Czech Journal of Civil Engineering

2023
Volume 09
Issue 01

Experimental study of properties of concrete with dosage of recycled steel fibers

Experimentálna štúdia vlastností betónu s dávkou recyklovaných oceľových vlákien

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PROFESSIONAL/PRACTICAL ARTICLE

ABSTRAKT

V súčasnosti je vo svete pozorovaný významný nárast množsva odpadových pneumatík. Každý rok ich pribudne viac ako 1 miliarda, čo prináša environmentálne a zdravotné problémy. S využitím materiálového zhodnocovania jednotlivých odpadov sa naskýtá potenciál získať recyklované oceľové vlákna (RSF). Dávka RSF v betóne výrazne zlepšujú pevnosť v ťahu a absorpciu energie recyklovaného betónu vystuženého oceľovými vláknami (RSFRC). Cieľom experimentálneho výskumu prezentovaného v tomto príspevku bolo zistiť pevnosť RSFRC v tlaku, pevnosť v priečnom ťahu a určiť konkrétne lomovo-mechanické parametre RSFRC pri rôznych dávkach RSFC. Skúšky pevnosti v tlaku RSFRC boli vykonané na troch vzorkách pre každú dávku RSF podľa STN EN 12 390-3. Skúška pevnosti betónu v priečnom ťahu bola vykonaná podľa STN EN 12390-6 na troch válcových vzorkách. Vybrané lomové mechanické vlastnosti boli stanovené na troch nosníkoch RSFRC so zárezom pre každú dávku RSF podľa JCI-S-001-2003 a JCI-S-002-2003. Experimentálny výskum ukázal, že pri dávke RSF vyššej ako 1,9 % obj. sa pozoroval nárast pevnosti RSFRC v tlaku. Ďalej sa zistilo, že s rastúcou dávkou RSF rástla pevnosť betónu v priečnom ťahu. Výsledkom ohybového testu je rastúci trend lomovej energie so zvyšujúcou sa dávkou RSF. Z tohto experimentálneho výskumu vyplynulo, že dávku RSF je potrebné zvoliť minimálne s hodnotou 1,9 % obj.

Klíčová slova: *Recyklované vlákna; Pevnosť v tlaku; Pevnosť v priečnom ťahu; Ohybové správanie; Lomová energia*

ABSTRACT

Currently, is observing a huge increase in waste tires in the world. Over 1 billion waste tires increase yearly, bringing environmental and health issues. Material recovery of particular waste allows for obtaining recycled steel fibers (RSF). RSFs incorporated in concrete significantly improve recycled steel fiber reinforced concrete's tensile strength and energy absorption (RSFRC). The goal of the experimental research presented in this paper is to investigate the compressive strength of RSFRC, tensile splitting strength and to determine particular fracture mechanical parameters of RSFRC with different doses of RSF. RSFRC compressive strength tests were carried out on three samples for each batch of RSF according to STN EN 12 390-3. Determination of tensile splitting was executed according standard STN EN 12390-6 in case three specimens, cilinders in shape. Selected fracture mechanical properties were determined on three RSFRC beams with a notch for each batch of RSF according to JCI-S-001-2003 and JCI-S-002-2003. Experimental research has shown that with a dose RSF higher than 1.9% by volume an increase in RSFRC compressive strength was observed. Further was invented, that with increase dosage of RSF increase tensile splitting strength of concrete. The bending test result is an increasing trend of fracture energy with an increasing dose of RSF. From this experimental research, it emerged that it is necessary to choose a dose of RSF of at least 1.9% by volume.

Key words: *Recycled fibers; Compressive strength; Tensile splitting strength; Flexural behavior; Fracture energy*

