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Investigation of the Mechanical Properties of Concrete Incorporating Recycled Rubber Particles

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Abstract:

Quantity of waste rubber generated by automobile tires is growing, posing an environmental threat. Rubber tire recycling was studied for usage in asphalt and waterproofing systems during past few decades. Globally, concrete is the most widely used building material. About 7% of CO_2 emissions come from the cement production. The purpose of this research is to assess if using waste rubber and Portland cement together in composite material for structural applications is feasible. Waste tires (shredded to 0/1 mm) were used as fine aggregate replacement (in 2.5 and 7.5 %), together with PC and natural stone. An investigation of properties in fresh (slump test, bulk density, air content) and hardened state (bulk density, compressive strength) was performed on the rubberized concrete. The compressive strength decreased by increasing the rubber content for all w/c ratios (0.55-0.4). The addition of fine-sized rubber did not cause a retardation in cement hydration mechanism. According to the obtained compressive strengths, all designed rubberized concretes belong to a group of structural concretes.

***Keywords**: Construction materials; Alternative raw materials; Recycling; Cement composite; Waste rubber; Physico-mechanical properties.*

1. Introduction

An estimated 1.5 billion waste rubber tires (WRT) are being produced in the world annually, adding to the massive quantity of tires that are already disposed of in stockpiles and landfills [1]. The total quantity of WRT generated across the EU in 2020 by domiciles and various economy sectors was 2135 million tons, or 4815 kg per capita [2]. According to the Serbian Environmental Protection Agency (SEPA), 360,000 tons of tires were placed on the market between 2011 and 2021. During the same period, approximately 50,000 tons of scrap tires were handled, with practically all of them being managed in accordance with the law, while only about 500 tons were discarded into landfill sites. The Waste Disposal Regulation prohibits disposal in landfills, because it takes 50 to 80 years for a tire to fully degrade. WRT tires are regarded as a separate waste stream, along with batteries, waste oils, and electrical debris, due to the requirement for their special management procedures (collecting, transportation, and treatment). Recycling waste tires and using them as energy sources are two main streams, according to the Rulebook on the method and procedure of waste tire management (i.e., not more than 20% of the waste tires collected the previous year should be used for energy purposes, and at least 80% of the entire amount should be recycled) [3]. The growing abundance of waste tires and the lack of a coordinated processing or recycling framework present a growing concern for the

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management of this material. Due to recent global recognition and strong environmental awareness, many authorities have imposed strict rules and regulations regarding this waste product to prevent excessive stockpiles and landfill operations.

The possibility of using WRT in civil engineering is actively investigated for over 30 years. Researchers now have the chance to explore sustainable practices and alternate uses for waste tires as the number of WRT rises and legal fines are in place [4]. In order to achieve Sustainable Development Goals in the built environment, methods and tactics that optimize material reuse, repair, and recycling must be established. In particular, the use of WRT in the construction sector has made it possible to sustainably reuse the tires. Previously, they would have to be thrown away without any preparation or put in landfills, which would have had negative effects on the environment and society [5-7]. Authorities worldwide have been pushed to implement strict laws and regulations to curb excessive WRT landfilling operations and support the circular economy by identifying alternative measures for WRT disposal, recycling, and reuse [8]. Two processing techniques are used in WRT recycling: ambient size reduction and cryogenic size reduction [9, 10]. Thereby, the WRT-derived products are classified as cuts (>300 mm), shreds (50–300 mm), chips (10–50 mm), granulates (1–10 mm), powder (<1 mm), and fine powder (<500 μm) [1, 9]. Tire composition has a substantial impact on the essential characteristics of the recovered product; thus, it must be evaluated before recycling, primarily to reduce any potential risks to the environment (the details of the physico-chemical properties of WRT can be found in the literature [11, 12]). The best solutions for WRT disposal are the reutilization of crumb rubber (CR) and rubber aggregates (RA) in concrete and asphalt mixtures. The least preferred option is energy recovery techniques like incineration due to the possibility of severe pollution. Besides concrete and asphalt manufacturing, WRT has applications in geotechnical engineering (soil stabilization), sand replacement in pavement systems, tire bales used as gravity retention systems, etc. [13–15].

