Construction and Building Materials 65 (2014) 201–217

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production

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HIGHLIGHTS

- State of the art systematic review on the study of recycled aggregates for concrete production.
- Statistical analysis of the main properties of recycled aggregates and comparison with those of conventional aggregates.
- Proposal of a performance-based classification system for recycled aggregates meant for concrete production.

ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form 21 April 2014
Accepted 22 April 2014
Available online 20 May 2014

Keywords:
Recycled aggregates
Construction and demolition waste
Concrete
Contaminants
Density
Water absorption
Mechanical properties
Chemical composition
Size
Shape

ABSTRACT

Arising from a systematic, as opposed to narrative, literature review of 236 publications published over a period of 38 years from 1977 to 2014, the paper examines the factors affecting the physical, chemical, mechanical, permeation and compositional properties of recycled aggregates sourced from construction and demolition waste, intended for concrete production. Classifications based on their composition and contaminants have been studied. The data were collectively subjected to statistical analysis and a performance-based classification, mainly for use in concrete construction, is proposed. The results allowed producing a practical means of measuring the quality of recycled aggregates, which can be used to produce concrete with predictable performance.

1. Introduction

Development has inflicted severe damage on the environment and may endanger its sustainability. The exploitation of natural resources, in particular non-renewable resources, for construction purposes leads to millions of tonnes of construction and demolition waste (CDW) every year. Since most countries have no specific processing plan for these materials, they are sent to landfill instead of being reused and recycled in new construction.

1.1. Background

The global market for construction aggregates is expected to increase 5.2% this year, and again next year, up to 48.3 billion tonnes [1]. In the United States, the Environmental Protection Agency [2] estimated that the generation of debris, from the construction, demolition, and renovation of residential and non-residential buildings in 2003, was close to 170 million tonnes. According to Eurostat [3], the total amount of waste generated in the European Union in 2010 was over 2.5 billion tonnes, of which almost 35% (860 million tonnes) derived from construction and demolition activities and 27% (672 million tonnes) belonged to mining and quarrying operations. In 2010, these two economic sectors generated more waste than any other (Fig. 1a). Of the total waste

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http://dx.doi.org/10.1016/j.conbuildmat.2014.04.117
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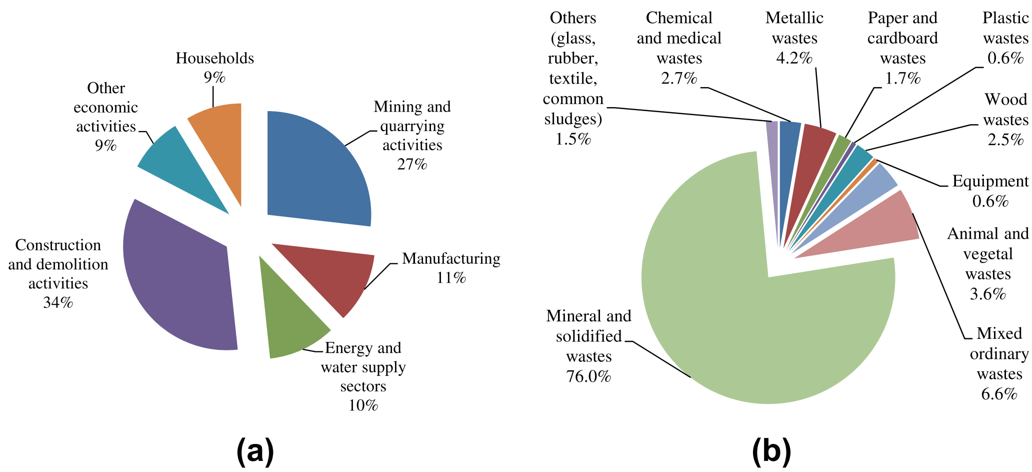

Fig. 1. Total waste generated in European Union according to: (a) economic activity; (b) waste category [3].

generated by the construction and demolition activities, and mining and quarrying operations, 97% was mineral waste or soils (excavated earth, road construction waste, demolition waste, dredging spoil, waste rocks, tailings, and others). The share of mineral and solidified wastes in relation to the total amount of waste produced was 76% (Fig. 1b).

Whilst recycling is often cited as the best way to manage CDW, there are still several obstacles to using recycled aggregates (RA) in construction:

- Lack of confidence of clients and contractors.
- Uncertainty as to its environmental benefits.
- Lack of standards and specifications that concrete producers can take into account.
- Low quality of the final product, owing to lack of knowledge and/or interest of CDW recycling plant owners.
- Distance between construction and demolition sites and recycling plants.
- Lack of a consistent supply of good quality RA that can satisfy existing demand.

Hoping to encourage and promote the use of RA, government agencies the world over have often introduced levies and legislation in an attempt to overcome barriers, with varying degrees of success. The European Union Directive No. 2008/98/CE [4] encourages the reuse and recycling of waste materials. It is expected that by 2020 new building structures will include at least 5% of recycled materials. These include paper, metal, plastic and glass, from households or other origins whose waste stream is similar to that of households, and also non-hazardous CDW. The variability of building construction methods naturally means that RA sourced from construction and demolition activities will vary in quality and composition, which will indubitably produce new construction materials of varying quality.

1.2. Importance of selective demolition

The approach to demolishing a building structure may be either conventional or selective. The construction and demolition industries still see the concept of selective demolition as being of debateable economic benefit and little practical value. A detailed economic analysis of conventional *versus* selective demolition [5] found that although the economic viability of selective demolition (with less material sent to landfill) depends largely on local conditions (i.e. labour costs, tipping fees, and market prices for recovered materials), it may ultimately be more profitable than the conventional demolition approach.

From an environmental point of view, too, there are clear benefits from using selective demolition [6,7], mainly arising from a direct reduction in the material sent to landfill. In another study [8], a life cycle assessment was performed on the environmental impacts of several conventional and selective demolition method scenarios. The results were very clear in that the selective demolition approach ensured a significant reduction of the environmental impacts specifically caused by climatic change, acidification, summer smog, nitrification and amount of heavy metals. These result from the emission of a wide array of substances, all of which are known to be important pollutants.

It was also found [8] that partial selective demolition (i.e. removal of non-structural elements for recycling, followed by traditional demolition of all other materials and their disposal in landfill) does not imply a significant environmental impact reduction. The use of this incomplete approach may even slightly aggravate the impact on the environment by increasing transportation distances and other impacts. This is largely because the means of transportation mostly used in the construction and demolition industries is road, with diesel trucks. From a complete life cycle perspective and to gain an obvious environmental impact reduction, it was estimated that the recycling rate must rise to above 90% and efforts must be made to incorporate the resulting materials into new construction.

Apart from the aforementioned advantages of the selective demolition approach, it is also the most effective way of minimizing the amount of contaminants in CDW materials. The recycling industry is well aware of this fact and realizes that if this is not done the final product is worth a great deal less, which would be very harmful to further development of the sector. Therefore, recycling plants try to promote selective demolition by imposing strict control procedures and different gate fees depending on the origin, composition and amount of contaminants present in these materials [9].

1.3. Recycled aggregate use in construction

There is a high potential for reuse and recycling of CDW since most of its components have a high resource value. There is a reuse market for RA derived from CDW in landscaping, road construction (unbound sub-base and base layers, hydraulically bound layers, bituminous surface pavements), cementitious mortars and concrete [10]. Even though the properties and types of RA studied in this paper are predominantly of interest for mortar and concrete production, several studies have obtained positive outcomes after using them in various applications for road construction [11–27]. Generally, when incorporating RA from masonry rubble or asphalt-based materials, the mechanical performance declines [17,21,23]; however, these materials showed enhanced performance with the use of RA from crushed concrete [11,16,18–20,22,24–26]. This improvement can be explained by the self-cementing properties of the unhydrated cement of the crushed concrete particles and rougher surface, which increases inter-particle friction, causing even load redistributions.

