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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

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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.

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

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.

Fig. 1. Original structural LWCHD (left) and no-fines non-structural LWCM (right).

Table 2
Mix proportions – reference lightweight concretes.

Mixes	Coarse LHD (L/m^3)	Coarse LM (L/m^3)	Coarse sand (kg/m^3)	Fine sand (kg/m^3)	Cement (kg/m^3)	Effective water (L/m^3)	Effective w/c	Original LWA (%)
LWCHD	350	–	565	260	350	192.5	0.55	35.0
LWCM	–	630	–	–	150	90	0.60	63.0

2.2. Mix proportions, concrete mixing and tests

Four concrete families comprising twelve mixes were produced with a replacement ratio of 0% (reference concrete-RC), 20%, 50% and 100%, as listed in Table 3. To ensure comparability the mixes were produced with the same target slump of 125 ± 10 mm. The maximum aggregate size was 11.2 mm. All concrete compositions are given in Table 3. The water/cement ratio (w/c) relates to the effective water available for cement hydration. Different size fractions of RLCA were combined to give the same grading curve as the original lightweight aggregate.

The mixes were produced in a vertical shaft mixer. The coarse aggregate and natural sand were wetted for 3 min with 50% of the total water, before mixing. The absorption of LWA and RLCA in the mix was estimated beforehand to take into account the correction of the total mix water, according to Bogas et al. (2012b). The cement and the rest of the water were then added. The total mixing time was 7 min.

The following specimens were produced for each mix: twelve 150 mm cubic specimens for compressive strength tests at 7, 28 and 90 days according to EN 12390-1 (2012); three ϕ150 × 300 mm cylinders for 28 days splitting tensile tests according to EN 12390-6 (2009), and three ϕ150 mm cylinders for 28 days modulus of elasticity according to LNEC E397 (1993). In addition, three prismatic specimens of 50 × 70 × 70 mm were sawn from 100 mm cubic specimens for abrasion resistance tests, in accordance with DIN 52108 (2002). After demoulding at 24 h, the specimens were kept in water until testing.

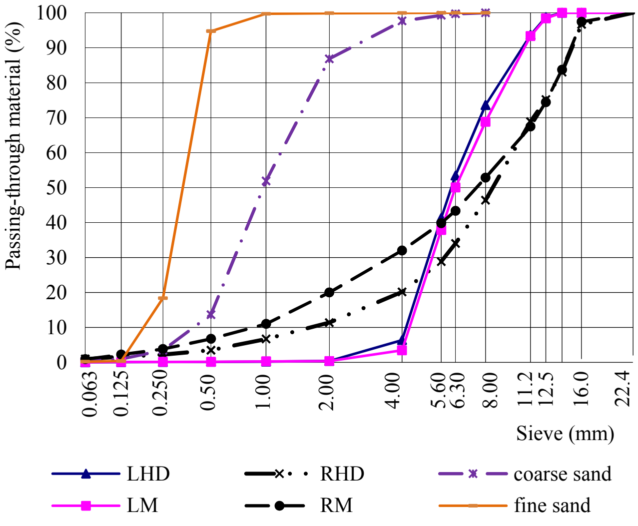

Fig. 2. Average grading curves of aggregates.

The procedure to determine the modulus of elasticity consisted of at least 8 cycles of loading and unloading, where the applied stress varied between 1 MPa and 1/3 of the estimated compressive strength. The test was finished when the difference between the average strain for consecutive cycles was less than 10%. The loading rate was about 0.5 ± 0.01 MPa/s, as mentioned in LNEC E397 (1993). Axial deformations were measured with two linear variable displacement transducers (LVDT) of 25 mm capacity located at mid-height of the specimens in diametrically opposite positions and operating over an initial gauge length of 150 mm.

The abrasion resistance was determined at 90 days, in accordance with DIN 52108 (2002). The process included the following main steps: before the test and after water curing, the specimens were dried until their mass stabilized; then they were measured and a known quantity of abrasive sand was placed on the disk; after that the specimens were positioned widthways under a calibrated weight; next, four cycles of a set number of rotations were performed; finally the weight and final size of the specimens were measured (Fig. 3).

The average values of dry density, ρ_d, compressive strength, f_{cm}, structural efficiency, f_{cm}/ρ_d, elasticity modulus, E_{cm}, and abrasion resistance are listed in Table 4.

3. Results and discussion

For easier interpretation, the results are presented for different series of recycled lightweight concrete: the series with LHD and its partial replacement with RHD (series CHDRHD) or RM (series CHDRM); the series with LM and its partial replacement with RHD (series CMRHD) or RM (series CMRHD).

3.1. Properties of aggregates

Contrary to what happens with recycled normal weight aggregates, the dry particle density of recycled lightweight concrete aggregates increased 60% (RM) and 50% (RHD) when compared to the original LM and LHD. This is due to the higher density of the adhered mortar on the surface of the RLCA. As expected, the

Table 3
Mix proportions – recycled lightweight concretes.

