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Original Research Article

Evaluation of the rheological behavior of fresh self-compacting rubberized concrete by using the Herschel–Bulkley and modified Bingham models

E. Güneyisi[a], M. Gesoglu[a], N. Naji[b], S. İpek[a,*]

[a] Department of Civil Engineering, Gaziantep University, 27310 Gaziantep, Turkey
[b] Department of Civil Engineering, Anbar University, Anbar, Iraq

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ABSTRACT

The study herein presents the use of the Herschel–Bulkley and modified Bingham models to monitor the rheological behavior related to workability of the fresh self-compacting concrete containing waste rubber. Therefore, the self-compacting rubberized concretes were produced at a constant water-to-binder ratio of 0.35 and binder content of 520 kg/m^3. Class F fly ash was incorporated as 30% of total binder content by weight. Two types of waste scrap tire rubber, crumb rubber and tire chips, were utilized instead of natural fine and coarse aggregate at various level, respectively. The tire chips and three different graded crumb rubbers (No.18, No.5, and mixed crumb rubber) and five designated rubber contents of 5%, 10%, 15%, 20%, and 25% were considered as experimental parameters. The rheological behavior related to workability of the fresh concretes was investigated by using the ICAR rheometer. The torque–speed relationship obtained from rheometer was used to characterize the rheological behavior of fresh self-compacting rubberized concrete by applying the Herschel–Bulkley and modified Bingham models to experimental data. The results revealed that the self-compacting concretes produced in this study exhibited shear thickening behavior and increasing the rubber content resulted in higher exponent 'n' values for the Herschel–Bulkley and c/μ coefficients for the modified Bingham models.

1. Introduction

Concrete, which is described by rheologists as one of the most difficult materials to study, is thixotropic material according to extensively studies in the literature [1,2]. The thixotropic materials have a yield stress and a plastic viscosity which is the result of hydration in concrete [1,3,4]. However, the utilization of certain materials such as special cements, artificial aggregates, micro-fines, fibers, chemical admixtures, and waste products in the concrete production changes both the workability and hardened properties of concrete. The certain test methods measuring the workability are not enough to identify the workability of new generation concretes [5]. For instance, self-compacting concrete (SCC), which is more liquid than conventional concrete, is one type of these

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* Corresponding author. Tel.: +90 342 3172449; fax: +90 342 3601107.
E-mail address: sipek@gantep.edu.tr (S. İpek).

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new generation concretes. In order to better understand the fresh behavior of self-compacting concrete, the rheological behaviors must be also investigated. The Bingham model (Eq. (1)), which is the most applied rheological model on the fresh concrete to simulate its rheological behavior, was expressed by Tattersall and Banfill [1]:

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

where τ, τ_0, μ, and $\dot{\gamma}$ are shear stress (Pa), yield stress (Pa), plastic viscosity (Pa s), and shear rate (1/s), respectively. However, the Bingham model considers that the yield stress and plastic viscosity are constant in time. Namely, thixotropy and loss of workability are not incorporated in this model [1,3].

The workability of SCC can be described accurately by using the rheology and it can also be used in the design of the SCC mixtures. For example, Saak et al. [6] studied on the effect of wall slip between the fresh concrete and rheometer on the yield stress and viscoelastic measurements of cement paste and their assumption on a design methodology for SCC was that reduced viscosity with minimized yield stress are required for restraining segregation. The research of Feys et al. [4] was on the rheological behavior of fresh SCC and their study revealed that the fresh SCC had shear thickening behavior. Changing the mix proportions of concrete influences the rheological properties, particularly yield stress and viscosity, has been evaluated in more detail [4]. Furthermore, mineral and chemical admixtures are generally used in the production of SCC [7]. Güneyisi [7] focus on the influences of fly ash incorporation on the fresh state behavior of SCC and the results of this study found out that fly ash significantly improved the fresh state properties of SCC. The same findings on the effect of fly ash on the fresh properties of SCC were observed in the studies of Gesoğlu and Özbay [9] and Madandoust and Mousavi [10]. Flatt [8] studied on the effects of superplasticizer on the rheological behavior of the concrete and it was revealed by this research that the utilization superplasticizer, one of these chemical admixtures, caused decreasing of yield stress. Moreover, the viscosity of the SCC can be increased by many ways, such as adding more fine materials, and adding a viscosity modifying agent, to maintain the stability of the SCC (flowing under its own weight, resisting to segregation, and meeting other requirements) [4,11].

All around the world, there have been huge amount of waste materials and their disposal is one of the most serious environmental problems. Waste tire is one of these disposal waste materials. Using the waste tires as aggregate in the cement-based materials is a good alternative rather than disposing as waste to the nature or burning them [12–15]. In the literature, there are many studies about the effect of rubber on the properties of conventional concrete such as workability, mechanical, and durability [12–16]. Gesoğlu and Güneyisi [13] and Güneyisi et al. [15,16] used the waste tire rubber aggregate in the production of the conventional concrete and they experimentally investigated the mechanical, durability and permeability properties. In these studies, it was noticed that the replacing the natural aggregate with waste tire rubber aggregate significantly influenced the aforementioned properties. Also, Yung et al. [14] experimentally investigated the influences of waste tire rubber utilization on durability performance of SCC production and they found out that durability of SCC remarkably affected by incorporating the waste tire rubber into SCC. Although there have been number of studies concerning the utilization of waste tire rubber in conventional concrete, the study on its use in the self-compacting concrete is still deficient.

This study mainly aims to investigate the rheological behavior of the fresh SCC produced with crumb rubber and tire chips at various replacement levels. For that reason, the natural aggregate was replaced with three different sized crumb rubbers (No.18, No.5 and mixed crumb rubber) and tire chips at the replacement level of 5%, 10%, 15%, 20%, and 25% at a constant water-to-binder (w/b) ratio of 0.35 and the total binder content of 520 kg/m^3. Besides, the class F fly ash was used as 30% of total binder content by weight to improve the workability of SCCs. Totally 21 self-compacting rubberized concrete (SCRC) mixtures mixes were designed and ICAR rheometer was used to obtain the torques and rotational speeds. The Herschel–Bulkley and modified Bingham models were applied on experimental data for each concrete mixture. The rheological properties of plain and rubberized self-compacting concretes in the fresh state were evaluated and discussed comparatively.

2. Experimental study

2.1. Materials

Ordinary Portland cement (CEM I 42.5R) and class F fly ash (FA) according to ASTM C 618 [17] with density of 3.15 g/cm^3 and 2.25 g/cm^3, respectively, were used in this study. They had Blaine fineness of 326 and 379 m^2/kg, respectively. Physical properties and chemical compositions of the cement and fly ash are presented in Table 1.

