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Combined effects of recycled hydrated cement and recycled aggregates on the mechanical properties of concrete

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HIGHLIGHTS

- We study the mechanical behavior of concretes with RA and RHC.
- The amount of recycled aggregates is determinant in the strength of the concretes.
- The size of the RHC particles is determinant in the strength of the concretes.
- Amount of RHC and dehydration temperature are not significant in the final strength.

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ABSTRACT

This paper analyses the mechanical properties of concrete manufactured replacing simultaneously different amounts of cement and natural coarse aggregates with recycled hydrated cement (RHC) and recycled aggregates (RA), respectively. The effect of four variables in the mechanical behavior is analyzed: amount of RHC, maximum RHC particle size, RHC rehydration temperature and percentage of RA. The goal is to determine their optimal combination to maximize the reuse of recycled materials maintaining the performance of the material and minimizing its environmental impact. Results show how RHC and RA can be used simultaneously without significant losses in the mechanical properties of the concrete. The optimum combination of the four parameters considered is: 20% of RA, 5% of RHC replacement with a maximum size of 75 μm and dehydrated at 900 °C. However, the low significance of the amount of RHC and the dehydration temperature suggest that the former may be increased and the later lowered maximizing the reuse of construction and demolition waste and decreasing the energetic cost of the new material.

1. Introduction

Concrete is one of the materials with higher contribution to the amount of construction and demolition waste (CDW) generation, what, added to its extended use, makes the study of its environmental impact a social obligation for engineers and researchers.

In concrete production the main responsible for CO_2 emissions is the use of ordinary Portland cement with a contribution rate roughly equivalent to 80–90% [1]. Hence, an effective way to reduce the environmental impact of concrete production is to minimize these emissions related to cement. During the last few decades, several alternatives have been proposed, most of them regarding the replacement of some amount of cement by different residuals. One of these materials is recycled hydrated cement (RHC). Old rejected cement, after being grinded and dehydrated through thermal processes can be reused as a replacement at a certain percentage of cement [2–7]. Following Gastaldo et al. [2], when 30% of RHC is used, a clinker with the same mineralogical composition can be produced releasing almost 1/3 less CO_2 from the powder during burning. On the other hand, in addition to CO_2 emissions reduction, the use of RHC reduces the need of natural resources and amount of CDW. Therefore, RHC can be considered not a waste but, as far as its composition makes it appealing, as raw component to be used in the chain of cement production in partial substitution of natural quarried materials [2].

The use of untreated fine recycled material in new concrete should be controlled carefully because it shows obvious angular characteristics with high water absorption rate and low specific gravity. As for the concrete containing this material, there is a

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mechanical strength reduction of 15–30% compared to the normal concrete. Moreover, it causes higher drying shrinkage and increases creep [4].

Therefore, one of the issues concerning the use of RHC is the thermal treatment it must suffer before it can substitute traditional cement. It has been recognized that after exposure to high temperature, a sequence of the physical and chemical processes takes place. The release of free water and bond water in the hydration products is the main process, and some hydration products are gradually dehydrated at elevated temperatures, such as ettringite, calcium silicate hydrate (C–S–H gel) and calcium hydroxide (CH). The dehydration process of HCP is completed at the temperature of 800 °C or above. The stage reached at any given temperature is depends also on the heating rate since all the reactions are not instantaneous [6]. According to Alarcon–Ruiz et al. [8] the following reactions take place with an increase of temperature in cement paste and concrete. From 30 to 105 °C, the evaporable water and a part of the bound water escape. It is generally considered that the evaporable water is completely eliminated at 120 °C. From 110 to 170 °C, the decomposition of gypsum (with a double endothermic reaction), the decomposition of ettringite and the loss of water from part of the carboaluminate hydrates take place. From 180 to 300 °C, the loss of bound water from the decomposition of the C-S-H and carboaluminate hydrates undergoes. From 450 to 550 °C, the dehydroxylation of the portlandite (calcium hydroxide) happens. And from 700 to 900 °C, the decarbonation of calcium carbonate. The dehydrated cement can be successfully rehydrated after thermal treatment, but the obtained hydration products have lower performances than the original ones, probably because of a reduced packing density and crystallization degree of the new hydrates [4]. As a result, the new C–S–H gel is partially formed by the rehydration reaction of transformation products with water. In addition, during the whole rehydration process, the initially dehydrated cement could react with water and form the additional hydration products. The energetic waste in this procedure may not be trivial.