Mixes	LWA/RLAC replacement ratio (%)	Coarse LHD (L/m^3)	Coarse LM (L/m^3)	Coarse RHD (L/m^3)	Coarse RM (L/m^3)	Coarse sand (kg/m^3)	Fine sand (kg/m^3)	Cement (kg/m^3)	Effective water (L/m^3)	Effective w/c	Slump (mm)	Fresh density, ρ_f (kg/m^3)	Mortar fraction (%)	Original LWA (%)
RCHD	0	350	–	–	–	565	260	350	192.5	0.55	130	1897	65.0	35.0
CHD20RHD	20	280	–	70	–	565	260	350	192.5	0.55	120	1910	69.8	30.2
CHD50RHD	50	175	–	175	–	565	260	350	192.5	0.55	130	1983	76.9	23.1
C100RHD	100	0	–	350	–	565	260	350	192.5	0.55	125	2092	88.8	11.2
CHD20RM	20	280	–	–	70	565	260	350	192.5	0.55	125	1888	67.6	32.4
CHD50RM	50	175	–	–	175	565	260	350	192.5	0.55	135	1866	71.5	28.5
RCM	0	–	350	–	–	565	260	350	192.5	0.55	125	1710	65.0	35.0
CM20RM	20	–	280	–	70	565	260	350	192.5	0.55	130	1761	67.6	32.4
CM50RM	50	–	175	–	175	565	260	350	192.5	0.55	130	1809	71.5	28.5
C100RM	100	–	0	–	350	565	260	350	192.5	0.55	125	1842	78.0	22.1
CM20RHD	20	–	280	70	–	565	260	350	192.5	0.55	130	1728	69.8	30.2
CM50RHD	50	–	175	175	–	565	260	350	192.5	0.55	125	1897	76.9	23.1

absorption is higher in RLCA than in the original LWA. This can be explained by the higher content of broken particles in RLCA and also by the adhered mortar surrounding the lightweight aggregate. The amount of mortar adhered to the LWA also led to an increase of 25% (RHD) and 38% (RM) in the crushing strength of recycled aggregates. This is a unique feature of RLCA, since the strength of the aggregate is lower than that of the surrounding mortar. There is also a possible confinement effect exerted by the surrounding paste that can contribute to the higher strength increment of RM relative to RHD.

It is thus clear that the characteristics of the RLCA and the concrete produced with them are strongly affected by the mortar adhered to the original lightweight aggregate. RHD includes about 36% of LHD and 64% of mortar and RM includes about 63% of LM and 37% of paste. This was determined from the density of LWA and RLCA (Table 1) and by knowing the density of the old mortar present in the RLCA. Taking this into account, Table 3 shows the total percentage of mortar and original LWA for each concrete mix.

As Table 3 shows, the replacement of LWA by RLCA led to an overall reduction in the total volume of coarse aggregates in concrete and a consequent increment in the volume of mortar. The increment in the mortar volume is higher in concrete with RHD because RM was obtained from concrete produced without fines (Fig. 1).


Fig. 3. Abrasion test according to DIN 52108 (2002).

The more angular shape of RLCA is typical of recycled concrete aggregates (Matias et al., 2013; De Brito et al., 2005). However, due to the nature of the original lightweight concrete, the shape index of RHD is much higher than that of RM (Table 3). The less angular shape of RM results from the easier detachment of the agglutinated aggregates in no-fines low-strength concrete (Fig. 1).

3.2. Concrete density

For all mixes, the dry density of concrete was less than 2000 kg/m^3 (Table 4), which is the upper limit established in EN 206-1 (2005) for lightweight concrete.

Fig. 4 clearly shows that the hardened concrete density increases proportionally with the replacement of LWA by RLCA. This was expected since the density of RLCA is higher than that of the original LWA. The density increases by up to 14% when LHD is replaced with RHD and by up to just 7% when LM is replaced with RM. However, the trend is different when LHD is replaced with the lower density RM. In this case, the use of recycled non-structural lightweight aggregate is beneficial in terms of reducing concrete density.

3.3. Compressive strength

The compressive strength increases as the LWA is replaced with the stronger RLCA (Figs. 5 and 6). At 28 days, this increment is 14% when LHD is totally replaced with RHD and 74% when LM is replaced with RM. As shown in Table 4, the strength increment in recycled lightweight concrete is explained by the higher crushing strength of RLCA and the lower volume of coarse lightweight aggregate in the mix. An exception is when LHD is replaced with the weaker RM, leading to a maximum compressive strength reduction of 13% (Fig. 5). Although the incorporation of RM reduces the total volume of LWA, its crushing strength is lower.

As expected, the compressive strength increases with age for all mixes (Figs. 5 and 6). However, the strength development is not very important after 7 days, especially for mixes with low RLCA content. This is explained by the lower contribution to concrete strength of the weaker original lightweight aggregate (Table 1).

At 7 days the compressive strength has developed less, when LWA is replaced with RLCA. This is because the mortar is less mature and so its influence on the compressive strength is greater. At later ages the compressive strength is governed by the capacity of the aggregates and the difference between mixes is more evident (Fig. 5). Therefore, whether the RLCA has more or less influence on

Table 4
Compressive strength at 7, 28 and 90 days.

