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Research Article

Rheology and Permeability of Self-Compacting Concretes with Recycled Blue Aggregate

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Since the sustainability of concrete became a very important property in the past decades, 15 mixes of self-compacting concrete (SCC), as well as control mixes, were examined to find out the effect of replacing natural aggregates with recycled blue glass (RBG) waste on the rheological properties and permeability of self-compacting concrete. For this purpose, 3 series of SCCs were mixed: the 1st group replaced the natural aggregate (NFA) with fine recycled waste blue glass (RFWBG), the 2nd group replaced the natural coarse aggregate (NCA) with coarse recycled waste blue glass (RCWBG), and the last group replaced the natural aggregate with recycled blue glass (RGA). Each group contains 5 ratios of replacement (0%, 20%, 40%, 60%, 80%, and 100%). The results showed that the torque increased with the increase in recycled green glass replacement; for instance, it increased from 0.95 for control mixes to 1.302, 1.384, and 1.459 Nm for 100% replacement in the 1st, 2nd, and 3rd groups. Meanwhile, the permeability tests include chloride ion permeability (RCPT), a water sorptivity test, and a gas permeability test at 28 days; likewise, this study showed that these characteristics increase with the increase of recycled blue glass.

1. Introduction

Sustainability is an innovation of new composite matters which leads to a decrease in the great exhaustion of natural resources. During the last two decades, considerable development has been made to understand the attitude of SCC toward recycled garbage materials, especially with glass, since glass has high pozzolanic reactivity and chemical and physical properties that are approximately similar to natural aggregates [1].

SCC is a kind of high-performance concrete that, due to its weight and stability, can flow without any vibration. Since SCC has a high fill capacity, that property leads to low honeycomb construction and high-quality structures [1, 2].

Rheology is a science that has many definitions. Mindees et al. [3] define rheology as the science related to the deformation of flow under stress, while rheology is the science related to the deformation and flow of matter according to Daczko and Joseph [4]. Also, Cornman [5] defined rheology as the science of the deformation and flow of materials.

Saak et al. [6] showed that the rheology of concrete is determined by the fluidity of the matrix and the packing density, volume, and particle size distribution of the aggregate. They also foundthat the rheology of concrete is enhanced at a cement paste yield stress and that the viscosity simply rises sufficiently to avert segregation. However, segregation resistance is improved for SCC at the highest yield stress and viscosity during the self-flow zone.

The Bingham model is the best way to define the flow of concrete mixtures because it assumes that there is a linear relationship between shear rate and shear stress and calculates initial yield stress.The Bingham model is the most generally utilized model for clarifying the flow of concrete mixes. It postulates a linear relationship between shear rate and shear stress and counts initial yield stress, determining the flow conductivity of concrete mixes more neatly than other models. This model demands finding out two factors: the dynamic yield stress and the plastic viscosity [7].

Fluid rheology is confirmed knowledge that is straightly useable to the workability of fresh concrete. Yield stress explains a lower limit of force wanted to begin the concrete's flow. For plain concrete, vibration is that force. Plastic viscosity could be qualified as the resistance to flow or the stiffness of fresh concrete [8, 9].

Plain concrete has a higher yield stress than SCC, which makes SCC easily flowable. Figure 1 shows differences in the flow curves of plain concrete with various SCC mixes. Because plain concrete has a high dynamic yield stress, it requires supplement power in the form of vibration for compaction after it has been poisoned in various forms. The SCC mixes have the least dynamic yield stress and compact under their own weight, but the rheological characteristics vary depending on the viscosity. The SCC with a high plastic viscosity will be glutinous and hard to finish, whereas the mixture with a minimum plastic viscosity will resort to segregation. So, by utilizing various mix ratios and admixtures, the best evenness between resistance to segregation and resistance to segregation has to be realized for satisfying behavior [10, 11].

Wang and Huang [12] explained that the utilization of glass accounted for up to 30% of the durability properties of self-compacting blue glass concretes (SCBGCs) since the chloride ion penetration decreased to 100 coulombs (C) at 180 days, while Ling et al. [11] produced self-compacting white cement mortar with 100% recycled glass as sand replacement. The results showed that the initial surface absorption and final water absorption of concrete increased as the number of glasses increased.

Adhikary et al. [13] reported on the use of expanded glass as a lightweight in concrete and the different properties of various types of concrete.

Also, Mehta and Ashish [14] presented the utilization of fly ash and waste glass as a powder on the workability, strength, and durability properties of concrete in addition to microstructural analysis, which was studied.

