Construction and Building Materials 153 (2017) 704–715

Contents lists available at ScienceDirect

Construction and Building Materials

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

Investigation of mechanical properties and carbonation of concretes with construction and demolition waste and fly ash

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HIGHLIGHTS

- Mechanical properties and durability of concretes with recycled aggregate and fly ash were evaluated.
- Five levels of recycled coarse aggregate (RCA) substitution for construction and demolition (C&D) materials and 5 levels of fly ash in replacement Portland cement were investigated.
- For results analysis, statistical analysis (ANOVA) and mathematical models were used.
- The increase in the substitution level of natural aggregate by recycled aggregate reduces the mechanical properties.
- The synergic effect of RCA and fly ash in carbonation process was investigated.

ARTICLE INFO

Article history:
Received 28 March 2017
Received in revised form 14 July 2017
Accepted 17 July 2017

Keywords:
Concrete
Construction and demolition waste
Fly ash
Mechanical properties
Carbonation

ABSTRACT

The cement industry is one of the segments that release large amounts of carbon dioxide into the atmosphere during its manufacturing process, which consists of fuels burning. As the demand for concrete grows every year, the use of recycled coarse aggregate (RCA) in the construction industry can pose a significant effort to achieve a more sustainable construction. The present study investigated the mechanical properties (compressive and tensile strength) and durability (water absorption and carbonation depth) of concretes with different RCA substitution levels (25%, 50%, 75%, and 100%) instead of natural coarse aggregate, as well as replacement of Portland cement by fly ash in some levels (10%, 15%, 25%, and 30%) for different water/binder ratios (0.40, 0.45, 0.50, 0.55, and 0.65). All the results were statistically analyzed and showed that the mechanical properties decrease with the increase of replacement levels. Besides, the fly ash has a major influence on concretes with higher RCA replacement levels and water binder ratio. The carbonation of concretes with RCA and fly ash have a holistic effect, when 30% of replacement of cement by fly ash the carbonation over time was quite similar to the reference concrete.

1. Introduction

The increase in industrialization and urbanization rates due to economic and population growth has turned the civil construction industry into one of the segments that consumes the most amount of natural resources, generating solid waste that negatively impacts the environment [1,2]. Considering this scenario, it is possible to affirm that the use of recycled coarse aggregate (RCA) is an alternative to reduce the impact that those residues may cause to the environment. Limbachiya et al. [3] suggest that incorporating the maximum amount possible of recycled material in concrete would contribute to the reduction of greenhouse gases emission as well as minimize the amount of energy spent in concrete production. Must be pointed that the use of RCA in the production of new construction products has been considered one of the most efficient methods to add value to these materials, regarded as worthless [4]. It is estimated that the annual production of cement is of approximately 1.6 billion tons, which corresponds to about 7% of the global load of carbon dioxide into the atmosphere; as for the production of concrete, it is estimated that between 10 and 11 billion tons of aggregates are consumed per year [5].

Currently the construction and demolition (C&D) materials are used extensively with several materials, such as fly ash [1,6–8], rice husk ash [9–11], silica fume [12–14] as Pozzolanic materials, and

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.143
0950-0618/

as a pavement base/sub base applications [15–19], recycled sand in masonry [20–22], and as filling material and substructure piping [23,24]. According to Mohammadinia et al. [25] the C&D materials geopolymers stabilized with viable materials used in various applications such as civil engineering, as a base and sub base in decks, filling and construction of sidewalks and these applications would make a great contribution in CO_2 uptake.

Seeking to use energy and natural resources more sustainably, some researchers have looked for alternatives to reuse the solid waste originating from construction and demolition in the construction industry itself, thus minimizing the industry's impact to the environment [14,26–28]. In this context, feasibility studies for the use of RCA in substitution to natural aggregate in production of concrete have been carried out by several authors [13,29,30], showing the potential use of this material. Kou et al. [31] observed that for a w/c ratio of 0.55, concretes with 20% and 50% of RCA replacement by weight at 28 days had their compressive strengths reduced in 7.28% and 14.35% respectively, compared to reference concrete. However, Bajad et al. [8] replaced 20% of natural aggregate by RCA (w/c ratio = 0.50 at 28 days) by weight, and obtained results that were very close to reference concrete.

Another byproduct type, which has also been used in the construction industry for quite some time, is the fly ash, derived from burning pulverized coal during the power generation in thermal power plants. Several studies show that the use of fly ash partially replacing Portland cement in concrete production improves its durability and contributes to the reduction of CO_2 emissions [3,32]. For a more in-depth understanding of the influence of fly ash in concrete, many studies have investigated the role of this byproduct in cement hydration as well as in the process of pozzolanic reaction [7,33–35]. Chindaprasirt et al. [36] pointed out that the use of fly ash as pozzolanic material tends to increase the durability of mortars and concretes due to pore refinement and reduction of calcium hydroxide in the matrix of cement paste. However, according Meddah [37] and Chindaprasirt et al. [36] the effect of pore refining on concrete performance must be carefully investigated, because the drying shrinkage that may occur and consequently induce the cracking and minimize the concrete resistance to chemical attack, decreasing the service life of structures.

