Advances in Concrete Construction, *Vol. 14, No. 6 (2022) 427-440*
https://doi.org/10.12989/acc.2022.14.6.427

Effect of crumb rubber and silica fume on the fresh, hardened and concrete-steel bond strength properties of SCC

Muhammad Usman [1a], Syed Asad Ali Gillani[*2], Rashid Hameed [2b],
Muhammad Rizwan Riaz [2c], Muhammad Ilyas [3d] and Ahmed Farouk Deifalla [4e]

[1] *Deputy Secretary Development, Punjab Irrigation Department, Government of the Punjab, Pakistan*
[2] *Department of Civil Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan*
[3] *Department of Civil Engineering, Lahore Leads University, Lahore, Pakistan*
[4] *Structural Engineering Department, Faculty of Engineering and Technology, Future University in Egypt New Cairo 11835, Egypt*

(*Received February 16, 2022, Revised November 17, 2022, Accepted January 3, 2023*)

Abstract. In recent years, the use of various industrial by-products and waste materials in concrete has attracted the attention of researchers around the globe to reduce their impact on the environment and to find sustainable solution to conserve natural resources. The use of end-of- life tires of vehicles in concrete is one such example. This research study investigates fresh and hardened properties, and bond stress-slip behavior of self-compacting rubberized concrete with and without silica fume. RILEM-FIP-CEB beam testing arrangement was employed to perform bond tests. The first part of the study focused on the development of self-compacting rubberized concrete (SCRC) with and without silica fume (SF) and investigating its fresh and hardened properties (compressive and tensile strengths). The second part focused on investigating bond stress-slip behavior of SCRC with different percentages of Crumb Rubber (CR) varying from 5% up to 30% as sand replacement by volume. Total 12 concrete mixes were prepared for this study. The experimental results showed that the replacement of sand with CR has negative effect on the fresh and hardened properties of SCRC. The bond strength was found to be decreased by 38% with 30% replacement of sand with CR. Further, presence of CR in the concrete mix caused detrimental effect on the bond stiffness and toughness. However, SF improved the mechanical properties and bond strength of SCRCs. This study found that replacement of sand with 10% CR by volume and addition of SF in concrete resulted in similar mechanical properties and bond strength as that of normal self-compacting concrete which demonstrates the potential use of SCRC in structural applications.

Keywords: bond stress-slip response; crumb rubber; fresh & hardened properties; SCC; silica fume

1. Introduction

In the last two decades, eco-friendly solutions and sustainable development have been the focus of researchers because of rising environmental problems related to the disposal of used and expired materials. One such material, which poses a serious threat to the environment, is large number of discarded tires of vehicles. Tire piles are excellent breeding places for insects particularly mosquitoes because of their shape and impermeability. They hold rainwater for a longer time and serve as the best sites for the development of mosquito larvae. Further, if discarded tires catch fire, generally it is very difficult to extinguish them, and the emission of toxic gases causes pollution of air and health hazards as well. About 1.5 billion tires are discarded every year as a result of ineffective methods of disposing of waste tires (AbdelAleem and Hassan 2018). In this regard, the construction industry provides a solution to the growing problem related to the disposal of end-of-life tires by using them in concrete in the form of crumb rubber as partial replacement of fine aggregates.

In recent years, numerous research studies were carried out to explore the possibility of using end-of-life tires as aggregates in concrete and the resulting composite is called rubberized concrete. Most of the research studies mainly focused on fresh and hardened properties of rubberized concrete and found that the addition of crumb rubber in concrete decreased the workability (AbdelAleem and Hassan 2018, Bisht and Ramana 2017) because of increased friction and irregular shape of rubber particles (Ly *et al*. 2015, Ismail and Hassan 2016, Hamdi *et al*. 2021). The mechanical properties of rubberized concrete were found to decrease with the increase in rubber content in the concrete mix due to poor ITZ and low stiffness of rubber particles (Ismail and Hassan 2016, Hamdi *et al*. 2021, Siddique and Naik 2004, Thomas and Gupta 2016, Bisht and Ramana 2017, Gravina *et al*. 2021, Mezidi *et al*. 2021, Shah *et al*. 2021, Mallek *et al*. 2021). Since rubber particles are softer than sand particles, on applying load, stress concentration occurs around the rubber particles, which results in premature cracks initiation around the rubber particles,

---

[*]Corresponding author, Ph.D., Assistant Professor,
E-mail: asadgillani@uet.edu.pk
[a] M.Sc. Student, E-mail: engrusman170@gmail.com
[b] Professor, E-mail: rashidmughal@uet.edu.pk
[c] Associate Professor, E-mail: rizwan.riaz@uet.edu.pk
[d] Professor, E-mail: ilyas@ucest.edu.pk
[e] Professor, E-mail: ahmed.deifalla@fue.edu.eg

ISSN: 2287-5301 (Print), 2287-531X (Online)

which ultimately leads to failure (Guneyisi 2010, Fakhri and Saberi 2016). Smaller reduction in mechanical strength was reported with smaller rubber particles used in the concrete mixes than larger rubber particles (Aiello and Leuzzi 2010, Su *et al.* 2015, Gesoglu *et al.* 2015). The replacement level of sand with crumb rubber is an important parameter on which level of reduction in mechanical properties of concrete directly depends. Thomas and Gupta (2016) reported that reduction in the mechanical properties of concrete could be limited if fine aggregates are replaced with lesser than 20% crumb rubber by volume.

To minimize the reduction in the mechanical properties of concrete resulting from using CR, numerous research studies reported that the addition of different supplementary cementing materials such as silica fume, metakaolin and fly ash enhanced the mechanical properties of vibrated rubberized concrete due to their pozzolanic effects (AbdelAleem and Hassan 2018, Ismail and Hassan 2016, Gupta *et al.* 2016, Onuaguluchi and Panesar 2014, Ahmad *et al.* 2019, Alaloul *et al.* 2021, Fakhri *et al.* 2021). Silica fume in rubberized concrete fills the nano-metric voids in cement mortar resulting in a denser structure and, in turn, compressive strength is increased (Sohrabi and Karbalaie 2011). Ramdani *et al.* (2019) used rubber aggregates and glass powder as a partial replacement of sand and cement, respectively. Results of their study showed improved compressive strength with the incorporation of glass powder along with the rubber aggregates, especially with rubber aggregate content 10% and 20%. Furthermore, the combined use of rubber waste and glass powder enhanced the concretes workability and high fresh density. Hesami *et al.* (2016) reported that the incorporation of polypropylene fibers enhanced the mechanical properties of rubberized concrete due to the bridging effect of fibers.

In case of vibrated rubberized concrete, previous researchers reported that during vibration, CR particles tend to float towards the concrete's surface due to their low density combined with their hydrophobic behavior, thus increasing the risk of segregation (Guneyisi 2010, Turatsinze *et al.* 2005, Topcu and Bilir 2009). To avoid such kind of issues in rubberized concrete, Self-Compacting Rubberized Concrete (SCRC) could be a better option. Moreover, it has been reported in the literature (Sonebi *et al.* 2000, Chan *et al.* 2003, Foroughi-Asl *et al.* 2008) that Self-Compacting Concrete (SSC) has higher bond strength than normal vibrated concrete. Similar to normal vibrated concrete, the mechanical properties of the self-compacting concrete deteriorate with the addition of rubber particles (AbdelAleem and Hassan 2018, Turatsinze and Garros 2008, Alaloul *et al.* 2021).

The bond between steel and concrete is considered as one of the most important properties as the bond enables the two materials to behave as a composite material. Bond strength defines the development length and splice length of steel bar in the different structural applications. In concrete, the bond between steel and concrete is developed by three mechanisms (i) chemical adhesion (ii) friction, and (iii) bearing of ribs on steel bar and concrete (Hong and Park 2012, Hameed *et al.* 2013). In rubberized concrete, the bond between steel bar and concrete is modified due to the presence of rubber particles in concrete. Hall and Najim (2014) conducted pull out tests on plain and self-compacting rubberized concrete with 14% and 18% replacement of mineral aggregates (both fine and coarse aggregates) with mortar pre-coated crumb rubber. The test results showed that bond strength was decreased with the increase in rubber content. Gesoglu *et al.* (2015) studied varying percentages (0-30%) of the fine and coarse aggregates replaced with crumb rubber and tire chips. Their study showed that the replacement of 30% rubber with aggregates by volume decreased the bond strength by 40% and this was attributed to weak adherence between rubber particles and the cement paste, and also to reduced friction between steel re-bar and its environment due to CR being softer than natural aggregates. Gravina *et al.* (2021) reported that local bond behavior is affected by the inclusion of rubber in concrete and a larger slip at the peak bond stress is observed for concrete with crumb rubber partially replacing fine aggregates. Romanazzi *et al.* (2021) studied the bond strength between rubberized concrete and deformed steel bar by performing pull-out tests and found that bond strength did not vary when replacement of stone aggregate with rubber was lower than 12%, however, for higher replacement level, bond strength was reduced.

