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Mechanical characterization of concrete produced with recycled lightweight expanded clay aggregate concrete

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A B S T R A C T

In this paper the main mechanical properties of concrete produced with recycled aggregates obtained from crushing both structural and non-structural lightweight concrete are characterized. Various concrete mixes with replacement ratios of 20%, 50% and 100% of two types of coarse lightweight aggregates (LWA) by recycled lightweight concrete aggregates (RLCA) were studied in terms of their compressive strength, tensile strength, modulus of elasticity and abrasion resistance. Generally the experimental results show that all the studied properties are improved with the introduction of RLCA. In particular, concrete with RLCA has higher structural efficiency than the reference concrete, with LWA alone. It is thus concluded that more cost-effective structural lightweight concrete (LWC) can be produced with the introduction of RLCA. Moreover, it is shown that the RLCA obtained from non-structural lightweight concrete can be used to produce structural LWC. There is a slight reduction of the concrete's mechanical properties when the stronger LWA is replaced with the more porous RLCA obtained from non-structural lightweight concrete.

1. Introduction

The concrete industry is today the largest user of natural resources in the world. It is estimated that the worldwide consumption of concrete is currently around 10 billion tonnes every year (Meyer, 2009). If one assumes that concrete is 70% aggregates and uses 300 kg/m^3 of cement then nearly 1.2 billion tonnes of cement and 7.5 billion tonnes of aggregates are consumed annually by the industry. In addition, the concrete production involves a high energy consumption and its demolition generates large amounts of construction waste. The relevance of the energy use in the industrial sector is highlighted by Lu et al. (2013), where any energy saving can assume a relevant environmental impact. Therefore, using recycled aggregate could make a significant difference to the effort to improve the sustainability of the building industry (Kwan et al., 2012; Marie and Quiasrawi, 2012).

Contrary to normal weight concrete (NWC), the density of lightweight concrete (LWC) is usually below 2000 kg/m^3 and its thermal conductivity is below 1.0 W/m °C (Newman, 1993; Bogas, 2011). Therefore, lightweight concrete could be used instead of normal weight concrete, especially where lighter and more energy-efficient solutions are required.

Even though lightweight concrete has been used since the early days of the Roman Empire, it is only since the middle of the 20th century, after the birth of artificial lightweight aggregate (LWA), that LWC has come to be widely used in bridges and buildings, especially in non-structural insulating solutions (Holm and Bremner, 2000; Chandra and Berntsson, 2003). At present there is no accurate estimate of the total LWC waste produced every year, but its reuse and recycling are still not a common practice. Moreover, the production of artificial LWA is very costly in terms of energy consumption, resulting in a serious economic and environmental impact.

Therefore, for construction to be more cost-effective and environmentally-friendly it could be useful to combine the building of new lightweight structures with the use of a secondary lightweight aggregate source.

A great deal of experimental research has already been carried out on the physical and mechanical characterization of recycled

Abbreviations: LM, Leca M; LHD, Leca HD; LWA, lightweight aggregates; LWC, lightweight concrete; LWCM, no-fines non-structural lightweight concrete with Leca M; LWCHD, structural lightweight concrete with Leca HD; NA, natural aggregates; NWC, normal weight concrete; RCA, recycled concrete aggregates; RLCA, recycled lightweight concrete aggregates; RNWC, recycled normal weight concrete; RLWC, recycled lightweight concrete; RM, recycled aggregates from fines non-structural lightweight concrete with Leca M; RHD, recycled aggregates from structural lightweight concrete with Leca HD.

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normal weight concrete (RNWC) (e.g. Mefteh et al., 2013; Medina et al., 2014).

The major difference between natural aggregates (NA) and recycled concrete aggregates (RCA) is the adhered mortar on the surface of the RCA (Evangelista and de Brito, 2007; Kwan et al., 2012). This makes RCA a more porous material, usually with higher absorption, lower bulk density and lower crushing strength than natural aggregates (Kikuchi et al., 1998; Mefteh et al., 2013).

The lower angularity of NA means that replacing this aggregate with RCA usually requires additional water to achieve the same workability, even though the effective water/cement ratio does not necessarily have to increase (Ferreira et al., 2011; Saikia and de Brito, 2012). Tabsh and Abdelfatah (2009) report needing 10% more water for RNWC to achieve the same slump as NWC.

Regarding the physical and mechanical properties of RNWC, it was found that concrete density (Evangelista and de Brito, 2007; Medina et al., 2014), compressive strength (Khatib, 2005; Barbudo et al., 2013), tensile strength (Lovato et al., 2012; Medina et al., 2014) and modulus of elasticity (Evangelista and de Brito, 2007; Barbudo et al., 2013) decrease with increasing RCA content. Bazuco (1999) reported a compressive strength reduction in RNWC that varied between 14% and 32%. According to Tavakoli and Soroushian (1996) the weaker aggregate/old paste transition zone in RCA lowers the strength of RNWC. There is usually a greater reduction in the modulus of elasticity than in the other mechanical properties because the concrete stiffness is more affected by the aggregates' characteristics.