Mixes	LWA/RLAC replacement ratio (%)	Dry density, ρ_d (kg/m^3)	Compressive strength						f_{cm}/ρ_d ($\times 10^2$ m) 28 days	Tensile strength		Modulus of elasticity	Abrasion resistance	
			$f_{cm,7d}$ (MPa)	CV_{fc} (%)	$f_{cm,28d}$ (MPa)	CV_{fc} (%)	$f_{cm,90d}$ (MPa)	CV_{fc} (%)		$f_{ctmsp,28d}$ (MPa)	CV_{fctsp} (%)	$E_{cm,28d}$ (GPa)	Wear (mm)	ΔMass (g)
LWCHD	0	–	34.1	4.1	37.2	3.6	37.7	5.1	–	2.8	4.34	–	–	–
LWCM	0	–	0.7	18.7	0.6	7.4	–	–	–	–	–	–	–	–
RCHD	0	1628	32.8	4.0	38.4	4.5	39.3	5.2	23.6	2.96	15.4	20.8	4.6	9.3
CHD20RHD	20	1672	33.9	5.5	40.4	2.8	41.3	4.6	24.2	2.88	8.1	20.7	4.2	9.0
CHD50RHD	50	1739	34.4	0.6	43.1	1.7	46.8	0.4	24.8	3.52	15.7	23.4	4.1	8.5
C100RHD	100	1852	36.1	2.7	43.7	1.7	48.5	1.5	23.6	3.92	5.6	25.4	4.5	9.4
CHD20RM	20	1612	33.1	1.6	38.5	2.8	39.2	5.6	23.9	2.99	7.2	21.3	4.5	9.5
CHD50RM	50	1590	32.2	3.1	36.3	2.8	38.7	5.6	22.8	2.86	20.9	21.2	4.2	8.5
RCM	0	1453	16.0	9.3	19.2	10.3	20.7	3.1	13.2	1.53	1.7	12.8	5.8	12.2
CM20RM	20	1473	21.6	5.8	25.1	5.7	26.5	2.3	17.0	2.51	3.1	19.1	4.7	9.9
CM50RM	50	1503	23.8	7.2	27.7	4.8	30.5	5.0	18.4	2.45	8.0	19.8	3.6	7.5
C100RM	100	1552	27.7	5.1	33.4	5.1	34.6	4.8	21.5	2.74	4.7	20.6	4.1	8.5
CM20RHD	20	1533	22.6	2.7	26.4	3.8	28.6	7.0	17.2	2.53	2.0	18.4	4.9	10.0
CM50RHD	50	1653	24.2	8.8	30.7	5.1	32.8	0.6	18.6	2.75	17.1	21.8	3.6	8.1

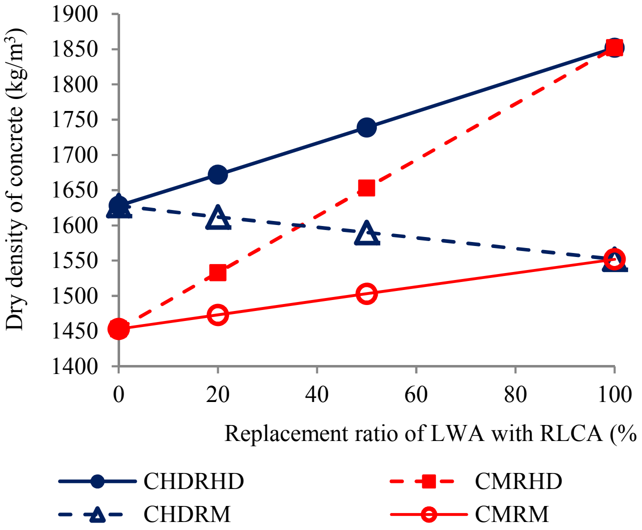

Fig. 4. Dry density of concrete.

the compressive strength also depends on the w/c ratio of the mortar.

The compressive strength improves more when the non-structural LM is replaced with RM, especially with RHD. The higher strength capacity of RLCA increases the potential strength of concrete produced with LM only, which is characterized by a very low ceiling strength (Bogas and Gomes, 2013). According to Fig. 5, with the replacement of LM by RLCA it is possible to change from a non-structural to a structural LWC. In other words, the introduction of recycled lightweight concrete aggregates not only increases the aggregate capacity but it also induces greater mobilization of the mortar strength.

The original lightweight aggregates and recycled LWA are able to promote internal curing, which in both cases will contribute to the better long-term hydration of the surrounding paste (Holm and Bremner, 2000; Chandra and Berntsson, 2003). Due to this effect and the higher porosity of the aggregates, the aggregate-paste interface transition zone is also improved and the compressive strength is essentially affected by the strength of the aggregate.