1 INTRODUCTION

As a consequence of improper approach of waste tires, they accumulate in landfills around the world. Hu [5] states that 1.5 billion units of billions of new tires are produced every year in the world and one billion waste tires is added. Blessen et al. [6] predict that 1.2 billion tires will be added yearly in 2030´s. There are now strong incentives to reverse this trend. According to the "Council Directive 1999/31/EC" [7] of the European Commission on landfills, since 2003 it is not possible to store waste tires for consumers, and since 2006 these regulations have to apply to both whole and torn tires [8]. The way to reduce the enormous amount of waste tires is to recycle them. Liew [9] states that recycling tire production is sustainable, ecological, and health-friendly, and also provides an economical way of energy for cement production. By recycling tires, it is possible to eliminate landfills, which are a breeding ground for mosquitoes that can transmit potentially fatal diseases to humans [9]. [10] reports that over the past 20 years, an increase in the material recovery of supported tires has been observed with new technologies that have the ability to recover components obtained from waste tires. In the material recovery process, the rubber component of the tires is separated from the steel and textile reinforcement of the tires using mechanical crushing and separation using a strong magnet, pyrolysis decomposition or cryogenic reduction. Every year, 500 thousand tons of recycled steel fibers (RSF) can be obtained from waste tires [11, 12]. Currently, 60 million are consumed in the world. It is estemated that RSF could contribute to the demand for the above commercial fibers [8].

It is generally known that cement composite is a brittle material with low tensile strength and low toughness. According to [13], RSFs modify brittle concrete into a more ductile material that has the ability to withstand large deformations before losing its bearing capacity. Working with fresh concrete (FC) with a dose of RSF does not require specialized service and a higher requirement of workmanship is also achieved due to the limitation of possible undesirable movement of traditional rebar reinforcement during the stage of casting concrete into the formwork [13].

There are studies focused on the compressive strength of recycled steel fiber reinforced concrete (RSFRC). In studies by [11, 13, 14], it was found that the compressive strength of RSFRC increased with the dosage of RSF, and [14] attributed this phenomenon to the use of a planetary mixer for mixing the FC mixture. In the studies [8, 10, 14, 15], was not observed in the compressive strength of RSFRC, respectively, was a decrease in the compressive strength of RSFRC. [14] used a mixer with a gravity mixing method for the preparation of concrete mixtures in the case of a decrease in the compressive strength of concrete. [8] concluded that the compressive strength of RSFRC is mainly influenced by the strength of the concrete matrix. The different conclusions of the authors above are probably due to the different geometrical and strength characteristics of RSF.

In the study [8], [13], which dealt with fracture mechanical properties, the toughness of concrete was demonstrably increased. [9], confirmed that the behavior of RSFRC depends not only on the type and quality of the fiber, but also on the dosage that was added to the concrete. Recycled steel fibers have the ability to bridge cracks and have a positive effect on their propagation. [9, 13], also confirmed that steel fibers can provide comparable results to industrially produced fibers. This conclusion can be partially explained by the conclusions of the study [16], which attributes this phenomenon to the relatively large aspect ratio of RSF.

From the abovementioned conclusions from the research works, it is not possible to predict with certainty the behavior of RSFRC in compression and also its response in bending. Different conclusions are most probably related to different geometric and mechanical parameters of RSF and probably also to different concrete receptures. For this reason, it was necessary to develop a statistical analysis of the geometric and mechanical parameters of the RSF in this contribution and to carry out an experimental investigation of the samples stressed by uniaxial tension and bending.

2 MATERIALS AND METHODS

2.1 Recycled steel fibers

2.1.1 *Geometrical parameters*

Origin RFS come from a local waste tire processing plant based in the Slovak Republic. The fibers were supplied in paper bags. Each RSF has different geometric and mechanical properties due to the origin and technology of the separation process. For this reason, it was necessary to perform a statistical analysis. In the statistical analysis for the characterization of the geometric parameters, 1050 RSFs were randomly selected, which are shown in **Fig. 1**.

Fig. 1 Sample of 1050 RSF.

The length of the RSF l_f was measured using a digital vernier caliper with an accuracy of 0.01 mm. The length l_f represents the direct distance between the two ends of the RSF. The average length of RSF was 12.38 mm with CoV. 41.0% minimum respectively maximum length of RSF was 1.55 mm respectively 59.13 mm.

The diameter RSF d_f was measured using a digital micrometer with an accuracy of 0.001 mm. The average value of the diameter was obtained from the measurements at both ends and at the center part of each RSF. The mean RSF diameter was 0.241 mm with CoV. 83.7%. The minimum respectively maximum diameter of RSF was 0.066 mm respectively 1,882 mm.

