Hindawi
Advances in Materials Science and Engineering
Volume 2019, Article ID 8372547, 14 pages
https://doi.org/10.1155/2019/8372547

Research Article

Fresh and Mechanical Properties of Self-Compacting Rubber Lightweight Aggregate Concrete and Corresponding Mortar

Jing Lv,[1] Qiang Du,[2] Tianhua Zhou,[1] Zuoqian He,[1] and Kunlun Li[1]

[1]*School of Civil Engineering, Changan University, Xian, Shaanxi 710061, China*
[2]*School of Economics and Management, Changan University, Xian, Shaanxi 710064, China*

Correspondence should be addressed to Qiang Du; q.du@chd.edu.cn

Received 12 November 2018; Revised 20 January 2019; Accepted 27 January 2019; Published 24 February 2019

Academic Editor: Zbyšek Pavlík

Increasing amount of waste tires caused huge environment issues in recent years. Recycling concrete is an effective way. In this paper, waste tires are crushed into particles and incorporated in lightweight aggregate concrete to prepare a special concrete (self-compacting rubber lightweight aggregate concrete (SCRLC)). A detailed experimental research of effects of rubber particles on the properties of SCRLC and corresponding mortar is conducted. The results show that increasing the rubber particles replacement ratio leads to a raising of yield stress and plastic viscosity of mortar pastes. Flowability, filling capacity, and passing ability of SCRLC decline and the segregation resistance property of SCRLC improves as the rubber particles replacement ratio increases. Well, linear correlations between slump flow of SCRLC and shear stress of corresponding mortar pastes and segregation ratio of SCRLC and plastic viscosity of corresponding mortar pastes are obtained. In order to ensure that rubber lightweight aggregate concrete can compact by itself, the upper limit of shear stress of corresponding mortar pastes is 231.7 Pa and the lower limit of plastic viscosity of corresponding mortar pastes is 3.72 Pa·s. Compressive strength, splitting tensile strength, flexural strength, and elastic modulus of SCRLC and compressive strength of corresponding mortar decrease as the rubber particles replacement ratio increases. The 28-day compressive strength of SCRLC can meet the requirements of lightweight aggregate concrete structures until the rubber particles replacement ratio reaches 50%.

1. Introduction

Waste rubber, one type of automotive industry waste which is discharged increasingly in recent years, leads to a series of environmental issues in case of willful disposal [1]. In order to dispose waste rubber, plenty of solutions are attempted. Reclamation of waste rubbers as an aggregate in concrete may be one of the preferable ways for handling waste tires [2]. Rubber can exist soundly in the alkaline environment of concrete [3], and enormous utilization of concrete can consume large amount of waste rubber thus tackling the waste rubber issue.

To date, a large number of research works were conducted to detect the effects of rubber particles on properties of concrete. It has been reported that most of the recycling ways were to crush waste rubber tires into various dimension particles and utilize them in concrete [4]. Workability [5–8], mechanical properties [9, 10], durability [11, 12], and application [13, 14] of normal concrete containing rubber particles were studied subsequently. Meanwhile, the rubber particles were also utilized in lightweight aggregate concrete [15, 16].

Unlike normal rubber concrete, rubber lightweight aggregate concrete (RLC) with virtues of low unit weight, high flexibility, and suitable mechanical properties was proposed in recent years. And a well application prospect would be achieved in future. However, due to the lightweight of aggregate and rubber particles, it is difficult to ensure a well distribution of them in concrete. Thus, the properties of RLC are uneven. Similar to the self-compacting concrete, the self-compacting technology can also be used in RLC to solve the nonuniform distribution of aggregate and rubber particles

[17, 18]. However, so far, very few previous studies were focused on self-compacting rubber lightweight aggregate concrete (SCRLC).

Bouzoubaâ et al. [19] reported that the relevance between properties of fresh concrete and hardened concrete was close. So it is necessary to study the properties of fresh concrete. Also, Ng et al. [20] indicated that the workability of concrete is closely related to the rheological properties of corresponding mortar. So, it may be feasible to use the rheological properties of mortar to predict the workability of corresponding concrete. Thus, in order to prepare outstanding fresh properties of SCRLC, understanding the rheological properties of corresponding mortar is one effective way. But, so far, few of the references reported the effects of rubber particles on rheological properties of mortar and the relation between fresh properties of SCRLC and rheological properties of corresponding mortar. Meanwhile, there was a lack of findings with respect to the mechanical properties of SCRLC and corresponding mortar.

Based on the above cases, in order to prepare RLC with excellent performance, the self-compacting technology was tried in this research. A number of experiments were carried out to examine the effects of rubber particles on the fresh and mechanical properties of SCRLC and corresponding mortar. SCRLC mixture layouts include 6 varying mixes. The fine aggregate was replaced by the same particle-size distribution rubber particles with the volume replacement from 0 to 50% in the 6 mixes. The properties of mortar include yield stress, plastic viscosity, and compressive strength. The tests of properties of SCRLC include slump flow test, V-funnel test, L-box test, U-box test, column segregation test, compressive strength test, splitting tensile strength test, flexural strength test, and elastic modulus test. A relationship between the results of properties of fresh SCRLC and rheological properties of corresponding mortar was also investigated. Therefore, a better understanding of factors affecting the properties of SCRLC was inferred.

2. Experimental Program

2.1. Materials. In this study, ordinary Portland cement and fly ash were utilized as the main components of the binders. In addition, fine aggregate (FA), lightweight aggregate (LWA), rubber particles, water-reducing agent, thickener, and water were used to prepare the mixture. The chemical constituents of cement and fly ash were tested by an X-ray fluorescence spectrometer (Bruker D8 Advance X-ray diffractometer) as shown in Table 1. The properties of cement were specific gravity 3.16 and Blaine fineness value 331 m^2/kg. According to the ASTM C618 [21], the fly ash falling under class F and the gross of $SiO_2 + Al_2O_3 + Fe_2O_3$ (approximated to 81.05%) could meet the requirements of pozzolanic reactivity (70%). The specific gravity and Blaine fineness value of fly ash were 2.21 and 275 m^2/kg, respectively. Natural sand provided from local river was utilized as fine aggregate. The properties of sand were modulus of fineness 2.8 and density 2650 kg/m^3. Lightweight aggregate as shown in Figure 1 was a crushed shale ceramsite product from Hubei Yichang Baozhu Ceramsite Development Co., Ltd., with a water absorption capacity of 2.3%, a crushing strength of 8.82 MPa, a loose bulk density of 842 kg/m^3, and a particle size range from 4.75 mm to 19 mm. Rubber particles (shown in Figure 2) were used to replace sand by volume and supplied by the manufacturer. The properties of rubber particles were modulus of fineness 2.7, density 1.19 g/cm^3, and loose bulk density 365 kg/m^3. Particle size gradation of sand and rubber particles is given in Figure 3.

Table 1: Chemical constituents of cement and fly ash.

Chemical analysis (%)	Ordinary Portland cement	Fly ash
CaO	62.45	5.31
SiO_2	20.18	48.92
Al_2O_3	4.91	26.27
Fe_2O_3	3.88	5.86
MgO	2.67	0.84
SO_3	2.14	1.21
K_2O	0.47	0.79
Na_2O	0.29	0.22
Loss on ignition	2.05	3.60
Specific gravity	3.16	2.21
Fineness (m^2/kg)	331	275

Figure 1: Crushed shale ceramsite.

The water-reducing agent was a polycarboxylate-based high-range water reducer (HRWR) with a solid content of approximately 40% from Sika (China) Limited. The thickener was hydroxypropyl methyl cellulose ether manufactured by National Starch Industry (Shanghai) Co., Ltd. The viscosity was 20000 MPa·s provided by the company. The mixing water was tap water.

2.2. Mixing Proportions and Procedure. In this research, fresh and mechanical properties of SCRLC and corresponding mortar were investigated, respectively. The six groups of mix proportions of SCRLC are shown in Table 2. A control mix proportion was designed as 1.00 : 0.20 : 1.65 : 1.44 : 0.00048 : 0.012 : 0.42 (cement : fly ash : FA : LWA : thickener : HRWR : water). The sand was replaced by rubber particles, and the volume replacement ratios were 10%, 20%, 30%, 40%, and 50% in this paper. To maintain the workability of SCRLC, thickener and water-reducing agent were selected. The dosage of the thickener and the water-reducing agent was 0.04% and 1%, respectively (by weight of binding materials). The ratio of water to binding materials was fixed

Figure 2: Rubber particles.