The bond test is commonly performed using a direct pull-out test in which the reinforcement and concrete are under different stress conditions. The concrete is in compression and steel is in tension. In actual structural applications, both steel and concrete are either in tension or compression (ACI 408R-03 2012). However, in a pull-out test, concrete being stronger in compression, the confinement pressure in the direct pull-out test results in higher bond strength than the actual. To represent the actual stress state in an RC structure as closely as possible, an alternate testing set up has been recommended by RILEM (RILEM 1973) to study the bond between reinforcing steel re-bar and surrounding concrete under monotonic two-point bending. The beam specimen comprises two half-beams connected to each other at the center with a steel hinge at the top which takes the compression in positive bending and a deformed steel re-bar at the bottom which takes the tension. It is pertinent to mention here that the previous research studies on the bond strength of rubberized concrete reported in this paper (Hall and Najim 2014, Gesoglu *et al.* 2015, Gravina *et al.* 2021, Romanazzi *et al.* 2021) were performed by carrying out pull-out tests while in this study, RILEM beam tests were performed to investigate the bond behavior. Further, significance of present study also lies in the fact that influence of silica fume on the steel-concrete bond strength in SCC is investigated.

Research studies carried out in the recent past have shown that the presence of crumb rubber in concrete improves its toughness, ductility, energy dissipation, damping, durability, impact resistance and sound transmission property (Thomas *et al.* 2014, 2016, Thomas and Gupta 2015, Al-Tayeb *et al.* 2013, Atahan and Yücel 2012, Najim and Hall 2010, Ho *et al.* 2012, Najim and Hall 2012, Gillani *et al.* 2016, 2020, 2022, Chalangaran *et al.* 2021, Javed *et al.* 2022). Moreover, the use of crumb rubber obtained from end-of-life tires in concrete promotes the idea of developing sustainable and eco-friendly concrete. The literature indicates that rubberized concrete has the potential to be used in pavement overlays and slabs on grade with the large surface area but not subjected to heavy loadings like side walkways (Turatsinze *et al*. 2018), and in such applications mostly plain concrete is used. However, limited research has been carried out to investigate the behavior of reinforced rubberized concrete and its application in structural members such as beams and columns (Hassanli *et al*. 2017, Ganesan *et al*. 2013, Xue and Shinozuka 2013, Son *et al*. 2011). In this regard, bond behavior of rubberized concrete needs to be adequately investigated to develop design procedure for the structural members to be built using rubberized concrete. For this purpose, this study investigates the effect of crumb rubber and silica fume on the fresh and hardened properties of SCC, moreover, investigation of bond stress-slip behavior of deformed steel re-bar embedded in SCC containing crumb rubber and silica fume by RILEM beam test method (RILEM 1973) is also another main objective of this paper.

2. Experimental program

2.1 Materials

Ordinary Portland cement conforming to ASTM Type-I was used as a binder. Silica Fume (SF) was used as a partial replacement of cement and its dosage of 12% by weight was kept constant. Natural crushed limestone and natural river sand was used as coarse and fine aggregates, respectively to prepare all concrete mixes. Properties of cement and aggregates (fine and coarse) are provided in Table 1 while detail regarding their particle size distribution is given in Tables 3 and 4. Crumb rubber aggregates were obtained from end-of-life tires of vehicles after removing textiles and wires, and they had sizes ranging from 0.5 to 4mm, specific gravity of 1.2 and negligible water absorption. Crumb rubber along with fine aggregates used in this study are shown in Fig. 1. In order to achieve the desired fresh properties of SCC and SCRC, a high range water reducer “Chemrite SP-303” was used in this study. Properties of SF and “Chemrite SP-303” are given in Table 2. To study the bond stress-slip behavior, deformed steel

Table 1 Properties of cement and aggregates

Cement		**Fine aggregates**		**Coarse aggregates**	
Soundness	9 mm	Max. particle size	4 mm	Max. particle size	19 mm
Fineness	8%	Specific gravity	2.71	Specific gravity	2.73
Initial & final setting	50&460 min	Water absorption	1.47%	Water absorption	1.15%
Standard consistency	28%	Fineness modulus	2.8	Fineness modulus	3.27

Table 2 Properties of silica fume and admixture

Silica Fume		**Chemrite SP-303**	
Specific gravity	2.3	Type	Carboxylic acid derivatives
Mean practical size	0.5 μm	Form	Whitish pale liquid
Specific Surface	25 m^2/g	Density at 25ºC	1.06 kg/Lit
Cry bulk density	450 kg/m^3	Chloride Content	Nil
Amorphous	$SiO_2 \geq 90\%$	Toxicity	Non-toxic

Table 3 Sieve analysis of fine aggregates

Sieve		**Weight retained**	**Percentage retained**	**Cumulative retained**	**Percentage passing**	**% age passing limits [ASTM C-33]**	
#	mm	(gm.)	(%)	(%)	(%)	Min	Max
#4	4.75	32	3.2	3.2	96.8	95	100
#8	2.36	84	8.4	11.6	88.4	80	100
#16	1.18	191	19.1	30.7	69.3	50	85
#30	0.6	184	18.4	49.1	50.9	25	60
#50	0.3	390	39	88.1	11.9	5	30
#100	0.15	93	9.3	97.4	2.6	0	10
pan	0	10	1	98.4	1.6		

Table 4 Sieve analysis of coarse aggregates

Sieve		**Weight retained**	**Percentage retained**	**Cumulative retained**	**Percentage passing**	**% age passing limits [ASTM C-33]**	
#	mm	(gm.)	(%)	(%)	(%)	Min	Max
3/4	19	0	0	0	100	100	100
1/2	12.5	45	2.25	2.25	97.75	90	100
3/8	9.5	785	39.25	41.5	58.5	40	70
1/4	4.75	892	44.6	86.1	13.9	5	15
1/5	2.4	238	11.9	98	2	0	5
Pan	0	30	1.5	99.5	0.5		

Crumb Rubber **Fine aggregates**

Fig. 1 Crumb rubber and fine aggregates

Table 5 Concrete mixes and their composition

Sr. No.	Mix designation	Cement	SF	Coarse aggregates	Sand	Water	CR	WR
		kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
1	SCC	500	-	686	980	200	0	7.5
2	SCRC-5CR	500	-		931		18	7.5
3	SCRC-10CR	500	-		882		36	7.5
4	SCRC-15CR	500	-		833		54	7.5
5	SCRC-20CR	500	-		784		72	7.5
6	SCRC-30CR	500	-		686		108	7.5
7	SCC-SF	440	60		980		0	9
8	SCRC-5CR-SF	440	60		931		18	9
9	SCRC-10CR-SF	440	60		882		36	9
10	SCRC-15CR-SF	440	60		833		54	9
11	SCRC-20CR-SF	440	60		784		72	9
12	SCRC-30CR-SF	440	60		686		108	9

*SRRC: Self compacting rubberized concrete; SF: Silica fume; WR: Water reducer

bars of 19 mm diameter with a minimum tensile yield stress of 420 MPa were used to prepare the test specimens (beams).

2.2 Concrete mixes

Total 12 concrete mixes were prepared for this work: two mixes of SCC with and without SF and ten mixes of SCRC with SF (five mixes) and without SF (five mixes). Table 5 summarizes the detail of each concrete mix with respect to its constituents. To design SCC and SCRC, numerous trials of mix design were carried out in accordance with the guidelines of EFNARC (2002). W/C ratio of 0.4 was kept constant in all the mixes. In rubberized concrete mixes, sand was replaced with CR by volume varying from 5% up to 30%. Regarding the nomenclature of each concrete mix presented in Table 5, SCC represents a control mix for this study. SCC-SF represents self-

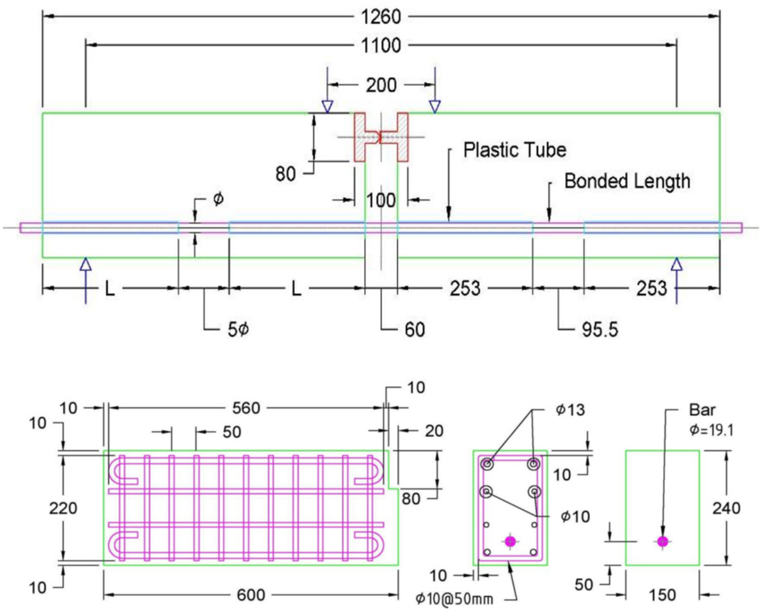


Fig. 2 Detail of test specimen for bond test (all dimensions in mm)

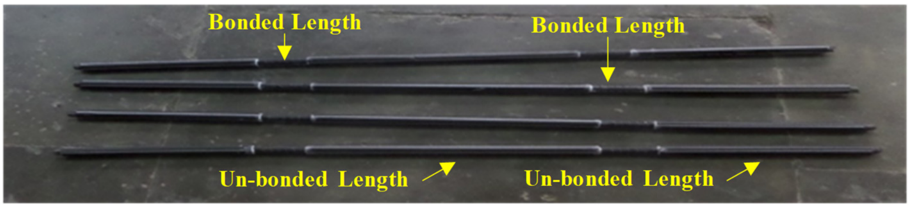


Fig. 3 Bonded and un-bonded regions of steel bar using PVC pipes

compacting concrete made using SF. SCRC-5CR represents a mix of self-compacting rubberized concrete with 5% CR but without SF. Similarly, SCRC-5CR-SF represents a mix of self-compacting rubberized concrete with 5% CR and with SF.