The aspect ratio l_f/d_f was determined by entering the ratio of the length of the RSF and the diameter of the RSF for a particular fiber. It was found that the average value of the aspect ratio was 61.6. Minimum respectively the maximum RSF aspect ratio was 8.8 respectively 233.9 with CoV. 42.7%.

http://doi.org/10.51704/cjce.2023.vol9.iss1.pp69-76
ISSN (online) 2336-7148

2.1.2 *Mechanical parameters*

Sample for determining the tensile strength consist of 55 RSF. To record the force at which the RSF failed, a digital scale with a measurement range of 0-500 N and a measurement accuracy of 0.1 N was used. When the RSF was broken, the force was recorded, which was noted into relation (1).

$$f_{t,RSF} = \frac{F_{t,max}}{A_{RSF}} \tag{1}$$

where:

- $f_{t,RSF}$ - tensile strength RSF [MPa],
- $F_{t,max}$ – force in time of rupture RSF [N],
- A_{RSF} – section area of RSF [mm^2].

2.2 Mixture of recycled steel fibers reinforced concrete

The concrete used in the experiment was made from dry concrete mix packed in paper bags. The specification of the dry concrete mixture and the volume of added water are shown in **Tab. 1**.

Tab. 1 Specification of the concrete and volume of mixing water in concrete.

Name of the product	Specification of the concrete	Volume of mixing water per 1 kg of dry concrete mix
Cemix Beton Basic 430	EN 206+A2:2021 - C20/25 – X0, XC1 – (SK, F1) – Cl 0,1 – D_{max} 4	0.134 l/kg

For the experiment, concrete mixtures were prepared with a dose of RSF of 0%, 0.4%, 0.9%, 1.4%, 1.9% and 2.4% by volume. The density of RSF ρ_{RSF} was determined by measurements to be 6950 kg/m^3. This knowledge made it possible to calculate the exact weight of RSF that needed to be added to the concrete mix.

2.3 Methods

The concrete mixture was mixed in a gravity mixer. The total length of mixing time for each the concrete mixture was 12 minutes, while in the first phase of mixing, the mixer was filled with dry concrete mixture and water was gradually added. RSF was gradually added manually to the concrete mixture after 3 minutes. After a further 5 minutes, the first slump test was carried out according to STN EN 12350 – 2 [17], with the mixing process being stopped during particular time. After the first slump test was performed, stirring was started for another two minutes. After this time, a second cone settling test was carried out and after its completion, a final mixing phase was carried out for two minutes. After finishing the mixing process, the concrete mixture was placed in forms. The concrete mixture was compacted in the molds using a vibrator. After 24 hours, the samples were placed in treatment tanks with water for 7 days. After abovementioned time, the samples were further matured in the air until they reached the age of 28 days.

The plastic molds in which the cubes were demolded for testing the compressive strength of RSFRC had an edge length of 150 mm. The steel molds in which the beams were deformed for the bending response had dimensions of 100 x 100 x 400 mm. The steel molds was cylinder in shape with diameter 150 mm and length 300 mm.

Before the test, the samples were measured using a caliper and weighed using a digital scale with an accuracy of 1 g.

The test for determining the compressive strength of concrete was carried out according to [1]. The Controls Advantest 9 device was used for the test. During the test, the cube was placed in the test device so that the side that was not in contact with the mold was placed on its side. Tensile splitting strength was examined according [2]. The response of the RSFRC to bending stress was tested according to [3, 4] on the three-point loading scheme in **Fig. 2**.

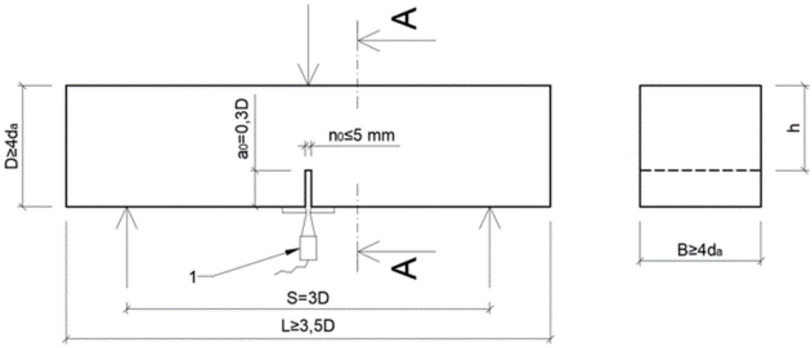

Fig. 2 Three points loading scheme for determination of response RSFRC, 1 – CMOD clip gauge.

