and demolition debris as sub-base recycled aggregate. Their laboratory study consisted mainly of CBR tests (California Bearing Ratio), comparing the performance of recycled materials with that of limestone aggregates. Their results have shown that the CBR values of crushed concrete were similar to those of the natural aggregates. On the other hand, demolition debris showed reduced CBR values when compared to the natural aggregate.

Bennert et al. (2000) evaluated the behaviour of recycled concrete aggregate in road base and sub-base applications. Bennert et al. (2000) concluded that a mixture of 25% of recycled concrete aggregate with 75% of natural aggregate is able to achieve the same permanent deformation properties and resilient response of a dense-graded aggregate base coarse commonly used in base and sub-base layers.

Chini et al. (2001) investigated the properties of road base samples using recycled concrete aggregate (RCA) produced from a demolished concrete pavement in Santa Rosa County, Fla, which had a design strength of 20 MPa. Table 6 presents their laboratory test results for RCA. The results have revealed that the properties of the RCA used in their study compared very well with those of virgin aggregate and are within the limits established in most highway agency specifications for concrete aggregates. The exceptions were the gradation and the results of the soundness test using sodium sulphate. Related to the last exception, Chini et al. (2001) considered that the cement mortar adherent to the recycled aggregate was reactive to sodium sulphate and contributed to an increased loss in the soundness test.

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The resilient response of a sub-base material composed of four recycled aggregates from different sources was studied by Nataatmadja and Tan (2001).These researchers found that the resilient response of a sub-base material made with recycled aggregates (obtained by crushing concrete with compressive strengths ranging from 15 MPa to 75 MPa) and that of natural aggregate was comparable. The resilient response of the sub-base material was found to be dependent on the strength of the original concrete, on the amount of soft material contained in the recycled aggregates and on the flakiness index of the recycled crushed aggregate.

In the Netherlands, Molenaar and van Niekerk (2002) carried out a study of C&D materials and the influence of composition, particle size and the degree of compaction (recycled concrete and masonry rubble) on their mechanical characteristics. Their study showed that any of the analysed parameters (composition, particle size and degree of compaction) have a strong influence on the mechanical properties of the recycled materials, but the degree of compaction has the greatest relevance. This was an important conclusion for construction practice, since the degree of compaction is easier to control in situ than other factors such as gradation and composition. The results have shown that masonry rubble and recycled concrete can produce good-quality road bases.

Park (2003) tested the physical and compaction properties of two recycled aggregates obtained from a housing redevelopment site and from a concrete pavement rehabilitation project. The behaviour of these recycled materials was compared with the performance of natural materials (crushed stone aggregate and gravel).

Using the gyratory shear factor, Park (2003) evaluated the shear resistance and stability of RCA in the U.S. Army Corps of Engineers Gyratory Testing Machine (GTM). An aggregate with a higher gyratory shear factor is more stable than an aggregate with a lower gyratory shear factor. Figure 2 compares the gyratory shear factor achieved for the

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recycled concrete aggregate (RCA), the crushed stone aggregate (CSA), and gravel in dry conditions and after 48 hr soaking (wet conditions). The results indicated that RCA and CSA are very stable with increasing GTM revolutions, however, the gravel showed to be less stable after 300 GTM. Under wet conditions (48 hr soaking) the gyratory shear factor decreases.

Gyratory shear represents the resistance of a material to shear stress and it is used in the evaluation of stability of soils, asphalt mixtures and aggregates. The evolution of the gyratory shear with GMT revolutions for the three aggregates under dry and wet conditions is illustrated in Figure 3. The RCA showed the best performance in dry and wet conditions.

Park (2003) concluded that recycled concrete aggregates (RCA) can be used as alternative materials to crushed stone aggregates in bases and sub-bases of roadways. The shear resistance and stability of the recycled aggregates (in dry conditions) were higher than those of the gravel and very similar to, or even better than the values achieved for the crushed stone aggregate. In wet conditions, as expected, the stability and shear resistance were lower than in dry conditions, however, the reduction rate is similar to the one observed in the natural aggregates.

Park (2003) also used recycled aggregates and crushed stone aggregates as base and sub-base materials for a concrete pavement site. In the field, the results for the deflection of the recycled aggregates section, using the Falling Weight Deflectometer (FWD), were similar to the results recorded in the section constructed with crushed stone aggregates.

At the Hong Kong Polytechnic University, Poon and Chan (2006) developed a laboratory study on the possibility of using RCA and crushed clay bricks as aggregates in unbound sub-bases of roadways. Their results revealed that the use of an aggregate composed of 100% recycled concrete led to an increase of the optimum moisture content and to the reduction of the maximum dry density of the sub-base material when compared to the values of raw materials. Moreover, the replacement of recycled concrete aggregates by crushed clay brick further increased the optimum moisture content and decreased the maximum dry density. This results from the lower particle density and higher water absorption of crushed clay bricks compared to those of RCA. The CBR values (unsoaked and soaked) of 100% recycled concrete aggregates mixture were lower than those of natural materials. Even so, the soaked CBR values for all recycled sub-base materials were higher than 30% (minimum value required in Hong Kong Specifications).

For road construction, Vegas et al. (2008) studied the possible use of secondary materials from three waste flows (C&D wastes, Waelz slag and Municipal Solid Waste Incineration bottom ash) through a the technical characterization of these materials according to the Spanish General Technical Specifications for Road Construction (Order/FOM/891, 2004).

Table 7 summarizes the results achieved for C&D recycled aggregates, as well as the limits established in Spanish Specifications (Order/FOM/891, 2004). Article 330 of these specifications establishes different categories of soils according to the fundamental characteristics of the materials. For use in roadbeds the following categories are defined: selected soils (SS), appropriate soils (AS), tolerable soils (TS) and marginal soils (MS). Selected soils and appropriate soils can be used at the top of the roadbed, immediately below the sub-base. Tolerable soils can be used in the core of roadbeds or embankments. All the different types of C&D materials analysed by Vegas et al. (2008) have satisfied the Spanish technical requirements as tolerable soil for roadbeds.

The results obtained by Vegas et al. (2008) also showed that Waelz slag can be suitable for usage in granular structural layers, while C&D material fits better as granular material

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in roadbeds. Fresh MSWI bottom ash can be used as roadbed material as long as it does not contain a high concentration of soluble salts.

The importance of the degree of compaction and the composition of the C&D materials on their mechanical behaviour was also studied by Leite et al. (2011). These authors found that the particle size distribution of recycled aggregate is quite affected by the compaction process. C&D particles presented some decrease in their size during compression, with this decrease accentuating when the compaction energy increased. The CBR values of the tests carried out on C&D materials were quite similar to those obtained with natural aggregates commonly used in the construction of roadway infrastructures. The resilient moduli achieved for natural aggregates were similar to those obtained with aggregates composed of recycled C&D materials.

