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FRACTURE OF CONCRETE CONTAINING CRUMB RUBBER

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Abstract. Every year, colossal amounts of used and non-biodegradable rubber tyres are accumulated in the world. Experience shows that the most efficient way to increase the concrete fracture energy G_F (N/m) is to use metal or polypropylene fibres. The optimal content of fibre increases concrete resistance to stress (especially tensile stress under bending force). Concrete fracture is not brittle; concrete continues deforming after maximum stresses and is able to resist certain stresses, there is no abrupt decrease in loading. The research has proved that crumb rubber can be used in concretes as an alternative to metal and polypropylene fibres. The investigation has found that rubber waste additives, through their specific properties can partly take up tensile stresses in concrete and make the concrete fracture more plastic; besides, such concrete requires a significantly higher fracture energy and concrete samples can withstand much higher residual strength at 500 μm crack mouth opening displacement (CMOD) and deflection.

Keywords: concrete fracture; crumb rubber; bending strength; CMOD; deflection.

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Introduction

Every year, colossal amounts of used tyres are accumulated in the world. Waste tyres do not decompose through natural processes. In the United States alone, 275 million of tyres are disposed of each year (Papakonstantinou, Tobolski 2006); and in Europe, used tyres amount to 180 million. English researcher Martin (2001) found that 37 million of used tyres were disposed of in the UK in 2001. It was also found that in 2001, from 37 million waste tyres 11% were exported, 62% were reserved for future use, recycled or used for heat recovery, whereas 27% were accumulated in legal landfills and disposed of illegally in human surroundings. In less developed countries, the environmental pollution with waste tyres is much more significant.

Highway construction provides a significant market potential for waste tyre recycling. Extensive studies have been conducted on crumb rubber modified asphalt. Starting with 1995, all United States of America are required to deliver an equivalent of 5% of their annual federally funded paving projects using tyre rubber modified asphalt. In 1998, 20% of the federally funded paving projects were required to use rubber-modified asphalt.

However, these requirements have been postponed due to the high cost of crumb rubber production as well as time and efforts required for incorporation of the rubber into asphalt paving mixes using the so-called 'wet' process (Segre *et al.* 2006). The consumption of waste tyres in asphalt pavement construction varies from state to state, with the maximum consumption of 20%. In their studies, other researchers suggested adding crumb tyre rubber to hot-mixed asphalt (Azevedo *et al.* 2012; Mohammad *et al.* 2011; Navarro, Gámez 2012; Rahman *et al.* 2012; Uzun, Terzi 2012). It is used well as bitumen additive (Dong *et al.* 2011; Putman, Amizkhanian 2010; Xiaoqing *et al.* 2009; Zhang *et al.* 2010).

Owing to the problems associated with waste tyre modified asphalt, more and more attention has been given to waste tyre modified Portland cement concrete. As opposed to waste tyre modified asphalt, which requires for the wet process, waste tyre modified

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concrete utilizes the low costing 'dry' process, with a portion of aggregates replaced by waste tyre rubber. Such concrete is very tough, which is highly desirable, as conventional concrete is a brittle material. High toughness suggests that the modified concrete has higher cracking and fracture resistance (Papakonstantinou, Tobolski 2006; Skripkiūnas *et al.* 2007).

The most efficient way of increasing the fracture energy G_F (N/m) of concrete (Bažant 2002) is the use of metal or polypropylene fibre. The optimum fibre content increases the resistance of concrete to tensile stress. Fibres prevent brittle damage of concrete, thus, after maximum stress the concrete continues to retain certain deformation load and there is no sudden drop in load (Centonze *et al.* 2012). Rubber admixture could be used in concrete as an alternative to metal or polypropylene fibres. Due to certain specific characteristics, these admixtures could intercept certain tensile stresses in concrete and ensure more plastic fracture. Such concrete would need much higher fracture energy (Grinys *et al.* 2012).

