CHAPTER 11- QUALITY CONTROL ON RECYCLED AGGREGATES

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Abstract: Various studies have shown that recycled aggregate can be used to make new concrete. However, in the same way as with natural aggregate, recycled aggregate also needs to be assessed in terms of grain-size distribution, absorption, abrasion, etc. since it must comply with national standards. In order to evaluate the use of recycled aggregate, standards and guidelines from sixteen countries were analyzed and compared in order to determine the most important quality criteria for the physical and mechanical properties of concrete. The results of this analysis led to the proposal of a set of recommendations.

Keywords: quality control; recycled aggregate; classification; properties

Chapter Contents

1. Introduction

Over the last fifty years, rising volumes of construction and demolition waste have become a cause of growing concern (Debieb and Kenai, 2008). For this reason, the construction sector has made significant efforts to find ways to re-use the huge amounts of this waste that are generated each year. A practical solution for this problem is the use of recycled aggregate as a replacement for natural aggregate. In fact, this has become a frequent practice since it conserves natural resources, decreases production energy, and reduces the amount of waste deposited in landfills (Barbudo et al., 2012; Oikonomou, 2005; Uchikawa, 2000). Although demolition waste was first recycled in Germany after the Second World War, only recently has this practice spread to other countries as a promising method of reusing construction waste (Rao et al., 2007).

Various studies have shown that recycled aggregate can be used to make new concrete (ACI Committee, 2002; Rao et al., 2007; Tam et al., 2008). However, in the same way as with natural aggregate, recycled aggregate also needs to be assessed in terms of grain-size distribution, absorption, abrasion, etc. (Rao et al., 2007) since it must comply with national standards. In order to evaluate the use of recycled aggregate, standards and guidelines from sixteen countries were analyzed and compared in order to determine the most important quality criteria for the physical and mechanical properties of concrete. The results of this analysis led to the proposal of a set of recommendations.

2. Composition and classification of recycled aggregate (RA)

Research studies have recently combined and integrated various classifications of recycled aggregate (RA), based on its composition. Most of these classifications are derived from the criteria in the European Standard EN 933-11 of 2009 (Agrela et al, 2011; Barbudo et al., 2012; González-Fonteboa et al., 2011, Jimenez et al., 2011; Mas et al., 2011). Alternatively, RA classification can also be performed “de visu” (Poon et al., 2002), as well as by the measure of the porous structure of RA using the mercury intrusion technique (Corinaldesi and Moriconi, 2010a), or by petrographic tests in order to obtain its mineralogical characterization (Calvo Pérez et al., 2002).

It is well known that the composition of RA can directly affect the mechanical behavior of concrete (Angulo and Müeller, 2009; Angulo et al., 2010). For example, ceramic material can produce adverse effects (Yang et al., 2011) though according to Khatib (2005), there is a higher rate of strength development between 28 and 90 days of concrete attributed to the pozzolanic reaction brought on by the silica and alumina content of ceramic and the products of cement hydration. Similarly, the presence of minor damaging components (e.g. asphalt, gypsum, glass etc.) is the result of inadequate selection and cleaning at the site where the construction and demolition waste (C&DW) have been originated. The hand-sorting of aggregate should thus be improved since visual inspection is not sufficiently accurate and is largely based on the external appearance of the grain (Angulo et al., 2004). Most technical standards thus specify RA types, based on composition, and to a lesser extent, on the density, maximum compressive strength, and application of the RA.

Metal impurities in recycled aggregate concrete have also been studied but the technical documents reviewed do not consider this type of substance separately, but rather mention it in conjunction with various others. More specifically, the standards consulted refer to the percentage of metal, glass, soft materials, bitumen, etc. The maximum permitted values for these substances range from 0.1% to 5% (see Table 1).

According to Park and Noguchi (2012), aluminum impurities in recycled aggregate diminish the mechanical properties and durability of recycled aggregate concrete even when the aluminum content is minimal (0.1%). This occurs because the aluminum impurities react with the alkaline concrete to produce hydrogen gas. This gas creates gas layers, foam, cracks and rock pockets in hardened concrete, thus causing its mechanical properties to deteriorate. As a result, there is an evident need for more effective screening methods even though such methods increase the cost of recycled aggregate and reduce its positive environmental value (Pacheco-Torgal et al. 2012).

Table 1 shows the composition-based classification in the national standards and guidelines analyzed in this study. As can be observed, there are basically two or three categories, depending on the presence of concrete and/or ceramic material as well as other components that might affect the quality of the recycled aggregate. The RA classification proposed in this research is derived from the relevant bibliography and facilitates the analysis of aggregate properties. This new classification, which is based on composition, includes the following categories of recycled aggregate made from C&DW (Table 1): (i) recycled concrete aggregate (RCA); (ii) recycled masonry aggregate (RMA); and (iii) mixed recycled aggregate (MRA).

Table 1. Classification of recycled aggregate based on composition

Scope	Standard/ Guidelines	Standard class	Unified class	Concrete	Masonry	Natural aggregate	Organic material	Contaminants/Impurities	Lightweight materials	Fines
Australia	CSIRO	Class 1A	RCA	< 100	-	-	n.a.	1	n.a.	n.a.
		Clase 1B	MRA	< 70	< 30	-	n.a.	2	n.a.	n.a.
Belgium	PTV 406	Concassé de débris de béton	RCA	> 90	< 10	-	0.5	0.5 (a)	n.a.	n.a.
		Concassé de débris de mixtes	MRA	> 40	> 10	-	0.5	1 (a)	n.a.	n.a.
		Concassé de débris de maçonnerie	RMA	< 40	> 60	-	0.5	1 (a)	n.a.	n.a.
Brazil	NBR 15.116	ARC	RCA	> 90	-	(b)	n.a.	3	n.a.	7
		ARM	MRA	< 90	-	(b)	n.a.	3	n.a.	10
China (c)	DG/TJ07/008	Type I	RCA	> 95	< 5	-	0.5	1	n.a.	n.a.
		Type II	MRA	< 90	> 10	-	n.a.	n.a.	n.a.	n.a.
Denmark	DS 2426	GP1	RCA	> 95	-	-	n.a.	n.a.	n.a.	n.a.
		GP2	MRA	> 95		-	n.a.	n.a.	n.a.	n.a.
Germany	DIN 4226-100	Type 1	RCA	> 90	< 10		n.a.	1 (e)	n.a.	1
		Type 2	RCA	> 70	< 30		n.a.	1 (e)	n.a.	1.5
		Type 3	RMA	< 20	> 80	< 20	n.a.	1 (e)	n.a.	3
		Type 4	MRA	> 80 (d)			n.a.	1 (e)	n.a.	4
Hong Kong	WBTC 12	Type II	RCA	< 100	-	-	n.a.	1	0.5	4
Japan (c)	JIS A 5021	ARH	RCA	-	-	-	n.a.	3	n.a.	1
Netherlands	CUR	ARH	RCA	> 95	< 5	-	n.a.	0.1	n.a.	-
	NEN 5905	ARH	RCA	< 80	-	< 20	n.a.	n.a.	0.1	3
Norway	NB 26	Type 1	RCA	> 94	< 5	(b)	n.a.	1 (e)	0.1	n.a.
		Type 2	MRA	> 90		(b)	n.a.	1 (e)	0.1	n.a.
Portugal	LNEC E 471	ARB 1	RCA	> 90	< 10	(b)	n.a.	0.2 (f)	1	n.a.
		ARB 2	RCA	> 70	< 30	(b)	n.a.	0.5 (f)	1	n.a.
		ARC	MRA	> 90		>10	n.a.	1 (f)	1	n.a.
Spain	EHE-08	RCA	RCA	-	< 5	-	0.5	(g)	1	2
Switzerland	SIA 2030	BC	RCA	-	< 3	-	n.a.	1	n.a.	n.a.
		BNC	MRA	-	-	-	n.a.	2	n.a.	n.a.
United Kingdom	BS 8500-2	RCA	RCA	> 95	< 5	-	n.a.	1 (h)	0.5	5
		RA	MRA	-	<100	-	n.a.	1 (h)	1	3
	BRE Digest 433	RCA I	RMA	-	< 20	>80	n.a.	5	1	n.a.
		RCA II	RCA	< 20	-	>80	n.a.	1	0.5	n.a.
		RCAIII	MRA	< 10	< 10	>80	n.a.	5	2.5	n.a.
	RILEM	Type I	RMA	-	< 100	-	1	5	1	3
		Type II	RCA	< 100	-	-	0.5	1	0.5	2
		Type III	RCA	< 20	< 10	> 80	0.5	1	0.5	2

n.a.: no limit available in the standard or guideline.