The purpose of this article is to study the attitude of SCCs when using recycled blue glass (RBG). For this reason, 16 mixtures of SCBGCs were classified into 3 series, with 5 ratios of replacement used (20%, 40%, 60%, 80%, and 100%) for each series. The 1st series contained RFWBG as a replacement for sand, the 2nd series contained RCWBG as a replacement for gravel, and the final series contained RBG as a replacement for both sand and gravel in addition to the reference mix. The tests utilized in this article are rheology for fresh SCGCs and hardening concrete, the rapid chloride penetration test (RCPT), gas permeability, and water sorptivity at 28 days.

2. Experimental Work

2.1. Materials. In this study, Portland cement used in whole SCBGCs mixes was ordinary cement denotated as CEM I 42.5 R, which is identical to the European EN 197-1 [15]. Three different series of SCBGCs were designed with a fixed water/binder content of 0.35 and binder materials of 570 kg/m^3 [16]. Blue bottles have been collected from the garbage and then cleaned and crushed into a fine and coarse blue glass. Moreover, fly ash (FA) was used in concrete as a substitution material by weight of cement at a 20% level. The chemical and physical properties of cement, FA, and RBG are registered in Table 1. The physical characteristics of RBG and natural aggregates (NA) were as stated by ASTM C127 [17]. Under this consideration, a superplasticizer (SP) with a specific gravity of 1.07 was utilized to gain the coveted workability.

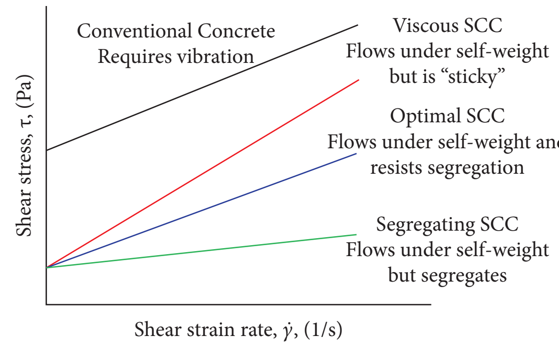


Figure 1: Flow curves [10].

NA was replaced at various levels by the weight of RBG. In such consideration, recycled fine waste blue glass aggregate (RFWBG) had a particle size of 0–4 mm and a specific gravity of 2.58, while recycled coarse waste blue glass aggregate (RCWBG) was used with a particle size of 4–11.2 mm and a specific gravity of 2.62 (Figure 2). RBG's 24-hour absorption ability was insufficient and could be neglected. Meanwhile, river sand-type natural coarse aggregate (NCA) and natural fine aggregate (NFA) stratifying to the TS 706 EN 12620-A1 [18] were utilized. The ultimate sizes of NCA and NFA were 16 and 4 mm, while their 24-hour absorption abilities were 0.77% and 1.09%, respectively. However, the physical control of RBG displayed a sharp edge, smooth surfaces, and an angular shape. The physical properties and sieve analysis of the aggregates utilized in this investigation appear in Table 2. For this, 16 different SCBGC mixes were prepared, as presented in Table 3.

2.2. Test Procedure. Rheology deals with the relationships between strain, stress, rate of strain, and time [20]. One of the pioneers of concrete rheology was Tattersall, and he invented the way to describe the behavior of fresh concrete using the Bingham model [21], as shown in Figure 3. The next equation was used to calculate the shear stress for each mix:

$$t = t_0 + \mu\gamma, \quad (1)$$

where t denotes the shear stress [Pa], t_0 is the yield stress [Pa], μ is the plastic viscosity [Pa·s], and γ is the shear rate [s^{-1}].

The rapid chloride permeability test (RCPT), as recommended by ASTM C1202, was utilized to locate the resistance of concrete to the permeation of chloride ions [22], as shown in Figure 4.

The sorptivity test measured the rate at which water is pulled into the pores of the concrete, as demonstrated in Figure 5.

Table 1: Characteristics of cement, blue glass, and fly ash.

