Impact performance of rubber reinforced concrete with waste steel fibres

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Abstract. This study introduces cementitious composite with rubber granulate and waste steel fibres as a new material for construction industry with an enhanced energy absorption capability and impact toughness. Detailed research on physico-mechanical properties of high-performance concrete with waste steel fibres and partial replacement of the aggregates by rubber granulate was performed, with emphasis on impact energy absorption potential. Different aggregate replacement ratios (0-30% wt.) and fibre amount (0-3% wt.) were investigated. The influence of rubber sizes, rubber content and steel fibre content on the mechanical parameters of the rubberized concrete at both quasistatic and dynamic loads was evaluated and discussed. With increasing amount of rubber granulate, the concrete suffered from reduction of its mechanical parameters – compressive and flexural strength, however the energy dissipation capability showed rising trend. This study demonstrated the potential of rubberized concrete with waste steel fibres for use in structures with higher impact resistance requirements.

1. Introduction

In 2016, around 3.5 million tonnes of waste tires were produced in EU [1]. High percentage was recycled and used for the production of playground and sport pitches tiles, in hot mix asphalt as a highway construction material, subgrade insulation, sound absorbing barriers, lightweight fill material, drainage materials, flowable fills, and road embankments or energy recovery, but still about 160,000 tonnes of tires (about 4.6%) were landfilled. Taken into account the numbers of landfilled tires, it is clear, that there is a wide space for new applications with waste tires content. A tire consists of rubber elastomer, carbon black, metal, textile fabric and additives. The amount of each constituent varies depending on tire type and producer, but approximately the tire contains 47% rubber, 22% carbon black, 17% steel cords, 5% fabrics, and the remaining percentage consists of some other minor additives, as reported by Evans [2]. The possibility of both rubber-based material and steel wire are currently widely tested to partially replace the raw materials for production of several cement-based composites. Concrete is the most spread material in the construction industry. Optimizing its composition towards a greener and more cost-effective variants while maintaining its physico-mechanical parameters is a global challenge, significant to society. Due to the high strength, uniform properties, elasticity, and inert behaviour towards the cement matrix, rubber from tire waste appears to be a potentially suitable component for substituting part of coarse and fine aggregates. Up to now, published studies have mainly focused on evaluating the mechanical parameters of rubberized concrete at quasistatic load. The substitution of aggregate by rubber recycle usually results in a reduction of the mechanical parameters of concrete, especially its compressive and flexural strength. However, to some extent, it may shift the
properties of concrete towards a higher ability to dissipate impact energy [1]. Siddika [1] and Gereges [3] reported in their studies a significant reduction in the compressive strength of concrete when aggregate was replaced by rubber granulate. (Up to 63% reduction in compressive strength when 20% aggregate was substituted has been observed). According to the study of Thomas and Gupta [4], the optimal rate of replacement of fine aggregate with rubber granulate is 12.5%, in terms of maintaining the strength of concrete, resistance to water absorption and carbonation. Dynamic properties of standard concrete and fibre reinforced concrete have been widely studied in the last decades, e.g. [5-8], but not much data has been published yet regarding the dynamic properties of concrete with rubber particles. It is generally known that materials subjected to impact loading must exhibit high impact energy absorption capacity and toughness. The research work carried out so far also shows that the addition of crushed rubber to concrete increases toughness and impact resistance [9-12]. For example, the performance of the concrete with waste tire particles content has been studied by Atahan [12], who carried out crash tests on barriers made of rubber concrete. His results indicate that the presence of the rubber particles improves absorption of the vehicle's kinetic energy during the crash to the barrier and reported as the most effective the replacement ratio of the aggregates by the rubber particles between 20-40% [12]. The behaviour of rubberized concrete at high strain rates using Split Hopkinson pressure bar was investigated by Liu et al. [9]. The results published in his study show that the energy absorption capacity increases with the increasing rate of rubber granules in the concrete, but only up to 10% of the rubber content. Above this amount, the absorption capacity decreases again. A decrease of impact resistance when a higher percentage of aggregates is replaced by rubber granulate was also reported by Atahan [13], who observed that 100% replacement of aggregate with rubber recycalate resulted in a significant reduction of impact load resistance (72%). On the other hand, Corinaldesi and Donnini [14] and Al-Tayeb [15] observed improved impact energy absorption when 50% sand was replaced by rubber granulate. The majority of studies mentioned above have confirmed that the presence of rubber particles can increase the energy dissipation capability of concrete and its impact resistance, which can be crucial in some applications such as road construction (restraint systems, guardrails). Rubberized concrete, therefore, appears to be a suitable candidate for impact load applications. Still, more data is needed regarding the energy dissipation capability and impact toughness of rubberized concrete with the addition of commercial and waste steel fibres; studies available in this field are scarce and results are not entirely consistent. The main goal of the presented research is thus to enhance the knowledge in this field. The obtained results will be used in the ongoing development of elements for safety enhancement, e.g., in the field of transport or critical infrastructures protection.

