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Flexural fatigue performance and mechanical properties of rubberized concrete

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Preliminary note

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Flexural fatigue performance and mechanical properties of rubberized concrete

Results of experimental investigation of concrete containing waste tyre crumb rubber are presented in the paper to determine mechanical properties such as the compressive strength, splitting tensile strength, and flexural strength of concrete. The C35/45 compressive strength class concrete was used in this study. Five to twenty-five per cent of sand volume was replaced with waste tire crumb rubber, and the results were compared to ordinary concrete test results. The results revealed that the performance slightly increased by 1.46 % and 1.96 % at 5 % and 10% of crumb rubber replacement compared to ordinary concrete.

Key words:
waste tyre crumb rubber, compressive strength, splitting tensile strength, flexural strength

Prethodno priopćenje

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Ponašanje pri zamoru uslijed savijanja i mehanička svojstva betona s dodatkom gumenog granulata

U radu se prikazuju rezultati eksperimentalnog ispitivanja betona s dodatkom gumenih granulata kako bi se utvrdila mehanička svojstva kao što su tlačna čvrstoća, vlačna čvrstoća cijepanjem te čvrstoća betona na savijanje. U istraživanju je korišten beton razreda tlačne čvrstoće C35/45, pri čemu je 5 do 25 % volumena pijeska zamijenjeno gumenim granulatima iz otpadnih guma, a dobiveni rezultati uspoređeni su s rezultatima ispitivanja običnog betona. Rezultati pokazuju malo poboljšanje u ponašanju od 1,46 % i 1,96 % s 5 %, odnosno 10 % gumenog granulata.

Ključne riječi:
gumeni granulat iz otpadnih guma, tlačna čvrstoća, vlačna čvrstoća cijepanjem, čvrstoća na savijanje

Vorherige Mitteilung

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Verhalten bei Ermüdung infolge von Verbiegung und mechanische Eigenschaften von Beton mit Zugabe von Gummigranulat

In der Arbeit werden die Ergebnisse einer experimentellen Untersuchung von Beton mit Zugabe von Gummigranulat aus Altreifen zur Festlegung der mechanischen Eigenschaften wie Druck-, Reiß- und Biegefestigkeit dargestellt. In der Untersuchung wurde Beton mit der Druckfestigkeitsklasse C35/45 verwendet, wobei 5 bis 25% des Sandvolumens durch Gummigranulat aus Altreifen ersetzt wurde. Die gewonnenen Ergebnisse wurden mit den Ergebnissen der Prüfung von gewöhnlichem Beton verglichen. Beton mit 5 % bzw. 10 % Granulat ergab ein besseres Verhalten von 1,46 % und 1,96 % im Vergleich zum gewöhnlichen Beton.

Schlüsselwörter:
Gummigranulat aus Altreifen, Druckfestigkeit, Reißfestigkeit, Biegefestigkeit

1. Introduction

Waste disposal is becoming a serious problem in many industries. It assumes greater significance in a country like India with the population count of more than one billion. The growing demand for automobiles has generated a huge amount of waste tires, and the disposal of these tires in an economical and environment-friendly manner is a challenge for all countries. Waste materials can be disposed of in two ways: firstly by burning the tires and, secondly, by placing them in landfills due to their low density and poor degradation properties. Presently some countries do not accept disposal through incineration as burning waste tires produce a large amount of CO_2 that mixes with natural air, ultimately leading to global warming. The second method involving landfill disposal is also not advisable because of uneven settlement. The inadequate disposal of tires may, in some cases, be detrimental to human health (fire risk, haven of rodents or other pests such as mosquitoes), and pose an environmental risk. To prevent the environmental problem, new techniques are needed to dispose of waste tires without affecting the environment. Reuse of these waste tires by incorporating them into concrete mixes avoids the environmental issue associated with the disposal of waste tires. The main reason for incorporating rubber waste into concrete is the low density, high sound absorption, and high elasticity of this material [1-5]. As the rubber content in concrete increases, the ductility, resistance to wear, and impact resistance also increase [6]. The rubber will ensure better resistance to dynamic loading and cracking, better noise reduction [7], and better hydro – abrasive resistance [8].