Chemical analyses (%)	Cement	Fly ash	Blue glass
CaO + MgO	67.16	4.63	8.15
SiO_2	19.80	57.20	74.91
Al_2O_3	3.87	24.40	0.05
Fe_2O_3	4.18	7.10	0.03
Na_2O	—	0.38	15.72
B_2O_3	—	—	0.6
As_2O_3	—	—	0.244
CoO	—	—	0.45
Other oxides	2.35	2.65	—
Loss on ignition	0.89	1.50	—
Specific gravity	3.15	2.04	2.6
Specific surface area (m^2/kg)	326	379	—

In the gas permeability test, the coefficients of apparent oxygen gas permeability are specified, as stated by RILEM [23], on totally dry specimens. As shown in Figure 6. Stratify the next equation on each specimen to calculate apparent gas permeability, and after the average of two specimens, we obtain $Ki = 2P_2QL\mu/\mathrm{A}\ (\mathrm{P}_1 - \mathrm{P}_2)^2$, where K is the gas permeability coefficient (m^2), P_1 represents the inlet gas pressure (N/m^2), P_2 represents outlet gas pressure (N/m^2), A represents the cross-sectional area of the specimen (m^2), L represents the height of the specimen (m), μ represents the viscosity of oxygen (2.02×10^{-5} Nsn/m^2), and Q represents the rate of flow of an air bubble (m^3/s).

3. Results and Discussion

3.1. Rheology Test. Figures 7(a)–7(c) represent the torque and rotational speed obtained from the ICAR rheometer for the 1st, 2nd, and 3rd series compared to the ref. mix. It can be noticed that the torque values increased with the increase in RBG since the rotational speeds stayed the same for each mixture. However, there is a relationship between the torque values and the amount of RBG. The torque values increased as the amount of RBG increased. For example, the torque values in mix 1 (ref. mix) were 0.95 compared to 1.302 Nm in mix 6. Also, from Figures 7(a)–7(c), it appeared that the intensity of shear thickening became remarkable whenever RBG was present and/or its content increased, particularly between 80% and 100% replacement levels. Moreover, series no. 1 was less susceptible to shear thickening compared with other series.

The rheology results declared that the yield stress values of the tested SCBGCs were less than 10 Pa. However, the plastic viscosity of SCBGCs changed between 36.3 and 52.3 Pa.s for the ref. mix and full replacement of BG concrete, respectively.

3.2. Rapid Chloride Permeability Test (RCPT). Figure 8 shows the results of the rapid chloride permeability test, which was carried out on the average of 3 samples at 28 days' age for SCBGCs. As illustrated in Figure 8, the conclusions of the RCPT of SCBGCs categorized these mixes as moderate according to ASTM C1202 [22]. From Figure 8, the results obtained show an inverse relationship between the amount of RBG and the total charge passed. For paradigm, the total charges passed over the ref. mix (mix 1) were 2074.89 coulombs, compared to the total charges passed of 3130.308, 3326.74, and 3512.4 coulombs for the 1st, 2nd, and 3rd series for 100% replacement of RBG (mix 6, mix 11, and mix 16). This attitude may refer to the existence of microcracks inside recycled blue glass during the pulverizing process. Figure 8 also shows that the total charge passed through series no. 2 and 3 was more than the total charge passed through series no. 1. For instance, the total charge passed through the 1st series was 33.7%, compared to 37.6% and 40.9% in series nos. 2 and 3, respectively. This attitude may be due to the rise in the size and amount of microcracks due to the particles of RBG.

3.3. Sorptivity Index. The average of water motion inside the concrete specimens beneath the action of capillary strengths is the definition of the water sorptivity test [25]. Figure 9 represents the sorptivity coefficient of SCBGCs in the average of 3 samples at 28 days, accounting for the type and substitution ratios of recycled blue glass. The test results showed that the substitution of BRG instead of NA hurt the sorptivity coefficients. For instance, the sorptivity coefficient for ref. mix (mix no. 1) was 0.07 $mm/min^{0.5}$ compared to (0.096, 0.1006, and 0.1076 $mm/min^{0.5}$) at 100% substitution of fine, coarse, and both (mix 6, mix 11, and mix 16), respectively. Since the blue recycled glasses have a corner shape and an acute rim, which leads to a rise in the quantity of air, resulting in a rise in the porosity due to a rise in the continuity and quantity of air inside the concrete structure, this rising of sorptivity may be due to capillary absorption of SCBGCs.