2.3 Test specimens

For each mix, six cylinders of 300 mm height and 150 mm diameter were casted for compressive and tensile strength determination. Three cylinders were used for the compressive strength test and the other three were used for the split tensile test. For bond test as per RILEM recommendation, two beam specimens were casted. Test specimen for beam test is shown in Fig. 2. The beam specimen is split into two halves which are connected at the bottom by a steel re-bar and the top end is connected by a metal hinge to develop the internal resisting couple. To develop bonded and un-bonded length along the steel re-bar, PVC pipes were used as shown in Fig. 3, and to avoid penetration cement slurry into un-bonded region, the ends were sealed with silicon sealant. A bonded length equal to five times the diameter of the rebar was maintained (Choi 1988). The reinforcement detail of beam specimens as per RILEM recommendation is shown in Fig. 2. To avoid shear failure, steel bars of 10mm diameter were used at a spacing of 50 mm center to center as transverse reinforcement. For the casting of test specimens, the compaction of concrete was done using a mechanical vibrating table. The test specimens were de-molded after 24 hours and were placed in a curing room at a temperature of 20°C and a relative humidity of 100% for 28 days. Casted beam specimen for bond test is shown in Fig. 4.

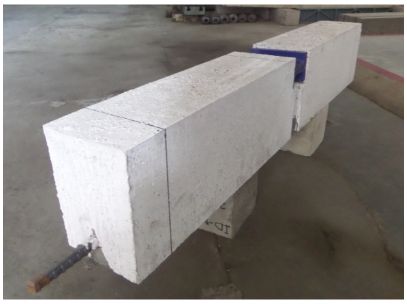
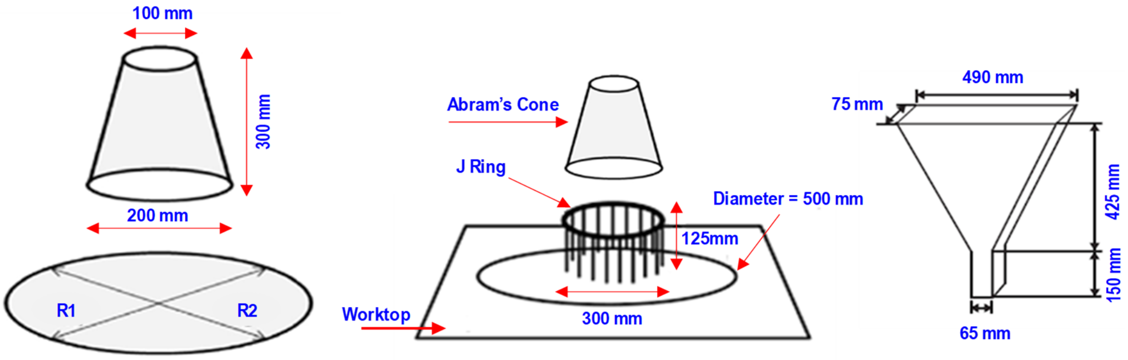


Fig. 4 Test specimen for pull-out test

2.4 Testing procedure

2.4.1 Fresh properties

The filling ability of developed SCRC mixes was determined by slump flow conducted as per guidelines of (ASTM C1611 2005). According to EFNARC recommendations, the slump flow diameter of SCC should



Slump Flow Test Apparatus J Ring Test Apparatus V- Funnel Test Apparatus

Fig. 5 Apparatus for fresh properties tests on SCC (EFNARC)

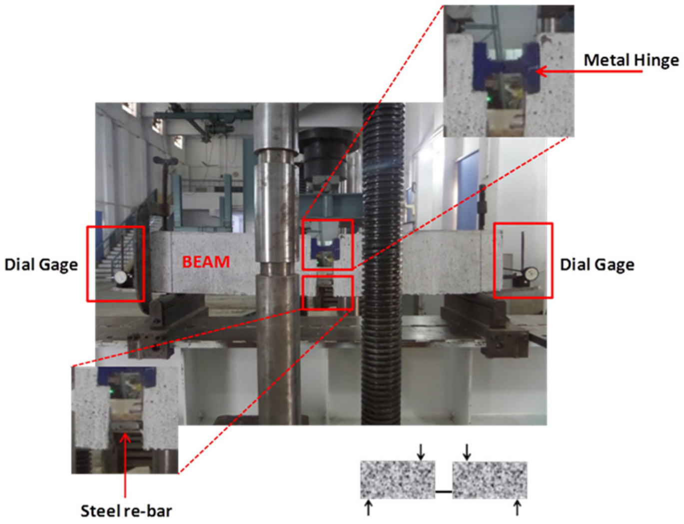


Fig. 6 Bending test for bond strength evaluation

range from 650 to 800 mm. The ability of concrete to flow through congested reinforcement was measured by J-Ring test. The height difference of SCC inside and outside of J-Ring is a measure of J-Ring value in millimeters. According to EFNARC guidelines, the difference in flow diameters between slump flow and J-ring flow should be less than 50 mm for a good SCC mix. The segregation resistance of SCC is measured by the V-funnel test. Due to a higher risk of segregation in SCC, this test is of great importance with respect to fresh properties of SCRC. For conducting this test, around 12 liters of concrete is required to fill the funnel. The time required by SCC to completely exit the funnel under its own weight is known as the V-funnel time. After measuring this time, fill the cone with SCC again and leave it for 5 minutes. If there is any increase in V-funnel time after 5 minutes of filling of funnel as compared to V-funnel time suddenly after filling, then it shows segregation. The test was performed as per the guidelines of EFNARC. The time to empty the V-funnel should range between 6 to 12 seconds. Testing apparatus for slump flow diameter, J Ring and V-funnel tests is shown in Fig. 5.

2.4.2 Hardened properties

Compressive strength and split tensile strengths tests were carried out on cylindrical specimens, as per guidelines outlined in ASTM C39 (2021) and ASTM C496 (1996), respectively using a universal testing machine of maximum loading capacity of 2000 kN. Three specimens of each concrete composition were tested for each test and average values of indirect tensile strength and compressive strength are presented in this paper. To study the bond stress-slip response of steel re-bar embedded in concrete, displacement controlled bending tests were performed on beam specimens, as per RILEM recommendation, using a universal testing machine of a maximum loading capacity of 1000 kN, as shown in Fig. 6. Bending tests were carried out at a constant rate of 2 mm/min. Two dial gauges were used to measure and record the slip of the steel bar on both ends corresponding to each load value. Data obtained from this test were analyzed to study effect of CR and SF on bond stress-slip response, bond strength, slip corresponding to bond strength, initial stiffness and bond toughness.

3. Results and discussion

3.1 Fresh properties

The effect of CR on the fresh properties of SCC including slump flow diameter, J-ring flow, and V-funnel is

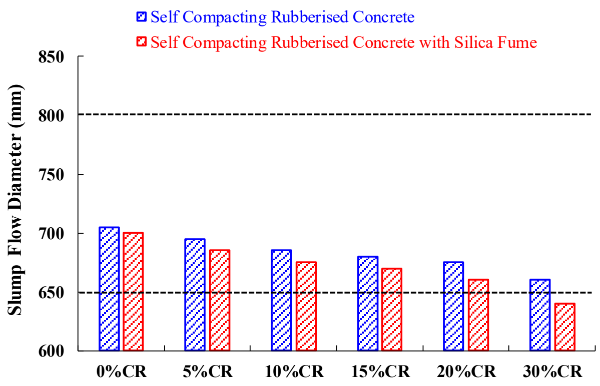


Fig. 7 Slump flow diameter (blue lines indicate EFNARC limits)

Fig. 8 Observation of slump flow and J Ring flow tests

highlighted in this section. The slump flow test was performed as per the guidelines of ASTM C1611 (2005), and the results are presented in Fig. 7. Results in this figure confirmed the findings of previous studies (AbdelAleem and Hassan 2018, Turatsinze and Garros 2008) that CR has a negative effect on the slump flow diameter of SCC (refer to Fig. 8) and this detrimental effect on flow diameter increases with the increase of CR content. The angular shape and rough surface texture of the rubber particles are the factors which offered more resistance to the flow of concrete resulting in less value of the flow diameter of SCRC. Further, the SCRC mixes with SF exhibited lower flow diameters due to more water demand by SF which reduced the necessary water required for lubrication of natural aggregates. As per EFNARC guidelines, the slump flow diameter of SCC should be between 650 and 800 mm. It is obvious in Fig. 7 that the slump flow diameter of all concrete mixes except the SCRC-30CR-SF mix was within this range.

The ability of concrete to flow through congested reinforcement was measured by the J-Ring test (refer to Fig. 8) and the results are presented in Fig. 9. It is evident from the results that the J-Ring flow of concrete mix was slightly decreased when sand was replaced with CR. It can be further observed that with the increase of CR content, the value of J-ring flow is decreased. Like slump flow diameter, the addition of SF in SCRC further reduced the value of J-Ring flow diameter as evident in Fig. 9. According to EFNARC guidelines, the difference in flow diameters between slump flow and J-ring flow should be less than 50 mm. It can be noticed in Fig. 10 that all concrete mixes prepared for this study fulfilled this requirement.