Benazzouk *et al*. (2007) analyzed fracture mechanics of hardened concrete modified with different content of waste rubber. They noticed that rubber admixtures reduced concrete brittleness and increased plasticity by creating larger plastic deformations in concrete. Batayneh *et al*. (2008) obtained large plastic deformations above threshold stress intensities in concrete with waste rubber admixtures. Atahan and Yücel (2012) noticed that increasing the amount of rubber decreases the compressive strength and elastic modulus of the concrete, while significantly increasing impact time and energy dissipation capacity. It was determined that replacing 20–40% of aggregates with crumb rubber created concrete mixes that could be useful for concrete safety barriers in locations with high demands for strength, fracture resistance and energy dissipation. Authors (Sukontasukkul, Chaikaew 2005; Tlemat *et al*. 2006) calculated concrete fracture energy from stress-strain diagrams and 3-point bend test. Thai researchers Sukontasukkul and Chaikaew (2005) determined that compared to reference concretes, much higher fracture energy was required for the fracture of concretes modified with waste rubber. Segre *et al*. (2006) performed a detailed analysis of fatigue crack development under tensile stress in concretes modified with waste rubber admixture. Subsequent to a microscopic analysis, Segre *et al*. (2006) noticed that cracks developed with growing tensile stress, and these cracks usually occurred along the contact zone of rubber particle and cement matrix. They also found that specimens with waste rubber admixture withstood tensile stress of certain intensities and resisted to the development of wider cracks. American researchers Kumaran *et al*. (2008) found that concretes with waste rubber admixture absorbed much higher fracture energy compared to concretes without waste rubber admixture. Taha *et al.* (2008) observed that the fracture toughness of rubber modified concrete increased considerably with rubber content, where the maximum increase was at 75% vol. rubber replacement, which resulted in a 350% increase in comparison with the base reference mix (compared to an 132% increase at 25% vol. replacement). These findings are in general agreement with several other studies (Najim, Hall 2010; Sukontasukkul, Chaikaew 2006; Turatsinze *et al.* 2005; Turgut, Yesilata 2008).

The addition of chipped rubber aggregate can also increase impact resistance substantially in both the first crack and failure stages (Liu *et al*. 2012; Najim, Hall 2010). However, the crack width and propagation is larger in comparison with natural aggregate concrete. This behaviour presumably results from the higher strain rate, which leads, in turn, to an increase in energy absorption. In experiments designed to explore this behaviour, crack width propagation was found to be 187% greater when shredded tyre chips were used as 100% wt coarse aggregates replacement (Atahan, Sevim 2008; Najim, Hall 2010).

Interestingly, rubberized concrete toughness appears to be greater than that of ordinary concrete, where for a 20% volume crumb rubber replacement (for both fine aggregates and coarse aggregates) the highest 'post-peak response' was recorded and the peak load decreased, which caused a considerable reduction in fracture energy (Sukontasukkul, Chaikaew 2006).

Rubberized concrete (RC) has also been found to have greater ductility than plain concrete, since the higher strain rates permit much greater plastic deformation before the yield point (Snelson *et al*. 2009). Zheng *et al*. (2008) reported that since the ductility performance of RC (using chipped rubber) was higher than normal concrete, it had a lower brittleness index (Topçu *et al.* 1997) than conventional concrete. The highest result was achieved when the replacement was 15% wt total aggregate using both fine aggregates and coarse aggregates replacement. Ho *et al.* (2012) estimated that brittleness of concrete composite decreased with the addition of rubber aggregates. Brittle index decreases with the increase of rubber content in the concrete and it is almost zero for a concrete composite containing 40% of rubber aggregate content. Also, Ho *et al*. (2012) observed that kinetics of fracture process of rubberized concrete were slow in comparison to concrete without rubber aggregates. Benazzouk *et al.* (2007) have reported that the incorporation of rubber particles decreased brittle index values at rubber additive level of beyond 10%. They established that 10% was an optimal rubber content, which characterized the transition from brittle to ductile material and reflected an increase in plastic deformation energy. The decrease in brittleness index became even greater as rubber content increased. Typical crack/rubber interaction in concrete specimens with rubber particles after failure, are shown in Figure 1. As demonstrated, the crack was stopped by the rubber particles leading to crack pinning and crack arrest.