When compared to traditional (unmodified) concrete mixtures, the use of CR in concrete, often referred to as rubberized concrete (RC), has improved the material's freeze-thaw resistance. The application of CR enhanced sustainability credentials by lowering lifecycle costs due to the lesser maintenance requirements throughout the RC's design life [16–18]. Investigations were also conducted regarding the impact of partially substituting fine aggregates with CR in high-strength concrete [19]. It has been revealed that RC mixes are more resistant to acids and chloride ion (Cl-) permeability, which qualifies them as building materials for use in maritime environments [20], even though opposite results were reported, too [21]. The incorporation of rubber granulates or fillers in concrete mixtures increases their thermal resistance. Concrete mixes with granulated rubber reduce the requirement for interior heating appliances in buildings and reduce CO_2 emissions. They also function as insulation materials due to increased thermal resistance [18]. Granulated RC concrete compositions exhibit a lower propensity for shrinkage and cracking, in addition to greater impact resistance and energy absorption capacity as compared to traditional concrete [22]. Despite the advantages, the use of WRT in concrete mixtures has limitations due to the formation of a low-strength composite, mostly as a result of the rubber-cement weak adherence [23, 24]. Before adding rubber particles to the concrete mix, its surface is frequently chemically treated to enhance the bonding properties between the rubber and cement [25]. An alternative method involves applying a silane coupling agent (usually an admixture or water-repelling additive) to the rubber particle in order to create hydrophilicity on the modifier's surface [26]. Although numerous original studies and multiple state-of-the-art reviews on WRT application have been conducted, they usually detail and discuss the mechanical and durability characteristics. However, very limited efforts have been made to extensively explain the rubber-cement interaction on its microstructural level and to connect it to its influence on combination of physical, structural, and durability characteristics of concrete.

Concrete is a brittle material that, when loaded to its maximum capacity, causes the structure to break. As a result, the ductility of CR particles can help reduce concrete brittleness [27]. In addition, several advantages of recycled rubber concrete (CRC) have been reported in research papers, including improved deformation capacity, energy absorption, wetting capacity, and resistance to cyclic freezing and thawing, as well as reduced water permeability, chloride penetration, and thermal expansion [27, 28]. The main disadvantage of CRC over conventional concrete is its lower compressive strength. This shortage, however, can be remedied by increasing the amount of cement, lowering the water-cement ratio, and applying appropriate chemical and mineral additives. This study attempts to overcome the mentioned gap in knowledge regarding mechanical strength decrease by using rubber crumbs in concrete as a replacement for fine aggregate at concentrations of 2.5 and 7.5%. Three concrete mixtures were designed, and each was tested (in its fresh state) for slump consistency, bulk density, and air content. The changes in the properties of fresh concrete were monitored at 10, 30, and 60 minutes after adding water to the mix. Tests on hardened concrete (bulk density, compressive strength) were conducted after 3, 7, and 28 days. The properties obtained on concrete specimens prepared with 2.5 and 7.5% replacement of the fine fraction with CR were compared to the reference concrete, which had a water-cement ratio of w/c = 0.55, 0.50, 0.45, and 0.40. The underlining concept behind this work is to design a concrete waste resource (waste rubber tires, or WRT), which will overtake the role of air-entraining admixture. Thereby, this novel tailor-made concrete and its preparation methodology go beyond the state-of-the-art. The outcomes of this work will contribute to the enabling of the long-term management of recycled car tires, the creation of new uses for this waste while maintaining the robustness of concrete's performance, as well as environmental preservation in accordance with the Net-zero principles.

2. Materials and methods

2.1. Characterization of raw materials

The main component materials for making experimental samples of rubberized concrete (RC) were cement, fine aggregate and coarse aggregate (employed in following grain-classes: 0/4, 4/8 and 8/16 mm), crumb rubber, superplasticizer and water. In the concrete mix design, 2.5 and 7.5 % of the fine aggregate were replaced with crumb rubber. Cement content was 360 kg/m^3. Ordinary Portland cement, strength class 42.5 R, produced by Lafarge BFC was employed in the experiment. The specific mass of cement was 3110 kg/m^3. Cement's specific surface was 4320 cm^2/g. The chemical composition of cement is shown in Table I.

Crumb rubber (a photograph of the sample is shown in Figure 1), produced by cutting and shredding used pneumatic tires, was obtained from the producer of recycled rubber waste ECO-RECYCLING. The specific mass of the rubber was 1170 kg/m^3. The chemical composition of CR is given in Table 1. The grain-size distribution of CR is shown in Figure 2. After visual examination, it was determined that crumb rubber particles are of a sharp-edge shape, while their surface texture is smooth and impermeable, which is in agreement with the literature [29, 30]. The volumetric mass without voids and pores of CR particles is in the range of 1050–1150 kg/m^3 [31]. The bulk density of crumb rubber is in the range of 260 to 460 kg/m^3 [32]. Fraction 0/1 mm for CR was used in the experiment.

Natural (river) fractionated stone aggregate (0/4, 4/8, and 8/16 mm) was used. Mineralogically, the composition of aggregate corresponds to limestone. Its specific mass was 2650 kg/m^3, while its fineness modulus was 3.06. The grain-size distribution of aggregate is shown in Figure 2.

The superplasticizer Sika Viscocrete 4077x, based on polycarboxylate (manufactured by Sika Serbia) with a specific mass of 1065 kg/m^3, was used in this research. Tap water was used for the preparation of the concrete samples.

Chemical analysis, i.e., identification and quantification, of major oxides and minor elements was conducted on a EDXRF analysis on a Spectro Xepos system (SPECTRO Analytical Instruments, Chelmsford, MA, USA) equipped with a 50Wand 60 V X-ray tube with a binary Co/Pd alloy thick target anode. The excitation mode of the X-ray tube was combined with polarized/direct excitation. The characteristic radiation emitted by the elements present in the sample was detected by a silicon drift detector with Peltier cooler system. Pulverized slag samples (d50 < 63 µm) were used in the analysis (Table I). Grain-size distribution was determined using a sieve analysis (Figure 2).