(a) Less than 5% of bituminous material in all types
(b) Included in the percentage of recycled concrete aggregate
(c) This standard classifies recycled aggregate according to its properties
(d) 20% bituminous materials and others
(e) For bituminous materials 1% in all types
(f) Contaminants of bituminous materials. ARB 1 <5%; ARB 2<5%; ARC<10%
(g) Bituminous materials <1%; glass, metals, plastics, etc <1%
(h) Bituminous materials, RCA<5%; RA<10%

3. Quality criteria for the use of recycled aggregate

RA properties are not uniform because of the following: (i) the aggregate source (Marinkoviç et al., 2010); (ii) the recycling plant that produces the C&D aggregate, especially the method used to crush the concrete (Katz, 2003; Mas et al., 2011; Padmini et al., 2009); (iii) the lack of quality data for the C&DW (Oikonomou, 2005).

The quality criteria to be met by recycled aggregate (RA) for structural concrete must be the same as those required for natural aggregate (NA) for the same use. This means that recycled aggregate should be classified according to conventional physical and chemical specifications. The revision of approximately 60 research studies as well as 26 sets of regulations and guidelines made it possible to systematize RA quality criteria in four categories based on the following property types: (i) physical; (ii) mechanical; (iii) chemical; (iv) geometrical. RA properties and their typical values in these standards and guidelines are described in the following sections.

3.1 Physical characteristics of recycled aggregates

Table 2 shows the physical characteristics of RA in national standards and guidelines, according to RA type. As can be observed, density and absorption are the ones that are most widely included, regardless of aggregate type. Although porosity is a parameter that is not explicitly in the regulations, it is closely, linked to density and absorption. Since it has been studied by numerous authors, it is also mentioned in this section.

As shown in Table 2, the physical properties in practically all of the regulations for RCA are oven-dry density and absorption. Those that appear less frequently are bulk density, specific gravity, and losses of ignition. Despite the fact that density and absorption are two of the main characteristics that define RA quality, there are regulations that do not include density or any of its variants (EHE-08, 2008; NBR 15.116, 2005; NEN 5905, 2004). Others do not include absorption either (BS 8500-2, 2006; CUR, 1984, 1986 and 1994; DS 2426, 2009; prEN 12620, 2010; NTC, 2008). In fact, quite surprisingly, the BS 8500-2 standard does not mention any of these properties.

Table 2. Physical requirements for RA in standards and guidelines

Scope	Standard/ Guidelines	Oven-dry density (kg/m³)	Surface dry density (kg/m³)	Bulk density (kg/m³)	Specific gravity (kg/m³)	Absorption (%)	Losses of ignition (LOI) (%)
Australia	CSIRO		●✦	●✦	●✦	●✦	●
Belgium	PTV-406	●■				●■	
Brazil	NBR 15.116					●✦	
China	DG/TJ07/008	●				●	
Denmark	DS 2426	●	✦				
Europe	EN 12620	●					
Germany	DIN 4226-100	●■✦				●■✦	
Hong Kong	WBTC 12	●				●	
Italy	NTC	●	✦				
Japan	JIS A 5021 /5022/5023	●				●	
Korea	KS F2573				●	●	
Netherlands	NEN 5905					●	
	CUR	●■					
Norway	NB 26	●	●✦	✦		●	✦
Portugal	LNEC E 471			●	✦	●	✦
Spain	EHE-08					●	
United Kingdom	BS 8500-2						
	RILEM	●■				●■	
● RCA ■ RMA ✦ MRA							

3.1.1 Density

RA is always less dense than NA because of the presence of adhered mortar, ceramic materials, and other impurities, such as gypsum (Katz, 2003; Sim and Park, 2011). Although research has been conducted on how cement paste, such as chloride binding, can benefit RA (Ann et al. 2008), it is less likely to inhibit corrosion and aggressive ions because RA is more porous than NA.

The lower density of RA produces concrete of lower workability and a higher water demand in its fresh state. This type of concrete is also not as strong and is less durable after it hardens. Table 3 shows the density types in the references as well as the maximum and minimum density values, depending on RA type (all-in-one, coarse, and fine aggregate). The data seem to indicate that higher density values are linked to larger aggregate grain size (Becerra Cabral et al, 2010; Etxeberria and Vazquez, 2010; Kou et al., 2011a; Kou et al., 2011b; Padmini et al., 2009; Poon et al., 2007; WRAP, 2007). Research also confirms that RCA has higher density values than RMA (Agrela et al, 2011; Angulo and Müeller, 2009; Becerra Cabral et al, 2010; Corinaldesi and Moriconi, 2009;

Dapena et al., 2011; Jiménez et al., 2011; Martín-Morales et al., 2011; Padmini et al., 2009; Tam and Le, 2007; WRAP, 2007; Yong and Teo, 2009). In contrast, RMA was found to have the lowest density values (Becerra Cabral et al, 2010; Debieb and Kenai, 2008; Miranda and Selmo, 2006; Müeller, 2004; Poon and Chan, 2007).

Table 3. Maximum and minimum density values in the references.

Density	Aggregate	Minimum (kg/m^3)	Maximum(kg/m^3)
Oven-dry density	All-in-one	2,045 (WRAP, 2007)	2,620 (Tam and Le, 2007)
	Coarse	1,170 (Limbachiya et al., 2000)	2,760 (Angulo and Mueller, 2009)
	Fine	1,913 (Evangelista and de Brito 2007 and 2010)	2,500 (Martín-Morales et al., 2011)
Surface-dry density (10 min)	All- in-one	2,470 (Gonzalez-Fonteboa and Martínez-Abella, 2005)	2,480 (Gonzalez-Fonteboa and Martínez-Abella, 2005)
	Coarse	2,070 (Agrela et al., 2011)	2,450 (Fonseca et al., 2011)
Surface-dry density (24 h)	All-in-one	1,940 (WRAP, 2007)	2,650 (WRAP, 2007)
	Coarse	2,060 (Agrela et al., 2011)	2,678 (Zhu et al., 2011)
	Fine	1,310 (Barbudo et al., 2012)	2,650 (Barbudo et al., 2012)
Bulk density	All-in-one	1,427 (Padmini et al., 2009)	1,568 (Padmini et al., 2009)
	Coarse	1,060 (Lovato et al., 2012)	2,730 (Angulo et al., 2004)
	Fine	1,010 (Debied and Kenai, 2008)	1,530 (Miranda and Selmo, 2006)
	Fines	1,320 (Miranda and Selmo, 2006)*	
Specific gravity	All-in-one	2,380 (Padmini et al., 2009)	2,670 (Tam and Le, 2007)
	Coarse	1,860 (Becerra Cabral et al., 2010)	2,890 (Bairagi et al., 2012)
	Fine	1,850 (Müller, 2004)	2,680 (Miranda and Selmo, 2006)
	Fines	2,600 (Miranda and Selmo, 2006)*	
*Only typical values have been included in these studies			

3.1.2 Water absorption

Water absorption values also reflect important differences between RA and NA. In the case of RA, the water absorption rate is increased by the presence of adhered mortar (Lopez-Gayarre et al., 2009; Padmini et al., 2009), ceramic material, and impurities, such as gypsum (Agrela et al., 2011). These substances are also closely related to density values and affect the behavior of concrete both in its fresh and hardened state.