3.4. Gas Permeability. The apparent gas permeability has been studied, as mentioned by the Hagen–Poiseuille connection for the laminar flow of a compressible fluid inside a porous body with small capillaries under stable-status conditions [24]. As per the demand of RILLIM [23], the average of 2 samples according to RELIM of the gas permeability coefficient was determined by using 150, 200, and 300 kPa inlet pressures. Figure 10 illustrates the gas permeability coefficients of SCBGCs tested at 28 days. From Figure 10, it can be seen that the gas permeability coefficient rises with the increments in recycled junk blue glass quantity. For instance, the gas permeability coefficient of ref. mix (mix no. 1) was $1.9787 \times 10^{-16}\ m^2$, matched to 5.84 and $6.254 \times 10^{-16}\ m^2$ for 100% replacement of NFA (series no. 1) and NCA (series no. 2). For both substitutions (series no. 3), the gas permeability coefficient was $5.3528 \times 10^{-16}\ m^2$ for an 80% replacement. Since the amount of air was very large for RFBGA100RCBGA100 substitutions (Mix 16, 100% substitution of naturally fine and naturally coarse aggregate by RFBGA and RCBGA), it cannot be calculated. It could be noticed that the same direction of the sorptivity index was coming back for gas permeability coefficients. This attitude is due to raising the size of pores and pore

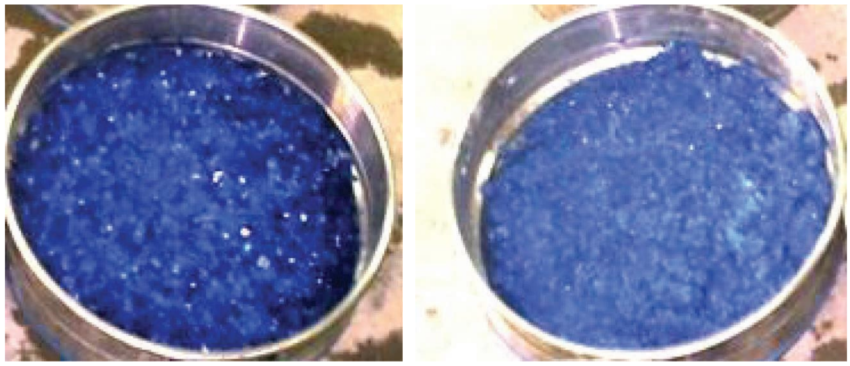


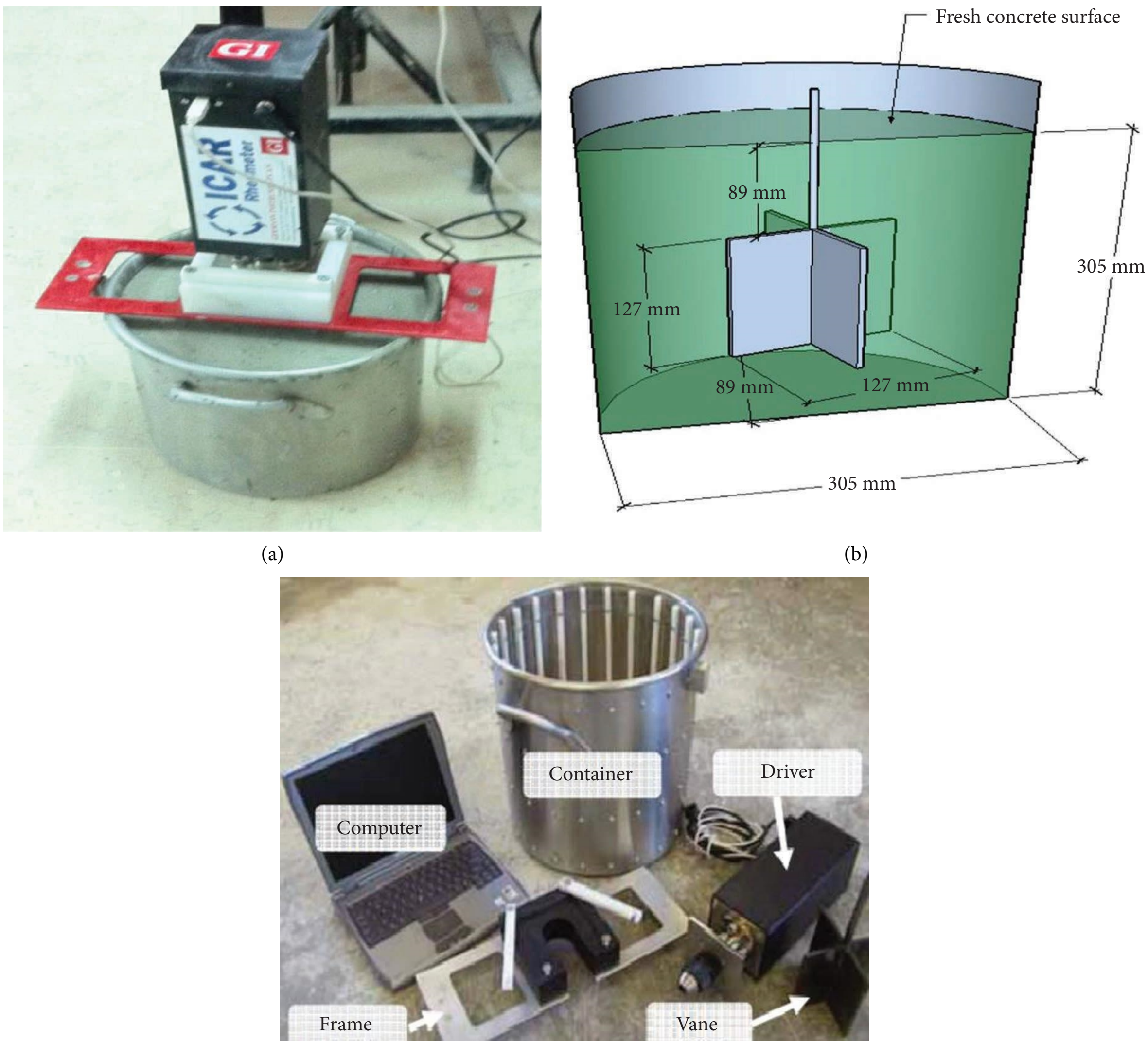
Figure 2: Recycled glass coarse and fine aggregate.