The coarse aggregate was river gravel with a nominal maximum size of 16 mm and the fine aggregate, a mixture of natural river sand and crushed limestone, was used with a maximum size of 4 mm. River sand, crushed sand, and river gravel had densities of 2.65 g/cm^3, 2.43 g/cm^3, and 2.71 g/cm^3, respectively. The particle size gradation obtained through the sieve analysis of the fine and coarse aggregates are given in Fig. 1.

Two types of scrap tire rubber, crumb rubber (CR) and tire chips (TC), came from used truck tires castaway after a second

Table 1 – Physical properties and chemical compositions of Portland cement and fly ash.

Analysis report (%)	Cement	Fly ash
CaO	62.58	4.24
SiO_2	20.25	56.20
Al_2O_3	5.31	20.17
Fe_2O_3	4.04	6.69
MgO	2.82	1.92
SO_3	2.73	0.49
K_2O	0.92	1.89
Na_2O	0.22	0.58
Loss on ignition	3.02	1.78
Specific gravity (g/cm^3)	3.15	2.25
Specific surface area (m^2/kg)	326	379

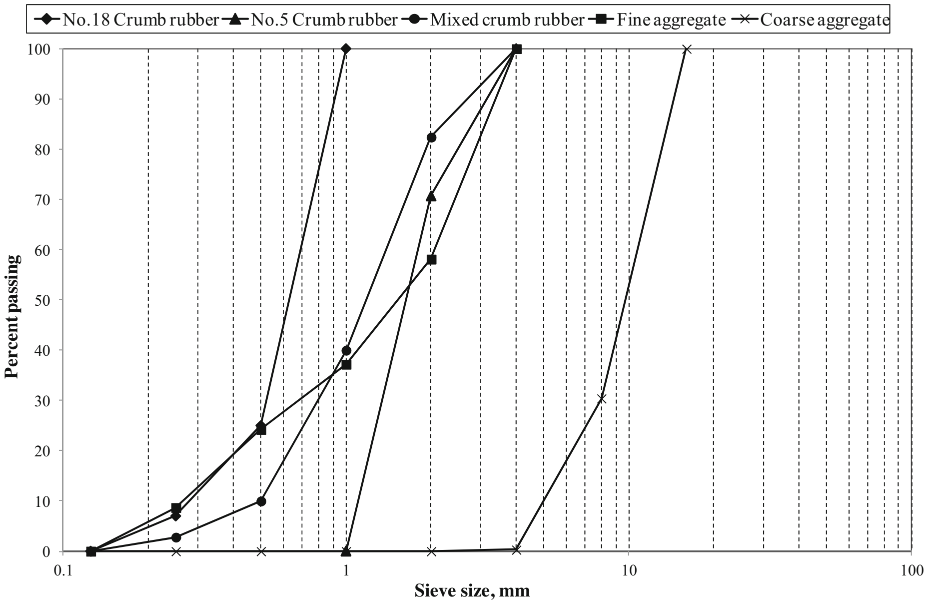


Fig. 1 – Sieve analysis of No.18, No.5, mixed crumb rubbers, fine and coarse aggregates.

recapping were utilized. No.18 crumb rubber (No.18 CR) and No.5 crumb rubber (No.5 CR) are two different sizes of crumb rubbers. The No.18 CR is a fine material passing from 1-mm sieve whereas the No.5 CR is a material retaining on 1-mm sieve and passing from 4-mm sieve. Moreover, the No.18 CR and No.5 CR were mixed to obtain a new fine material with a gradation close to that of the sand. A crumb rubber of which gradation is very close to that of the sand was achieved by mixing 40% of No.18 CR and 60% of No.5 CR. The density of No.18 CR and No.5 CR were 0.50 g/cm^3 and 0.67 g/cm^3, respectively. The particle size distribution for the No.18 CR, No.5 CR, and Mixed CR is also presented in Fig. 1. The density of tire chips was 1.02 g/cm^3 and it was not possible to determine its gradation as for normal aggregates since they are elongated particles between 10 and 40 mm. Additionally, the photographs of No.18 CR, No.5 CR, and TC are illustrated in Fig. 2.

A polycarboxylic ether type of superplasticizer (SP), which acts by steric hindrance effect [18], with density of 1.07 g/cm^3 was employed to achieve the desired workability in all concrete mixtures.

2.2. *Mixture design*

SCRC mixtures were designed having a constant w/b ratio of 0.35 and total binder content of 520 kg/m^3. The class F fly ash was used as a 30% of the total binder content by weight in all mixtures. The fine aggregate was replaced with No.18 and No.5 crumb rubbers separately and also it was substituted with mix of No.18 CR and No.5 CR whereas coarse aggregate was replaced with tire chips at five designated contents of 5%, 10%, 15%, 20%, and 25% by volume. These rubber contents were selected according to previous studies on both conventional and self-compacting concretes. Totally 21 different SCRC mixtures were designed regarding to above variables. The detailed mix proportions for SCRCs are presented in Table 2. Column named as fine aggregate in Table 2 consisted of two type of sand, natural and crushed sands, of which total volume was the volume of fine aggregate. 5, 10, 15, 20, and 25% of fine aggregate volume was substituted with No.18 CR in the mixtures coded as CR18, No.5 CR in the mixtures coded as CR5, and Mixed CR in the mixtures coded as MCR. The same procedure was followed in the preparation of the mixtures coded TC. 5, 10, 15, 20, and 25% of coarse aggregate volume was replaced with tire chips. Thereafter, the volumes of rubbers were converted to weight by multiplication of specific gravity of each rubber type. However, Mixed CR was the mix of 40% of No.18 CR and 60% of No.5 CR by mass. For this reason, the weights of No.18 and No.5 crumb rubbers in this mixture group were calculated according to their percentage.

2.3. *Concrete casting*

To achieve the same homogeneity and uniformity in all SCRC mixtures, the batching and mixing procedure proposed by Khayat et al. [19] was followed since the mixing sequence and duration are very vital in the self-compacting concrete production. According to this mixing procedure, the rubber, fine and coarse aggregates in a power-driven revolving pan mixer were mixed homogeneously for 30 s, and then about half of the mixing water was added into the mixer and it was allowed to continue the mixing for one more minute. After that, the rubber and aggregate were left to absorb the water in the mixer for 1 min. Thereafter, the cement and fly ash was added to the mixture for mixing another minute. Finally, the SP with remaining water was poured into mixer, and the concrete was mixed for 3 min and then left for a 2 min rest. At the end, to complete the production, the concrete was mixed for additional 2 min. The rheology of the concrete mixtures was determined as soon as mixing procedure finished.

