Journal of Advanced Concrete Technology
Materials, Structures and Environment

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Journal of Advanced Concrete Technology, volume 15 (2017), pp. 524-535

Scientific paper

Effect of Supplementary Cementitious Materials on Rheology of Different Grades of Self-Compacting Concrete Made with Recycled Aggregates

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Received 13 May 2017, accepted 27 August 2017 doi:10.3151/jact.15.524

Abstract

Rheology of two grades of Self-Compacting concrete containing selected volumetric replacement levels of coarse Recycled Concrete Aggregates (SCRCA) is investigated. Fly ash, metakaolin and silica fume were used in different combinations of cementitious materials to achieve the normal- and the medium-strength SCRCAs. Irrespective of the RCA replacement level, a shear thickening response was noted in both the normal- and the medium-strength SCRCAs and their flow behaviour could be described using the Modified Bingham (MB) as well as the Herschel-Bulkley (HB) model. The decrease in the degree of shear thickening with an increase in concrete grade is attributed to the use of either silica fume or metakaolin as part of the ternary cement in the higher strength concretes with silica fume being relatively more effective. Within a given grade, shear thickening increased with increase in the recycled aggregate replacement level. The MB as well as the HB model were equally effective in representing observed flow behaviour.

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 (Feys *et al.* 2008). 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 traditional Bingham model for describing the flow behaviour of SCC 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 (Feys *et al.* 2009). The Herschel-Bulkley (HB) and the Modified Bingham (MB) model (Feys *et al.* 2007; Yahia and Khayat 2001) 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.* (2014), 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.

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.

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 (Shejwadkar *et al.* 2016). 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 (Ravindrarajah *et al.* 1987; Padmini *et al.* 2002; Safiuddin *et al.* 2011; Poon *et al.* 2004; Xiao *et al.* 2005; Xiao *et al.* 2006; Khatib 2005; Choi and Yun 2013; Etxeberria *et al.* 2007a; Etxeberria *et al.* 2007b; Yang *et al.* 2008; Oikonomou

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Table 1 Chemical and physical properties of the cement, the fly ash, the metakaolin and the silica fume.

Parameter	Cement	Fly ash	Metakaolin	Silica fume
CaO (%)	63.64	1.56	0.92	2.32
SiO_2 (%)	18.01	57.62	55.83	90.06
Al_2O_3 (%)	4.27	30.14	35.49	0.71
Fe_2O_3 (%)	4.86	4.60	3.57	1.12
MgO (%)	3.27	0.64	0.12	0.25
SO_3 (%)	2.99	0.14	0.27	0.63
K_2O (%)	0.53	2.13	0.55	0.95
Na_2O (%)	0.52	0.08	0.28	0.32
Loss on ignition (%)	0.62	1.46	0.87	3.01
Specific gravity	3.15	2.34	2.62	2.10
Specific surface (m^2/kg)	306	329	13500	19585

2005; Kapoor *et al.* 2017). However, relatively little attention has been paid to rheology of SCC made with recycled concrete aggregates. According to Guneyisi *et al.* (2016a), 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.* (2015) 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). This investigation has been undertaken in response to this gap and the rheology of two grades of SCRCAs each containing selected replacement levels of coarse recycled concrete aggregates has been investigated with a concrete rheometer. The two grades of SCRCAs were designed by suitable addition of fly ash, metakaolin and silica fume as supplementary cementitious materials (SCMs) in the mixes. Appropriate models have been recommended for describing the flow behaviour of the two SCRCA grades recorded with the help of a concrete rheometer and effect of the addition of supplementary cementitious materials and RCA replacement levels on the rheological response is reported.

2. Research significance

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. In this investigation, rheology of two grades of SCC with different combinations of cementitious materials and each containing selected amounts of coarse recycled concrete aggregates has been investigated with a concrete rheometer. Relevant flow models have been proposed to describe observed behaviour and it is shown that both the parameters under investigation impacted rheology.

3. Experimental program

3.1 Materials

The SCCs were designed using Portland cement conforming to IS 8112-2013 (BIS 2013) and where ever required metakaolin, silica fume and ASTM Class-F fly ash were used in binary and ternary cementitious blends. Properties of the cement, the metakaolin, the fly ash and the silica fume are summarized in **Table 1**. Natural river sand having a specific gravity of 2.64 was used as Fine Aggregate (FA) and crushed stone aggregates of 12.5 mm maximum size and having a specific gravity of 2.70 were used as the Natural Coarse Aggregates (NCA). Coarse Recycled Concrete Aggregates (RCA) used in this study were obtained by crushing with the help of a jaw crusher waste concrete specimens obtained from the Concrete Laboratory of the authors' host institute. Although the laboratory produced recycled aggregates may not be representative of field produced recycled aggregates, the author's reckon that the use of the former will be associated with a 'worst-case' scenario. This is because the amount of residual mortar is expected to be the maximum in laboratory produced RCA particles as compared to those obtained from commercial concrete recycling plants. Therefore, the results of this investigation remain valid for the laboratory produced recycled aggregates only. 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

Table 2 Physical and mechanical properties of the aggregates.

Aggregate	Bulk density (kg/m^3)	Water absorption (%)	Specific gravity	Fineness modulus	ACV* (%)	AIV** (%)	Residual mortar content (%)
NCA	1710	0.70	2.70	6.29	17.82	16.23	-
RCA	1615	3.92	2.48	-	23.87	22.14	40.08
FA	1645	1.02	2.64	2.60	-	-	-

* Aggregate Crushing Value
** Aggregate Impact Value

Table 3 Mixture constituents of the SCRCAs.