An alternative to reduce even more the CO_2 emissions and the amount of CDW from concrete production is to replace, not only some amount of cement, but also other raw materials, such as coarse aggregates. Several studies [9–12] have proven the feasibility of the use of recycled aggregates (RA) if the percentage of replacement is limited [13–20]. Differences between the mechanical properties of traditional concretes and concretes with the RA have been mainly attributed to the old mortar adhered to the surfaces of the RA. Two interfaces have to be considered when using RA rather than one, the old interface, between the old mortar and the RA, and the new one, between the RA and the new cement mixture [10]. The quality of these interfaces, given by the quantity and quality of the old adhered mortar, is a key factor influencing the mechanical behavior of recycled concrete [11,21]

Despite the use of RA and RHC has been studied in construction materials, there is still a lack of information concerning the mechanical behavior of concretes produced with both residuals simultaneously. Therefore, the goal of this research is to analyze the effects of the simultaneous replacement of RHC as cement and RA as natural coarse aggregates, in particular, on the mechanical properties (compressive and flexural strength) of concrete mixtures, to efficiently maximize the reuse of concrete waste. The aim of this study is to optimize the mixture, combining the considered parameters, maximizing the amount of RHC and RA reused.

2. Materials characterization

Fig. 1 shows the procedure to obtain both recycled materials from the same residual. The waste concrete was first crushed in a jaw crusher to get the recycled aggregates. Then, these aggregates were put under a mortar reducing mechanical process through abrasion, using 300 rev in a Los Angeles abrasion machine. The purpose of this process is double, to enhance the physical properties of RA and to obtain the fine material (under 75 μm) or hydrated cement. After that, those sieved powders of RHC were submitted to the controlled heating regime up to selected temperatures. The furnace was heated at a rate of 10 °C/min, starting from room temperature. When the desired temperature was reached, the powders were kept in the furnace for 4 h.

2.1. Natural and recycled aggregates

Natural and recycled aggregates were used to prepare the concrete mixtures. The RA were obtained from a low quality concrete form the slab of a demolished residential building and their nominal sizes were 19.3 mm, 12.5 mm and 9.5 mm. To reduce the amount of adhered mortar, the aggregates were put through a 300 rev abrasion process using a Los Angeles machine. The removed mortar from these aggregates was later used as RHC.

The physical properties of the coarse aggregates are shown in Table 1. Natural sand was used in all of the concretes. Natural aggregates (NA) present higher values of density than recycled ones. The decrease, of around 7%, in the density is caused by the presence of adhered mortar in RA. When the amount of mortar removed increases by increasing the revolutions applied the difference decreases. On the other hand, the water absorption is around 3.6 times bigger in RA than in NA.

2.2. RHC and cement

Pozzolanic cement, equivalent to ASTM type P cement is used. Different percentages of this cement will be replaced by RHC classified by the maximum size of its particles and the maximum temperature used in its treatment.

The chemical analysis of cement and RHC is shown in Table 2. Three maximum temperature levels of the RHC are considered (400 °C, 650 °C and 900 °C) and three maximum particles sizes (75 μm, 150 μm and 300 μm). Data show similar composition for both, with lower content of silica in the RHC, and significantly higher content of sodium in it, likely due to the ancient practice to add sodium nitrate (easily available in Chile) to the concrete mixture as set accelerator and, at higher dosages, also as antifreeze admixture. The higher iron content could be, instead, attributed to corrosion phenomena of the reinforcing steel.

The mineralogical analysis of the RHC after suffering the three different maximum temperature levels, 400 °C, 650 °C and 900 °C, was carried out by XRD, SEM micrograph and EDS analysis. The analyses are carried out considering three maximum particle sizes, 75 μm, 150 μm and 300 μm. The results, shown in Figs. 2–5, indicate that preheated RHC consists of dehydrated and transformed components of the initial hydration products.

The effects of the particle size distribution and its maximum size can be observed in these figures. The main basic elements found in the preheated RHC samples are calcium and silica in all cases, independently of their maximum size and preheating temperature.

In order to study RHC behavior, the distribution of the crystalline phases is analyzed in Fig. 6. The main crystalline phases found in the RHC are fine natural sand, calcite, gehlenite and bredigite (dehydrated cement), with contents that vary according to the preheating temperature (Fig. 6) independently of the particle size. Indeed, calcite (partly present in the natural aggregate and mostly originated by the concrete carbonation) disappears for the preheating temperature of 900 °C, since its thermal decomposition starts at about 700 °C, while gehlenite and bredigite