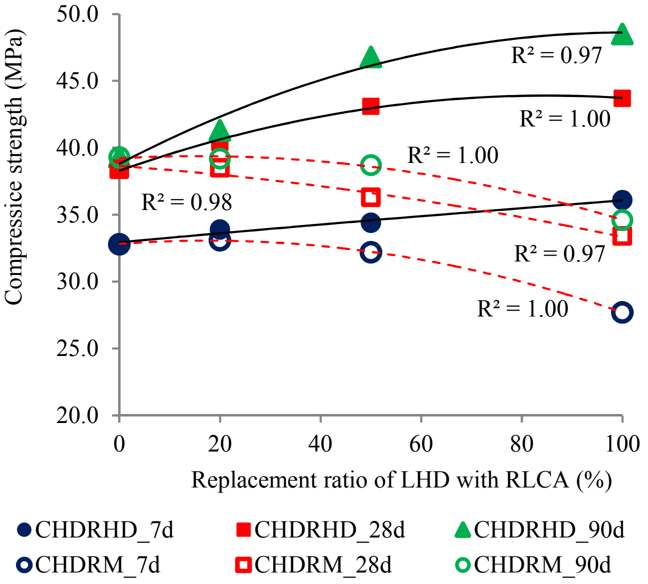

Fig. 5. Influence of RLCA replacement on the compressive strength of series CHD.

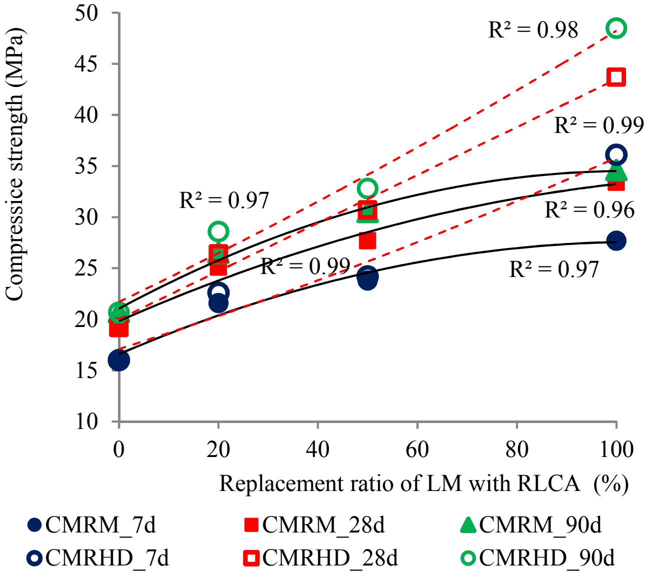

Fig. 6. Influence of RLCA replacement on the compressive strength of series CM.

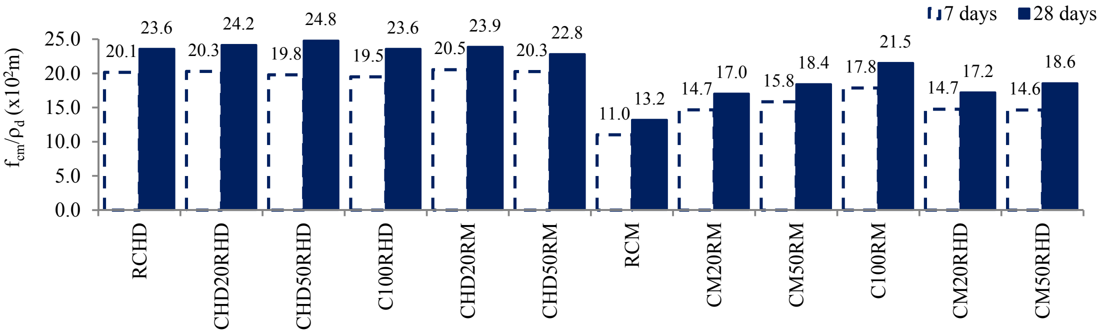

Fig. 7. Structural efficiency at 28 days.

3.4. Structural efficiency

The ratio f_{cm}/ρ_{cm} enables analysis of the structural efficiency of a specific mix and is usually determined for lightweight concrete.

In general, it is found that the structural efficiency increases with the progressive replacement of LWA with RLCA (Fig. 7). This is a very important conclusion that makes recycled lightweight concrete a very competitive alternative to conventional lightweight concrete.

In series CHDRHD the highest structural efficiency is obtained for 50% replacement of LHD with RHD (mix CHD50RHD). In fact, for 100% replacement of LHD with RHD the increment in strength is offset by the increment in density. This is explained by the higher strength of the RHD and by the limited contribution of the mortar. Due to the lower strength of the mortar with a w/c ratio of 0.55, the compressive strength increases only slightly. In other words, the compressive strength is less affected by the strength of aggregates for replacement ratios above 50% (Fig. 7). However, for stronger mortars the structural efficiency for 100% replacement is expected to be higher than that for 50% replacement.

Regarding series CHD, the variation in the structural efficiency is almost negligible for replacement ratios of up to 20%. In fact the replacement of lightweight aggregate with 20% of RLCA corresponds to an effective aggregate replacement of only 13% (RLM) and 7.2% (RHD) (3.1). The rest is additional mortar.

However, there is a relevant improvement in the structural efficiency when the more porous non-structural LWA is replaced with RLCA (series CM), even when the recycled aggregates are obtained from non-structural LWC. As mentioned in Section 3.3, there is an important increment in the ceiling strength of recycled lightweight concrete with the incorporation of RLCA.

The structural efficiency of lightweight concrete with LHD is only slightly reduced with the incorporation of the weaker RM. This reduction is only 9% when the more expensive LHD is entirely replaced with RM. This means that the recycled aggregates obtained from non-structural concrete can be used in structural lightweight concrete without greatly compromising its mechanical properties.

