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Long-term behaviour of concrete produced with recycled lightweight expanded clay aggregate concrete

J. Alexandre Bogas *, J. de Brito, J. Cabaço

DECivil/ICIST, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

HIGHLIGHTS

- Concrete with recycled lightweight concrete aggregates (RLCA).
- Long-term term behaviour of recycled lightweight concrete (RLWC).
- Shrinkage, capillarity, immersion absorption, carbonation, chloride penetration.
- General reduction of the long-term properties with the incorporation of RLCA.
- RLWC may be a viable alternative solution with higher structural efficiency.

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ABSTRACT

In this paper some of the main long-term properties of concrete produced with recycled aggregates obtained from crushing both structural and non-structural lightweight concrete (LWC) are analysed. The properties studied are drying shrinkage, capillary and immersion absorption, and carbonation and chloride penetration resistance. A comprehensive experimental study was carried out on a series of concrete mixes in which ratios of 20%, 50% and 100% of two types of coarse lightweight aggregates (LWA) were replaced with two types of recycled lightweight concrete aggregates (RLCA). Long-term shrinkage is affected by the paste adhered to LWA and increases as the replacement ratio of LWA with RLCA goes up. However, the internal curing promoted by RLCA reduces the early shrinkage. In terms of durability, the experimental results show that generally all the properties studied decay due to the progressive replacement of structural LWA with RLCA. However, despite the general reduction of long-term properties, recycled lightweight concrete (RLWC) can be also durable, regardless of the type of RLCA. Moreover, it is shown that even for low to moderate strength RLWC the mechanism of carbonation is not a determinant factor for durability. On the other hand, the carbonation and chloride penetration resistance of concrete with non-structural LWA tends to improve with the incorporation of RLCA. It can thus be concluded that RLWC may be a viable and more cost-effective alternative solution, especially given its higher structural efficiency. In addition, RLCA obtained from non-structural LWC can be incorporated in concrete without significantly compromising its durability.

1. Introduction

Environmental sustainability has been one of the main issues troubling human society in recent decades. The construction sector is involved in an abusive use of natural resources and the production of large amounts of waste. Indeed, the concrete industry is still the largest user of natural resources in the world. It is estimated that it consumes about 1.2 billion tonnes of cement and 7.5 billion tonnes of aggregates annually [1]. In addition to this significant environmental impact, a growing amount of waste results from the demolition of concrete structures. Replacing natural aggregate

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 no-fines non-structural lightweight concrete with Leca M; RHD, recycled aggregates from structural lightweight concrete with Leca HD.

* Corresponding author. Tel.: +351 218418226; fax: +351 218418380.
E-mail address: abogas@civil.ist.utl.pt (J.A. Bogas).

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wholly or partially with recycled aggregate has been one of the options most often used to achieve a more sustainable construction [2].

Lightweight concrete (LWC) is an alternative solution to normal weight concrete (NWC), especially when lighter and more energy-efficient solutions are required [3–5]. Contrary to normal weight concrete, the density of lightweight concrete is usually below 2000 kg/m^3 and its thermal conductivity is as much as 1.0 W/m °C [3,6]. Owing to these features, since the middle of the 20th century LWC has been widely used in bridges and buildings, especially in non-structural applications [4,5].

Presently there is no accurate estimate of the total LWC waste produced every year, but its reuse and recycling is still not a common practice. Moreover, artificial LWA is very costly to produce in terms of energy consumption, which has serious economic and environmental impacts.

It is therefore useful to explore more cost-effective and environmentally-friendly solutions based on lightweight concrete produced from secondary lightweight sources. Not only will this reuse otherwise useless waste but it can also greatly reduce the extraction of natural resources and energy consumption.

Several recent studies have characterised the physical and mechanical properties and durability of recycled normal weight concrete (RNWC) (e.g. [2,7–10]).

Recycled concrete aggregate (RCA) differs from natural aggregates (NA) mostly because of the adhered mortar on its surfaces [2,10,11]. Therefore, RCAs usually have higher porosity, lower bulk density and lower crushing strength than NAs [7,12,13]. Because of these specific properties, it is reported that the density [10,12,14], compressive strength [15–18] and modulus of elasticity [10,16] of concrete usually decrease with increasing RCA content. Bazuco [12] reported a compressive strength reduction of 14–32% in RNWC. According to Tavakoli and Soroushian [19] the weaker aggregate/old paste transition zone in RCA lowers the strength of RNWC. The reduction in the modulus of elasticity is usually even greater because the concrete stiffness is more significantly affected by the aggregates' properties.