Fatigue failure occurs when the strength of a concrete structure is exceeded by the design load after exposure to many stress cycles. Fatigue may be defined as a process of progressive and permanent internal damage in a material subjected to repeated loading. The fatigue strength of concrete is influenced by the range of cyclic loading. In general, a decrease in the maximum stress level or stress range enhances the fatigue life of concrete [9-12].

In view of possible application of concrete with waste tire crumb rubber, it should be noted that rubber can be added in large volumes, amounting to 40 % - 50 % of the aggregate volume, without major workability problems. However, in most applications, a considerable strength reduction occurs due to high rubber content. If the strength is not a major factor in the design, such as in case of light weight concrete walls, building facades, or other architectural units of buildings, then such rubberized concrete mixes could be a viable alternative to the normal weight concrete. On the other hand, the rubberized concrete could be used in nonstructural applications such as traffic noise barriers on highways, sidewalks, sports courts, and may also represent a viable material for other nonstructural applications. [13].

2. Experimental programme

2.1. Materials used

CEM1 Portland cement (52.5 MPa) was used in this study as it conforms to EN 197-1:2000 [14]. The physical properties of cement are presented in Table 1. Locally available river sand having a maximum particle size of 4.75 mm, fineness modulus of 2.51, and a specific gravity of 2.65 was used. The coarse aggregate used in the concrete mixtures has a maximum size of 12.5 mm, a fineness modulus of 5.94, and a specific gravity of 2.72. In the present study, waste tire crumb rubber is used as a partial replacement of fine aggregate. The fineness modulus is 3.72, and specific gravity is 0.84. Figure 1 shows the crumb rubber used in the current study.Light Brown Superplasticizer (SikaViscoCrete 20HE) with the specific gravity of 1.08 was used to improve the workability.

Table 1. Physical properties of cement

No.	Property	Results	Limits as per EN 197-1:2000
1	Initial setting time [min]	85	≥ 45
2	Soundness by e-Chatelier [mm]	1	≤ 10
3	Compressive strength [MPa] 2 days 28 days	 38.60 56.96	 ≥ 30 ≥ 52.5

Figure 1. Crumb rubber

Table 2. Mix proportion (per m³)

Mix proportion \ Mix designation	R0	R5	R10	R15	R20	R25
C [kg]	380	380	380	380	380	380
FA [kg]	865.00	793.25	751.50	709.75	668.25	626.25
CA [kg]	1010	1010	1010	1010	1010	1010
CR [kg]	-	12.6	12.6	37.2	50.4	63.0
Note: CR - Crumb Rubber, C - Cement, FA - Fine Aggregate and CA - Coarse Aggregate						
R0 – content of crumb rubber 0 % (ordinary concrete) R5 – content of crumb rubber 5 % R10 – content of crumb rubber 10 %			R15 – content of crumb rubber 15 % R20 – content of crumb rubber 20 % R25 – content of crumb rubber 25 %			

2.2. Details of specimens and mix proportions

Concrete cubes measuring 150 mm were cast for the compressive strength test. Concrete cylinders 150 mm in diameter and 300 mm in length were cast for splitting tensile strength, and concrete prisms measuring 100 mm in width, 100 mm in depth, and 500 mm in length, were cast for the static flexural strength and fatigue test. The C35/45 compressive strength class concrete had cement, fine aggregate and coarse aggregate ratio of 1:2.27:2.65, and the water - cement ratio of 0.32. One percent of superplasticizer was mixed into the concrete mix to improve workability. Fine aggregate was partially replaced with crumb rubber (5 %, 10 %, 15 %, 20 % and 25 % by volume). Concrete specimen mixing and curing was carried out at room temperature, and potable water was used for both mixing and curing. Compaction of fresh concrete in the mould was carried out for two minutes using a table vibrator. Three sets of specimens were cast for each test. The identification and details of concrete mix are given in Table 2.

