Experimental investigation on bond-slip behavior of selfconsolidating rubberized concrete

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Abstract. Reducing the industry’s impact on the environment is the goal of sustainable construction which can be achieved by using renewable and recyclable resources such as scrap tire waste. Great potential of this waste is found in construction mostly as a partial replacement of mineral aggregate in concrete and mortars, asphalt mixtures and geotechnical works. Previous studies on the selfconsolidating rubberized concrete (SCRC) are mostly concerned with mechanical properties of rubberized concrete. However, in order to allow structural application, it is also necessary to investigate bond-slip behavior of SCRC and reinforcement bars. Thus, in this paper pull-out tests are performed on 24 cubic samples with reinforcement confinement. Three different SCRC mixtures are made, first with concrete without rubber particles as reference mixture, second with 10%, and third with 15% rubber particles and 5% silica fume. The other parameter varied is diameter of steel bars (Ø12, Ø16, and Ø20 mm). From the results obtained in experimental investigation, key bond parameters and failure modes of SCRC are compared with bond-slip behavior of self-consolidating concrete (SCC).

1. Introduction
In order to reduce waste and use recyclable materials, great potential is found in scrap tire waste due to their enormous amounts produced each year which is resulting in landfilling, burning, burying or grinding. Least harmful solution, as it is for the environment, so it is for people, is grinding scrap tires and reusing them. Potential use of tire waste is found in construction mostly as a partial replacement of mineral aggregate in concretes and mortars, asphalt mixtures and geotechnical works [1].

Previous studies have shown both positive and negative impact on concrete’s properties by replacing mineral aggregate with rubber particles [2], [3]. Increased hardness and ductility, enhanced dynamic properties, increased resistance to freezing and thawing, and resistance to HCl are some of improved properties. On the other hand, reduced resistance to carbonation, increased resistance to abrasion, water absorption and permeability, reduced compressive strength and modulus of elasticity of the concrete are results of negative impact of rubber addition.

Another very important property is bond-slip behavior of self-consolidating rubberized concrete (SCRC) and steel bars in reinforced concrete constructions. Main assumption in case of these structures is strong connection between concrete and rebar, and compatibility of deformations of between these two materials, \( \varepsilon_c = \varepsilon_s \). Thus bond strength between them enables stress transition from rebar to concrete without slip. In order to ensure these compatibility conditions, it is necessary to follow directions regarding adhesion and anchoring of reinforcement bars given in guidelines [4].
Some of the investigations on this property of rubberized concrete were carried out by Hall and Najim [5]. They conducted pull-out test in order to compare bond-slip behavior for four different mixes, plain rubberized concrete (PRC) and self-consolidating rubberized concrete (SCRC) with plain concrete (PC) and self-consolidating concrete (SCC), respectively. From the obtained results it was observed that the maximum bond strength $\tau_{\text{max}}$ was decreased while the bond coefficient values $\gamma$ were increased in PRC and SCRC mixes compared to PC and SCC mixes. Also, representing slip displacement that occurred at the maximum bond slip stress $\tau_{\text{max}}$ decreased significantly for mixes with rubber. Bompa and Elghazouli [6] examined the complete bond-slip behavior between deformed rebar and rubberized concrete. Their test results offered direct interpretation of the bond behavior under low levels of confinement as well as its influence on the failure modes. Anu Bala et al. [7] investigated how will replacement of mineral aggregate by rubber particles and of cement by fly ash (FA) up to 40% and 30%, respectively, influence bond strength. Results shown that the addition of rubber decreased bond strength, while the addition of FA improves it, however for replacement levels up to 20% of FA. Gesoglu et al. [8] replaced total aggregate volume in concrete with up to 30% of rubber particles. Results of their experiment have shown that bond strength of those concretes with rubber was lower than that of plain concrete. They found the reason is because rubber particles are much softer than the natural aggregate and that causes bond strength loss as the friction between reinforcement bar and the concrete decreases with the use of rubber aggregates.

In this paper pull-out tests are performed on 24 cubic samples of self-consolidating concrete with reinforcement confinement in order to investigate key bond parameters and failure modes of bond-slip behavior of SCRC concrete.

