The suitability of concrete using recycled aggregates (RAs) for high-performance concrete (HPC)

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Abstract: Most studies related to concrete made with recycled aggregates (RA) use uncontaminated aggregates produced in the laboratory, revealing the potential to re-use as much as 100%. However, industrially produced RA contain a certain level of impurities that can be deleterious for Portland cement concrete, thus making it difficult for the concrete industry to use such investigations unless uncontaminated RA are used. This chapter reviews current knowledge on concrete made with RA, with a focus on the crucial importance of the presence of impurities, and how those aggregates are not suitable for the production of high-performance concrete (HPC). The potential of geopolymers to produce HPC based on high volume RA is also discussed.

Key words: concrete and demolition waste (C&DW), recycled aggregates (RA), impurities, high-performance concrete (HPC), geopolymers.

17.1 Introduction

The high volumes of concrete and demolition waste (C&DW) that are currently generated constitute a serious problem in terms of landfill space. Pacheco-Torgal and Jalali (2011) estimate that non-recycled C&DW, generated in the 15 leading EU member states (MS), represents a volume occupying 10m in height across 13 km² of landfill each year. Such estimates are only approximate, because these kinds of wastes are illegally dumped in most countries. C&DW recycling rates differ from country to country. While the European average is only 47% (Solis-Guzman *et al.*, 2009), some countries may reach 80%, as is the case in Denmark or in the Netherlands (Chini, 2005). Eurostat (2010) mention a total of 970 million tons/year of C&DW, representing almost 2 tons per capita. However, currently the average recycling rate of C&DW for the 27 EU MS is just 47% (Table 17.1).

According to the Revised Waste Framework Directive 2008/98/EC, the minimum recycling percentage of C&DW by the year 2020 should be at least 70% by weight. This target and also the initiative, 'A resource efficient

Recycling rates of C&DW in Europe

	Recycling rates%
Flanders)	>90
Estonia, Germany, Ireland, Netherlands	>70
Belgium, France, Lithuania, UK	60–70
Poland, Portugal, Slovenia	40–60
Average recycling rate for EU–27	47
Czech Republic, Finland, Greece, Hungary, Poland, Spain	<40
Italy, Malta, Romania, Slovakia, Sweden	No data available

Monico *et al.*, 2010.

(COM, 2011), shows the determination of the EU to promote the use of recycling. Consumption of aggregates worldwide amounts to about 1 billion tons/year and an annual growth rate of 4.7% is expected (Vitz and Bahn-Walkowiak, 2011). More than one-third of this production is related to concrete production. Concrete is the most used construction material on Earth, with approximately 10 km³ produced every year (Vitz and Macphie, 2011).

Environmental impacts of primary aggregates include consumption of non-renewable raw materials, energy consumption and the reduction of biodiversity at extraction sites. Since the cost of aggregates is highly dependent upon transport distances, extraction operations have to be near construction sites, which in turn increases the number of quarries and their impact upon biodiversity. However, the environmental impacts of proper C&DW management are not solely environmental.

An example of the economic benefits associated with recycling C&DW is provided by the Environment Agency of the United States, which looks at the job creation from C&DW. Incineration of 10 000 tons of waste can lead to the creation of 1 job, landfilling can create 6 jobs, but if the same amount of waste is recycled, it can create 36 jobs (Pacheco-Torgal and Jalali, 2011). The report, 'Strategic Analysis of the European Recycled Materials and Products Market in Construction Industry,' states that the market for recycled construction materials generated revenues of €744.1 m in 2010, and is estimated to reach €1.3 bn by 2016. However, this is a low estimate, because it does not consider the 100% C&DW re-use scenario.

Although the use of recycled aggregates (RA) in concrete has been studied for many years (Pacheco-Torgal and Jalali, 2011), modern concrete structures are still made with primary aggregates. The reasons for this stem from their low cost, the high carbonation taxes for C&DW, and the lack of positive discrimination toward the use of RA. Furthermore, the use of RA concrete in high-grade applications is discouraged, because of its poorer compressive strength and high variability in mechanical behaviour (Tam *et al.*, 2005). This low performance means less durable concrete structures, which require frequent maintenance and conservation

operations, or even entire replacement (with the associated consumption of more raw materials and energy).

The importance of durability in the context of eco-efficiency of construction and building materials has been ascertained by Mora (2007), who state that increasing concrete durability from 50 to 500 years would mean a reduction of its environmental impact by a factor of 10. According to Hegger *et al.* (1997), an increase in the amount of compressive strength in concrete would mean a reduction in reinforced steel by as much as 50%. These are crucial issues when considering the efficiency of materials (Pacheco-Torgal and Jalali, 2011; Allwood *et al.*, 2011), highlighting the need for studies that allow for high mechanical strength and high durability concretes capable of reusing a high volume of RA.

