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Evaluation of self-compacting recycled concrete robustness by statistical approach

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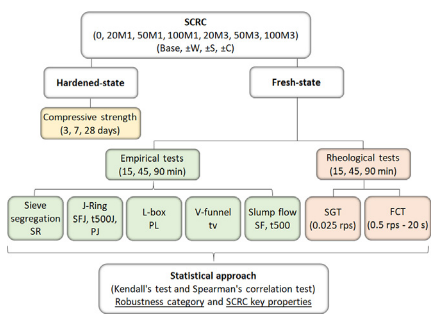
HIGHLIGHTS

- Robustness of self-compacting recycled concrete (SCRC) was analysed using statistical approach.
- SCRCs with 20%, 50% and 100% recycled aggregate were modified introducing material variations.
- Water control was found to be the key factor that affects SCRC robustness.
- Six key properties of SCRC were identified as those best to measure robustness.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of self-compacting recycled concrete appears as to be a very interesting technology for the sustainable construction future. However, one of the major obstacles to a more widespread use of self-compacting concrete is to obtain a robust material. Therefore, the emphasis of this work is placed on analysing both practice and theory to understand the properties that control and assess self-compacting recycled concrete robustness.

Hence, forty-nine different mixes were produced with several replacement percentages of recycled concrete coarse aggregate (0, 20, 50 or 100%) and with two different mixing procedures (all aggregates in dry-state conditions or recycled aggregate with a 3% of natural moisture). The experimental program consisted of making, in the fresh state, rheological tests (a stress growth test and a flow curve test) and empirical characterization tests (slump flow, V-funnel, L-box, J-Ring and sieve segregation) at 15, 45 and 90 min from cement-water contact. In the hardened state, compressive strength was measured at 3, 7 and 28 days.

All results were analysed using a statistical approach based on Kendall's coefficient of concordance and Spearman's rank correlation. This approach allowed us to successfully identify six key properties that can be measured to evaluate SCRC robustness (capacity of the material to tolerate certain variations in material characteristics and mixture parameters). For each mix, a ranking that defines its robustness category was obtained by considering all properties. Also, it showed that water control is the key factor that affects SCRC robustness.

1. Introduction and objectives

In the near future, using recycled materials in conventional and high performance applications should be a priority area [1]. At this

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stage, it is fundamental to analyse the characteristics of recycled materials, recycling procedures and manufacturing processes. The main difference between natural aggregate and the recycled concrete aggregate is the adhered mortar [2,3]. The presence of this material decreases with the number of crushing processes, the size fraction and the original waste quality [4,5].

In general terms, the quality of vibrated recycled concrete is lower than that of conventional concrete with the same mix proportions [6,7]. Many of the current studies in vibrated recycled concrete field deal with short-term analysis related to basic properties and structural performance, and a few of them have studied the long-term behaviour [8,9]. The compressive and splitting tensile strengths and modulus of elasticity decrease when the percentage of recycled aggregate increases, and the shrinkage and creep increase deformations [10,11]. These variations are mostly due to the adhered mortar.

On the other hand, self-compacting concrete is a highly flowable concrete that spreads rapidly into place and fills formwork without vibrating compaction in order to ease casting and to achieve durable concrete structures [12,13]. At the construction site, it has increasingly been used over the past two decades and it is empirically described according to its filling ability, passing ability and segregation resistance [14]. Most of studies state that, if a SCC is well designed, it can provide similar mechanical properties to its equivalent vibrated concrete [15]. However, the SCC flow properties and its fresh rheological behaviour diverge from what is expected from vibrated concrete of normal consistency [16].

One of the major obstacles to a more widespread use of self-compacting concrete is to obtain a robust material [17,18]. Robustness is the capacity of a concrete to maintain its properties when changes in materials, mixing parameters or environmental variables take place [19,20].

Self-compacting concrete has shown to be more sensitive to variations in its design process than vibrated concrete [21,22]. The mix design is a critical step to obtain high quality self-compacting concrete. A large number of variables must be considered in the mix design process and its interactions are difficult to predict [23].