The role of water absorption is decisive in the manufacture of concrete. For this reason, specifications can be found in most standards (86% for RCA; 75% RMA; and 62% for MRA). In fact, it has an important impact on the relation water and binder. If RA is not pre-treated, more water is required to mix the cement paste. This reduces the strength of the product. To solve this problem, some researchers presoaked granular materials and then measured absorption after 10 minutes, 30 minutes, and 24 hours in order to model absorption behavior (Evangelista and de Brito, 2010; González-Fonteboa and Martínez-Abella, 2008; Mas et al., 2011; Tam et al., 2005; Tam et al., 2008; Tam and Tam, 2008; Dejerbi, 2012). This presoaking improved the final performance of the concrete, thanks to the formation of a more solid and denser interface (Barra de Oliveira and Vazquez, 1996; Kou et al., 2011a). It also created an internal water supply that reduced drying-shrinkage. This pre-treatment was found to prevent excessive water absorption in the aggregate during mixing, and consequently, maintained concrete workability (Corinaldesi and Moriconi, 2010b; Domingo-Cabo et al., 2009). In this sense, certain authors propose the presoaking of coarse RA in a saturated surface-dry condition before the mixing procedure in order to ensure a uniform blending during the concrete manufacturing process (Debieb and Kenai, 2008; Katz, 2003). Etxeberria and Vazquez (2010) prepared concrete using RA with an 80% moisture content, whereas Tam et al. (2007) propose presoaking RA in acid before it is used to make concrete, to removal the attached cement mortar.

In comparison to RA density, the higher the absorption value of RA, the smaller the size of the aggregate (Barbudo et al., 2012; Corinaldesi and Moriconi, 2009; Debieb and Kenai, 2008; Müeller, 2004; Poon and Chan, 2007). Therefore, absorption values of ceramic material (Agrela et al, 2011; Becerra Cabral et al, 2010; Debieb and Kenai, 2008; WRAP, 2007; Yang et al., 2011) are higher than RMA and RCA absorption values (Becerra Cabral et al, 2010; Evangelista and de Brito, 2007 and 2010; Katz, 2003; Kou and Poon, 2009; Kou et al., 2011a; Martín-Morales et al., 2011; Miranda and Selmo, 2006; Sim and Park, 2011; Zega and di Maio, 2011).
The absorption coefficient of RA, measured at 24h, was 0.57%-13.2% (Tam and Le, 2007; WRAP, 2007) although values depended on aggregate type. In the case of coarse RA, values ranged from 1.21% (Angulo et al., 2004) to15.62 % (Becerral Cabral et al., 2010). For fine RA, they were between 2.0% (Miranda and Selmo, 2006) and 30.9% (Poon and Chan, 2007). Finally in the case of coarse RA from sanitary ceramic material and from electrical ceramic material, the water absorption rate was lower than 1% because of the compactness of these materials (Medina et al., 2012; Senthamarai et al., 2011).

3.1.3 Porosity

Porosity is closely linked to density and absorption. This means that higher porosity values (59.54%) are found in RA from ceramic material (Debieb and Kenai, 2008), and lower values (0.32%) are found in RA from sanitary ceramic material because of its compactness (Medina et al., 2012). No significant differences were found between RCA (8.46%) (Kou et al., 2011a) and RMA with porosity values between 9.13% and 14.86% (Etxeberria and Vazquez, 2010; Gómez-Soberón, 2002; González-Fonteboa and Martínez-Abella, 2008; Kou et al., 2011b; Poon et al., 2007). Nonetheless, Katz (2003) states that the porosity of RA rises significantly when the amount of cement paste is increased and aggregate size is smaller.

3.2 Mechanical behavior of recycled aggregates

The mechanical properties of the original materials have a significant impact on the mechanical performance of concrete made with RA (Ajdukiewicz and Kliszczewicz, 2002). Table 4 shows the mechanical requirements specified in the standards and guidelines, depending on RA type. As can be observed, the mechanical performance of recycled aggregate is mainly defined in terms of its Los Angeles abrasion coefficient, 10% fine value (TFV), and soundness. These tests are only performed on the coarse fraction of the aggregate, and the results are extrapolated to the fine fraction.

The mechanical specification that is most frequently included in the standards is the Los Angeles abrasion coefficient. This coefficient is included in most of the European standards and in the Korean norm. To a lesser extent, soundness also appears in the norms. In all cases, however, it is required for recycled concrete aggregate and in some cases, for ceramic and mixed recycled aggregate.

Table 4. Mechanical specifications for RA in standards and guidelines

Scope	Standard/ Guidelines	Los Angeles abrasion coefficient	10 % fine value TFV (KN)	Soundness (%)
Australia	CSIRO			●
Belgium	PTV-406	●■✦		
Brazil	NBR 15.116			
China	DG/TJ07/008			●
Denmark	DS 2426			
Europe	EN 12620	●		
Germany	DIN 4226-100	●■✦		
Hong Kong	WBTC 12		●	
Italy	NTC	●✦		●✦
Japan	JIS A 5021 /5022/5023			
Korea	KS F2573	●		●
Netherlands	NEN 5905	●		
	CUR			
Norway	NB 26			
Portugal	LNEC E 471	●		
United Kingdom	BRE Digest 433			
	BS 8500-2			
	RILEM			
Spain	EHE-08	●		●
Switzerland	SIA 2030			
	OT 70085			
● RCA; ■ RMA; ✦ MRA				

3.2.1 The Los Angeles abrasion coefficient

The Los Angeles abrasion coefficient is the basic parameter used to measure the resistance of aggregate to fragmentation during handling. Despite its contribution to the mechanical strength of concrete, relatively few standards recommend it for RCA (EHE-08, 2008; prEN 12620, 2010; KS F2573, 2006, LNEC E 471, 2006; NEN 5905, 2004). Only the Italian standard (NTC, 2008) requires it for RMA.

Because of the adhered mortar, RA has a higher Los Angeles coefficient value than NA (Domingo Cabo et al., 2009). This value ranges from 29% to 53% for all-in-one RA (Padmini et al., 2009; WRAP, 2007) and from 17.4% to 44% (Yoon et al., 2007; Mas et al., 2011) for coarse RA. There was also a high correlation between the ceramic material content and gypsum content. RMA has a low resistance to fragmentation, which means that it has a lower Los Angeles coefficient (IHOBE, 2011).

3.2.2 10% fine value (TFV)

The 10% fine value (TFV) is only included in the Hong Kong Standard (WBTC 12, 2002) and is limited to RCA. The TFV measures aggregate resistance to crushing, which is applicable to both weak and strong aggregate to a minimum value of 100 kN. This parameter ranges from 61.36 to189.38 kN (Tam and Le, 2007). The British guide WRAP (2007) points to a possible link between a high TFV and the RA content in concrete.

3.2.3 Soundness or mass loss

Soundness determines the mass loss of the aggregate through its resistance to disintegration by weathering and, in particular, freeze-thaw cycles. In the standards where it is mentioned, soundness is only recommended for RCA (CSIRO, 1998; EHE-08, 2008; NTC, 2008; DG/TJ07/008, 2007). Nevertheless, this parameter has not been studied in depth since RA is considered to be less resistant to freezing because of its marked water absorption (Barra de Oliveira and Vazquez, 1996). Furthermore, the available research data are contradictory. Whereas Gokce et al. (2004) obtained results well over the limit specified for coarse RA (18.4-48.3), attributable to the adhered mortar, Marinkovic et al. (2010) obtained positive results (1.2-1.8).