Table 2: Physical characteristics of natural and glass aggregates [19].

Sieve sizes (mm)	Natural aggregate		Glass aggregate	
	NFA	NCA	RFWBG	RCWBG
16	100	100	100	100
8	100	30.40	100	24.10
4	100	0	100	0
2	58.13	0	51.57	0
1	37.20	0	30.89	0
0.5	24.24	0	10.63	0
0.25	8.70	0	3.43	0
0.125	0	0	0	0
Fineness modulus	3.72	6.70	4.03	6.76
Specific gravity	2.39	2.69	2.53	2.55

Table 3: Concrete mixture proportions.

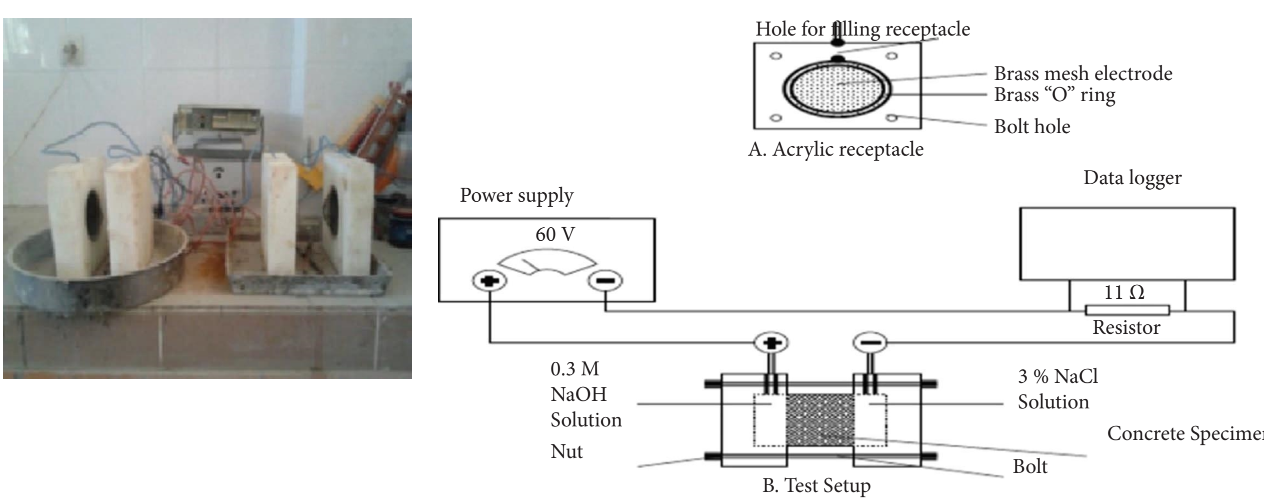
Series no	Mix. no	Mix ID	Vol. fraction (%)				SP (kg/m^3)
			Fine aggregate		Coarse aggregate		
			NFA	RFGBA	NCA	RCBGA	
Ref	Mix 1	RFGBA 0 RCBGA 0	100	0	100	0	4.45
Series no. 1	Mix 2	RFGBA 20 RCBGA 0	80	20	100	0	4.39
	Mix 3	RFGBA 40 RCBGA 0	60	40	100	0	4.22
	Mix 4	RFGBA 60 RCBGA 0	40	60	100	0	4.13
	Mix 5	RFGBA 80 RCBGA 0	20	80	100	0	3.99
	Mix 6	RFGBA 100 RCBGA 0	0	100	100	0	3.88
Series no. 2	Mix 7	RFGBA 0 RCBGA 20	100	0	80	20	4.39
	Mix 8	RFGBA 0 RCBGA 40	100	0	60	40	4.33
	Mix 9	RFGBA 0 RCBGA 60	100	0	40	60	4.33
	Mix 10	RFGBA 0 RCBGA 80	100	0	20	80	4.29
	Mix 11	RFGBA 0 RCBGA 100	100	0	0	100	4.28
Series no. 3	Mix 12	RFGBA 20 RCBGA 20	80	20	80	20	4.28
	Mix 13	RFGBA 40 RCBGA 40	60	40	60	40	4.10
	Mix 14	RFGBA 60 RCBGA 60	40	60	40	60	3.99
	Mix 15	RFGBA 80 RCBGA 80	20	80	20	80	3.88
	Mix 16	RFGBA 100 RCBGA 100	0	100	0	100	3.76