3. Results and discussion

3.1. Compressive strength

Concrete cubes were tested after 28 days using a compression testing machine with a maximum capacity 2000 kN in accordance with EN 12390-3: 2009 [15]. The compressive strength of C35/45 mix was measured with different percentage of replacement of fine aggregate by waste tire crumb rubber, and the test results were compared with control concrete (without rubber). The compressive strength versus mix ID is presented in Figure 2. The result shows that the addition of crumb rubber resulted in the reduction of compressive strength when compared to the control concrete. The 28-day decrease in compressive strength of concrete with the addition of 5 %, 10 %, 15 %, 20 % and 25 % of waste tire crumb rubber amounted to 7.85 %, 13.34 %, 21.92 %, 29.9 % and 46.44 %, respectively, compared to control concrete.

The strength reduction in concrete cubes resulting from an increase in rubber content is due to two reasons. First, rubber particles have a greater air content compared to river sand, which leads to a lack of adhesion between rubber particles and other concrete materials [13, 16]. Second, compared to aggregate, rubber has lower stiffness, and so a higher proportion of rubber particles in concrete reduces the mass stiffness and decreases its load bearing capacity [17].

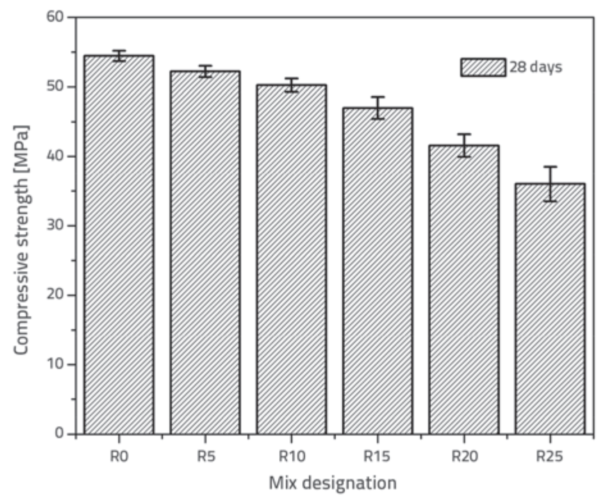

Figure 2. Compressive strength of concrete at 28 days

3.2. Splitting tensile strength

The splitting tensile strength test was conducted as per EN 12390-6:2009 [18]. Cylinders measuring 150 mm in diameter and 300 mm in length were cast and tested. The corresponding test results are shown in Figure 3. The splitting tensile strength reduced with an increase in the proportion of crumb rubber in concrete, which is similar to the compressive strength testing. The 28-day decrease in the splitting tensile strength of concrete with an addition of 5 %, 10 %, 15 %, 20 % and 25 % of waste tire crumb rubber amounted to 1.65 %, 4.49 %, 8.74 %, 11.52 % and 14.65 %, respectively, when compared to control concrete.

This implies that the strength reduction of concrete with crumb rubber is lower in the splitting tensile strength testing, compared to the compressive strength testing.

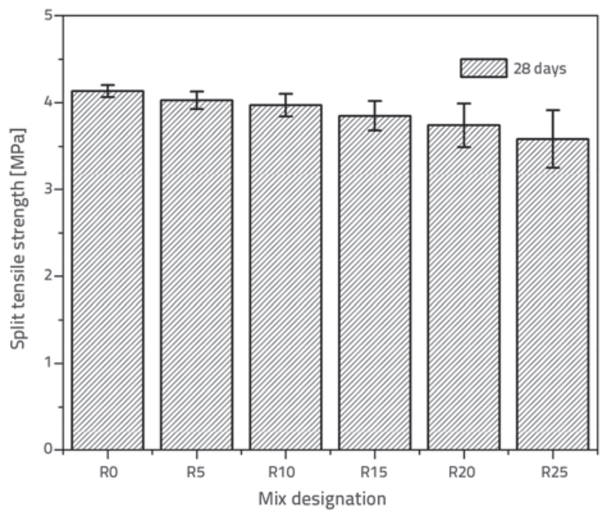

Figure 3. Splitting tensile strength of concrete at 28 days

3.2. Static flexural strength

The objective of the static flexural strength testing was to fix the maximum and minimum load limits of the fatigue test. Hence, the flexural strength was tested as per EN 12390-5: 2009 [19]. Two-point load was applied to the specimens and the breaking load of specimens was measured. This breaking load information was used to calculate the flexural strength of the specimen. Three specimens were tested for each mix, and the average value was reported as the flexural strength of the mix. These test results are presented in Figure 4.