Some researches show that the fly ash particles size has an important influence on the mechanical properties and durability of the concretes with supplementary materials. Chindaprasirt et al. [36] performed tests with mortars with different particle sizes. The authors used 3 different fly ash particle fineness for mortars production. The first one was produced with unsifted fly ash, for the second one the fly ash was sifted through a sieve with 200 μm, and for the third one the fly ash was sifted through a sieve with 325 μm. The modified slump was set at 110 ± 5 mm, and the w/b ratio ranged between 0.40 and 0.50. The compressive strength of mortars with sifted fly ash were approximately 3% and 7.7% higher than the mortar with unsifted fly ash at 90 days. The authors performed other tests with mortars using finer particle of fly ash and observed that the higher the fineness of the fly ash particles the higher was the compression resistance gain of the mortars in comparison to natural ones. Based on this study, the authors concluded that fine fly ash with a more elevated specific surface were more reactive and consequently resulted in resistance increase in mortars, whose similar results were obtained by other researchers [34,38,39]. However, as the fineness increase, must be pointed that more water content is necessary to achieve the same workability, decreasing the physical and mechanical properties. In this way, the use of water reducers can be a feasible alternative to avoid the excessive water content in based-cement materials.

Other studies have already been performed using fly ash and recycled aggregate in concretes [1,32,40]. Poon et al. [27] conducted compressive strength tests in concretes with w/b ratio equal at 0.55 at 90 days. The results obtained showed that concrete with 20% of replacement of natural coarse aggregate by RCA in weight and 25% fly ash incorporated as partial cement replacement presented a 12.79% higher compressive strength compared to reference concrete. Concretes with 50% of RCA and 25% fly ash presented values of compressive strength 1.31% smaller compared to reference concrete.

Kim et al. [41] observed that concretes produced with 30% fly ash as partial cement replacement caused a decrease in compressive strength compared to the reference concrete of approximately 3% at 91 days. The concrete with 30% of fly ash replacement and 30% of recycled coarse aggregate replacement showed 7% of reduction in compressive strength. However, the concrete with 30% of fly ash and 100% of RCA presented values approximately 11% lower than reference concrete, mainly due the small strength of RCA compared to the natural aggregate [1,42–44]. So, is very important to consider the mechanical properties of aggregates (natural and RCA) in the definition of the mechanical properties of concrete. Besides, Kim et al. [41] and Lima et al. [32] suggested that the addition fly ash incorporated as partial cement replacement also decreases the strength of the concrete as a function of the delay in the cement hydration process, leading to slower development of long-term resistance.

According to Aboustait et al. [45], the knowledge of the fly ash composition allows a better understanding of the physical and chemical properties of these materials. In Table 1 it shown the results of the chemical composition of the fly ash found by other authors.

The physical properties and the chemical composition of the fly ash vary according to their origin and processing. Table 2 shows results found in other studies.

The mean diameter of particles (Table 2) was of approximately 29.5 μm, while the mean diameter of fly ash used in this study was 46.04 μm. Kiattikomol et al. [38] performed a study in mortars with milled and ground fly ash with different average sizes ranging between 1.9 and 17.2 μm and unground fly ash with average sizes ranging between 18.3 and 44.2 μm. The authors employed replacement levels of 20% and the compressive strength tests were performed at 7 and 28 days. According to the authors, the highest resistance values were obtained in mortars with finer fly ash due to the greater particles reactivity to promote the pozzolanic reaction, whose sum of the main oxides ($SiO_2 + Al_2O_3 + F_e2O_3$) was higher than 70%. The authors observed that the greatest influencing factor for mortar resistance was not the chemical composition, but the fly ash particle fineness.

Several studies showed that the effectiveness of pozzolanic reaction in cement matrix can be attributed to particles size, specific surface area and mineralogical composition [51–53]. Chindaprasirt et al. [50] used two fly ash types in mortars: one with medium diameter of 19.1 μm ($SiO_2 + Al_2O_3 + Fe_2O_3 = 81.54\%$) and other, sieved and ground, with medium diameter of 6.4 μm ($SiO_2 + Al_2O_3 + Fe_2O_3 = 79.44\%$). The results showed that the hydration and pozzolanic reactions, packaging and nucleation effect were better with the use of sieved fly ash, resulting in a more homogeneous and compact matrix. Kiattikomol et al. [38] verified that the mortar produced with original fly ash whose medium particle size ranged between 18.3 and 44.2 μm showed inferior resistance than the natural mortars at 3 and 90 days, and these results are closely related to the particles size, because the larger they are the higher the porosity and w/b ratio.

In this context, this research aims to present a contribution to the study of RCA and fly ash influences on the mechanical properties (compressive and tensile strength) and durability indicator (water absorption and carbonation resistance) in concrete.