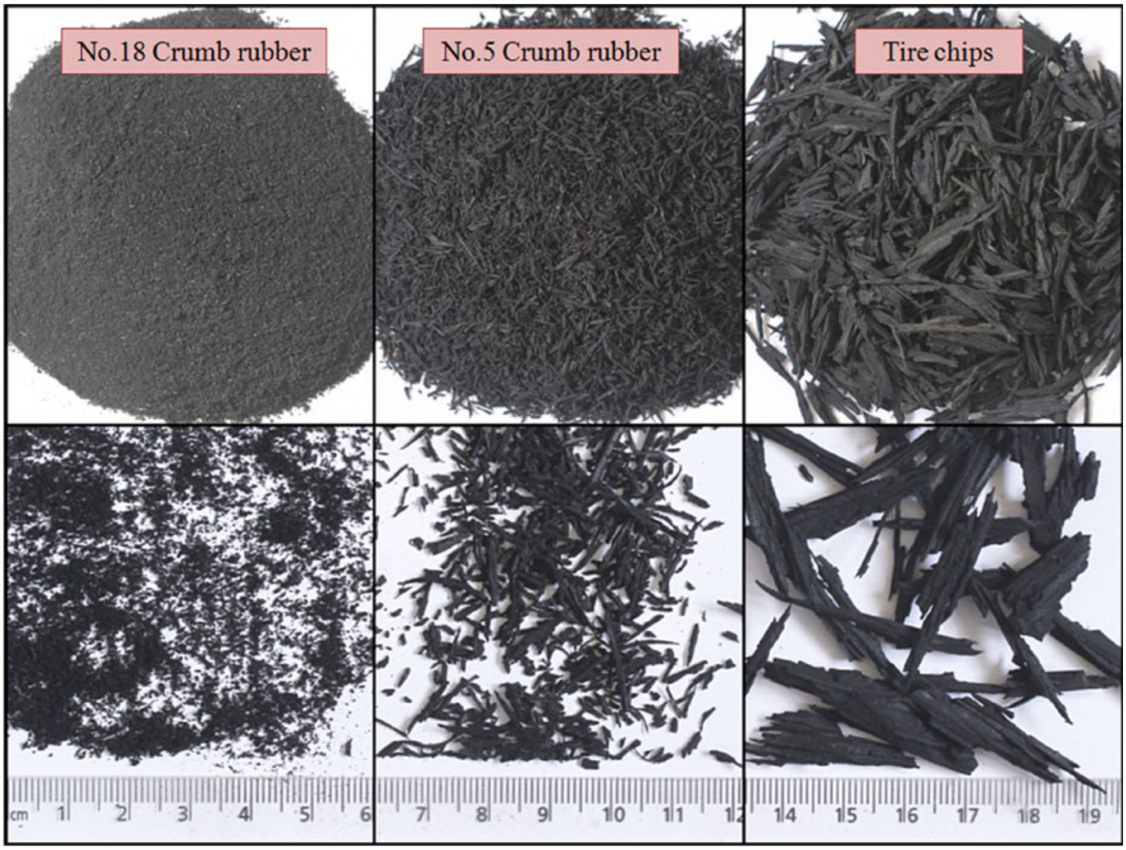


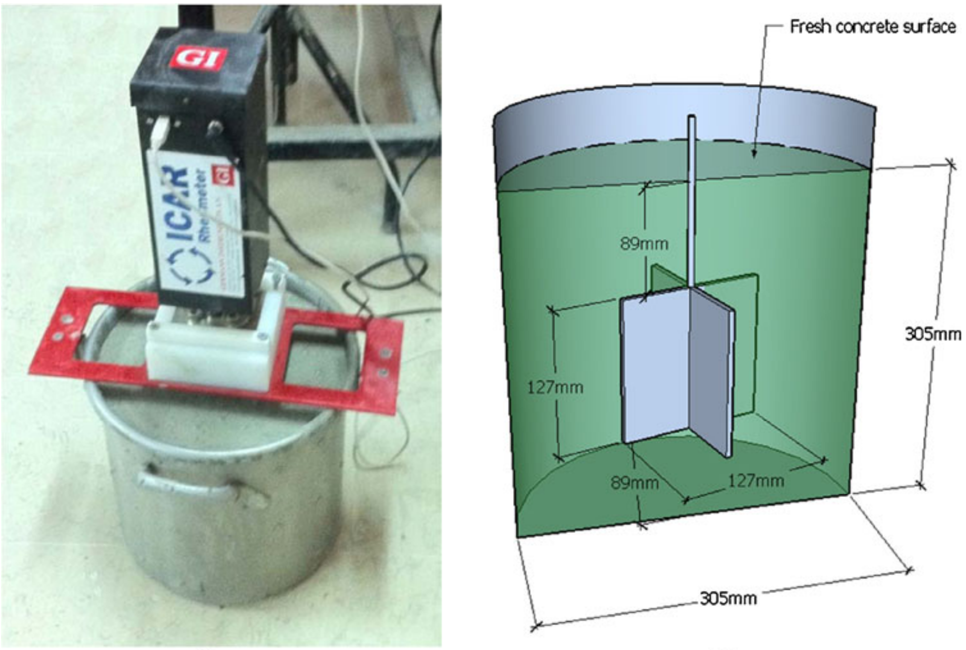
Fig. 2 – The photographic views of No.18 and No.5 crumb rubbers and tire chips.

Table 2 – Mix proportions for self-compacting rubberized concrete (kg/m^3).

Mix ID	w/b[a]	Cement	Fly ash	Water	SP[b]	Coarse aggregate	Fine aggregate		No.18 crumb rubber	No.5 crumb rubber	Tire chips	Density
							Natural sand	Crushed sand				
Control	0.35	364	156	182	3.4	819.4	573.6	245.8	0.0	0.0	0.0	2344
5CR18	0.35	364	156	182	3.6	819.1	544.9	233.5	7.9	0.0	0.0	2311
10CR18	0.35	364	156	182	3.9	818.7	516.2	221.2	15.9	0.0	0.0	2278
15CR18	0.35	364	156	182	4.2	818.4	487.5	208.9	23.8	0.0	0.0	2245
20CR18	0.35	364	156	182	4.4	818.1	458.9	196.7	31.8	0.0	0.0	2212
25CR18	0.35	364	156	182	4.7	817.8	430.2	184.4	39.7	0.0	0.0	2179
5CR5	0.35	364	156	182	3.6	819.1	544.9	233.5	0.0	10.6	0.0	2314
10CR5	0.35	364	156	182	3.9	818.7	516.2	221.2	0.0	21.3	0.0	2283
15CR5	0.35	364	156	182	4.2	818.4	487.5	208.9	0.0	31.9	0.0	2253
20CR5	0.35	364	156	182	4.4	818.1	458.9	196.7	0.0	42.6	0.0	2223
25CR5	0.35	364	156	182	4.7	817.8	430.2	184.4	0.0	53.2	0.0	2192
5MCR	0.35	364	156	182	3.6	819.1	544.9	233.5	3.7	5.6	0.0	2313
10MCR	0.35	364	156	182	3.9	818.7	516.2	221.2	7.5	11.2	0.0	2281
15MCR	0.35	364	156	182	4.2	818.4	487.5	208.9	11.2	16.9	0.0	2249
20MCR	0.35	364	156	182	4.4	818.1	458.9	196.7	15.0	22.5	0.0	2218
25MCR	0.35	364	156	182	4.7	817.8	430.2	184.4	18.7	28.1	0.0	2186
5TC	0.35	364	156	182	3.6	778.4	573.6	245.8	0.0	0.0	15.4	2319
10TC	0.35	364	156	182	3.9	737.4	573.6	245.8	0.0	0.0	30.8	2294
15TC	0.35	364	156	182	4.2	696.5	573.6	245.8	0.0	0.0	46.3	2268
20TC	0.35	364	156	182	4.4	655.5	573.6	245.8	0.0	0.0	61.7	2243
25TC	0.35	364	156	182	4.7	614.5	573.6	245.8	0.0	0.0	77.1	2218

[a] w/b, water-to-binder ratio.