Graeff *et al.* (2012) investigated fatigue resistance and cracking mechanism of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres. Authors found that specimens reinforced with recycled fibres could sustain higher stress levels than plain concrete, as well as have longer service life.

The objective of the work was to analyze the effect of fine composition of the elastic aggregate made from crumb rubber (CR) on the fracture properties of concrete under the static load.

1. Materials and methods

In order to determine the effect of CR on hardened concrete properties, the research authors used several different concrete mixtures: without CR and concrete with different amount of rubber fraction and waste additive.

The research used Portland cement CEM I 42.5R produced in Akmenės Cementas (Lithuania) according to the European standard EN 197-1. Water content for normal consistency cement slurry was 24.5% and fineness of cement – 371 m^2/kg. As a fine aggregate, 0/4 sand fraction was used. Part of the fine aggregate of this mixture was replaced by a CR from used tyres (5, 10, 20 and 30% from aggregate by mass). The coarse aggregate used crushed gravel 4/16. Coarse aggregate content in all concrete mixtures was the same – 949 kg for one cubic meter of concrete. In the mixtures, plasticizing admixture at 0.5% of the cement content was used. The plasticizing admixture based on policarboxile polymers was used with density of solution 1040 kg/m^3.

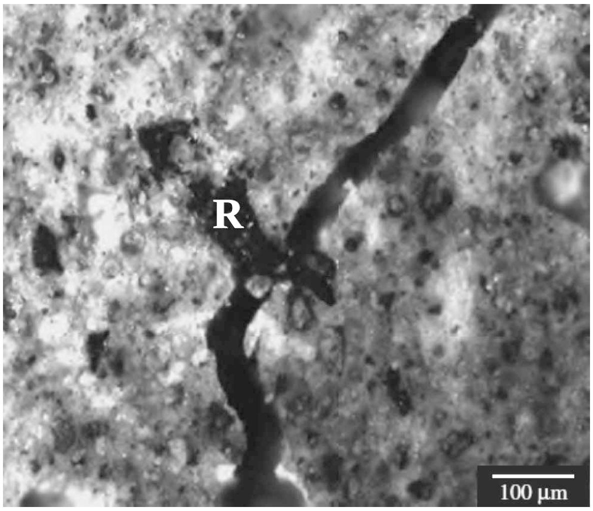

Fig. 1. Crack/rubber interaction in concrete specimens with rubber particles after failure (Segre *et al.* 2006)

Mechanically crumbed rubber from used tyres was used in the mixtures. CR was classified to three different fractions: fine size 0/1 mm fraction (CR 0/1), 1/2 mm fraction (CR 1/2) and the largest up to 3 mm rubber particle grain size of 2/3 mm fraction (CR 2/3). CR was produced in JSC 'Metaloidas' (Šiauliai, Lithuania), with density of 1021 kg/m^3.

To determine the properties of the concrete fracture, $100 \times 100 \times 400$ prisms were formed. All specimens were cured for 28 days in standard conditions. After curing, an artificial crack of 10 mm in depth was formed in a centre of all specimens, using a circular saw. All fracture tests were performed using an automatic hydraulic press 'Toni Technik'. Concrete fractures with CR were analyzed under the three-point bending load, determining the deflection and load-crack mouth opening displacement (CMOD). Deformations were measured using two displacement transducers fixed to the press; therefore, the deflection and load-crack mouth opening displacement of the samples were measured at the same time (Figs 2 and 3).

Based on Hilleborg's concrete fracture analysis, the work (W_F) was calculated from available deflection and CMOD curves σ-ε by using area computation software 'Origin' in the samples with different CR additive content and different grain size and in control samples. Fracture energy (G_F) required for the complete failure of the samples was calculated using Eqn (1):

$$G_F = \frac{W_F}{b(D - a_0)}, \quad (1)$$

where: W_F – the work [J]; b – the sample thickness [m]; $D–a_0$ – the length of the fragmentation plane [m] (D – the sample height [m]; a_0 – the artificial crack depth [m]).