17.2 High performance concrete (HPC) with recycled aggregates (RAs): an overview

17.2.1 HPC trials

Very few studies related to the re-use of RA were able to achieve a high performance in terms of both mechanical properties and a greater resistance to chemical attack typical of HPC (Aitcin, 2003). Ajdukiewicz and Kliszczewicz (2002) obtained 80 MPa compressive strength concretes, but used RA from an original concrete of about 60 MPa. Since the possibility of RA produced in recycled plants coming from 60 MPa used concretes is almost zero, it is unrealistic to expect that RA HPC could be produced in this way. Other authors (Tu *et al.*, 2006) also attempted (and failed) to produce such material, reporting a 28 days' compressive strength of around 30 MPa (Fig. 17.1) and concluding that, 'It is suggested not to utilize RA for high, concrete strength applications, due to long-term durability problems'.

17.2.2 Other relevant mechanical strength and durability studies

Recent studies using RA produced under laboratory conditions show that the use of fine RA must not exceed 30%, otherwise the concrete performance could be at risk. For instance, the CO₂ penetration depth increased by about 110% for concrete made solely with fine RA (Evangelista and Brito, 2007). Etxeberria *et al.* (2007) studied the performance of concrete with natural fine aggregates and different replacement percentages of coarse RA, concluding that a replacement percentage of 25% is associated to a compressive strength of almost 40 MPa.

These authors used a type I 52,5R cement, which is not cost-efficient and has a high amount of clinker. Therefore it is not obvious that the environmental advantages associated with the use of RA outweigh those of using cement with high CO₂ emissions. Berndt (2009) also studied concretes with RA, fly ash and

17.1 The compressive strength of recycled aggregates HPC versus the age and the w/b ratio (Tu *et al.*, 2006)

blast furnace slag ($W/C = 0.4$), obtaining a compressive strength loss of around 40 MPa. Corinaldesi and Moriconi (2009) demonstrated that it is possible to use 100% industrially produced RA (70% old concrete, 27% bricks and tiles and 3% miscellaneous (asphalt, glass, wood, paper, and other similar construction debris)) with a compressive strength of almost 45 MPa, as long as silica fume are used with a W/C of 0.4.

Those authors further mention that no organic or alkali-silica reactive (ASR) materials were detected, and the amount of chlorides and sulphates were below 0.04 and 0.15% (by weight), respectively. Xia *et al.* (2012) reviewed research concerning the mechanical property, durability and the structural performance of RA concrete that has been carried out in the past 15 years (1996–2011) in China, concluding that mechanical performance, as well as durability, is lower when compared to conventional concrete.

The poor performance of RA concrete is associated with cracks and fissures, which are formed in RA during processing, thereby rendering the aggregate weaker and more susceptible to permeation, diffusion and absorption of fluids. These drawbacks limit the utilisation of the RA with higher percentages (>30%) in structural concrete (Kou and Poon, 2012). The use of SCMs can compensate for the drawbacks associated with the use of RA; however, permeability and

sorptivity of the matrix increases and the ingress of atmospheric CO_2 is facilitated, leading to an increase in concrete carbonation (Pacheco-Torgal *et al.*, 2012).

17.2.3 The problem of impurities in RAs

The majority of studies related to the re-use of C&DW in concrete use non-contaminated aggregates produced in the laboratory, making the results difficult to extrapolate when contaminated RA from recycled plants are used. Even those RA obtained from real wastes containing almost zero contamination have been previously submitted to specific treatments, which are costly and increase the environmental impact of RA. Current RA have particles of impurities such as soil, plastics, waste paper, wood, metals and organic matter. Organic matter can delay Portland cement hydration, thus leading to lower mechanical performance and lower concrete durability.

The use of RA contaminated with gypsum particles is a risk factor for concrete durability. Concrete deterioration is caused by the chemical reaction of sulphate ions with the alumina of the aggregates or with the tricalcium aluminate (C_3A) of the hardened cement paste in the presence of water; both expansion products that can lead to the cracking of concrete, which is why the regulations on C&DW limit the presence of SO_3 to less than 1%. Aggregates that come from concrete structures affected by ASR or with a high chloride or sulphate content can also be considered to be containing some kind of impurities. Algarvio (2009) studied a 50 to 80 ton/h C&DW recycling plant, noticing that contaminant percentage is very low, with wood and metals identified as the most frequent (0.048 and 0.047%, respectively).