Taking into consideration that a large amount of mixed recycled aggregates (concrete and masonry) is produced in the Mediterranean area, the possible relation between different constituents of these mixed recycled aggregates and their mechanical behaviour for possible application in roads were studied by Barbudo et al. (2012). These authors studied 31 types of aggregates (4 natural and 27 recycled from 11 different treatment plants). Their study showed that the soluble sulphate content is strongly influenced by the proportion of gypsum and crushed clay brick in the C&D material. The natural aggregates showed a lower Los Angeles coefficient, lower optimum moisture content and higher dry density measured with the Modified Proctor than the recycled C&D materials. According to Barbudo et al. (2012), recycled aggregates with less than 25% of masonry can be used in roadway sub-bases. Furthermore, mixed recycled aggregates and ceramics have shown a good mechanical performance for use in low traffic roads, especially because they have a high bearing capacity, measured by the CBR index.

Effective practices to improve the quality of recycled aggregates are very important and should include the selection and removal of impurities and a pre-screening at the beginning of the recycling process. Therefore, treatment plants have adequate quality control of C&D wastes at the entrance to the treatment centres, so that the recycled aggregates can be used as sub-base materials in roadways (Barbudo et al., 2012).

Jiménez et al. (2012) evaluated the performance and the environmental impact of recycled aggregates from non-selected C&D materials via the construction of an experimental unpaved rural road with two sections. The sections of this unpaved rural road were formed with a poor subgrade and two structural layers: the first section consisted of a base course and a surface built using a natural aggregate and a low quality mixed recycled aggregate and the second section, used as reference for the study, consisted of a crushed limestone aggregate.

In both sections, no statistically significant differences in the dry density mean values over time were detected, although the density of the compacted recycled aggregates increased slightly after 3 years of traffic. Higher mean values of the dry density of soft crushed limestone were recorded when compared to those of the mixed recycled aggregates. The mean values of the surface deflection, measured using a Falling Weight Deflectometer, were slightly lower in the section built with mixed recycled aggregate than those recorded in the section built with the soft crushed limestone aggregate. The surface deflections recorded in both sections were very uniform (Jiménez et al., 2012).

Arulrajah et al. (2011) published the results of a laboratory characterization of recycled crushed brick and the assessment of its performance as a pavement subbase material. An extensive experimental program, including tests such as particle size distribution, modified Proctor compaction, particle density, water absorption, California bearing ratio, Los Angeles abrasion loss, pH, organic content, static triaxial, and repeated load triaxial tests, is presented. CBR values were found to satisfy the Australian roadway authority requirements for a lower sub-base material. The Los Angeles abrasion loss value was just above the maximum limits specified for pavement sub-base materials. The results of the repeat load triaxial tests indicated that only recycled crushed brick with a moisture ratio of around 65% is a viable material for usage in pavement sub-base applications (Arulrajah et al., 2011). Arulrajah et al. (2011) concluded that crushed brick may have to be blended with other durable aggregates to improve its durability and to enhance its performance in pavement sub-base applications.

Arulrajah et al. (2013a) evaluated the geotechnical and geoenvironmental properties of five types of C&D materials: recycled concrete aggregate (RCA), crushed brick (CB), waste rock (WR), reclaimed asphalt pavement (RAP) and fine recycled glass (FRG). The RCA and the WR studied by Arulrajah et al. (2013a) revealed geotechnical properties equal or superior to quarry granular sub-base materials. The behaviour of CB, RAP and FRG has shown that these materials may be improved with additives or mixed in blends with high quality aggregates to enable their usage in pavement sub-bases (Arulrajah et al., 2013a).

Table 8 summarizes the main geotechnical properties of the recycled C&D materials analysed by Arulrajah et al. (2013a).

Bearing in mind that RCA, CB and RAP have attracted great interest in recent years as alternative materials for pavement base or sub-base layers, (Rahman et al., 2013a) studied the resilient moduli response and performance of these C&D materials reinforced with geogrids by repeated load triaxial tests.

Figure 4 illustrates the increase on the resilient moduli of recycled concrete aggregates (RCA) and crushed bricks (CB) reinforced with biaxial and triaxial geogrids when compared with unreinforced materials, as well as the decrease on permanent deformations.

The reinforcement of these C&D materials with geogrids has important effects on the resilient modulus and permanent deformations. As expected, the triangular geometry of the triaxial geogrid, developed mainly for traffic applications, has revealed a better performance related to the resilient modulus, when compared with the biaxial geogrid (Figure 4a). The permanent deformations were not as influenced by the recycled materials nor by the geogrid (Figure 4b). The crushed bricks reinforced with triaxial geogrid exhibited the best performance. This probably resulted from the shape of the grains, since the particle size distribution of the concrete aggregate (RCA) and the crushed bricks (CB) studied by (Rahman et al., 2013b) was similar.

Following previous studies (Arulrajah et al. 2011; Arulrajah 2013a), Arulrajah et al. (2014b) developed a comprehensive laboratory evaluation of physical and shear strength characteristics of several recycled C&D materials (recycled concrete aggregate-RCA, crushed brick-CB, reclaimed asphalt pavement-RAO, waste excavation rock-WR, fine recycled glass-FRG and medium recycled glass-MRG). All the recycled C&D materials are classified as well-graded materials and their compaction curves are controlled by water absorption and surface characteristics. Arulrajah et al. (2014b) have classified the shear responses of the recycled C&D materials into two groups: dilatancy induced peak strength and dilatancy associated strain-hardening behaviours. RCA, WR and CB were classified as dilatancy induced peak strength materials, since their peak shear strength was clearly observed after the occurrence of the maximum dilatancy ratio. Higher dilatancy ratios in these materials were associated with higher peak friction angles. RAP, FRG and MRG were classified as dilatancy associated strain-hardening materials, exhibiting strain-hardening behaviour even with a relatively high magnitude of dilatancy.

Based on the evaluation of the shear strength characteristics, these authors have concluded that compacted C&D materials have the potential to be used in pavement base/sub-base applications, as they have the required minimum effective friction angles.

The use of C&D materials as recycled aggregate in sub-base and base layers of roadways was also studied by Neves et al., (2013) through the construction and instrumentation of four experimental test sections. These sections were instrumented with strain gauges and load cells placed in pavement layers and subgrade soil. Selected construction and demolition materials (crushed concrete and ceramic mixtures) and reclaimed asphalt material (crushed asphalt and milled material) were used as recycled aggregates in the experimental sections. Crushed limestone was also used as a reference material.

The deformability of the experimental sections was evaluated by loading tests performed by the Falling Weight Deflectometer (FWD). The pavement of the experimental sections was composed of a 30 cm thick granular base layer of recycled materials. The test sections were located in a small embankment and they had a similar subgrade constituted of a sand soil (Neves et al., 2013). A bituminous layer was constructed as a final wearing course in all the experimental sections.

The loading in situ tests carried out by Neves et al. (2013) revealed that recycled materials have a different behaviour from natural material, but it could be considered that, in general, all the recycled materials tested demonstrated an acceptable performance.