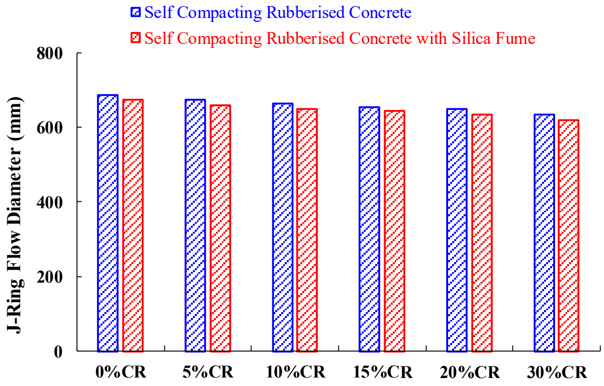


Fig. 9 J-ring flow diameter

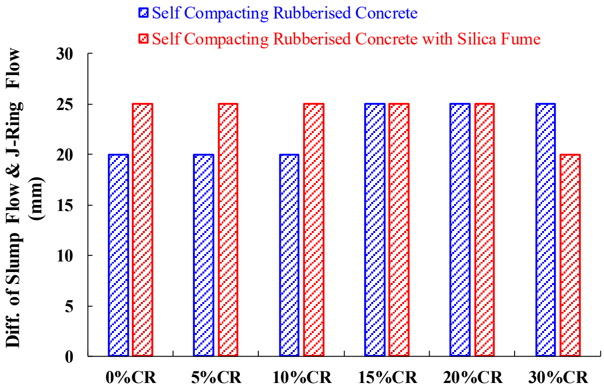


Fig. 10 Difference in slump flow and J-ring flow

The V-funnel time measures the segregation resistance of concrete. Due to a higher risk of segregation in SCRC than SCC, this test is of great importance with respect to fresh properties of SCRC. The test was performed as per the guidelines of EFNARC. The time to empty the V-funnel should range between 6 to 12 seconds. The test results presented in Fig. 11 show that V-funnel time was increased with the increase in rubber content due to an increase in viscosity of mix and friction induced by CR. The value was

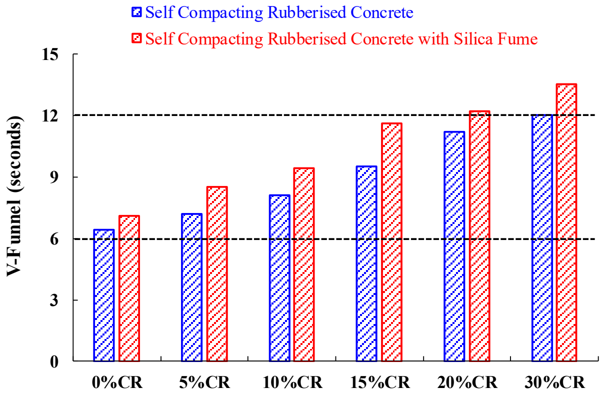


Fig. 11 V-funnel test results (blue lines indicate EFNARC limits)

further increased in the presence of SF. It is clear that the V-funnel time of all SCRC compositions with and without SF apart from the SCRC-30CR-SF mix, is within limits specified by EFNARC.

From the results presented in Figs. 7, 9, 10 and 11 regarding the fresh properties requirement of concrete to be declared as SCC, it appears that SCC may be designed by replacing the sand with CR up to 30% by volume. However, the substitution of cement by SF (12% by weight) in SCRC containing 30% CR resulted in some undesirable fresh properties of concrete. Up to 20% CR content in SCRC, SF did not pose any problem with respect to fresh properties.

3.2 Mechanical properties

3.2.1 Compressive strength

Compressive strength values are presented in Fig. 12. It is clear that sand replacement with CR caused a reduction in compressive strength, as expected. Drop in compressive strength was increased with the increase of CR content in the concrete. With the replacement of sand with 5%, 10%, 15%, 20% and 30% CR in concrete, reduction in compressive strength of 10%, 17%, 25%, 34% and 54% was observed, respectively. Poor ITZ between cement paste and crumb rubber particles, and low modulus of elasticity of rubber particles are the main reasons of decrease in the compressive strength of SCRC (Turatsinze *et al.* 2006, Pham *et al.* 2018). However, the presence of SF positively affects the compressive strength of rubberized concrete and this observation is in line with the findings of other researchers (Gupta *et al.* 2016, Guneyisi *et al.* 2004, Onuaguluchi and Panesar 2014, Elchalakani 2015, Pelisser *et al.* 2011). An increase in compressive strength of 23%, 20.7%, 19.9%, 18.6%, 19.4% and 29.1% by the partial replacement of cement with SF was observed for rubberized concrete containing 0%, 5%, 10%, 15%, 20% and 30% CR, respectively. This improvement in compressive strength of SCRCs was due to binding and filling effects of SF which ultimately led to improve the filling of voids and to pozzolanic reaction that resulted in stronger ITZ between cement paste and CR. SCRC containing 10% CR and SF exhibited compressive strength almost equal to that of control concrete (SCC) which indicates full recovery of lost strength due to CR. Further, SCRC containing 30%CR and SF exhibited such value of compressive strength (30.1 MPa) which is fairly acceptable with respect to field applications of normal strength concrete.

3.2.2 Tensile strength

Results of split tensile test are shown in Fig. 13 which indicates that incorporation of CR in concrete resulted in reduction of tensile strength. Similar to compressive strength, the tensile strength was decreased with an increase in content of CR. Replacement of sand with 5%, 10%, 15%, 20% and 30% CR in concrete caused reduction in tensile strength of 5.8%, 11.7%, 20.5%, 23.5% and 38.2%, respectively. It is obvious that partial replacement of cement with SF in SCRC exhibited a positive effect on tensile strength. It is important to highlight that SCRC with 10% CR and SF exhibited tensile strength even greater than the control concrete (SCC). Due to SF, an increase in tensile strength of 17.6%, 18.7%, 20%, 18.5%, 15.4% and 23.8% was observed for rubberized concrete containing 0%, 5%, 10%, 15%, 20% and 30% CR, respectively. The reduction in split tensile strength is less than that of compressive strength and it is mainly attributed to the fact that rubber aggregates act like a hole at the crack tip and thus decrease the tip sharpness of the first micro-crack resulting in stress relaxation and ultimately slow down the kinetics of propagation of first micro-crack (Turatsinze *et al.* 2005, Si *et al.* 2018).

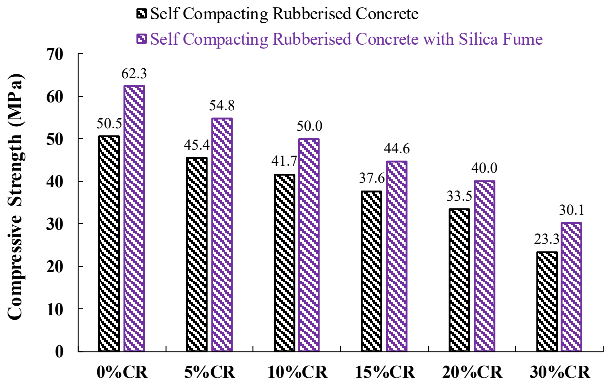


Fig. 12 Compressive strength values

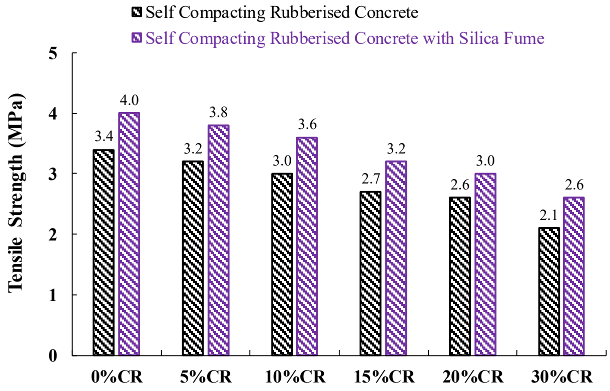


Fig. 13 Tensile strength values

3.2.3 Bond stress-slip response

Bond stress-slip response of steel re-bar embedded in SCC and SCRCs without silica fume is presented in Fig. 14, which shows a marked detrimental effect of CR on the bond behavior. With the increase of rubber content in the concrete, the negative effect of CR was observed to increase systematically. Furthermore, on replacing sand with different content of CR, an overall change in the curve shape was noticed. Based on the results presented in Fig. 14, the bond stress-slip curve of SCC can be categorized as tri-linear curve, while for SCRC containing 30% CR, it can be categorized as a bi-linear curve, as presented in Fig. 15. The first part of the curves represents the micro-slip corresponding to elastic deformation of the cementitious matrix present between the steel bar lugs as shown in Fig.16. The second part of the curve (as for SCC) corresponds to the stage of cracking/damage evolution along the failure surface (Fig. 16). Up to the end of the