2. Experimental program

2.1. Materials and specimen preparation

Cement CEM 42.5 R (700 kg/m³), silicious sand (624 kg/m³); Střeleč quarry) with grain size of 0–2 mm, coarse aggregates with grain size of 2–4 and 4–8 mm (298 and 446 kg/m³, granodiorite, Olbramovice quarry), rubber granulate with grain size of 0–1, 1–3 and 3–6 mm (processed and supplied by RPG Recycling, see figure 1, left) and water (189 kg/m³) were the main components of the reference concrete mixture R0. Superplasticizer Glenium 422 produced by BASF, was added. The proportion of superplasticizer was varied in range of 15–20 kg/m³, as to keep similar and sufficient workability for all mixes. Silica fume Elkem 940U (150 kg/m³), produced by BASF, was used to add fine fractions to achieve the maximum compaction of the mixture and to exploit its pozzolanic properties. The waste steel fibres from tires, without further classification, were added as the reinforcement, see figure 1 right (processed and supplied by RPG Recycling). The fibres shape parameters vary, the distribution of their diameter and length depctes figure 2. For comparison, steel fibres KrampeHarex 30/0.6DE (length 30 mm, diameter 0.6 mm), without coating, has been used. The mixes are summarized in table 1. In total, 10 mixes were prepared and investigated. Concrete mixes were prepared with water/cement ratio of 0.27; first the components were dry-mixed for 2–3 minutes in concrete mixer, then the water with superplasticizer was added and mixed for another 2 minutes. As the last step, the fibres were added to
the mixture and homogenized for 60 seconds. Prepared mixtures were placed into steel moulds treated with releasing agent and vibrated on a table vibrator. After demoulding, the specimens were stored in water for 28 days. Beams with dimensions of 100 × 100 × 400 mm were prepared for the quasi-static tests. For dynamic tests, slabs of 400 × 400 × 40 mm, cubes of 150 mm edge and prismatic specimens with dimensions of 300 × 100 × 100 mm were prepared.

**Figure 1.** Coarse rubber particles used in the mixtures (left), unclassified waste steel fibres (right).

**Figure 2.** The distribution of fibre diameter and length.

2.2. **Physico-mechanical parameters**
Mechanical parameters were tested on a TIRAtest 2710, R58/02 press machine at a 5 mm/min loading rate. First, a flexural tensile strength test (three-point) was carried out, followed by a compressive strength test performed on the fractions of the test specimens. Both strength tests and bulk density determination were performed according to the standard ČSN EN 12390-3. Additionally, the water absorption was determined according to the ČSN 73 1325 standard.
Table 1. Description of the mixes.

| Designation | Fibre content (vol. %) | Total vol. % of aggregate replacement | Replacement percentage (vol. %) |
|-------------|------------------------|---------------------------------------|-------------------------------|
|             |                        |                                       | Rubber 0–1 mm | Rubber 1–3 mm | Rubber 3–6 mm |
| R0          | 0                      | 0                                     | 0               | 0             | 0             |
| R10/10-10-10| 0                      | 10                                    | 10              | 10            | 10            |
| R20/20-20-20| 0                      | 20                                    | 20              | 20            | 20            |
| R30/30-30-30| 0                      | 30                                    | 30              | 30            | 30            |
| R20/44-0-0  | 0                      | 20                                    | 44              | 0             | 0             |
| R20/0-0-62  | 0                      | 20                                    | 0               | 0             | 62            |
| FR20/1      | 1.0                    | 20                                    | 20              | 20            | 20            |
| FR20/2      | 2.0                    | 20                                    | 20              | 20            | 20            |
| FR20/3      | 3.0                    | 20                                    | 20              | 20            | 20            |
| FR20/3KH    | 3.0                    | 20                                    | 20              | 20            | 20            |