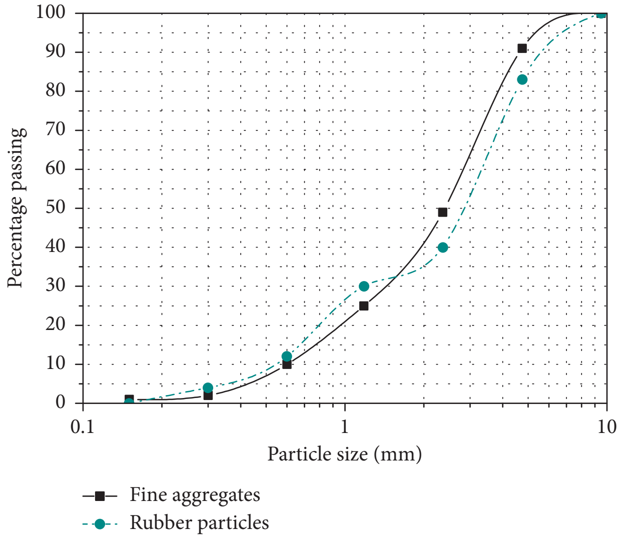


Figure 3: Particles size gradation of fine aggregate and rubber particles.

Table 2: Mix proportions.

Type of concrete	Replacement (by volume) (%)	Weight per cubic meter (kg/m^3)							
		Cement	Fly ash	Rubber	FA	LWA	Thickener	HRWR	Water
SCLC	0	425	85	0	700	610	0.204	5.1	179
SCRLC10	10	425	85	31	630	610	0.204	5.1	179
SCRLC20	20	425	85	62	560	610	0.204	5.1	179
SCRLC30	30	425	85	93	490	610	0.204	5.1	179
SCRLC40	40	425	85	124	420	610	0.204	5.1	179
SCRLC50	50	425	85	155	350	610	0.204	5.1	179

to 0.42. The mix proportions of mortar were based on the concrete compositions without lightweight aggregate.

For mortar paste, cement, fly ash, rubber particles, and sand were firstly mixed dry for 1 min and then the thickener and water-reducing agent together with water were poured into the dry mixture following a mixing of 2 min. After mixing, the rheological test of mortar paste was conducted immediately at a controlled environment of 20 ± 5°C. For concrete, cement, fly ash, rubber particles, sand, and lightweight aggregate were dry-mixed firstly for 1 min. Then, water mixing with thickener and reducing agent was added into the mixer and mixed for another 2 min. After these sequences of preparation, the slump flow test, L-box test, V-funnel test, U-box test, and column segregation test were conducted immediately at a controlled environment of 20 ± 5°C. Then, the mortar paste and fresh self-compacting lightweight aggregate were casted into the molds and demolded after 24 h, respectively. All samples were cured at 20 ± 5°C and RH > 95% for 7 d, 28 d, and 90 d. The mechanical properties tests of harden mortar and SCRLC were conducted subsequently.

2.3. Rheological Properties Test. The rheological properties of mortar pastes were detected using an R/S plus rheometer, as illustrated in Figure 4. The flow curves including a linear

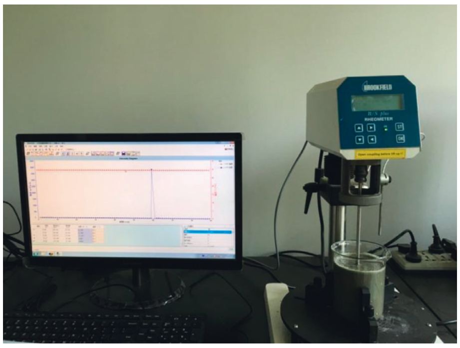


Figure 4: Rheometer apparatus.

growth and a linear descending in the shear rate from 0 s^{-1} to 40 s^{-1} and 40 s^{-1} to 0 s^{-1} were obtained from the rheological test. The descending section of the flow curves was used to analyze rheological properties. Based on the previous studies [22–26], the Bingham model was generally used to describe the rheological characterization of cement pastes. Thus, the Bingham model might be adequate for depicting the rheological properties of mortar containing rubber particles and was chosen to have a try to analyze the rheological properties. The yield stress and plastic viscosities could be acquired using the Bingham model as follows:

$$\tau = \tau_0 + \eta\gamma, \quad (1)$$

where τ is the shear stress, τ_0 is the yield stress, γ is the shear rate, and η is the plastic viscosity.

2.4. Mixture Properties Test. In order to understand the variation of self-compactability of SCRLC along with the rubber particles replacement ratio, a series of experiments including slump flow test, L-box test, V-funnel test, U-box test, and column segregation test were conducted according to EFNARC [27]. The slump flow test (Figure 5) was used to evaluate the flowability and flow rate of SCRLC. The SF (slump flow diameter) and T_{500} (the time in which the slump flow diameter reached 500 mm) was obtained from the slump flow test and utilized to describe the flowability and flow rate, respectively. The V-funnel test was utilized to estimate the viscosity and filling capacity of fresh SCRLC. The test was carried out using a V-funnel (Figure 6), and the V-funnel flow time (T_v) was recorded to estimate the variation of viscosity and filling capacity of fresh SCRLC. The L-box test (Figure 7) was devoted to conclude the passing ability of fresh SCRLC. By the L-box test, the PA (the ratio between height of the horizontal section of the fresh SCRLC (H_2) and height of the vertical section of fresh SCRLC (H_1)) and T_{400} (the time in which the fresh SCRLC flowed to 400 mm from the steel bars) were obtained to investigate the diversification of the passing ability of fresh SCRLC. The U-box test (Figure 8) was used to study the passing ability and filling ability of fresh SCRLC in combination with the L-box test and V-funnel test. The main index measured from the test was the height difference of fresh SCRLC between the two boxes (Δh). The column segregation test (Figure 9) used in this research was the sieve segregation resistance test. It was conducted to assess the resistance of fresh SCRLC to segregation. The segregation ratio (SR) can be calculated as the measure value from the test.

2.5. Mechanical Properties Tests. The mechanical properties tests of hardening SCRLC and corresponding mortar were conducted in this paper. For SCRLC, the compressive strength test, splitting tensile strength test, flexure strength test, and elastic modulus test were conducted. Meanwhile, for mortar, the compressive strength test was performed. The compressive strength and splitting tensile strength of SCRLC were obtained for the cubic specimens of 100 × 100 × 100 mm in dimension in accordance with GB/T 50081 [28]. The elastic modulus of SCRLC was determined for the prismatic specimens of 100 × 100 × 300 mm in dimension in accordance with GB/T 50081 [28]. The flexure strength of SCRLC was obtained for the prismatic specimens of 100 × 100 × 400 mm in dimension in accordance with GB/T 50081 [28]. The compressive strength of mortar was determined for three 70.7 × 70.7 × 70.7 mm cubical specimens according to JGJ/T 70 [29]. All specimens for the mechanical properties tests were manufactured without compacting. Above tests were all accomplished by using a computer-controlled servo-hydraulic universal testing machine. The compressive strength, splitting tensile strength, and flexure strength of SCRLC, and the compressive strengths of corresponding mortar were tested at 7 d, 28 d, and 90 d. The elastic modulus of SCRLC was tested at 28 d. For each mixture and age, the average value of three readings was used to be the representative strength.

3. Results and Discussion

3.1. Rheological Properties of Mortar Pastes. The flow curves of mortar pastes on various replacement levels of rubber particles are obtained from rheological tests and shown in Figure 10. A good linear correlation (R^2 values > 0.98) between shear rate and shear stress can be seen from Figure 10. Despite adding rubber particles to mortar pastes, the relations between shear rate and shear stress on various replacement levels of rubber particles are still fitted by using the Bingham model. The regression equations derived from the flow curves are summarized in Table 3.

The results of rheological properties including yield stress and plastic viscosity are shown in Figure 11. Yield stress is the maximum stress hindering the plastic deformation of slurry. Plastic viscosity is a characteristic hindering the fluidity of slurry [30]. It can be observed that the shear stress and plastic viscosity of mortar pastes increase as the rubber particles replacement ratio rises. It means that the fluidity of mortar pastes decreases with increasing rubber particles replacement ratio. In the case of 10% rubber particles replacement ratio, shear stress increases by around 15% with almost no increment in plastic viscosity. When the rubber particles replacement ratio is higher than 10%, both yield stress and plastic viscosity increase drastically. Compared to plain mortar pastes, increment of around 424% in yield stress and 35% in plastic viscosity occurred. It indicates

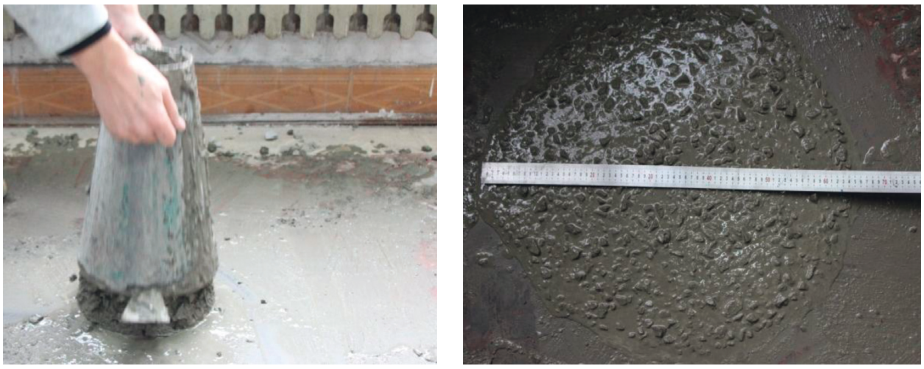

(a) (b)

Figure 5: Slump flow test.