Different studies have been developed to analyse self-compacting concrete robustness. In general, aggregate density and size, paste density, type of mixer, mixing protocol, mixing time and total mixing energy are factors that have to be taken into account to analyse robustness [24]. Some works conclude that robustness can be influenced by the water to powder volume ratio, the superplasticiser to powder weight ratio and the solid volume [25–27]. Others state that errors in weighing water and fines content [19] or those affecting aggregate moisture [28] are of capital importance.

Lastly, a new material, self-compacting recycled concrete (SCRC) appears as a self-compacting concrete made with recycled aggregate, in this work, recycled concrete coarse aggregate. This concrete has to combine successfully the behaviour of a self-compacting concrete and that of a vibrated recycled concrete [29]. The materials used to produce SCRC are the same as in self-compacting concrete, but recycled aggregates are used as replacement of natural aggregates [30,31]. The type and shape of coarse aggregate, combined gradation of sand and coarse aggregate, content of cement and supplementary cementitious materials, paste volume, and water to powder ratio must be considered when designing SCRC as in self-compacting concrete [32–35]. The use of recycled aggregate could improve the environmental aspects of self-compacting concrete without significant impact on workability and strength characteristics when low replacement percentages are used (up to 50%) [36–39]. However, not so much works have studied the rheological properties of SCRC, measuring the static yield stress and plastic viscosity [30,38,40,41], and analysed the specificity of its rheological behaviour [42].

Keeping the above in mind, extensive scientific research has been developed on vibrated recycled concrete over the last decades [7,11]. At the same time, high performance concretes have become a great challenge and one of the most remarkable topics in the field of materials engineering. In this context, the use of self-compacting concrete introducing new variables, as the replacement of natural aggregates with recycled aggregates, appears as to be a very interesting technology for the sustainable construction future.

As a consequence, SCRC has been studied only for a short time and there is a significant gap in the knowledge of its robustness [43]. SCRC involves multi-physics phenomena related to the specific intrinsic characteristics of recycled aggregates and the other components and variables of concrete design. Therefore, the emphasis of this work is placed on analysing both practice and theory to understand the properties that control and assess SCRC robustness.

In order to be successful in this approach, a statistical analysis is made with results from a wide experimental program. Taking into account the work of Naji et al. [21] on conventional self-compacting concrete, Kendall's coefficient of concordance and Spearman's rank correlation can be used to evaluate self-compacting recycled concrete robustness and to select adequate concrete properties that could be measured to determine it. Therefore, in this work, a statistical approach to SCRC robustness is carried out with the aim of determining which tests provide more sensitivity when the robustness of a SCRC mix is evaluated.

2. Methodology

Two research stages were conducted, an experimental stage and an analytical stage. The former consisted of 49 mixes of SCRA in which several replacement percentages of recycled aggregate and relevant parameters (mixing procedure and constituent materials) were varied. In the second stage, a statistical approach was performed to draw general conclusions and to reduce the number of properties that could provide a reliable understanding of SCRC robustness.

2.1. Testing program

In this work, the studied mixes were prepared with a Portland cement (CEM-I 52.5-R), with a density of 3110 kg/m^3 and a specific surface (BET) of 1.02 m^2/g. A limestone filler was also used with a density of 2710 kg/m^3 and a specific surface (BET) of 1.77 m^2/g. The properties of cement and filler are given in Tables 1 and 2. A superplasticiser (a modified polycarboxylate) was used as chemical additive. It showed a solid content of 35% and a density of 1080 kg/m^3. This kind of superplasticiser is used to produce high performance, high strength and flowable concretes.

Table 1
Properties of cement.

CEM-I 52.5-R Physical and mechanical properties	
Initial setting time	190 min
Final setting time	260 min
Soundness	0.3 mm
Initial strength	45.5 MPa
Strength	64 MPa