2.3. Impact resistance drop test

The impact resistance drop test device, including the test methodology, was developed in Research Institute for Building materials. It consists of a solid steel stand with dimensions of 400 × 400 mm on which the test specimen is fixed. The stand is connected with the support structure with two brackets through which a vertical steel guiding rod with a spherical ending is passed (see figure 3). The steel rod is equipped with a 4 kg weight that can move freely vertically along the rod. The weight is repeatedly dropped from a height of 700 mm to the centre of the test specimen, and the number of blows required to produce the first visible crack (so called initial crack) and the ultimate failure is recorded. The total absorbed energy for both stages is then calculated using the following formula:

$$E = m \cdot a_g \cdot h \cdot x$$  \hspace{1cm} (1)

Where:
- $E$...Total absorbed energy [J]; $m$...Weight of the impactor [kg]; $a_g$...Gravity acceleration [m.s$^{-2}$]; $h$...Height of drop [m]; $x$...Number of the drops [-].

2.4. Rebound test

Rebound test has been carried out on cubes with the edge length of 150 mm. A steel ball weighing 0.5 kg was used for the measurements. During the test, the ball was released from a certain height (1000 mm) towards the centre of the test specimen. After rebounding from the specimen, the reached height was recorded using the Nikon J5 high-speed camera. The absorbed energy was calculated as the difference of the potential energies of the steel ball at the release and after the rebound, see equation 2:

$$E = E_{p,in} - E_{p,r}$$  \hspace{1cm} (2)

Where:
- $E_{p,r} = m \cdot a_g \cdot h_r$ \hspace{1cm} (3)
- $E_{p,in} = m \cdot a_g \cdot h_{in}$ \hspace{1cm} (4)

and $m$...Weight of the impactor [g]; $a_g$...Gravity acceleration [m.s$^{-2}$]; $h_{in}$...Height of drop - initial [m]; $h_r$...Height of drop - rebound [m]
2.5. Energy dissipation under dynamic compression tests

Dynamic compression tests were performed on the specimens with 0, 10, 20 and 30% replacement of the natural aggregates with rubber particles (specimens R0, R10-10-10, R20-20-20, R30-30-30) with the aim to determine and compare the energy dissipated in viscoelastic regime. The maximum applied load was 30% of the compressive elastic limit of the concrete in order to comply with the testing condition in the viscoelastic range. To determine the dissipated energy, following calculations according to the methodology described in [16] were used:

\[
W = \int_0^{\pi/2} \omega \sigma d\varepsilon dt \tag{5}
\]

where \( \omega \) is the angular frequency (rad/s) of the applied load, \( \sigma \) is compressive stress, \( \varepsilon \) is unitary deformation. Substituting \( \sigma = \sigma_0 \sin(\omega t) \), \( \varepsilon = \varepsilon_0 \cos(\omega t - \delta) \), the following can be obtained:

\[
W = \sigma_0 \varepsilon_0 \cos \delta + \pi \sin \delta \tag{6}
\]

Where \( \sigma_0 \) is the amplitude of the compressive stress, \( \varepsilon_0 \) is the maximum amplitude of the unitary deformation and \( \delta \) is the phase shift coefficient that expresses the delay between strain and stress.

From the point of view of the whole cycle, the retained elastic energy is zero. But designating as \( \Delta W \) the elastic energy dissipated in a cycle and as \( W_a \) the maximum density of elastic stored energy during the load stage, the equation (7) can be obtained [16]:

\[
\Delta W W_a = 2\pi \tan \delta. \tag{7}
\]

It can also be expressed in the next form:

\[
\Delta W = \pi \sigma_0 \varepsilon_0 \sin(\delta) = \pi \varepsilon_0^2 E'' \tag{8}
\]

The relation \( \Delta W / W_a \) is denominated as specific loss [16]. It shows the percentage of the dissipated energy with regard to maximum elastic energy stored during the load. Two frequencies, 10 and 20 Hz, were used for tests.

3. Result and discussion

3.1. Physico-mechanical properties

The results of determined physico-mechanical properties are summarized in table 2. The compressive strength was negatively affected by replacement of the natural aggregates with rubber granulate, even though the replacement levels were not very high. The values of compressive strength dropped from 120.1 to 53.8 MPa (30% replacement), which is almost 55% reduction. Similar reduction of compressive strength was observed also by Alsaif et al [17], Gonen [18] and Gupta et al [19]. This is probably due to the different parameters of the cement matrix and the rubber particles, with the rubber being significantly more elastic. When loaded, cracks then form at the interface between the rubber and the matrix, which subsequently reduce the load-bearing capacity of the concrete. Additionally, the replacement of high-strength aggregate by rubber with low load bearing capacity must reduce the total load-carrying potential of the whole composite. The other reason of the compressive strength reduction is the weaker chemical interaction and adhesion between the rubber particles and cement matrix and generally more porous structure of rubberized concrete. This can partly be mitigated by surface treatment of rubber granulate, e.g. by NaOH, H₂SO₄, Ca(OH)₂, methanol, ethanol, silane coupling agent, acetone or CH₃COOH [20] and Mohammadi [21]. Further addition of steel fibres did not improve the compressive strength, see table 2.


