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TYRE RUBBER ADDITIVE EFFECT ON CONCRETE MIXTURE STRENGTH

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Abstract. This article describes the observed and examined effect of crumb rubber on the strength (compressive, bending and splitting tensile) of concrete. The tests have shown that the change in the strength of concrete with crumb rubber waste additives can be forecasted from exponential equations. These relationships enable to foresee the regularities of strength properties when a certain amount of crumb rubber of a certain size fraction is added to concrete. The obtained exponential equations show that concrete compressive, flexural and splitting tensile strengths decrease with increasing crumbed rubber additive amount. The testing has also shown that the addition of a small amount of crumbed rubber slightly increases (7%) the tensile splitting strength. The reason is better adhesion of the cement stone with rubber particles compared to the adhesion of sand, which was replaced by crumbed rubber. With higher content of crumbed rubber additive in the concrete, the tensile splitting strength decreases due to the significant increase of entrained air content and lower density.

Keywords: concrete strength, crumbed rubber, compressive strength, bending strength, splitting tensile strength.

1. Introduction

Interaction of several elements of the transport system wears down car wheel tyres and asphalt surfaces or other pavement. In time, the tyre rubber and asphalt pavement layer no longer correspond to performance parameters, as their structure requires to be changed, reinforced or improved (Sivilevičius 2011).

Old asphalt pavement can be recycled by using appropriate technologies and specialised facilities. Reclaimed asphalt pavement (RAP) features can be restored by adding a certain amount of new material (lower viscosity bitumen, mineral aggregates) and mixing it with RAP granules. Dynamics of mechanical mixing of old and new materials as well as diffusion processes determine the structure and properties of recycled hot mix asphalt (HMA) (Mučinis *et al.* 2009; Čygas *et al.* 2011; Karlsson, Isacsson 2003; Noureldin, Wood 1987; Shirodkar *et al.* 2011).

Non-recycled or utilised, used vehicles tyres can become a type of road waste, which could threaten the environment. Due to rapid expansion of the automobile industry in recent years, more and more waste tyre rubber got accumulated. Such rubber consist of three important components: approx. 22% of weight is synthetic fibre, 18% of weight is steel wire, and more than 60% of weight is rubber mixture, all of, which were produced from non-renewable resources (Dong *et al.* 2011). It was discovered that tyre rubber crumbs can be used for bituminous binders and asphalt mixtures (Zhang *et al.* 2010; Çelik, Atiş 2008; Lee *et al.* 2008; Xiao *et al.* 2009; Putman, Amirkhanian 2010; Xiao-qing *et al.* 2009). Crumbed rubber (CR) from vehicle tyres, mixed in with concrete, changes the properties of concrete (Ling 2011, 2012; Gesoğlu, Güneysi 2011; Wong, Ting 2009; Rodezno *et al.* 2005; Vydra *et al.* 2012; Muhammad *et al.* 2012; Najim, Hall 2012; Sukontasukkul, Tiamlon 2012). Once added to building construction materials different size fractions of CR from used tyres produce various changes in acoustic properties, thus having a noise reduction effect (Venslovas *et al.* 2011).

Vast amounts of used and non-biodegradable rubber tyres get accumulated in the world every year (Gaidučis *et al.* 2009). Recently the researchers started showing increased interest in the reuse of CR in concrete applications. Most authors (Siddique, Naik 2004; Skripkiūnas *et al.* 2007a, b, 2009; Stankevičius *et al.* 2007) who studied cement concretes modified with crumb rubber, detected deterioration in concrete strength properties when fine aggregates were replaced with CR. In different studies, authors have noticed that the size of rubber particles, their proportion in concrete and different surface texture have a significant effect on concrete strength properties. Some authors noted that reduction in concrete strength is greater when coarse aggregate is replaced with CR compared to the replacement of fine aggregate (Eldin, Senouci 1993, 1994; Lee *et al.* 1993; Siddique, Naik 2004; Topçu, Avcular 1997; Topçu, Sarıdemir 2008).