Group	Mix ID	Constituents									
		Cement (Kg/m^3)	Fly ash (Kg/m^3)	Metakaolin (Kg/m^3)	Silica fume (Kg/m^3)	Water (Kg/m^3)	NCA (Kg/m^3)	RCA (Kg/m^3)	FA (Kg/m^3)	HRWRA (%)	VMA (%)
Normal-strength	NFR0	305	305	-	-	207.4	668.25	-	798.60	0.26	0.30
	NFR50	305	305	-	-	207.4	334.13	306.60	798.60	0.29	0.30
	NFR100	305	305	-	-	207.4	-	613.8	798.60	0.28	0.30
Medium-strength	MFKR0	437	156	32	-	212.5	668.25	-	798.60	0.44	0.30
	MFKR50	437	156	32	-	212.5	334.13	306.60	798.60	0.44	0.30
	MFKR100	437	156	32	-	212.5	-	613.8	798.60	0.44	0.30
	MFSR0	434	155	-	31	210.8	668.25	-	798.60	0.44	0.30
	MFSR50	434	155	-	31	210.8	334.13	306.60	798.60	0.44	0.30
	MFSR100	434	155	-	31	210.8	-	613.8	798.60	0.44	0.30

specified coarse aggregate grading limits of IS: 383-2002 (BIS 2002), **Fig. 1**. The physical and mechanical properties of the aggregates are presented 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.

3.2 Mix proportions

A total of 9 SCC mixes were designed using the absolute volume method. In each mix, the total paste content was kept nominally fixed at 43% 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 0.55. 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 relative proportions of the 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 2% was assumed in the mix design. The normal-strength control SCC mix, NFR0, **Table 3**, (with a target 28-day cube compressive

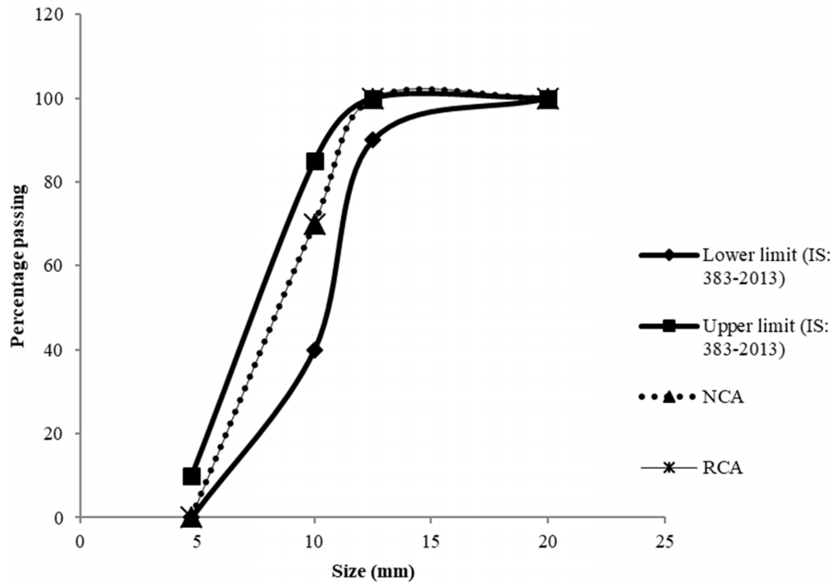

Fig. 1 Grading curve of the coarse aggregates.

strength of 32 *MPa*) was designed with a binary blend of cement and fly ash (F), a *w/c* of 0.34, crushed stone as the natural coarse aggregates (NCAs) and river sand as the fine aggregate. The target strength was achieved by adjusting the powder composition in this mix through a process of trial and error to a combination (by weight) of 50% fly ash + 50% of cement with the paste volume being kept at 43%. Once NFR0 had been designed, the normal-strength mixes containing RCA (NFR50 and NFR100, **Table 3**) were obtained by volumetric substitution of 50% and 100% respectively of the NCAs in NFR0 with the RCA keeping the total paste volume of NFR0 unchanged.

In order to achieve the strength targeted for the medium strength SCC, either silica fume or metakaolin were used in a ternary blend with cement and fly ash. Keeping the paste volume the same as in NFR0, the medium-strength control SCC mix, MFKR0, was designed by adjusting the relative proportions by weight of the ternary blend of cement, fly ash (F) and metakaolin (K) to 70%, 25% and 5% respectively of the total powder content. These proportions were obtained through a process of trial and error such that a 28-day target cube compressive strength of 50 *MPa* could be achieved. Volumetric replacement of 50% and 100% of the NCAs in MFKR0 with the RCAs gave the mixes MFKR50 and MFKR100, respectively. In the medium-strength SCC mix, MFSR0, keeping the paste volume unchanged from the previous mixes, the relative proportions by weight of the ternary blend of cement, fly ash (F) and silica fume (S) in the total powder content were 70%, 25% and 5% respectively. Again, these proportions being determined through a process of trial and error such that the 28-day target compressive strength of 50 *MPa* could be achieved. Volumetric replacement of 50% and 100% of the NCAs with the RCAs in MFSR0 gave the mixes MFSR50 and MFSR100, respectively.

It may be noted that both the NCAs and the RCAs were used in the saturated surface-dry (SSD) moisture condition which was sought to be achieved by presoaking them for a period of 24 *h* prior to casting. After completion of the soaking period, the aggregates were spread on a clean laboratory floor and any water attached to the surface of the aggregate particles was removed with a soft cloth following which the aggregates were batched in the concrete mixer. HRWRA and VMA dosages in the SCCs were suitably adjusted in order to obtain the required fresh properties and these dosages are reported in **Table 3**. This table shows that the HRWRA demand (by weight of powder) of 0.26% - 0.29% in the NFR series containing fly ash as the only SCM was lower when compared to the demand (0.44%) in the medium-strength concretes (MFKR series and MFSR series) which contain a relatively lesser amount of fly ash. This observation is consistent with the workability enhancing role of fly ash reported in the literature (Puthipad *et al.* 2016).