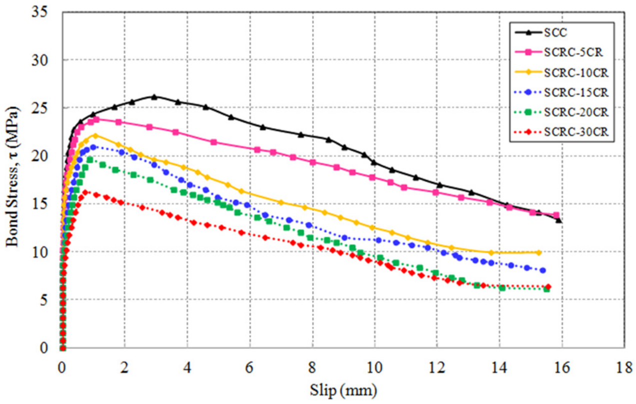


Fig. 14 Bond stress-slip curves of SCC and SCRC

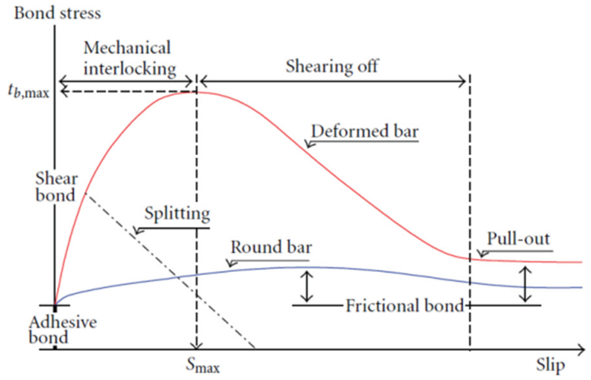
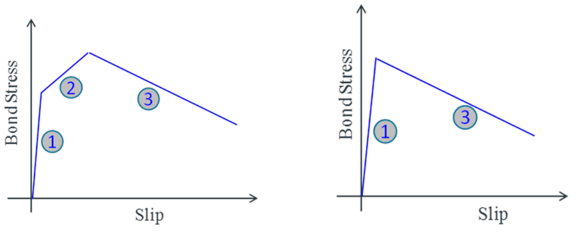


Fig. 17 Typical bond-stress slip relationship (Hong and Park 2012)



(a) Tri-linear curve (b) Bi-linear curve

Fig. 15 Trend of bond stress-slip curve

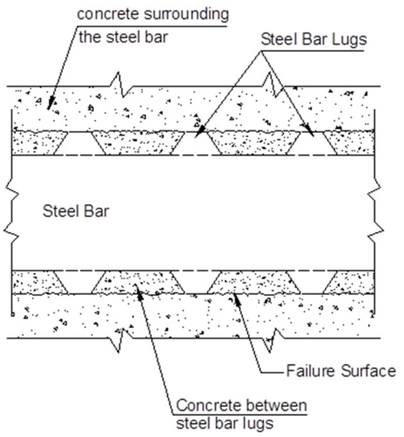


Fig. 16 Element of reinforced concrete (Hameed *et al*. 2013)

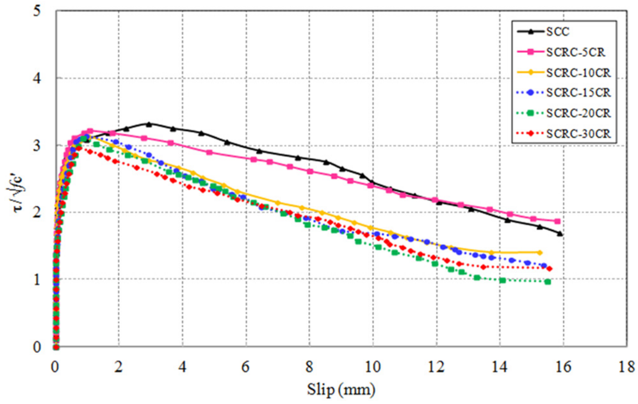


Fig. 18 Normalized bond stress-slip curves of SCC and SCRC

second stage, which corresponds to maximum bond stress, bond stress development is mainly attributed to mechanical interlocking action that includes adhesive bond and shear bond (Hong and Park 2012). After the peak bond stress, the shearing off stage, as indicated in Fig. 17, starts and bond stress gradually decreases along with a significant increase in slip value. Finally, pulling out of steel bar at a constant small value of bond stress is started where the main role is played by the frictional bond between steel re-bar and concrete. It is quite clear in the bond stress-slip curves of SCC and SCRCs in Fig. 14 that the range of the second stage of the tri-linear curve of SCC is gradually decreased with the increasing content of CR and finally leads to bi-linear curve exhibited by SCRC with 5% CR. It indicates that the development and propagation of damage along the oriented failure surface are more rapid with less resistance and this rate of damage development is increased with the increase of CR content in the concrete matrix. The presence of crumb rubber aggregate on the crack path also causes crack path elongation resulting in stress relaxation (Hall and Najim 2014). In the case of SCRC with 30%CR, the rapid development of distinct failure path at the steel/concrete interface due to the presence of more rubber particles in the matrix results in lesser peak bond stress and early start of shearing off stage with almost zero slip (Fig. 14). As far as the failure mode of the test specimen is concerned, in all the cases, pull-out failure was observed without any cracking in the two blocks of beam specimen.

Internal confinement due to concrete present around the steel re-bar is an important factor that significantly affects the bond strength, and it is dependent on the compressive strength of the concrete. To allow for direct comparison of the bond stress-slip response of SCC and SCRCs without silica fume, bond stress was normalized with the square root of the compressive strength of each concrete mix and the results are presented in Fig. 18. It is clear in this figure that the peak value for all SCRCs was close to each other and also almost similar to that of control concrete (SCC). However, the slip value corresponding to peak for all SCRCs was less as compared to the value of the control mix (SCC). The post-peak behavior of SCRC containing 5% CR

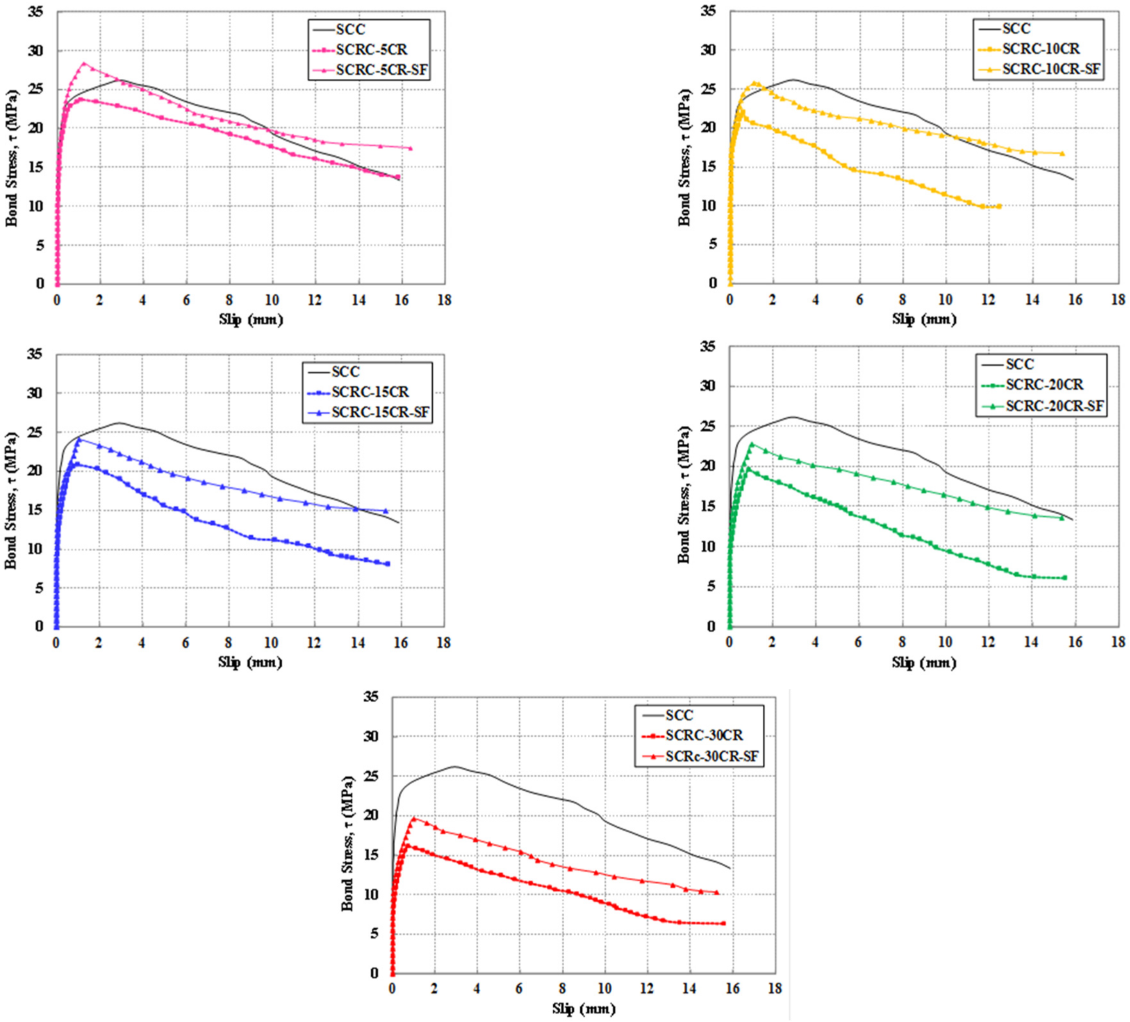


Fig. 19 Bond stress-slip curves of SCC and SCRCs

(SCRC-5CR) was approximately similar to that of SCC; however, normalized values of bond stress in the post-peak region for all other SCRCs containing 10% or more CR were on the lower side in comparison of SCC.

In Fig. 19 bond stress-slip response curves of SCRCs with SF are presented along with similar response curves of control mix (SCC) and corresponding SCRC without SF. It is clear from these response curves that the substitution of cement by SF (12% by weight) considerably improves the bond behavior of SCRC. In case of SCRC containing 5% CR, bond stress-slip response up to the peak was observed to be even better than as exhibited by control mix (SCC) and in the post peak region, up to 10 mm slip the response close to that of SCC and after this slip value, an improvement in the residual bond stress value compared to SCC was observed. In case of SCRC containing 10% CR, results indicate that SF made it possible to recover noticeable percentage of the lost bond stress due to CR. For SCRCs containing 15%, 20% and 30% CR, presence of SF improved the bond strength and also residual bond strength in the post peak region but the values remained less than that of control mix (SCC).