3.5. Splitting tensile strength

As with compressive strength, splitting tensile strength is directly related to the RLCA content (Fig. 8). Tensile strength increases by up to 30% when LHD is replaced with RHD and up to 80% when LM is replaced with RM. Again, the exception is the replacement of LHD with the weaker RM. However the tensile strength decreases by only 10% when LHD is totally replaced with RM.

There is a slightly more marked evolution of splitting tensile strength with the replacement ratio of RLCA than of compressive strength. This suggests that the introduction of RLCA has greater influence on the tensile strength.

Besides the higher strength capacity of RLCA, their more angular shape also contributes to better tensile strength behaviour of the recycled lightweight concrete. In fact, the tensile strength is mostly affected by the mortar strength and quality of the aggregate-paste transition zone and by the texture and tensile strength of the aggregate (Neville, 1995; Bogas, 2011). However, all mixes showed the same mode of failure, with the failure path crossing the aggregates. Therefore, the higher tensile strength of RLCA is probably the most relevant factor.

As clearly seen in Fig. 9, series CHDRM and CMRHD have intermediate values compared to those found for series CHDRHD and CMRM, with just one type of lightweight aggregate.

Fig. 9 shows a good correlation between the compressive and tensile strength, for all series. In fact, both properties are essentially affected by the same main factors. However, there is a more marked increment in the tensile strength when RHD is incorporated in the mix than when the less angular shaped RM is used.

The actual results and those estimated from the equation given in EN 1992-1 (2010), concerning the tensile strength prediction of lightweight concrete, are also compared in Fig. 9. The equation from EN 1992-1 (2010) was calculated based on the dry densities given in Table 4 and assuming that: cylinder compressive strength is about 90% of the cube compressive strength; axial tensile strength is about 90% of the splitting tensile strength.

Despite the similar trend of the results obtained in this study, the EN1992-1 (2010) equation provides estimates that are conservative by about 20%, on average.

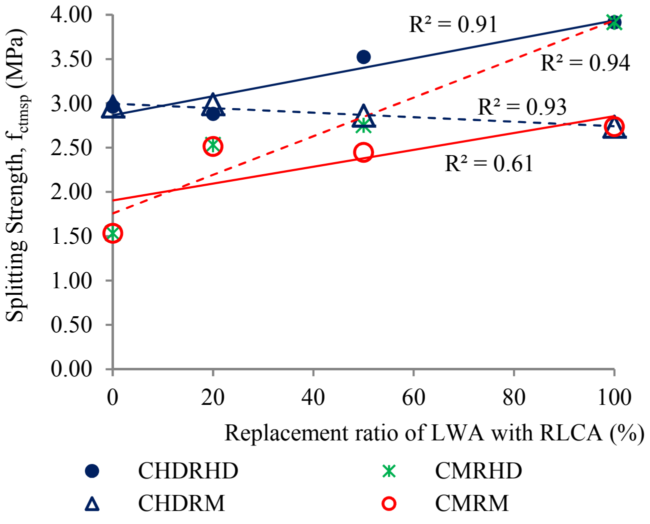

Fig. 8. Influence of RCLA replacement on the splitting tensile strength at 28 days.

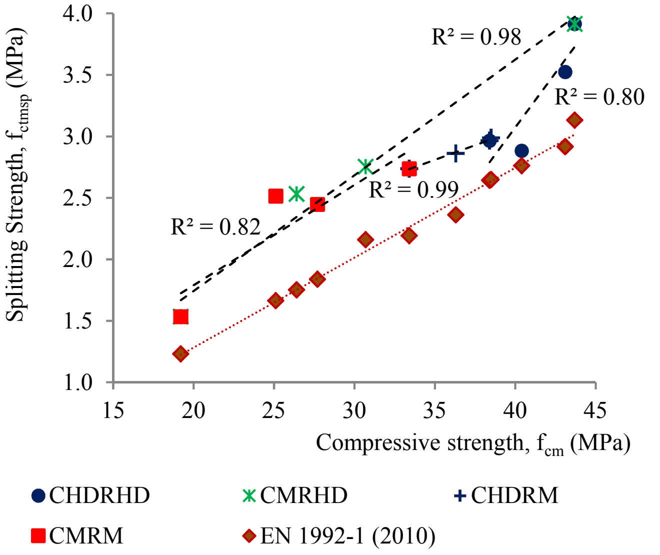

Fig. 9. Relationship between compressive strength, f_{cm}, and splitting tensile strength, f_{ctmsp}, at 28 days.

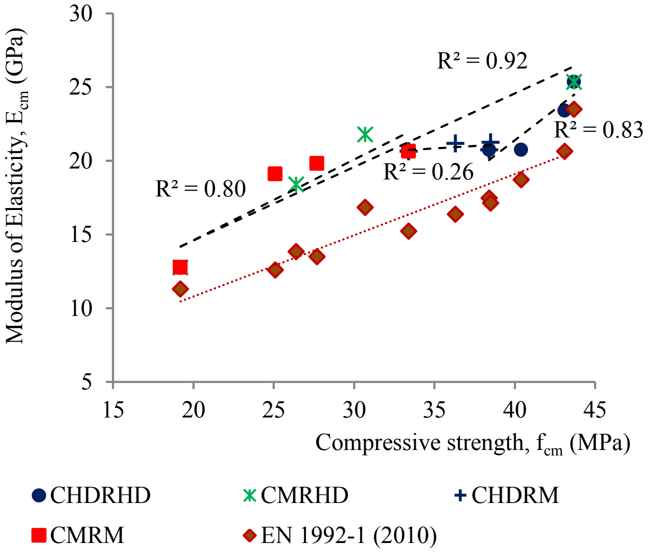

Fig. 11. Relationship between compressive strength, f_{cm}, and modulus of elasticity, E_{cm}, at 28 days.