A serious concern about using recycled materials in road construction is their leachability. Uncontrolled processed CDW may contain leachable hazardous materials to human health and the environment (e.g., lead-based paint, mercury-contained in fluorescent lamps, treated wood, and asbestos) that in turn can contaminate groundwater [28,29]. These factors need to be taken into account when using RA in applications susceptible to leaching.

1.4. Industrial waste materials used in concrete production

The generation of industrial by-products has been increasing at an alarming rate. Depending on the type of industry, there is a wide range of industrial by-products. One such type of material is ground granulated blast furnace slag (GGBS), which is typically obtained from blast-furnaces of steel industries. GGBS, which is mostly comprised of silicates and alumina, may have binding properties and thus can be used as partial cement replacement. There have been some studies on the use of this material as aggregate and part of the binder in the production of concrete [30–33]. It is clear that GGBS is most beneficial if it is used as cement replacement, since increasing its incorporation may enhance workability. Consequently, a smaller amount of water is required in order to maintain the same workability as that of a corresponding ordinary Portland cement concrete mix, leading to enhanced mechanical performance. The use of this material has also led to superior resistance to sulphate attack and to chloride ion penetration, in comparison to ordinary Portland cement.

Fly ash or pulverised fuel ash is a by-product obtained from coal burning industries. Similarly to GGBS, it is comprised of silicates and alumina, and, when used as partial cement replacement, may cause pozzolanic reactions. The effects of using fly ash in concrete are well-known [34–39]. A judicious use of this material may lead to improvements in concrete workability, pumpability, cohesiveness, finishing, mechanical and durability performance.

The abundant production and consumption of glass (especially in bottle manufacturing) calls for the need of additional recycling methods for this product. Besides the typical recycling process into new bottles, there are several studies that have assessed its application in the production of concrete [40–50]. Generally, the incorporation of glass waste aggregates causes a decrease in the mechanical performance of concrete. This decrease is mainly attributed to the fragile behaviour of glass waste aggregates and to the difficulty in obtaining proper bond strength between them and the cement paste. However, the use of very fine glass waste aggregates, up to given replacement levels, may lead to a filler effect, improving some mechanical properties and also the durability-related performance (reduced permeability and chloride ion penetration).

The use of plastic waste as a natural aggregate substitute in concrete is a relatively recent concept. One of the first significant reviews on the use of waste plastic in concrete [51] focused on the advantages and financial benefits of such use, besides its effects on the physical and mechanical properties. There have been many studies on the use of plastic waste aggregates in the production of concrete [52–60]. There is a common ground in that the use of plastic waste aggregate in the production of non-structural concrete is viable, even though the performance of most properties strongly declines.

At the end of its life cycle, the final destination of a tyre may vary greatly: from illegal disposal; landfill disposal; energy recovery as fuel; and introduction of ground tyre waste aggregate in hot mix asphalt production. The rising production of rubber-based products has led to a growing interest by several authors [61–66], in alternative recycling methods, specifically in their use as aggregates, fillers and partial cement replacement, in the production of concrete. The use of increasing contents of these materials causes significant losses in mechanical performance. Rubber waste aggregates, which have very low moduli of elasticity, act as voids in concrete when subjected to loading. There is, however, some improvement in resistance to chloride ion penetration and to abrasion.

A number of experimental research campaigns were performed on the use of other unconventional aggregates from industrial by-products, such as stone slurry [67], leather [68], ethylene–vinyl acetate (EVA) [69,70], oyster shells [71], palm tree shell [72] and even sewer sludge [73–75], for the production of concrete. Generally, the use of these materials as NA replacement causes a significant decline in the mechanical and durability-related performance of concrete, unless when added in small percentages and as ultra-fine material.

The approach adopted generally tends to assess the effect of RA directly by evaluating the performance of the resulting concrete without considering the nature and characteristics of the aggregate used. This makes the meaningful assessment of the role of the aggregate(s) extremely difficult, if not impossible. Thus, the main purpose of this study was to carry out a systematic review of the literature on the physical and chemical characteristics of RA and see how these can affect the concrete produced. Physical properties such as size and shape, density, water absorption, mechanical properties, mineralogical composition and contaminants, were examined. The data collected from this review enabled a statistical analysis to be performed on the main influencing physical properties of aggregates, and this led to the creation of the performance-based classification system of RA that is proposed in this paper.

2. Recycled aggregates sourced from construction and demolition wastes

2.1. Classification

The three main types of material derived from most CDW are crushed concrete, crushed masonry, and mixed demolition debris. After crushing and undergoing beneficiation in certified recycling plants, the resulting aggregates may be assigned to one of the four following categories.

2.1.1. Recycled Concrete Aggregates (RCA)

Concrete is found in most RA because it is the most used construction material in structural applications. Organizations in various countries have developed specifications [76–90] which include a definition for RCA. Many of them [80,84,85,87] seem to agree that to be considered RCA they must comprise a minimum of 90%, by mass, of Portland cement-based fragments and NA. In the proposed amendment to EN 12620 [78], crushed concrete is classified by the designation Rc. This category also includes mortar and concrete masonry units. It is intended that this will lead to grades of RA in which: (i) $Rc \geqslant 90\%$, (ii) $Rc \geqslant 70\%$, and (iii) $Rc < 70\%$, where the quality of the RA is determined by the recycled brick (Rb) content.

2.1.2. Recycled Masonry Aggregate (RMA)

Masonry rubble is a collective designation for various mineral building materials resulting from the construction and demolition of buildings and civil engineering structures. This family of materials may include aerated and lightweight concrete blocks, ceramic bricks, blast-furnace slag bricks and blocks, and sand-lime bricks. Masonry rubble often contains mortar rendering and burnt clay materials such as roofing tiles and shingles [10]. It is composed of a minimum of 90%, by mass, of all the materials mentioned above. RA with high recycled brick content are commonly produced by best-practice recycling centres in which a concerted effort has been made to separate concrete and asphalt to other stockpiles.

2.1.3. Mixed Recycled Aggregates (MRA)

This material is composed of crushed and graded concrete and masonry rubble. The resulting aggregate is a mixture of two main components obtained from the beneficiation of CDW. Some specifications [77,85] establish its composition as less than 90%, by mass, of Portland cement-based fragments and NA. In other words, it may contain several other common CDW materials such as masonry-based materials (ceramic, light-weight concrete).

2.1.4. Construction and Demolition Recycled Aggregates (CDRA)

Throughout this investigation, it was found that, on the whole, the literature contains limited information on the origin and composition of aggregates and so, where it was not possible to fully categorize the RA they were deemed CDRA. In other cases, RA contained high levels of contamination (e.g. asphalt, glass, plastics, wood) and were also classified into this category since they did not belong to any of the others (RCA, RMA, MRA). These materials may be the result of waste coming from construction and demolition sites that have not been through any type of sorting and therefore may contain valuable materials as well as contaminants.

2.2. Contaminants

The variety of contaminants that can be found in RA from the demolition of existing structures can severely degrade the strength of concrete made with them. Such materials include asphalt, gypsum, metals, plastic, rubber, soil or wood [91].

2.2.1. Asphalt

Bituminous materials have a general effect of reducing strength, depending on their construction application. Hansen [10] reported that the addition of 30% by volume of asphalt reduced the compressive strength by about 30%. Other authors [92] noticed a 75% compressive strength loss with a replacement level of 64%, by weight of total aggregate content. The proposed amendment to EN 12620 [78] will allow the use of RA with a maximum bituminous materials content of 10%. However, in all likelihood many producers will aim to produce RA meeting strict limits of 5% [77] or even 1% by mass [90].

2.2.2. Glass

This material is usually removed from buildings prior to demolition and, given the recycling efforts in most of the UK and Europe, it tends not to be present in CDW and RA. This pre-sorting is vital because of its similar density to stone's and brick's, which makes it difficult to separate glass from the rest of the heavyweight materials through wet separation or air sifting procedures. Also, because glass is brittle it usually ends up in the fines content following the crushing procedures in recycling plants, which makes recycled sands more liable to having high percentages of this contaminant than the coarser fractions. In the proposed amendment to EN 12620 [78], as well as in many other specifications for RA [77,79,80,86,87], glass content is specified not to exceed 1% by mass.