Agrela *et al.* (2011) analysed the physical and chemical characteristics of 35 mixed RA obtained from 11 different C&DW treatment plants in Spain, noticing that 25.7% of aggregates showed 2% of gypsum. Other authors (Martin-Morales *et al.*, 2011) also detected a high sulphate content of 1.52%, which clearly exceeds the Spanish Structural Concrete Code EHE-08 upper limit of 0.80%. Debieb *et al.* (2012) studied the performance of concrete with RA contaminated by chlorides rather than sulphates, stating that the contamination did not seem to influence mechanical performance. However, they mentioned that concrete with contaminated RA is much more prone to corrosion (Fig. 17.2).

Those authors mention that precautions and specific measurements need to be taken, especially with aggregates from hazardous or critical origins such as sewage water plants, road infrastructures or buildings under marine environments. Park and Noguchi (2012) studied concrete containing metal impurities of various sizes and contents, finding that aluminum contained in RA, caused performance degradation in both mechanical properties and durability of RA concrete, even at quantities of less than 0.1% (Fig. 17.3). The chemical reaction between aluminum impurity and alkaline concrete can generate hydrogen gas which, in turn, is responsible for gas layer, foam, crack and rock pockets in hardened concrete. This leads to the significant degradation of mechanical properties of concrete, pointing

17.2 Half-cell potential of recycled reinforced concrete beams (Debieb *et al.*, 2012).

17.3 Relationship between aluminium impurity content and residual ratio of compressive strength (Park and Noguchi, 2012).

to more efficient screening methods that may increase the cost of RA, reducing its environmental advantage.

17.2.4 RA concrete standards

Different countries have different standards related to the production of RA concrete. In Portugal, the standard LNEC E 471 (2006) puts into practice the content of Directive EN 12620:2002. According to LNEC E 471, C40/50 is the

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Table 17.2 Impurity content in the Japanese, British and Korean standards

Standard	Contents of impurities	Limit by mass fraction (%)	
JIS A 5021 (Japan)	A	Tile, brick, ceramics, asphalt concrete lump	2.0
	B	Glass piece	0.5
	C	Gypsum, plasterboard piece	0.1
	D	Inorganic board	0.5
	E	Plastic piece	0.5
	F	Wood, wastepaper, asphalt lump	0.1
		Limit of total amount	3.0
BS 8500-2 (UK)	Maximum masonry content	5.0	
	Maximum fines	5.0	
	Maximum lightweight material	0.5	
	Maximum asphalt	0.5	
	Maximum other foreign material, e.g. glass, plastics, metals	1.0	
KS F 2576 (Korea)	Wood, wastepaper, plastic piece, etc. (volume fraction (%))	1.0	
	Tile, brick, ceramics, asphalt concrete lump, etc.	1.0	

Source: Park and Noguchi, 2012.

maximum compressive strength class allowed for structural concrete made with RA. This standard limits the volume of RA to 25% for the C40/50 strength class, and requires that concrete and stone aggregates should be at least 90%, as well as setting upper limits for the impurity content. Glass and other undesirable particles cannot exceed 0.2%.

Other standards also set limits on the impurity content (Table 17.2). DIN 4226-100 (2002) limits the maximum content of impurities to less than or equal to 1% in terms of aggregates weight. The existing standards in this field also make the evaluation of ASR contamination mandatory, as well as leaching tests. However, these prerequisites represent a cost that will reduce the attractiveness of concrete made with RA.

17.3 Applications of HPC using RAs

To date, studies related to the geopolymerisation of C&DW are scarce (Lampris *et al.*, 2009; Allahverdi and Kani, 2009). Nevertheless, it seems that this binder has potential features for the re-use of RA in the production of HPC. For the same

water/binder ratio, several authors report that geopolymers present a higher mechanical strength than Portland cement. Wang (1991) states a case of a geopolymeric concrete with 125 MPa compressive strength. Other authors (Davidovits, 1994) declare having obtained a 20 MPa strength after just 4 h, increasing to 70 to 100 MPa after 28 days' curing time. Fernandez-Jimenez *et al.* (1999) studied mortars ($w/b = 0.51$) activated with NaOH and waterglass, reporting 100 MPa for compressive strength. Fernandez-Jimenez and Palomo (2005) used slag/fly ash mixtures activated with NaOH and waterglass ($w/b = 0.35$), announcing a 90 MPa compressive strength after just 20 h.