The test result shows that the flexural strength of concrete with the 10 % crumb rubber replacement is high but, when the crumb rubber replacement increased by more than 15 %, the strength becomes lower. The increased flexural strength of concrete is mainly due to the elastic behaviour of rubber. Normally, rubber exhibits a more ductile or flexural behaviour, and the improvement of flexural strength is limited to a relatively small rubber content [20].

In the compressive and splitting strength tests, the uniformly distributed load was applied to the specimen, but in the flexural strength test the two point load (excluding supports) was applied to the specimen. During compression and tension the crack propagation around rubber particles was very fast because the rubber particles are much softer (due to lower stiffness) than cement paste, which led to the failure of the rubber – cement matrix. For that, the compressive and split tensile strength was decreased if the crumb rubber increased.

During the flexural strength testing, the specimen is subjected to both compression (at top) and tension (at bottom). Normally, during flexural failure, a small crack starts from the bottom and may occur before the maximum load is applied since the microcracks form when the post peak zone is reached and propagate after exceeding this stage. However, crumb rubber particles may work to delay the formation of microcracks by stress relaxation. Consequently, rubberized concrete offers measurable improvements to pre-microcracks strain capacity, and so would most likely reduce shrinkage cracking in a similarly beneficial manner and improve the flexural strength of the specimen [21]. This improvement of flexural strength is limited to relatively small rubber contents.

Therefore, it can be explained that the flexural strength increases significantly with the addition of lower volume of rubber to the concrete. Accordingly, in this study, the flexural strength was increased with a low volume of rubber (5 and 10 %), and the strength was decreased with a higher volume of rubber (15, 20 and 25 %).

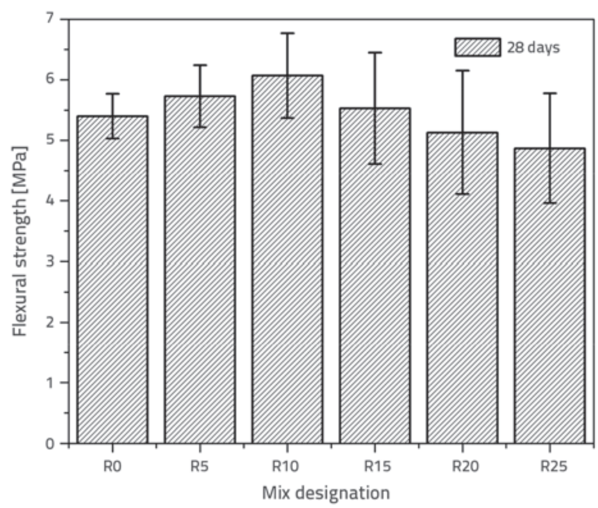

Figure 4. Flexural strength of concrete at 28 days

3.3. Fatigue behaviour

The fatigue behaviour of concrete was analysed by means of the S-N curve, which relates the applied stress (ratio of the maximum loading stress to flexural strength) to the number of load repetitions (N), which cause the fatigue strength. A single logarithmic equation was used to calculate flexural strength. The relationship established is known as the Wohler's Equation [12].

$$S = \frac{\sigma_{max}}{MoR} = A - B\ln(N)$$

where:

- S - stress ratio
- σ_{max} - maximum loading stress [MPa]
- MoR - modulus of rupture or flexural strength [MPa]
- A & B - experimental coefficients that vary with mixture and loading conditions
- N - number of load repetitions.

The waveform applied was a half sine form, and the load applied was decided based on the adopted stress ratio. The applied load was varied while the frequency was kept constant. The load applied and the loading frequency was set in the computer system. The hydraulic

Table 3. Fatigue life data

Stress ratio	Rubber content [%]	Number of specimens	Average number of cycles to failure [N]	Standard deviation
0.8	0	3	1182	24.98
	5	3	3720	65.06
	10	3	3492	67.26
	15	3	1920	32.16
	20	3	321	16.92
	25	3	204	12.16
0.7	0	3	9066	26.12
	5	3	13338	46.16
	10	3	18756	44.21
	15	3	10254	26.16
	20	3	1242	22.13
	25	3	705	20.16
0.6	0	3	58983	16.51
	5	3	62589	14.16
	10	3	100000	7.35
	15	3	55893	15.21
	20	3	44568	14.23
	25	3	25647	13.21
0.5	0	3	100000	The test was stopped after 10^5 cycles as all the specimens with 0.5 stress levels did not fail.
	5	3	100000	
	10	3	100000	
	15	3	100000	
	20	3	100000	
	25	3	100000	

system of the accelerated fatigue testing apparatus was actuated and the testing continued until failure of the specimen. The number of load applications until specimen failure was recorded.