3.3 Chemical suitability of recycled aggregates

Table 5 shows the chemical requirements for RA in the various standards and guidelines. As can be observed, the most frequently included ones pertain to the chloride and sulfate content of the aggregate. The reason for this is that these chemicals can potentially lead to the corrosion and deterioration of hardened concrete. Also mentioned are the presence of substances, such as clay lumps, soft particles, and lightweight particles, which can prove harmful to the setting and hardening of concrete. Finally, the presence of organic matter is also mentioned.

Chemical requirements are most frequently specified for RCA. Surprisingly, the Danish, Australian, Japanese, and Korean standards do not limit these substances. They only make recommendations concerning chlorides and organic material without any reference to sulfur compounds, which can be so detrimental to concrete.

Table 5. Chemical requirements for RA in standards and guidelines

Scope	**Standard/ Guidelines**	**Water-soluble sulfates (%)**	**Acid-soluble sulfates (%)**	**Total sulfur compounds (%)**	**Acid-soluble chloride (%)**	**Water-soluble chloride (%)**	**Total chloride (%)**	**Lightweight particles (%)**	**Clay lumps (%)**	**Organic matter (%)**
Australia	CSIRO						✦			●✦
Belgium	PTV-406	■✦	●	●■✦	●■✦	■✦		●■		●■✦
Brazil	NBR 15.116	●		✦		●✦		✦	●✦	●
China	DG/TJ07/008		●		●					●
Denmark	DS 2426						✦			
Europe	EN 12620	●	●	●						
Germany	DIN 4226-100	■✦	●		●■✦	■✦	■✦			
Hong Kong	WBTC 12	●				●		●		
Italy	NTC	●	●✦	●✦	✦					
Japan	JIS A 5021 /5022/5023					●				●
Korea	KS F2573								●	●
Netherlands	NEN 5905			●	●					●
	CUR	■	●		●■			●		●■
Norway	NB 26						✦	●✦		●
Portugal	LNEC E 471	●	●✦	●✦	●✦	✦	✦	●✦		●
Spain	EHE-08		●	●		●	●	●	●	
Switzerland	SIA 2030	●	●	✦	✦		●✦			
	OT 70085		●✦		●		✦			
United Kingdom	BRE Digest 433		●	■		■				
	BS 8500-2	■	●■	✦				●■		
	RILEM	●	■			■		●■		●■
● RCA; ■ RMA; ✦ MRA										

3.3.1 Sulfur compounds

Sulfur compounds can cause cement expansive reactions, which significantly reduce the durability of concrete. RA can contain dangerously large amounts of these compounds because of the gypsum used in construction work. In this regard, IHOBE (2011) confirmed the high solubility of sulfates in RA by performing a thermogravimetric study that detected gypsum, ettringite, and portlandite. The results obtained also reflect the close correlation between the contents of granular gypsum and sulfate (in whatever form) in RA. To a lesser extent, this correlation also exists with the ceramic content though the WRAP (2007) disagrees.

The standards and guidelines limit the total sulfur compounds in RCA (CUR, 1984, 1986 and 1994; EHE-08, 2008; NEN 5905). Acid-soluble sulfates are those most often mentioned for RCA (BS 8500-2, 2006, CUR, 1984, 1986 and 1994; DIN 4226-100, 2002; DG/TJ07/008, 2007; EHE-08, 2008). In contrast, specifications for water-soluble sulfates are not included as frequently (NBR 15,116, 2005; RILEM, 1994; WBTC 12, 2002).

Research on sulfur compounds in RA shows that their presence is variable. Values for total compounds ranged from 0.003% (Tam and Le, 2007) to 6.0% (Jimenez et al., 2011) in RMA. For acid-soluble sulfates, the values were between 0.00% (WRAP, 2007) and 6.98% (Mas et al., 2011), whereas water-soluble sulfate values ranged from 0.00% (Calvo Pérez et al., 2002) to 3.93% (Barbudo et al., 2012). The highest values corresponded to RA that had been in contact with gypsum, which is highly soluble in alkaline media (IHOBE, 2011).

3.3.2 Chlorides

In the presence of moisture, the chloride in aggregate can corrode the steel reinforcement in concrete. Unlike sulfates, the presence of chlorides in RA is not related to aggregate type, but rather to factors such as the use of certain additives and exposure to marine environments or to freezing with deicing salts (Sanchez de Juan and Alaejos, 2006).

With the exception of the Chinese standard (DG/TJ07/008, 2007), most of the regulations and guidelines set an overly restrictive limit on acid-soluble chloride in RCA (CUR, 1984, 1986 and 1994; DIN 4226-100, 2002; OT 70085, 2006; WBTC 12, 2002). However, the EHE-08 is the only standard that mentions water-soluble chlorides. In fact, in Annex 15, it recommends the total chloride test for RA since in some circumstances, combinations of certain chlorides can be reactive and attack the steel reinforcement in concrete. In regards to RMA and MRA, the acid-soluble chloride content has basically the same limits (CUR, 1984, 1986 and 1994; DIN 4226-100, 2002) though the German and Brazilian standards (DIN 4226 -100, 2002; NBR 15116, 2005) permit a higher content in RMA.

According to recent research, the acid-soluble chloride content of RA was found to range from 0.00% to 0.08% for all-in-one RCA and RMA (WRAP 2007). Water-soluble sulfates reached values between 0.00% (WRAP, 2007) and 0.13% in coarse RMA (Mas et al., 2011). Finally, total chloride had values ranging from 0.00% to 0.17% in fine RMA (Müeller, 2004).

3.3.3 Damaging substances

Clay lumps, soft particles, and lightweight particles are all regarded as damaging substances that can be found in certain types of aggregate. Their presence alters the setting of concrete and decisively affects its strength and durability. Specifications only appear in research conducted in Spain since the former Spanish EHE Concrete Code (EHE, 1998) included limit values for these substances.

The Brazilian standard (NBR 15116, 2005) limits clay lumps in RCA and MRA, whereas the current Spanish Code (EHE-08, 2008) only limits them in RCA. Values for clay lumps in coarse RMA ranged from 0.00% (González-Fonteboa and Martínez-Abella, 2005) to 0.22% (Mas et al., 2011). Limits for soft particles only appear in the former Spanish Code (EHE 1998). In the one research study available on this topic (González-Fonteboa and Martínez-Abella, 2005), the soft particle content was found to be as high as 20.36%. Lightweight particles in RCA (BS 8500-2, 2006; EHE-08, 2008; RILEM, 1994; WBTC 12, 2002) and RMA (BS 8500-2, 2006; RILEM, 1994) ranged from 0.00% (Jimenez et al, 2011) to 5.85% in coarse RMA (Alaejos and Sánchez de Juan, 2004).

3.3.4 Organic matter

The organic matter in aggregate can slow the setting of cement, even to the point of paralyzing the process completely. Consequently, many standards and guidelines limit organic matter for concrete made from RCA (CUR, 1984, 1986 and 1994; NBR 15,116, 2005), RMA (CUR, 1984, 1986 and 1994; RILEM, 1994) and MRA (CSIRO, 1998; NBR 15.116, 2005).

Given that there is little quantitative data available with results between 0.15 and 0.95% (Barbudo et al., 2012), it is impossible to evaluate RA quality, based on this parameter. However, in Martín-Morales et al. (2011), RA compliance with this parameter was qualitatively analyzed, based on color as compared to a reference substance (EN 1744-1, 2010). In contrast, IHOBE (2011) showed that there was a low correlation between organic matter and RA quality, which confirmed that this test should not be used to evaluate aggregate.