## Table 2. Properties of the designed steel fibre reinforced rubberized concrete.

| Designation | Bulk density (kg.m⁻³) | Compressive strength (MPa) | Flexural strength (MPa) | Water absorption (%) |
|-------------|-----------------------|---------------------------|------------------------|---------------------|
| R0          | 2,422                 | 120.1                     | 11.9                   | 2.5                 |
| R10/10-10-10| 2,270                 | 102.0                     | 11.3                   | 3.7                 |
| R20/20-20-20| 2,130                 | 75.1                      | 9.8                    | 4.2                 |
| R30/30-30-30| 2,091                 | 53.8                      | 6.0                    | 5.1                 |
| R20/44-0-0  | 2,165                 | 68.4                      | 9.3                    | 4.5                 |
| R20/0-0-62  | 2,149                 | 86.4                      | 8.6                    | 4.6                 |
| FR20/1      | 2,193                 | 75.2                      | 16.3                   | 4.3                 |
| FR20/2      | 2,260                 | 72.5                      | 17.3                   | 4.5                 |
| FR20/3      | 2,321                 | 71.0                      | 18.9                   | 4.9                 |
| FR20/3KH    | 2,315                 | 72.1                      | 18.1                   | 4.9                 |

The results show that also the size of rubber particles affects the compressive strength of rubberized concrete. Higher compressive strength was achieved in the case of concretes with coarser fraction of rubber granulates, which is in coherence with findings of Liu [9], but in contradiction with results of study published by Gonen [18]. This divergence may be attributed to different overall composition of the tested concretes, as well as different aggregate gradation. Flexural strength was also reduced when the natural aggregates was replaced by rubber, but the level of reduction was generally lower, in particular in the case of 10% replacement. Other authors reported similar trends for comparable replacement ratios [9]. The opposite trend was reported by Jokar [22] for content of rubber aggregate limited to 5%.

The addition of steel fibres both commercial and waste improved the flexural strength, to similar extent. Rubberized concrete presents higher water absorption value; the water absorption value increases with rising rubber particle replacement ratio and is not affected by particle size.

### 3.2. Impact resistance drop test

The number of impacts required to produce the first crack and complete failure of the slab specimen was evaluated as part of the impact energy absorption rate assessment. The corresponding energy was then calculated according to equation 1. The impact drop test device and the specimen after the test are depicted in figure 3. Test results (mean value of 3 slabs) for all specimens are summarized in table 3.

## Table 3. Impact drop test results.

| Designation | Number of blows at first crack (-) | Number of blows for ultimate failure (-) | Impact energy at first crack (J) | Impact energy at ultimate failure (J) |
|-------------|-----------------------------------|----------------------------------------|---------------------------------|---------------------------------------|
| R0          | 8                                 | 11                                     | 220                             | 302                                   |
| R10/10-10-10| 13                                | 16                                     | 357                             | 439                                   |
| R20/20-20-20| 14                                | 18                                     | 384                             | 494                                   |
| R30/30-30-30| 16                                | 20                                     | 440                             | 549                                   |
| R20/44-0-0  | 13                                | 19                                     | 357                             | 522                                   |
| R20/0-0-62  | 12                                | 17                                     | 384                             | 467                                   |
| FR20/1      | 91                                | 120                                    | 2,500                           | 3,297                                 |
| FR20/2      | 95                                | 244                                    | 2,610                           | 6,704                                 |
| FR20/3      | 104                               | 299                                    | 2,858                           | 8,215                                 |
| FR20/3KH    | 120                               | 330                                    | 3,297                           | 9,067                                 |
Figure 3. Impact drop test device (left) and slab specimen FR20/3KH after the test (right).