[b] SP, superplasticizer.



(a) (b)

Fig. 3 – Views of (a) rheometer and (b) detailed schematic representation.

3. Measurement of rheological properties

The rheology of SCRC mixtures was measured by using ICAR rheometer as shown in Fig. 3a. The container, which fresh concrete mixtures were poured up to a height of 305 mm, had 305-mm diameter. After the fresh concrete mixtures placed into the container, four-bladed vane with the diameter, *d*, of 127 mm and height, *h*, of 127 mm was positioned in the center of the concrete mixtures. When the vane was placed into the fresh concrete mixture, there was an 89-mm spacing above and below the vane as shown in Fig. 3b. The radii of the inner cylinder, R_i, and outer cylinder, R_o, are 63.5 and 152.5 mm, respectively. Outer cylinders are equipped with ribs to prevent slippage between the concrete and the steel surface [20]. Flow curves for each fresh concrete mixture was obtained after entering breakdown speed and time, number of points, time per point, initial speed, and final speed as input. The vane was first rotated at a speed of 0.5 rps for a breakdown period of 20 s. Torque measurements were then recorded for seven speeds ranging in descending order from 0.5 rps to 0.05 rps. For analyzing rheological parameters of the fresh concrete properties, Eq. (2) was used for plotting the flow curves in relative units after the best-fit line was calculated for each mixture:

$$T = G + HN \tag{2}$$

where *T*, *G*, *H*, and *N* are the torque (Nm), the intercept of this line with the *T*-axis (Nm), the slope of this line (Nm s) related to plastic viscosity, and rotational speed (rps), respectively [21,22].

The rotational velocity and torque obtained from the rheometer must be considered in the calculations to describe the non-linear rheological properties. The formulae given by Ferguson and Kemblowski [23] supply the opportunity to transform 'N' and 'T' into the fundamental rheological parameters, shear stress and shear rate. Nehdi and Rahman [24] have been customized these formulae as following Eqs. (3) and (4):

$$\tau = \frac{(R_i^2 + R_o^2)}{4\pi h R_i^2 R_o^2} T \tag{3}$$

$$\dot{\gamma} = \frac{(R_i^2 + R_o^2)}{(R_o^2 - R_i^2)} N \tag{4}$$

These formulae can be used for any material, independently from the real rheological properties. The velocity distribution in the gap must be linear, which can be achieved if the gap is small ($R_i/R_o > 0.99$) [25]. However, a small error in the test results will occur, if this requirement is not satisfied [24,26].

When the Bingham model is applied on the rheological behavior of the SCC, some problems may occur and in order to solve these problems, the Herschel–Bulkley model (Eq. (5)), which is the most common non-linear model also having a yield stress, can be used to describe the rheological behavior of the SCC [27].

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{5}$$

In the equation, exponent '*n*' describe the non-linearity and if $n < 1$, $n > 1$, and $n = 1$, the SCC behave as shear thinning, shear thickening and the Bingham model, respectively. The results obtained from the rheometer were used in this model, and a better fit of the test data compared to the Bingham model was achieved.

The other most suitable model describing the rheological behavior of the SCC is the modified Bingham model of which equation is given in Eq. (6). This model can be considered as an extension of the Bingham model with a second order term, but also as a second order Taylor development of the Herschel–Bulkley equation [25]:

$$\tau = \tau_0 = \mu\dot{\gamma} + c\dot{\gamma}^2 \tag{6}$$

In the modified Bingham model, taking the ratio of second order term to the linear term can be applied to describe non-linear behavior, indicating shear thinning, shear thickening, and the Bingham model when $c/\mu < 0$, $c/\mu > 0$, and $c/\mu = 0$, respectively.

As a result, in this study the *T*–*N* relationship has been transformed to following expression (Eq. (7)) to be able to calculate the fundamental rheological Herschel–Bulkley parameters (τ_0, K, and n).

$$T = G_{\mathrm{HB}} + H_{\mathrm{HB}}(N)^J \tag{7}$$

where G_{HB}, H_{HB}, and J are parameters predicted by Herschel–Bulkley for a *T*–*N* relationship. After that, the fundamental rheological Herschel–Bulkley parameters were determined by Eqs. (8)–(10):

$$\tau_0 = \frac{G_{\mathrm{HB}}}{4\pi h}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right)\frac{1}{\ln(R_o/R_i)} \tag{8}$$

$$K = \frac{H_{\mathrm{HB}}}{2^{2n+1}\pi^{n+1}h}n^n\left(\frac{1}{R_i^{2/n}} - \frac{1}{R_o^{2/n}}\right)^n \tag{9}$$

$$n = J \tag{10}$$

The Herschel–Bulkley equations were achieved after the fundamental rheological parameters of the Herschel–Bulkley model were determined. However, for the modified Bingham model, Eqs. (3) and (4) were used to determine the shear stresses and shear rates. These shear stress and shear rates were plotted in order to obtain the equations of the modified Bingham model. Moreover, the curve, relationship between the shear stress and shear rate, for the Herschel–Bulkley model at each mixture was plotted by the same shear rates calculated for the modified Bingham model.

In addition to rheological properties of the SCC mixture, the 28-day compressive strength of concrete has been conducted with respect to ASTM C39 [28]. The compressive strength test has been carried out on three cube specimens (150 mm × 150 mm × 150 mm) and the results presented as average of three specimens.

4. Results and discussion

The plain SCC mixture produced in this study had the slump flow diameter of 765 mm. Utilization of waste rubbers instead of natural aggregates decreased the slump flow diameter. The slump flow diameter for the SCC mixtures produced with No.18, No.5, and mixed crumb rubber ranged between 680 and 750 mm. However, the utilization of tire chips resulted in higher decreasing of the slump flow diameter than crumb rubber using. The SCC mixtures produced with tire chips had the slump flow diameter ranging from 560 to 710 mm.