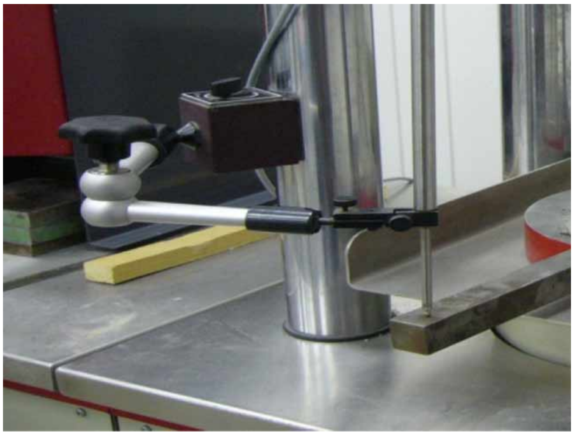

Fig. 2. Sample deflection measuring sensor

Fig. 3. Sample CMOD measuring sensor

In CR concretes, for determining deflection and load-crack mouth opening displacement, mixtures were prepared using 0, 5, 10, 20 and 30% of aggregate mass, replacing part of sand by waste rubber. Proportions of the concrete mixtures are presented in Table 1. Quality control of concrete mixtures was checked using Cattaneo's method (Cattaneo, Mola 2012).

For concrete mixture, it was found that due to segregation of aggregates, concrete lost homogeneity when using the 2/3 fraction at 30% of rubber waste additive. Consequently, the concrete mixture No. R 2/3_30 was no longer used in further experiments.

2. Results and discussion

Deformation limits in CR modified concretes subjected to tensile stress make up 60–80% of the maximal tensile strength in contrast to compressive stress (30%); after elastic deformations are exceeded, there are much lower plastic deformations before the destruction of concrete occurs. Due to these reasons, the conglomerate experiences natural brittleness under tensile stress in contrast to compressive stress. Concrete fracturing under load occurs due to the development of cracks. Most researchers (Bažant 2002; Hillerborg *et al*. 1976), analyze concrete fracture as the intensity of crack development and the critical crack size.

Several fracture parameters were analyzed: crack mouth opening displacement (Hillerborg *et al*. 1976) and deflection, while fracture energy G_F was calculated according to the idealized crack model (Hillerborg *et al*. 1976). As a specimen is loaded more than the peak load, under CMOD-control, a fracture process zone forms (FPZ) at the tip of the crack. The FPZ is a zone in which the matrix is intensively cracked. Along the FPZ there is a discontinuity in displacements, but not in stresses. The stresses are themselves a function of the crack opening displacement (COD). At the tip of the FPZ, the tensile stress is equal to the tensile strength, and it is gradually reduced to zero at the tip of the artificial crack.

Concrete is a brittle material with low resistance to tensile stress and low absorption of energy generated during these stresses. Metal or polypropylene fibres are most often used to improve the tensile stress resistance. Using CR could be one of the possible ways to increase concrete resistance to tensile stress. The resistance of CR to tensile loads is approximately three times greater than cement matrix resistance. The effect of rubber admixture on concrete deflection and crack mouth opening displacement under tensile stress was analyzed. To this end, different rubber particle sizes and CR contents were tested. Reference concrete specimens without the CR were tested in parallel. The relationship between tensile stress, CMOD and deflection depending on the size of rubber particles are presented in Figures 4–9.

