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Steel-fibre-reinforced self-compacting concrete with 100% recycled mixed aggregates suitable for structural applications

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HIGHLIGHTS

- New experimental material consisting of SFRSCC with 100% recycled mixed aggregates.
- Pre-saturation was found the most effective method.
- The additive content was not enough to prevent water absorption by the aggregates.
- Design oriented to applications with limited structural performance.
- Compressive strength make this material suitable for structural elements.

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ABSTRACT

This research focuses on designing and characterizing steel-fibre-reinforced self-compacting concrete using recycled aggregates (SFR-SCC-RA). Six different concrete dosages have been designed, and two extensive mechanical and physical characterization programs have been conducted. The first program was developed in a concrete production plant to verify the compatibility of the new material with the existing production systems. The second program was developed in a laboratory under controlled temperature and humidity conditions. Although compressive strengths greater than 25 N/mm^2 have been reached (which allows the material to be classified as structural), the design in this initial phase is oriented to applications with limited mechanical requirements (e.g., foundations, earth retaining walls and pavements, in which design forces are moderate).

1. Introduction

The social perception in reference to the construction sector and, in particular, the use of concrete as a building material has become increasingly negative [1]. Cement production is one of the most energy intensive processes: the cement industry consumes 5% of the total global industrial energy. Due to the dominant use of carbon intensive fuels, e.g., coal, in clinker making, cement manufacture is a major emitter of CO_2. More than 5% of the total global emissions of CO_2 are attributed to the cement sector; it contributes the same proportion of emissions to greenhouse gas emission [2,3].

One way to promote more sustainable construction and minimize its impact on the environment is to apply the following "3Rs" concept: reduce – reuse – recycle [4]. Strategies have already been adopted to reduce the amount of CO_2 emitted into the atmosphere through measures such as reducing the percentage of clinker in cement by partially replacing additives such as fly ash, blast furnace slag, silica fume or pozzolan, among others, and replacing concrete aggregates with recycled aggregates [5–11].

The sources of aggregates for the construction industry in Europe are shown in Fig. 1 [12]. More than 90% consists of natural aggregates extracted from quarries and gravel pits, which contributes to the negative ecological impact and the negative social view of the material. In contrast, only 5% of global production involves recycled aggregates (RA, hereinafter) from construction waste and demolition. This percentage of reuse is low because of technological challenges (formulation and manufacturing, mechanical problems and durability) associated with the use of RA in structural concrete and also the particular constraints associated with the regulations in each country. Although the literature concerning the technological aspects of using RA is extensive, the

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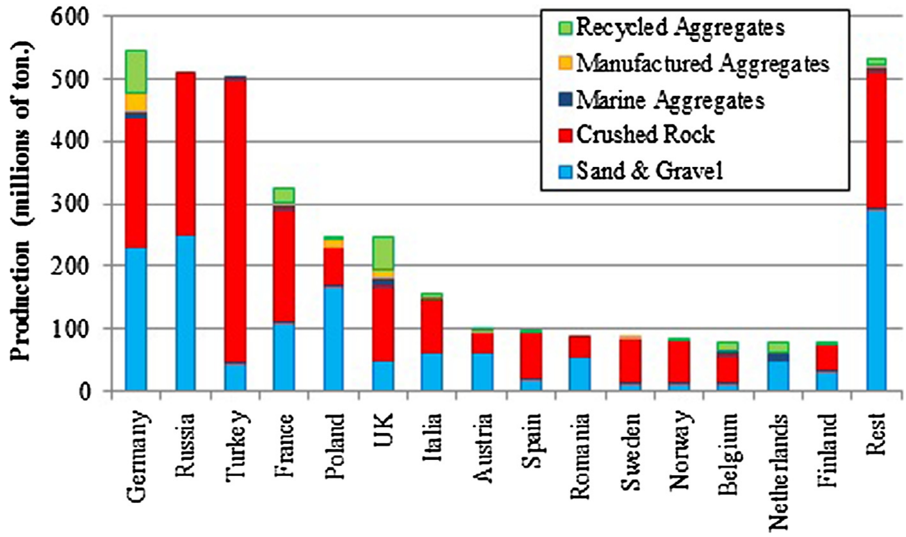

Fig. 1. Production of aggregate by country and proportion according to its origin [12].

construction sector is still not predisposed to use this material in structural applications.