Eldin and Senouci (1993, 1994) determined that when coarse aggregate was replaced in full with mechanically crumbled waste rubber the compressive strength dropped by 85% whereas splitting tensile strength went down by 50%. However, when fine aggregate was replaced in full with waste rubber, the authors observed lower reduction in compressive strength (65%) and the same reduction in splitting tensile strength (50%). Studies conducted by authors Topçu and Avcular (1997), Lee *et al.* (1993), Parant *et al.* (2007) showed greater reduction in compressive strength when coarse aggregate was replaced with CR compared to the replacement of fine aggregate.

Segre and Joekes (2000) analysed the change in compressive and bending strength of concrete with CR added at 10% of the total aggregate content. To obtain a better adhesion of cement matrix and rubber, the authors soaked rubber particles in NaOH solution. Scanning Electron Microscopy testing has shown that rubber particles, which were soaked in NaOH solution, were much more covered with cement hydrates and there were more newly formed cement crystals on the surface of soaked rubber particles compared to the particles that were not soaked in NaOH solution. Nevertheless, the compressive strength of concrete, where 10% of the total aggregate content was rubber particles not soaked in NaOH, and concrete with rubber particles soaked in NaOH solution reduced by the same, i.e. 33%, compared to control specimens. The highest bending strength was observed in concretes where waste rubber not soaked in NaOH solution was used. The bending strength of such concrete compared to control specimens and to concrete containing rubber soaked in NaOH solution was higher by 94% and 10%, respectively. The reduction in compressive strength and increase in bending strength in concrete with rubber waste additives was also detected by Chinese researchers (Wu *et al.* 2002). Whereas tests of other authors (Papakonstantinou, Tobolski 2006; Hernández-Olivares *et al.* 2002; Hernández-Olivares, Barluenga 2004; Barluenga, Hernández-Olivares 2004; Güneyisi *et al.* 2004; Gesoğlu, Güneyisi 2007; Bignozzi, Sandrolini 2006; Zhu *et al.* 2002; Wang *et al.* 2005; Albano *et al.* 2005; Benazzouk *et al.* 2006; Chou *et al.* 2007; Taha *et al.* 2008; Li *et al.* 2004) demonstrated that both bending strength and compressive strength in concrete with CR was lower compared to concretes without CR.

Authors (Papakonstantinou, Tobolski 2006; Hernández-Olivares *et al.* 2002; Batayneh *et al.* 2008; Albano *et al.* 2005; Colom *et al.* 2006; Chou *et al.* 2007; Li *et al.* 2004) analysed the effect of CR on concrete's splitting tensile strength. Comprehensive analysis of literature has revealed that tensile strength reduces with the addition of CR. Splitting tensile strength of concrete reduces the more the higher amount of CR is added.

Most authors (Papakonstantinou, Tobolski 2006; Güneyisi *et al.* 2004; Albano *et al.* 2005; Benazzouk *et al.* 2006), who analysed concrete strength, noticed that compressive strength reduces much more than bending and tensile strengths in concretes modified by CR. Benazzouk *et al.* (2006) explained lower reduction in bending and tensile strengths in concrete containing CR by rougher rubber particle surface texture compared to the replaced fine and coarse aggregates (sand, gravel), which have smooth surface and spherical shape. Due to their rough surface, rubber particles bind with cement stone better and, therefore, resist tensile stress more effectively.

The authors explain the reduction in concrete strength properties as follows:

1. Rubber particles have lower strength than concrete matrix around them, and thus, when force is applied, the cracks first of all appear in the contact zone of rubber and concrete matrix (Papakonstantinou, Tobolski 2006; Güneyisi *et al.* 2004; Khatib, Bayomy 1999; Eldin, Senouci 1993, 1994; Lee *et al.* 1993; Topçu, Avular 1997). Cracks gradually propagate under load until concrete crumbles. Such rubber performance discrepancy makes rubber particles similar to voids in concrete (Bignozzi, Sandrolini 2006; Benazzouk *et al.* 2006; Eldin, Senouci 1994).

2. When aggregates of bigger density and strength are replaced with less dense CR, the compressive strength decreases because properties of the aggregate have a big effect on compressive strength of concrete (Papakonstantinou, Tobolski 2006; Batayneh *et al.* 2008; Eldin, Senouci 1994).