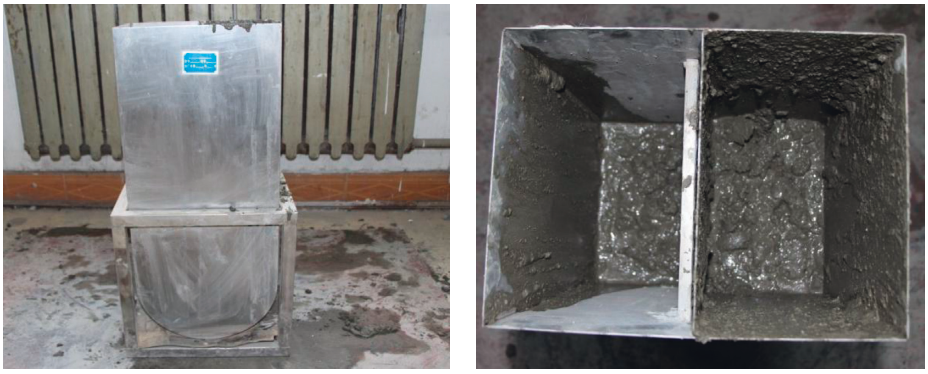

(a) (b)

Figure 6: V-funnel test.


(a) (b)

Figure 7: L-box test.

that the flow properties of mortar pastes drop as the rubber particles replacement ratio increases, especially the rubber particles replacement ratio is bigger than 10%. The phenomenon of variation in yield stress and plastic viscosity is presumably attributed to amount the morphological features of rubber particles. Although rubber particles have approximately the same particles size gradation with sand, surface appearance is quite different. Compared with sand, surface of rubber particles is rough and irregular. A larger rubber particles replacement ratio would also cause an increase in frictional resistance and collision opportunities between rubber particles in mortar pastes; thus, the yield stress and plastic viscosity will uplift. Furthermore, in the mortar pastes containing more rubber particles, flocculent structure formation is much easier; thus, the quantity of free water in the mortar pastes would decrease. The decrease in



(a) (b)

Figure 8: U-box test.

(a) (b)

Figure 9: Column segregation test.

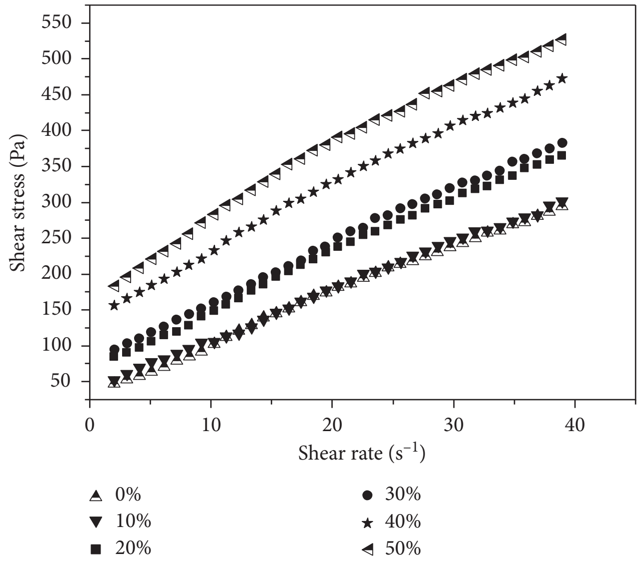


Figure 10: Flow curves of mortar pastes on various replacement levels of rubber particles.

the amount of free water would lead to a decline in the fluidity of mortar pastes.

Figure 12 presents the influence of the shear rate on the plastic viscosity of mortar pastes. Similar to the rheological properties of Portland cement paste [24], shear-thinning behavior can be clearly obtained. Below the critical shear rate value, a drastic reduction of plastic viscosity occurs. When the shear rate exceeds the critical value, plastic viscosity exhibits slight change with an increase in shear rate.

3.2. Fresh Properties of SCRLC.

Experimental tests containing slump flow test, V-funnel test, L-box test, U-box test, and column segregation test on the fresh properties of SCRLC were conducted, and the results are shown in Table 4. Analysis and discussion are given as follows.

3.2.1. Slump Flow Test.

The diversifications of slump flow diameter and T_{500} of SCRLC along with the rubber particles replacement ratio are shown in Figures 13 and 14. It can be seen that substitution of sand by rubber particles affects the slump flow diameter and T_{500} obviously. The slump flow diameter decreases, while T_{500} increases as the rubber particles replacement ratio raises. With the rubber particles replacement ratio increasing from 0 to 50%, slump flow diameter of fresh SCRLC decreases from 785 mm to 580 mm and T_{500} of fresh SCRLC increases from 5.6 s to 9.4 s. The reduction in slump flow diameter is approximately 26%, and the increment in T_{500} is approximately 58%. The changes of the slump flow diameter and T_{500} indicate that both

Table 3: Rheological parameters of mortar pastes.

No.	Replacement (by volume) (%)	Yield stress (Pa)	Plastic viscosity (Pa·s)	Regression equation	Correlative efficient
1	0	35.55	6.79	$y = 35.55 + 6.79\gamma$	0.9956
2	10	40.93	6.76	$y = 40.93 + 6.76\gamma$	0.9976
3	20	70.50	7.79	$y = 70.50 + 7.79\gamma$	0.9967
4	30	80.14	7.94	$y = 80.14 + 7.94\gamma$	0.9975
5	40	147.81	8.57	$y = 147.81 + 8.57\gamma$	0.994
6	50	186.27	9.20	$y = 186.27 + 9.20\gamma$	0.9872

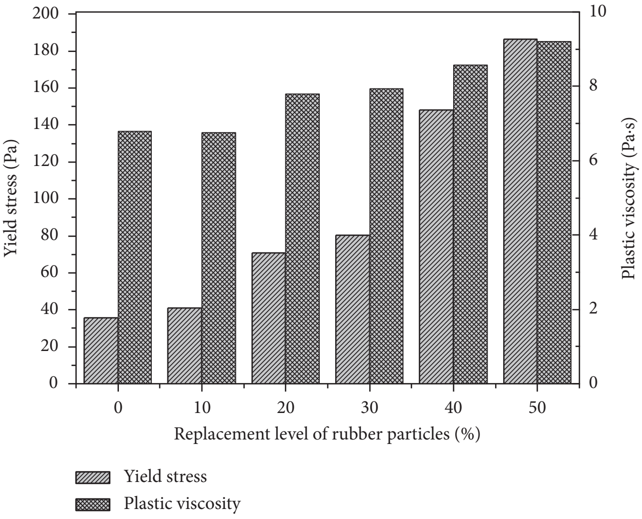


Figure 11: Rheological parameter of mortar pastes at different replacement levels of rubber particles.

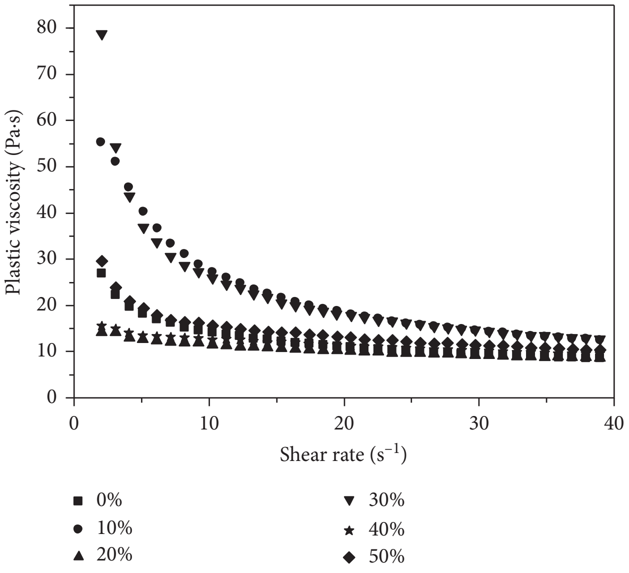


Figure 12: Influence of shear rate on plastic viscosity of mortar pastes.

flowability and flow rate of SCRLC depress as the rubber particles replacement ratio rises. Nonetheless, both slump flow diameter and T_{500} can meet the standard requirements [27] (slump flow diameter > 500 mm and $T_{500} > 2$ s) until the rubber particles replacement ratio is less than 50%. The phenomenon of degeneration on flowability of SCRLC may be mainly ascribed to the rough surface and irregular shape of rubber particles. Increase of rubber particles content will lead to an addition of flow resistance of mortar pastes and then the flowability of SCRLC drops.