Based on evidence that a possible drawback of recycled C&D materials is the risk of crushing during repeated loading, Sivakumar et al. (2004) carried out repeated loading tests in a large direct shear apparatus on crushed concrete, building debris and crushed basalt (for comparison purposes). The results show that the shear strength of the recycled materials is not significantly different to that of crushed basalt. However, the recycled

C&D materials were more susceptible to particle crushing regarding the amount of crushing influenced by both the vertical pressure and the number of loading cycles.

In recent years, studies relating to cement stabilization of recycled aggregate for base and sub-base layers of roadway infrastructures have also been carried out (Disfani et al., 2014, Mohammadinia et al., 2014). Mohammadinia et al. (2014) concluded that cement-treated C&D materials are viable alternative materials for cement-treated pavement base/sub-base applications. Their results have shown that the strength of C&D materials increases as the cement content increases and the materials become denser and stiffer. However, considering the swelling potential of blends with high cement dosage, resilient modulus may decrease due to recoverable cracks generated in the hydration process.

To evaluate the performance of crushed brick as a supplementary material in cement stabilized recycled concrete aggregate, Disfani et al. (2014) carried out an extensive laboratory research program on crushed brick and recycled concrete aggregate blends stabilized with 3% cement. Their results have shown that cement stabilized blends with up to 50% crushed brick content and 3% cement have physical and strength properties which comply with the Australian roadway authority requirements.

Disfani et al. (2014) also concluded that the modulus of rupture and flexural modulus for all the cement-stabilized blends indicated that these blends are suitable for applications such as cement-stabilized pavement sub-bases.

## 4.2 Geosynthetic reinforced structures

As reported in the last section, many studies have been carried out on the application of recycled C&D materials mainly focused on the production of aggregates for use in roadway construction. The first study on the use of C&D materials as backfill in geosynthetic reinforced structures was presented by Santos and Vilar (2008).

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The geotechnical properties of the C&D material (a mixed material composed mainly of soils, bricks and small particles of concrete) have shown low variability (Table 9) following the guidelines of the *British Standard* and *Federal Highway Administration* for use as backfill material of geosynthetic reinforced structures (Santos and Vilar, 2008). Although the C&D materials had an alkali pH (Table 9), they met the recommendations suggested by (Anderson et al., 1992) for use with polyester geogrids.

To characterize the behaviour of geogrid/C&D material interfaces, Santos and Vilar (2008) carried out direct shear tests and pullout tests. Table 10 summarises the results of pullout tests on a polyester biaxial geogrid, with a tensile strength of 61 kN/m and 30 kN/m on machine direction and cross direction, respectively.

The results of pullout tests have shown that geogrid/C&D material interfaces presented higher strength than that of sand/geogrid interfaces (used as reference by the author). The values of the adherence factor (ratio between the interface pullout strength and the backfill shear strength) achieved for the geogrid/C&D material interfaces were in the range of the values obtained by other researchers for soil/geogrid interfaces (Lopes and Ladeira, 1996).

The potential use of alternative materials such as recycled C&D materials in geosynthetic reinforced walls was subsequently investigated by Santos et al. (2013) and Santos et al. (2014) through the construction, instrumentation and monitoring of 3 full scale reinforced walls. Two walls were constructed with recycled C&D as backfill material and a third wall was constructed using silty sand. These walls were built over a collapsible foundation, which is common in the capital city of Brasilia. One of the walls constructed with C&D material was reinforced with a polyester geogrid and the other one with a polypropylene nonwoven geotextile. In the third wall, built with a silty sand backfill, a metallic grid was used as reinforcement element. The monitoring of the structures was carried out during dry and wet rainy seasons.

Figure 5 illustrates the normalized horizontal displacements of the 3.6 m high wrapped face wall, constructed with recycled C&D backfill and reinforced with polyester geogrid – at the end of construction and up to a year after construction (Santos et al., 2013). At the end of construction, a maximum outward normalized horizontal displacement of 1.4% at an elevation of 0.83H was recorded. Negative horizontal displacements were recorded close to the crest of the wall with a maximum (Figure 5), indicating body rotation of the reinforced structure according to the authors. This pattern of horizontal displacement was judged to be a consequence of non-uniform deformation of the foundation soil (Santos et al., 2013).

According to Santos et al. (2013), the wall deformations and reinforcement strains were similar to those expected from similar structures constructed with conventional select granular backfills placed over competent foundations.

More recently, Arulrajah et al. (2013d) studied the interface shear strength properties of geogrid-reinforced recycled C&D materials to assess the viability of their use as alternative construction materials. The C&D materials used in their research were recycled concrete aggregates (RCA), crushed bricks (CB) and reclaimed asphalt pavement (RAP), with grading in the 0.075 to 19 mm range.

Following previous research carried out by the same team (Arulrajah et al., 2013a, Rahman et al., 2013a) (Rahman et al., 2013a) biaxial and triaxial geogrids were tested. Table 11 shows the geotechnical characteristics of the different C&D materials investigated by Arulrajah et al. (2013c).

The interface shear strength properties of unreinforced and geogrid-reinforced C&D materials were determined with a large-scale direct shear test apparatus. Table 12 summarizes the peak shear strength properties of unreinforced and geogrid-reinforced C&D materials studied by Arulrajah et al., (2013c).

The highest values of the interface shear strength were achieved with geogrid-reinforced RCA. Unreinforced RCA also revealed higher shear strength than that of CB and RAP (Table 12). RAP was found to have the lowest interface shear strength properties of the studied C&D materials.

According to Arulrajah et al. (2013b), the tensile strength of the geogrid also had an influence on the interface shear strength. Higher interface shear strength properties were obtained with the triaxial geogrids than with the biaxial geogrids. The highest interface shear strength should be attributed to the geogrid configuration (triangular geometry of the polypropylene elements), which promotes the interlocking of the particles of the C&D material, rather than to its highest tensile strength.

As usual with granular materials, the direct shear tests results carried out by Arulrajah et al. (2013c) indicated that the interface shear strength properties of the geogrid reinforced C&D materials were lower than that of the unreinforced material. However this evidence was attributed by Arulrajah et al. (2013d) to the lack of interlocking between the geogrids and the recycled C&D aggregates, as well as the fact that conventional testing method induces a shear plane at the boundary between the lower and upper boxes where the geogrid is placed. Based on this evidence, Arulrajah et al. (2013b) used a modified large scale direct shear test apparatus to characterize interface shear strength properties of geogrid reinforced C&D materials. This modified method uses a geosynthetic-clamping steel frame of 7 mm thickness attached to the top of the lower shear box (Figure 8). Testing the interface with the modified shear box would induce a shear plane 7 mm beyond the geogrid placement level. The thickness of the steel frame (7 mm) was selected since the aggregate size used for road pavement sub-base

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applications is typically less than 14 mm (Arulrajah et al., 2013b) and therefore a shearing plane at the midpoint of the aggregates is achieved.

Arulrajah et al. (2013b) states that with this modified method the provision of a smooth interface is avoided and significant interlock is realised, thereby representing the true field conditions. The authors of this review have a different view about this imposed shearing plane: the modified method proposed by Arulrajah et al. (2013b) induces greater interface shear strength since the failure does not occur at the weaker plane, but this does not mean a better simulation of field conditions.