The impact resistance of rubberized concrete, for both first crack and ultimate failure, is higher compared to the specimen without rubber particles. According to Munoz-Sanchez [23], the higher toughness of rubberized concrete is produced from rubber’s ability to absorb high tensile loads. Rubberized concrete showed better resistance to crack control, because it has overall better ductility compared to concrete with only natural aggregates. Rubber particles are able to absorb sudden shock because of its nature, this cannot be achieved by natural aggregates because of their brittle nature [1]. With 30% replacement of natural aggregate, the impact energy at ultimate failure was 81% higher compared to the reference specimen. The effect of rubber particle size cannot be properly assessed, as the results of impact energy at first crack and ultimate failure are not coherent – further research in this field is required. Even though the addition of rubber particles enhances the impact resistance, the most significant improvement of impact resistance was achieved with addition of fibres. The highest values of impact energy were achieved for specimen FR20/3KH with 3 vol.% of commercial fibres (3,297 J at first crack and 9,067 J at ultimate failure), but competitive result was achieved also in the case of specimen FR20/3 with 3 vol.% of waste steel fibres (2,858 J and 8,215 J, respectively). From the perspective of drop impact, the presence of fibres, not rubber particles, has determinative influence on the final impact resistance of the concrete, which is in accordance with the findings of Medina [24].

3.3. Rebound test and energy absorption

Test results from rebound test are summarized in Figure 4. It was observed, that increasing amount of rubber particles enhances the amount of absorbed energy – with 0, 10, 20 and 30% replacement, 6.3%, 7.3% and 11.2% increase was detected. During the impact load, some of the energy which the rubberized concrete is exposed to, can be absorbed by the rubber particles; this brings higher impact resistance in comparison with the standard concrete. Similar method to evaluate the impact energy absorption (rebound test) was also performed by Gupta [19] and Medina [24] with consistent results of rising absorption capacity with increasing replacement level up to 25% [19] and 30% [24].
3.4. Energy dissipation under dynamic compression tests

The ΔW/Wa values calculated (according to the methodology described in 2.5) for tested specimens are given in figure 5. The graph summarizes the percentage of dissipated energy (at frequencies of 10 and 20 Hz) as a function of replacement ratio of rubber particles. The dependence on rubber particle amount and frequency can be stated. At frequency of 20 Hz, larger dissipated energy was observed compared to 10 Hz. With increasing content of rubber particles, the dissipated energy was rising. The amount of dissipated energy was calculated 26–29% (20 Hz) and 22–26% (10 Hz), which makes rubberized concrete promising material for absorbing energy under dynamic actions. 5, 10 and 20 Hz frequency measurements on concrete with 3.5 and 5% of rubber fibres were performed by Hernandez-Olivares [16], who also reported better values of dissipated energy for specimens with higher rubber content and dependency of the dissipated energy on the frequency.

4. Conclusions

Mechanical parameters of rubberized concrete with waste steel fibres, with emphasis on impact energy absorption potential, were evaluated, using the drop test, rebound test and energy dissipation under dynamic compression test. The influence of addition of steel fibres and amount of the rubber particles on the mechanical properties of the material was also investigated.

The following conclusions can be drawn:

- Replacing part of the aggregate with rubber granulate reduces the compressive strength of the
concrete. The rubberized concrete with 20 and 30% replacement ratio dropped about 37 and 55%, respectively, in the compressive strength. This mainly can be attributed to decreased amount of high-strength natural aggregates and the weaker bonding between the rubber and the cement.

- The addition of fibers, both waste, and reference, does not affect the compressive strength of the concrete with rubber particles. However, they have a significant improving effect on the flexural tensile strength and overall impact resistance.
- Rubberized concrete presents higher water absorption value; the water absorption value increases with rising rubber particle replacement ratio and is not affected by particle size.
- Evaluating the overall impact resistance assessed by impact drop test, the impact resistance was significantly higher influenced by the addition of steel fibres then by addition of rubber particles.
- The amount of energy dissipated by rubber concrete during the dynamic compressive test was calculated 26–29% (for 20 Hz frequency) and 22–26% (for 10 Hz frequency). Within the investigated range of rubber particles amount, the rising trend of dissipated energy was observed with increasing amount of rubber particles in the concrete mixture.
- The effect of rubber particle size on energy absorption was also investigated, but with inconsistent results. Further research will be performed in this field.
- According to the aforementioned findings, rubberized concrete with addition of waste steel fibres shows better energy absorbing potential compared to similar concrete without rubber and fibre presence; thus, has potential to be used in applications where energy absorption capability, deformability and toughness are of importance. Other advantage is lower price of the composite and environmental benefit of waste utilization and raw material saving.

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