2.2.3. Other constituents

Organic materials, for example wood and plastic, are often difficult to separate from CDW prior to crushing. Good practice is to separate these materials using air blowers, water processing (they tend to float to the surface) or sometimes by hand from a conveyor belt moving between the primary and secondary crushing procedures. Any non-floating wood, paper and plastic remaining within RA are classified as "other constituents". Wood and plastic, which float in water, are classified separately as floating non-stone material and content may be limited to a maximum of 0.1% by mass.

Although smaller than 4 mm, soil and clay particles frequently stick to stone and brick. If not removed, their presence may adversely affect the properties of concrete. However, washing RA prior to use should remove most soil and clay. Like non-floating wood and plastic, clay and soil are classified as "other constituents".

After jaw crushing, ferrous metals are usually removed from CDW by means of magnetic belts, whilst eddy currents may be used to remove non-ferrous metals. In addition, hand picking may be used at recycling plants to remove metals from a moving conveyor belt prior to the use of a secondary crusher. Both ferrous and non-ferrous metals are also classified as "other constituents".

It has been suggested [10] that strict limits should be placed on the gypsum content to prevent sulphate expansion. In the Netherlands, CDW containing gypsum are regarded as contaminated. These contaminated CDW, along with sewer sand and contaminated soil, must be extensively washed before they can be used to produce RA. In the proposed amendment to EN 12620 [78], gypsum is classified in the family of "other constituents".

2.3. Chemical composition

Ascertaining the chemical composition of RA is important because the history and properties of the original materials of CDW are not likely to be known. Considering the vast range of environments and conditions that these materials have been exposed to, their chemical composition (e.g. sulphate, chloride and alkali content) could compromise the performance of concrete. Therefore, the chemical composition of the RA must be known for limitations to be imposed that will result in good quality aggregates, thus preventing complications arising from their use.

2.3.1. Sulphate content

Water-soluble sulphates in RA (sourced from gypsum plaster) are potentially reactive and may give rise to expansive reactions [78]. Gypsum occurs in finely dispersed form and originates mainly from plasterwork. Gypsum has a negative effect on the material's quality for reasons of solubility, low hardness and low density.

By performing a statistical analysis on RA derived from different sources, researchers [93] found that that the soluble sulphate content in both water and acid tests is strongly influenced by the percentage of gypsum and crushed clay brick in the RA. It was also found that materials from which large contaminants were not selectively removed had the highest values of sulphate content.

It has been suggested that RCA may have higher sulphate content than NA because of sulphates from cement of the adhered mortar [94]. A high correlation was found between the adhered mortar content and sulphate content (i.e. samples with higher mortar content had higher sulphate content), though the sulphate content limit of 1.0% was met by every sample, as per EN 12620 [78].

Another investigation [95] showed that there were no concerns about expansion resulting from the use of gypsum-contaminated

RCA, provided the gypsum content was sufficiently low (i.e. the total sulphate content of the aggregate was less than 1% by mass).

According to BS 8500-2 [77], the maximum acid-soluble sulphate content of RA must be determined on a case-by-case basis. However, setting a very narrow limit for the acid-soluble sulphate content may unnecessarily exclude the use of RA. Most specifications concerning the use of RA in concrete have established a maximum sulphate content, by mass, of 0.8% [79,80,84,87] or 1.0% [85,86,88–90]. The proposed amendment to EN 12620 [78] would include two categories for RA based on water-soluble sulphate content: (i) with a limit on water-soluble sulphate content of 0.2%, by mass, and (ii) with no limit.

2.3.2. Chloride content

Structural concrete containing RA with high chloride content may deteriorate more rapidly due to the corrosion of reinforcement bars. For this reason, it is important to establish strict limits for the chloride content in RA.

Researchers [96] found that RA, sourced from concrete subjected to marine/estuarine environments, may have a high soluble chloride content. This would clearly restrict the use of such RA in steel reinforced concrete. The use of contaminated aggregates consequently needs a specific approach to guarantee a sufficiently low concentration of chloride or sulphate ions. Chlorides contaminating the RA may leach if they are soaked in water. Washing with water is one way of reducing the concentration of these constituents because they are not linked to the cementitious microstructure and are thus easy to remove from RCA. After a thorough washing or total immersion in water for at least 2 weeks, the amount of chlorides decreases to a point where these RA can be used in concrete and even in reinforced or pre-stressed concrete without any risk of corrosion [97].

In specifications for the use of RA, particularly those containing concrete or mortar, where chlorides may be combined in the calcium aluminate and other phases, limits between 0.01% and 1.0%, by mass of cement, were placed on the chloride content, based on the sum of the contributions from all constituents. The total content of chlorides is unlikely to be extracted using water in the procedures described in EN 1744-1 [98], even if the sample is ground to a fine powder before extraction [78]. Chloride contributions from RCA for use in this calculation are measured by an acid-soluble test [99] that provides a worst-case value [95] and probably overestimates the availability of chlorides, thus providing a margin of safety [78].

2.3.3. Alkali content

The presence of alkalis, usually from cement, and reactive silica in aggregates may lead to expansive alkali-silica-reaction. Care should therefore be taken to limit the alkali content of the constituents of concrete. Concerns are often raised over the use of RA because they can contain fractions of alkali-rich hydrated cement in the crushed concrete fractions, as well as alkalis from the product. In one specific experimental research [100], it was shown that in most cases the total equivalent sodium oxide values for Portland cement concrete containing RCA are below the recommended limit of 3.5 kg/m^3. As a result, these RCA could be regarded as a normal reactivity aggregate, as was also observed in other studies [96,101,102]. In general, it is appropriate to regard RA as a potentially reactive aggregate unless it has been specifically established as non-reactive. In both cases, the possibility of unpredictable composition variability should be considered [78].

2.4. Size and shape

The type of crushing devices used to break down larger pieces and the number of processing stages influence the size and shape of the resulting aggregates. The recycling process normally uses primary and secondary crushing stages. Jaw crushers, which are typically used in the primary crushing stage, provide the best grain-size distribution of RA for concrete production. A second crushing usually leads to rounder and less sharp particles. Therefore, if RA only undergo a primary crushing process they will tend to be somewhat flat and sharp, as observed by some researchers [103,104]. Cone crushers are suitable as secondary crushers as they normally have a 200 mm maximum feed size and give a more spherical shape to RA. Impact crushers, also used for secondary crushing stages, produce aggregates with a good grain-size distribution and lower flakiness index.

It has been concluded that coarse aggregates meet the size specification range by simply adjusting the setting of the crusher aperture, and that it is reasonably easy to produce good quality coarse aggregates [10]. However, it was found that during the production of fine RA, these tend to become coarser and more angular than any of the standard sands used in the production of concrete [91]. Also, this coarseness and increased angularity are the reasons why the workability of concrete made with these materials may sometimes be a problem.

2.5. Density

The simplest and commonest method for characterizing aggregates is in terms of their specific gravity, i.e. (i) normal weight, (ii) lightweight and (iii) heavyweight. Normal weight aggregates are the largest group of aggregates for concrete and include natural sands, gravels and crushed rocks (e.g. granite, dolerite, basalt, limestone and sandstone). RA also usually belong to this group, along with manufactured aggregates such as air-cooled blast furnace slag and recycled glass aggregates.

Several parameters were identified that may affect the density of RA, as discussed below.

2.5.1. Recycling procedure

Since mortar is less dense than NA, the more adhered cement paste in RCA the lower the density of the aggregates [10,105]. The number of processing stages will determine the amount of mortar adhered to the surface of the aggregates. Researchers [106] who assessed the effects of the number of crushing stages on the properties of RCA found that the more stages there are, the higher the density of the resulting RA due to the cumulative breaking up of adhered cement paste on the surface of the coarse RCA. An outcome of this is the increasing density of the coarse fraction, while the fine fraction density decreases with increasing processing levels. Therefore, for high quality RA the processing stages should not be too few, or too many, otherwise the produced aggregates are too fine to be used in some applications [107].