2. Case study
In order to assess the bond-slip ($\tau$-$s$) behavior between steel bars and concrete, 24 cubic specimens with reinforcement confinement were prepared in order to perform pull-out test. The parameters investigated in this research were diameter of the rebar ($\varnothing$12, $\varnothing$16, $\varnothing$20 mm) with a rubber amount in self-consolidating concrete. Two mixtures of SCRC were made, one as referent, without rubber, and the other one with 10% rubber particles replaced by volume of both fine and coarse mineral aggregate. Compressive strength, and modulus of elasticity of concrete were also tested to obtain general mechanical properties.

2.1. Materials
Materials used for production of concrete mixes include Portland cement 42.5 R, which conforms to HRN EN 197-1:2005, mineral (MA) and recycled aggregates (RA), silica fume (SLF), dolomite powder (DP), water and admixtures. Mineral aggregates consisted of fine aggregates (FA) of 0–2 mm and 2–4 mm fraction, and coarse aggregates (CA) which included gravel of 4–8 mm and 8–16 mm fraction. Recycled aggregate crumb rubber (CR) with particles of 0.5–4 mm size and density of 1050 kg/m3 was used in concrete mixes as substitute for 10%, and 15% ratio of the volume of both mineral and recycled aggregate. Dolomite powder was also used in order to fill pores in concrete mixture. For bars were used hot rolled steel bars with diameter of 12, 16 and 20 mm. Steel grade was B500B.

2.2. Mix design
Self-consolidating concrete (SCC) mixtures are labelled with SCC-xCR-ySLF where CR and SLF represents crumb rubber and silica fume, respectively. Labels x and y refers to the percentage of crumb rubber (0-15%) and Silica fume (0-5%) in mixtures, respectively.

From table 1 can be seen that in each concrete mixture, water to binder (w/b) factor kept constant. Referent SCC had a composition of 450 kg/m3 of cement, 938.45 kg/m3 of sand, and 814.90 kg/m3 of gravel of different fractions, 180 kg/m3 of tap water, 6.75 kg/m3 of super-plasticizer (SP) Energy FM 500 to obtain better workability. Additional water was necessary due to the dry surface of natural aggregates. Other rubberized concrete mixtures in this group contained rubber which replaced 10–15% of volume of sand. Quantities of rubber used were 66.0 kg/m3 and 98,75 kg/m3 for ratio of 10% and 15% of crumb rubber, respectively. Super-plasticizer Glenium ACE and viscosity modifying agent
RheoMATRIX (RM) were used in order to enable the right balance between fluidity, passing ability, and resistance to segregation.

Table 1. Concrete mixtures design.

| Mixture ID | w/b  | Cement [kg/m³] | SLF [kg/m³] | Water [kg/m³] | SP [kg/m³] | VMA [kg/m³] | DP mm | CR 0–4 mm | FA 0–2 mm | 4–8 CA mm | 8–16 mm | CR 0–4 mm | FA 0–4 mm | CA 4–8 mm | CA 8–16 mm |
|------------|------|----------------|-------------|---------------|-------------|-------------|-------|-----------|-----------|-----------|---------|-----------|-----------|-----------|-------------|
| SCC-0CR-0SLF | 0.40 | 450.00        | 0.00        | 180.00        | 6.75        | 1.35        | 80.00 | 0.00      | 324.45   | 614.00    | 362.18  | 452.72    | 324.45       | 452.72    |
| SCC-10CR-0SLF | 0.40 | 450.00        | 0.00        | 180.00        | 6.75        | 1.13        | 80.00 | 66.00     | 324.34   | 438.42    | 362.05  | 452.56    | 324.34       | 452.56    |

The results of fresh properties of concrete are presented in table 2 and it can be seen that mass and density are decreased with the addition of rubber particles. On the other hand, porosity increased with the addition of rubber while addition of silica fume decreased it. Results regarding viscosity, flowability and passing ability met criteria for self-consolidating concrete.