3. A decrease in mechanical properties of concrete containing CR is also explained by low adhesion between rubber particles and cement matrix (Segre, Joekes 2000; Güneyisi *et al.* 2004; Siddique, Naik 2004; Li *et al.* 2004). To increase the adhesion, some authors recommended soaking waste rubber in NaOH solution (Segre, Joekes 2000; Güneyisi *et al.* 2004; Siddique, Naik 2004; Li *et al.* 2004; Papakonstantinou, Tobolski 2006); however authors (Hernández-Olivares *et al.* 2002; Benazzouk *et al.* 2006; Papakonstantinou, Tobolski *et al.* 2006) observed strong adhesion in the contact zone of rubber particles and cement matrix.

2. Used materials

Portland cement CEM I 42.5 N manufactured by *AB Akmenės cementas* was used as a binding material. 0/4 fraction sand from *Kvesai* quarry was used as a fine aggregate. 4/16 fraction gravel macadam from *Kvesai* quarry was used as a coarse aggregate.

Waste automotive tyres were mechanically shredded into separate fractions of 0/1, 1/2 and 2/3 and used as a crumb rubber waste additive. Waste tyre shredding equipment belongs to *UAB Metaloidas*, Šiauliai. Sand was replaced by CR at 5%, 10%, 20% and 30% of the total aggregate amount. Superplasticizer Muraplast FK63,30 based on polycarboxylic resins was used in experimental testing.

To determine the influence of CR on the compressive strength, bending strength (Fig. 1) and splitting tensile strength properties of hardened concrete, different mixtures were made under laboratory conditions: control

Table 1. Compositions of concrete mixtures

Notation	CR fraction, mm	Materials content for 1 m^3 of concrete mixture						
		Volume of R, %	R amount, kg	Cement, kg	Sand 0/4, kg	Gravel macadam 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*		30	210.83		328			

* none technological mixture

mixture – non rubberised (NR) concrete and concrete with different size and amount of CR. Three different types of waste rubbers granules sized between the ranges of 0–1, 1–2 and 2–3 mm were used as waste rubber aggregates. Proportions of the concrete mixtures are presented in Table 1.

As regards concrete mixture it was found that using 2/3 fraction of 30% of CR homogeneity of concrete was lost due to segregation of aggregates. For this reason, the concrete mixture notated R 2/3_30 was not used in further experiments.

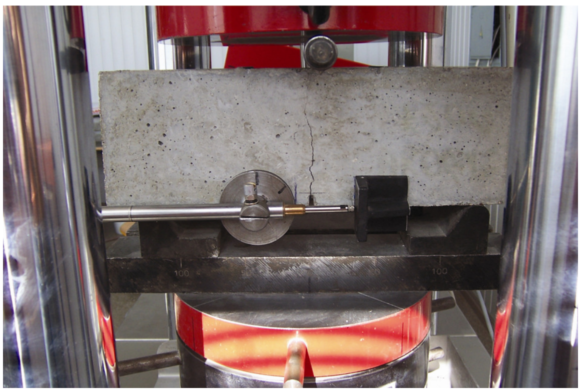

Fig. 1. Testing of concrete bending strength

3. Experimental procedure

3.1. The effect of crumbed rubber size fraction and amount on compressive strength of concrete

Fig. 2 illustrates the change in compressive strength of concrete modified with different amounts of CR. The tests revealed that the amount of CR and fraction size had a significant effect on the compressive strength of concrete. The average compressive strength of specimens without CR is 64.3 MPa (standard deviation σ = 2.5 MPa). The addition of CR caused the compressive strength to decrease. When CR additive was added at 5% of the total aggregate amount, the compressive strength of concrete decreased to 46.2 MPa (σ = 3.6 MPa). According to tests, compressive strength reduced with smaller fraction size of CR additive (Fig. 2). These tests showed that when the amount of CR was increased to 10% of the total aggregate amount, the compressive strength decreased to 33.8 MPa (σ = 3.1 MPa). In concretes with 10% of CR the compressive strength decreased very similarly as in concretes with 5% CR. When the size fraction of rubber particles was smaller, the compressive strength decreased more. In this case, the compressive strength values were noticed to go down to 22.9 (σ = 3.4 MPa), 22.2 (σ = 4.7 MPa) and 14.2 (σ = 2.6 MPa) MPa depending on the CR size fraction. According to the data of Fig. 2, it may be concluded that compared to the control specimens, the highest decrease in the compressive strength of concrete was obtained when the highest amount of CR was used (at 30% of the total aggregate amount). Fig. 2 shows that CR of ½ size fraction added at 30%, decreased the compressive strength by 84%, and 0/1 fr. additive decreased the compressive strength by 85%.

