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Influence of recycled aggregates containing sulphur on properties of recycled aggregate mortar and concrete

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ABSTRACT

This paper presents the main results of the research carried out to analyse the technical feasibility of concrete incorporating recycled aggregates from crushed tested concrete specimens. The main objective is to demonstrate that producers of concrete waste from tested specimens can use this waste for recycled concrete despite the presence of capping sulphur. However, the presence of sulphur in the recycled aggregates thus obtained may have effects on the properties of the concrete in which it is incorporated. In this work, a characterisation program of recycled aggregate containing sulphur and recycled concrete has been undertaken. It is concluded that the use of recycled aggregate concrete, with or without sulphur, is viable for the manufacture of recycled structural concretes for applications without exposure to high temperatures. However, the use of the fine fraction means a significant loss of properties.

1. Introduction

The material on which this research focuses is concrete made by incorporating recycled aggregate from concrete test specimens. A great deal of research has been dedicated to finding ways of using recycled aggregate (RA) in the manufacture of concrete and, in particular, the use of recycled aggregates from concrete [1–10]. The properties of recycled aggregates from concrete make it the most appropriate for the production of recycled concrete (RC) [11,12]. However, most studies have focused on aggregates obtained from demolitions of structural concrete. These concretes have, in many cases, uncertain characteristics and may even have suffered damage or degradation processes throughout their in-service life.

In this research, recycled aggregates obtained by crushing concrete specimens (tested or not) (SRA) from control laboratories are analysed and used in RC. The characteristics of tested concrete specimen are well known and are generally tested at early ages; in most cases 7 and/or 28 days. This implies a positive effect on the characteristics of the recycled aggregates of the specimens (SRA) and the RC made with them. Normally, the concrete specimens have not been exposed to aggressive environments and therefore do not introduce hazardous agents in the RC [13]. In other studies, it has been shown that the properties of early age recycled concrete aggregates can be improved [14], thus enhancing the characteristics of the RC with time.

The motivation for this current work is based on the number of control specimens tested in Spain in recent years; in 2007, for example, this number exceeded 5 million [15,16]. This large number constitutes a mass of waste material of approximately 60,000 tons, which is, however, a tiny amount when compared to the overall quantity of RC. However, the good performance of this material means that it is of great value for recycling, for example in a precasting plant using its own wastes.

Usually, these compressive test specimens need to be capped before testing [17,18]. Sulphur or sulphur mortar is the most widely used material in the capping process of cylindrical specimens. This leads to uncertainty as to whether the sulphur found in the SRA may or may not adversely affect the properties of the RC. The incorporation of sulphur into the RC can have adverse effects on the properties of fresh concrete [19] both for edged and for angular grain shape [20]. It can also lead to a loss in the mechanical properties of the hardened concrete. Due to the hardness and low tenacity of the incorporated sulphur [21], the addition of other materials with low mechanical properties and low bonding with the concrete [22–26] and the problems caused by the lower melting temperature of sulphur [27], Grugle [28] and Vlaovic [29] suggest that sulphur presents good features in environments subjected to acids and salts but cannot be used in an environment that exceeds 120 °C. Chemically, in principle, sulphur in an alkaline matrix such as cement paste is a stable material [30].

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Therefore, the use of sulphur from capping does not entail an environmental problem regarding the generation of sulphates, sulphites or acids.

In order to resolve these doubts, the SRA obtained from these waste materials have been characterised. Also, the RC has been characterised in terms of its physical and mechanical properties. The chemical and deformational compatibility between concrete and sulphur and their durability have been analysed.

One assessment of the durability of concrete is in terms of the resistance it offers against the penetration of harmful agents into the material. To evaluate this, the maximum penetration depth of water under pressure test and the oxygen permeability test have been carried out. Lightweight aggregate concrete, like the SRA, is more porous and permeable compared with normal-weight aggregate [31,32].

Moreover, a fast and simple methodology is proposed in this paper to analyse the durability of concrete. The use of variable coatings to evaluate the protection offered on the steel bars used as a reinforcement of structural concrete by the recycled concrete is proposed.

2. Materials

2.1. Waste from concrete specimens

The waste used was obtained from 5000 concrete specimens tested and broken under compression. Before manufacturing the SRA, the tested specimens were separated into two different wastes: firstly, the one obtained from the cylindrical specimens with presence of sulphur from capping, and secondly, another waste composed only of concrete without sulphur obtained by removing manually the capping layer. Tis will make it possible to define the influence of sulphur on the SRA and the RC.