3.3 Casting

Among other parameters, the rheology of SCC depends on ambient temperature, mixer type, mixing efficiency and mixing sequence (Khayat *et al.* 2006; Skarendahl *et al.* 2000) and care was taken to ensure that the aforesaid conditions remained nominally unchanged during production of the different SCCs. The SCCs were produced in the laboratory in a tilting-drum mixer with the fine and the coarse aggregates being first dry-mixed for 30 *s* followed by addition of one-third of the total water after which all the ingredients were allowed to mix for one more minute. Subsequently, all of the cement and the SCM(s) were added and mixing was continued for another minute after which the next one-third of water was introduced in the mixer followed by another 2 minutes of mixing. Afterwards, the remaining one-third of the total water mixed with the HRWRA and the VMA was poured into the mixer and the constituents were allowed to mix for 2 minutes. After completion of this round of mixing, the ingredients in the mixer were left to rest for 2 minutes and at the end, after another 2 minutes of mixing, the production of SCC stood completed. During casting and testing of the SCCs, ambient temperature in the laboratory varied in the range 20^0 C-30^0 C and although this range of temperature can have a significant effect on rheology, the following mitigating factors would have helped in this regard. First, the 30^0 C upper bound of the laboratory temperature was less than the 32^0 C upper limit of ambient temperature to produce good quality concrete specified by the ACI (ACI 305R-77). Further, it has been reported in the literature that the effect of temperature on plastic viscosity is insignificant as long as the ambient temperature is below 35^o C (Martini and Nehdi 2007; Nehdi and Martini 2009). The other rheological parameter of interest, yield stress, is related to slump of concrete (Mori and Tanigawa 1990; Ferraris and Larrarad 1998; Struble and Chen 2005). Since in the reported investigation slump flow across all the SCCs was maintained to the range of 735±20 *mm* by adjusting the HRWRA dosages, the effect of temperature on yield stress was therefore indirectly accounted for in the experiments. Therefore, the above range of laboratory temperatures is not likely to have any significant effect on the reported results.

3.4 Rheological measurements

Attributes of self-compactability such as filling ability, passing ability and stability were measured in terms of slump flow diameter, T_{50cm} time, V-funnel time, V-funnel time after 5 min., L-box blocking ratio and U-box filling height. For verifying compliance, results of the aforesaid tests have been compared with the requirements of EFNARC (EFNARC 2005; EFNARC 2002) and are reported in a subsequent section. Rheology of the SCCs was measured using an ICAR concrete rheometer and the typical test configuration and setup is presented in **Fig. 2**. Rheological measurements were carried out after a nominal interval of 15 minutes following first contact of water with the cement in the SCCs. The fresh concrete to be tested was poured into the rheometer container (having a diameter of 405 *mm*) up to a height of 395 *mm* and a four-bladed vane having a diameter of 127 *mm* and a height of 127 *mm* was concentrically placed in the concrete inside the container. The motor of the vane was connected to a computer for receiving signals related to the test. The following two types of tests can be performed with a rheometer: stress growth test and the flow curve test. The stress growth test involves rotating the vane of the rheometer at a low constant speed with the build-up of torque being monitored and the maximum torque corresponds to the static yield stress. Besides static yield stress, the stress growth test is also used to investigate thixotropy in flowing concrete. On the other hand, flow behaviour is conveniently studied using a flow curve test in which the relationship between torque and rotational speed of the vane is measured. A typical test starts with a break-down or a pre-shearing period followed by a generation of a series of flow curve points (ICAR 2014). The objective of the break-down period, which consists of vane rotation at the maximum test speed (0.5 *rps*), is to minimise the effects of thixotropy and provide a consistent shear history for the test. No measurements are made during the break-down period which lasts for 20 *s* at the end of which the generation of flow curve (relationship between torque and rotational speed) is started. The flow curve was obtained by varying the vane speed from the peak value of 0.5 *rps* in seven equal steps to 0.05 *rps* with the vane speed being held constant at each step for a period of 5 s. This variation of vane speed with time, which served as the input in the flow curve test, is illustrated in **Fig. 3**. Flow curves of the SCCs were obtained by entering breakdown period, breakdown speed, number of steps, time interval for each step, the initial speed and the final speed as inputs in the software controlling the rheometer. The rheometer output was obtained in

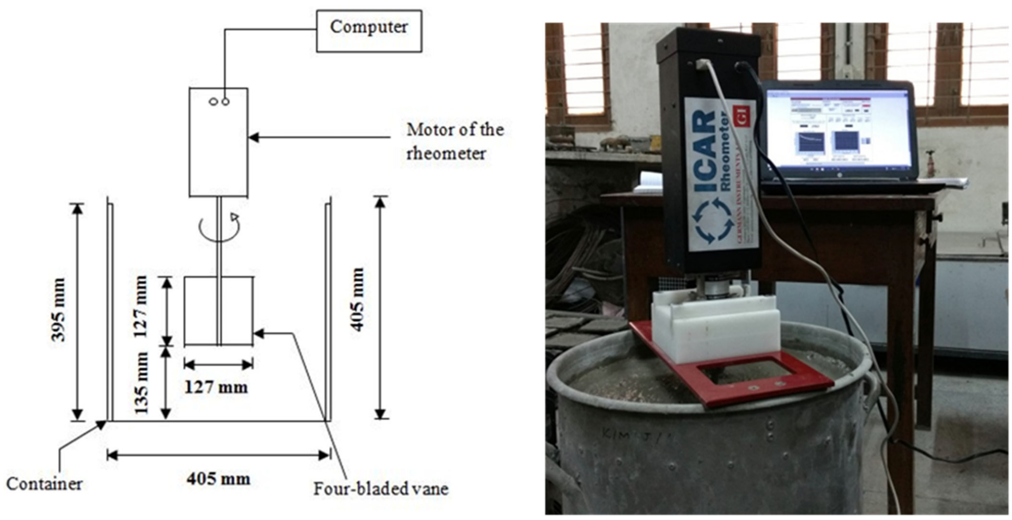

Fig. 2 (a) Test-setup configuration and (b) Test-setup for the rheological measurements.