3.4 Geometric properties of recycled aggregates

Table 6 shows the geometric requirements in the standards and guidelines according to RA type. As can be observed, compliance with specifications of particle size, shape, and distribution is crucial to assure high-quality concrete. According to Table 6, limits are most often specified for fines content and then for flakiness index. In contrast, the maximum aggregate size and crushing value are seldom mentioned. Finally, various standards do not include any geometric requirements at all for RA (BRE Digest 433, 1998; CUR, 1984, 1986 and 1994; DS 2426, 2009; NB 26, 2003; OT 70085, 2006; SIA 2030, 2010).

Table 6. Geometric specifications for RA in standards and guidelines

Scope	Standard/ Guidelines	Maximum size of the aggregate (mm)	Recycled sand content (< 4mm)	Shape index (%)	Flakiness index (%)	Crushing value (%)	Sand equivalent index	Fines content (< 0,063 mm)	Shell content (%)
Australia	CSIRO			●✦		●✦			
Belgium	PTV-406				●■✦			●■	●■✦
Brazil	NBR 15.116							●✦	
China	DG/TJ07/008		●		●	●			
Denmark	DS 2426								
Europe	prEN 12620			●	●		●	●	
Germany	DIN 4226-100							●■✦	
Hong Kong	WBTC 12		●		●			●	
Italy	NTC		✦	●✦	●✦		●	●✦	
Japan	JIS A 5021 /5022/5023							●	
Korea	KS F2573	●						●	
Netherlands	NEN 5905								●
	CUR								
Norway	NB 26								
Portugal	LNEC E 471		✦		●			●✦	✦
Spain	EHE-08		●		●		●	●	
Switzerland	SIA 2030								
	OT 70085								
United Kingdom	BRE Digest 433								
	BS 8500-2	●■						●■	
	RILEM		●■					●■	
● RCA; ■ RMA; ✦ MRA									

3.4.1 Aggregate

Aggregate size should be as large as possible since the larger the grain size, the greater the strength of the aggregate. This evidently enhances the mechanical strength of concrete. In this respect, only the Korean and British Standards (BS 8500-2, 2006; KS F2573, 2006) limit maximum aggregate size for RCA and the BS 8500-2 (2006) in the case of RMA. However, for the selection of the maximum particle size of the aggregate, it is necessary to take into account the sieve effect produced by the reinforcement and formwork.

3.4.2 Recycled sand content

The standards and guidelines limit the recycled sand content because it can reduce the compressive strength of concrete (Padmini et al., 2009; Sim and Park, 2011). Most regulations do not permit the use of fine RCA (BRE Digest 433, 1998; BS 8500-2, 2006; EHE-08, 2008; LNEC E 471, 2009; NTC, 2008; WBTC 12, 2002). However, in certain standards and guidelines, recycled sand is allowed for RCA (Annex 15 of EHE-08, 2008; CUR, 1984, 1986 and 1994; DIN 4226-100, 2002; DS 2426, 2009; JIS A 5021, 2005; NB 26, 2003; NBR 15.116, 2005; RILEM, 1994; SIA 2030, 2010) and RMA (DIN 4226-100, 2002; NBR 15.116, 2005; SIA 2030, 2010). In contrast, the only standard that restricts the use of fine RMA is the BS 8500-2 (2006).

A recycled fine sand fraction replacement by natural sand invariably improves recycled concrete (Ajdukiewicz and Kliszczewicz, 2002). According to Corinaldesi and Moriconi (2009) and Evangelista and de Brito (2007), 30% is the maximum replacement percentage that will not jeopardize its mechanical properties. These authors base their assertion on Katz (2003) who claims that the optimal compressive strength of concrete is directly related to a high fine RA replacement. The reason for this lies in the levels of hydrated and non-hydrated cement, which can be as high as 25% of the mix weight. In contrast, as a way of increasing concrete strength, BecerraCabral et al. (2010) propose the use of fine recycled ceramic material because of its pozzolanic capacity (Khatib, 2005). This occurs because of the high content of portlandite that is fixed by the ceramic fines in the initial days of reaction (IHOBE, 2011).

Therefore, if the standards and guidelines are strictly complied with, there is no fine or all-in-one RA suitable for manufacturing concrete.

3.4.3 Shape index

As its name implies, the shape index is a method used to measure the shape of coarse aggregate, and indicates how rounded the particles are. Of the standards studied, the only one that includes this index as a quality parameter for RA is the former Spanish Concrete Code (EHE 1998), which is no longer in force. Research results show shape index values ranging from 0.07% for fine RMA (Mas et al., 2011) to 0.47% for coarse RMA (Gómez-Soberón, 2002). Nevertheless, RA particle shape is more irregular than natural aggregate and has a coarser surface (Padmini et al., 2009).

3.4.4 Flakiness index

The flakiness index is also used to measure the shape of coarse aggregate. However, unlike the shape index, it determines the quantity of aggregate particles that are elongated, instead of cubicle. The standards and guidelines that include this index specify very different limit values. Based on the little data available, RMA and RMA generally seem to have a higher flakiness index than RCA. In fact, a higher flakiness index seems to be characteristic of aggregate with a small particle size (Gómez-Soberón, 2002; WRAP, 2007). The percentage values were found to range from 5.50% for RCA (WRAP, 2007) to 29.52% for RMA (Tam and Le, 2007). However, the flakiness index is not only dependent on the type of RA, but is also related to the crushing method of the construction waste (Padmini et al., 2009).

3.4.5 Crushing value

The crushing value quantifies the percentage of crushed particles and is seldom mentioned in standards and guidelines. In fact, only the CSIRO restricts concrete and mixed RA in regards to crushed particles though the DG/TJ07/008 (2007) establishes limit values for RCA. There is also very little research on this parameter and the few studies available show extremely heterogeneous values, such as 1.73% for coarse MRA (Gokce et al, 2004) and 32% for all-in-one RCA (Padmini et al., 2009). This seems to indicate that aggregate of larger particle size has a lower crushing value.

3.4.6 Fines content

The fines content is evidently more limited in the coarse aggregate fraction. This not only applies to its quantity but also to its quality. From a granulometric perspective, a good-quality fines content (i.e. one that is not clayey) enhances the workability and cohesion of fresh concrete and improves the impermeability and durability of hardened concrete. Moreover, there is no need to add more water or cement.

Practically all standards and guidelines limit the fines content in RA. According to research results, values range from 0.2% (González-Fonteboa and Martínez-Abella, 2005) to 1.17% (Martín-Morales et al., 2011) for all-in-one RA; from 0.1% (González-Fonteboa and Martínez-Abella , 2005) to 1.14% (Alaejos and Sánchez de Juan, 2004) for coarse RA; and from 0.5% (Corinaldesi and Moriconi, 2009) to 46% (Miranda and Selmo, 2006) for fine RA.

3.4.7 Sand equivalent index

The sand equivalent index measures the quality of the fines content in fine aggregate (i.e. its degree of clayeyness). Only the Spanish concrete code (EHE-08, 2008) states that aggregate should not have a sand equivalent index below 70 and 75, depending on environmental exposure. In fact, this index has been the focus of very few studies. Based on available research on the fines fraction (0/2mm), RA was found to have a sand equivalent index ranging from 64.75 (González-Fonteboa and Martínez-Abella, 2005) to 93.6 (Gómez-Soberón, 2002).

4. Guidelines for technical parameters

4.1 Physical characteristics of recycled aggregate

Table 7 shows the requirements in standards and guidelines regarding the physical properties of the recycled aggregate described in the previous section.