Fig. 3 illustrates the standard deviation in the compressive strength of concrete. The standard deviation of compressive strength ranged from 1.2 MPa, when 0/1 fr. CR was added at 30% of the total aggregate amount, to 4.7 MPa, when respectively 1/2 fr. and 20% CR was used. It may be stated that CR additive has no effect on the standard deviation of the compressive strength of concrete. Low standard deviation values obtained in testing confirmed insignificant variation of results, thus proving the reliability of obtained results.

Decreased compressive strength resulting from modification of concrete with CR can be explained by several reasons:

1. Rubber particles are more elastic and weaker compared to the surrounding cement matrix, therefore, the formation of cracks begin in the contact zone of rubber and cement matrix (Khatib, Bayomy 1999; Eldin, Senouci 1993, 1994; Lee *et al.* 1993; Topçu, Avcular 1997). When load is applied, the cracks gradually propagate and concrete crumbles. Such rubber performance discrepancy makes rubber particles act similarly to voids in concrete (Eldin, Senouci 1994).

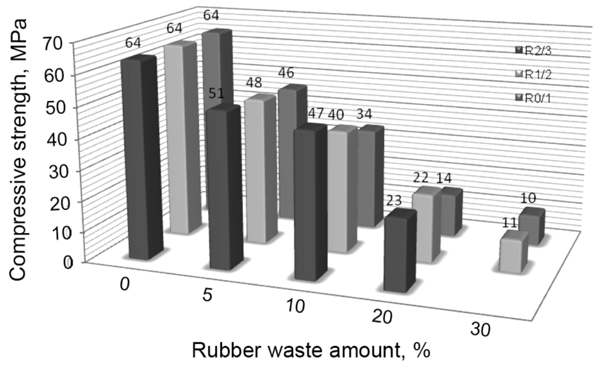

Fig. 2. The change in the compressive strength of concrete with CR of different amount and size fraction

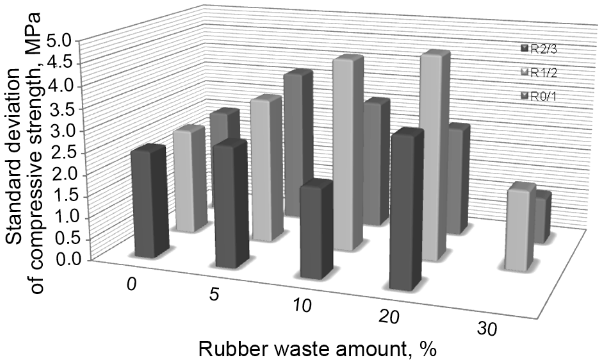

Fig. 3. Standard deviation of the compressive strength of concrete

2. When aggregates of higher density and strength (Mačiulaitis *et al.* 2009) are replaced with lower density and strength CR, the compressive strength will decrease because the strength properties of concrete, which is composite material, depend on the strength of constituents (Eldin, Senouci 1994).

Observations revealed that the change in the compressive strength of concrete resulting from introduction of different amounts of CR can be mathematically approximated by exponential equation in a very precise manner. The approximation is presented in equations 1–3 (Eq. (1) is for CR 0/1 fr., (2) – for CR 1/2 fr., and (3) – for CR 2/3 fr.):

$$y = 97.502e^{-0.065x}; \quad (1)$$

$$y = 104.69e^{-0.0594x}; \quad (2)$$

$$y = 104.88e^{-0.0508x}, \quad (3)$$

where: x – CR amount in concrete, % by weight; e is the base of the natural logarithms.

The correlation factor (determination coefficient R^2) in these exponential curves changes from 0.97 to 0.99 depending on the CR size fraction (varies from 0.91 to 0.97 in linear curve depending on CR fraction R^2). The calculated correlation factor confirmed that the change in the compressive strength of concrete obtained from exponential equations shown in Fig. 4 was reliable. From mathematical functions presented in equations 1–3 we can reliably forecast the reduction in compressive strength with the addition of the certain amount of CR. For example, if CR is introduced at 1% of the total concrete volume, the compressive strength will drop by approx. 4% depending on the CR size fraction.