The lower stiffness of RCA is the main reason for the usually higher shrinkage of concrete produced with recycled normal weight aggregates [20–22]. Hansen and Boegh [22] found that shrinkage was 70% higher when natural aggregates were totally replaced by coarse and fine RCA. However, Evangelista and de Brito [10] found that the internal curing provided by RCA can beneficially delay drying shrinkage and also extend the hydration reactions of RNWC.

It should be noted that the physical, mechanical and durability properties of concrete produced with RCA can vary considerably according to the quality and content of the old mortar surrounding the primary aggregates.

Regarding durability, it is usually reported that normal weight concrete produced with RCA has a worse long-term performance than traditional NWC of equivalent composition [2,10,21]. Buttler [21] reported 40% greater water absorption by immersion in RNWC because of the higher porosity of recycled aggregates. Similar findings were obtained by Kwan et al. [2]. The higher porosity of RCAs is also responsible for the lower carbonation resistance of RNWC [20]. A reduction of 65% in carbonation resistance was obtained by Evangelista and de Brito [10] in concrete produced with fine RCA. A slightly smaller reduction of 30% compared to conventional concrete was reported by Amorim et al. [23] for concrete produced with coarse RCA.

On the other hand, Levy [24] found that the chloride penetration in RNWC was 36% higher than in conventional concrete, and concluded that the higher the replacement percentage of aggregates by RCA the lower the durability performance of RNWC. Similar conclusions were drawn by Evangelista and de Brito [10] for recycled concrete produced with coarse and fine RCA and they also report a linear correlation between the chloride penetration of RNWC and its water absorption by immersion. However, several authors believe that the chloride penetration and the carbonation resistance should be affected more by the quality of the paste than by the type of aggregate [24–26].

To the best of our knowledge only a few studies have been published on the production and characterisation of recycled lightweight concrete (RLWC) and these basically only focus on their mechanical properties. EuroLightConR26 [27] presents a short study where the compressive strength of a recycled modified density concrete (2180 kg/m^3) produced from a mixture of brick and concrete aggregates is compared with the compressive strength of a conventional concrete. Kralj [28] analysed the compressive strength and thermal conductivity of non-structural lightweight concrete with recycled aggregates containing expanded glass.

Reinhardt and Kummel [29] studied the shrinkage of concrete produced with recycled expanded clay lightweight concrete aggregates. The authors found that shrinkage increased as the percentage replacement of natural aggregates with recycled lightweight concrete aggregates (RLCA) also increased. The shrinkage increment was nearly 50% for concrete with 54% RLCA.

In a more recent work, Figueiredo [30] studied the main physical and mechanical properties of RLWC produced with partial or total replacement of LWA with RLCA. The authors found that the compressive strength, tensile strength, modulus of elasticity and abrasion resistance generally improved with the incorporation of RLCA. In particular, concrete with RLCA showed higher structural efficiency than the reference concrete, with 100% LWA.

This paper aims at characterising the long-term behaviour of concrete produced with the partial or total replacement of LWA with recycled aggregates obtained from crushing both structural and non-structural lightweight aggregate concrete. The shrinkage, absorption, chloride penetration and carbonation resistance of RLWC are investigated and compared with those of conventional LWC using expanded lightweight aggregates.

2. Experimental programme

2.1. Materials and methods

The experimental work reported in this paper involved the characterisation of various concrete mixes produced when 20%, 50% and 100% of two types of coarse lightweight expanded clay aggregates (LWA) were replaced with crushed LWC 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 characterisation of these aggregates can be found elsewhere [30,31].

Given their specific properties, the selected LWA are classed as type LM (Leca M) and type LHD (Leca HD), which represent LWA 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, respectively, from a no-fines non-structural lightweight concrete produced with LM (LWCM) and a structural concrete produced with LHD (LWCHD) (Fig. 1). After 28 days the concrete slabs 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 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. Cement type I 42.5 R was used.

Contrary to recycled normal weight aggregates, the dry particle density of RLCA increased 60% (RM) and 50% (RHD) when compared to the original LM and LHD (Table 1). This is due to the higher density of the adhered mortar on the surface of RLCA. As also expected, the 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 original LWA. It is thus clear that the RLCA characteristics and the concrete produced with them are strongly affected by the mortar adhered to the primary LWA. RHD contains about 36% LHD and 64% mortar and RM contains about 63% LM and 37% paste. This is easily determined from the density of LWA and RLCA (Table 1) and by knowing the density of the old mortar present in RLCA. Taking this into account, Table 2 shows the total