4.1.1 Density

Density is an important quality parameter for recycled aggregate, and thus, it is included in most standards and guidelines. Table 7 shows the requirements regarding the physical properties of the aggregate. As can be observed, recommended values for oven-dry density, regardless of RA type, are 1,500-2,500. However, most of these values are higher than 2,000 kg/m^3. In all likelihood, those standards that specify a minimum value (1,500 kg/m^3) are following harmonized standard prEN 12620. This value is also included in other European standards (NTC, 2008; DIN 4226-100, 2002), which is a reflection of the incipient harmonization process. Only the JIS A 5022 establishes a minimum value of 2,200 kg/m^3 for fine aggregate.

Surface-dry density is regarded as somewhat less crucial, and is contemplated only in the Australian (CSIRO, 1998) and Norwegian (NB 26, 2003) norms. Moreover, they only mention RCA and MRA. In both standards, values are ≥ 2,100 kg/m^3 for RCA and ≥ 1,800 kg/m^3 for MRA.

Similarly to surface-dry density, bulk density is also only mentioned in two standards (CSIRO, 1998; LNEC E 471, 2009) though they do not agree on the recommended limit values. For RCA, the CSIRO recommends a value of 1,200 kg/m^3, whereas the value in the LNEC E 471 is 2,200 kg/m^3. The recommendations in the two standards also significantly diverge in regards to MRA, for which the CSIRO recommends a value of 1,000 kg/m^3 and the LNEC E 471, a value of 2,000 kg/m^3.

Finally, specific gravity for RCA is limited in the CSIRO (Class 1) and the KS F2573 with a minimum value of 2,500 kg/m^3. The KS F2573 also establishes a minimum specific gravity value of 2,200 kg/m^3 for fine RCA.

4.1.2 Absorption

The absorption values for coarse RCA in Table 7 fall in two groups: (i) a more restrictive group that sets limits at 5-7% (DG/TJ07/008, 2007; EHE-08, 2008; JIS A 5022, 2006; JIS A 5023, 2007; NEN 5905, 2004; NBR 15.116, 2005), and a less restrictive group that sets limits at 9-10 %. It is striking that the value established by Asian countries is 3%. Regarding RCA fines, the NBR 15.116 and JIS A 5023 include values of 13%. However, the JIS A 5021 recommends much lower values (3-7%), depending on the use of the concrete.

Table 7. Requirements for physical properties in standards and guidelines

Property		RA	Limits	Most restrictive standard	Least restrictive standard
Density (kg/m³)	Oven-dry density	RCA	≥ 1500-2500 CA	JIS A 5021	EN 12620; NTC
			≥ 2200 FA	JIS A 5022	JIS A 5022
		RMA	≥ 1500-2000	CUR	RILEM (Type I)
		MRA	≥ 1500-2200	DS 2426	DIN 4226-100 (Type 4); NB 26 (Type 1)
	Surface-dry density	RCA	≥ 2100	CSIRO Class 1A; NB 26 Type 2	CSIRO Class 1A; NB 26 Type 2
		MRA	≥ 1800	CSIRO Class 1B NB 26 Type 1	CSIRO Class 1B; NB 26 Type 1
	Bulk density	RCA	≥ 1200-2200	LNEC E 471	CSIRO Class 1A
		MRA	≥ 1000-2000	LNEC E 471	CSIRO Class 1A
	Specific gravity	RCA	≥ 2440-2500 CA	KS F2573	CSIRO Class 1A
			≥ 2200 FA	KS F2573	
Water absorption (%)		RCA	≤ 3 - 10% CA	KS F2573; JIS A 5021	DIN 4226-100 Type 1; DG/TJ07/008 Type II; WBTC 12; RILEM Type II; NB 26 Type 2
			≤ 3 - 13% FA	JIS A 5021	JIS A 5023
		RMA	≤ 9 - 20%	PTV-406	DIN 4226-100 Type 3; RILEM Type I
		MRA	≤ 8 - 20%	CSIRO Class 1B	NB 26 Type 1

In reference to RMA, most of the standards agree on a less restrictive value (≤ 20%). Nevertheless, the Belgium standard specifies a value of 9%. The recommendations for MRA absorption show percentages ranging from 8% (CSIRO, 1998) to 20% (NB 26, 2003) with an intermediate percentage of 15% in the case of the DIN 4226-100. In this sense, the Brazilian standard is the only one that establishes values for fine MRA with a maximum value of 17%.

4.2 Mechanical behavior of recycled aggregate

Table 8 lists the requirements in the standards and guidelines in regards to the mechanical properties of recycled aggregate.

4.2.1 Resistance to fragmentation

Despite the fact that resistance to fragmentation is a crucial parameter for concrete, it is only contemplated in the EHE-08 and NEN 5905 with a value of 40-50 for RCA (Table 8). Nonetheless, in the same way as for other properties, the prEN 12620 states that the manufacturer should declare the category of the aggregate, depending on the value obtained in each test, when the standard does not include a limit value. Accordingly, other European standards with a view to harmonization with the prEN 12620 also establish this category assignment. In the specific case of the Los Angeles Test, the manufacturer should declare a category for RCA (DIN 4226-100, 2002; prEN 12620, 2010; LNEC E 471, 2009; NTC, 2008; PTV 406, 2003) in the range of 10-60%.

4.2.2 10% fine value –TFV

The 10% fine value is a mechanical parameter that is only specified in the WBTC 12. As can be observed in Table 8, the RA should have a value greater than 100 kN.

4.2.3 Soundness (Table 8)

According to Table 8, the mass loss of RA, when it is subject to the crystallization of salts, is 9% or 18% for coarse RCA. The only exception is the KS F2573, which specifies a limit of 12%. This same standard limits mass loss to 10% for fine RCA. Furthermore, as in the Los Angeles Test, the manufacturer should declare the category of the aggregate when the soundness is in the range of 1-50 % for RCA (prEN 12620, 2010; NTC, 2008) and for MRA (NTC, 2008).

Table 8. Requirements for mechanical properties in standards and guidelines

Property	RA	Limits	Most restrictive standard	Least restrictive standard
Los Angeles abrasion coefficient	RCA	≤ 40-50%	EHE-08; NEN 5905	LNEC E 471
10% fine value	RCA	>100kN	WBTC 12	
Soundness	RCA	≤ 9-18% CA	CSIRO	DG/TJ07/008; EHE-08
		≤ 10% FA	KS F2573	

4.3 Chemical suitability of recycled aggregates

Table 9 lists the requirements in the standards and guidelines related to the chemical properties of recycled aggregate. The following section provides a detailed analysis of each of them. As can be observed, there is no difference in the limit values established for different aggregate types.

4.3.1 Sulfur compounds

In order to analytically obtain sulfur compounds (e.g. water-soluble sulfate, acid-soluble sulfate, and total sulfate compounds), the standards establish different tests, the values for which appear in Table 9. Water-soluble sulfates are limited in all of the standards and for all aggregate types to a maximum of 1%. The exception is the LNEC E 471, which gives a limit value of 0.2% for RCA and MRA. Furthermore, if the standard does not explicitly include a limit, the manufacturer should declare that water-soluble sulfate is within the range of 0.2-1.3% for RCA (prEN 12620, 2010; NTC, 2008) and for MRA (NTC, 2008).

Acid-soluble sulfate compounds should have values of 0.8 or 1%. In those cases that the manufacturer is obliged to classify the RA in regards to this parameter, they should do so within the range of 0.2-1% for RCA (prEN 12620, 2010; NTC, 2008; PTV-406, 2003), RMA (PTV-406, 2003) and MRA (NTC, 2008; PTV-406, 2003).

Finally, for total sulfate compounds, regardless of the aggregate source, the standards unanimously establish a maximum value of 1%. In addition, it is necessary to specify RA classification in the PTV-406 within the range of 1-2%.