3.2.4 Bond strength

Values of bond strength obtained by SCC and SCRCs with and without SF are shown in Fig. 20 which reveals that replacement of sand with 5%, 10%, 15%, 20%, and 30% CR in concrete caused gradual drop in bond strength of 9%, 15.6%, 20.2%, 25.2%, and 38.1%, respectively. It is clear that partial substitution of cement by SF enhanced the bond strength of SCRCs. Like other mechanical properties, SCRC with 10% CR and 12% SF developed bond strength close to the value exhibited by SCC. Due to SF, enhancement in bond strength of 16.8%, 19.3%, 16.8%, 14.8%, 16.3% and 20.9% was observed for concrete mixes containing 0%, 5%, 10%, 15%, 20% and 30% CR, respectively. As mentioned earlier, improvement in the bond strength due to SF is mainly attributed to the better cementing effects because of SF which improved the ITZ between rubber particle and cement paste and microstructure of rubberized concrete.

3.2.5 Slip at peak bond stress

Slip values corresponding to peak bond stress of SCC and SCRCs with and without SF are presented in Fig. 21. It appears in this figure that slip corresponding to peak bond stress is decreased significantly for SCRCs in comparison to

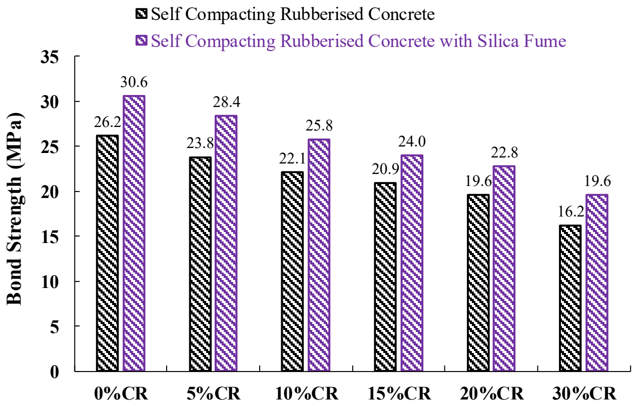


Fig. 20 Variation in bond strength with different percentages of CR

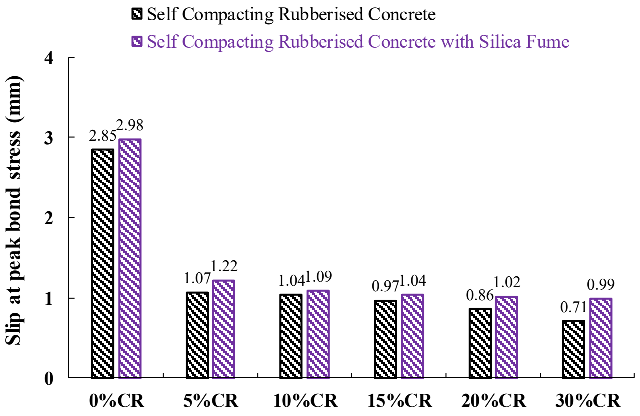


Fig. 21 Slip values at peak bond stress

SCC. Decrease in slip value due to the presence of CR in concrete is mainly attributed to low strength and stiffness of CR which induced low fracture energy at the interface between concrete and steel re-bar. As a result of 5% sand replacement with CR, the slip was reduced by 62.4% in comparison to SCC. With the increase of CR content in the concrete from 5% to 30%, the slip at peak bond stress was slightly decreased gradually. It can be noticed that a slight increase in the slip at peak bond stress was obtained due to SF in the concrete.

3.2.6 Stiffness

Stiffness is defined here as the pull-out force required to produce unit slip of steel re-bar and it is mainly dependent on the mechanical characteristics (particularly elastic modulus) of the concrete matrix present around the steel re-bar (Fig. 16). In this study, stiffness has been calculated for the part of the bond stress-slip curve before peak as shown in Fig. 22, which corresponds to initiation and propagation of cracking/damage in the concrete matrix around the steel bar. The values of stiffness obtained for each concrete mix are presented in Fig. 23, where the negative effect of CR on stiffness is apparent. Reduction in stiffness is mainly attributed to the low modulus of elasticity of the rubberized concrete. Results presented in Fig. 23 reveal that replacement of sand with 5%, 10%, 15%, 20% and 30% CR in concrete resulted in drop in stiffness value of 25%, 44.8%, 49.3%, 58.8% and 63.9%, respectively. It is evident that the substitution of cement by SF improved the stiffness by 18.4%, 15.7%, 22.5%, 14.1%, 10.7% and 12.2% for concrete mixes containing 0%, 5%, 10%, 15%, 20% and 30% CR, respectively.

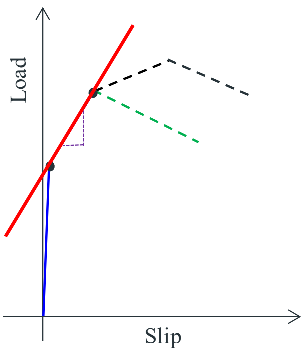


Fig. 22 Stiffness calculation

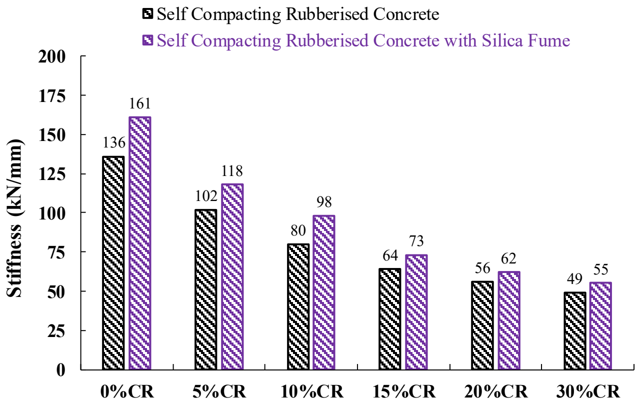


Fig. 23 Initial stiffness values

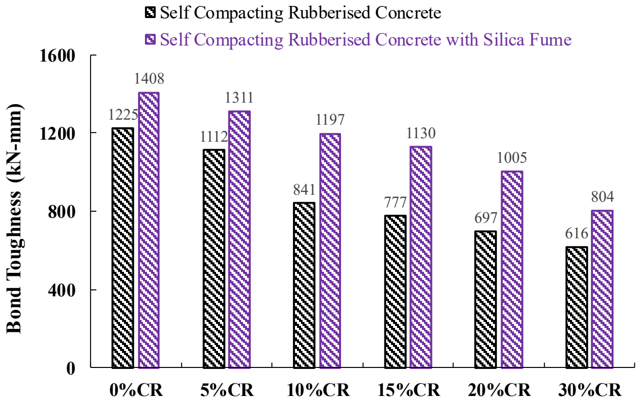


Fig. 24 Bond toughness values

3.2.7 Bond toughness

Bond toughness is one of the important properties of reinforced concrete with respect to its application in seismic resistant structures and it is the ability of a material to absorb energy. In this study, the bond toughness was computed as area under the load-slip curve up to 15 mm slip. The values of bond toughness of SCC and SCRCs with and without SF are presented in Fig. 24 where the negative effect of CR on the bond toughness is apparent. Bond toughness was decreased by 9.2%, 31.3%, 36.6%, 43.1%, and 49.7% when sand was replaced with 5%, 10%, 15%, 20%, and 30%, respectively. Like other mechanical properties discussed above in this paper, bond toughness was also improved in the presence of SF in the mix. It is pertinent to mention here that the concrete mix SCRC-10CR-SF exhibited almost similar value of bond toughness as that of the control mix (SCC). Substitution of cement by SF improved the bond toughness by 14.9%, 17.9%, 42.3%, 45.4%, 44.2% and 30.5% for concrete mixes containing 0%, 5%, 10%, 15%, 20% and 30% CR, respectively.

4. Conclusions

This study aimed to investigate the influence of the partial replacement of fine aggregates with crumb rubber and cement with silica fume on the self-compacting concrete's fresh and hardened properties and bond with steel reinforcement. The following conclusions are drawn from the detailed experimental investigation carried out in this study:

- Replacement of sand with crumb rubber aggregates exhibited negative influence on the fresh properties of SFRC and by substituting cement with silica fume, the fresh properties are further decreased. For the w/c ratio and silica fume dosage used in this study, the maximum replacement level of sand with crumb rubber aggregates to satisfy the flow diameter and V-funnel time limits of EFNARC guidelines is 20% when replaced in combination with SF.
- Presence of crumb rubber aggregates in SCC has negative effect on its compressive strength and splitting tensile strength. The loss in these strength values is found to be more pronounced at higher crumb rubber contents. The replacement of cement with silica fume appeared to have slightly improved the compressive and indirect tensile strengths of SCRC.
- Local bond stress – slip response of deformed steel re-bar embedded in SCC was negatively affected by using crumb rubber and this effect was noticed to be more pronounced at higher content of CR in the concrete mix. After the elastic deformation limit, initiation and propagation of cracking at the steel-concrete interface were more rapid in the presence of crumb rubber aggregates resulting in lesser bond strength. In the case of SCRC with 5% CR, bond behavior normalized by compressive strength was almost similar to that of control SCC, however, a maximum decrease of 38.1% was exhibited by SCRC containing 30% CR.
- It is possible to reduce the detrimental effect of CR on the bond stress-slip response by the use of SF. The positive influence of SF on the bond strength of SCRCs is evident from the results and it is mainly due to the improved mechanical properties of the concrete matrix because of the filling and pozzolanic effect of SF. SCRC with 10% CR and 12% SF developed nearly the same bond strength as that of control SCC.
- A significant reduction in the slip value at peak bond stress occurred as a result of replacing 5% sand with CR. With the increase of CR content in the mix from 5% to 30%, a slight but gradual decrease in the slip value at peak bond stress was also obvious. Partial replacement of cement with SF resulted in a noticeable increase in the slip value corresponding to peak bond stress for SCRC with the maximum increase observed for the case of SCRC containing 30% CR.
- The stiffness and bond toughness of the composite in the bond test was adversely affected by the presence of CR in the concrete matrix and it was observed to be gradually decreased with the increasing content of CR from 5% to 30%. However, the substitution of cement by SF made it possible to recover the loss in stiffness and bond toughness due to CR up to a certain percentage but no SCRC mixture with SF was able to develop stiffness equal to that of the control SCC. On the other hand, it was possible to get almost the same value of bond toughness as exhibited by control SCC with SCRC containing 10% CR.