Table 1. Proportions of concrete mixtures

		Materials content for 1m^3 of concrete mixture						
Notation	CR fraction	Quantity of CR,%	CR amount, kg	Cement, kg	Sand 0/4, kg	Crushed gravel 4/16, kg	Chemical additive, kg	Water, l
NR	–	–	–	451	875	949	2.255	160
R 0/1_5	0/1	5	35.14	451	784	949	2.255	160
R 0/1_10		10	70.28		693			
R 0/1_20		20	140.55		510			
R 0/1_30		30	210.83		328			
R 1/2_5	1/2	5	35.14	451	784	949	2.255	160
R 1/2_10		10	70.28		693			
R 1/2_20		20	140.55		510			
R 1/2_30		30	210.83		328			
R 2/3_5	2/3	5	35.14	451	784	949	2.255	160
R 2/3_10		10	70.28		693			
R 2/3_20		20	140.55		510			
R 2/3_30[a]		30	210.83		328			

[a]Non-technological mixture.

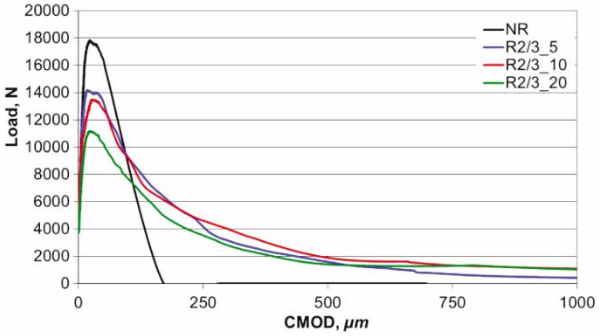

Fig. 4. The function of stress and CMOD when 2/3 fraction is used

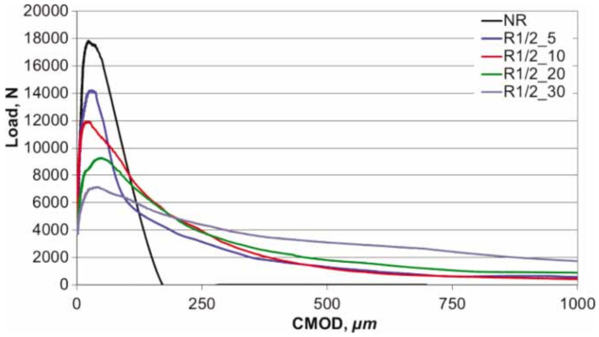

Fig. 5. The function of stress and CMOD when 1/2 fraction is used

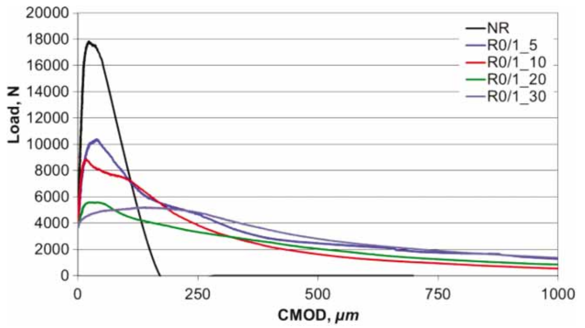

Fig. 6. The function of stress and CMOD when 0/1 fraction is used

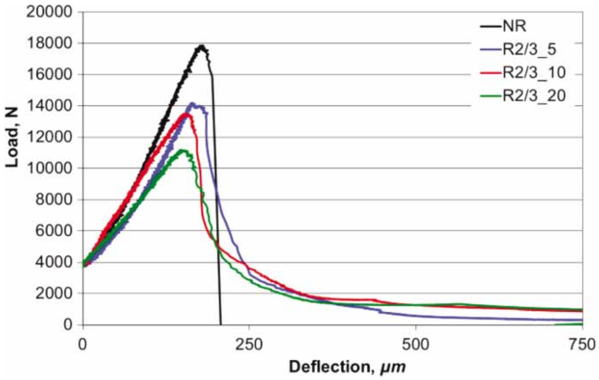

Fig. 7. The function of stress and deflection when 2/3 fraction is used

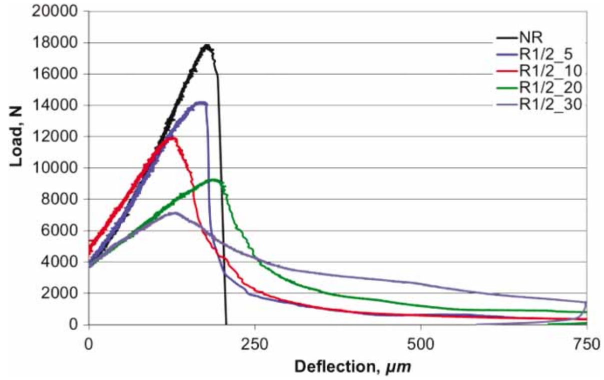

Fig. 8. The function of stress and deflection when 1/2 fraction is used

The functions of stress and deformations (Figs 4–9) clearly demonstrate that reference specimens without CR undergo the highest fracture stress. The calculated fracture strength was 6.49 MPa in specimens unmodified with CR and subjected to tensile stress, whereas in CR modified specimens, the critical strength ranged from 5.34 to 2.15 MPa. The functions presented in Figures 4–9 demonstrate that peak strength under three-point bending load reduce, when higher CR content and smaller CR fraction in concrete specimens were used. However, it was obtained that concrete specimens with CR fracture were more plastic because of greater plastic deformations.