Another aspect of the recycling procedure is the existence and quality of sorting techniques. Recycling plants separate the major part of light contaminants, such as paper, plastic and wood, using water-based or air-sifting methods.

2.5.2. Quality of the original material

Naturally, the type of the original material also has an influence on the density of the resulting aggregate. The density values of RMA are normally lower than that of RCA because of their higher porosity levels [108]. The particle density values for MRA can be estimated through their composition ratios, since the RMA and RCA contents affect this property. MRA exhibit a decrease in density as the RMA content increases [109].

Concrete mixes with enhanced strength usually require a greater cement content, which, besides increasing packing and yielding a more resistant cement paste, results in a less porous mixture, and so it could be expected that this would increase the density of the resulting aggregates. However, some studies [110–113] have established that RCA from concrete materials of varying compressive strength and subjected to similar recycling procedures had essentially similar density values. However, in another experimental study [114], RCA from three concrete mixes with strength of 60.7, 49.0 and 28.3 MPa had saturated surface-dry particle densities of 2420, 2410 and 2370 kg/m^3, respectively. This downward trend was also observed in other studies [106,115]. It would be reasonable to assume that the strength of the original concrete has some effect on the density of the resulting aggregate.

For RMA, a correlation was found [20] between the density and compressive strength of the original bricks, and the density of the resulting aggregates. The results clearly showed that materials with higher mechanical characteristics resulted in aggregates with higher density values. Similar results were obtained in another research [116], which studied the use of crushed clay bricks as coarse aggregate in concrete. Several aggregates from bricks with various compressive strengths were compared and, despite the low correlation between the two properties, a definite trend was observed, showing that clay bricks with higher compressive strength resulted in aggregates with higher density values. Based on this information, when mixing RCA and RMA (resulting in MRA), the density of the resulting aggregates is expected to increase with the RCA content, regardless of the strength of the source material, and decreases with the RMA content, more so if the strength of the source material is relatively poor.

2.5.3. Size

Several studies [14,94,114,117–121] have shown that there is a clear relationship between the size of RA and their density. In one of these studies [94], which looked at the influence of the attached mortar content on the properties of RCA, it was found that the attached mortar content increases as the fraction size decreases. This can be explained by the recycling processes used. The use of several mechanical processing stages of RA decreases the amount of cement paste adhered to coarse aggregates, and as it is progressively broken up the cement paste accumulates in the fine fraction of the RA [114]. Considering this, it is expected that the density of fine RA is lower than that of the coarse RA, from the same origin [117].

2.6. Water absorption

Generally, NA have water absorption (WA) values between 0.5% and 1.5%, which is normally omitted for most concrete applications. However, more precautions must be taken when using RA because of their greater porosity. RA will almost always exhibit higher WA values than NA, the extent of which vary according to the same factors as those described in Section 2.5 for density.

2.6.1. Recycling procedure

Depending on the processing method, the contents of materials such as unbound aggregates, concrete, brick, asphalt and other contaminants in RA may change. It is known that these materials have varying physical properties, one of which is WA. The WA of an aggregate is directly related to its porosity [122]. Therefore, the WA of RA that have not been subjected to effective sorting or contamination removal techniques will naturally increase due to the presence of highly porous materials (e.g. brick, tiles, wood and soil) [123].

Concrete subjected to a secondary crushing procedure in an impact crusher will normally result in RCA with less adhered mortar than when only a primary crushing procedure is used. Therefore, and since hardened cement paste exhibits higher porosity than that of unbound NA, as the adhered mortar content increases so does the RA's WA [10,94,124].

The process of washing crushed CDW may also have a great effect on the WA of RA. The results of a study [125] showed that, after RA were washed WA values fell by between 35% and 55%. This was because very fine particles were removed, which conferred quite high WA values on the RA.

2.6.2. Quality of the original material

In a study [106] on whether the recycling process harmed the properties of RCA, it was found that the strength of the original material had a slight influence on the WA of the resulting aggregate. In other words, the RA's WA decreased as the strength of the original material increased. This was also observed in other research [115,126]. However, other studies [112,127] showed that the WA remained pretty well unaffected as the strength of the original material increased. Therefore, it can be concluded that the increasing strength of the original material may cause a reduction on the WA of the resulting aggregate.

The porous nature of clay bricks means that aggregates derived from them have higher WA values than NA and RCA do [120]. The degree of porosity of crushed brick aggregates depends on the type of clay used to manufacture the original brick and the duration and temperature of firing. If RMA are to be used as an aggregate in concrete, a more consistent and lower value for the porosity is desirable since it can influence how water is transported within concrete [116]. It was also found that the strength of the original brick has a strong influence on the WA of the resulting RMA [128]. Stronger bricks may result in less porous aggregates and thus lower WA values. Therefore, when comparing two MRA with the same content of RCA and RMA, WA is expected to increase when the strength of the source materials decreases for either type, but more so for the RMA.

As far as MRA are concerned, the use of both RCA and RMA leads to WA values between those obtained for each aggregate type. It is true that for MRA this property is mainly affected by the porous nature of RMA; however, the adhered mortar content also helps to increase the values. The porosity of MRA depends on the RCA and RMA content; however, as RMA are more porous than RCA, higher content of the first material will most definitely increase the WA of the resulting aggregates [93,109,129].

De Brito et al. [130], who studied the effect of multiple recycling on the properties of concrete, found that the WA of RCA progressively increased after each cycle because the adhered mortar content increased. However, considering the small number of cycles performed, it was not possible to conclude with certainty whether this rising trend would go on indefinitely or whether absorption would tend asymptotically to a fixed value.

2.6.3. Size

After various processing stages, coarse RCA have lower WA than the corresponding fine fraction. This can be explained by the increasing amount of crushed cement paste accumulating in the fine aggregate fraction, which increases the resulting WA [113,131].

Poon and Chan [14] studied the properties of coarse and fine RCA and RMA and also found that fine RMA may have higher WA values than the coarser fraction. When RCA and RMA were blended, the resulting aggregate (i.e. MRA) exhibited WA values in between those obtained for each individual aggregate type and they increased as the size of the aggregates decreased.

2.7. Mechanical properties

For a given water to cement ratio, increasing the cement content in a concrete's mix design will eventually lead to constant compressive strength, known as the ceiling strength [132]. For low to medium strength concrete mixes, the compressive strength intrinsically depends on the cement paste strength. However, if the aggregate's compressive strength is around half that of the cement paste, the concrete's compressive strength becomes dependent on the strength of its aggregates, as in the case of lightweight aggregates and RMA, but generally not with RCA [132]. Therefore, it is important to assess the strength of RA to determine the quality of their original materials and gain a better understanding of their effect on the properties of concrete. The mechanical performance of RA was found to be mainly influenced by the recycling procedure used and the quality of the original materials.

2.7.1. Recycling procedure

For NAC, it is widely recognized that the controlling factor limiting the strength of the cement-aggregate matrix is a porous narrow band which forms at the cement paste/aggregate interface called the interfacial transition zone or ITZ. For RAC there are effectively two transition zones, between the old adhered mortar and the original aggregate, and between the old mortar and the new cement paste. Generally, RA have a greater influence than NA on the properties of concrete. One reason for this is that the several processing methods of the RA can result in micro cracks at the original aggregate/adhered mortar ITZ, thus rendering them more susceptible to fragmentation [133].

As mentioned, the number of crushing stages has a great influence on the amount of cement paste adhered to RCA, which is generally its weakest area. It is therefore expected that high amounts of this material will affect the mechanical performance of RA. Some studies have reported a high correlation between the amount of adhered cement paste and the amount of RCA mass lost through fragmentation; as the former increases so does the latter [93,94,134].

Naturally, the recycling procedure also plays a defining role in the content of the constituents of an RA, which will also affect its mechanical properties; RCA are expected to show greater resistance to fragmentation than RMA [14,119]. The results of a statistical analysis [93] of RA derived from different sources showed that the Los Angeles (LA) abrasion mass loss increased or decreased with increasing RMA or RCA content, respectively. Therefore, a measure of physical performance such as the LA abrasion coefficient may be a means of estimating the composition without the need of a manual assessment technique [96].