Table 9. Requirements for chemical properties in standards and guidelines

Property	RA	Limits	Most restrictive standard	Least restrictive standard
Water-soluble sulfate (%)	RCA	≤ 0.2- 1%	LNEC E 471	RILEM (Type II); WBTC 12; NBR 15.116
	RMA	≤ 1%	RILEM (Type I)	
	MRA	≤ 0.2-1%	LNEC E 471	NBR 15.116
Acid-soluble sulfate (%)	RCA	≤ 0.8-1%	DIN 4226-100; EHE-08; LNEC E 471	BS 8500-2; BRE Digest 433; CUR; DG/TJ07/008 Type I; OT 70085
	RMA	≤ 0.8-1%	DIN 4226-100	BS 8500-2; CUR
	MRA	≤ 0.8-1%	DIN 4226-100; LNEC E 471	OT 70085
Total sulfur (%)	RCA	≤ 1%	EHE 08; prEN 12620; NEN 5905; NTC; LNEC E 471	
	RMA	≤ 1%	BRE Digest 433	
	MRA	≤ 1%	NTC; LNEC E471; BRE Digest 433; SIA 2030	
Water-soluble chloride (%)	RCA	≤ 0.03-1%	EHE-08	NBR 15.116 Class A
Acid-soluble chloride (%)	RCA	≤ 0.03-0.25%	OT 70085	DG/TJ07/008 Type I
	RMA	≤ 0.04-0.06%	DIN 4226-100 Type 3	PTV-406
	MRA	≤ 0.04-1%	DIN 4226-100 Type 2	NBR 15.116 Class A
Total chloride (%)	RCA	≤ 0.03-0.15%	EHE-08; SIA 2030	EHE-08
Lightweight particles (%)	RCA	≤ 0.1-1%	CUR; NB 26 Type 2	EHE 08; LNEC E 471
	RMA	≤1%	PTV-406; RILEM Type I; BS 8500-2	
	MRA	≤1%	LNEC E 471	
Clay lumps (%)	RCA	≤ 0.2-2%	KS F2573	NBR 15.116
	MRA	≤ 2%	NBR 15.116	
Organic matter	RCA	≤ 0.10-2%	CUR; NEN 5905	NBR 15.116 Class A
	RMA	≤ 0.5-1%	PTV-406	RILEM Type I; CUR
	MRA	≤ 0.15-2%	CSIRO Class 1B	LNEC E471; NBR 15.116 Class A

4.3.2 Chlorides

In the same way as for other compounds, chlorides are divided into water-soluble, acid-soluble, and total chlorides. According to Table 9, the maximum value of water-soluble chloride in RCA generally ranges from 0.04% (JIS A 5021; 2005) to 0.05% (EHE-08, 2008; WBTC 12, 2002). It should be highlighted that the EHE-08 limits chlorides, depending on whether the concrete is mass concrete, reinforced concrete, or pre-stressed concrete, to values of 0.15, 0.05, and 0.03%, respectively. This contrasts with the NBR 15.116, which establishes a limit of up to 1% for the non-structural use of concrete. This limit is significantly less restrictive than the value of 0.15% in the Spanish standard.

In reference to acid-soluble chloride, for all RA, the standards establish limit values of 0.03-0.06%. However, for RCA, the DG/TJ07/008 recommends a more permissive value of 1%. Furthermore, for MRA, the standards recommend values that should not exceed 0.15% (DIN 4226-100, 2002) and 1% (NBR 15.116, 2005). According to the LNEC E 471, the manufacturer should specify the classification of the RA for RCA as well as for MRA.

Total chloride is limited in two standards (EHE-08, 2008; SIA 2030, 2010) though only for RCA. In the case of the EHE-08, the limit values are the same as for water-soluble chloride. However, the SIA 2030 is more restrictive in the case of mass concrete (0.12%) as well as in that reinforced concrete (0.03%), which coincides with the value for pre-stressed concrete in the Spanish standard.

4.3.3 Damaging substances

Lightweight particles, soft particles, and clay lumps are regarded as damaging substances. As shown in Table 9, only the soft particles are not included in any of the standards. For lightweight particles in RCA, there are three groups of standards with a wide range of values: (i) a first group with a less restrictive value of 1%; (ii) a second group with an intermediate value of 0.5% (BS 8500-2, 2006; EHE-08, 2008; RILEM, 1994; WBTC 12, 2002); (iii) a third group with a more restrictive value of 0.1%. In contrast, RMA and MRA are assigned a sole limit value of 1%.

Clay lumps are only mentioned in three of the standards and with very different values. For coarse RCA, values for this substance are limited to 0.2% (KS F2573, 2006), 0.6% (EHE-08, 2008), and 2% (NBR 15.116, 2005). As can be observed, the Brazilian norm is extremely permissive. In fact, this same standard also limits clay lumps in MRA to 2%.

4.3.4 Organic matter

The most characteristic limit values for RA content in organic matter in the standards consulted are 0.5% (DG/TJ07/008, 2007; JIS A 5021, 2005; RILEM, 1994) and 0.1%. The NBR 15.116 has the least restrictive limit value of 2%. Similar limit values are established for RMA and MRA (See Table 9).

4.4 Geometric properties of recycled aggregates

Table 10 lists the requirements in standards and guidelines for the geometric properties of the RA.

4.4.1 Maximum aggregate size

Maximum grain size is only contemplated in the KS F2573 and BS 8500-2, which specify the following similar values for RCA: (i) 25/20 mm in the Korean standard; (ii) 20 mm in the British standard. In addition, the British standard (BS 8500-2, 2006) establishes the same value for RMA (Table 10).

4.4.2 Recycled sand content

In this case, the standards that permit the use of recycled sand only sanction the use of sand from concrete. As shown in Table 10, the recycled sand content should generally be less than 5%. The RILEM recommendations in its Type II application permit the same content of sand from mixed aggregate.

4.4.3 Shape index

The shape index should have a maximum value of 35% for RCA as well as for MRA (Table 10). In this sense, for RCA, the European standard (prEN 12620, 2010), the DIN 4226-100, and the NTC state that the producer should declare whether the shape index is in the range of 15-55%. This should be declared in accordance with the relevant category of the aggregate. The DIN 4226-100 also includes this requirement for RMA and MRA, whereas the NTC includes it for MRA.

4.4.4 Flakiness Index

In the case of RCA, the flakiness index has widely different values (15-50%), depending on the standard or guideline. As shown in Table 10, the EHE-08 and the LNEC E 471 set a value of 35% and the WBTC 12, a value of 40%. For MRA, only the Portuguese standard has a limit value of 50%. In addition, similarly to the shape index, the flakiness index should be declared by the producer in accordance with the relevant category, depending on the application or end use. This is made explicit for RCA (prEN 12620, 2010; NTC, 2008; PTV 406, 2003), for RMA (PTV 406, 2003), and for MRA (NTC, 2008; PTV 406, 2003) when the test is not required and when the flakiness index value is 10-50%.

4.4.5 Crushing value

The crushing value is the percentage of crushed particles in the recycled aggregate. This value only appears in the Chinese norm for Type I RCA (see Table 10). In this sense, the SCIRO has the same limit value (30%) for RCA and MRA.

4.4.6 Sand equivalent index

The sand equivalent index is only contemplated in the EHE-08 (Table 10). This standard states that fine RCA should not have an index lower than 70-75, depending on the general class or type of exposure of the concrete produced with this aggregate. As with the other properties, this value should be determined in order to assign the aggregate to the relevant category with an interval of 30-65 (prEN 12620, 2010).