Three mechanisms can be identified at soil/geosynthetic interfaces (Lopes, 2012): skin friction along the reinforcement, soil-soil friction and passive thrust on the bearing members of the reinforcement. When a shearing plane 7 mm above the interface level is imposed, as proposed by Arulrajah et al. (2013b), only soil-soil friction will be mobilized.

The influence of the soil particle size on soil-geogrid interaction in direct shear movement was studied by Jewell et al. (1985), who concluded that the coefficient of interaction increases with the soil particle size and has its maximum value when the grain size is similar to that of the geogrid apertures. When the grain size is lower than the dimensions of the grid apertures, the failure surface is tangent to the bearing members of the geogrid. If the grain size is similar to that of the geogrid apertures, the soil particles will place against the bearing members and the failure surface will rise to the soil mass.

The aperture sizes of the geogrids studied by Arulrajah et al. (2013b) were 46 mm and 39 mm for the triaxial and biaxial geogrid, respectively. The particle size distribution of the recycled construction and demolition materials ranged from 0.075 mm to 19 mm. So, a failure surface tangent to the bearing members of the geogrids is supposed.

Results of physical, mechanical and environmental characterization of recycled C&D materials, as well as the direct shear behaviour of geogrid/recycled C&D material interfaces were presented by Vieira et al. (2014). A fine grain recycled C&D material coming from the demolition of single-family houses and the cleaning of land with illegal deposition of C&D wastes was studied. Vieira et al. (2014) have concluded that properly selected and compacted recycled C&D materials could exhibit similar shear strength (even greater) than the backfill materials commonly used in the construction of geosynthetic reinforced structures. Their results provide evidence that geogrid/C&D material interfaces show high values of shear strength, with coefficients of interaction in the range of the usual values for soil/geogrid interfaces. Results from laboratory leaching tests have shown that the analysed C&D material fulfilled the acceptance criteria for inert landfill (Vieira et al., 2014).

### 4.3 Other applications

The pioneer reference to the possible reuse of C&D materials in retaining structures was presented by (Lima, 1999). This author stated that C&D materials had the required strength and dimensions for being used as gabion filling materials. Different types of C&D materials (concrete, plaster, bricks, pebbles and bricks with mortar) were also studied by (Nawagamuwa et al., 2012) to verify the possibility of being used as gabion filling material. According to their study, considering the durability and compressive strength of the five selected C&D materials, only concrete could be considered as suitable for use in gabions. All the other four materials failed from either the durability aspect or compressive strength aspect, or both.

In addition to the geotechnical applications mentioned above, other functions to be performed by recycled C&D materials were also studied. Examples of these applications are their use in seawall foundations (Yeung et al., 2006), as alternative pipe backfilling materials (Rahman et al., 2014), in landfill cover layer (Harnas et al., 2013) and in vibro ground improvement processes (McKelvey et al., 2002).

The use of permeable pavements as urban stormwater management systems has been increasing in recent years. Based on this, Rahman et al. (2015) investigated the use of recycled C&D materials (crushed brick, recycled concrete aggregate and reclaimed asphalt pavement) in combination with nonwoven geotextile to assess their suitability as filter material in permeable pavements. Besides physical and geotechnical characterization, hydraulic conductivity tests were also carried out to investigate the effects of variations in the properties of filter media, sediment particle sizes, density of the filter media and clogging effects over time. Rahman et al. (2015) found that the geotextile layer increases pollutant removal efficiency of C&D materials. However, the continuous accumulations of sediments during long periods can cause clogging. In terms of their usage in permeable pavement filter layers, C&D materials have shown geotechnical and hydraulic properties equivalent or superior to those of typical quarry granular materials.

Recycled crushed glass has also been studied in recent years as a potential construction material for geotechnical engineering applications (Arulrajah et al., 2014a, Disfani et al., 2011, Grubb et al., 2006, Wartman et al., 2004). Crushed glass usage as a sustainable material in pavement bases/sub-bases was investigated by Arulrajah et al, (2014a) through field and laboratory evaluation of their performance. The use of recycled glass as backfill material in embankments, drainage blanket, filter media and road pavement material was also evaluated by Wartman et al. (2004).

Several factors, such as the waste stream from which the glass particles have been produced and the crushing process, affect the geotechnical characteristics of recycled glass. Disfani et al. (2011) refer to insufficient knowledge on the geotechnical characteristics of recycled glass as the most important obstacle to its sustainable application in geotechnical engineering.

## 5 CONCLUSIONS

With the increasing world population sustainable development should be of particular importance, and the construction industry can contribute to this aim. Part of the solution to achieving this goal is the use of recycled C&D materials in embankments and roadways construction.

The full or partial replacement of soils and conventional aggregates by C&D materials can contribute significantly to the mitigation of environmental impacts induced by the construction industry, and thereby contribute to the reduction of our ecological footprint.

Overall, the application of recycled C&D materials in the construction industry is progressing quite rapidly in some countries of the EU, more slowly in some other countries, unfortunately (Table 1). The studies that have been developed in recent years have shown the possible use and acceptable performance of C&D materials as recycled aggregate. The use of different types of C&D materials (recycled concrete aggregates, crushed bricks, reclaimed asphalt pavement) in base and sub-base layers of roadways has been proven to be an excellent alternative to natural aggregates without a great loss of infrastructure performance. Among the main conclusions of the studies reported in this review the following should be highlighted: the CBR values achieved with selected C&D materials are, in general, similar to those obtained with natural aggregates (O'Mahony and Milligan, 1991; Nataatmadja and Tan, 2001; Leite et al., 2011; Arulrajah et al., 2013a); some recycled C&D materials, like crushed bricks, may have to be blended with other durable aggregates to enhance their performance in pavement sub-base applications

(Arulrajah et al., 2011); mixed recycled aggregates have shown a good mechanical performance for use in low traffic roads (Barbudo et al., 2012); effective practices to improve the quality of recycled aggregates are very important and should include the selection and removal of impurities and a pre-screening at the beginning of the recycling process (Barbudo et al., 2012).

Studies related to the use of recycled C&D wastes as filling material in geosynthetic reinforced embankments have also been carried out. The reported studies allow us to conclude that recycled C&D materials, when properly selected and compacted, can exhibit similar shear strength to the backfill materials commonly used in the construction of geosynthetic reinforced structures. Geogrid/C&D material interfaces have shown high values of shear strength (Arulrajah et al., 2013c, Santos and Vilar, 2008, Vieira et al., 2014). Notwithstanding the encouraging results, more studies are still needed to promote this application.

Despite all the studies that have been carried out in recent years related to the use of recycled C&DW materials, some of which are reported in this review, there still is a lack of studies carried out from a geotechnical perspective.