The plasticity of concrete fracture may be evaluated by residual strength at 500 μm CMOD and deflection. The fracture results of concrete specimens with CR are presented in Tables 2 and 3. It was found that concrete specimens with CR 2/3 fraction required much greater fracture energy for complete sample destruction compared to unmodified specimens. It was determined that depending on the amount of CR, the specimens withstood tensile stresses of 0.22–0.48 MPa in the presence of 500 μm deflection deformation, while in the presence of 500 μm crack mouth opening, the specimens withstood 0.53–0.73 MPa stress (Table 2). Meanwhile,

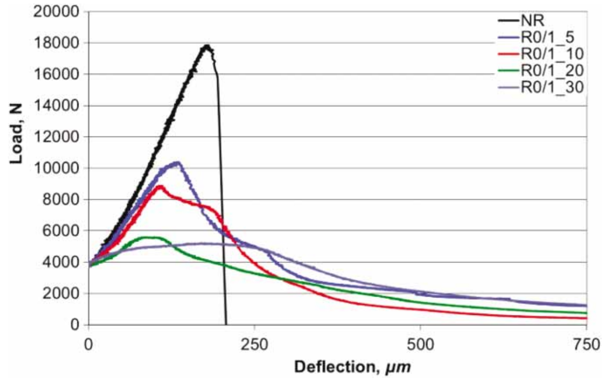

Fig. 9. The function of stress and deflection when 0/1 fraction is used

Table 2. Evaluation of concrete fracture plasticity

Notation	CR fraction, mm	Quantity of CR,%	Residual strength at 0.5 mm crack, MPa	Residual strength at 0.5 mm deflection, MPa
NR	–	–	0	0
R 2/3_5	2/3	5	0.70	0.22
R 2/3_10		10	0.73	0.47
R 2/3_20		20	0.53	0.48
R 1/2_5	1/2	5	0.47	0.24
R 1/2_10		10	0.48	0.25
R 1/2_20		20	0.69	0.45
R 1/2_30		30	1.18	0.97
R 0/1_5	0/1	5	0.94	0.79
R 0/1_10		10	0.63	0.36
R 0/1_20		20	0.77	0.53
R 0/1_30		30	1.65	0.91

unmodified specimens completely break when reaching 200 μm of deflection and 200 μm of crack.

Similar fracture results were observed when 1/2 and 0/1 fraction CR were used. The tests showed that lower maximum strains developed in concretes with CR 1/2 compared to concretes with a CR 2/3. From Figures 5 and 8, we may see that depending on the rubber content, the maximum strains in concrete with CR 1/2 reduced approximately 2.5 times compared to the reference specimens, from 6.49 MPa (reference specimen) to 3.6 MPa (30% rubber of 1/2 fraction).