3.2.2. V-Funnel Test. Figure 15 shows the V-funnel flow time T_v changes for various rubber particles replacement ratios. As shown in the figure, T_v increases as the rubber particles replacement ratio raises. From the various rubber particles replacement ratio of 0–50%, T_v prolongs from 14.7 s to 24.3 s which is about a 65% prolongation. It indicates that the filling capacity of fresh SCRLC descends with increase of the rubber particles replacement ratio. Although the non-absorbent characteristic of rubber particles will result more free water in concrete mixes and then improve the fluidity of fresh concrete [31], the rough and irregular surface of rubber particles will cut down the fluidity of fresh concrete. Overall, the negative factors are more dominant than positive factors. Thus, T_v prolongs as the rubber particles replacement ratio increases. According to the EFNARC [27], T_v with the rubber particles replacement ratio ranging from 0 to 50% can be attributed to the second grade (V-funnel flow time between 9 s and 25 s).

3.2.3. L-Box Test. The results of T_{400} and h_2/h_1 are presented in Figure 16. It can be seen that T_{400} increases, while the h_2/h_1 decreases as the rubber particles replacement ratio raises. The addition of the rubber particles replacement ratio from 0 to 50% leads to an increase of T_{400} from 7.3 s to 10.9 s and a reduction of h_2/h_1 from 0.98 to 0.82. The variations of T_{400} and h_2/h_1 indicate that the passing ability of fresh SCRLC decreases as the rubber particles replacement ratio increases. The reason for the degradation of passing ability of fresh SCRLC may also be the shape and surface features of rubber particles as explained earlier. Furthermore, all h_2/h_1 when the rubber particles replacement ratio is lower than 50% can meet the criterion of h_2/h_1 (>0.8).

3.2.4. U-Box Test. As can be observed from the results of the U-box test shown in Figure 17, the Δh value approximately increases linearly with rubber particles replacement ratio raise. For the 10%, 20%, 30%, 40%, and 50% increase in the replacement ratio of rubber particles, Δh is increased by 33.3%, 133.3%, 200%, 366.7%, and 500%. The dramatic increment of Δh indicates that passing ability and filling ability of fresh SCRLC drop with increasing the rubber

Table 4: Test results of fresh properties of SCRLC.

Type of concrete	SF (mm)	T_{500} (s)	T_v (s)	T_{400} (s)	h_2/h_1 (s)	Δh (mm)	SR (%)
SCLC	785	5.6	14.7	7.3	0.98	3	10.8
SCRLC10	770	5.8	15.6	7.5	0.97	4	9.7
SCRLC20	740	6.2	16.9	8.1	0.94	7	8.3
SCRLC30	710	6.7	18.5	8.5	0.92	9	7.5
SCRLC40	650	7.9	21.6	9.3	0.87	14	4.9
SCRLC50	580	9.4	24.3	10.9	0.82	18	3.2

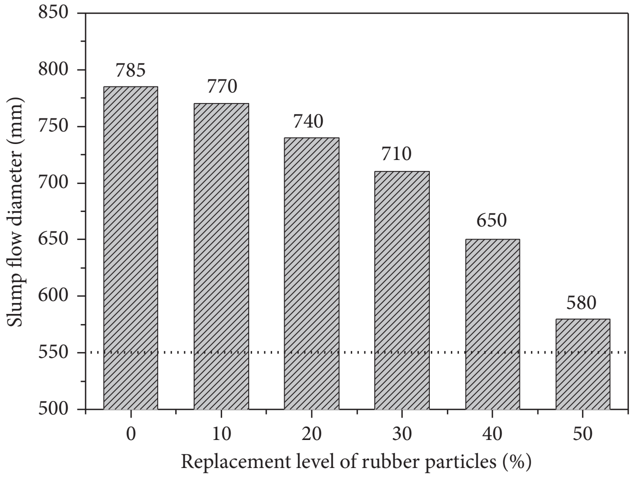


Figure 13: Effect of the replacement level of rubber particles on slump flow.

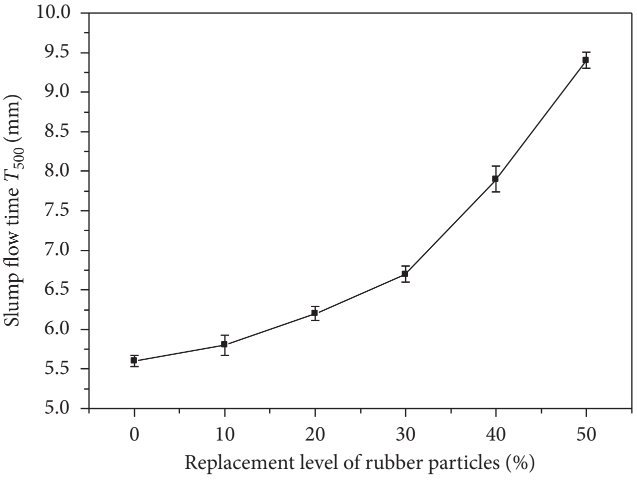


Figure 14: Effect of the replacement level of rubber particles on slump flow time T_{500}.

particles replacement ratio which is in accordance with the results of V-funnel test and L-box test.

3.2.5. Column Segregation Test. The segregation effect of replacing sand with rubber particles at the volume replacement ratio from 0 to 50% in SCRLC can be seen in Figure 18. The increase in sand replacement by rubber particles, while keeping the water content constant, leads to a reduction in the segregation ratio. It means that the segregation resistance property of SCRLC is improved by the addition of rubber particles. Compared with the plain sample, a significant reduction approximately 70% occurred as the rubber particles replacement ratio reaches 50%. The phenomenon for the reduction of the segregation ratio can be mainly attributing to the thickening effect of rubber

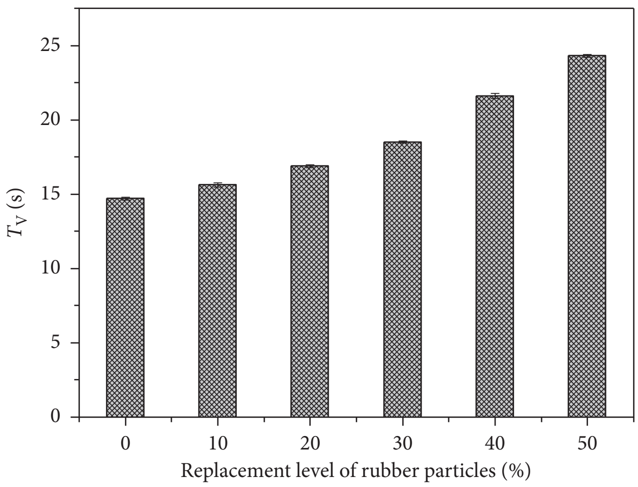


Figure 15: Influence of the replacement level of rubber particles on V-funnel flow time T_v.

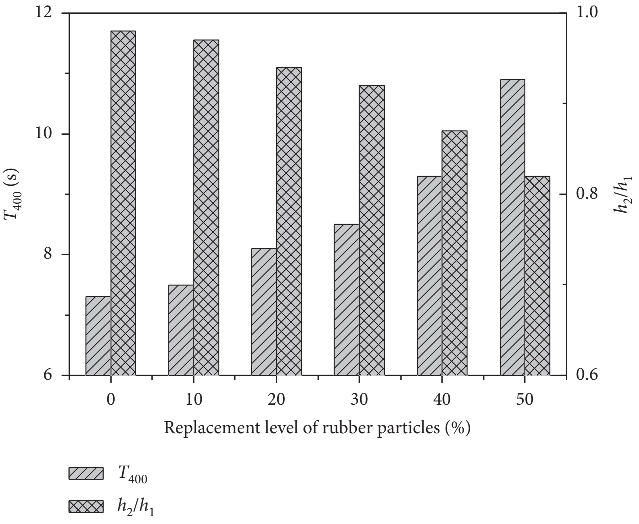


Figure 16: Influence of the replacement level of rubber particles on T_{400} and h_2/h_1.