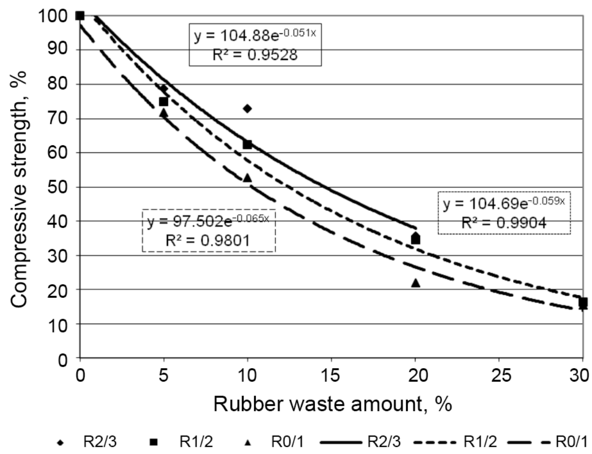

Fig. 4. Effect of CR amount and size fraction on the compressive strength of concrete

3.2. The effect of crumbed rubber size fraction and amount on flexural strength of concrete

Fig. 5 illustrates the flexural strength of concrete as a function of CR size fraction and CR amount. Here it may be seen that the flexural strength of concrete decreases depending on the amount of introduced CR. Fig. 5 shows that the average flexural strength of concrete, which is not modified with CR, is 6.5 MPa (standard deviation σ = 0.22 MPa). When CR of the smallest size fraction is added, the flexural strength decreases from 4.1 MPa (σ = 0.30 MPa) with CR added at 5% of the total aggregate amount, down to 1.8 MPa (σ = 0.21 MPa) with CR added at 30% of the total aggregate amount. In any case, the comparison of the flexural strength of control specimen with the flexural strength of specimens containing CR of bigger size fraction revealed similar tendencies. Fig. 5 shows that when fine aggregate is replaced with 1/2 fr. CR at 5% of the total aggregate amount, the flexural strength drops by 21% (5.1 MPa, σ = 0.24 MPa). With higher amount of 1/2 fr. CR (10, 20, 30% of the total aggregate amount) the flexural strength, in comparison with control specimens, decreased by 28% (4.7 MPa, σ = 0.22 MPa), 45% (3.60 MPa, σ = 0.48 MPa) and 60% (2.6 MPa σ = 0.11MPa) respectively. The test results of specimens with the biggest size fraction (2/3) CR showed the decrease in compressive strength (compared to concrete not modified by CR) by 18% (5.3 MPa, σ = 0.32 MPa), 24% (5.0 MPa σ = 0.16 MPa) and by 39% (3.9 MPa σ = 0.36 MPa) with the increase of CR amount by 5%, 10% and 20%, respectively.

The spread of the test results was determined from the obtained flexural stresses (Fig. 6). The obtained standard deviation values ranged from 0.11 MPa to 0.48 MPa. The tests showed that the standard deviation of the flexural strength had the highest value of 0.48 MPa when CR of 1/2 fr. was added at 20% of the total aggregate amount, whereas specimens with CR of fr. 1/2 added at 30% of the total aggregate amount showed the least standard deviation of 0.11 MPa. It may be stated that the obtained results are reliable because the values of standard deviation of the flexural strength are low.

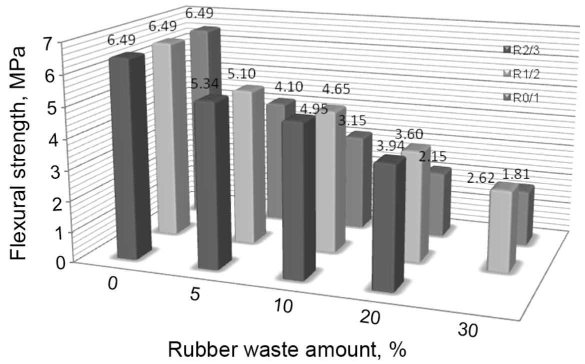

Fig. 5. The change in the flexural strength of concrete with CR of different amount and size fraction