3.6. Modulus of elasticity

The modulus of elasticity of concrete depends mostly on the proportion and stiffness of its ingredients, particularly the paste and aggregates. As shown in Table 4, the replacement of LWA with RLCA implies increased mortar content in the mix, especially when RHD is incorporated. Therefore, since the mortar is stiffer than LWA, there is a natural increment in the modulus of elasticity (Fig. 10). In fact, the modulus of elasticity increased by up to 22% when LHD was replaced with RHD and up to 62% when LM was replaced with RM.

However, there is little influence on the modulus of elasticity when LHD is replaced with RM. Although the density of RM is slightly lower than that of LHD (Table 1), their stiffness appears to be very similar. One possible reason is that the paste surrounding RM has a confinement action that helps to further increase its stiffness. Once again, series CHDRM and CMRHD have intermediate values relative to those obtained for series CHDRHD and CMRM.

Fig. 11 shows a reasonable correlation between compressive strength and modulus of elasticity, since both properties are generally affected by the same main factors. The correlation between these properties tends to be lower than that obtained between compressive strength and splitting tensile strength. In fact, the modulus of elasticity can be differently affected by the concrete constituents. For example, for concrete produced with weaker aggregates (RLM) an increment in the mortar characteristics has a higher impact on the modulus of elasticity than on the compressive strength. Contrary to the modulus of elasticity compressive strength is mainly governed by RLM. However, for the same mortar properties, the incorporation of stronger aggregates will simultaneously increase the modulus of elasticity and compressive strength of the mix, which justifies the good correlation obtained for series CMRM, CMRHD and CHDRHD.

Fig. 11 also shows the comparison between the actual results and those estimated from the equation given in EN 1992-1 (2010), based on the dry densities given in Table 4. Apart from series CHDRM, the normative predictions follow the same trend as the experimental results, but lead to estimates that are conservative by

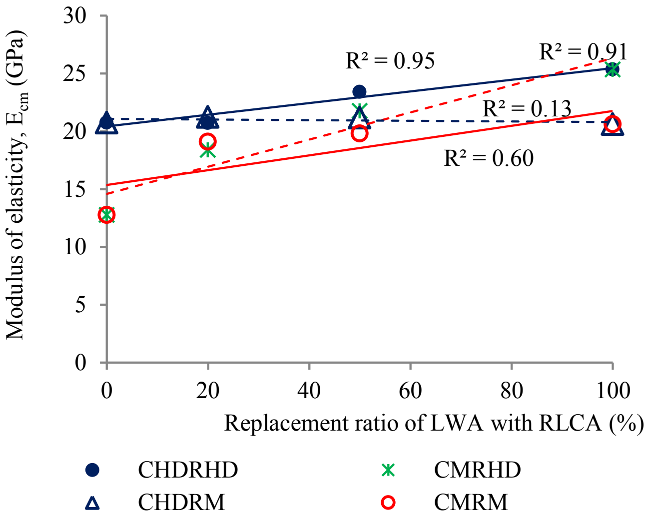

Fig. 10. Influence of RCLA replacement on the modulus of elasticity at 28 days.

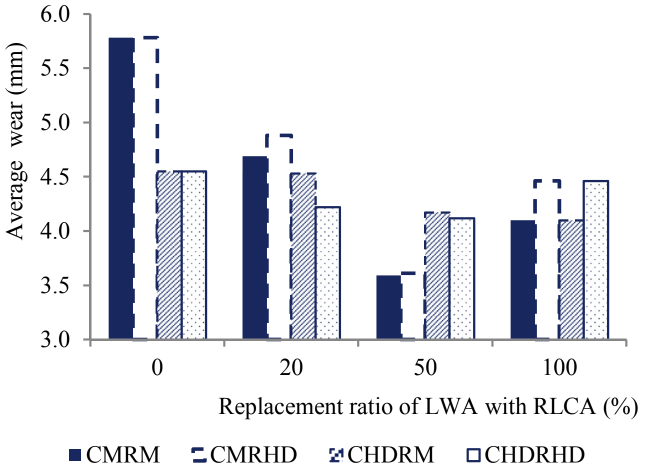

Fig. 12. Influence of RLCA replacement on the average wear at 90 days.

about 10–30%. Closer estimates are obtained when RM is not used. Actually, the normative equation cannot account for the stiffness improvement of the RM caused by the confinement action of the adhered paste.