From Fig. 2, it follows that for the chosen size of the sample, the actual size of the notch is a_0 = 30 mm and the span S = 300 mm. The value da represents the size of the maximum aggregate grain, which is given in Tab. 1. The dimension n_0 should not exceed 5 mm according to the standards [3, 4].

3 TEST RESULTS AND DISCUSSION

3.1 Test results of fresh and hardened RSFRC

The results from the slump test and the resulting RSFRC strengths are shown in **Tab. 2**. In the obtained results, it can be observed that the average compressive strength of concrete with a 0% dose of RSF is 16.1 MPa. In samples with a fiber dose of 0.4%, 0.9%; 1.9% and 2,4% was noted increase in RSFRC compressive strength. In samples with a dosage of fibers 1.4% was noted decrease of compressive strength of RSFRC. This phenomenon can be explained by the fact that RSF in such particular doses significantly deteriorated the workability of fresh concrete, but does not bridge the microcracks that increase when uniaxial pressure is applied to the sample. In the sample with a dosage of 2.4%, despite the deteriorated workability, the effect of the fibers on bridging expanding microcracks from the action of uniaxial pressure was manifested.

Tab. 2 Results of slump and compressive strength of RSFRC.

Dosage of RSF [%]	Slump test [mm]	$f_{cm,cube}$ [MPa]	St. dev. [MPa]
0	120	16.1	0.59
0.4	22	16.9	1.05
0.9	22	17.8	0.52
1.4	24	16.0	0.73
1.9	25	18.9	0.33
2.4	15	20.7	0.27

http://doi.org/10.51704/cjce.2023.vol9.iss1.pp69-76
ISSN (online) 2336-7148
www.cjce.cz

3.2 Results of splitting tensile strength od RSFRC

Results from testing tensile splitting strength are shown in the **Fig 3**. From obtained results is possible to observe trend, where with higher dosage of RSF increase tensile splitting strength of RSFRC.

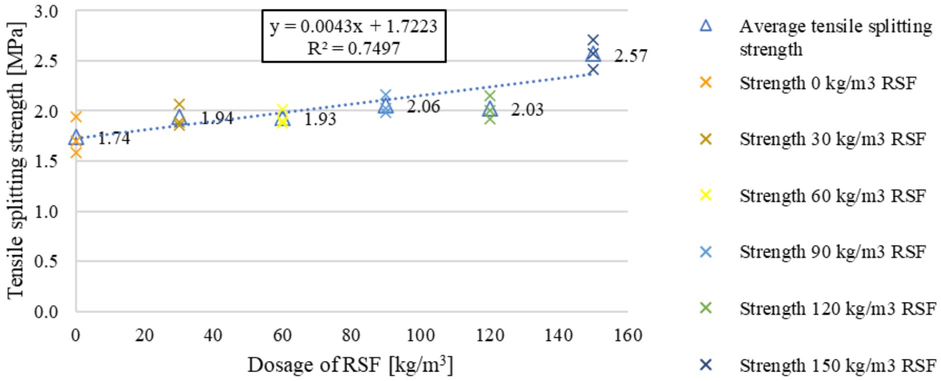

Fig. 3 Tensile splitting strength results.

3.2. Flexural tests results of RSFRC

In this section, the dependence curves of F-CMOD, values of fracture energy and maximum values of force under bending stress, which were determined during the experimental testing of the RSCRF beam with a notch, are presented. In **Fig. 3** shows the curves with F-CMOD dependence. From the averaged curves, it can be observed that the samples with 0% RSF broke immediately after the first crack appeared. In the case of samples with 0.4%, 0.9%, and 1.4% RSF, a sharp drop in load is observed after the appearance of the first crack. This phenomenon can be explained by the fact that RSFs are activated with a certain delay in the concrete matrix. The maximum value of CMOD at these reinforcement doses is related to the failure of the specimen at a given CMOD. In the case of samples with 1.9% and 2.4% RSF, it is possible to observe a negligible decrease in strength after the appearance of the first crack. The final CMOD value of approximately 4600 μm is conditioned by the range of the CMOD clip gauge, which after exceeding the value shown in **Fig. 4** separated from the glued steel blades.