During the flexural fatigue test, the failure of the specimen was sudden and the testing apparatus was switched off. An iron platform was provided below the specimen to prevent it from falling after failure. In addition, the accelerated testing apparatus was equipped with a cut-off-switch, which switches off automatically after failure. The number of cycles to failure was recorded both in the computer system and the servo amplifier. Details on the number of cycles to failure and the test set up and failure specimens are shown in Figures 5.a and 5,b, respectively. The flexural fatigue test was conducted on three specimens for each mix at every stress ratio, and the average fatigue life data for concrete, at various waste tire crumb rubber contents, are listed in Table 3.

Figure 5. Testing of specimens: a) Fatigue test setup; b) Failure specimen

As to fatigue behaviour, when the frequency was kept at the constant amplitude of 3 Hz, concrete's fatigue life decreased with an increase in load. As shown in Figure 6, the number of cycles to failure is greater for mix R10. Failure specimens are shown in Figure 7.

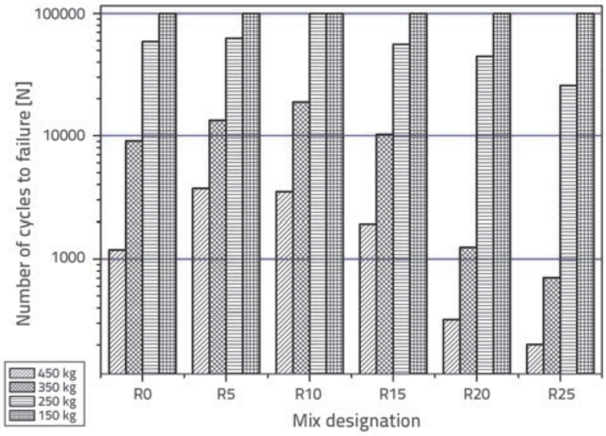

Figure 6. Variation of number of cycles to failure at applied frequency of 3 Hz

The objective of most studies written on the fatigue strength of concrete has been to interrelate the applied fatigue stress and the fatigue life of concrete. This relationship is shown as the S-N curve or Wohler curve. The S-N curve enables prediction of the mean fatigue life at given constant amplitude of the cycles of stress. Most of the studies mainly focus on simple S-N relationships, which allows prediction of the mean fatigue life of concrete under a given fatigue stress level. However, it is known that the fatigue data on concrete exhibit great variability due to material heterogeneity. Moreover, it gives scattered results that are not easy to interpret even when tests are done on several duplicates. The analysis of fatigue test is conducted using regression analysis.

Figure 7. Failure specimens after fatigue testing

Flexural fatigue test results for the frequency of 3 Hz at the stress level of 0.80, 0.70, 0.60 and 0.50, respectively, are expressed as an S-N curve, as shown in Figure 8. Regression equations connecting the stress level with the number of cycles to failure were obtained for all specimens, as presented in Figure 8. The relationship S = A ln (N) + B was obtained at the frequency of 3 Hz between the frequency (F) and the fatigue cycle number (N) generated through linear regression. Experimental coefficients in F-N models are shown in Table 4. The fatigue performance of concrete depends on two important parameters in the fatigue equation. These parameters are A and B, and they reflect the height and slope of the fatigue curve, respectively. As the parameter A becomes larger, the fatigue curve becomes higher, indicating better fatigue performance. As the value of B increases, the fatigue curve becomes steeper indicating greater sensitivity of fatigue life to stress variations.