3.7. Abrasion resistance

Fig. 12 shows a reduction in the average wear of the specimens as the replacement ratio of lightweight aggregate with recycled concrete aggregates increases up to 50%. This reduction is about 9% when LHD is replaced with RHD and 39% when LM is replaced with RM. In lightweight concrete the abrasion resistance depends on the lightweight aggregates, on the strength of the matrix and on the bond between the aggregates and the cement paste (FIP, 1983). Besides the higher strength of RLCA, their incorporation in the mix leads to an important increment of the mortar phase proportion (Table 3), characterized by a higher abrasion resistance than for lightweight aggregate. Moreover, the higher angularity of RLCA also contributes to improving the aggregate-paste interface. A sharper reduction of concrete wear is observed for series CM, because there is a higher impact when the very weak LM is replaced with the much stronger RLCA, confined by the surrounding paste.

However, an opposite trend is observed for the total replacement of LWA with RLCA. This less expected trend is obtained in all series and is also reported by Olorunsogo (1999) for normal weight recycled concrete. However, it should be pointed out that the differences in the average wear between mixes with 50% or 100% of RLCA replacement are not very significant. In general, it may be concluded that the abrasion resistance is improved when recycled lightweight aggregates are incorporated, especially for series CM with the non-structural LM.

It is interesting to note that the use of RM or RHD leads to similar abrasion resistance, which means that the recycling of non-structural lightweight concrete is very effective.

As with the other mechanical properties analysed in this study, the abrasion resistance generally follows the same trend as compressive strength.

4. Conclusions

This study analysed the mechanical performance of recycled lightweight aggregates concrete produced by crushing both lightweight structural and non-structural concrete. The following main conclusions have been drawn:

- It is possible to produce structural recycled lightweight concrete with aggregates from crushed lightweight structural and non-structural concrete with densities below 2000 kg/m^3;
- All the mechanical properties were improved with the replacement of LWA with RLCA. Even for LWC produced with the less porous structural LWA (LHD), the compressive strength increases by up to 14%, the splitting tensile strength by up to 32% and the modulus of elasticity by up to 22%. When the weaker non-structural LWA is replaced with RLM the increment of these mechanical properties is over 60%;
- The structural efficiency increased with the introduction of RLCA. This means that RLWC is a viable alternative solution for the production of more sustainable structural lightweight concrete;
- The exception is when structural lightweight aggregate is replaced with recycled aggregates from crushed non-structural lightweight concrete, even though the mechanical properties are only slightly reduced. Therefore, it can be concluded that these weaker RLCA are adequate for the production of cheaper structural lightweight concrete without compromising its mechanical properties;
- Contrary to non-structural lightweight aggregates, the recycled aggregates from non-structural LWC can be used for the production of structural lightweight concrete;
- Estimates that are conservative by about 20% in the splitting tensile strength and 10–30% in the modulus of elasticity were obtained using the equations recommended in EN1992-1 [37];
- The abrasion resistance increased slightly as the replacement ratio of LWA with RLCA increased to 50%. Similar results were obtained for recycled lightweight concrete, regardless of the type of RLCA. An unexpected reduction in the abrasion resistance occurred when more than 50% of LWA was replaced with RLCA.

In general, it can be concluded from this study that recycled lightweight aggregate concrete is a potential competitive alternative to conventional lightweight concrete.

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References

Barbudo, A., De Brito, J., Evangelista, L., Bravo, M., Agrela, F., 2013. Influence of water-reducing admixtures on the mechanical performance of recycled concrete. J. Clean. Prod. 59 (15), 93–98.

Bazuco, R.S., 1999. The Use of Recycled Concrete Aggregates for the Production of New Concrete (*In Portuguese*). MSc thesis in Civil Engineering. Federal University of Santa Catarina, Florianópolis, Brazil.

Beltrán, M.G., Barbudo, A., Agrela, F., Galvín, A.P., Jiménez, J.R., 2014. Effect of cement addition on the properties of recycled concretes to reach control concretes strengths. J. Clean. Prod. 79, 124–133.

Bogas, J.A., 2011. Characterization of Structural Lightweight Expanded Clay Aggregate Concrete. PhD thesis in Civil Engineering. Technical University of Lisbon, Instituto Superior Técnico, Lisbon, Portugal (in Portuguese).

Bogas, J.A., Mauricio, A., Pereira, M.F.C., 2012a. Microstructural analysis of Iberian expanded clay aggregates. Microsc. Microanal. 18, 1190–1208.

Bogas, J.A., Gomes, A., Gloria, M.G., 2012b. Estimation of water absorbed by expanding clay aggregates during structural lightweight concrete production. Mater. Struct. 45, 1565–1576.

Bogas, J.A., Gomes, A., 2013. Compressive behavior and failure modes of structural lightweight aggregate concrete - characterization and strength prediction. Mater. Des. 46, 832–841.

Chandra, S., Berntsson, L., 2003. Lightweight Aggregate Concrete, Science, Technology and Applications. Noyes publications - William Andrew Publishing, USA.

Chen, S.-H., Wang, H.-Y., Jhou, J.-W., 2013. Investigating the properties of lightweight concrete containing high contents of recycled green building materials. Constr. Build. Mater. 48, 98–103.

De Brito, J., Pereira, A.S., Correia, J.R., 2005. Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. Cem. Concr. Compos 27 (4), 429–433.