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# TABLES

Table 1 - Statistics of the quantities of C&D wastes generated and recycled in the EU-27 (EC DG ENV, 2011).

| Country | Arising (million tonnes) | % Re-used or recycled |
|---|---|---|
| Austria | 6.60 | 60% |
| Belgium | 11.02 | 68% |
| Bulgaria | 7.80 | No data available |
| Cyprus | 0.73 | 0% |
| Czech Republic | 14.70 | 23% |
| Denmark | 5,27 | 94% |
| Estonia | 1.51 | 92% |
| Finland | 5.21 | 45% |
| France | 85.65 | 14% |
| Germany | 72.40 | 86% |
| Greece | 11.04 | 5% |
| Hungary | 10.12 | 16% |
| Ireland | 2.54 | 80% |
| Italy | 46.31 | No data available |
| Latvia | 2.32 | 46% |
| Lithuania | 3.45 | 60% |
| Luxembourg | 0.67 | 46% |
| Malta | 0.80 | No data available |
| Netherlands | 23.9 | 98% |
| Poland | 38.19 | 28% |
| Portugal | 11.42 | 5% |
| Romania | 21.71 | No data available |
| Slovak Republic | 5.38 | No data available |
| Slovenia | 2.00 | 53% |
| Spain | 31.34 | 14% |
| Sweden | 10.23 | No data available |
| UK | 99.10 | 75% |
| EU-27 | 531.38 | 46% |

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Table 2 - Classification of acceptable earthworks materials (adapted from Department of Transport, 1993).

| | Class | General material description | Permitted Constituents |
|---|---|---|---|
| General Granular Fill | 1A | Well graded granular material | Any material or combination of materials, other than material designated as Class 3 in the Contract. Recycled aggregate. |
| | 1B | Uniformly graded granular material | Any material or combination of materials, other than chalk. Recycled aggregate. |
| | 1C | Coarse granular material | Any material or combination of materials, other than material designated as Class 3 in the Contract. Recycled aggregate. |
| General Cohesive Fill | 2A | Wet cohesive material | Any material or combination of materials, other than chalk. |
| | 2B | Dry cohesive material | |
| | 2C | Stony cohesive material | |
| | 2D | Silty cohesive material | |
| | 2E | Reclaimed pulverised fuel ash cohesive material | Reclaimed material from lagoon or stockpile containing not more than 20% furnace bottom ash. |
| Selected Granular Fill | 6I | Selected well graded granular material | Natural gravel, natural sand, crushed gravel, crushed rock, crushed concrete, slag, chalk, well burnt colliery spoil or any combination thereof except that chalk shall not be combined with any other constituent. None of these constituents shall include any argillaceous rock. Recycled aggregate except recycled asphalt. |
| | 6J | Selected uniformly graded granular material | |

| | | | |
|---|---|---|---|
| Selected Cohesive Fill | 7C | Selected wet cohesive material | Any material, or combination of materials, other than unburnt colliery spoil, argillaceous rock and chalk. |
| | 7D | Selected stony cohesive material | |

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Table 3 - Grading requirements for acceptable earthworks materials (adapted from Department of Transport, 1993).

| Class | Percentage by mass passing the size shown | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 500 mm | 300 mm | 125 mm | 75 mm | 14 mm | 2 mm | 600 µm | 63 µm | 2 µm |
| 1A | | 100 | 95-100 | | | | | < 15 | |
| 1B | | | 100 | | | | | < 15 | |
| 1C | 100 | | 10-95 | | | | 0-25 | < 15 | |
| 2A & 2B | | | 100 | | | 80-100 | | 15-100 | |
| 2C | | | 100 | | | 15-80 | | 15-80 | |
| 2D | | | 100 | | | | | 80-100 | 0-20 |
| 6I & 6J | | | 100 | 85-100 | 25-100 | 15-100 | 9-100 | < 15 | |
| 7C | | | 100 | 85-100 | 83-100 | 80-100 | 60-100 | 15-45 | 0-20 |
| 7D | | | 100 | 85-100 | 40-90 | 15-79 | 15-75 | 15-45 | 0-20 |

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Table 4 - Gradation requirements for soil-aggregate materials according to (ASTM D 1241 – 07, 2007).

| Sieve Size | Weight Percent Passing Square Mesh Sieves | | | | | |
|---|---|---|---|---|---|---|
| | Type I | | | | Type II | |
| | Gradation A | Gradation B | Gradation C | Gradation D | Gradation E | Gradation F |
| 50.0 mm (2 in.) | 100 | 100 | - | - | - | - |
| 25.0 mm (1 in.) | - | 75 – 95 | 100 | 100 | 100 | 100 |
| 9.5 mm (3/8 in.) | 30 - 65 | 40 – 75 | 50 – 85 | 60 – 100 | - | - |
| 4.75 mm (No. 4) | 25 – 55 | 30 – 60 | 35 – 65 | 50 – 85 | 55 – 100 | 70 – 100 |
| 2.0 mm (No. 10) | 15 – 40 | 20 – 45 | 25 – 50 | 40 – 70 | 40 – 100 | 55 – 100 |
| 425 µm (No. 40) | 8 – 20 | 15 – 30 | 15 – 30 | 25 – 45 | 20 – 50 | 30 – 70 |
| 75 µm (No. 200) | 2 – 8 | 5 – 15 | 5 – 15 | 8 – 15 | 6 – 15 | 8 – 15 |

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Table 5 – Gradations and mixtures for sub-base, base and surface courses materials (adapted from ASTM D1241-07, 2007).

| Application | Type I | | | | Type II | |
|---|---|---|---|---|---|---|
| | Gradation A | Gradation B | Gradation C | Gradation D | Gradation E | Gradation F |
| Sub-base materials | X | X | X | X | X | X |
| Base Course materials | X | X | X | X | X | X |
| Surface Course materials | | | X | X | X | X |

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Table 6 - Laboratory test results for RCA base course studied by Chini et al. (2001).

| Laboratory test | Results for RCA | Requirements of Natural Aggregate Standards |
|---|---|---|
| Gradation | - | Fail, RCA was found to be deficient amount of material finer than 9.525 mm |
| Limerock bearing ratio (LBR) | 238% | Pass, 238 % > 100 % |
| LA abrasion | 40% | Pass, 40 % < 45 % |
| Soundness sodium sulphate | 34% | Fail, 34 % > 15 % |
| Sand equivalent | 75% | Pass, 75 % > 28 % |

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Table 7 - Characterization of the different C&D recycled aggregates for roadway construction (adapted from Vegas et al., 2008).

| Parameter | C&D recycled aggregates | | | Limits (%) (PG3) |
|---|---|---|---|---|
| | From concrete | From ceramic | From mixed debris | |
| Plasticity | Non-plastic | Non-plastic | Non-plastic | SS: LL < 30 and PI < 10<br>AS: LL < 40 and PI < 4 IF LL < 30<br>TS: LL < 65 and PI > 0.73(LL-20) IF LL > 40 |
| CBR | 82–107% | 64–91% | 69–90% | SS: CBR > 20%<br>AS: CBR > 5%<br>TS: CBR > 3% |
| Organic matter | 0.47–0.62% | 0.12–0.38% | 0.44–0.90% | SS: <0.2%<br>AS: <1%<br>TS: <2%<br>MS: <5% |
| Soluble salts | 1.76–2.99% | 0.14–1.46% | 2.88–3.30% | SS: <0.2% and AS: <0.2% |
| Water-soluble sulphates | <0.20–0.31% | 0.23–0.42% | 0.61–0.86% | TS: <1% |
| Gypsum content | 0.32–2.03% | <0.20–2.57% | 0.98–1.20% | TS: <5% |

LL: liquid limit; PI: plasticity index

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1065 Table 8 – Some geotechnical properties of C&D materials studied by Arulrajah et al.