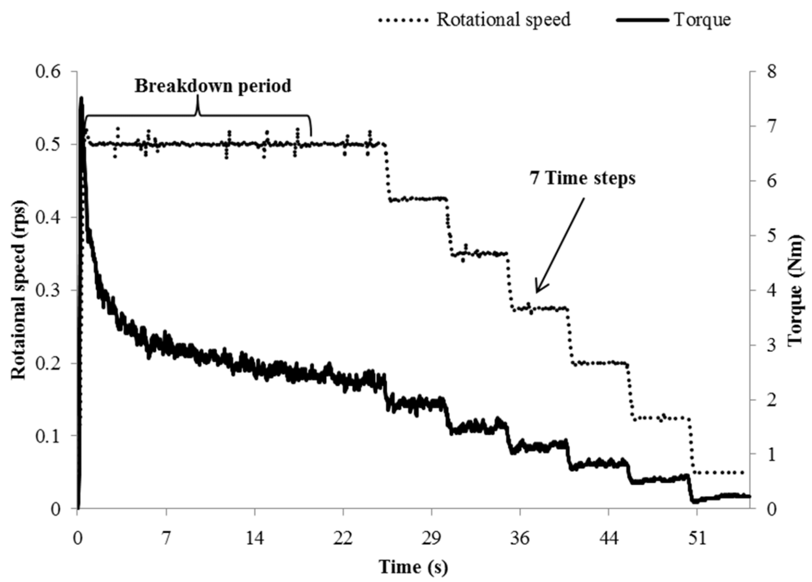

Fig. 3 Measured torque versus time values for the mix MFKR50.

Table 4 Measured fresh properties of the SCRCAs.

Group	Mix ID	Slump-flow(mm)	T_{50cm} (s)	V_f (s)	V_{f5min} (s)	L-Box ratio	U-Box (mm)	Environmental temperature (°C)	Concrete temperature (°C)	Relative humidity (%)
		Acceptable range as per EFNARC (EFNARC 2002; EFNARC 2005)								
		(650-800 mm)	(2-5 s)	(6-12 s)	(6-15 s)	(0.8-1)	(0-30 mm)			
Normal-strength	NFR0	740	2.2	7.2	9.3	0.95	10	20.8	21.5	45
	NFR50	750	2.5	8.2	11.0	0.84	10	21.1	21.7	35
	NFR100	755	2.6	8.8	11.1	0.86	18	21.7	22.6	34
Medium-strength	MFKR0	715	2.2	7.3	9.2	0.88	20	29.6	27.1	34
	MFKR50	730	2.2	7.5	9.8	0.93	8	28.3	27.3	40
	MFKR100	750	2.0	7.0	9.1	0.91	2	29.3	27.0	35
	MFSR0	720	3.1	6.1	7.9	0.86	21	30.3	29.0	36
	MFSR50	730	3.3	6.2	8.1	0.84	25	30.5	28.7	32
	MFSR100	745	3.0	6.0	8.8	0.88	23	30.5	29.6	30

terms of torque and rotational speed which was processed using the relevant transformation equations to obtain the dynamic yield stress and plastic viscosity. The relevant details are discussed in the next section.

4. Results and discussions

Fresh densities of the SCCs measured using the procedure recommended in ASTM (ASTM C138/C138M-16a) are presented in **Fig. 4** which shows that the decrease in fresh density in each grade upon replacement of the NCAs with the RCAs was marginal and not more than 5% in any case. For example, the fresh density of MFKR0 was 2332 kg/m^3 which decreased to 2280 kg/m^3 when all the natural coarse aggregates were replaced with the RCA. This trend of decrease in the fresh density with increasing RCA replacement level is in agreement with results reported in the literature (Kou and Poon 2009). Measured fresh properties of the SCCs are compiled in **Table 4** and they were noted to be in compliance with the requirements of EFNARC (EFNARC 2002). The 28-day compressive strengths of the two grades of SCRCAs are summarized in **Fig. 5** which shows that both the normal and the medium-strength SCRCA were not significantly sensitive to RCA replacement level. In both these concrete grades, compressive strength decreased by not more than 5% for complete replacement of the NCAs with the RCAs.

Various authors (Senas *et al.* 2016; Guneyisi *et al.* 2016b; Revathi *et al.* 2013; Kou and Poon 2009) have stated that behaviour of fresh self-compacting concrete is significantly affected by the use of recycled aggregates. According to Guneyisi *et al.* (2016b), "the self-compactability characteristics of the concrete are remarkably improved by the replacement levels of CRCA and FRCA used in the SCC mixtures". This conclusion of Guneyisi is attributed to the rough surface texture and the high porosity of such aggregates which in turn leads to high water absorption (McNeil and Kang 2013). In the present investigation, the Recycled Concrete Aggregates (RCA) were used in the Saturated Surface-Dry (SSD) moisture state. Internal curing due to the SSD moisture state is speculated to improve both the fresh as well as the hardened properties of concrete. In internal curing, the saturated pores in the RCA particles (in the SSD moisture state) act as 'water reservoirs'. When the internal humidity of the system drops, water is released from the 'reservoirs' and self-desiccation of the hydrating cement paste is prevented while concurrently promoting continuing hydration of the cement particles. Further, since internal curing reduces self-desiccation, tensile stresses inside pores within the hydrating cement

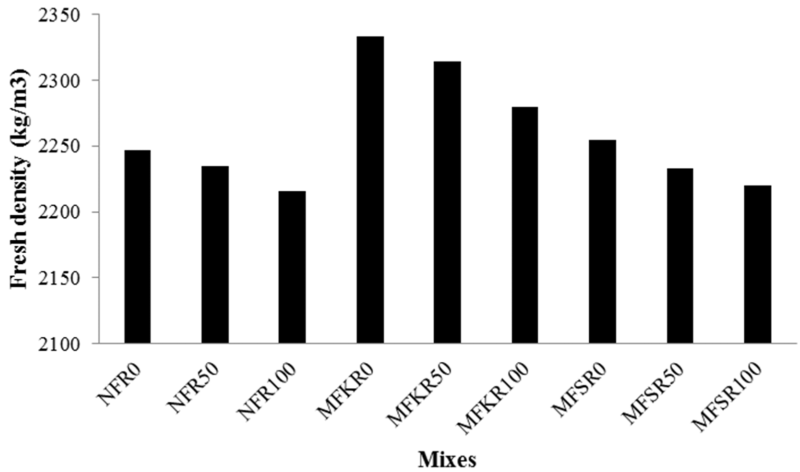

Fig. 4 Fresh density of the SCRCAs.

Table 5 Measured torques at different rotational speeds.