Hence, the use of SCRC containing crumb rubber aggregates as a partial replacement of sand by volume and silica fume as partial substitution of cement by weight as structural concrete is promising, and this will certainly bring noticeable environmental and sustainability benefits. Further, it will also contribute to developing or enhancing the circular economy.

Acknowledgments

Technical support from Dr. Wajahat H. Mirza, General Manager Imporient Chemicals (Pvt)Ltd. Lahore-Pakistan and Prof. Dr. Anaclet Turatsinze from LMDC INSA-UPS Toulouse, France is highly acknowledged.

References

AbdelAleem, B.A. and Hassan, A.A.A. (2018), "Development of self-consolidating rubberized concrete incorporating silica fumes", *Const. Build. Mater.*, **161**, 389-397. https://doi.org/10.1016/j.conbuildmat.2017.11.146

ACI 408R-03 (2012), Bond and development of straight reinforcing bars in tension. (Reapproved in 2012)

Ahmad, S., Umar, A., Masood, A. and Nayeem, M. (2019), "Performance of self-compacting concrete at room and elevated temperature incorporating silica fume", *Adv. Concrete Constr., Int. J.*, **7**(1), 31-37. https://doi.org/10.12989/acc.2019.7.1.031

Aiello, M.A. and Leuzzi, F. (2010), "Waste tyre rubberized concrete: Properties at fresh and hardened state", *Waste Manage*, **30**, 1696-1704. https://doi.org/10.1016/j.wasman.2010.02.005

Alaloul, W.S., Musarat, M.A., Haruna, S., Law, K., Tayeh, B.A., Rafiq, W. and Ayub, S. (2021), "Mechanical properties of silica fume modified high-volume fly ash rubberized self-compacting concrete", *Sustainability*, **13**, 5571. https://doi.org/10.3390/su13105571

Al-Tayeb, M.M., Bakar, B.H.A., Ismail, H. and Akil, H.M. (2013), "Effect of partial replacement of sand by recycled fine crumb rubber on the performance of hybrid rubberized-normal concrete under impact load: experiment and simulation", *J. Cleaner Prod*, **59**, 284-289. https://doi.org/10.1016/j.jclepro.2013.04.026

ASTM C1611 (2005), Standard Test Method for Slump Flow of Self-Consolidating Concrete.

ASTM C33 (2018), Standard specification for concrete aggregates.

ASTM C39 (2021), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

ASTM C496 (1996), Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

Atahan, A.O. and Yücel, A.Ö. (2012), "Crumb rubber in concrete: Static and dynamic evaluation", *Const. Build. Mater*., **36**, 617-622. https://doi.org/10.1016/j.conbuildmat.2012.04.068

Bisht, K. and Ramana, P.V. (2017), "Evalutaion of mechanical and durability properties of crumb rubber concrete", *Const. Build. Mater*., **155**, 811-817. https://doi.org/10.1016/j.conbuildmat.2017.08.131

Chalangaran, N., Farzampour, A., Paslar, N. and Fatemi, H. (2021), "Experimental investigation of sound transmission loss in concrete containing recycled rubber crumbs", *Adv. Concrete Constr*., *Int. J*., **11**(6), 447-454. https://doi.org/10.12989/acc.2021.11.6.447

Chan, Y.W., Chen, Y.S. and Liu, Y.S. (2003), "Development of bond strength of reinforcement steel in self-consolidating concrete", *Struct. J*., **100**, 490-498.

Choi, K. (1988), "Anchorage of beam reinforced at conventional and fibrous beam-column connections", Ph.D. Thesis; Michigan State University, MI, USA.

EFNARC (2002), Specification and Guidelines for Self-Compacting Concrete.

Elchalakani, M. (2015), "High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers", *Struct*., **1**, 20-38. https://doi.org/10.1016/j.istruc.2014.06.001

Fakhri, M. and Saberi, F. (2016), "The effect of waste rubber particles and silica fume on the mechanical properties of roller compacted concrete pavement", *J. Cleaner Prod*., **129**, 521-530. https://doi.org/10.1016/j.jclepro.2016.04.017

Fakhri, M., Yousefian, F., Amoosoltani, E., Aliha M.R.M. and Berto, F. (2021), "Combined eggects of recycled crumb rubber and silica fume on mechiancla prorties and mode I fraqcture toughness of self-cmpacitbng concrete", *Fatig. Fract. Eng. Mater. Struct*., **44**, 2659-2673. https://doi.org/10.1111/ffe.13521

Foroughi-Asl, A., Dilmaghani, S. and Famili. H. (2008), "Bond strength of reinforcement steel in self-compacting concrete", *Int. J. Civil Eng*., **6**, 24-33.

Ganesan, N., Bharati, R. and Shashikala, A.P. (2013), "Behavior of self-consolidating rubberized concrete beam-column joints", *ACI Mater. J*., **110**, 697-704.

Gesoglu, M., Güneyisi, E., Hansu, O., Ipek, S. and Asaad, D.S. (2015), "Influence of waste rubber utilization on the fracture and steel–concrete bond strength properties of concrete", *Const. Build. Mater*., **101**, 1113-1121. https://doi.org/10.1016/j.conbuildmat.2015.10.030

Gillani, S.A., Toumi, A. and Turatsinze, A. (2016), "Effect of incorporating rubber aggregates and fiber reinforcement on the durability of thin bonded cement-based overlays", *Proceedings of the 8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements*, **13**, 619-625. https://doi.org/10.1007/978-94-024-0867-6_87

Gillani, S.A.A., Toumi, A. and Turatsinze, A. (2020), "Cyclic bridging law of steel fibre-reinforced and rubberised cement-based materials", *Eur. J. Environ. Civil Eng*., **26**(4), 1336-1348. https://doi.org/10.1080/19648189.2019.1709559

Gillani, S.A.A., Riaz, M.R., Hameed, R., Qamar, A., Toumi, A. and Turatsinze, A. (2022), "Fracture energy of fiber-reinforced and rubberized cement-based composites: A sustainable approach towards recycling of waste scrap tires", *Energy Environ*. https://doi.org/10.1177/0958305X221089223

Gravina, R.J., Xie, T., Roychand, R., Zhuge, Y., Ma, X., Mills, J.E. and Yousaf, O. (2021), "Bond behavior between crumb rubberized concrete and deformed steel bars", *Structures*, **34**, 2115-2133. https://doi.org/10.1016/j.istruc.2021.08.076

Guneyisi, E. (2010), "Fresh properties of self-compacting rubberized concrete incorporated with fly ash", *Mater. Struct*., **43**, 1037-1048. https://doi.org/10.1617/s11527-009-9564-1

Guneyisi, E., Gesoglu, M. and Ozturan, T. (2004), "Properties of rubberized concretes containing silica fume", *Cem. Concr. Res*., **34**, 2309-2317. https://doi.org/10.1016/j.cemconres.2004.04.005

Gupta, T., Chaudhary, S. and Sharma, R.K. (2016), "Mechanical and durability properties of waste rubber fiber concrete with and without silica fume", *J. Cleaner Prod*., **112**, 702-711. https://doi.org/10.1016/j.jclepro.2015.07.081

Hall, M.R. and Najim, K.B. (2014), "Structural behaviour and durability of steel-reinforced structural Plain/Self-Compacting Rubberised Concrete (PRC/SCRC)", *Const. Build. Mater*., **73**, 490-497. https://doi.org/10.1016/j.conbuildmat.2014.09.063

Hamdi, A., Abdelaziz, G. and Farhan, K.Z.J. (2021), "Scope of reusing waste shredded tires in concrete and cementitious composite materials: A review", *J. Build. Eng*., **35**, 102014. https://doi.org/10.1016/j.jobe.2020.102014

Hameed, R., Turatsinze, A., Duprat, F. and Sellier, A. (2013), "Bond stress-slip behaviour of steel reinforcing bar embedded in hybrid fiber-reinforced concrete", *KSCE J. Civil Eng*., **17**, 1700-1707. https://doi.org/10.1007/s12205-013-1240-x

Hassanli, R., Youssf, O. and Mills, J.E. (2017), "Experimental investigations of reinforced rubberized concrete structural members", *J. Build. Eng*., **10**, 149-165. https://doi.org/10.1016/j.jobe.2017.03.006