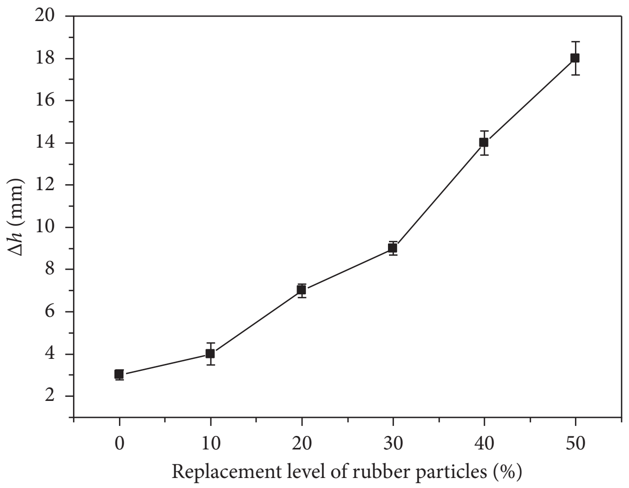


Figure 17: Influence of the replacement level of rubber particles on Δh.

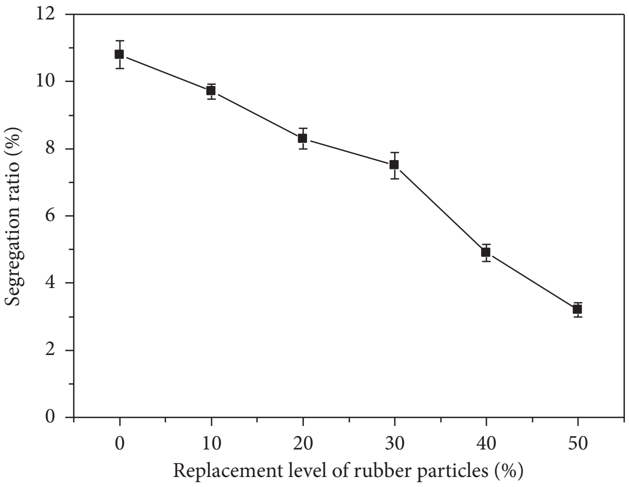


Figure 18: Influence of the replacement level of rubber particles on segregation percent.

particles. Otherwise, all mixtures with the rubber particles replacement ratio ranging from 0 to 50% can conform up to the standard of segregation (segregation ratio ≤ 20%).

3.3. Relation between Fresh Properties of SCRLC and Rheological Properties of Corresponding Mortar Pastes.

Generally, concrete can be viewed as composition of mortar and aggregate. Fresh properties of concrete are closely connected to the rheological properties of mortar pastes and surface characteristics of aggregate. Previous studies [32–35] indicate that keeping the aggregate unchanged, flowability of concrete mainly depends on shear stress of mortar and segregation resistance property of concrete is mainly controlled by plastic viscosity of mortar pastes. Thus, in order to detect the correlation between rheological properties of mortar and fresh properties of SCRLC, the statistical analysis is conducted as follows.

The correlation between slump flow of SCRLC and shear stress of corresponding mortar pastes is presented in Figure 19. A mathematical equation fitting to the variation of slump flow of SCRLC with shear stress of corresponding mortar pastes is proposed and given below:

$$y = -0.77x + 637.2, \tag{2}$$

where y is the shear stress of mortar pastes (Pa) and x is the slump flow of SCRLC (mm).

From Figure 19, it can be seen that a high correlation coefficient (0.984) is obtained from the analytical regression. It indicates that the correlation between slump flow of SCRLC and shear stress of corresponding mortar pastes is fairly good. The slump flow of SCRLC increases as the shear stress of corresponding mortar pastes depresses. According to the EFNARC [27], slump flow of self-compacting concrete should be higher than 550 mm. In combination with the equation above, ensuring self-compactability of rubber lightweight aggregate concrete, the shear stress of corresponding mortar pastes should be less than 231.7 Pa.

Figure 20 represents the relationship between segregation ratio of SCRLC and plastic viscosity of corresponding mortar pastes. The equation regressed from the test points is given as follows:

$$y = -0.327x + 10.26, \tag{3}$$

where y is the plastic viscosity of mortar pastes (Pa·s) and x is the segregation ratio of SCRLC (%).

As indicated in Figure 20, the correlation between segregation ratio of SCRLC and plastic viscosity of corresponding mortar pastes is good and relationship is linear. Decreasing of plastic viscosity of mortar pastes leads to an increase in the segregation ratio of SCRLC. Based on the EFNARC [27], self-compacting effect of concrete can be realized that partially depends on the segregation ratio of fresh concrete (≤20%). Thus, in order to make sure the rubber lightweight aggregate concrete can compact by itself, the plastic viscosity of corresponding mortar pastes must be greater than 3.72 Pa·s.

3.4. Mechanical Properties of SCRLC.

The influence of the rubber particles replacement ratio on compressive strength, splitting tensile strength, flexural strength, and elastic modulus of SCRLC are summarized in Table 5.

3.4.1. Compressive Strength.

The variations of compressive strength of SCRLC with the rubber particles replacement ratio are shown in Figure 21. It can be seen from Figure 21 that the compressive strength of SCRLC decreases as the rubber particles replacement ratio increases at 7, 28, and 90 days. Compared to control mixture, a dramatic reduction of compressive strength occurs as the rubber particles replacement ratio reaches 50% at 7, 28, and 90 days. The reduction of compressive strength may be mainly ascribed to the lower strength of rubber particles and weaker adhesion between rubber particles and hardened cement paste.

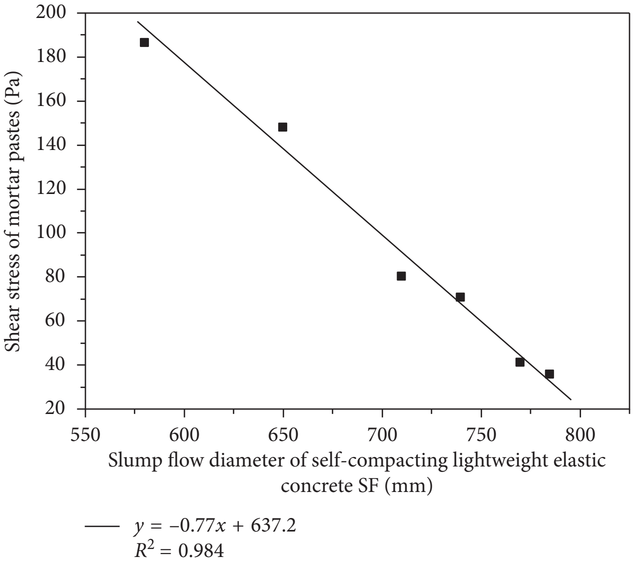


Figure 19: Relationship between slump flow of SCRLC and shear stress of corresponding mortar pastes.

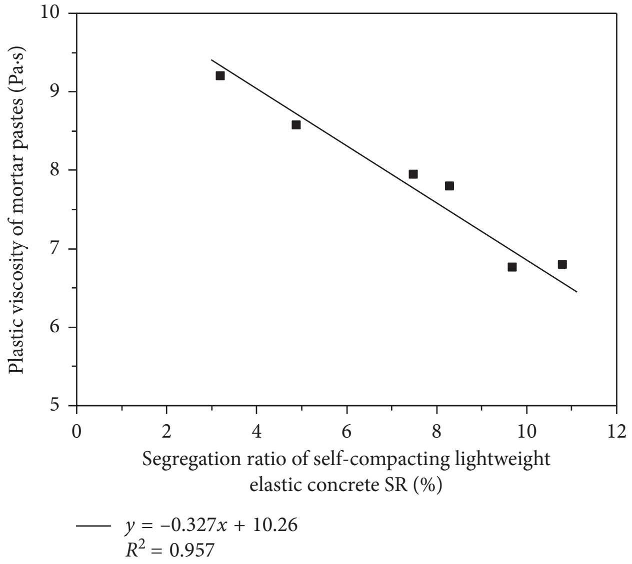


Figure 20: Relationship between segregation ratio of SCRLC and plastic viscosity of corresponding mortar pastes.

The 28-day compressive strength of SCRLC with 50% rubber particles replacement ratio is 20.8 MPa which is still higher than minimum requirements (>17 MPa) of compressive strength of concrete for lightweight aggregate concrete structures [36]. So, the rubber particles replacement ratio level of 50% is found to be acceptable in SCRLC which may be utilized in lightweight aggregate concrete structures.

3.4.2. Splitting Tensile Strength. The splitting tensile strength of SCRLC at 7, 28, and 90 days are presented in Figure 22. As indicated in the figure, similar to the variation of compressive strength, the splitting tensile strength of SCRLC drops as the rubber particles replacement ratio increases. As the rubber particles replacement ratio varies from 0 to 50%, the splitting tensile strength values of SCRLC decrease by 38.7% for 7 days, 46.7% for 28 days, and 44.4% for 90 days. The reductions at 28 and 90 days are greater than 7 days. Apparently, rubber particles play a negative role in splitting tensile strength of SCRLC. The trend of the ratio of splitting tensile strength to compression strength of SCRLC is evident from Figure 23. Increasing the rubber particles replacement ratio increases the ratio of splitting tensile strength to compression strength of SCRLC. It means that the toughness of SCRLC improves as the rubber particles replacement ratio rises. Meanwhile, as the curing age prolongs, the increment of the ratio of splitting tensile strength to compression strength of SCRLC at each rubber particles replacement ratio increases.