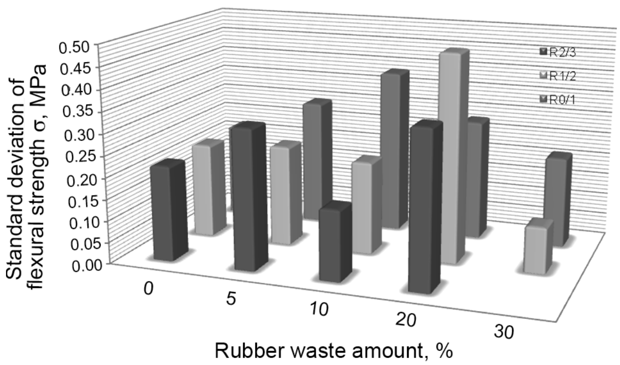

Fig. 6. Standard deviation of the flexural strength of concrete

Fig. 7 illustrates the change in the bending strength of concrete modified with different amounts of CR of different fraction size after 28 days of curing. The tests showed that there is exponential dependence in the decreasing of bending strength and different amount of crumb rubber. Exponential equations and R^2 values are presented in Fig. 7. It was noted that the correlation factor of the obtained curve changed from 0.92 to 0.99, subject to the CR size fraction. From the calculated R^2 values, we see that the curves obtained are reliable to forecast the bending strength; therefore based on equations 4, 5 and 6, we may forecast the bending strength of concrete modified by 0/1 fr., 1/2 fr and 2/3 fr. CR when a certain amount of CR is introduced:

$$y = 83.198e^{-0.0407x}; \quad (4)$$

$$y = 95.945e^{-0.0286x}; \quad (5)$$

$$y = 96.87e^{-0.0239x}. \quad (6)$$

From the obtained exponential equations it may be easily forecasted that the bending strength of concrete will decrease by approx. 2.4% when CR is introduced at 1% of the total concrete volume. The relation of the decrease in bending strength and compressive strength of concretes modified with CR was also compared in the tests. The obtained results showed that introduction of CR at 30% of the total aggregate amount decreased the compressive strength of concrete by more than 6 times compared to non-modified concretes; whereas the bending strength of concretes modified with the same amount of CR decreased only by 3.6 times (30% of 0/1fr. rubber waste additive). Lower decrease in bending strength than in compressive strength in rubber modified concretes can be explained by better adhesion of cement stone to rubber particles than the adhesion of substituted sand with cement paste (Jakušovas, Daunys 2009; Daunys, Česnavičius 2009). Microscopy tests (Fig. 8a–d) showed that rubber particles up to 3 mm in size have more regular shape and smoother texture; the shape of smaller particles becomes irregular and their surface texture is rougher with numerous voids. More complicated surface texture of rubber particles gives better cohesion of cement matrix with rubber particles (Fig. 8e) (Eldin, Senouci 1993).

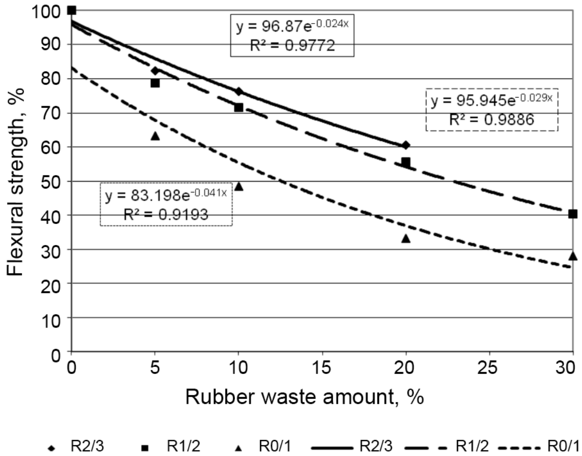

Fig. 7. Effect of CR amount and size fraction on the flexural strength of concrete

The surface of rubber particles is much rougher than the surface of sand, which is smooth and even (Fig. 8a–d); therefore, the hardened cement paste has better adhesion to rubber particles. This is the reason why the bending strength decreases less in concretes modified with rubber waste additive.