Approximately 30 tons of concrete waste with sulphur and 30 tons of waste without sulphur were obtained. The specimens were structural concretes, with an average age of 22 days, made with different Portland cement types (I–III), with limestone aggregates and, in some cases, with silica sand. Also, the specimens were tested under compression according to the specifications of the standards [17,33]. The average compressive strength was 35 MPa. Due to the type of cement of the original concretes, a further improvement in their mechanical properties is expected in the new cement paste [14] and suggest that a SRA with acceptable features may be obtained.

2.2. Sulphur from capping

In the process of capping, pure sulphur or sulphur mixed with natural dry sand (ISO 12390-2) was used [30]. For the cylindrical concrete specimens used, the amount of capping sulphur is around 0.75% of the weight of the specimen.

2.3. Aggregates

Limestone coarse aggregates, siliceous and limestone fine aggregate have been used. Fig. 1 shows the particle size distribution of the different natural aggregate (NA) used.

The SRA, with and without sulphur, were obtained from crushing concrete specimens by using a HARTL© SUPERTRACK 504 PCV impact crusher [34] obtaining an aggregate with 0–32 mm. It was then separated into three distinct fractions: 0–6 mm (FA), 6–12 mm (FB) and 12–18 mm (FC). Fig. 2 shows the particle size distribution [35] of these fractions.

The geometrical properties of the two types of aggregates, with sulphur (SRA-I) and without sulphur (SRA-II) are indistinguishable. However, in terms of physical properties, significant differences are found.

In Table 1, the physical properties of the NA and SRA are presented. The density of the SRA is lower than the density of the natural aggregates. Also, it is shown that the density of the smaller fractions of the SRA have a lower density due to the higher volume of adhered mortar [12]. There are different values of density for SRA-I and SRA-II: the fine fraction of the SRA-II has a higher density due to the absence of sulphur. The crystallized free sulphur has an apparent density of 1.96 g/cm^3.

Table 2 shows the compositional, durability and tribological properties of NA and SRA. The Los Angeles coefficient, significantly lower than the 38–40% found in the literature [12,36], indicates that the SRA comes from a high quality original concrete.

Chemical and mineralogical analyses of each of the fractions are presented in Table 3. Three specimens, in powder form (<0.063 mm), obtained after the crushing and sieving of 250 g of an SRA sample were analysed. It is significant that 70% of the capping sulphur present in the aggregate is in the fine (SRA-FA) fraction. This effect may be due to the high friability of the sulphur. During the process of testing, crushing and screening of the specimens, the sulphur undergoes greater fragmentation than the concrete.

In order to check the crystalline state in which the sulphur is presented, and to evaluate the influence on the characteristics of the SRA and RC, mineralogical analyses have been performed by X-ray diffraction [37] on each fraction of the SRA-I. Figs. 3–5 show the results obtained. It has been proved that most of the sulphur detected in the crystalline state is stable rhombohedral sulphur. The 0.9% sulphur base, observed in the SRA-II chemical analysis (Table 3) from the cement of the original concrete, is not detected in the diffraction patterns.

2.4. Steel

As a complement to the analysis of the SRA and RC, an analysis for determining the protective capacity of concrete on steel exposed to an aggressive environment has been conducted. To this end, specimens of RC, with embedded steel bars, were prepared. Table 4 shows the chemical composition (in weight) of the 16 mm ribbed steel bar used.

2.5. Chemical analysis of cements

For the preparation of the mortars and RC, a CEM II 42.5 (according to the EN 197-1) cement was used. The chemical composition by XRF (weight percentage) is presented in Table 5.

2.6. Recycled mortars

In the design of the mix proportions of the mortars, standard proportions for the mechanical characterisation of cement were used [38]: 450 g of cement; 1350 g of silica sand and 225 g of water. From this, maintaining the volumetric proportions, six control mortar specimens ($40 \times 40 \times 160$ mm) with the same silica/limestone sand ratio as the concrete (Section 2.7) were prepared. After that, six recycled mortar specimens were prepared using the fine fraction (FA) of the SRA-I (M-SRA-I) and SRA-II (M-SRA-II) maintaining the same silica sand amount and replacing the limestone sand volume with the SRA. Also, six mortar specimens with SRA-I and SRA-II sand incorporating 10% weight of crushed sulphur from capping as addition were prepared: M-SRA-I-0.1S and M-SRA-II-0.1S (see Table 6).

Table 7 shows the mix proportions of mortar. All mix proportions maintain the same water/cement ratio. The M-SRA mix also maintains the aggregate volume. In the M-SRA-0.1S, 10% by