Table 2. Results of fresh concrete’s properties.

| Mixture ID | Mass [kg] | Density [kg/m³] | Porosity [%] | Viscosity T500 [s] | Flowability Slump flow | Passing ability PJ [mm] | H₂/H₁ |
|------------|-----------|----------------|-------------|---------------------|------------------------|------------------------|-------|
| SCC-0CR-0SLF | 8.06       | 2388.15        | 1.50        | 2.79                | 800                    | 7                      | 0.95  |
| SCC-10CR-0SLF | 7.854      | 2327.11        | 1.90        | 3.26                | 735                    | 10                     | 0.90  |

2.3. Specimen preparation and testing

According to HRN EN 12390-1:2012 [9] guidelines for shape, dimensions of specimens and moulds, and HRN EN 12390-2 [10] guidelines for making and curing specimens, both cubic (150×150×150 mm³) and cylindrical (⌀150 mm×300 mm) specimens were casted for each mixture. In figure 1 is shown the process of making cubic specimens for pull-out test, while in table 3 are given numbers of specimens per mixture and testing. The cylinders and cubes were demoulded 24 h after casting and then continuously moist-cured for 28 days. After this period, test specimens were measured and prepared for testing.

Figure 1. (a) confinement of pull-out test specimens; (b) concrete poured in moulds; (c) specimens after 28 days ready for testing.

Compressive strength and modulus of elasticity were tested under uniaxial compression in a four column high stiffness welded frame Controls Automatic Compression machine, while tensile strength of steel bars and pull-out tests were conducted on tensile testing machine Shimadzu AGXplus. Experimental setups are shown in figure 2.
### Table 3. Number of specimens per mixture and testing.

| Mixture ID               | Diameter [mm] | Cubic specimens | Cylindrical specimens | Pull-out test | Compressive strength $f_c$ [MPa] | Modulus of elasticity $E_{cm}$ [MPa] |
|--------------------------|---------------|-----------------|-----------------------|---------------|----------------------------------|-------------------------------------|
| SCC-0CR-0SLF (M1)        | $\phi_{12}$   |                 |                       | 4             |                                  |                                     |
|                          | $\phi_{16}$   |                 |                       | 4             | 3                                | 3                                   |
|                          | $\phi_{20}$   |                 |                       | 4             |                                  |                                     |
| SCC-10CR-0SLF (M2)       | $\phi_{12}$   |                 |                       | 4             | 3                                | 3                                   |
|                          | $\phi_{16}$   |                 |                       | 4             |                                  |                                     |
|                          | $\phi_{20}$   |                 |                       | 4             |                                  |                                     |
| $\Sigma$                 |               | 24              |                       |               | 6                                | 6                                   |

![Figure 2](image)

**Figure 2.** Experimental setup for (a) compressive strength; (b) modulus of elasticity; (c) pull-out test.

### 3. Test results and data analysis

#### 3.1. Compressive strength and modulus of elasticity of self-consolidating rubberized concrete

Results obtained from tests that include mean values ($\mu$) and coefficient of variation ($CoV$), are given in table 4. It can be seen that the ultimate compressive strength reduces with increase of rubber particles amount. Results of modulus of elasticity also show that it is decreased with the addition of rubber, while silica fume did not show any positive impact.

### Table 4. Test results of compressive strength and modulus of elasticity.

| Mixture ID               | Compressive strength $f_c$ [MPa] | Modulus of elasticity $E_{cm}$ [MPa] |
|--------------------------|----------------------------------|-------------------------------------|
|                          | $\mu$                            | $CV$                                | $\mu$ | $CoV$ |
| SCC-0CR-0SLF (M1)        | 43.7                             | REF 0.06                            | 38576.62 | REF 0.08 |
| SCC-10CR-0SLF (M2)       | 31.25 -28.49%                     | 0.09 35256.04 -8.57%                | 0.03 | 0.03 |
3.2. Bond-slip behavior of self-consolidating rubberized concrete

Results of pull-out tests describe bond-slip behavior (τ-s) of SCRC which is presented in figure 3 as comparison of τ-s curve obtained for three different bar diameters for each concrete mixture. In figure 4 is presented comparison of τ-s curves for the same bar diameter but different concrete mixture. From these figures can be seen that bond strength (τ_{slip}) is reduced both with the addition of rubber and increase in bar diameter. Similar to the compressive strength, difference in ultimate bond strength (τ_{max}) between M1 and M2 is not big as that between M2 and M1, again probably due to the addition of silica fume. Another observation is made regarding relative slip (s). From the results given in table 5 it can be seen that relative slip s at τ_{max} reduces with increase in bar diameter.