Hesami, S., Hikouei, I.S. and Emadi, S.A.A. (2016), "Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber", *J. Cleaner Prod*., **133**, 228-234. https://doi.org/10.1016/j.jclepro.2016.04.079

Ho, A.C., Turatsinze, A., Hameed, R. and Vu, D.C. (2012), "Effects of rubber aggregates from grinded used tyres on the concrete resistance to cracking", *J. Cleaner Prod*., **23**, 209-215. https://doi.org/10.1016/j.jclepro.2011.09.016

Hong, S. and Park, S.K. (2012), "Uniaxial bond stress-slip relationship of reinforcing bars in concrete", *Adv. Mater. Sci. Eng*., **12**, 328570. https://doi.org/10.1155/2012/328570

Ismail, M.K. and Hassan, A.A.A. (2016), "Use of metakaolin on enhancing the mechanical properties of self-consolidating concrete containing high percentages of crumb rubber", *J. Cleaner Prod*., **125**, 282-295. https://doi.org/10.1016/j.jclepro.2016.03.044

Javed, A., Gillani, S.A.A.; Abbass, W., Riaz, M.R., Hameed, R., Abbas, S., Salmi, A. and Deifalla, A.F. (2022), "Mechanical Performance of Amorphous Metallic Fiber-Reinforced and Rubberized Thin Bonded Cement-Based Overlays", *Sustainability*, **14**, 8226. https://doi.org/10.3390/su14138226

Lv, J., Zhou, T., Du, Q. and Wu, H. (2015), "Effects of rubber particles on mechanical properties of lightweight aggregate concrete", *Const. Build. Mater*., **91**, 145-149. https://doi.org/10.1016/j.conbuildmat.2015.05.038

Mallek, J., Daoud, A., Metalssi, O.O. and Loulizi, A. (2021), "Performance of self-compacting rubberized concrete against carbonation and chloride penetration", *Struct. Concrete*, **22**, 2720-2734. https://doi.org/10.1002/suco.202000687

Mezidi, A., Kettab, R.M., Benzahar, H.H. and Touhari, M. (2021), "Behavior of modified concrete based on crumb rubber: experimental test and numerical simulation", *Adv. Concrete Const., Int. J.*, **12**(2), 31-37. https://doi.org/10.12989/acc.2021.12.2.125

Najim, K.B. and Hall, M.R. (2010), "A review of the fresh/hardened properties and applications for plain- (PRC) and self-compacting rubberised concrete (SCRC)", *Const. Build. Mater.*, **24**, 2043-2051. https://doi.org/10.1016/j.conbuildmat.2010.04.056

Najim, K.B. and Hall, M.R. (2012), "Mechanical and dynamic properties of self-compacting crumb rubber modified concrete", *Const. Build. Mater.*, **27**, 521-530. https://doi.org/10.1016/j.conbuildmat.2011.07.013

Onuaguluchi, O. and Panesar, D.K. (2014), "Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume", *J. Cleaner Prod.*, **82**, 125-131. https://doi.org/10.1016/j.jclepro.2014.06.068

Pelisser, F., Zavarise, N., Longo, T.A. and Bernardin, A.M. (2011), "Concrete made with recycled tire rubber: Effect of alkaline activation and silica fume addition", *J. Cleaner Prod.*, **19**, 757-763. https://doi.org/10.1016/j.jclepro.2010.11.014

Pham, N.P., Toumi, A. and Turatsinze, A. (2018), "Rubber aggregate-cement matrix bond enhancement: Microstructural analysis, effect on transfer properties and on mechanical behaviors of the composite", *Cem. Concrete Compos.*, **94**, 1-12. https://doi.org/10.1016/j.cemconcomp.2018.08.005

Ramdani, S., Guettala, A., Benmalek, M.L. and Aguiar, J.B. (2019), "Physical and mechanical performance of concrete made with waste rubber aggregate, glass powder and silica sand powder", *J. Build. Eng.*, **21**, 302-311. https://doi.org/10.1016/j.jobe.2018.11.003

RILEM, FIP-CEB. (1973), "Tentative recommendations for reinforcing steel, bond test for reinforcing steel: 1-Beam test (7-ii-28 d) 2-Pull-out test (7-ii-128)", *Mater. Struct.*, **6**(2), 79-118.

Romanazzi, V., Leone, M., Tondolo, F., Fantili, A.P. and Aiello, M.A. (2021), "Bond strength of rubberized concrete with deformed steel bar", *Const. Build. Mater.*, **272**, 121730. https://doi.org/10.1016/j.conbuildmat.2020.121730

Shah, S.N., Mo, K.H., Yap, S.P., Putra, A. and Othman, M.N. (2021), "Assessment of lightweight crumb rubber-cement composite produced by replaced method", *Adv. Concrete Const., Int. J.*, **11**(5), 409-417. https://doi.org/10.12989/acc.2021.11.5.409

Si, R., Wang, J., Guo, S., Dai, Q. and Han, S. (2018), "Evaluation of laboratory performance of self-consolidating concrete with recycled tire rubber", *J. Cleaner Prod.*, **180**, 823-831. https://doi.org/10.1016/j.jclepro.2018.01.180

Siddique, R. and Naik, T.R. (2004), "Properties of concrete containing scrap-tire rubber – an overview", *Waste Manage*, **24**, 563-569. https://doi.org/10.1016/j.wasman.2004.01.006

Sohrabi, M.R. and Karbalaie, M. (2011), "An experimental study on compressive strength of concrete containing crumb rubber", *Int. J. Civil Env. Eng.*, **11**, 23-27.

Son, K.S., Hajirasouliha, I. and Pilakoutas, K. (2011), "Strength and deformability of waste tyre rubber-filled reinforced concrete columns", *Const. Build. Mater.*, **25**, 218-226. https://doi.org/10.1016/j.conbuildmat.2010.06.035

Sonebi, M., Bartos, P.J.M., Zhu, W., Gibbs, J. and Tamimi, A. (2000), "Final report task 4, Hardened properties of SCC, Brite-EuRam Contract No. BRPRTC96-0366", Hardened properties of SCC, Brussels, p. 75.

Su, H., Yang, J., Ling, T.C., Ghataora, G.S. and Dirar, S. (2015), "Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes", *J. Cleaner Prod.*, **91**, 288-296. https://doi.org/10.1016/j.jclepro.2014.12.022

Thomas, B.S. and Gupta, R.C. (2015), "Long term behaviour of cement concrete containing discarded tire rubber", *J. Cleaner Prod.*, **102**, 78-87. https://doi.org/10.1016/j.jclepro.2015.04.072

Thomas, B.S. and Gupta, R.C. (2016), "A comprehensive review on the applications of waste tire rubber in cement concrete", *Renew. Sust. Energ. Rev.*, **54**, 1323-1333. https://doi.org/10.1016/j.rser.2015.10.092

Thomas, B.S., Gupta, R.C., Kalla, P. and Cseteneyi, L. (2014), "Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates", *Const. Build. Mater.*, **59**, 204-212. https://doi.org/10.1016/j.conbuildmat.2014.01.074

Thomas, B.S., Gupta, R.C. and Panicker, V.J. (2016), "Recycling of waste tire rubber as aggregate in concrete: durability-related performance", *J. Cleaner Prod.*, **112**, 504-513. https://doi.org/10.1016/j.jclepro.2015.08.046

Topcu, I.B. and Bilir, T. (2009), "Experimental investigation of some fresh and hardened properties of rubberized self-compacting concrete", *Mater. Des.*, **30**, 3056-3065. https://doi.org/10.1016/j.matdes.2008.12.011

Turatsinze, A. and Garros, G. (2008), "On the modulus of elasticity and strain capacity of self-compacting concrete incorporating rubber aggregates", *Resour. Conserv. Recycle*, **52**, 1209-1215. https://doi.org/10.1016/j.resconrec.2008.06.012

Turatsinze, A., Bonnet, S. and Granju, J.L. (2005), "Mechanical characterisation of cement-based mortar incorporating rubber aggregates from recycled worn tyres", *Build. Env.*, **40**, 221-226. https://doi.org/10.1016/j.buildenv.2004.05.012

Turatsinze, A., Granju, J.L. and Bonnet, S. (2006), "Positive synergy between steel-fibres and rubber aggregates: Effect on the resistance of cement-based mortars to shrinkage cracking", *Cem. Concrete Res.*, **36**, 1692-1697. https://doi.org/10.1016/j.cemconres.2006.02.019

Turatsinze, A., Measson, M. and Faure, J.P. (2018), "Rubberized concrete: from laboratory findings to field experiment validation", *Int. J. Pave. Eng.*, **19**, 883-892. https://doi.org/10.1080/10298436.2016.1215688

Xue, J. and Shinozuka, M. (2013), "Rubberized concrete: A green structural material with enhanced energy dissipation capability", *Const. Build. Mater.*, **42**, 196-204. https://doi.org/10.1016/j.conbuildmat.2013.01.005

Youssf, O., ElGawady, M.A., Mills, J.E. and Ma, X. (2014), "An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes", *Const. Build. Mater.*, **53**, 522-532. https://doi.org/10.1016/j.conbuildmat.2013.12.007

CC

Abbreviations

CR	Crumb Rubber
SCC	Self Compacting Concrete
SCRC	Self Compacting Rubberized Concrete
SF	Silica Fume
ITZ	Interfacial Transition Zone
ASTM	American Society for Testing and Materials
RILEM	Réunion Internationale des Laboratoires et Experts des Matériaux (French)