(a) (b)

(c)

Figure 3: View of (a) a rheometer, (b) a detailed schematic representation, and (c) an ICAR device with its accessories.



(a) (b)

Figure 4: RCPT test setup: (a) a pictorial vision of the RCPT test setup and (b) a graphical show of the test setup for RCPT.

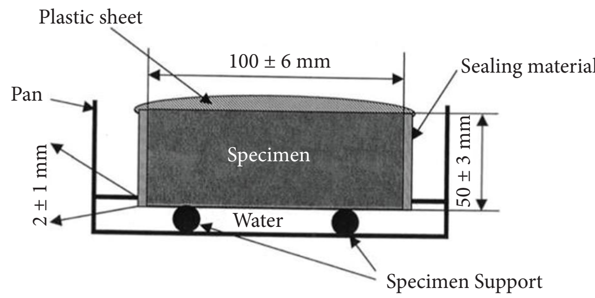


FIGURE 5: Schematic of the water sorptivity measurement.

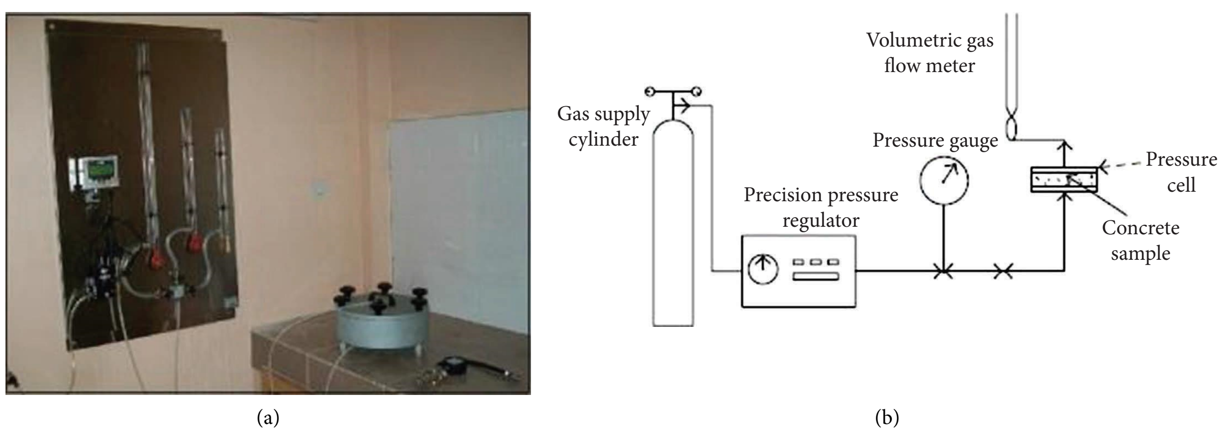


FIGURE 6: (a) Pictorial vision of the gas permeability test setup; (b) graphical show of the gas permeability test setup [24].