4.4.7 Fines content

In all of the standards, the fines content is one of the most important geometrical properties of the aggregate. Requirements generally establish that the fines content of fine RCA should be 6-16% (Table 10). Approximately half of the norms set a value of 6%, whereas the other half places this value at 16%. An exception is the DIN 4226-100, which gives a maximum value of 10%. In the case of coarse RCA, all of the standards establish maximum values of 1-4% except for the NBR 15.116 with a maximum fines content of 10%. In regards to RMA and MRA, all of the standards have fines content values of 3-5% for coarse RA and 10% for fine RA.

Nonetheless, for MRA, this fines content can have maximum values of 18-20% (DIN 4226-100, 2002; NBR 15.116, 2005).

4.4.8 Shell content

The shell content in RA is only relevant for coarse aggregate. This test is only recommended in the Belgian standard (PTV-406, 2003) and the Netherlands standard (NEN 5905, 2004). It is probably no accident that the two countries are also geographical neighbors. In both documents, the shell content is limited to a maximum of 10% and only for RCA (Table 10).

Table 10. Requirements for RA geometric properties in standards and guidelines

Property	**RA**	**Limits**	**Most restrictive standard**	**Least restrictive standard**
Maximum aggregate size (mm)	RCA	≤ 20-25mm	BS 8500-2	KS F 2573
	RMA	≤ 20	BS 8500-2	
Recycled sand content (< 4mm)	RCA	≤ 5%	DG/TJ07/008 Type I; EHE 08; WBTC 12; RILEM Type II	
	RMA	≤ 5%	RILEM Type II	
Shape index (%)	RCA	≤ 35%	CSIRO	
	MRA	≤ 35%	CSIRO	
Flakiness Index (%)	RCA	≤ 15-50%	DG/TJ07/008	LNEC E 471
	MRA	≤ 50%	LNEC E 471	
Crushing value (%)	RCA	≤ 30%	CSIRO; DG/TJ07/008 Type I	
	MRA	≤ 30%	CSIRO	
Sand equivalent index	RCA	>70-75	EHE-08	
Fines content (< 0.063 mm)	RCA	≤6-16% FA	EHE-08	
		≤1-10% CA	JIS A 5021; KS F 2573	NBR 15.116
	RMA	10% FA	DIN 4226-100	
		3-5% CA	RILEM Type I; BS 8500-2	PTV-406
	MRA	≤10-20% FA	DIN 4226-100 Type 2	NBR 15.116 Class A
		≤3-10% CA	LNEC E 741	NBR 15.116 Class A
Shell content of coarse aggregates (%)	RCA	<10%	PTV-406; NEN 5905	

5. Parameters affecting compliance with quality criteria

5.1. Physical properties

The density of RA (Table 3) is usually slightly lower than that of NA. Nevertheless, it should be relatively easy to comply with the limit values in the standards and guidelines analyzed (Table 7). Absorption capacity is one of the most important physical parameters for RA. The absorption capacity of RA is greater than that of natural aggregate. RA water absorption values can vary, depending on the type and size of RA (Angulo et al., 2004; Becerral et al., 2010; Miranda and Selmo, 2006; Poon and Chan, 2007; Tam and Le, 2007). The comparison of typical RA absorption capacity values with those in standards and recommendations (Table 7) indicate that it might be difficult for RA to comply with even the least restrictive values. The problem is greater in the case of fine RA than for coarse RA (Miranda and Selmo, 2006). An exception is RA from sanitary ceramic and electrical ceramic materials, whose typical absorption capacity is lower than all of the limit values in the standards because of the compactness of such material (Medina et al., 2012; Senthamarai et al., 2011).

Absorption capacity and density values are directly related to the cement mortar attached to aggregate particles. Consequently, typical values could be significantly reduced by improving the on-site selection of the C&DW as well as its processing at the treatment plant.

5.2. Mechanical properties

Mechanical properties of RA generally comply with the limit values in standards and guidelines. In the case of the Los Angeles coefficient and the TFV, compliance depends on the RA sample. In the case of soundness or mass loss, RA samples easily fulfill the limit values in the standards.

The typical Los Angeles coefficient values for RA in the references analyzed were found to be 17.4 and 53% whereas the standards and guidelines give limit values lower than 40-50% (Table 8). This means that certain types of RA (e.g. coarse RA) might have compliance problems. The presence of ceramic waste and cement mortar attached to the aggregate particles gives them a lower resistance to fragmentation (Chini et al., 2001; Hansen and Narud, 1983; Sri Ravindrarajah et al., 1987). Thus, RA selection and treatment processes need to be improved in order to improve fragmentation resistance. In the case of TFV, typical values for RA were found to be 61.36-189.38 kN (Tam and Le, 2007) though the limit values in standards and recommendations are all higher than 100 kN.

5.3. Chemical properties

A comparison of typical RA chemical composition values with those in the standards and guidelines (Table 9) reflect that the chemical properties of RA are one of its weakest aspects because of its high content in sulfates and chlorine. Sulfate-based products, such as gypsum, are common contaminants in C&DW (Tam et al., 2008). Thus, sulfate-resistant cement should be seriously considered in situations where gypsum contamination is suspected. However, since a high percentage of the small particle-size fraction goes through the crushing process, the average sulfate content value in RA is 0-6%, depending on the characteristics and the processing of the C&DW. These values exceed the limits in the standards and guidelines (Table 9).

The maximum chlorine content in RA ranges from 0.08% to 0.13%. Although some values are only slightly higher than the limit values for certain types of RA, they can still lead to the corrosion of the steel reinforcement embedded in concrete. This has an extremely negative impact on concrete durability (Tam et al., 2008), and thus, it is crucial to control the presence of chlorine in concrete.

When the demolition process is selective and when there is a manual selection of waste before the crushing process, this facilitates the removal of gypsum, large impurities, clay, organic matter, and lightweight particles. The quality of the RA can thus be enhanced so that the RA can more easily comply with the limit values for chemical compounds in the standards and guidelines. However, the presence of chlorine compounds in RA is directly related to its exposure to a marine environment as well as to the use of certain additives. As a result, chlorine is more difficult to control or reduce in RA. Certain authors suggest that this content can be decreased by immersing the aggregate in water (Debied et al., 2009).

5.4. Geometric properties

The geometric properties that are most severely limited are the presence of recycling sand and fines. All of them are strictly limited in standards and recommendations (Table 10) because of their negative effects on concrete quality. Properties related to aggregate shape, such as the shape index, flakiness index, and crushing value, depend on the crushing and size selection equipment. Experience at recycling plants reflects that concrete tends to break into cubicle-shaped particles rather than elongated ones. Generally speaking, these characteristics should be controlled with suitable C&DW treatment procedures to obtain RA in compliance with the limit values in standards and guidelines.

6. Future trends

The results of quality studies reflect that in comparison to NA, RA needs to improve certain parameters. For this reason, it was necessary to establish reference values. Nevertheless, these values often show significant variation, depending on the standard or guideline. This study shows that the standards and guidelines, elaborated by technical committees, research agencies, and standards organizations are endeavoring to encourage the use of aggregate from C&DW in construction. For this reason, they all establish limit values concerning RA composition, properties, and end use. The conclusions that can be derived from this study are the following:

- In certain cases, the limit values in standards and guidelines vary considerably. This means that the possible revalorization of C&DW is significantly reduced in the most restrictive norms. Accordingly, what is needed is a set of harmonized regulations for recycled aggregate, which would homogeneously specify its possible end uses, depending on its application. This would undoubtedly favor its wider use in construction.
- In relation to RA, its absorption as well as its chloride, sulfate, and fines contents are the properties most in need of improvement because of their potentially devastating impact on concrete strength and durability.
- Selective demolition and a more effective treatment of C&DW at the plant are crucial in order to control and improve the properties that lower aggregate quality.
- Finally, mixing RA and NA is a way of improving RA quality when certain of its properties make it unsuitable for a given application or end use.

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