The data, torque (Nm) and rotational speed (rps), obtained from the rheometer are tabulated in Table 3 for the SCC mixtures. In this study, three batches have been produced from the same mixture and the data tabulated in Table 3 are the average of them. The results obtained from the rheometer indicated that at the same rotational speed, utilization of rubbers, which are not spherical as much as natural aggregate, increased the applied torque. Aggregate shape and texture are strongly effective on the rheology of the both conventional and self-compacting concretes [29]. The rubber particles as shown in Fig. 2 are not spherical, they are elongated particles. Although, the most spherical rubber is No.18 crumb rubber compared to other rubbers used in this study, it is not spherical as much as the natural fine aggregate. For this reason, there is an increasing in the torque when both natural fine and coarse aggregates were substituted with rubber. Moreover, increasing the rubber content caused increasing of the torque systematically. The highest increment in torque was observed in the SCC mixtures produced with tire chips of which longitudinal size ranging between 10 and 40 mm.

The Herschel–Bulkley model results are presented in Fig. 4a–d for the SCRC mixtures produced with No.18, No.5, mixed crumb rubber, and tire chips, respectively. The results indicated that there is shear thickening, which can be described in literature as "an increase in (apparent) viscosity with increasing shear rate" [30], when exponent '*n*' values were regarded. The exponent '*n*' values for the SCRC mixtures produced in this study are greater than 1 (one). Besides, utilization of rubber particles instead of natural aggregates caused an increment in the exponent '*n*' value which can be explained as increment in the shear thickening. This result obtained due to the surface texture and shape of the rubber particles. The plain SCC mixture has the exponent '*n*' value of 1.135, and this value systematically increased with increasing the rubber content from 0% to 25%. The highest exponent '*n*' value namely highest shear thickening value was obtained in the SCC produced with 25% tire chips. Use of 25% of No.18 crumb rubber resulted in 6.2% increase of the exponent '*n*' value while utilization of 25% of No.5 and mixed crumb rubbers increased the exponent '*n*' values as much as 24.2% and 20.2%, respectively. Moreover, replacing the 25% of natural coarse aggregate with tire chips resulted in 36.0% increment. This can be explained by the size and shape of the rubber particles. The finest and most spherical rubber is the No.18 crumb rubber. For this reason, lowest increasing was obtained in the SCC mixtures produced with No.18 crumb rubber.

Fig. 5a–d demonstrates the relationship between the shear stresses and shear rates of the SCC mixtures produced with No.18, No.5, mixed crumb rubber, and tire chips, respectively. The results presented in these figures were obtained by applying the modified Bingham model on the data obtained from rheometer. The same behavior, which was observed in Herschel–Bulkley model, was pointed out in the modified Bingham model. The SCRC mixtures produced in this study also behaved as the shear thickening when the modified Bingham model was applied. Coefficient of 'c/μ' for all mixtures was greater than 0 (zero), which means shear thickening. The highest 'c/μ' values were obtained in the

Table 3 – Torque and rotational speed values obtained from the rheometer for SCC mixtures.

Mix ID	Rotational speed value (rps)						
	0.050	0.125	0.200	0.275	0.350	0.425	0.500
	Torque value (Nm) (standard deviation)						
Control	0.054 (0.0027)	0.091 (0.0076)	0.146 (0.0073)	0.208 (0.0134)	0.235 (0.0118)	0.291 (0.0146)	0.360 (0.0180)
5CR18	0.101 (0.0090)	0.150 (0.0060)	0.236 (0.0094)	0.305 (0.0172)	0.412 (0.0165)	0.486 (0.0194)	0.565 (0.0226)
10CR18	0.114 (0.0079)	0.195 (0.0135)	0.282 (0.0165)	0.356 (0.0147)	0.472 (0.0227)	0.578 (0.0201)	0.663 (0.0259)
15CR18	0.139 (0.0057)	0.212 (0.0056)	0.305 (0.0091)	0.374 (0.0099)	0.514 (0.0136)	0.602 (0.0159)	0.695 (0.0184)
20CR18	0.186 (0.0071)	0.260 (0.0087)	0.356 (0.0145)	0.451 (0.0132)	0.565 (0.0164)	0.669 (0.0197)	0.778 (0.0203)
25CR18	0.229 (0.0106)	0.328 (0.0092)	0.407 (0.0119)	0.498 (0.0142)	0.619 (0.0105)	0.744 (0.0248)	0.84 (0.0261)
5CR5	0.124 (0.0056)	0.168 (0.0064)	0.240 (0.0099)	0.316 (0.0152)	0.401 (0.0168)	0.497 (0.0191)	0.580 (0.0188)
10CR5	0.156 (0.0042)	0.210 (0.0070)	0.298 (0.0055)	0.361 (0.0087)	0.461 (0.0154)	0.540 (0.0168)	0.667 (0.0203)
15CR5	0.213 (0.0108)	0.292 (0.0114)	0.340 (0.0095)	0.436 (0.0145)	0.547 (0.0142)	0.631 (0.0163)	0.754 (0.0198)
20CR5	0.240 (0.0075)	0.325 (0.0079)	0.384 (0.0088)	0.480 (0.0132)	0.585 (0.0149)	0.706 (0.0144)	0.820 (0.0219)
25CR5	0.274 (0.0116)	0.341 (0.0187)	0.426 (0.0214)	0.528 (0.0140)	0.625 (0.0168)	0.760 (0.0225)	0.885 (0.0234)
5MCR	0.113 (0.0017)	0.166 (0.0025)	0.230 (0.0048)	0.310 (0.0036)	0.398 (0.0097)	0.451 (0.0104)	0.568 (0.0096)
10MCR	0.142 (0.0023)	0.203 (0.0056)	0.289 (0.0068)	0.369 (0.0169)	0.456 (0.0114)	0.545 (0.0156)	0.670 (0.0094)
15MCR	0.184 (0.0062)	0.235 (0.0060)	0.323 (0.0069)	0.401 (0.0074)	0.508 (0.0094)	0.601 (0.0032)	0.710 (0.0091)
20MCR	0.220 (0.0054)	0.266 (0.0076)	0.361 (0.0100)	0.457 (0.0104)	0.570 (0.0081)	0.684 (0.0097)	0.792 (0.0146)
25MCR	0.246 (0.0082)	0.334 (0.0098)	0.409 (0.0111)	0.502 (0.0139)	0.628 (0.0135)	0.730 (0.0144)	0.874 (0.0198)
5TC	0.136 (0.0062)	0.180 (0.0038)	0.264 (0.0099)	0.328 (0.0120)	0.417 (0.0148)	0.506 (0.0201)	0.631 (0.0162)
10TC	0.201 (0.0043)	0.264 (0.0073)	0.332 (0.0052)	0.421 (0.0126)	0.490 (0.0179)	0.587 (0.0204)	0.732 (0.0183)
15TC	0.284 (0.0116)	0.324 (0.0138)	0.406 (0.0095)	0.498 (0.0174)	0.572 (0.0192)	0.690 (0.0217)	0.809 (0.0202)
20TC	0.327 (0.0093)	0.385 (0.0129)	0.438 (0.0142)	0.560 (0.0183)	0.659 (0.0211)	0.774 (0.0214)	0.907 (0.0248)
25TC	0.350 (0.0130)	0.416 (0.0128)	0.491 (0.0166)	0.581 (0.0105)	0.709 (0.0203)	0.813 (0.0183)	0.972 (0.0231)