1066 (2013a).

| | RCA | CB | WR | RAP | FRG | Regular Quarry Material |
|---|---|---|---|---|---|---|
| Gravel (%) | 50.7 | 53.6 | 44.7 | 48.0 | 0.0 | |
| Sand (%) | 45.7 | 39.8 | 45.1 | 46.0 | 94.6 | |
| Fines (%) | 3.6 | 6.6 | 10.2 | 6.0 | 5.4 | < 10 |
| USCS classification | GW | GW | SW | GW | SW | |
| $C_u$ | 31.2 | 44.4 | 74.7 | 25.6 | 7.5 | |
| $C_c$ | 0.9 | 2.0 | 5.4 | 2.5 | 1.5 | |
| Los Angeles abrasion (%) | 28 | 36 | 21 | 42 | 25 | < 40 |
| CBR (%) | 118 - 160 | 123 - 138 | 121 - 204 | 30 - 35 | 42 - 46 | > 80 |
| Maximum dry density (kN/m$^3$) | 19.13 | 19.73 | 21.71 | 19.98 | 17.40 | > 17.5 |
| Optimum moisture content (%) | 11.0 | 11,25 | 9,25 | 8.0 | 10.5 | 8-15 |
| Organic cont. (%) | 2.3 | 2.5 | 1 | 5.1 | 1.3 | < 5 |
| pH | 11.5 | 9.1 | 10.9 | 7.6 | 9.9 | 7 - 12 |
| Hydraulic conductivity (m/s) | $3.3 \times 10^{-8}$ | $3.3 \times 10^{-9}$ | $3.3 \times 10^{-7}$ | $3.3 \times 10^{-7}$ | $3.3 \times 10^{-5}$ | $> 3.3 \times 10^{-9}$ |
| Flakiness index | 11 | 14 | 19 | 23 | | < 35 |
| Cohesion (kPa) | 44 | 41 | 46 | 53 | 0 | > 35 |
| Friction angle (º) | 49 | 48 | 51 | 37 | 37 | > 35 |
| Resilient modulus 90% of the OMC | 239 - 357 | 301 - 319 | 121 - 218 | | | 125 - 300 |
| Resilient modulus 80% of the OMC | 487 - 729 | 303 -3 61 | 202 - 274 | | | 150 - 300 |
| Resilient modulus 70% of the OMC | 575 - 769 | 280 - 519 | 127 - 233 | | | 175 - 400 |

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Table 9 – Properties of C&D materials studied by Santos and Vilar (2008).

| Properties | Mean value | Coefficient of Variability (%) |
|---|---|---|
| Specific Gravity | 2.819 g/cm$^3$ | 3.1 |
| Unit Dry Weight | 1.844 g/cm$^3$ | 2.1 |
| Optimum Water Content | 14.9 % | 13.3 |
| CBR | 60 % | - |
| Friction angle | 41° | - |
| Cohesion | 13 kPa | - |
| pH | 9.1 | 4.3 |

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Table 10 – Summary of results obtained by Santos and Vilar (2008) in the pullout tests.

| Confining pressure (kPa) | Backfill | Pullout resistance (kN/m) | Adherence factor |
|---|---|---|---|
| 25 | Sand | 17.60 | 0.94 |
| | C&D | 31.46 | 1.3 |
| 50 | Sand | 30.36 | 0.81 |
| | C&D | 40.97 | 0.85 |
| 100 | Sand | 37.23 | 0.50 |
| | C&D | 49.92 | 0.52 |

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Table 11 – Geotechnical Properties of C&D materials study by Arulrajah et al. (2013c).

| Geotechnical Properties | RCA | CB | RAP |
|---|---|---|---|
| Particle density – coarse (g/cm$^3$) | 2.70 | 2.40 | 2.34 |
| Particle density – fine (g/cm$^3$) | 2.60 | 2.48 | 2.33 |
| Max dry density (g/m$^3$) | 2.08 | 2.04 | 1.94 |
| Optimum moisture Content (%) | 12.5 | 12.75 | 8.30 |
| California bearing ratio (%) | 172 | 135 | 39 |

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Table 12 – Peak shear strength properties of unreinforced and geogrid-reinforced C&D materials obtained by Arulrajah et al. (2013c).

| Material | Cohesion (kPa) | Friction angle (°) |
|---|---|---|
| RCA | 95 | 65 |
| RCA+biaxial geogrid | 75 | 50 |
| RCA+ triaxial geogrid | 83 | 52 |
| CB | 87 | 57 |
| CB+biaxial geogrid | 67 | 45 |
| CB+ triaxial geogrid | 80 | 49 |
| RAP | 15 | 45 |
| RAP+biaxial geogrid | 6.5 | 40 |
| RAP+ triaxial geogrid | 13 | 42 |
| Typical construction materials - dense sands and gravels | - | 40-48 |

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1144 **FIGURES**

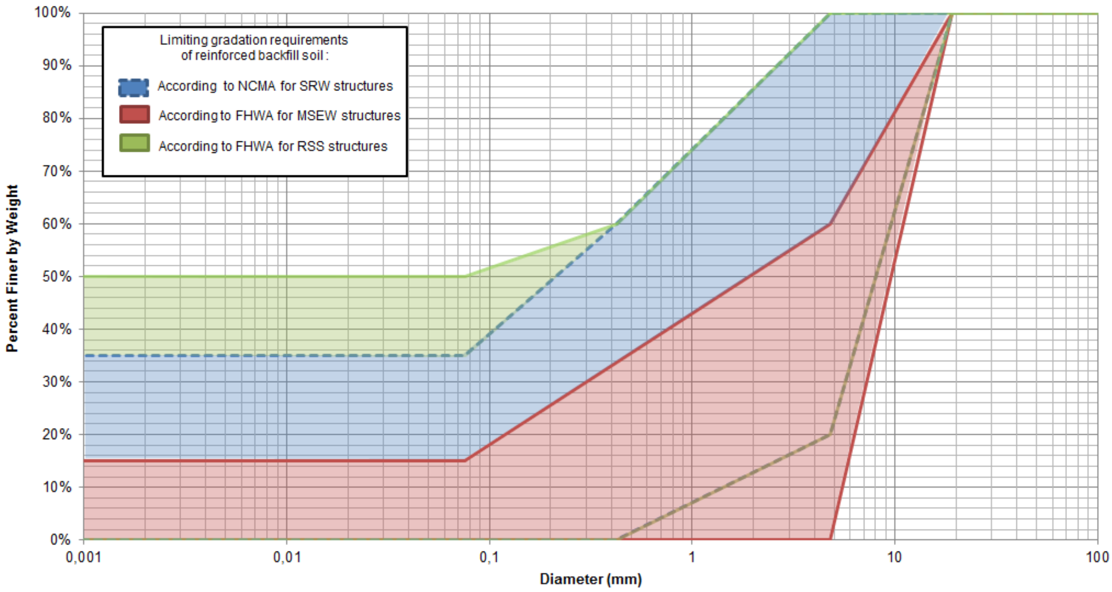


Figure 1 - Particle sizes recommended by FHWA (2010( and NCMA (2010).