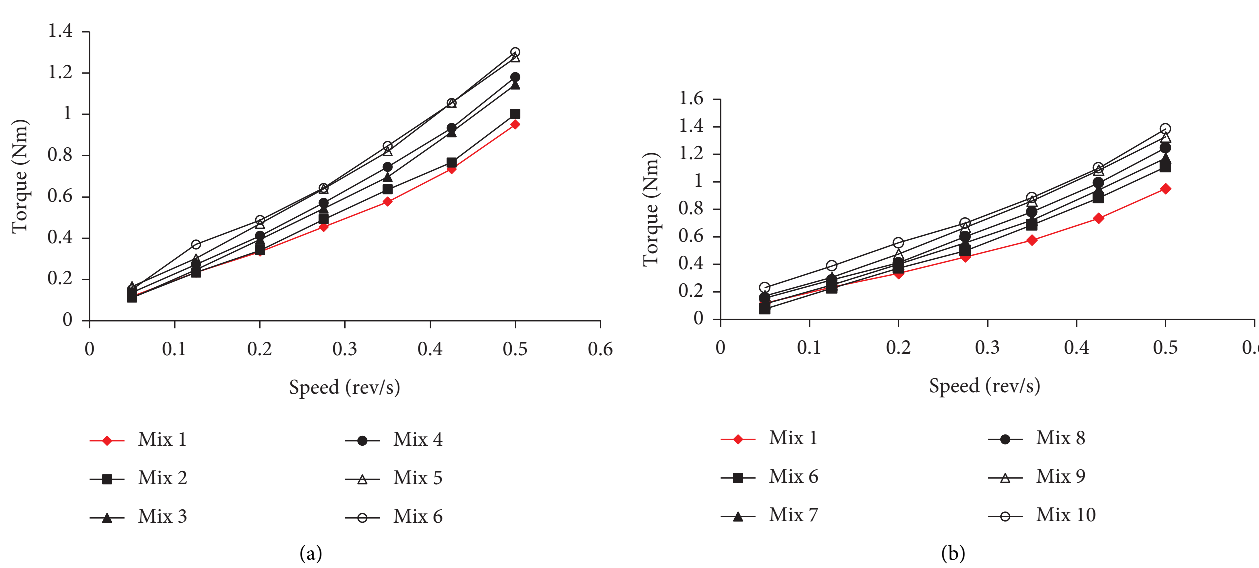
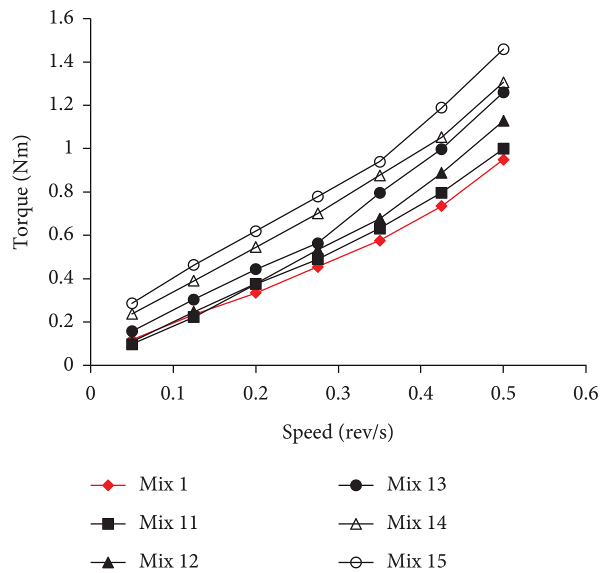


FIGURE 7: Continued.



(c)

Figure 7: Torque vs. speed variation for SCCs (a) series no. 1, (b) series no. 2, (c) and series no. 3.