3.3. The effect of CR size fraction and amount on splitting tensile strength of concrete

Fig. 9 illustrates the splitting tensile strength of concrete as a function of CR size fraction and CR amount. Here it can be seen that the splitting tensile strength of concrete slightly increases when a small amount of CR is introduced; whereas with bigger amounts of additive, the splitting tensile strength decreases and continues decreasing with the increase in CR amount.

From Fig. 9 it may be seen that splitting tensile strength of non-modified concrete is around 3.48 MPa. This value increases up to 3.68 MPa when the smallest size fraction CR is introduced at 5% of the total aggregate amount. Splitting tensile strength was also noted to increase in concretes with CR of bigger size fraction. We determined that small amount of 1/2 fr. CR increased the tensile stress up to 3.51 MPa and 2/3 fr. CR increased it up to 3.68 MPa. However, the splitting tensile strength of modified concrete compared to non-modified concrete started reducing when CR amount in concrete was increased (up to 30% of the total aggregate amount) irrespective of the additive size fraction. The tests revealed that with the highest CR amount (30% of the total aggregate amount) used in testing the splitting tensile strength decreased more than twice compared to the specimens without CR (Fig. 9).

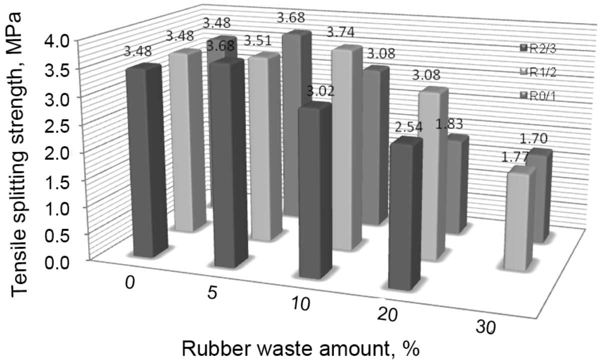

Fig. 9. The change in the splitting tensile strength of concrete

The obtained results showed that the splitting tensile strength of concrete modified with mechanically crumbed rubber of different size fractions decreased according to exponential equations (Fig. 10), the correlation factors of which changed in the interval of 0.73…0.90 depending on the size fraction of the additive.

Based on Eqs 7, 8 and 9 it was forecasted the splitting tensile strength of concrete modified by 0/1 fr., 1/2 fr and 2/3 fr. CR when a certain amount of waste rubber is introduced:

$$y = 109.54e^{-0.029x}; \quad (7)$$

$$y = 114.98e^{-0.022x}; \quad (8)$$

$$y = 105.86e^{-0.018x}. \quad (9)$$

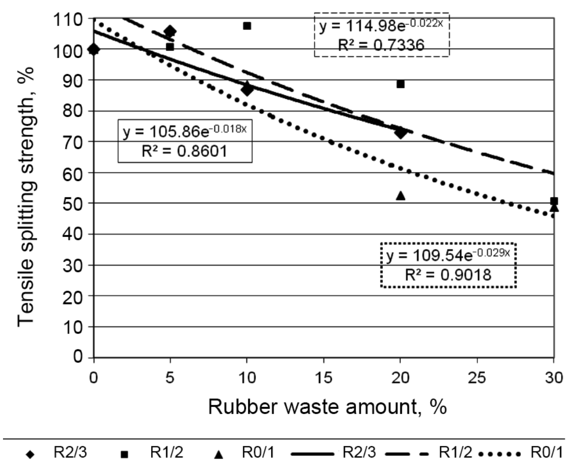

Fig. 10. Effect of CR amount and size fraction on the splitting tensile strength of concrete

a)
b)
c)
d)
e)