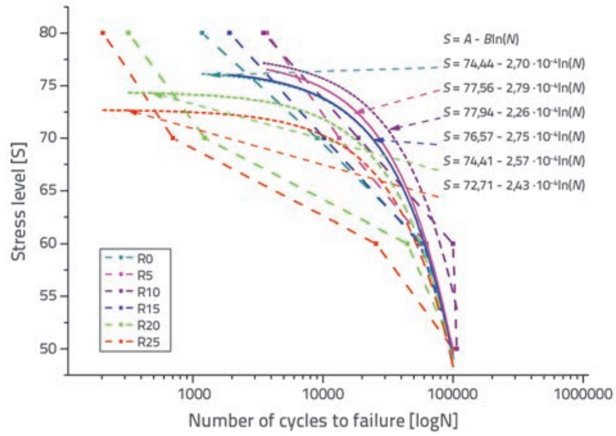

Figure 8. S-N curve

The rubber content at 10 % replacement showed the highest fatigue resistance irrespective of the stress levels applied. It was observed that the specimens subjected to the stress level of 0.8 (80 % of flexural strength) had a low fatigue life but, when the stress level was decreased, the fatigue life increased. The flexural fatigue strength increased from R0 to R10 and then decreased from R15 to R25. The test was stopped after 10^5 cycles as all specimens with 0.5 stress levels did not fail. The fatigue behaviour also followed the same pattern of failure criteria with mixes from R0 to R25.

A correlation between the stress levels and the number of cycles to failure was obtained for all specimens through regression equation, as shown in Figure 8. Experimental coefficients defined from regression equation are presented in Table 4.

Table 4. Experimental coefficients for RBC and CC

Coefficients / Mix designation	A	B	R^2
R0	76.44	$-2.70 \cdot 10^{-4}$	0.9053
R5	77.56	$-2.79 \cdot 10^{-4}$	0.9191
R10	77.94	$-2.26 \cdot 10^{-4}$	0.8258
R15	76.57	$-2.75 \cdot 10^{-4}$	0.9039
R20	74.41	$-2.57 \cdot 10^{-4}$	0.8220
R25	72.71	$-2.26 \cdot 10^{-4}$	0.6856

The coefficient A increased by 1.46 % and 1.96 % with an increase in rubber content amounting to 5 % and 10 %, respectively. This increase in the value of A indicates that the flexural fatigue performance of concrete containing up to 10 % of waste tire crumb rubber is better compared to control concrete (R0). The slight reduction was observed in the value of coefficient B for R5 and R10 mixes indicating a decrease in the sensitivity of their fatigue life to change in stress level.

4. Conclusions

Based on this investigation, the following conclusions are drawn:

- The compressive strength and splitting tensile strength decreased with an increase in rubber content. The main reason for the strength reduction was the entrapped air, the quantity of which increased with an increase in the percentage of rubber content, thus affecting adhesion between rubber particles and other concrete materials.
- An improvement in flexural strength was observed with an increase in rubber content up to 10 %. This may be due to elastic behaviour of rubber particles.
- The addition of waste tire crumb rubber to concrete results in an improvement of fatigue performance of concrete by around 10 %. The fatigue performance increased with an increase in rubber content in the range from 5 % to 10 %, and decreased when the rubber content in concrete amounted to 15 %, 20 % and 25 %.
- Fatigue life data of R0, R5, R10, R15, R20 and R25 increased with a decrease in stress level. The lower variability in the fatigue life distribution for R0, R5, R10, R15, R20 and R25 was obtained at a lower stress level.
- The target strength was achieved at 5 %, 10 % and 15 % crumb rubber replacement level, while this strength was not achieved at higher replacement levels, i.e. when sand was replaced with 20 % and 25 % of crumb rubber. Therefore, the compressive and splitting tensile strength reduction was acceptable up to 15 % of crumb rubber replacement as compared to ordinary concrete.
- From a practical point of view, crumb rubber content should not exceed 15 % of the total fine aggregate volume due to the resulting severe strength reduction (failure to achieve target strength). The test results imply that it is possible to produce a high strength rubberized concrete for structural applications with the addition of up to 15 % of rubber due to low reduction (target strength achieved) in the compressive and splitting tensile strength and improvement in the flexural strength and fatigue performance. However, when rubber content is increased by more than 15 %, the resulting concrete can safely be used for non-structural applications.

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