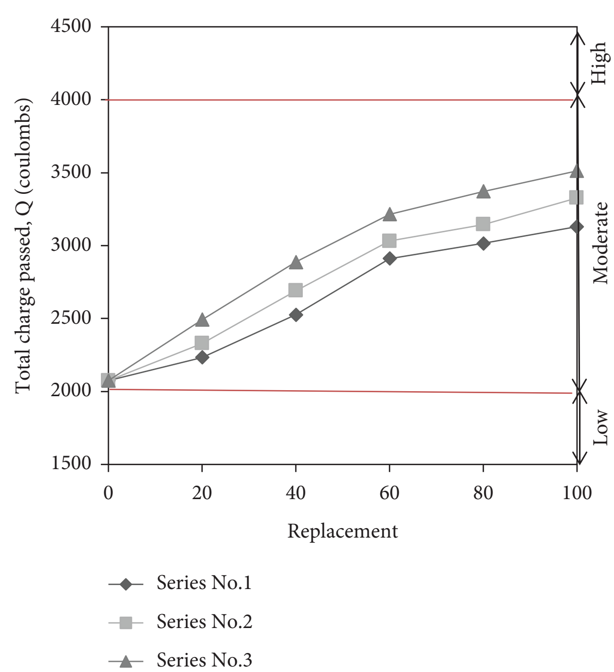


Figure 8: RCPT variations of SCBGCs.

structure in concrete with an increment of the recycled blue glass quantity since the glass has a corner shape and acute rim. Also, supposedly, there is a different cause for the existence of water in surplus of the need for concrete because of the low absorption of recycled blue glass. This surplus water turns into air pores within the concrete structure when the samples enter the oven, which leads to a rise in gas permeability coefficients.

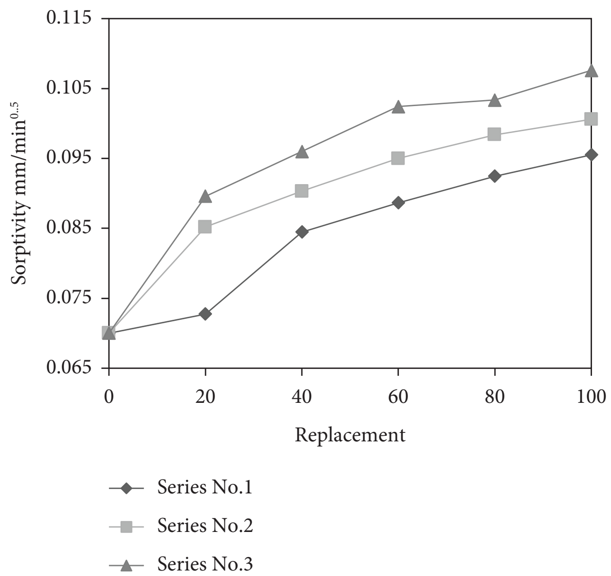


Figure 9: Water sorptivity variations of SCBGCs.

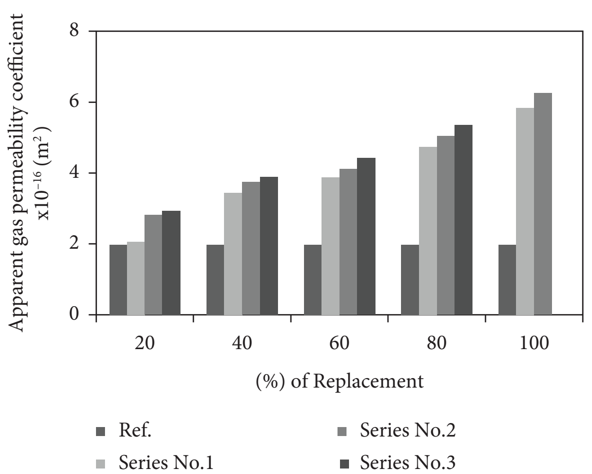


Figure 10: Gas permeability variations of SCBGCs.

4. Conclusions

Many conclusions were drawn from the results of the experimental investigation, as given in the following:

(i) The anatomy of the results acquired from the relationship between the rotational speed and torque display showed that increasing RBG content led to higher torque values.

(ii) The results based on Bingham models detected that the shear-thickening attitude became more distinct if RBG content increased in the SCC mixtures.

(iii) Test results on the rheological attitude detected that the flow curves were not linear, resulting in lower than 10 Pa yield stresses, which are recommended for perfect self-flow RBG concretes. This affair is very important and provides high potential for such concerts to be utilized for wider structural purposes.

(iv) A cumulative increment was noticed in the chloride ion penetration of the SCCs with the rising recycled blue glass aggregate quantity at 28 days of test results.

(v) Because of the existence of recycled blue glass aggregate in the concrete, porosity is badly influenced. As a result, the SCBGCs' water sorptivity values increased.

(vi) Increment in the quantity of recycled blue glass aggregate results in an increment in the apparent gas permeability of SCC.

(vii) From the abovementioned conclusions, it will be clear that the use of RFWBG at 20% does not lead to a significant decrease in the permeability properties of self-compacting concrete containing RBG.

Data Availability

All data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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