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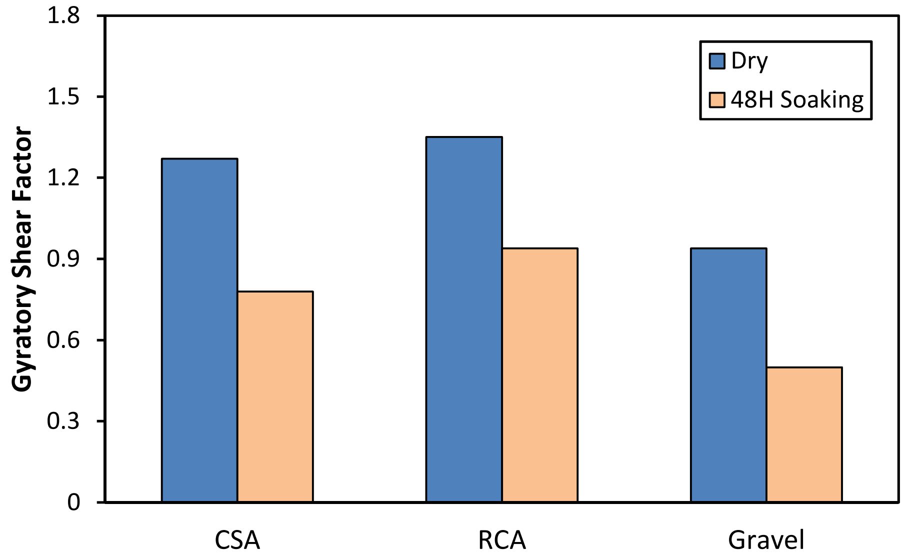
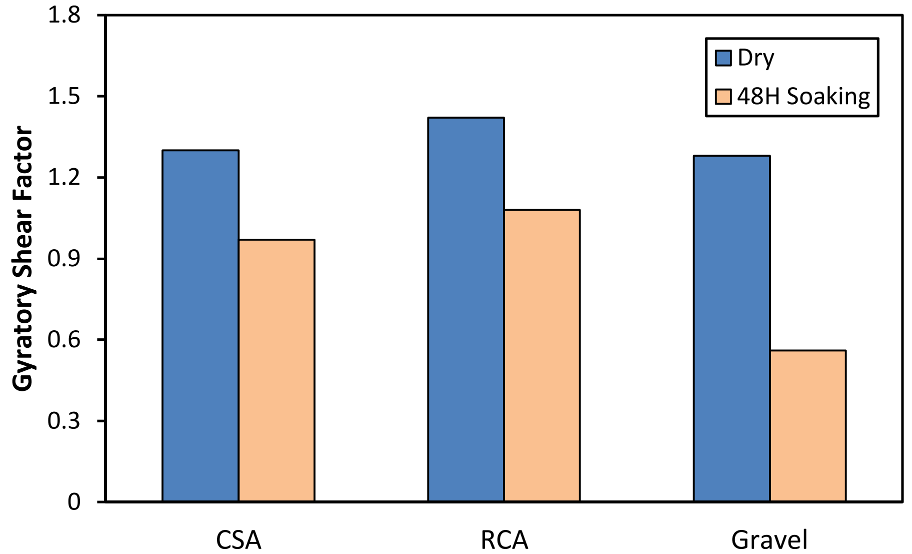



a)




b)

Figure 2 - Comparison of gyratory shear factor for different aggregates (Park, 2003): a) GMT-150 revolutions; b) GMT-300 revolutions.

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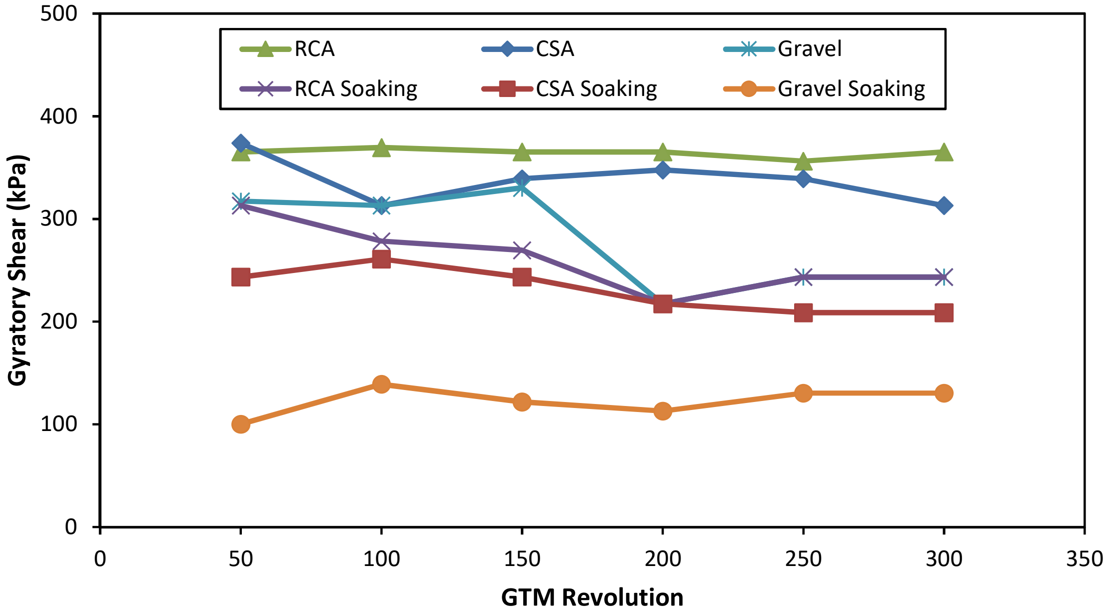


Figure 3 - Evolution of gyratory shear with GMT revolutions for different aggregates (adpated from Park, 2003).

