



Rheological behaviour of different grades of self-compacting concrete containing recycled aggregates

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HIGHLIGHTS

- Three grades of SCCs were designed using recycled aggregates (SCRCA).
- Normal-strength SCRCA showed shear thickening behaviour.
- Medium- as well as the high-strength SCRCA showed shear thinning behaviour.

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ABSTRACT

Rheological behaviour of three grades of Self-Compacting Concrete (SCC) containing selected volumetric replacement levels of coarse recycled concrete aggregates (SCRCA) is reported. The binder in the control SCC was cement. Fly ash and silica fume were added to the control mix in binary and ternary blends to achieve the normal-, the medium- and the high-strength SCRCA. Like the SCC made with the natural aggregates, the normal-strength SCRCA showed a shear thickening response. Its flow behaviour could be described using the Modified Bingham (MB) as well as the Herschel-Bulkley (HB) model. Although rheology of the medium- and the high-strength SCRCA could be represented by the Bingham model, a more detailed analysis of their flow data using the MB and the HB model indicated shear thinning behaviour. This response is attributed to the presence of silica fume in these two concrete grades. The results of this investigation have implications for formwork pressure, multi-lift casting, pumping and segregation resistance of SCRCA.

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1. Introduction

Steady-state rheology of conventional flowable concrete is traditionally represented by the Bingham model and attempts have been made to extend the scope of this model to Self-Compacting Concrete (SCC), a material which is characterized by a significantly lower yield stress [1]. Efforts to fit the Bingham model on the measured flow characteristics of SCC either result in a negative yield stress, which is physically inadmissible, or if the measured yield stress is less than about 10 Pascals (Pa) then a poor correlation is usually obtained between predictions of the Bingham model and the measured values. The invalidity of the Bingham model is attributed to shear thickening where in after accounting for the effects of thixotropy and loss of workability, SCC shows a non-linear relationship between shear stress and shear rate with the apparent

viscosity increasing with increasing shear rate [2]. The Herschel-Bulkley and the modified Bingham model [3,4] are the two commonly used relationships which can account for the shear thickening behaviour of SCC. It is generally accepted that irrespective of its grade (and hence composition) shear thickening is the typical rheological response of SCC containing natural aggregates. According to Rahman et al., shear thickening in SCC increases in the presence of metakaolin whereas ground quartz and fly ash have no effect and silica fume is reported to reduce it [5].

Shear thickening has practical consequences for casting of fresh concrete. In shear thickening, as viscosity increases with increasing shear rate, a larger increment of energy will be required to accelerate flow of concrete in high shear rate applications like mixing, pumping and extrusion etc. so much so that shear thickening may become the dominant phenomenon controlling system performance. Hence, if system breakdown is to be avoided then understanding shear thickening behaviour in particular and rheology of SCC in general is imperative.

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One of the possibilities being explored for reducing the environmental impact of concrete made using conventional materials is substitution of natural aggregates with aggregates derived from recycling of construction and demolition waste [6]. This is not only expected to reduce pressure on natural sources of aggregates but is also likely to help in safe and sustainable disposal of the huge volumes of construction and demolition waste generated across the world. The processing of waste concrete can yield both fine as well as coarse recycled aggregates which have potential applications in concrete. Besides attempts at using recycled concrete aggregates in conventionally vibrated concrete, their application has also been sought to be extended to SCC with both the hardened as well as the durability properties of SCC made with such aggregates being reported in the literature [7–19]. However, relatively little attention has been paid to the rheological behaviour of SCC made with recycled concrete aggregates. According to Guneyisi et al. [20], fresh SCC containing coarse as well as fine recycled aggregates is a shear thickening fluid whose behaviour is described by both the modified Bingham as well as the Herschel-Bulkley model. The effect of SCC grade (and hence its composition) on rheology has however not been discussed by the authors. Lopez et al. [21] report a significant increase in both static yield stress as well as plastic viscosity over time for all the fine recycled concrete aggregate replacement levels in the SCCs investigated by them. No attempts were however made by them to describe flow behaviour of their concretes with the help of rheological models. Besides these two studies, there is very little information in the literature on the rheology of Self-Compacting Concrete made with Recycled Concrete Aggregates (SCRCAs).