SCC mixtures produced with tire chips at each replacement level. Rubber replacement and increasing of rubber content increased the 'c/μ' values. The plain SCC mixture had the 'c/μ' value of 0.253 and it was the lowest value in this study. The replacing 25% of the natural fine aggregate with No.18 crumb rubber increased the 'c/μ' coefficient to 0.362 while the replacing the 25% of the natural fine aggregate with No.5 and mixed crumb rubbers resulted in increasing of 'c/μ' coefficient to 1.054 and 0.814, respectively. This result can be explained by the shape of the crumb rubber particles. Because the most spherical rubber particles were No.18 crumb rubber and the No.5 crumb rubber particles were more elongated than it as shown in Fig. 2. For that reason, the SCRC mixtures with mixed crumb rubber, which was the mixing of 40% of No.18 and 60% of No.5 crumb rubbers, resulted in moderate 'c/μ' values compared to the SCRC mixtures with No.18 and No.5 crumb rubbers. Moreover, tire chips, which contains the elongated particles having the length changing between 10 and 40 mm, gave the highest 'c/μ' coefficient. The replacing the spherical grains, natural aggregate, with longitudinal grains, rubber, needed the higher torque values at the same rotational speed. The shear stresses of each mixture were determined by these torque values and when the torque values had increased, the shear stress also increased. Therefore, 'c/μ' coefficient increased.

Additionally, Fig. 6 demonstrates the relationship between 'c/μ' coefficients obtained from the modified Bingham model and exponent 'n' values obtained from the Herschel–Bulkley model. The R-square value in Fig. 6 means that there is a strong relationship between 'c/μ' coefficients and exponent 'n' values.

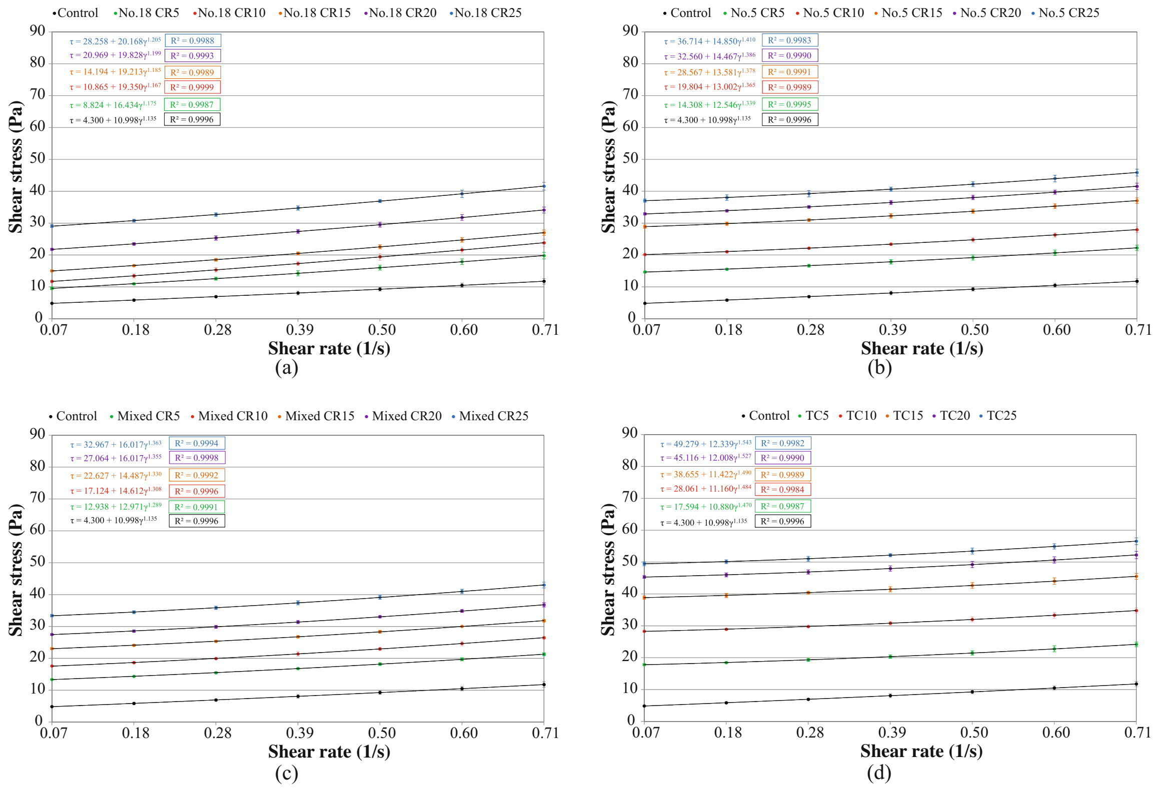


Fig. 4 – Application of the Herschel–Bulkley model on the rheological data for the SCC produced with: (a) No.18, (b) No.5, (c) mixed crumb rubbers, and (d) tire chips.