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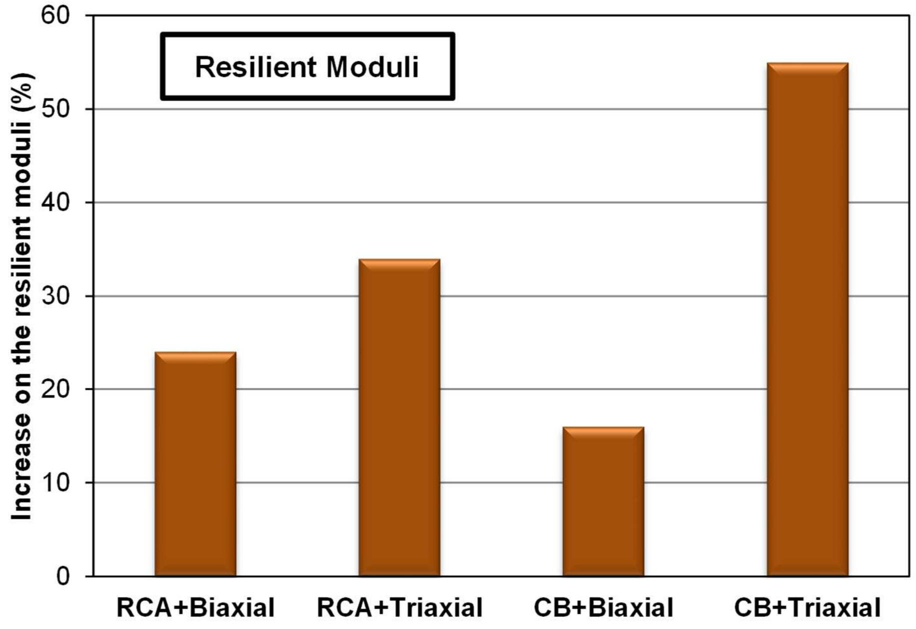
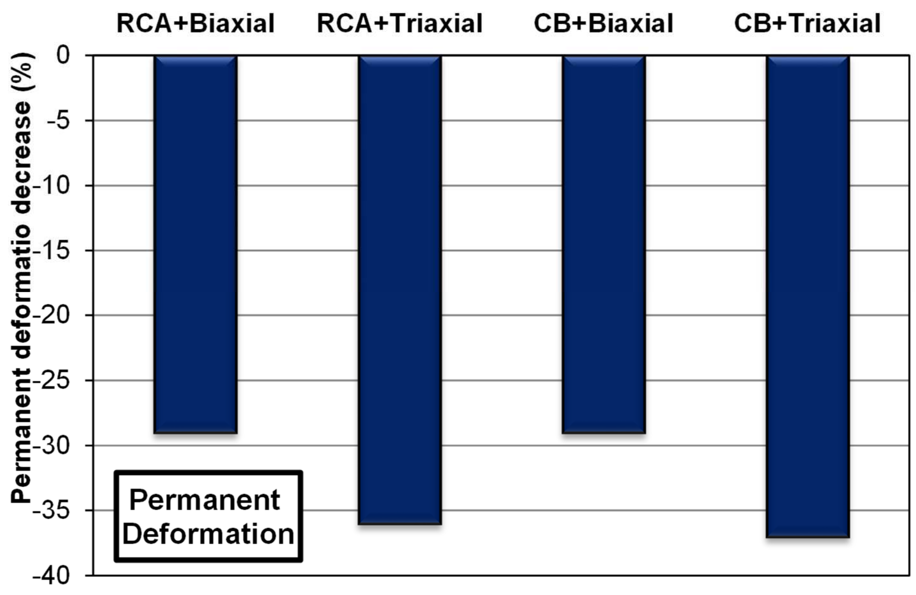



a)




b)

Figure 4 – Effects of the geogrid reinforcement achieved by Rahman et al. (2013) on: a) the resilient moduli; b) on permanent deformations.

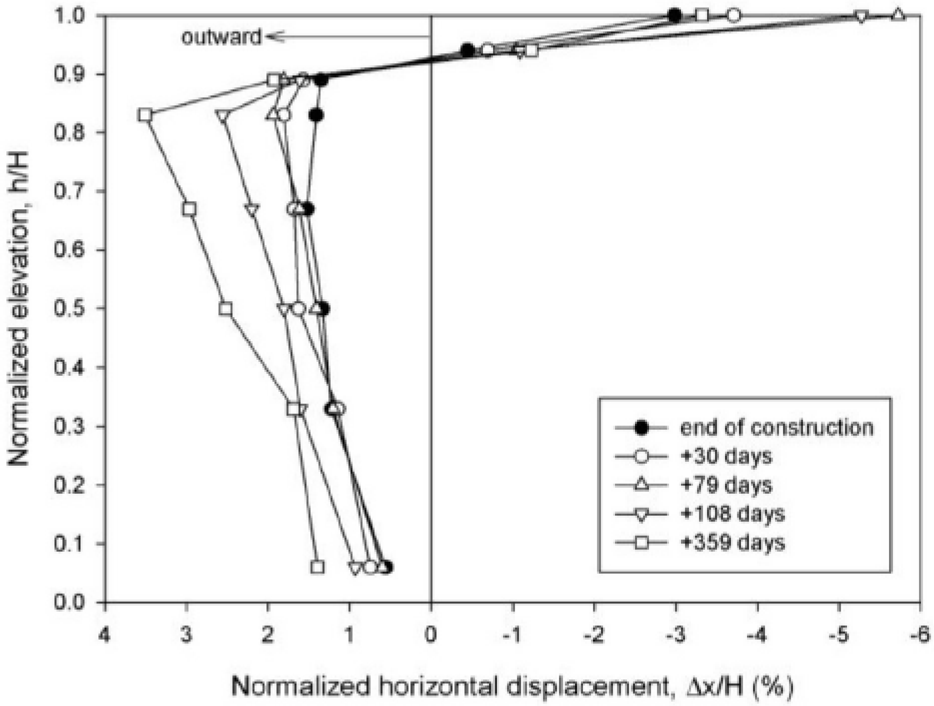



Figure 5 – Normalized horizontal displacements of the wall face recorded by Santos et al. (2013).

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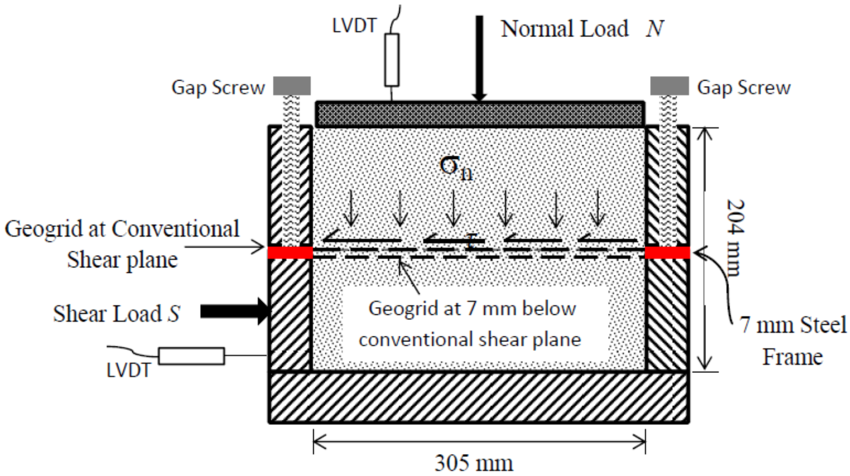


Figure 6 – Modified lower direct shear box with steel frame (Arulrajah et al., 2013b).