DIN 52108, 2002. Testing of Inorganic Non-metallic Materials: Wear Test with the Grinding Wheel According to Boehme.

EN 1992-1-1, 2010. Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings. European Committee for Standardization CEN.

EN 12390-1, 2012. Testing Hardened Concrete - Part 1: Shape, Dimensions and Other Requirements for Specimens and Moulds.

EN 12390-6, 2009. Testing Hardened Concrete - Part 6: Tensile Splitting Strength of Test Specimens.

EN 206-1, 2005. Concrete - Part 1: Specification Performance, Production and Conformity.

EuroLightConR26, 2000. Recycling Lightweight Aggregate Concrete. European Union - Brite EuRam III, BE96-3942/R26.

Evangelista, L., de Brito, J., 2007. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cem. Concr. Compos. 29 (5), 397–401.

Ferreira, L., de Brito, J., Barra, M., 2011. Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. Mag. Concr. Res. 63 (8), 617–627.

FIP, 1983. FIP manual of lightweight aggregate concrete. Fédération internationale de la précontrainte (FIP), second ed. Surrey University Press, Glasgow and London, UK.

Holm, T.A., Bremner, T.W., 2000. State-of-the-art Report on High-strength, High-durability Structural Low-density Concrete for Applications in Severe Marine Environments. Us Army Corps of Engineers, Washington, USA. Structural Laboratory, ERDC/SL TR-00-3.

Khatib, J.M., 2005. Properties of concrete incorporating fine recycled aggregate. Cem. Concr. Res. 35, 763–769.

Kikuchi, M., Dosho, Y., Narikawa, M., Miutra, T., 1998. Application of recycled concrete aggregate concrete for structural concrete. Part 1-Experimental study on the quality of recycled aggregate and recycled aggregate concrete. In: Sustainable Construction: Use of Recycled Concrete Aggregate. Thomas Telford, pp. 55–68.

Kralj, D., 2009. Experimental study of recycling lightweight concrete with aggregates containing expanded glass. Process Saf. Environ. Prot. 87 (4), 267–273.

Kwan, W.H., Ramli, M., Kam, K.J., Sulieman, M.Z., 2012. Influence of the amount of recycled coarse aggregate in concrete design and durability properties. Constr. Build. Mater. 26 (1), 565–573.

Li, X., 2008. Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete. Resour. Conserv. Recycl. 53, 36–44.

LNEC E 397, 1993. Concrete - Determination of Modulus of Elasticity in Compression. National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal (in Portuguese).

Lovato, P.S., Possan, E., Dal Molin, D.C.C., Masuero, A.B., 2012. Modeling of mechanical properties and durability of recycled aggregate concretes. Constr. Build. Mater. 26, 437–447.

Lu, S.-M., Lu, C., Tseng, K.-T., Chen, F., Chen, C.-L., 2013. Energy-saving potential of the industrial sector of Taiwan. Renew. Sustain. Energy Rev. 21, 674–683.

Marie, I., Quiasrawi, H., 2012. Closed-loop recycling of recycled concrete aggregates Original Research Article. J. Clean. Prod. 37, 243–248.

Matias, D., de Brito, J., Rosa, A., Pedro, D., 2013. Mechanical properties of concrete produced with recycled coarse aggregates - influence of the use of superplasticizers. Constr. Build. Mater. 44, 101–109.

Medina, C., Zhu, W., Howind, T., Rojas, M.I.S., Frías, M., 2014. Influence of mixed recycled aggregate on the physical – mechanical properties of recycled concrete. J. Clean. Prod. 68, 216–225.

Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L., Arabi, N., 2013. Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete Original Research Article. J. Clean. Prod. 54 (1), 282–288.

Meyer, C., 2009. The greening of the concrete industry. Cem. Concr. Compos. 31 (8), 601–605.

Neville, A.M., 1995. Properties of Concrete, fourth ed. Longman, England.

Newman, J.B., 1993. Properties of structural lightweight aggregate concrete. In: Clarke, J.L. (Ed.), Structural Lightweight Aggregate Concrete. Chapman & Hall, London, UK, pp. 19–44.

Olorunsogo, F.T., 1999. Early age properties of recycled aggregate concrete. In: International Seminar on Exploiting Waste in Concrete. University of Dundee, Scotland, pp. 163–170.

Saikia, N., de Brito, J., 2012. Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. Constr. Build. Mater. 34, 385–401.

Shafigh, P., Mahmud, H.B., Jumaat, M.Z.B., Ahmmad, R., Bahri, S., 2014. Structural lightweight aggregate concrete using two types of waste from the palm oil industry as aggregate. J. Clean. Prod. 80, 187–196.

Tabsh, S.W., Abdelfatah, A.S., 2009. Influence of recycled concrete aggregates on strength properties of concrete. Constr. Build. Mater. 23, 1163–1167.

Tavakoli, M., Soroushian, P., 1996. Drying shrinkage behavior of recycled aggregate concrete. Concr. Int. 18 (11), 58–61.

Uygunoğlu, T., Topçu, I.B., Çelik, A.G., 2014. Use of waste marble and recycled aggregates in self-compacting concrete for environmental sustainability. J. Clean. Prod. 84, 691–700.