2.7.2. Quality of the original materials

The mechanical performance of RCA is only as good as its weakest section and very often that is the cement paste, which is influenced by the strength of the original concrete. Several studies [106,110,135,136] have used different ways (aggregate crushing value; aggregate impact value; 10% fine value; and LA abrasion) to assess the mechanical performance of RCA sourced from concrete with different compressive strength values. The results have shown that concrete specimens with increasing compressive strength produced aggregates with progressively greater resistance to fragmentation. This trend can also be applied to masonry-based aggregates. In a study [128] on the production of concrete with RMA, there was a good correlation between the aggregate impact values and the uniaxial compressive strength of brick units. This means that the aggregate impact value and similar tests can be used to assess the quality of the original material, thus obtaining a good estimation of how the RA is going to affect the performance in future construction applications [116].

3. Statistical analysis

Throughout this investigation, the values of several physical properties of RA were collected from the literature cited in this paper, which were then compared and assessed for correlation purposes. These properties are oven-dried density (ODD), saturated and surface-dried density (SSDD), water absorption (WA), and Los Angeles (LA) abrasion mass loss.

An example of the normal distribution curves of the ODD, SSDD, WA and LA abrasion mass loss of coarse RCA is plotted in Fig. 2. These results corroborate much of what was already established in the literature review. Since there were not enough values (below 30), it was not possible to perform a normal distribution of fine RMA, or of the LA abrasion of coarse RMA and CDRA.

From a statistical point of view, it is possible to determine whether the data is normally distributed by analyzing the standard error of skewness and kurtosis [137–139] and the *p*-value given by the Shapiro–Wilk [140,141] test (Tables 1–4). The ratio of kurtosis to its standard error can be used as a test of normality, meaning that one can reject normality if the ratio is less than −2 or greater than +2. A large positive value for kurtosis indicates that the tails of the distribution are longer than those of a normal distribution; a negative value for kurtosis indicates shorter tails (becoming like those of a box-shaped uniform distribution). The ratio of skewness to its standard error can also be used as a test of normality, in the same interval as that of the kurtosis. A large positive value of skewness indicates a long right tail; an extreme negative value indicates a long left tail. As for the *p*-value given by the Shapiro–Wilk test, this must be above 0.05 in order to be considered as a normal distribution.

The information given in Tables 1 and 2, suggests that the data is normally distributed. Coarse RCA had higher average ODD (2327 kg/m^3) and SSDD (2442 kg/m^3) values than any other aggregate type, followed by CDRA (2280 kg/m^3 and 2399 kg/m^3), MRA (2167 kg/m^3 and 2332 kg/m^3) and RMA (1885 kg/m^3 and 2158 kg/m^3). This trend, however, may not hold for the fine fraction of RCA, since its average ODD (2065 kg/m^3) is slightly lower than that of MRA (2078 kg/m^3) and CDRA (2207 kg/m^3).

The statistical data of the normal distribution of the water absorption results of RA also confirms what has been observed in the literature review. Coarse RCA exhibited the lowest average WA values (4.7%), while coarse RMA had the highest (13.4%). As expected, MRA showed an average WA value (7.2%) in between those two. Like the trend observed for ODD, the average WA values of fine RCA (9.5%) were slightly higher than those of fine MRA (9.3%) and CDRA (8.0%).

The data presented in Table 3 show that, except for fine CDRA, all aggregate types had a normal distribution. As mentioned, the category of CDRA was created for the sole purpose of identifying RA whose composition was not stated in research articles or whose contaminant content was high, and thus it did not fit in any of the other RA categories. Most CDW recycling facilities do not use enough sorting and contamination removal techniques and do not determine the composition of the final aggregate. Naturally, since the composition is unknown, CDRA can be composed of a wide array of materials. This is more noticeable in the finer fraction (recycled sands) which accumulates materials with higher WA, such as shredded wood, soil, old cement paste particles, crushed tiles and brick powder; however, it may also contain significant amounts of materials with low WA, such as crushed glass and natural sand. For these reasons, CDW recycling plants often produce batches with extremely variable physical properties.

The information from Table 4 suggests that the data is normally distributed. As mentioned, it was only possible to plot the normal distribution of coarse RCA and MRA and, as expected, the average LA abrasion mass loss of RCA (32.5%) is lower than that of MRA (36.5%).

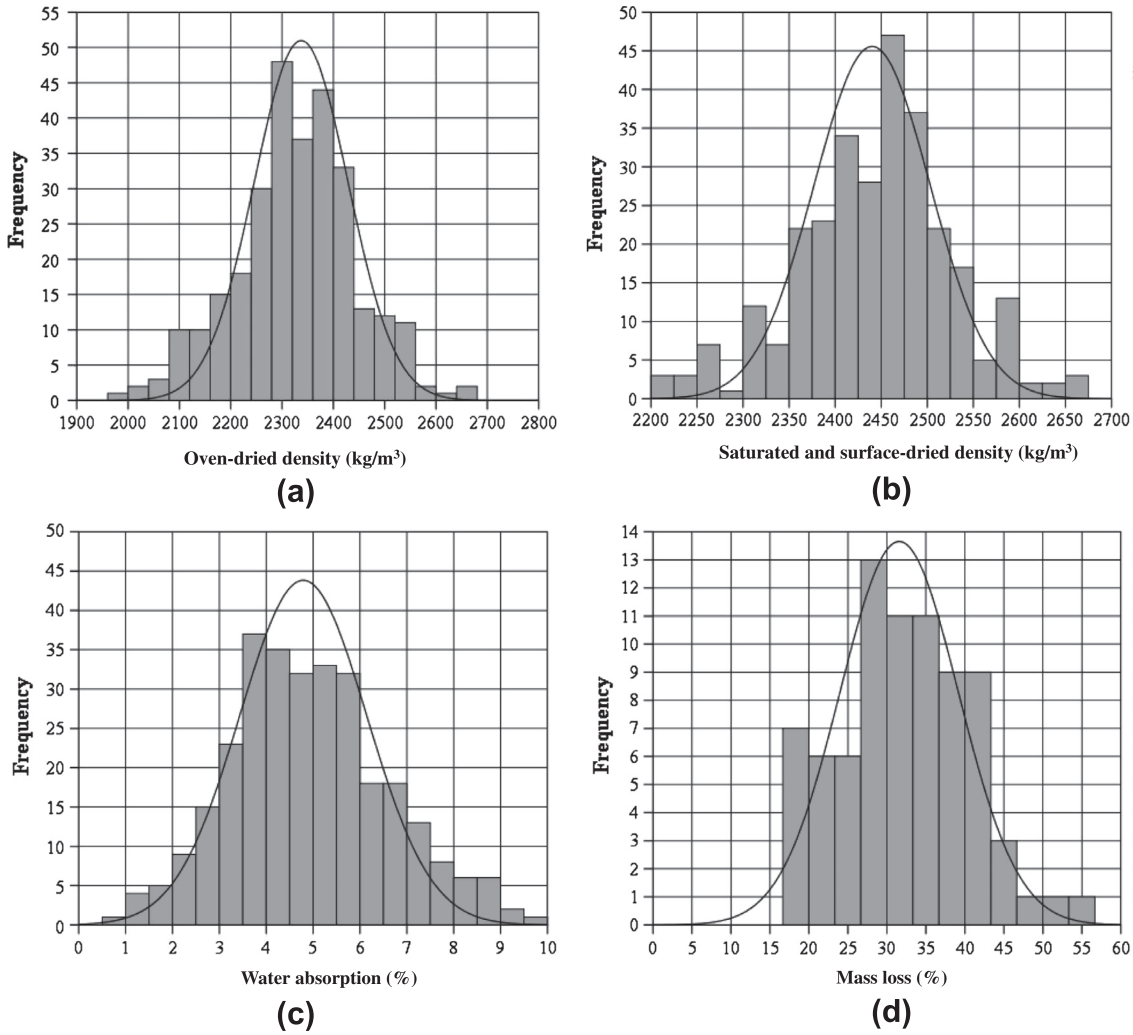

Fig. 2. Normal distribution of the (a) ODD, (b) SSDD, (c) WA and (d) LA abrasion mass loss of coarse RCA.