The fractured surface of splitting tensile strength test is presented in Figure 24. The rubber particles and lightweight aggregate distribute evenly in the fractured surface. Moreover, most of the lightweight aggregates are fractured, and most of the rubber particles are pulled out from hardened cement paste. It displays that the self-compacting effect of SCRLC is perfect.

3.4.3. Flexural Strength. Figure 25 shows that the flexural strength of SCRLC demonstrates a nearly linear decreasing trend with the increasing rubber particles replacement ratio while increasing with age. For the 0 to 50% increase in the replacement ratio of sand by rubber particles, the flexural strength of SCRLC decreased by 40.4%, 41.0%, and 40.0% at day 7, day 28, and day 90, respectively. Compared with the sample containing no rubber particles, the samples incorporating rubber particles exhibit a better toughness. The ratio of flexural strength to compression strength augments along with the rubber particles replacement ratio as seen in Figure 26. It means that the toughness of SCRLC improves as rubber particles content increases which is similar to those observed in flexural strength experiment phenomena. Most of the rubber particles are pulled out from the hardened cement paste which might be the reason for the improvement of toughness of SCRLC.

3.4.4. Elastic Module. The tendency of 28 days elastic modulus of SCRLC varying with the rubber particles replacement ratio is similar to that of splitting tensile strength, compressive strength, and flexural strength as shown in Figure 27. Compared with control mixture, the reduction ratios of the elastic modulus of SCRLC as the rubber particles replacement ratio varies from 10% to 50% are 9.33%, 15.3%, 25.7%, 32.5%, and 42.2%. It indicates that the rubber particles replacement ratio remarkably influences the elastic modulus of SCRLC. Due to the good plastic deformation capacity of rubber particles, energy dissipation capacity of SCRLC would be significantly improved with the incorporation of rubber particles.

3.5. Compressive Strength of Mortar. The changes of 7-day, 28-day, and 90-day compressive strengths of mortar are

Table 5: The results of compressive strength, splitting tensile strength, flexural strength, and elastic modulus of SCRLC.

Type of concrete	Compressive strength (MPa)			Splitting tensile strength (MPa)			Flexural strength (MPa)			Elastic modulus (GPa)
	7 d	28 d	90 d	7 d	28 d	90 d	7 d	28 d	90 d	28 d
SCLC	29.1	45.6	50.1	2.82	4.41	4.78	3.42	5.03	5.43	26.8
SCRLC10	27.5	43.3	47.2	2.68	4.19	4.51	3.27	4.84	5.12	24.3
SCRLC20	25.2	39.4	43.8	2.59	3.82	4.20	2.99	4.52	4.83	22.7
SCRLC30	21.5	33.8	37.9	2.35	3.36	3.65	2.57	4.07	4.38	19.9
SCRLC40	18.4	25.3	30.7	2.06	2.77	3.12	2.33	3.44	3.69	18.1
SCRLC50	14.7	20.8	25.6	1.73	2.35	2.66	2.04	2.97	3.26	15.5

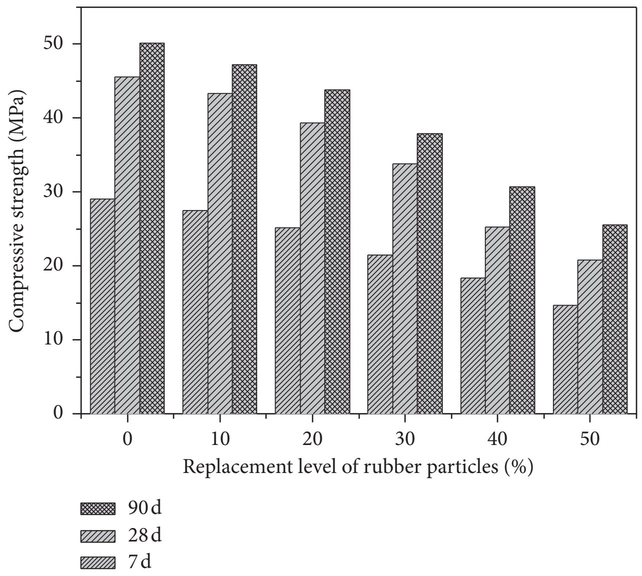


Figure 21: Compressive strength of SCRLC versus replacement level of rubber particles.

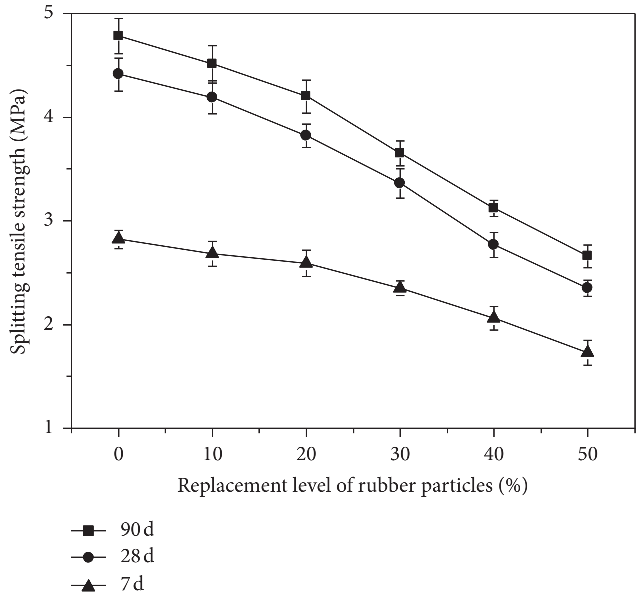


Figure 22: Splitting tensile strength of SCRLC versus replacement level of rubber particles.

shown in Figure 28. The compressive strength of mortar drops as the replacement ratio of rubber particles increases at each age. More than half of the compressive strength is achieved at 7 days. Increasing the rubber particles replacement ratio results in a reduction of the increment of compressive strength of mortar at 7 days. On the contrary, the increment in compressive strength of mortar between 28 days and 90 days rises as the rubber particles replacement ratio increases. Compared with the compressive strength of SCRLC in Section 3.4.1, the compressive strength of mortar is greater than that of SCRLC at each age obviously. It might be the reason why most of the SCRLC samples destroy under uniaxial load at the aggregate itself and the boundaries of aggregate and cement hydration products. Thus, one way to improve the mechanical properties of SCRLC is to enhance the aggregate strength and the adhesive performance between aggregate and cement hydration products.

4. Conclusions

In this paper, a series of experimental studies were conducted to detect the variation of properties of SCRLC and corresponding mortar. The conclusions are drawn as follows.

The Bingham model can be employed to fit the relations between shear rate and shear stress of mortar pastes on various rubber particles replacement ratios. Increasing the rubber particles replacement ratio in the mortar pastes significantly augments both the plastic viscosity and yield stress of mortar pastes. The fluidity of mortar depresses as the rubber particles replacement ratio rises.

With increase of rubber particles replacement ratio in SCRLC, the fresh properties of SCRLC including slump flow diameter, h_2/h_1, and segregation ratio drop, while T_{500}, T_v, T_{400}, and Δh rise. It indicates that flowability, filling capacity, and passing ability of SCRLC decline as the rubber particles replacement ratio increases. On the contrary, the segregation resistance property of SCRLC improves with the raising of the rubber particles replacement ratio.

The fresh properties of SCRLC and rheological properties of corresponding mortar pastes show a linear relationship. In order to ensure that the rubber lightweight aggregate concrete can compact by itself, the shear stress of corresponding mortar pastes should be lower than 231.7 Pa and the plastic viscosity of corresponding mortar pastes should be greater than 3.72 Pa·s.

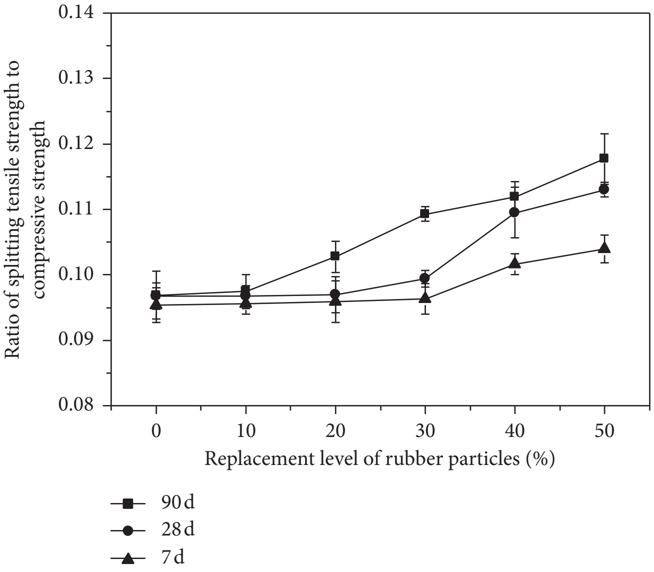


Figure 23: Ratio of splitting tensile strength to compression strength versus replacement level of rubber particles.