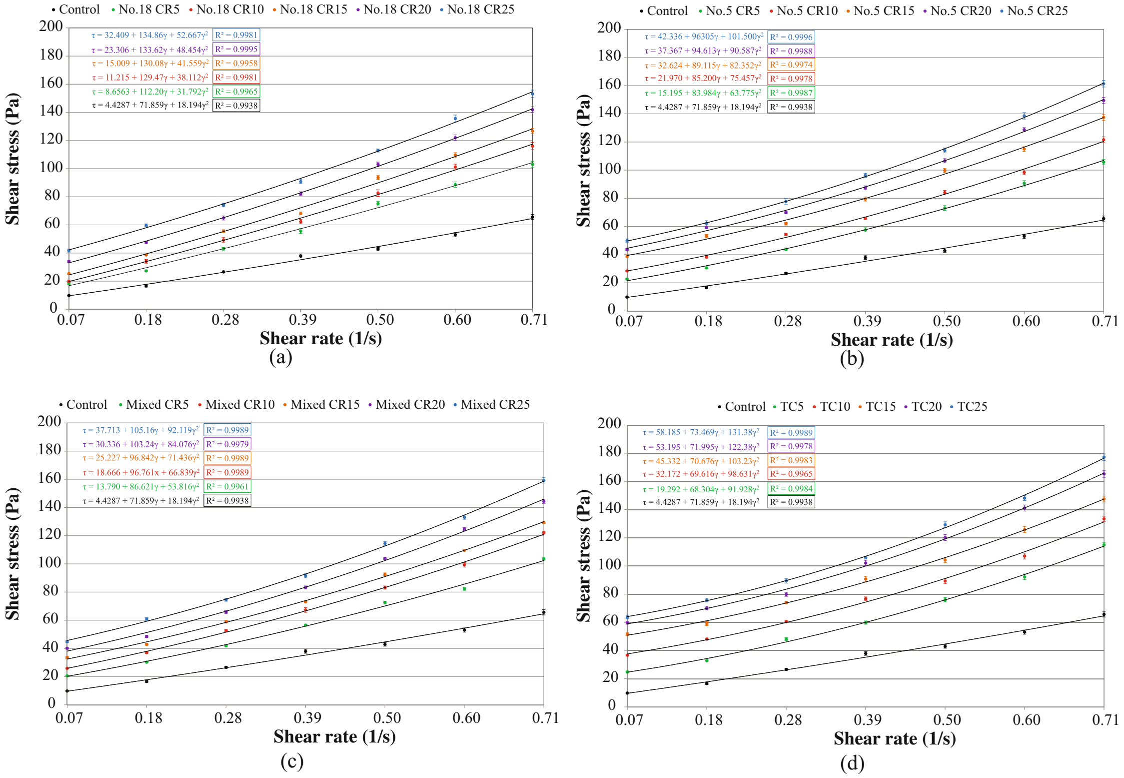


Fig. 5 – Application of the modified Bingham model on the rheological data for the SCC produced with: (a) No.18, (b) No.5, (c) mixed crumb rubbers, and (d) tire chips.

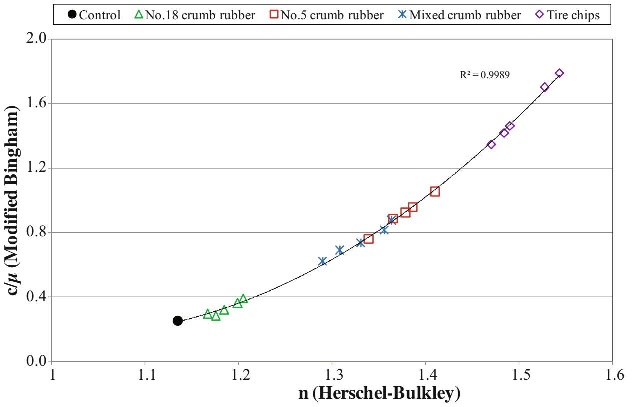


Fig. 6 – Relationship between c/μ and n coefficients.

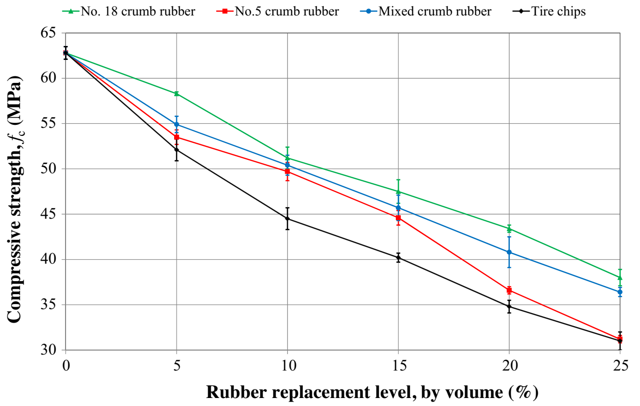


Fig. 7 – Variation in the compressive strength with respect to rubber replacement level.

As a result, the plastic viscosity cannot be given for the SCCs due to the non-linearity of the relationship between shear stresses and shear rates. Moreover, due to the particle migration, segregation, etc. very high shear rates cannot be imposed onto the material [31] and also due to the high aggregate dimensions, large geometries must be built, making concrete rheometry extremely difficult [11]. Besides, some processes in concrete industry occur at higher shear rates than those in rheometer tests. Mixing and pumping are the two best known examples. The resulting shear stress is gradually more dominated by the plastic viscosity and shear thickening behavior since the shear rates increases [11]. Therefore, the obtaining shear rate as in pumping and mixing process is difficult, but applying a reasonably high shear rate and careful observations during measurements may be a good tool to give some indication of the expected behavior.

The 28-day compressive strength that is the average of three specimens of the SCRC mixtures is presented in Fig. 7. Moreover, the compressive strength result of each specimen, average compressive strength, standard deviation of compressive strength, and standard uncertainty of results are tabulated in Table 4. The results indicated that replacing natural aggregate with waste rubber decreased the compressive strength. The compressive strength changing between 31.0 and 62.8 MPa was obtained during this study. The lowest compressive strength values were observed in the concrete series in which the natural coarse aggregate was replaced with tire chips at all rubber content. The compressive strength of

Table 4 – The compressive strength results and their standard deviation and uncertainty.

Mix ID	Compressive strength (MPa)					
	Sample 1	Sample 2	Sample 3	Average	Standard deviation	Standard uncertainty
Control	61.5	63.4	63.5	62.8	1.1	±0.7
5CR18	58.6	57.9	58.4	58.3	0.4	±0.2
10CR18	50.1	53.6	49.9	51.2	2.1	±1.2
15CR18	46.7	45.7	50.1	47.5	2.3	±1.3
20CR18	42.8	43.3	44.1	43.4	0.7	±0.4
25CR18	37.8	36.5	39.7	38.0	1.6	±0.9
5CR5	52.0	55.2	53.3	53.5	1.6	±0.9
10CR5	49.1	51.8	48.2	49.7	1.9	±1.1
15CR5	46.7	45.1	42.0	44.6	2.4	±1.4
20CR5	34.3	39.8	35.7	36.6	2.9	±1.7
25CR5	32.1	30.7	30.8	31.2	0.8	±0.5
5MCR	54.7	53.6	56.4	54.9	1.4	±0.8
10MCR	49.8	52.3	49.1	50.4	1.7	±1.0
15MCR	47.2	45.6	44.3	45.7	1.5	±0.8
20MCR	40.1	40.9	41.4	40.8	0.7	±0.4
25MCR	35.8	37.2	36.2	36.4	0.7	±0.4
5TC	54.4	50.7	51.2	52.1	2.0	±1.2
10TC	45.0	46.2	42.3	44.5	2.0	±1.2
15TC	40.5	40.9	39.2	40.2	0.9	±0.5
20TC	36.1	33.7	34.6	34.8	1.2	±0.7
25TC	30.8	32.8	29.4	31.0	1.7	±1.0

the SCRC mixtures was 38.0, 331.2, 36.4, and 31.0 MPa for the No.18, No.5, and mixed crumb rubber, and tire chips at 25% replacement level, respectively. The highest compressive strength was achieved in the concrete series containing No.18 crumb rubber at all replacement level. This type of concrete can be utilized in many construction areas such as highway guardrail, pavement, blinding concrete, retaining wall, beams, slabs etc. when the compressive strength values were considered.