Table 1
Statistical data of the normal distribution of RA's ODD.

Aggregate type	RCA		RMA	MRA		CDRA	
Aggregate size	Fine	Coarse	Coarse	Fine	Coarse	Fine	Coarse
Sample size	46	292	32	37	61	68	38
Mean	2065	2327	1885	2078	2167	2207	2280
95% Confidence interval for mean							
Lower bound	2018	2314	1810	2023	2130	2161	2241
Upper bound	2112	2341	1961	2133	2203	2253	2318
Standard deviation	158	117	210	164	143	191	118
Coefficient of variation (%)	7.7	5.0	11.1	7.9	6.6	8.6	5.2
Tests of normality							
Skewness/standard error	−1.314	−0.846	−0.908	1.189	1.132	0.352	0.302
Kurtosis/standard error	1.363	1.006	−0.460	1.446	−0.290	−0.725	0.304
Shapiro–Wilk *p*-value	0.213	0.465	0.737	0.129	0.294	0.593	0.638

4. Proposal of a classification system for recycled aggregates

Fig. 3 presents the relationship between the ODD and the WA of 589 aggregates of different types, sizes and origins, sourced from 116 publications [14,25,26,29,93,97,102–106,108,109,111,113,114,118,121,124,126–129,134,136,142–232]. These specific publications were selected from a larger sample for their content, for being published over the span of 18 years (from 1996 and 2013) and for representing over 20 countries from 4 continents. Fig. 3 shows that, regardless of the aggregate's type, size and origin, there

Table 2
Statistical data of the normal distribution of RA's SSDD.

Aggregate type	RCA		RMA	MRA		CDRA	
Aggregate size	Fine	Coarse	Coarse	Fine	Coarse	Fine	Coarse
Sample size	45	288	35	37	61	68	38
Mean	2300	2442	2152	2292	2332	2399	2399
95% Confidence interval for mean							
Lower bound	2270	2432	2104	2248	2304	2364	2366
Upper bound	2331	2452	2199	2336	2360	2433	2431
Standard deviation	101	84	139	131	111	144	99
Coefficient of variation (%)	4.4	3.4	6.4	5.7	4.8	6.0	4.1
Tests of normality							
Skewness/standard error	0.029	−1.507	−0.859	1.340	0.909	−0.060	0.030
Kurtosis/standard error	1.752	1.198	−1.121	1.304	−0.028	0.632	0.557
Shapiro–Wilk *p*-value	0.132	0.068	0.070	0.205	0.258	0.334	0.448

Table 3
Statistical data of the normal distribution of RA's WA.

Aggregate type	RCA	RMA		MRA		CDRA	
Aggregate size	Fine	Coarse	Coarse	Fine	Coarse	Fine	Coarse
Sample size	43	298	32	36	61	72	41
Mean	9.5	4.9	13.4	9.3	7.2	8.0	5.0
95% Confidence interval for mean							
Lower bound	8.7	4.7	11.5	8.4	6.6	7.1	4.5
Upper bound	10.3	5.1	15.3	10.2	7.8	8.9	5.5
Standard deviation	2.6	1.7	5.4	2.7	2.2	4.0	1.6
Coefficient of variation (%)	27.6	34.7	40.2	28.8	31.0	49.7	31.8
Tests of normality							
Skewness/standard error	−0.089	1.986	1.747	1.439	1.227	0.513	1.045
Kurtosis/standard error	−1.395	−0.318	0.718	1.088	0.012	−2.469	−0.280
Shapiro–Wilk *p*-value	0.371	0.095	0.347	0.050	0.193	0.000	0.422

Table 4
Statistical data of the normal distribution of RA's LA abrasion mass loss.

Aggregate type	RCA	MRA
Sample size	78	48
Mean	32.5	36.5
95% Confidence interval for mean		
Lower bound	30.6	34.9
Upper bound	34.4	38.0
Standard deviation	8.5	5.4
Coefficient of variation (%)	26.1	14.9
Tests of normality		
Skewness/standard error	0.810	0.866
Kurtosis/standard error	−0.416	0.798
Shapiro–Wilk *p*-value	0.365	0.428

is a relationship between the ODD and WA, which is mainly due to the porosity of the material. As the porosity increases, its ability to absorb water increases and density decreases. From a statistical point of view, although the results show some scatter they have relatively high coefficients of determination ($R^2 = 0.878$) and of correlation ($R = 0.937$), which, according to Piaw [233], means that there is a very strong correlation between the two variables.

Fig. 4 presents the relationship between the WA and ODD of the same aggregates plotted in Fig. 3, but organized by different aggregate type. It shows that the manner in which different aggregate types are spread along the curve corroborates the findings of the literature review and of the statistical analysis, i.e. NA show the highest ODD and lowest WA values (2580 kg/m^3 and 1.6%, respectively), followed by RCA (2288 kg/m^3 and 5.7%, respectively), MRA (2133 kg/m^3 and 8.1%, respectively) and RMA (1909 kg/m^3 and 14.0%, respectively).

The analysis for the 95% confidence interval, also shown in Fig. 4, revealed that there is a 95% chance that, for a given ODD, an aggregate will have a WA varying ±2.7% from that of the polynomial curve in Fig. 3. By performing the same analysis for each of the aggregate types, it was found that the 95% confidence interval increased as the quality of RA declined. For a given ODD, NA will have WA varying ±1.5% from that of the polynomial curve in Fig. 3, while RCA, MRA, CDRA and RMA vary ±2.5%, ±3%, ±4.7% and ± 5.2%, respectively. Considering these results, it can be said that the polynomial curve's variability is mostly due to the existence of lower quality materials (RMA), with production methods that may vary greatly, and materials with high levels of contamination (CDRA), whose physical properties vary greatly in comparison with other inert materials.

Fig. 5 gives the plots of the WA and ODD values of fine and coarse aggregates of different types. The polynomial regression curves suggest that for the same ODD, fine aggregates have higher WA values than coarse aggregates. However, this difference is marginal and can be attributed to differences in the test methods, or even to experimental errors experienced by different researchers when determining the WA of fine aggregates. It is common knowledge that the procedure proposed in the tests makes it is difficult to achieve a saturated and surfaced-dried fine RA [196], and thus it may have higher WA values than a coarse aggregate with a corresponding ODD. Bearing these results in mind, it can be