Figure 24: Fractured surface in the test.

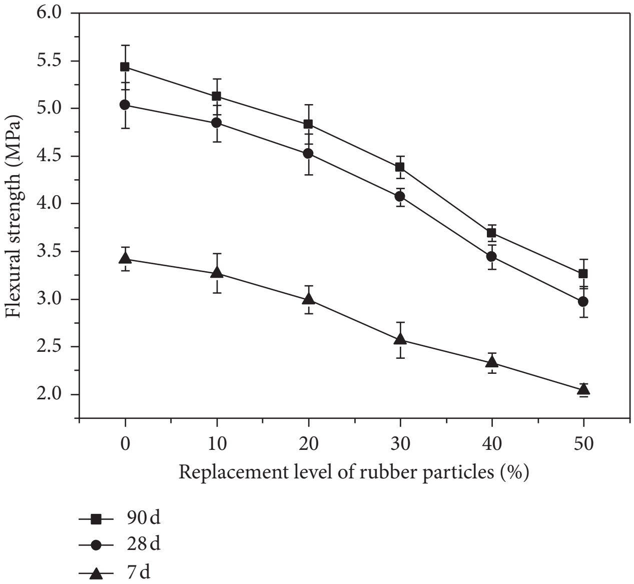


Figure 25: Flexural strength of SCRLC versus replacement level of rubber particles.

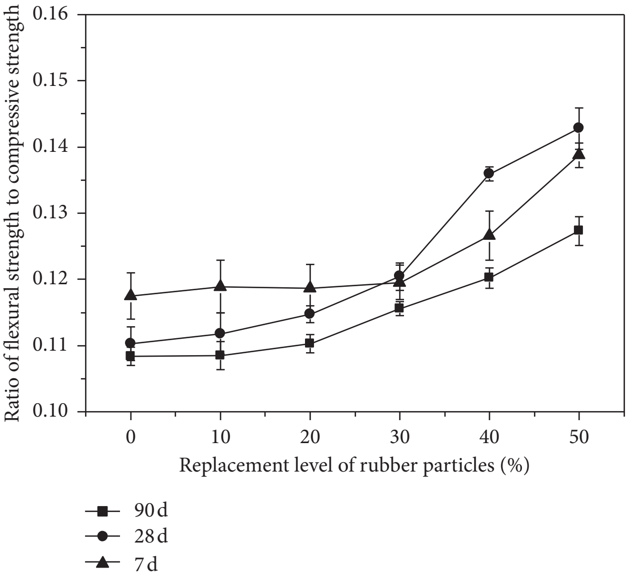


Figure 26: Ratio of flexural strength to compression strength versus replacement level of rubber particles.

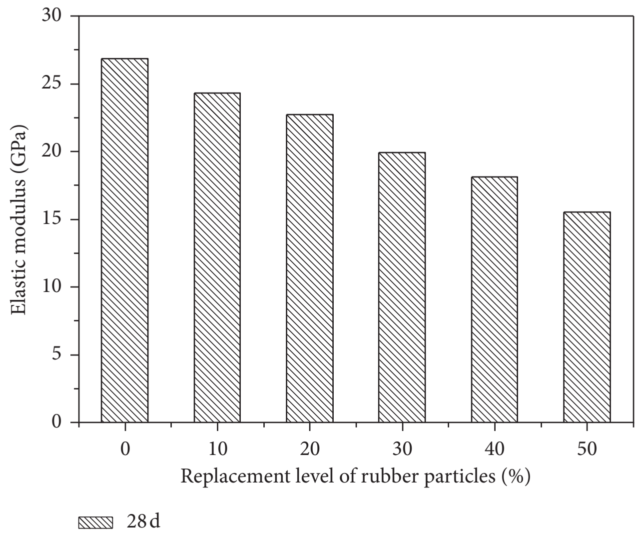


Figure 27: Elastic modulus of SCRLC versus replacement level of rubber particles.

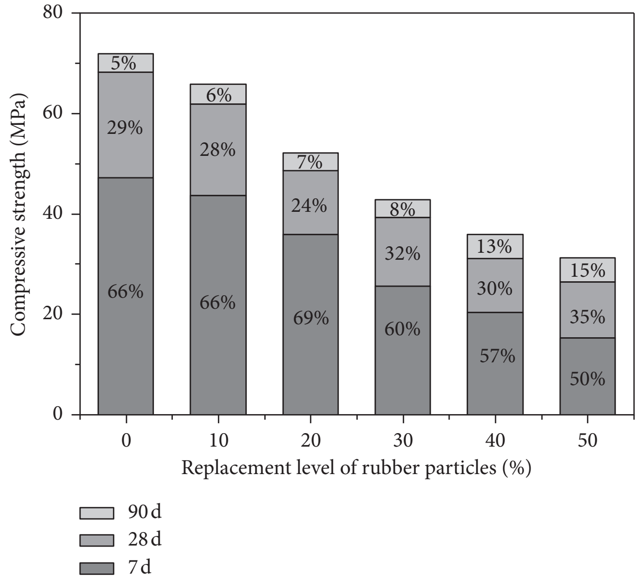


Figure 28: Compressive strength of mortar versus replacement level of rubber particles.

The compressive strength, splitting tensile strength, flexural strength, and elastic modulus of SCRLC and compressive strength of corresponding mortar reduce as the rubber particles replacement ratio increases. The compressive strength of SCRLC is lower than that of corresponding mortar. The SCRLC with the rubber particles replacement ratio below 50% can be utilized in lightweight aggregate concrete structures. In order to improve the mechanical properties of SCRLC, the aggregate strength and the adhesive performance between aggregate and cement hydration products should be enhanced.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors wish to acknowledge the financial support of the National Social Science Foundation of China (16CJY028), Fundamental Research Funds for the Central Universities (300102238303), and Natural Science Foundation Research Project of Shaanxi Province of China (2016JM5044).

References

[1] L.-J. Li, G.-R. Tu, C. Lan, and F. Liu, “Mechanical characterization of waste-rubber-modified recycled-aggregate concrete,” *Journal of Cleaner Production*, vol. 124, pp. 325–338, 2016.

[2] T. Gupta, S. Chaudhary, and R. K. Sharma, “Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate,” *Construction and Building Materials*, vol. 73, pp. 562–574, 2014.

[3] H. Huynh and D. Raghavan, “Durability of simulated shredded rubber tire in highly alkaline environments,” *Advanced Cement Based Materials*, vol. 6, no. 3-4, pp. 138–143, 1997.

[4] J. Lv, T. Zhou, Q. Du, and H. Wu, “Effects of rubber particles on mechanical properties of lightweight aggregate concrete,” *Construction and Building Materials*, vol. 91, pp. 145–149, 2015.

[5] A. M. Nayef, A. R. Fahadand, and B. Aluned, “Effect of microsilica addition on compressive strength of rubberized concrete at elevated temperatures,” *Journal of Material Cycles and Waste Management*, vol. 12, no. 1, pp. 41–49, 2010.

[6] E. Ozbay, M. Lachemi, and U. K. Sevim, “Compressive strength, abrasion resistance and energy absorption capacity of rubberized concretes with and without slag,” *Materials and Structures*, vol. 44, no. 7, pp. 1297–1307, 2010.

[7] M. A. Aiello and F. Leuzzi, “Waste tyre rubberized concrete: properties at fresh and hardened state,” *Waste Management*, vol. 30, no. 8-9, pp. 1699–1704, 2010.

[8] H.-Y. Wang, B.-T. Chen, and Y.-W. Wu, “A study of the fresh properties of controlled low-strength rubber lightweight aggregate concrete (CLSRLC),” *Construction and Building Materials*, vol. 41, pp. 526–531, 2013.

[9] N. Ganesan, J. Bharati Raj, and A. P. Shashikala, “Flexural fatigue behavior of self compacting rubberized concrete,” *Construction and Building Materials*, vol. 44, pp. 7–14, 2013.

[10] O. Onuaguluchi and D. K. Panesar, “Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume,” *Journal of Cleaner Production*, vol. 82, pp. 125–131, 2014.

[11] H. Zhu, J. Liang, J. Xu, M. Bo, J. Li, and B. Tang, “Research on anti-chloride ion penetration property of crumb rubber concrete at different ambient temperatures,” *Construction and Building Materials*, vol. 189, pp. 42–53, 2018.