		Rotational speed (rps)						
		0.5	0.425	0.350	0.275	0.200	0.125	0.050
Group	Mix ID	Torque (Nm)						
Normal-strength	NFR0	1.53	1.19	0.91	0.69	0.48	0.29	0.12
	NFR50	3.53	2.70	2.02	1.43	0.94	0.53	0.21
	NFR100	3.85	3.00	2.24	1.63	1.12	0.65	0.21
Medium- strength	MFKR0	1.77	1.49	1.22	0.99	0.76	0.53	0.29
	MFKR50	2.33	1.92	1.50	1.14	0.83	0.53	0.22
	MFKR100	1.15	0.91	0.73	0.56	0.40	0.25	0.10
	MFSR0	1.51	1.33	1.12	0.93	0.75	0.57	0.37
	MFSR50	0.97	0.79	0.65	0.51	0.38	0.24	0.11
	MFSR100	1.46	1.19	0.97	0.78	0.60	0.41	0.23

paste are relieved thus mitigating cracking. Thus, both the fresh as well as the hardened properties of SCC can be affected by the use of recycled aggregates in the SSD moisture state.

In addition to the torque versus rotational speed, another output of the flow curve test is the torque versus time profile and for the purpose of illustration, this profile for MFKR50 is illustrated in **Fig. 3**. **Table 5** contains a summary of the measured torque versus rotational speed data for the two SCRCA grades. In the first instance, an attempt will be made to describe the flow behaviour of the SCRCAs with the help of the traditional Bingham model presented in column 2 of **Table 6**. Towards development of the Bingham model from the measured torque, T, and the rotational speed, N, the parameters G and H of Eq. (1) in column 2 of **Table 6** need to be obtained. These parameters were found as the intercept and the slope respectively of the linear best fit between T and N with an example being shown in **Fig. 6** for the NFR, the MFKR and the MFSR series of SCCs. Knowing G and H, the dynamic yield stress, τ_0, and the plastic viscosity, μ, which define the Bingham model can be calculated using Eqs. (3) and (4) of **Table 6.** Results of the application of this model to the two SCRCA

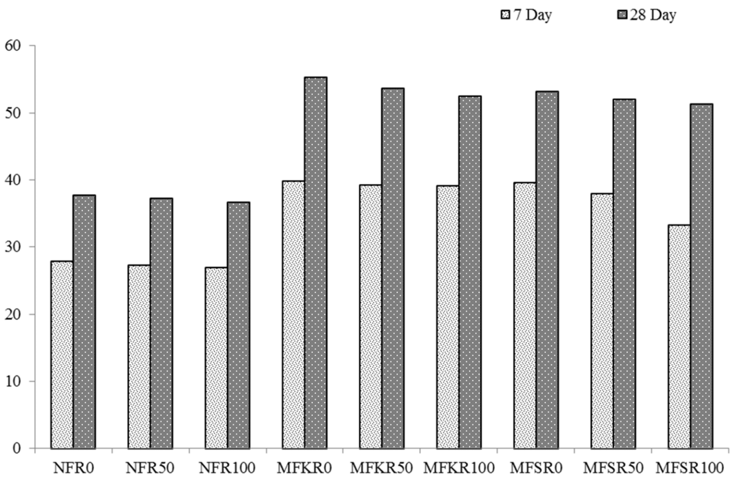

Fig. 5 Compressive strengths of the SCRCAs.

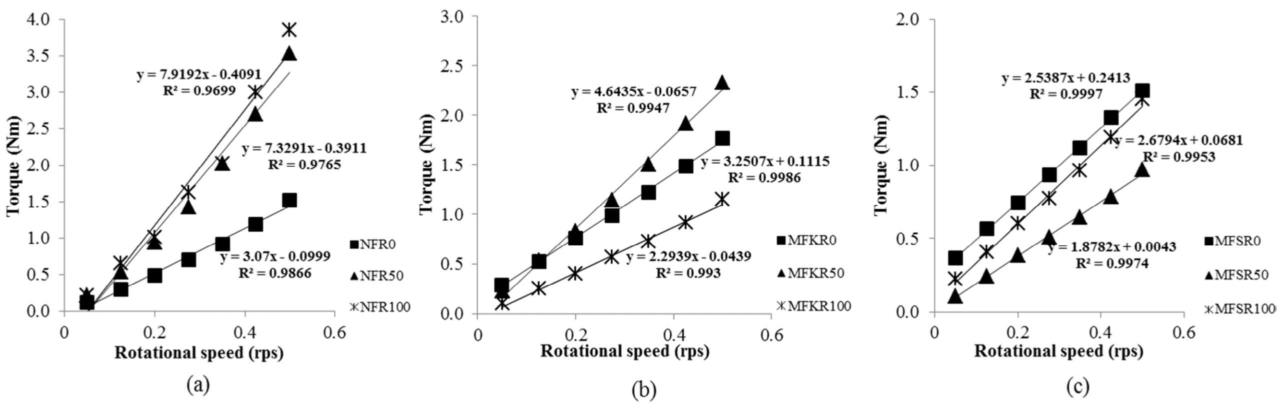

Fig. 6 Calculation of G and H values from the measured torque and rotational speed data: (a) NFR Series (b) MFKR Series (c) MFSR Series.

Table 6 Transformation formulae for the Bingham, the Herschel-Bulkley and the Modified Bingham model.

