Construction and Building Materials 165 (2018) 284–294

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical performance evaluation of concrete made with recycled ceramic coarse aggregates from industrial brick waste

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HIGHLIGHTS

- Recycled coarse ceramic aggregates (RCA) from industrial brick wastes were evaluated.
- Natural coarse aggregates (NCA) of concrete mixes were partially replaced by RCA.
- Partial replacement of NCA by RCA is mechanically feasible for low strength concrete.
- Mechanical performance decreases as the replacement ratio of NCA by RCA increases.
- Caution is mainly advised when exceeding 30% volume of RCA for structural purposes.

ARTICLE INFO

Article history:
Received 1 September 2017
Received in revised form 21 December 2017
Accepted 7 January 2018

Keywords:
Mechanical properties
Concrete
Coarse aggregates
Recycled aggregates
Industrial wastes
Brick wastes
Ceramic wastes

ABSTRACT

This paper describes an experimental research that aimed to evaluate the mechanical performance of concrete made with recycled ceramic coarse aggregates from industrial brick waste. Concretes incorporated natural fine aggregates (NFA), natural coarse aggregates (NCA) and the ceramic recycled coarse aggregates (RCA). The aggregates were characterized by particle size distribution, flakiness index, shape index, particle density, water absorption, loose bulk density, voids, crush resistance and resistance to fragmentation. Once the aggregates were studied, concretes were produced with RCA replacing NCA in absolute volume percentages of 0%, 10%, 30%, 50% and 75%. All the concretes were produced with the same workability and aggregate size gradation. In the hardened state, concretes were evaluated by the compressive strength, flexural strength, tensile splitting strength and density. The results showed the feasibility of partial replacement of NCA by RCA, despite the mechanical performance of concrete decreases with increasing replacement of NCA by RCA.

1. Introduction

The sustainable development concept comprises energy saving, environment protection and conservation of non-renewable natural resources. According to the European Union (EU) reports of 2011 [1], approximately 3 billion tonnes of waste are generated in EU 27 each year, being the construction and demolition waste (CDW) one of the heaviest and most voluminous waste streams, accounting for approximately one third of all generated wastes (i.e. 1 billion tonnes). The typical CDW includes materials such as concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil [1]. Some components of the CDW have a high resource value and can be reused for many applications in construction activities [2]. The use of CDW is therefore a strategic objective of the European Union [3]. The European Directive (2008/98/EC) of 19 November 2008 [4] provides a waste framework for moving towards a European recycling society with a high level of resource efficiency. In this context, a particular contribution is expected from the civil engineering sector.

One construction and demolition waste type with high potential to be used in concrete and mortars is the ceramic waste. The use of ceramic wastes in concrete has been actively researched for the last few years [5–28]. The sources of ceramic wastes being reported in such studies include crushed clean clay bricks [5,6,10,16,22], Industrial brick waste [28], bricks obtained from demolished construction [7,12,23], recovered floor and wall tiles [9,27], industrial rejects of sanitary ware [16,17,19,20] and ceramic electrical insulator industrial wastes [8,15]. The majority of these wastes are being tested as fine aggregates [7,9,10], coarse

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https://doi.org/10.1016/j.conbuildmat.2018.01.052
0950-0618/

aggregates [5,6,8,10,12,15–17,19,20,22,23,27] or mixed fine and coarse aggregates [10,16,28] to partially replace the natural aggregates in the production of concretes. There are other studies that explore the use of ceramic wastes as powder addition for partial replacement of cement [13,16,18,26].

The concrete hardened properties being evaluated in the reported studies that uses ceramic wastes are the compressive strength [5–28], tensile splitting strength [5,8,10,12,17,19,22,23,27,28], flexural tensile strength [6,9,27], modulus of elasticity [5,8,10,12,23,27,28], density [6,28], shrinkage [5,10,23], creep [5], abrasion resistance [6], water absorption [10,12,15,16,19], water permeability [10,16,19], pore size distribution [19], freeze-thaw resistance [20], carbonation and chloride penetration [12,15,16]. In these studies, fresh properties of concrete were consistently evaluated by performing slump-test and bulk density test. In fresh state, rarely the compaction factor and air content were measured.

The influence on concrete mechanical properties, resulting from the incorporation of recycled ceramic aggregates, is frequently done by specifying the replacement percentage of natural by recycled aggregates. However, it is known that the total solid volume of aggregates in the concrete mixture may vary depending on the volume of paste, which can differ from study to study. Furthermore, proportions between fine and coarse aggregates can vary between mixtures. To this extent, such replacement percentages are not directly comparable between different studies that use different volumes of paste, i.e., the same replacement percentage can represent different absolute volume of recycled aggregates per cubic meter of concrete. Other factors that difficult direct comparison of results are the range of compressive strength being analysed, as well as the resistance, surface texture, density and water absorption of recycled aggregates of different sources. Thus, in many situations, only general trends can be compared.