[12] J. Xu, Z. Fu, Q. Han, G. Lacidogna, and A. Carpinteri, “Micro-cracking monitoring and fracture evaluation for crumb rubber concrete based on acoustic emission techniques,” *Structural Health Monitoring*, vol. 17, no. 4, pp. 946–958, 2017.

[13] T.-C. Ling, “Prediction of density and compressive strength for rubberized concrete blocks,” *Construction and Building Materials*, vol. 25, no. 11, pp. 4303–4306, 2011.

[14] K. B. Najim and M. R. Hall, “A review of the fresh/hardened properties and applications for plain- (PRC) and self-compacting rubberised concrete (SCRC),” *Construction and Building Materials*, vol. 24, no. 11, pp. 2043–2051, 2010.

[15] L.-J. Hunag, H.-Y. Wang, and Y.-W. Wu, “Properties of the mechanical in controlled low-strength rubber lightweight aggregate concrete (CLSRLC),” *Construction and Building Materials*, vol. 112, pp. 1054–1058, 2016.

[16] N. M. Miller and F. M. Tehrani, “Mechanical properties of rubberized lightweight aggregate concrete,” *Construction and Building Materials*, vol. 147, pp. 264–271, 2017.

[17] T. M. Grabois, G. C. Cordeiro, and R. D. Toledo Filho, “Fresh and hardened-state properties of self-compacting lightweight concrete reinforced with steel fibers,” *Construction and Building Materials*, vol. 104, pp. 284–292, 2016.

[18] E. Mohseni, R. Saadati, N. Kordbacheh, Z. S. Parpinchi, and W. Tang, “Engineering and microstructural assessment of fibre-reinforced self-compacting concrete containing recycled coarse aggregate,” *Journal of Cleaner Production*, vol. 168, pp. 605–613, 2017.

[19] N. Bouzoubaâ, R. Patel, M. Shehata, M. Lamech, and K. M. A. Hossain, “Influence of paste/mortar rheology on the flow characteristics of high-volume fly ash self-consolidating concrete,” *Magazine of Concrete Research*, vol. 59, no. 7, pp. 517–528, 2007.

[20] I. Y. T. Ng, P. L. Ng, and A. K. H. Kwan, “Rheology of mortar and its influences on performance of self-consolidating concrete,” *Key Engineering Materials*, vol. 400–402, pp. 421–426, 2008.

[21] ASTM C 618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, ASTM International, West Conshohocken, PA, USA, 2015.

[22] J. E. Wallevik, “Rheological properties of cement paste: thixotropic behavior and structural breakdown,” *Cement and Concrete Research*, vol. 39, no. 1, pp. 14–29, 2009.

[23] J. Gołaszewski, “Influence of cement properties on new generation superplasticizers performance,” *Construction and Building Materials*, vol. 35, no. 10, pp. 586–596, 2012.

[24] A. Papo and L. Piani, “Effect of various superplasticizers on the rheological properties of Portland cement pastes,” *Cement and Concrete Research*, vol. 34, no. 11, pp. 2097–2101, 2004.

[25] H. B. Xie, F. Liu, Y. R. Fan et al., “Workability and proportion design of pumping concrete based on rheological parameters,” *Construction and Building Materials*, vol. 44, no. 3, pp. 267–275, 2013.

[26] D. P. Bentz, C. F. Ferraris, M. A. Galler, A. S. Hansen, and J. M. Guynn, “Influence of particle size distributions on yield stress and viscosity of cement-fly ash pastes,” *Cement and Concrete Research*, vol. 42, no. 2, pp. 404–409, 2012.

[27] EFNARC, *The European Guidelines for Self-compacting Concrete*, International Bureau for Precast Concrete (BIBM), Brussels, Belgium, 2005.

[28] GB/T50081-2002, *Standard for Test Method of Mechanical Properties on Ordinary Concrete*, Ministry of Construction of the PRC, China Architecture and Building Press, Beijing, China, 2003.

[29] JGJ/T70-2009, *Standard for Test Method of Basic Properties of Construction Mortar*, Ministry of Construction of the PRC, China Architecture and Building Press, Beijing, China, 2009.

[30] P. F. G. Banfill, “The rheology of fresh cement and concrete-a review,” in *Proceedings 11th International Congress on the Chemistry of Cement*, pp. 50–62, Liverpool, UK, 2003.

[31] S. Yang, X. Q. Yue, X. S. Liu, and Y. Tong, “Properties of self-compacting lightweight concrete containing recycled plastic particles,” *Construction and Building Materials*, vol. 84, pp. 444–453, 2015.

[32] O. H. Wallevik and J. E. Wallevik, “Properties rheology as a tool in concrete science: the use of rheographs and workability boxes,” *Cement and Concrete Research*, vol. 41, no. 12, pp. 1279–1288, 2011.

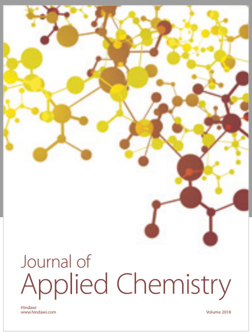
[33] A. W. Saak, H. M. Jennings, and S. P. Shah, “New methodology for designing self-compacting concrete,” *ACI Materials Journal*, vol. 98, no. 6, pp. 429–439, 2011.

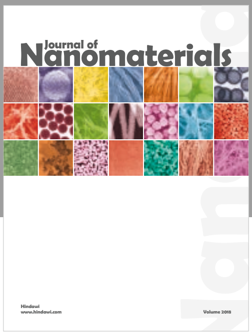
[34] N. Roussel, “A theoretical frame to study stability of fresh concrete,” *Materials and Structures*, vol. 39, no. 1, pp. 81–91, 2006.

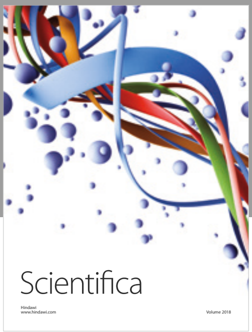
[35] Y. Akkaya, S. P. Shah, and V. K. Bui, “Rheological model for self-consolidating concrete,” *ACI Materials Journal*, vol. 99, no. 6, pp. 549–559, 2002.

[36] İ. B. Topçu and T. Uygunoğlu, “Effect of aggregate type on properties of hardened self- consolidating lightweight concrete (SCLC),” *Construction and Building Materials*, vol. 24, no. 7, pp. 1286–1295, 2010.

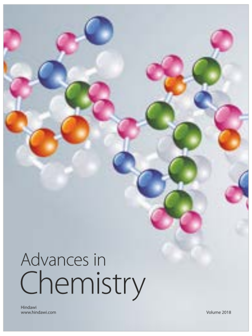

The Scientific World Journal

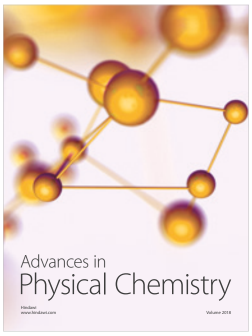

Journal of Applied Chemistry

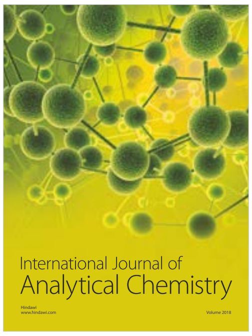

Journal of Nanomaterials

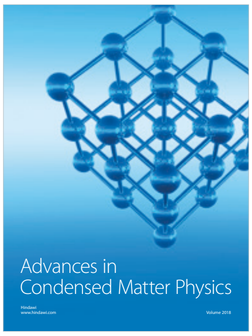

Scientifica


International Journal of Polymer Science


Advances in Chemistry

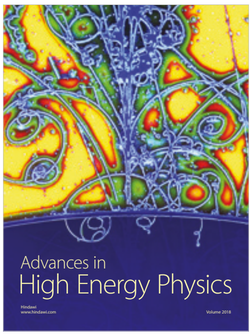

Advances in Physical Chemistry


International Journal of Analytical Chemistry


Advances in Condensed Matter Physics


Journal of Chemistry


International Journal of Biomaterials


Advances in High Energy Physics

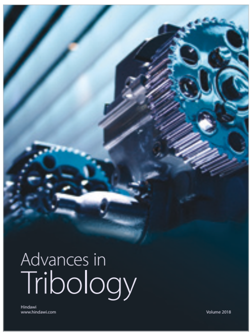

Journal of Engineering

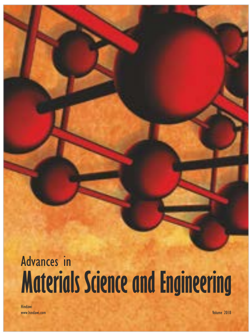

Journal of Nanotechnology


International Journal of Corrosion


Journal of Materials


BioMed Research International


Advances in Tribology


Advances in Materials Science and Engineering