	Bingham model	Herschel-Bulkley model	Modified Bingham model
Equations	$T = G+HN$ (1) $\tau = \tau_0 + \mu\gamma$ (2) where, T = Torque (Nm). N = Rotation velocity (rps). τ = Shear stress (Pa). τ_0 = Yield stress (Pa). μ = Plastic viscosity (Pa s).	$T = G_{HB}+H_{HB}N^n$ (5) $\tau = \tau_0 + \mu\gamma^n$ (6) where, T = Torque (Nm). N = Rotation velocity (rps). τ = Shear stress (Pa). τ_0 = Yield stress (Pa). μ = Plastic viscosity (Pa s). n = Flow index.	$T = G+HN+CN^2$ (9) $\tau = \tau_0 + \mu\gamma + c\gamma^2$ (10) where, T = Torque (Nm). N = Rotation velocity (rps). C = Second order parameter. τ = Shear stress (Pa). τ_0 = Yield stress (Pa). μ = Plastic viscosity (Pa s). c = Second order parameter (Pa s^2).
Transformation formulae	$\tau_0 = \frac{G}{4\pi h}\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)\frac{1}{In\frac{R_2}{R_1}}$ (3) $\mu = \frac{H}{8\pi^2 h}\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)$ (4) where, G = Intercept obtained by linear law between torque and rotational velocity (Nm). H = Inclination of linear law between torque and rotational velocity (Nm s) R_1 = Inner radius (m) R_2 = Outer radius (m) h = Height of vane (m)	$\tau_0 = \frac{G_{HB}}{4\pi h}\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)\frac{1}{In\frac{R_2}{R_1}}$ (7) $\mu = \frac{H_{HB}}{2^{2n+1}\pi^{n+1}h}n^n\left(\frac{1}{R_1^{2/n}}-\frac{1}{R_2^{2/n}}\right)^n$ (8) where, G_{HB}, H_{HB} = Parameters predicted by Herschel-Bulkley for a T-N relationship. R_1 = Inner radius (m) R_2 = Outer radius (m) h = Height of vane (m)	$\tau_0 = \frac{G}{4\pi h}\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)\frac{1}{In\frac{R_2}{R_1}}$ (11) $\mu = \frac{H}{8\pi^2 h}\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)$ (12) $c = \frac{C}{8\pi^3 h}\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)\left(\frac{R_2-R_1}{R_2+R_1}\right)$ (13) where, G, H, C = Parameters obtained from polynomial fit of second order for a T-N relationship. R_1 = Inner radius (m) R_2 = Outer radius (m) h = Height of vane (m)

grades are presented in **Fig. 7** which shows that for the NFR series, the τ_0 values are -12.08 *Pa*, - 47.24 *Pa* and - 49.42 *Pa* for 0%, 50% and 100% RCA replacement levels respectively. Since a negative yield stress is physically inadmissible it follows that the Bingham model is not valid for the NFR series of the SCCs. Also, the τ_0 values for the MFKR series (13.46 *Pa*, -7.93 *Pa* and - 5.30 *Pa* for 0%, 50% and 100% RCA replacement level respectively) and for the MFSR series (29.15 *Pa*, 0.52 *Pa* and 8.22 *Pa* for 0%, 50% and 100% RCA replacement level respectively) are either negative or are generally less than 10 *Pa* except for the mix MFKR0 and MFSR0. As has been stated earlier, the 10 *Pa* value is considered here to be the lower bound for the yield stress up to which the Bingham model remains valid (Gesoglu *et al.* 2015; Guneyisi *et al.* 2016b). Based on this criteria, the SCRCAs MFKR0 and MFSR0 can be classified as Bingham fluids though it will be shown later on that their flow behaviour is more accurately represented by both the HB and the MB models. This observation indicates that the 10 *Pa* lower bound to the yield stress recommended in the literature needs to be revisited.

The invalidity of the Bingham or a linear flow model for the SCRCAs of this investigation is indicative of the development of either shear thickening or shear thinning behaviour in these concretes. Such a response can be described using non-linear flow models. In the first instance, application of the Herschel-Bulkley (HB) model to these concretes is investigated since this is the most common non-linear rheological model for SCC (Larrard *et al.* 1998). The flow index, *n*, a non-dimensional parameter in the HB model (Eq. (6) of **Table 6**), is less than 1 for a shear thinning fluid, is equal to 1 for a Bingham fluid and is greater than 1 for a shear thickening fluid. Towards calibration of the HB model from the measured torque, T, and the rotational speed, N, the parameters G, H and *n* of Eq. (5) in column 3 of **Table 6** need to be found. These parameters are readily obtained by plotting a non-linear best fit curve between the measured T and N values. The transformation formulae given by Eqs. (7) and (8) in **Table 6** can then be used to convert G and H into the fundamental rheological units of the HB model (Guneyisi *et al.* 2016a). Occasionally, due to its mathematical simplicity, the modified Bingham model (Eq. (10), **Table 6**) is also used for modeling nonlinear flow behaviour when flow index values, *n*, are less than 2 (Feys *et al.* 2008).

It may be noted that the Modified Bingham (MB) model, Eq. (10), **Table 6**, is in essence a second order extension of the Bingham model as well as a second order Taylor development of the HB model (Larrard *et al.* 1998). The transformation formulae applicable for the MB model are given by the Eqs. (11), (12) & (13) of **Table 6**. In this model, the parameter c/μ defines SCC rheology as follows: if $c/\mu < 0$, SCC is shear thinning; if $c/\mu = 0$, SCC is a Bingham fluid and if $c/\mu > 0$, SCC is shear thickening.

Results of calibration of the HB model with the help of flow data of the three series of the SCRCAs are presented in **Fig. 8**. This figure shows that for all the mixes, the n (flow index) values in the HB model are greater than 1 (and less than 2), which is indicative of shear thickening behaviour. Also, since the n values were less than 2, the MB model can also be applied to these mixes. The results of calibration of the MB model with the help of flow data of the three series of the SCRCAs are shown in **Fig. 9**. This figure shows that in all cases, c/μ values were greater than 0 which reiterates shear thickening behaviour. Results of a similar nature, attributing shear thickening behaviour to SCCs made with natural aggregates, have been reported in other investigations (Feys *et al.* 2008; Yahia and Khayat 2001; Larrard *et al.* 1998).

