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Rheological behaviour of concrete made with fine recycled concrete aggregates – Influence of the superplasticizer

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HIGHLIGHTS

- The use of FRCA significantly increased the shrinkage and creep deformation.
- The FRCA's effect on rheological behaviour is influenced by the curing age.
- Superplasticizers increase early-age shrinkage but decrease it in the long-term.
- High-performance superplasticizer decreases creep deformation.
- The incorporation of FRCA partially hindered the effectiveness of the superplasticizers.

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ABSTRACT

This paper evaluates the influence of two superplasticizers (SP) on the rheological behaviour of concrete made with fine recycled concrete aggregates (FRCA). Three families of concrete were tested: family C0 made without SP, family C1 made with a regular superplasticizer and family C2 made with a high-performance superplasticizer. Five replacement ratios of natural sand by FRCA were tested: 0%, 10%, 30%, 50% and 100%. The coarse aggregates were natural gravels. Three criteria were established to design the concrete mixes' composition: keep the same particle size distribution curves, adjust the water/cement ratio to obtain a similar slump and no pre-saturation of the FRCA. All mixes had the same cement and SP content. The results show that the incorporation of FRCA significantly increased the shrinkage and creep deformation. The FRCA's effect was influenced by the curing age. The reference concrete made with natural sand stabilizes the creep deformation faster than the mixes made with FRCA. The incorporation of superplasticizer increased the shrinkage at early ages and decreased the shrinkage at 91 days of age. The regular superplasticizer did not improve the creep deformation while the high-performance superplasticizer highly improved this property. The incorporation of FRCA jeopardized the SP's effectiveness. This study demonstrated that to use FRCA and superplasticizer for concrete production it is necessary to take into account the different rheological behaviour of these mixes.

1. Introduction

The aggregates industry in the EU-27 plus EFTA countries comprises some 15,000 companies and 26,000 quarries and pits that employ around 238,000 workers. The production of aggregates in 2011 was estimated by the Aggregates European Association in 3 billion tonnes with an annual turnover of 20 billion €. The average aggregates demand in Europe is just under 5.8 tonnes per capita per year. These data show the great economic and environmental importance of this sector in the developed countries [1].

Abbreviations: CDW, construction and demolition waste; CNA, coarse natural aggregates; CRAC, coarse recycled aggregates concrete; CRCA, coarse recycled concrete aggregates; EFTA, European Free Trade Association; EU, European Union; FNA, fine natural aggregate; FRA, fine recycled aggregates; FRAC, fine recycled aggregates concrete; FRCA, fine recycled concrete aggregate; NA, natural aggregates; RA, recycled aggregates; RAC, recycled aggregates concrete; RC, reference concrete; RCA, recycled concrete aggregates; SCC, self compacting concrete; SP, superplasticizer; $(w/c)_{ef}$, effective water/cement ratio.

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The most common types of aggregates used in the construction sector are crushed rock from quarries (49%), natural gravel and sand from pits (41%), recycled aggregates from construction and demolition waste (CDW) (6%) and other such as marine aggregates, slag, bottom ash, fly ash, etc. (4%). Approximately 45% of the aggregates are consumed in the manufacture of concrete and mortar, 45% are used as unbound materials and the remaining 10% in asphalt concrete production [1].

Recycled aggregates from CDW are an alternative to natural aggregates, but the recycling rate varies greatly within the EU states. While countries like the Netherlands, Denmark, Germany, Ireland and United Kingdom have a recycling rate over 75%, others like Spain, Portugal and Italy have a recycling rate around 15–20%. The average recycling rate in the EU-27 was estimated at around 46% [2]. According to the Waste Framework Directive of the European Parliament on waste, a minimum of 70% by weight of non-hazardous CDW shall be prepared for re-use and recycling in 2020 [3], which highlights the need of these Southern European countries to achieve this rate.

In these Southern European countries the majority of recycled aggregates (RA) are used in road construction [4,5] and unpaved rural roads [6]. These uses have little added value but are a good alternative for RA with medium or low quality [7]. Using selective demolition techniques, RA of high quality with a high potential for recycling can be obtained [8]. The use of these high-quality aggregates in the manufacture of concrete and mortar gives more added value to these recycled materials. Hence, numerous researchers have been conducted in the last two decades to evaluate the performance of concrete and mortar made with RA. Most have focused on the use of RCA, since concrete represents 30% or 40% by weight of the total CDW generated in the EU [2].

Recycled concrete aggregates (RCA) are composed of NA with approximately 30% of adhered mortar [9]. The adhered mortar give the RCA a rough surface with numerous pores and micro-cracks [10], which justify the main characteristics of RCA: more porosity, much higher water absorption, lower density and greater angularity and irregular shape [11,12].