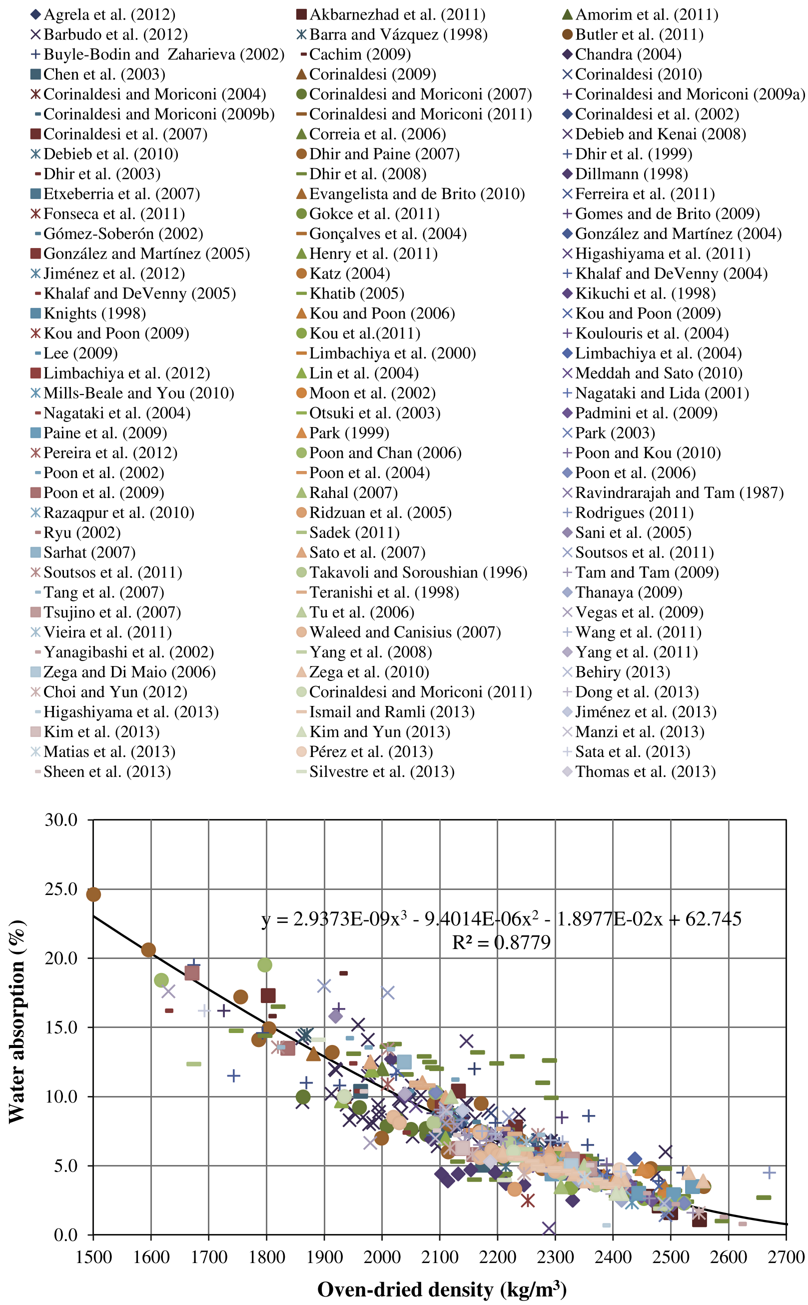

Fig. 3. Relationship between WA and ODD.

considered that fine and coarse aggregates have a similar behaviour in terms of their WA and ODD relationship. Therefore, in light of these results, the polynomial curve presented in Fig. 3 can be regarded as a general prediction model of the nature of an aggregate's WA/ODD relationship, regardless of its type, size and origin, provided the ODD of the aggregate lies between 1500 kg/m^3 and 2900 kg/m^3.

De Brito and Robles [234] and de Brito and Alves [235] found very good correlations between the combined density of RA and NA, and several properties of concrete. Generally, the use of lower-density aggregate blends resulted in concrete specimens with poorer performance.

Kikuchi et al. [167] had previously made a similar comparison, but using the weighed WA of RA and NA. As the weighed WA of the combined aggregates increased, the performance of concrete declined.

Dhir and Paine [102] investigated the possibility of using an alternative method for classifying RA that would overcome current barriers and concerns. They proposed different aggregate classes based on the SSDD, WA, LA abrasion and drying shrinkage value. Following this line of thought, a more comprehensive approach for the classification of RA is proposed in Fig. 6 and Table 5.

Several specifications for the use of RA in concrete consider some form of restriction on the ODD and WA of RA. However, some of these limitations are very conservative and take their composition into too much account, thus leaving out types of RA of good quality which could be used in the production of structural concrete. As Fig. 4 shows, MRA may have similar or even better

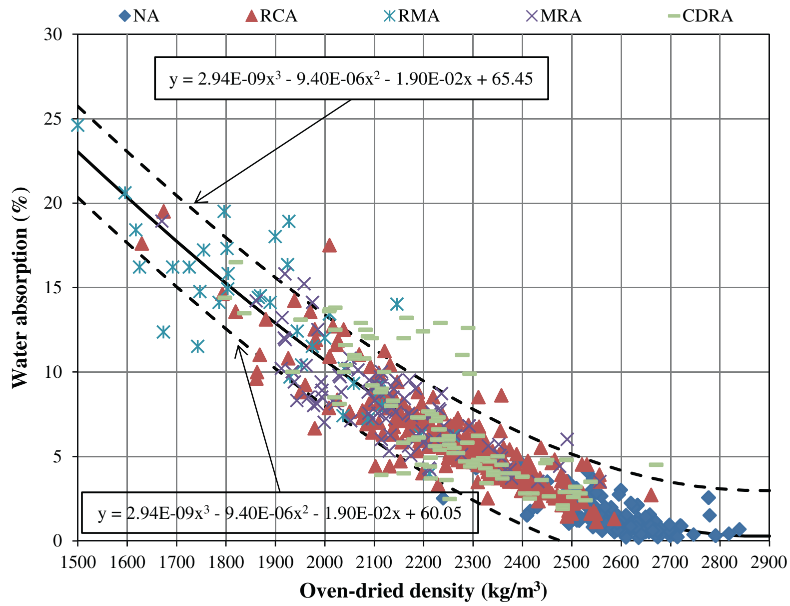

Fig. 4. Relationship between the WA and ODD of aggregates of different types and sizes.

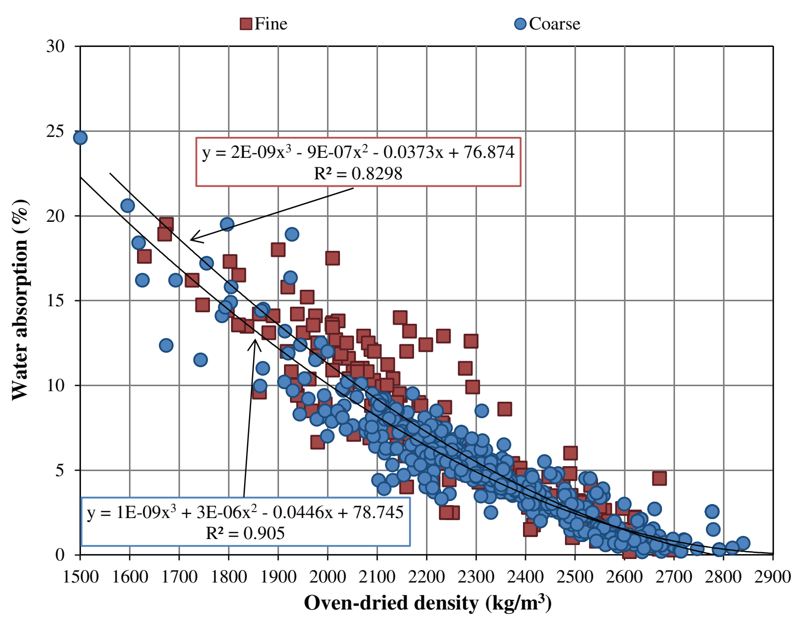

Fig. 5. Relationship between the WA and ODD of fine and coarse aggregates.

physical properties for use in concrete, relative to those of some RCA. Therefore, if they are of high quality, these types of aggregate should be used for reinforced concrete as well as for non-structural applications. Since a good correlation has been shown between the properties of an aggregate and those of the resulting concrete, it is only natural that aggregates should be classified based partly on their composition, but mostly on their physical properties.

By analyzing the normal distributions and taking into account the performance-based aggregate classification system proposed in Fig. 6 and Table 5, it was possible to estimate the probability of obtaining an aggregate belonging to each class, based on their ODD, WA and LA abrasion mass loss (Tables 6–8, respectively). Of all the aggregate types, the probability of coarse RCA belonging to the class A, in which NA reside, is the highest. For this reason, coarse RCA are often considered to be the most suitable RA for use in concrete production. Most RCA belong to the B class and it is unlikely to obtain an aggregate belonging to class C. As expected, the probability of obtaining a class A coarse MRA is much lower than that of obtaining a coarse RCA. Coarse RMA are likely to be included in classes C or D, and, therefore, this aggregate type should only be considered for use in low grade applications (i.e. non-structural concrete).