We observed that concretes modified with CR 2/3 behaved the same as concretes with CR 1/2, and subject to the CR content withstood 0.47–1.18 MPa stress after the development of 500 μm crack. We also observed that residual strength of concrete at 500 μm crack or 500 μm deflection increases with the increase of CR 1/2 content. Figures 6 and 9 illustrate the bending stress induced fracture of concrete modified with mechanically crushed CR 0/1. The fracture of concrete modified with this CR is much more plastic compared to unmodified concretes. The figures show that higher content of the finest size CR significantly reduces the maximum strains and the strains diminish in direct proportion to the higher content of CR admixture. Specimens with CR 0/1, as well as specimens containing CR 1/2 and CR 2/3, showed that concrete fracture gradually continued after the maximum load was exceeded; there was no abrupt post-peak load drop at a bigger crack opening or bigger deflection and, depending on the content of CR, the residual strength of concrete at 0.5 mm crack opening was 1.65 MPa.

Based on the Idealized Cohesive Zone Model, Hillerborg together with RILEM Committee proposed a practical methodology to calculate the fracture energy G_F (N/m) (Bažant 2002). A crack opening displacement (COD) is measured by a special sensor in the bending test. The work used for concrete destruction is calculated from the stress–strain curve. The fracture energy of the specimen is obtained by dividing the work by the fracture surface area. Based on Hillerborg's concrete fracture tests, the work (W_F) was calculated with computation software *Origin* from the fracture.

It was determined that W_F and G_F changed depending on the CR. Concrete unmodified with rubber required 85 N/m energy for crack development under tensile loads, whereas CR modified concretes required 3.5–5.4 times higher fracture energy of 296 N/m to 452 N/m to develop the same fracture crack. The amount of energy required for the development of deflection in rubber modified concretes is presented in Table 3. According to the obtained results, 2.3 times higher fracture energy is required for the deformation of rubber modified specimens compared to reference specimens. Calculation results (Table 3) showed that in the process of concrete fracture, that is, the development of specimen deflection and crack opening caused by tensile stress, the lowest fracture energy is used in specimens without

Table 3. Work and fracture energy used to break the specimens

			Stress-strain curve		Stress-COD curve	
Designation	CR fraction	Quantity of CR,%	Work W_F, J	Fracture energy G_F, N/m	Work W_F, J	Fracture energy G_F, N/m
NR	–	–	1.50	167.16	0.76	84.84
R 2/3_5	2/3	5	2.14	238.13	2.67	296.39
R 2/3_10		10	2.88	320.26	4.08	453.86
R 2/3_20		20	2.51	279.03	3.06	339.86
R 1/2_5	1/2	5	2.27	251.95	2.80	311.50
R 1/2_10		10	2.10	233.71	2.89	321.28
R 1/2_20		20	3.25	360.83	3.58	397.29
R 1/2_30		30	2.69	299.08	3.79	420.62
R 0/1_5	0/1	5	3.47	385.88	4.06	451.57
R 0/1_10		10	2.30	255.29	2.93	326.00
R 0/1_20		20	2.41	268.33	3.45	383.49
R 0/1_30		30	2.76	306.37	3.69	410.43

CR. When concrete is modified with CR, the fracture energy increases by 3.5–5.4 times.

The tests showed that the highest fracture energy (453.86 N/m) was used to destroy the specimen made of concrete with the CR of 2/3 fraction added at 10% of the total aggregate content. Similar fracture energy is used in specimens modified with the CR of 0/1 fraction added at 5% of the total aggregate content.

The most effective way to increase the fracture energy G_F (N/m) is to use metal or polypropylene fibre (Centonze *et al.* 2012). Augonis *et al.* (2007) calculated fracture energy G_F of concrete with metal and polypropylene fibres. It was demonstrated that fracture energy of concrete reinforced by metal fibres was 505–1422 N/m depending on the amount and type of the metal fibres in concrete mixture (11–20 kg/m^3), while fracture energy of the concrete beams reinforced by polypropylene fibres was 368–684 N/m depending on the amount of the polypropylene fibres in concrete mixture (2–8 kg/m^3).