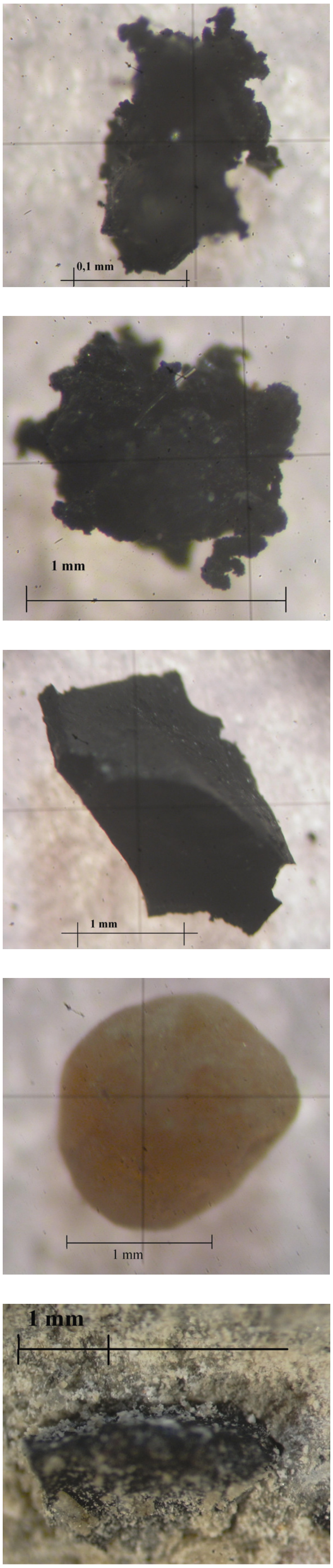

Fig. 8. Crumb rubber, particle size up to 0.5 mm (a); Crumb rubber, particle size up to 1.0 mm (b); Crumb rubber, particle size up to 3.0 mm (c); Sand particle (d); Contact zone of cement matrix and a rubber particle (e)

To generalise the results of examined splitting tensile strength in concrete modified with CR, it may be noted that there is a slight increase in the splitting tensile strength of concrete when a small amount of CR is introduced. One of the possible reasons of this increase might be better adhesion of cement matrix with rubber particles compared to the adhesion of substituted sand with cement stone. Most probably, rubber particles due to their irregular shape and rough surface with numerous voids (Fig. 8 a–c) absorb the tensile stress more effectively and therefore the splitting tensile strength of such a conglomerate increases. With higher amount of CR in concrete, the splitting tensile strength decrease due to higher volume of entrained air and lower density (Skripkiūnas *et al.* 2010), which have a direct effect on the change in the tensile strength of concrete.

Vast amounts of used and non-biodegradable rubber tyres are accumulated in the world every year. Utilisation of such waste is still unresolved. The modification of cement concrete mixtures with crumbed rubber waste allows producing concrete that has specific properties (less density and thermal conditions, higher deformability and plasticity, better absorption of vibration and better sound insulation) and resolving the utilisation of rubber waste. It was found that crumbed rubber additives improve vibration damping properties (Skripkiūnas *et al.* 2009), although reduce strength characteristics of the concrete. Crumbed rubber additives may be used for higher impact-sound insulation in the floors of buildings or vibration damping in foundations and industrials floors, also for road building elements, such as road partitions, acoustic highways walls and bridge sidewalk blocks.

4. Conclusions

1. Due to low elastic modulus and high deformability of the rubber particles, the compressive, flexural and splitting tensile strengths of concrete decrease by respectively 84%, 72% and 51% when crumbed rubber amount is increased up to 30% of the total aggregate amount.

2. Tests of tensile splitting strength of concrete with crumbed rubber have shown that the addition of a small amount of this additive slightly increases the tensile splitting strength (7%). Concrete with 30% of total aggregate amount of crumbed rubber has 61% lower decrease in bending strength than in compressive strength, when crumbed rubber additives are added to concrete. This can be explained by irregular shape and rough surface of rubber particles, which give better adhesion of rubber particles with cement stone than the adhesion of substituted sand with cement stone. With higher content of crumbed rubber additive in the concrete, the tensile splitting strength decreases due to the significant increase of entrained air content and lower density, which directly influence the change in the tensile splitting strength.

3. Changes in the strength (compressive, flexural and splitting tensile) of concrete with addition of a certain amount of crumbed rubber can be described by the calculated exponential mathematical functions.

4. Although concrete mixtures with crumbed rubber reduce strength characteristics of concrete, modification of cement concrete mixtures with crumbed rubber not only resulted in production of concrete that has specific properties (less density and thermal conditions, higher deformability and plasticity, better absorption of vibration and better sound insulation) but also resolution of rubber waste utilisation problem.

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