The literature review shows that general trends can be quite different when comparing concrete mechanical performance made with different ceramic source material as coarse aggregate. When using industrial rejects of sanitary ware as coarse aggregate to replace natural coarse aggregates in concrete mixtures with up to 25% replacement percentage, Medina et al. [17,19] have reported an increase in the compressive and tensile strengths with the replacement ratio. They argued that concretes with ceramic waste showed a more compact, less porous and less marked interfacial transition zone than reference concrete with natural aggregates. The recycled aggregates used by Medina et al. [17,19] have shown slightly higher water absorption than coarse natural aggregates.

Senthamarai and Manoharan [8] have tested industrial ceramic wastes got from electrical insulators as coarse aggregate for total replacement of natural coarse aggregates. Six concrete mixtures with different W/C ratios were produced. Concretes with 100% replacement of NCA by RCA, show a slightly reduction in compressive strength, tensile strength and modulus of elasticity when compared to reference concretes of the same W/C ratio. They have also reported higher slump values for concrete mixtures with 100% replacement of NCA by RCA when compared to reference concretes of the same W/C ratio, being this fact attributed to the lower water absorption and smoother surface texture of RCA compared to NCA.

Anderson et al. [27] have tested concrete with coarse recycled aggregates sourced from clean ceramic floor and wall tiles and waste ceramic wall tiles from demolition (with mortar and grout attached). They have used replacement percentages of NCA by RCA from 20% to 100%, and have found that, compared to reference concrete, the clean tiles had little effect on compressive strength as replacement percentage increase, whereas the waste tile showed a more significant decline for higher replacement percentages. Splitting tensile strength has shown overall improvement over reference concrete for all the clean and waste tiles, mainly below 100% replacement. Flexural strength exhibited a marked linear decrease over reference concrete, being 17.9% for clean tiles and 25% for waste tile when using 100% replacement, being attributed to the lower adherence between mortar and tile aggregates, leading to overall weaker bonding matrix. In this study, it was also concluded that clean floor tiles have low water absorption and dispense pre-soaking, while the clean wall and waste tiles needed pre-soaking due to higher water absorption. They also concluded that pre-soaking, if done correctly, had minimal effect on the overall properties.

In the scope of this article, it is especially relevant to analyse the studies concerning the use of ceramic wastes obtained from clay bricks and used as coarse aggregates. Mansur et al. [5] have tested crushed clay bricks as coarse aggregate for concrete by comparing with conventional concrete with natural aggregates of crushed granite. They have concluded that brick-aggregate concrete can attain the same compressive strength, gives a higher tensile strength, a lower drying shrinkage, and almost identical specific creep when compared with conventional concrete. However, it exhibits a substantially smaller modulus of elasticity. They concluded that the good mechanical performance was due to the higher angularity and roughness of RCA compared to NCA, which gives a better mechanical interlocking and better adhesion.

De Brito et al. [6] have tested concretes with replacement percentages of 33, 66 and 100% of natural coarse aggregates by crushed clean clay bricks coarse aggregates. They have reported an approximately linear reduction in compressive strength and flexural tensile strength over conventional concrete, with a decrease of 45% and 26% for 100% replacement, respectively. They attributed such reduction to the lower resistance of RCA compared to NCA. Martins [22] has tested concretes with replacement percentages of 0, 20, 50 and 100% of NCA by RCA sourced from clean clay bricks with the purpose to evaluate its mechanical behaviour under fire. For reference mixtures, not subjected to fire, he has also reported linear downward trends in compressive strength and splitting tensile strength, over conventional concrete, with a decrease of 36.6% and 8.9% for 100% replacement, respectively.

Gomes et al. [23] have tested concretes with replacement percentages of 6.25, 12.5, 25 and 50% of natural coarse aggregates by recycled coarse aggregates from demolition of hollow red clay brick walls (with mortar attached). They have concluded that, when compared to concrete with natural aggregates, the compressive strength reduces right from the start of the replacement (reaching 23.6% reduction for 50% replacement), tensile splitting strength shows a linear reduction trend as replacement ratio increases (with 20.1% reduction for 50% replacement) and the modulus of elasticity decreases with replacement ratio (with 22.2% reduction for 50% replacement).

González et al. [28] have tested the use of industrial clay brick wastes from rejected pieces in ceramic precast facilities (similar to the one used in the present study) to replace simultaneously fine and coarse natural aggregates in the production of concrete for precast prestressed beams. Replacement percentages of 20%, 35%, 50%, 70% and 100% were used. They concluded that compressive strength decreases progressively and very linearly, reaching a loss of 23% for a 100% replacement, when compared to the reference concrete (of 60 MPa). This decrease was lower than that obtained by Debieb and Kenai [10] in a similar study using a coarse fraction with higher particle size, reaching 40% reduction for 100% replacement, compared to reference concrete (<35 MPa). When analysing splitting tensile strength, González et al. [28] have reported a non-linear trend as replacement percentage increase; a slight increase was observed for low replacement percentages (up to 25%) and then a progressive decline from this point until a loss of 30% at 100% replacement. They have also found that modulus of elasticity decreases noticeably and linearly as replacement percentage