5. Conclusions

Based on the results obtained from the experimental study presented above, the following conclusions can be drawn:

- Data obtained from the rheometer indicated that the replacement of the natural aggregate with rubber particles needed higher torque at the same rotational speed. Especially, the tire chips utilization significantly increased the torque values.
- The self-compacting rubberized concretes produced in this study indicated the shear thickening behavior when both the Herschel–Bulkley and modified Bingham models were applied.
- The results for the Herschel–Bulkley and modified Bingham models showed that the utilization of rubber instead of natural aggregate resulted in increasing the exponent 'n' (the Herschel–Bulkley) values and 'c/μ' (the modified Bingham) coefficients, respectively. Besides increasing the rubber content from 0 to 25% increased systematically these values, which are the demonstration of shear thickening.
- The highest exponent 'n' values and 'c/μ' coefficients were obtained when the natural coarse aggregate was substituted with tire chips while the lowest values were achieved when the natural fine aggregate was replaced with No.18 crumb rubber at each replacement level.
- The compressive strength results indicated that replacing the natural aggregate with waste rubber decreased the compressive strength. However, it was observed that the compressive strength more than 30 MPa could be achieved in the self-compacting concrete including 25% crumb rubber or tire chips.

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REFERENCES

[1] G.H. Tattersall, P.F.G. Banfill, The Rheology of Fresh Concrete, Pitman, London, 1983.

[2] N. Roussel, A thixotropy model for fresh fluid concretes: theory, validation and applications, Cement and Concrete Research 36 (2006) 1797–1806.

[3] G.H. Tattersall, The rationale of a two-point workability test, Magazine of Concrete Research 25 (1973) 169–172.

[4] D. Feys, R. Verhoeven, G. De Schutter, Fresh self compacting concrete, a shear thickenings material, Cement and Concrete Research 38 (2008) 920–929.

[5] H.Ö. Öz, Properties of self-compacting concretes made with cold bonded fly ash lightweight aggregates, (Ph.D. thesis), University of Gaziantep, Gaziantep, Turkey, 2014.

[6] A.W. Saak, H.M. Jennings, S.P. Shah, The influence of wall slip on yield stress and viscoelastic measurements of cement paste, Cement and Concrete Research 31 (2001) 205–212.

[7] E. Güneyisi, Fresh properties of self-compacting rubberized concrete incorporated with fly ash, Materials and Structures 43 (2010) 1037–1048.

[8] R.J. Flatt, Towards a prediction of super-plasticized concrete rheology, Materials and Structures 27 (2004) 289–300.

[9] M. Gesoğlu, E. Özbay, Effects of mineral admixtures on fresh and hardened properties of self-compacting concretes: binary, ternary and quaternary systems, Materials and Structures 40 (2007) 923–937.

[10] R. Madandoust, S.Y. Mousavi, Fresh and hardened properties of self-compacting concrete containing metakaolin, Construction and Building Materials 35 (2012) 752–760.

[11] D. Feys, R. Verhoeven, G. De Schutter, Why is fresh self-compacting concrete shear thickening? Cement and Concrete Research 39 (2009) 510–523.

[12] R. Siddique, T.R. Naik, Properties of concrete containing scrap-tire rubber – an overview, Waste Management 24 (2004) 563–569.

[13] M. Gesoğlu, E. Güneyisi, Strength development and chloride penetration in rubberized concretes with and without silica fume, Materials and Structures 40 (2007) 953–964.

[14] W.H. Yung, L.C. Yung, L.H. Hua, A study of the durability properties of waste tire rubber applied to self-compacting concrete, Construction and Building Materials 41 (2013) 665–672.

[15] E. Güneyisi, M. Gesoğlu, K. Mermerdaş, S. İpek, Experimental investigation on durability performance of rubberized concrete, Advances in Concrete Construction 2 (3) (2014) 187–201.

[16] E. Güneyisi, M. Gesoğlu, T. Özturan, Properties of rubberized concretes containing silica fume, Cement and Concrete Research 34 (2004) 2309–2317.

[17] ASTM C 618-08, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete, Annual Book of ASTM Standard, No. 04.02, 2000.

[18] M. Collepardi, Chemical admixtures today, in: Proceedings of Second International Symposium on Concrete Technology for Sustainable Development with Emphasis on Infrastructure, Hyderabad, India, 27 February–3 March, (2005) 527–541.

[19] K.H. Khayat, J. Bickley, M. Lessard, Performance of self-consolidating concrete for casting basement and foundation walls, ACI Materials Journal 97 (3) (2000) 374–380.

[20] A.W. Saak, H.M. Jennings, S. Shah, The influence of wall slip on yield stress and viscoelastic measurements of cement paste, Cement and Concrete Research 31 (2001) 205–212.

[21] E.P. Koehler, D.W. Fowler, Development of a Portable Rheometer for Fresh Portland Cement Concrete, Aggregates Foundation for Technology, Research and Education (AFTRE), 2004.

[22] E.P. Koehler, Development of a portable rheometer for Portland cement concrete, (M.S. thesis), The University of Texas at Austin, 2004.

[23] J. Ferguson, Z. Kemblowski, Applied Fluid Rheology, Elsevier Applied Science, London, 1991.

[24] M. Nehdi, M.A. Rahman, Effect of geometry and surface friction of test accessory on oscillatory rheological properties of cement pastes, ACI Materials Journal 101 (2004) 416–424.

[25] D. Feys, R. Verhoeven, G. De Schutter, Evaluation of time independent rheological models applicable to fresh self-compacting concrete, Applied Rheology 17 (2007) 56244-1–56244-10.

[26] C.W. Macosko, Rheology – Principles, Measurements and Applications, Wiley-VCH, 1994.

[27] F. De Larrard, C.F. Ferraris, T. Sedran, Fresh concrete: a Herschel–Bulkley material, Materials and Structures 31 (1998) 494–498.

[28] ASTM C39/C39M-12, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, vol. 04-02, Annual Book of ASTM Standard, Philadelphia, 2012, 7 pp..

[29] H.A. Barnes, J.F. Hutton, K. Walters, An Introduction to Rheology, Elsevier, New York, 1989.

[30] H.A. Barnes, Shear-thickening (''Dilatancy'') in suspensions of nonaggregating solid particles dispersed in Newtonian liquids, Journal of Rheology 33 (2) (1989) 329–366.

[31] M.R. Geiker, M. Brandl, L.N. Thrane, D.H. Bager, O.H. Wallevik, The effect of measuring procedure on the apparent rheological properties of self compacting concrete, Cement and Concrete Research 32 (2002) 1791–1795.