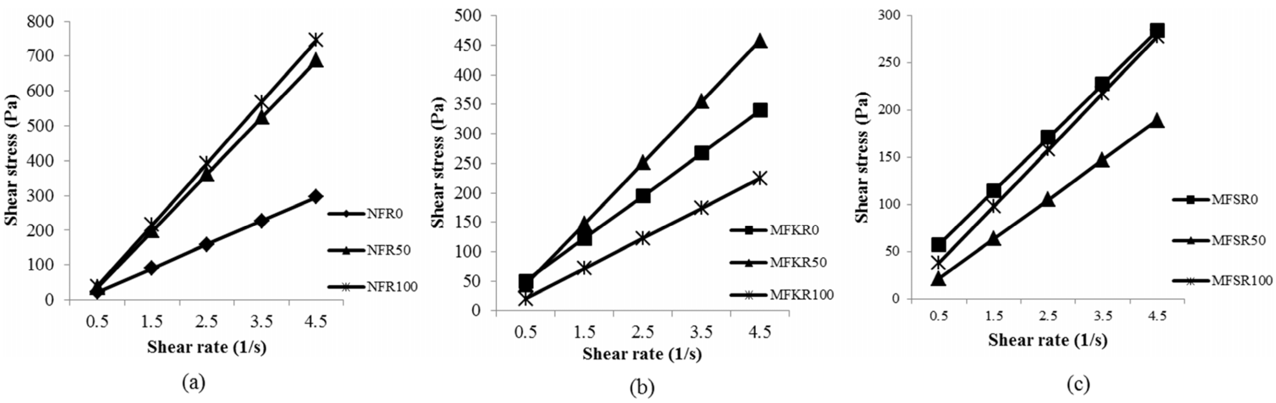

Fig. 7 Application of the Bingham model to: (a) NFR Series (b) MFKR Series (c) MFSR Series.

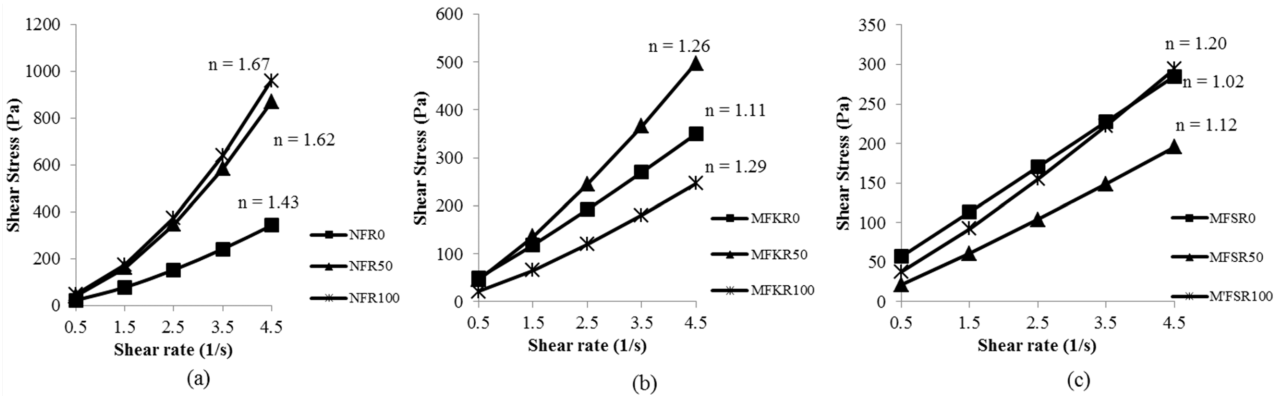

Fig. 8 Calibration of the Herschel-Bulkley model with the results of the: (a) NFR Series (b) MFKR Series (c) MFSR Series.

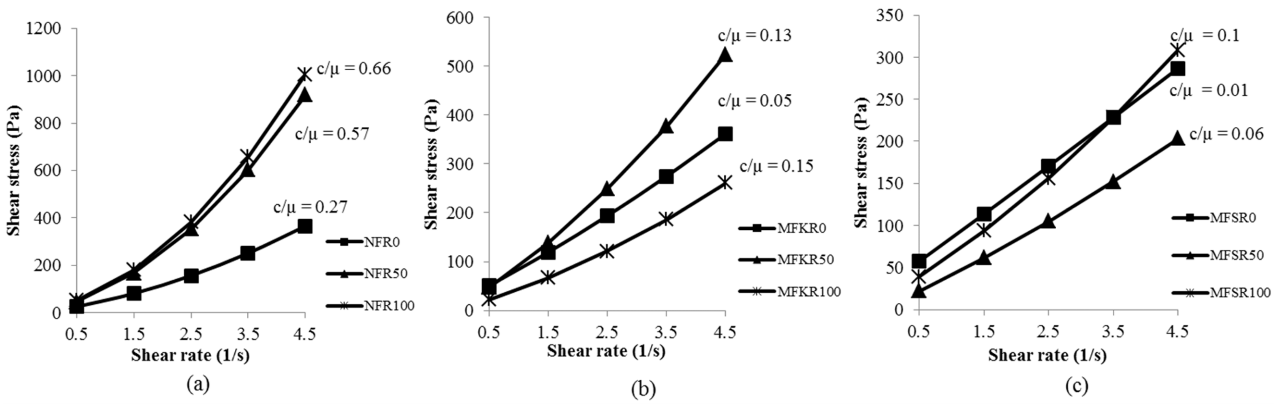

Fig. 9 Calibration of the Modified Bingham model with the results of: (a) NFR Series (b) MFKR Series (c) MFSR Series.

Review of the results shows that although shear thickening behaviour was noted in all the three series of the SCRCAs, the degree of shear thickening, when defined in terms of the flow index (*n*) values, was lower in the case of the medium-strength SCRCAs relative to the normal-strength mixes. As illustrated in **Fig. 8**, the *n* values were in the range of 1.43 to 1.67 for the normal-strength SCRCAs and in the range of 1.02 to 1.29 for the medium-strength SCRCAs. An approximately 25% decrease in the average flow index values (and an 82% decrease in the average c/μ values) is noted in the medium-strength SCRCAs relative to the normal-strength SCRCAs. This is indicative of a decrease in the degree of shear thickening with increase in the concrete grade and is attributed to the use of silica fume or metakaolin as supplementary cementitious materials in the medium-strength SCRCAs. Further, within the medium-strength SCRCAs, the degree of shear thickening in the mixes with silica fume (MFSR series) was relatively lower than that in the mixes with the metakaolin (MFKR series), **Fig. 8.** Further**,** the *n* values of 1.02, 1.11 for 0 % RCA replacement levels in the MFSR and the MFKR concretes practically correspond to a Bingham fluid. In the medium-strength SRCAs, the average flow index and the c/μ value in the mixes with silica fume were respectively about 8% and 45% lower when compared to the concretes with metakaolin. It is also noted that for a given RCA replacement level, the c/μ values of the MB model decreased with an increase in the concrete grade which is attributed to the ternary blend of cementitious materials in the medium-strength mixes. Like the *n* values, the c/μ values were noted to be the lowest for the MFSR series which contained silica fume as a constituent of the ternary cement.