However, it was also found that the mechanical properties are not much affected by low levels of NA replacement (up to about 25%) (Li, 2008; Barbudo et al., 2013).

Matias et al. (2013) have found that the better bond between the RCA and the surrounding mortar leads to higher abrasion resistance in RNWC than in normal weight concrete. Similar conclusions were obtained by De Brito et al. (2005) in RNWC produced with recycled ceramic aggregates. Less conclusive results were obtained by Olorunsogo (1999), who found lower abrasion resistance for 30% and 100% of NA-RCA replacement ratios but an opposite trend for 50% and 70% ratios.

Beltrán et al. (2014) studied the influence of different cement additions on the mechanical properties of recycled concrete. The authors found that a small increase in the volume of cement is enough to compensate the negative effect of the recycled aggregate on the mechanical strength. According to Uygunoğlu et al. (2014), small differences of less than 7% are obtained between the compressive and tensile strength of conventional concrete and those of concrete produced with recycled aggregate concrete.

However, thus far, only a few studies have been published on the production and characterization of recycled lightweight concrete (RLWC).

EurolightConR26 (2000) presents a short study where the compressive strength of a recycled modified density (2180 kg/m^3) concrete produced from a mixture of brickwork- and concrete-aggregates is compared with the compressive strength of a conventional concrete. Despite the lower w/c ratio, this modified density concrete suffered a reduction of 10% in compressive strength and a reduction of 8% in its density.

Other studies with recycled lightweight concrete have been developed, but none is focused on the direct use of recycled lightweight concrete aggregate. Kralj (2009) analysed the compressive strength and thermal conductivity of non-structural lightweight concrete with aggregates containing expanded glass. Chen et al. (2013) used recycled green building materials in different ratios and investigated their influence on the fresh and hardened properties of non-structural lightweight concrete. The authors found that a partial replacement of natural sand by LCD glass and waste led to a significant reduction of the compressive strength but a less relevant reduction of the unit weight of concrete. Shafigh et al. (2014) demonstrated that it is possible to produce structural lightweight concrete by incorporating high volume waste lightweight fine and coarse aggregates from the palm oil industry. Depending on the percentage of sand replacement, compressive strengths from 31 to 38 MPa were obtained.

This paper aims to evaluate the effect on the main physical and mechanical properties of concrete of incorporating recycled aggregates, obtained from crushing both structural and non-structural lightweight aggregate concrete. The objective was to find out whether recycled lightweight concrete can be successfully used as aggregates in concrete without compromising its hardened-state properties. The main physical and mechanical properties such as density, compressive strength, splitting tensile strength, modulus of elasticity and abrasion resistance are investigated for recycled lightweight concrete produced from the partial or total replacement of LWA with recycled lightweight concrete aggregate, and compared with those of conventional LWC using expanded lightweight aggregates.

2. Experimental programme

2.1. Materials and methods

The experimental work involved the characterization of various concrete mixes produced with the partial or total replacement of two types of expanded clay lightweight aggregates with crushed lightweight concrete aggregates obtained from concrete slabs previously produced with the same types of LWA. The two types of LWA were Leca M and Leca HD from Portugal. Their particle dry density, ρ_p, loose bulk density, ρ_b, crushing strength and 24 h water absorption, $w_{abs,24h}$, are listed in Table 1.

A more detailed microstructural characterization of these aggregates can be found in Bogas (2011) and Bogas et al. (2012a). In terms of their specific properties, the selected LWA are classed as type LM (Leca M) and type LHD (Leca HD), which represent lightweight aggregate of high and low porosity, for non-structural and structural purposes, respectively. The two types of recycled lightweight concrete aggregates (RLCA), RM and RHD, were obtained from a no-fines non-structural lightweight concrete produced with LM (LWCM) and a structural concrete produced with LHD (LWCHD), respectively (Fig. 1). After 28 days, the concrete slabs previously produced in the laboratory were crushed in a jaw crusher and the recycled aggregates were separated by size fraction. The composition of the original concrete is provided in Table 2 and the properties of the recycled aggregates RM and RHD are also listed in Table 1. Fine aggregates consisted of 2/3 coarse and 1/3 fine normal weight sand. Their main properties are also presented in Table 1. The grading curves of the aggregates used in the experiments are illustrated in Fig. 2. Cement type I 42.5 R was used.

Table 1
Aggregate properties.

Property	Natural sand		Lightweight aggregates		Recycled LWA	
	Fine sand	Coarse sand	LHD 4-12	LM 4-12	RHD	RM
Particle dry density, ρ_p (kg/m^3)	2604	2610	1092	595	1735	878
Loose bulk density, ρ_b (kg/m^3)	1495	1493	681	339	1000	463
24 h water absorption, $w_{abs,24h}$ (%)	0.2	0.2	12.6	23.2	15.7	29.4
Crushing strength (MPa)	–	–	5.7	1.2	7.6	2
Sieve size fraction (d_i/D_i)	0/1	0/4	4/11.2	4/11.2	0.5/16	0.5/16
Shape index (EN 933-4)	–	–	–	–	23.9	8.8