Analysis of Table 8 shows that, based on the LA abrasion mass loss, there is a high probability of obtaining coarse RCA (81.3%)

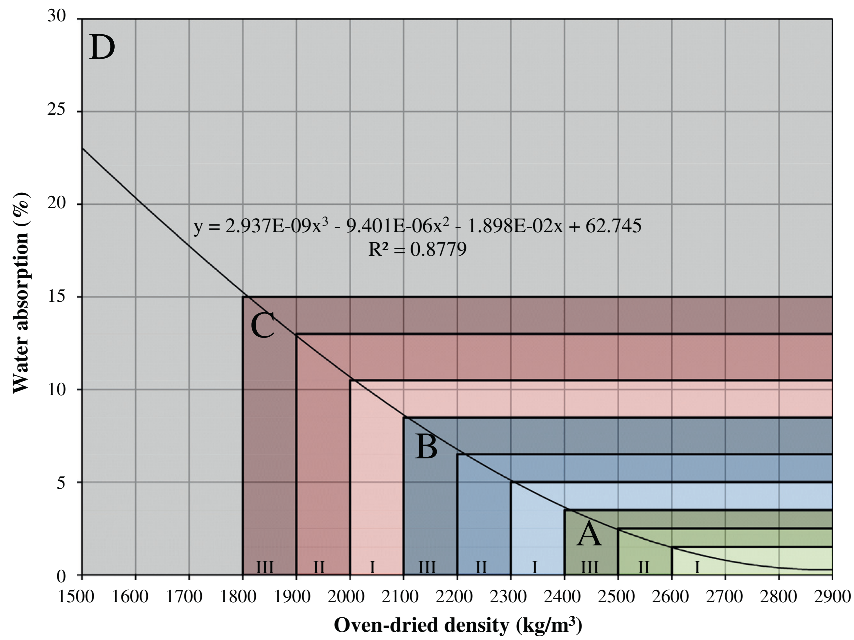

Fig. 6. Aggregate classification based on the relationship between WA and ODD.

Table 5
Physical property requirements for the proposed classes.

Aggregate class	A			B			C			D
	I	II	III	I	II	III	I	II	III	
Minimum oven-dried density (kg/m^3)	2600	2500	2400	2300	2200	2100	2000	1900	1800	No limit
Maximum water absorption (%)	1.5	2.5	3.5	5	6.5	8.5	10.5	13	15	
Maximum LA abrasion mass loss (%)	40			45			50			

Table 6
Probability of obtaining an RA of a given type and size in each aggregate class based on its ODD.

Aggregate class	RCA		RMA	MRA		CDRA	
	Fine	Coarse	Coarse	Fine	Coarse	Fine	Coarse
A	1.7	26.8	0.7	2.5	5.2	15.6	15.4
B	40.2	70.6	14.7	42.3	62.6	55.6	78.2
C	53.3	2.6	50.5	50.6	31.8	27.2	6.4
D	4.7	0.0	34.1	4.6	0.5	1.6	0.0

Table 7
Probability of obtaining an RA of a given type and size in each aggregate class based on its WA.

Aggregate class	RCA		RMA	MRA		CDRA	
	Fine	Coarse	Coarse	Fine	Coarse	Fine	Coarse
A	1.1	20.6	3.3	1.5	4.8	13.0	17.6
B	33.7	77.7	14.9	37.4	67.4	42.2	81.2
C	63.3	1.7	43.7	59.5	27.7	40.9	1.2
D	1.8	0.0	38.2	1.5	0.0	3.9	0.0

or MRA (74.2%) belonging to class A. This suggests that this factor is not as limiting as the ODD or WA, and could therefore be altered to be comparable to those two. Specifications limit the abrasion of coarse aggregate for use in concrete to a maximum ranging from 25% to 55%, depending on their future use. The EHE-08 – Code on Structural Concrete [236] states that, to produce reinforced

Table 8
Probability of obtaining an RA of a given type and size in each aggregate class based on its LA abrasion mass loss.

Aggregate class	RCA	MRA
A	81.3	74.2
B	11.7	20.0
C	5.0	5.2
D	1.9	0.6

concrete the maximum LA abrasion mass loss of RA may be the same as for NA (no greater than 40%). Since specifications for the use of NA already impose maximum LA abrasion mass losses between 40% and 50%, the same range of values was used to limit this property in the proposed performance-based classification system. Naturally, when acquiring RA, concrete producers can specify the maximum LA abrasion mass loss depending on the intended application of the concrete.

Fig. 7 illustrates the use of this performance-based classification system in the production of concrete. It shows that, for a given replacement level, the compressive strength loss of concrete is greater when using RA of lower quality. Whilst concrete specimens made with 100% class A RCA had compressive strength losses between 8% and 10%, specimens using class B RCA showed lost between 31% and 34%. Although the example of the application of this performance-based classification system was based on two references, further research is being pursued on how RA of a given quality degree and composition can change several other properties of concrete.

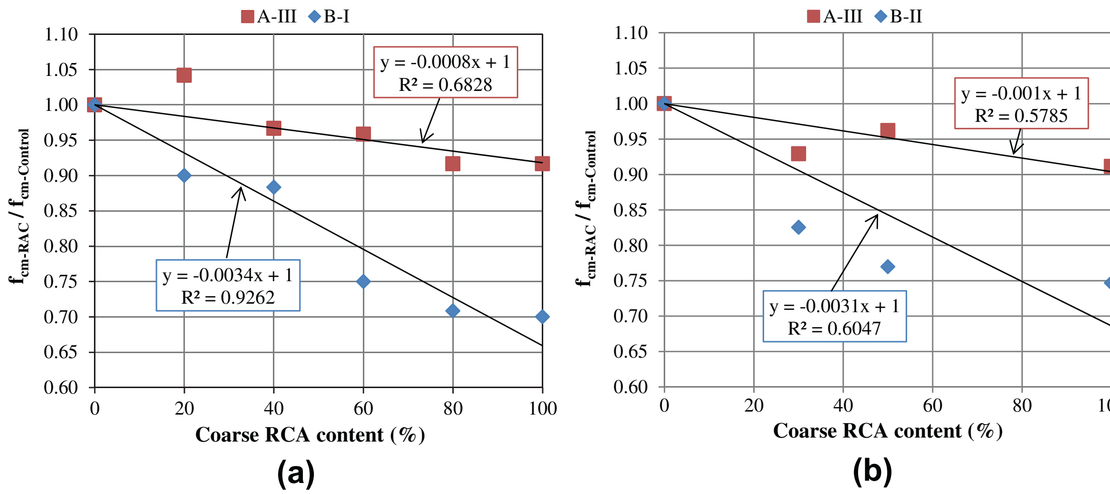

Fig. 7. Relative compressive strength between RAC and the control concrete with increasing RA content. Sourced from: (a) Akbarnezhad et al. [152]; and (b) Yang et al. [216].

5. Conclusions

This investigation examined the main physical properties and composition of recycled aggregates for use in concrete and undertook a statistical analysis of data available in the literature. This led the authors to propose a performance-based classification for the use of RA in concrete construction, based on their physical properties. The main conclusions that can be drawn from this study are:

- Selective demolition should be promoted and enforced whenever possible. This is an absolute necessity if we want to obtain material with minimum level of contamination, thereby adding value to the RA produced for its use in construction.
- The composition and physical properties of an RA should be determined prior to its acceptance for use in concrete production. This, besides making its classification easier, will allow a better understanding of the material and of its likely performance, facilitate its certification and help boost stakeholder confidence.
- When properly processed and categorized, RA may be considered as another type of normal aggregate, fit for use in construction as per national and international specifications.
- The use of term "contaminant" should depend on the intended application of the RA containing it. For example, when mainly composed of asphalt-based materials, it would be termed as reclaimed asphalt pavement (RAP). The literature shows that this material has been successfully used in the production of bituminous mixtures, but it is highly detrimental to cement bound materials. This further reinforces the notion of determining the composition and physical properties of processed CDW.
- Notwithstanding the variability of results, it was possible to produce a generic prediction model using the WA/ODD relationship of aggregates, regardless of their size, type and origin. This led to the proposal of a performance-based classification of RA that can attest to its quality.

Acknowledgements

The authors are grateful for the support of the ICIST Research Institute, IST, Technical University of Lisbon and the FCT (Foundation for Science and Technology).

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