Plots of the three series of SCRCAs in **Fig. 10** show that for a given grade, the c/μ values increased with an increase in RCA replacement level. Such a trend will also be visible in the *n* values. In the normal-strength SCRCAs, increase in the flow index value upon complete replacement of the natural coarse aggregates with the recycled aggregates was about 17% and a similar increase was noted in the medium-strength SCRCAs containing silica fume and containing metakaolin. This increase in the degree of shear thickening with increasing RCA replacement levels is attributed to higher degrees of inter-particulate friction associated with the larger volumes of the recycled aggregate particles.

Data related to the three series of SCRCAs were used to develop a correlation between the flow index, *n*, of the HB model and the parameter c/μ of the MB model and the results are presented in **Fig. 11**. This figure shows a strong correlation between these parameters for the two SCRCA grades and a similar observation with respect to SCC made with natural aggregates has been reported in the literature (Feys *et al.* 2008; Guneyisi *et al.* 2016a).

5. Conclusions

1) For each of the two grades, fresh density of the SCRCAs did not decrease by more than 5% upon complete replacement of the natural coarse aggregates with the recycled concrete aggregates.
2) For each of the two grades, 28-day compressive strength of the SCRCAs did not decrease by more than 5% upon complete replacement of the natural coarse aggregates with the recycled concrete aggregates.
3) Irrespective of grade, composition and recycled aggregate replacement level, shear thickening behaviour is indicated by both the Herschel-Bulkley as well as the modified Bingham model by all the SCRCAs of this investigation. The flow indices of the Herschel-Bulkley model which were calculated to be lying within the range of 1 and 2 support the use of the modified Bingham model for representing the rheology of the considered SCRCAs.
4) An approximately 25% decrease in the average flow index values and 82% decrease in the average c/μ

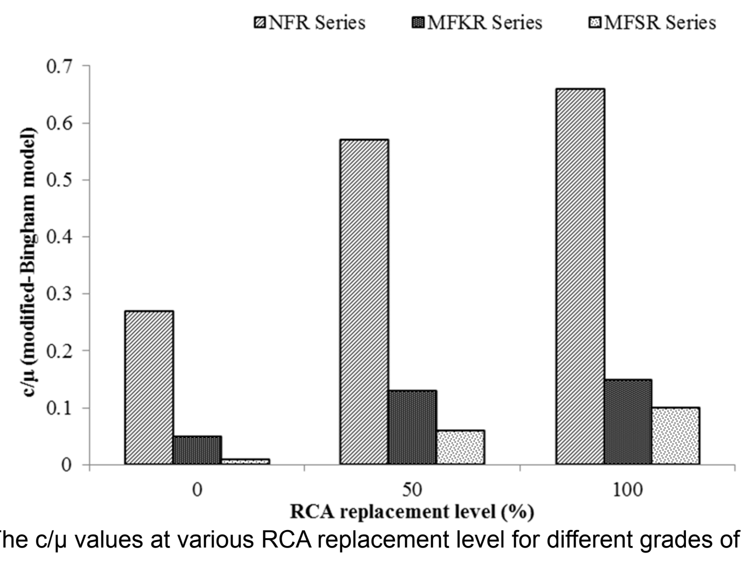

Fig. 10 The c/μ values at various RCA replacement level for different grades of SCRCAs.

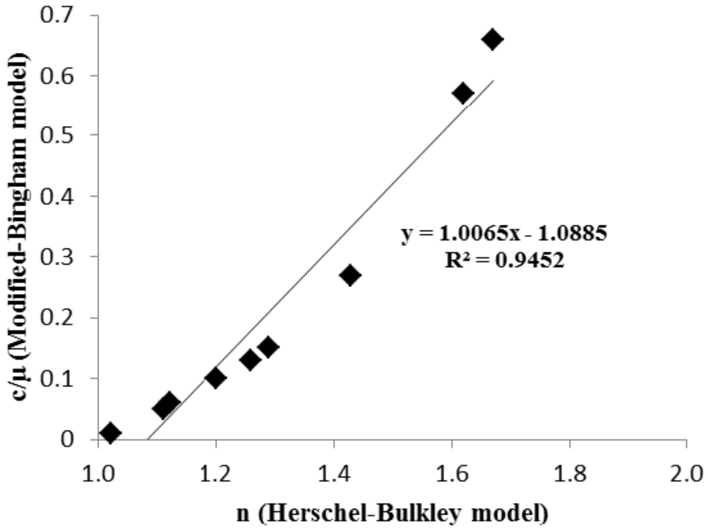

Fig. 11 Relationship between *c/μ* and *n* for the normal and the medium-strength SCRCAs.

values (of the modified Bingham model) was noted in the medium-strength SCRCAs relative to the normal-strength SCRCAs. This is indicative of a decrease in the degree of shear thickening and is attributed to the use of silica fume or metakaolin at a dosage of 5% by weight of the cementitious materials in the medium-strength concretes.

5) In the normal-strength SCRCAs, increase in the flow index value upon complete replacement of the natural coarse aggregates with the recycled aggregates was about 17% and a similar increase was noted in the medium-strength SCRCAs containing silica fume and containing metakaolin. This increase in the degree of shear thickening with increase in RCA replacement level is attributed to higher levels of interparticulate friction associated with larger dosages of the recycled aggregates.

6) A strong correlation between the flow index, *n*, of the Herschel-Bulkley model and the parameter, *c/μ,* of the Modified Bingham model is noted in this investigation. This indicates that either of these models is valid for representing non-linear flow behaviour of the SCRCAs.

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