Augonis *et al.* (2007) estimated dependence of concrete reinforced by fibres deflection upon loading is showed in Figures 10 and 11. As demonstrated, the optimal amount of added fibres increased the resistance of concrete to tensile stresses (especially tensile stresses under bending loads). The fracturing of fibre modified concrete is not brittle and gradually continues after the maximum load is exceeded, and there is no abrupt post-peak load drop.

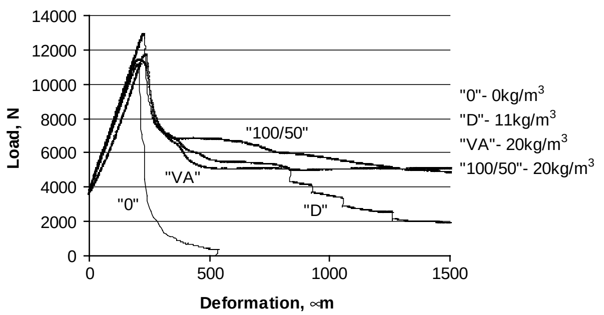

Fig. 10. The dependence of concrete reinforced by metal fibres deflection upon loading (Augonis *et al.* 2007)

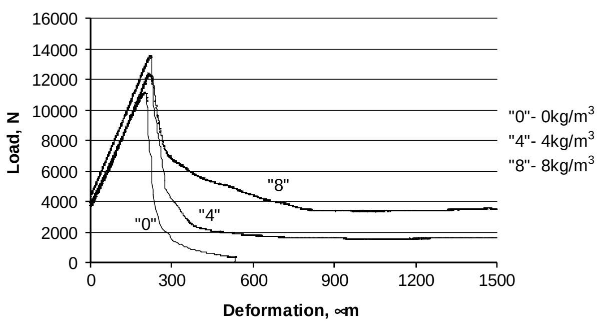

Fig. 11. The dependence of concrete reinforced by polypropylene fibres deflection upon loading (Augonis *et al.* 2007)

The test results indicate that CR could be used as an alternative to metal and polypropylene fibres. It was proved that due to their specific characteristics CR can intercept the tensile stress in concrete and make the deformation more plastic. Such concrete requires much higher fracture energy.

Conclusions

1. The fracture strength under three-point bending load was 6.49 MPa in specimens unmodified with CR and subjected to tensile stress, whereas in CR modified specimens, the critical strength decreased between 17% and 67%. It was determined that peak load under three-point bending load reduces with higher CR content and smaller size of rubber particles.

2. The plasticity of concrete fracture may be evaluated by the residual strength at 500 μm CMOD and deflection. It was found that subject to the amount and particle size of CR, the specimens withstood tensile stresses of 0.22–0.97 MPa in the presence of 500 μm deflection deformations, and in the presence of 500 μm crack mouth opening, the specimens withstood 0.47–1.65 MPa stress, while unmodified specimens completely broke under 200 μm deflection and 200 μm crack.

3. Concrete samples unmodified with CR required 85 N/m energy to fracture under tensile loads, while CR modified concretes specimens required 3.5–5.4 times higher fracture energy of 296 N/m to 454 N/m to fracture the samples.

4. Every year, colossal amounts of used and non-biodegradable rubber tyres are accumulated in the world. Utilization of this type of waste has not yet been solved. The modification of cement concrete mixtures with CR from used tyres allows producing concrete with specific properties and resolving the issue pertaining to utilization of such waste. The test results indicated that CR can intercept the tensile stress in concrete and make the deformation more plastic. Fracturing of such conglomerate concrete is not brittle, there is no abrupt post-peak load drop and gradually continues after the maximum load is exceeded. Such concrete requires much higher fracture energy and could be used as an alternative to metal and polypropylene fibres.

5. To optimally improve the fracture mechanism of concrete, recommended dosage of CR in concrete is up to 10% of the aggregate mass and coarser particle size of CR. With lower amounts and coarser particle size of CR, the bending strength results decreased, although smaller amounts of CR demonstrated the best improvement of fracture energy.

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