Rheology has important implications for high shear-rate applications like mixing and pumping to which SCC is usually subjected to. SCC made with natural aggregates is usually considered to be a shear thickening fluid with a limited number of studies reporting similar behaviour for SCC containing recycled concrete aggregates. Although a shear thickening rheological model may be valid for normal-strength SCC it may not hold good for higher grades because of differences in mixture composition due to use of significant amounts of supplementary cementitious materials to achieve higher strength together with flowability. If in addition, the SCC also contains coarse recycled concrete aggregates, which can potentially act as internal reservoirs of water in the concrete due to their high porosity, then the flow behaviour of such concrete may be significantly different from that of conventional SCC. This investigation has been undertaken in response to this gap and the rheology of three grades of SCRCAs each containing selected replacement levels of coarse recycled concrete aggregates has been investigated with a concrete rheometer. The three grades of SCRCAs were obtained by suitable addition of fly ash and silica fume as supplementary cementitious materials (SCMs) to a control SCC containing Portland cement as the only binder. Relevant flow models have been proposed to describe observed behaviour and it is shown that shear thickening is not the default rheological model for this concrete.

2. Experimental program

2.1. Materials

The SCCs were designed using Portland cement conforming to IS 8112-2013 [22] and where ever required, silica fume and ASTM Class-F fly ash were used as binary and ternary cementitious blends. The properties of the cement, the fly ash and the silica fume are summarized in Table 1. Natural river sand having a specific gravity of 2.42 was used as Fine Aggregate (FA) and crushed stone aggregates of 12.5 mm maximum size and having a specific gravity

Table 1

Chemical and physical properties of the cement, the fly ash and the silica fume.

Parameter	Cement	Fly ash	Silica fume
CaO (%)	64.32	1.98	–
SiO ₂ (%)	17.95	58.45	90.06
Al ₂ O ₃ (%)	4.01	28.15	–
Fe ₂ O ₃ (%)	4.63	5.87	–
MgO (%)	3.88	0.85	–
SO ₃ (%)	2.75	0.18	–
K ₂ O (%)	0.81	1.88	–
Na ₂ O (%)	0.79	0.15	–
Loss on ignition (%)	0.78	1.58	3.01
Specific gravity	3.15	2.24	2.10
Specific surface area (cm ² /g)	3166	3603	–

of 2.63 were used as the Natural Coarse Aggregates (NCA). Coarse Recycled Concrete Aggregates (RCA) were obtained by processing with the help of a jaw crusher waste concrete specimens obtained from the concrete laboratory of the author's host institute. The advantage of using laboratory produced RCA was that the amount of residual mortar on such aggregates can be expected to be the maximum which would correspond to a 'worst-case' scenario [23]. However, the use of laboratory produced RCAs limits the scope and therefore the validity of the results reported in this investigation when compared to results obtained using RCAs sourced from waste concrete processing plants. The author's had to take recourse to laboratory produced aggregates in the absence of sufficient quantity of waste concrete in and around the vicinity of their host institute. The output of the jaw crusher was manually blended in such a manner that RCA grading was similar to that of the NCA and was also within the specified coarse aggregate grading limits of IS: 383-2002 [24], Fig. 1. The physical and mechanical properties of the aggregates are shown in Table 2. A polycarboxylic ether-based compound having a specific gravity of 1.08 was used as the High-Range Water Reducing Admixture (HRWRA) and a Viscosity Modifying Admixture (VMA) with a specific gravity of 1.01 was employed to stabilize the SCC mixes.

2.2. Mixture proportions

A total of 12 SCC mixtures were designed using the absolute volume method. In all the SCC mixtures, the total paste content was kept nominally fixed at 40% with the remaining volume being made up of aggregates. Within the aggregate volume, the ratio of fine-to-total aggregates was also kept nominally constant at 0.62. The aforesaid limits were adopted so that differences in flow behaviour within a given grade of SCC could be attributed to the RCA replacement level and across different grades, for a given RCA replacement level, rheological differences could be attributed to dosage of the supplementary cementitious materials. The RCA replacement levels investigated in the experiments were 50% and 100% and are defined as the volumetric ratio of RCA to the total volume of coarse aggregates in the concrete mix. Depending upon the desired replacement level, direct substitution of NCA with an equal volume of RCA was carried out. Nominal air entrainment at 1.5% was assumed in the mix design. The control SCC mix, SRC0, Table 3, was designed with Portland cement as the binder, a w/c of 0.32, crushed stone as the natural coarse aggregates (NCAs) and river sand as the fine aggregate. In the mix design of SRC0, no target compressive strength was set with the objective being to satisfy all flowability criteria typically associated with SCC. Once SRC0 had been designed, the control mixes containing RCA (SRC50 and SRC100, Table 3) were obtained by volumetric substitution of 50% and 100% respectively of the NCAs in SRC0 with the RCA keeping the other constituents of SRC0 unchanged.

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