The main benefits that are achieved with the reuse of construction and demolition waste, as [13] note, include the following: (1) the conservation of natural resources; (2) a reduction in the energy consumption associated with the production and transport of aggregates; and (3) a solution to the current problem of uncontrolled dumping of waste.

However, the use of RA is limited by the recommendations established by various national regulations; in particular, mixed RA only used in non-structural applications [14–17]. The reason is that the compressive and tensile strength of concrete, as well as the modulus of elasticity, are affected by the use of RA, which directly affects the overall performance of the structure [18].

According to Ref. [19], the losses in strength when using RA are due to (1) the lower mechanical strength of the RA, (2) the greater water absorption of the RA and (3) an increase in fragile areas within the concrete (e.g., the interfacial transition zone). Poon et al. [20] found that the interfacial transition zone had a high porosity. Barra [21] found that concrete with RA from concrete requires a greater cement content to reach the compressive strength of conventional concrete. Etxeberria et al. [22] recorded a loss of 20%–25% of the compressive strength of concrete at 28 d for full replacement of coarse RA; when 25% of the aggregates were replaced, there were no significant changes to the compressive strength.

The quality of recycled concrete aggregates (RCA) is usually lower than the quality of natural aggregates [23]. In comparison with natural normal-weight aggregates, RCA are weaker, more porous and exhibit higher values of water absorption [24]. The density of concrete constructed from RCA is as much as 10% lower than concrete constructed from natural aggregates [19,20].

The water absorption of RCA ranges from 3.5% to 9.2% [24–27], which greatly affects the workability of the fresh concrete. Previous studies [28,29] have demonstrated that, in contrast to natural aggregates, in which absorption is relatively fast, absorption in RA is prolonged by as much as 24 h or longer, potentially lasting as long as 96–120 h. However, if proper pre-saturation of the aggregates is performed, satisfactory results can be obtained in terms of workability and mechanical behavior [30]. In addition, the granulometry of the RA also has a large influence because at the same density, the water absorption of fine aggregate can be up to 5% greater than that of coarse aggregate, which has a smaller surface area [31].

Generally, the use of construction and demolition waste for the manufacture of structural concrete is only partial, which precludes full revalorization of the product obtained. As such, there is room for improvement. In Spain, for example, the use of recycled aggregates in concrete for structural purposes is limited in the Spanish standard EHE-08 [32] to a maximum percentage of 20% substitution of the coarse fraction if the aggregates have been obtained from the crushing of concrete and their water absorption is less than 7%. EHE-08 requires that when exceeding 20% substitution, the suitability must be certified based on specific studies and further experimentation; this requirement leaves open the possibility of using high contents of recycled aggregate in structural applications of concrete. This approach is identical to that established in the UK and the Netherlands.

In contrast, other European countries are more flexible in allowing higher percentages of substitution. For example, in Germany, the percentage of substitution is between 25 and 45%, depending on the type of aggregate and the environment to which the concrete will be exposed, while up to 100% is allowed in Belgium and Denmark. The latter two countries even allow a restricted use of recycled fine aggregates.

This research focuses on designing and characterizing steel-fibre-reinforced self-compacting concrete using recycled aggregates (SFR-SCC-RA). To our knowledge, this material has not previously been reported in the literature.

The use of fibres to reinforce concrete is a standard practice and is regulated by the *fib* Model Code 2010 [33]. The main advantages are the optimization of execution times due to the partial or total elimination of the prestressed reinforcement and the increased post-cracking energy of the concrete, leading to more suitable cracking patterns to ensure the life of the structure [34,35]. Typical applications of fibre-reinforced concrete (FRC) are, for example, rings for lining tunnels [36–38] and sewerage pipelines [39,40]; it has been shown that the substitution of part or all of traditional passive reinforcement fibres in such applications also leads to clear and quantifiable advantages in terms of sustainability [41]. Moreover, the self-compactability of concrete reduces noise pollution and risks associated with the handling of vibrators [42], in addition to increasing the production rate and minimizing the probability of occurrence of voids and other finishing problems that can cause aesthetic defects or even compromise the durability of the structure. Ultimately, all of these added features improve the sustainability of the finished product.