Two fractions of RCA have been used by researchers in the manufacture of concrete: coarse recycled concrete aggregates (CRCA) for replacement gravels; and fine recycled concrete aggregates (FRCA) for replacement natural sand. The fine fraction has also been used in the manufacture of mortar [13,14].

The incorporation of CRCA significantly affects fresh concrete's density and workability [15]. Generally, the mechanical properties decrease as the CRCA ratio increases [16]. The incorporation of CRCA has a detrimental effect on shrinkage deformation [17]. The creep deformation of concrete increases with the incorporation of CRCA, due to the lower modulus of elasticity of CRAC caused by their lower stiffness [18]. The shrinkage and creep deformations cause internal strength, hence they have to be considered as fundamental properties of structural concrete. These deformations can cause the occurrence of cracks that compromise the durability of a structure. In durability-related terms, CRAC showed higher water absorption by immersion and capillarity [19]. The chloride penetration resistance and carbonation resistance decrease with the incorporation of CRCA [20].

Fewer studies on the use of FRCA have been carried out by researchers. This fraction shows worse physico-mechanical and chemical properties, such as greater amount of cement paste, porosity, water absorption and acid soluble sulphate content, which may limit its use in concrete [21]. The incorporation of FRCA reduces mechanical strength, increases shrinkage and has a negative effect on the durability behaviour of RCA [22–23]. For these reasons many codes allow the incorporation of CRCA in structural concrete but do not allow replacing FNA by FRCA in structural concrete production. Gonçalves and de Brito [24] made an extensive revision of the current standards that allow the use of RCA and of its restrictions.

Evangelista and de Brito [25] made an extensive state of the art on the use of FRCA in concrete production and concluded that it is possible to replace FNA by FRCA, provided that the properties of the recycled aggregates are taken into account in the mix design and production. Nevertheless, these authors concluded that there are some properties that need further investigation, such as the durability and rheological properties. They also highlighted the need to define the constitutive equations of concrete made with FRCA.

The use of SP reduces the mixing water maintaining the workability, which for the same cement content allows reducing the (w/c) ratio and improves the mechanical and durability properties of RCA [26–28].

To determine the effect of regular superplasticizer and high-performance superplasticizer on concrete's performance, an extensive study had been carried out at IST in Lisbon. This paper presents the influence of both kinds of superplasticizer on the rheological properties of concrete made with FRCA. From a theoretical point of view, rheology is the relationship between loading and deformation behaviour of materials that cannot be described by classical mechanics or elasticity. One of the major tasks of rheology is to empirically establish the relationships between deformations (or rates of deformation) and stresses, which has been addressed in this study. To the best of the authors' knowledge there are no other studies on the effect of superplasticizer on the rheological behaviour of structural concrete made with FRCA. This study follows another one of the same authors on the durability of concrete with FRCA and SP [29] and promotes its use in concrete production in order to reduce the consumption of non-renewable natural resources such as sand from river bank or crushed natural rock from quarries. This study also contributes to preventing the accumulation of the FRCA in landfills.

2. Literature review

This section is focused on the rheological behaviour of concrete made with FRCA, specifically on the shrinkage and creep deformation, and presents chronologically the studies published in the last decade that have been the basis of this work.

Khatib [30] examined the influence of replacing FNA by FRCA on the shrinkage. FRCA with particle size less than 5 mm was used and five replacement ratios by weight were tested: 0%, 25%, 50%, 75% and 100%. No data on the source concrete were available. A free water/cement ratio of 0.5 was used in all mixes. No superplasticizers were used. An increase in the slump was observed with the increase in FRCA content. The incorporation of FRCA caused a linear increase in shrinkage deformation.

Kou and Poon [31] used the same replacement ratios as Khatib [30]. In a first series the authors maintained a constant free water/cement of 0.53 in all mixes. The slump increased with the incorporation of FRCA, which was attributed to the greater amount of free water in the mix. The incorporation of FRCA had a detrimental effect on the drying shrinkage. At 112 days an increase of 26% was observed for the 100% replacement ratio relative to the RC. In a second series, water was added to obtain a slump of 60–80 mm in all mixes. In this case the drying shrinkage in the mix with 100% replacement ratio was higher by 22% than that of the RC.

Kou and Poon [32] in a second study showed the results of three series of SCC. In series I the FRCA were used as 0%, 25%, 50%, 75% and 100% by volume replacements of FNA. A constant w/c ratio of 0.53 was used. In series II fine fly ash was added to increase the cementitious materials content. The same replacement ratios of FNA by FRCA were tested with a constant w/c ratio of 0.44. In