Bakharev (2005) studied fly ash pastes activated with NaOH and waterglass ($w/b = 0.3$), stating a 60 MPa compressive strength after 2 days. Other authors (Pacheco-Torgal *et al.*, 2007, 2008) report a compressive strength higher than 30 MPa after only 1 day, reaching almost 70 MPa after 28 days' curing and 90 MPa at 90 days' curing (Fig. 17.4). In conventional concrete, the aggregates form a rigid skeleton of granular elements, which are responsible for compressive strength. In geopolymers, most of the compressive strength is related to the matrix characteristics, so this material does not rely on well-proportioned aggregate mixtures.

This makes geopolymeric concrete more suitable to RA. Concerning the resistance to acid attack, geopolymer performance is far better than that of Portland cement concretes because it does not contain $\text{Ca}(\text{OH})_2$, a soluble hydration product that constitutes the 'Achilles' heel' of Portland cement concrete. Davidovits *et al.* (1990) reported mass losses of 6 and 7% for geopolymeric binders immersed in 5% concentration hydrochloric and sulphuric acids over 4 weeks. For the same conditions he also observed that Portland cement-based concretes suffered mass losses of between 78 and 95%.

Other authors (Gourley and Johnson, 2005) mentioned that a Portland cement concrete with a service life of 50 years lost 25% of its mass after 80 immersion cycles in a sulphuric acid solution ($\text{pH} = 1$), while a geopolymeric concrete required 1400 immersion cycles to lose the same mass, thus meaning a service life of 900 years. More recently, Pacheco-Torgal and Jalali (2010a) mentioned an average mass loss of just 2.6% after being submitted to the attack of (sulphuric, hydrochloric and nitric) acids during 28 days, while the mass loss for Portland cement concretes is more than twice that value. Geopolymers are also less susceptible to generate expansion by ASR than OPC (García-Lodeiro *et al.*, 2007), and show excellent freeze-thaw resistance (Fu *et al.*, 2011).

These materials have another advantage over Portland cement concrete that is particularly interesting in the case of re-using contaminated RA; namely a high immobilisation capacity. According to Hermann *et al.* (1999), the use of alkali-activated binders is a good way to immobilise a wide range of harmful constituents such as toxic metals, hydrocarbonates and even nuclear wastes in a final product with high durability and costing much less than the current vitrification process. Vinsova *et al.* (2007) state that alkali-activated binders show a good performance

17.4 Compressive strength according to aggregate/binder mass ratio and H_2O/Na_2O molar ratio in AAMWM mortars made with different aggregates: (a) schist fine aggregates; (b) limestone coarse aggregates.

17.4 (Continued) (c) granitic coarse aggregates (Pacheco-Torgal *et al.*, 2007).

in the immobilisation of lead, cadmium and chromium, but being less effective for immobilisation of arsenic.

Lancellotti *et al.* (2010) showed that metakaolin-based geopolymer binders are able to immobilise toxic metals present in fly ash due to the incineration of municipal solid wastes. Immobilisation of a municipal solid waste incineration residue using geopolymers was recently reported (Galiano *et al.*, 2011). Other authors (Pacheco-Torgal *et al.*, 2010b; Zhang *et al.*, 2011) showed that geopolymeric binders can be used for the re-use of mine wastes. In addition, geopolymeric concretes are associated with lower CO_2 emissions than Portland cement concretes (Duxson *et al.*, 2007; Weil *et al.*, 2009; Habert *et al.*, 2011).

This is a crucial advantage, as Portland cement represents almost 80% of the total CO_2 emissions of concrete which, in turn, constitute about 6 to 7% of the planet's total CO_2 emissions (Shi *et al.*, 2011; Pacheco-Torgal *et al.*, 2012a). Nevertheless, geopolymers suffer from severe efflorescence (Pacheco-Torgal *et al.*, 2010b), because the bond between the sodium ions (Na^+) and the aluminosilicate structure is weak, thus explaining the leaching behaviour (Skvara *et al.*, 2008, 2009). According to those authors, it is the presence of water that weakens the bond of sodium in the aluminosilicate polymers, a

17.5 Geopolymer structure model (Rowles *et al.*, 2007).

behaviour confirmed by the geopolymer structure model proposed by Rowles *et al.* (2007) (Fig. 17.5). However, other authors (Temuujin *et al.*, 2009) mention that efflorescence does not occur when geopolymers are cured at elevated temperatures. This means the leachate sodium could be a sign of insufficient geopolymerisation, indicating that further investigations are needed to solve this issue.

Recently, Kani *et al.* (2011) showed that efflorescence can be reduced either by the addition of alumina-rich admixtures or by hydrothermal curing at temperatures of 65 °C or higher. These authors found that the use of 8% of calcium aluminate cement greatly reduces the mobility of alkalis, leading to minimum efflorescence.

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