Figure 3. Comparison of average τ-s curves of different bar diameter for each concrete mixture: (a) SCC-0CR-0SLF (M1); (b) SCC-10CR-0SLF (M2).

Figure 4. Comparison of average τ-s curves of different concrete mixture and the same bar diameter: (a) φ12; (b) φ16; (c) φ20.

Table 5. Comparison of pull-out test results.

| Diameter [mm] | Mixture ID       | Bond strength τ_{max} [MPa] | CV  | Bond strength τ_{max} [MPa] | CV  |
|--------------|------------------|----------------------------|-----|----------------------------|-----|
| 12           | SCC-0CR-0SLF     | 28.71                      | REF | 0.01                       | 0.064 | REF | 0.08 |
| 12           | SCC-10CR-0SLF    | 19.54                      | -31.94% | 0.03                       | 0.018 | -71.87% | 0.27 |
| 16           | SCC-0CR-0SLF     | 24.86                      | REF | 0.09                       | 0.019 | REF | 0.10 |
| 16           | SCC-10CR-0SLF    | 18.88                      | -24.05% | 0.25                       | 0.015 | -21.05% | 0.27 |
| 20           | SCC-0CR-0SLF     | 20.42                      | REF | 0.01                       | 0.014 | REF | 0.66 |
| 20           | SCC-10CR-0SLF    | 17.88                      | -12.44% | 0.08                       | 0.011 | -21.43% | 0.05 |

From figure 4 also can be observed two types of specimen’s failure modes First possible failure mode is due to the concrete splitting and second due to the bar pullout. From presented τ-s curves is concluded that in specimens named with PO-16-M1-Average, PO-20-M1-Average, and PO-20-M2-Average failure occurred due to the concrete splitting. In figure 5 are shown specimens after testing of both
concrete mixture in order to see relation between shape of the curve and failure modes. From these observations can be concluded that addition of rubber particles in concrete mixture contributes to more ductile failure, without concrete splitting. Similar conclusion was observed in [11] regarding compressive stress-strain curves of rubberized concrete.

![Figure 5. Failure modes of SCC-0CR-0SLF specimens with (a) φ12; (b) φ16; and (c) φ20 rebar diameter; and of SCC-10CR-0SLF specimens with (d) φ12; (e) φ16; (f) φ20 rebar diameter.](image)

4. Conclusions

Based on experimental results of compressive strength, modulus of elasticity and bond-slip behavior of self-consolidating rubberized concrete (SCRC), it can be concluded that the addition of rubber has significant influence compared to the referent self-consolidating concrete (SCC). Thus, compressive strength was reduced by 28.49% for 10% rubber particles, respectively, while modulus of elasticity was reduced by 8.57%.

On bond-slip behavior of SCC and SCRC influenced both rubber replacement and steel bar diameter. Results have shown that increasing both rubber particles amount and diameter decreased bond strength and slip displacement. Bond strength was decreased by 31.94% (φ12), 24.05% (φ16), and 12.44% (φ20) for 10% rubber replacement, respectively. From the failure modes that occurred on specimens, it was concluded that steel bar diameter has great influence on the type of failure. Reduction of bond strength and concrete splitting due to the greater bar diameter occurred probably due to three reasons: (1) lower ratio of concrete and steel bar of greater diameter; (2) ribs on steel bar cause earlier concrete splitting; (3) greater surface of steel bar gets in touch with concrete matrix and in case of higher amounts of rubber particles friction between them is much lower because of rubber’s softness and much lower modulus of elasticity. However, in order to derive more accurate conclusions, additional investigations need to be carried out.

5. References

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