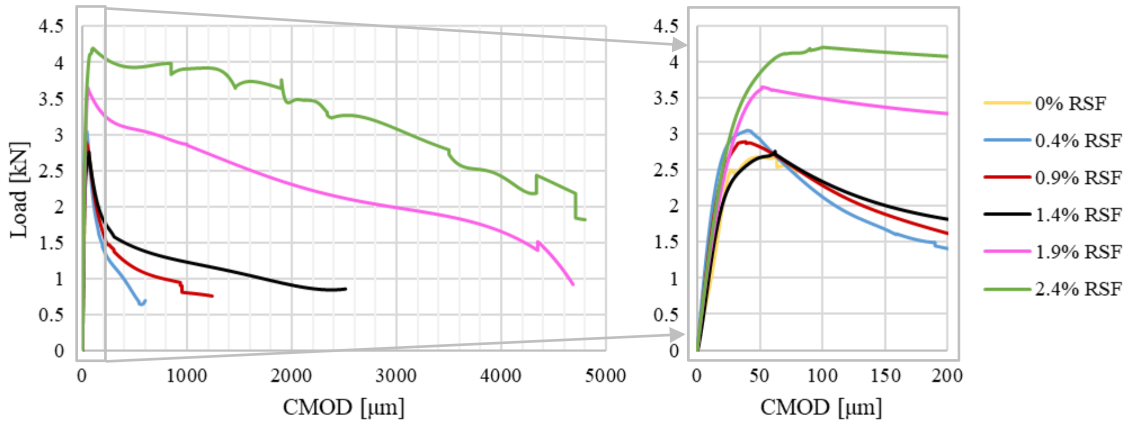

Fig. 4 Result dependencies F-CMOD.

Tab 3 shows the maximum load values from the bending test of the RSFRC beam with a notch. It can be observed that the trend of the maximum load value under bending stress correlates with the trend of the RSCRC mean compressive strength.

In **Tab 3**, the values of fracture energies calculated from the above curves, sample parameters and parameters of the test equipment are presented according to [3, 4]. The results show an increasing trend of fracture energies. It follows that RSF has tremendous potential in applications with a requirement for increased energy absorption.

Tab. 3 Flexural test results.

Dosage of RSF	$F_{max,mean}$ [N]	$F_{max,st.dev}$ [N]	$G_{F,mean}$ [N/mm]	$G_{F,st.dev}$ [N/mm]
0	2737.5	180.3	0.016	0.002
0.4	3132.0	162.7	0.074	0.030
0.9	2950.2	175.6	0.163	0.006
1.4	2557.8	270.6	0.386	0
1.9	3160.0	26.4	1.181	0.136
2.4	4396.4	164.4	1.716	0.232

4 CONCLUSION

In the paper, a description of the investigated materials and an analysis of the results from the experimental investigation of RSFRC depending on the dose of added RSF in the concrete matrix were presented. By analyzing the results, the following conclusions can be drawn:

- Added of RSF improve the compressive strength of RSFRC in case 0.4% RSF about 0,8 MPa, 0.9% RSF about 1, MPa, 1,9% RSF about 2.8MPa, and 2.4% RSF about 4.6 MPa. In the case of dose 1.4% RSF was decreased compressive strength about 0.1 MPa
- Increasing dosage of RSF improves tensile splitting strength of RSFRC against RSFRC with 0% RSF
- With an increasing dose of RSF, the fracture energy increases or energy absorption RSFRC
- The dose of RSF significantly affects the response of the RSFCR sample after the first crack
- At higher doses of RSF than 1.9% vol. the value of the load that causes the bending stress increases.

Despite the abovementioned conclusions, more extensive experimental and theoretical research by RSFRC is necessary, thanks to which it will be possible to safely use this material in practical applications.

5 ACKNOWLEDGEMENT

This work was supported by the Scientific Grant Agency VEGA under the contract No. VEGA 1/0358/23 and by the University Science Park (USP) of the Slovak University of Technology in Bratislava (ITMS: 26240220084).

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http://doi.org/10.51704/cjce.2023.vol9.iss1.pp69-76
ISSN (online) 2336-7148