Tab. I Chemical composition of cement and crumb rubber.

Oxide/ element	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	SO_3 (%)	Cu (mg/kg)	Pb (mg/kg)	Co (mg/kg)
Cement	19.83	4.26	2.51	63.41	1.67	0.25	0.78	2.80	-	-	-
CR	0.78	0.18	0.12	0.24	0.08	0.01	0.07	3.05	147	26	276

Fig. 1. Crumb rubber in fraction 0/1 mm (manufacturer Eco Recycling).

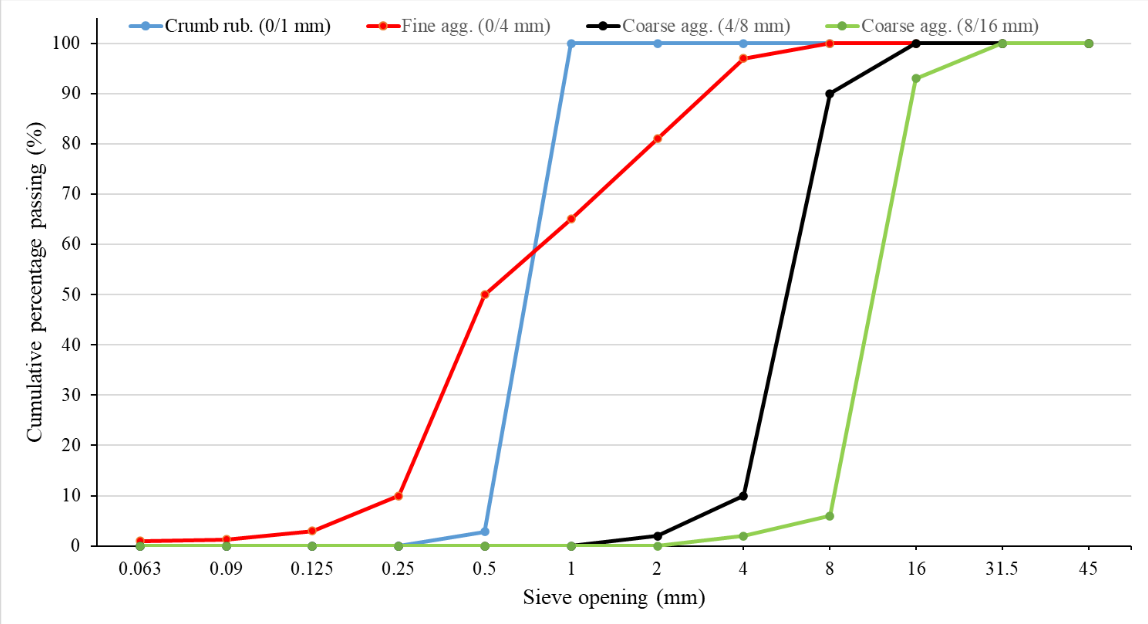


Fig. 2. Grain-size distribution of crumb rubber and natural aggregate.

2.2 Concrete mix-design

Three types of concrete were designed: ordinary concrete (OC), experimental concrete in whose mix-design fine aggregate is replaced with crumb rubber in 2.5 %, and experimental concrete in whose mix-design fine aggregate is replaced with crumb rubber in 7.5 %. All three varieties of concrete are prepared using the following water-to-cement (w/c) ratios: 0.55, 0.5, 0.45, and 0.4.

The designed concrete mixes were marked with the following labels: ordinary concrete (P1, P2, P3, and P4), concrete with 2.5 % of crumb rubber (P9, P10, P11, and P12), and concrete with 7.5 % of crumb rubber (P17, P18, P19, and P20).

Ordinary concrete mixes (P1, P2, P3, and P4) comprised the following aggregate classes: sand in fraction 0/4 mm (45 % of total mixture mass), gravel in fraction 4/8 mm (15 % of total mixture mass), and gravel in fraction 8/16 mm (40 % of total mixture mass).

Experimental concrete mixes P9, P10, P11, and P12 with fine 2.5 % crumb rubber contained the following aggregate classes: crumb rubber in fraction 0/1 mm (0.48 % of total mixture mass), sand in fraction 0/4 mm (44.52 % of total mixture mass), gravel in fraction 4/8 mm (15 % of total mixture mass), and gravel in fraction 8/16 mm (40 % of total mixture mass). The ratio between crumb rubber and river sand was 2.5:97.5.

The concrete mixes P17, P18, P19, and P20 that were used in the experiments had fine 7.5 % crumb rubber in them. The aggregates were sand (0.433 % of the total mixture mass), gravel (4.8 % of the total mixture mass), and crumb rubber (1.47 % of the total mixture mass). Additionally, there was gravel (8/16 mm) (40 % of the total mixture mass). The ratio between crumb rubber and river sand was 7.5 : 92.5.

The grain-size distribution of the aggregate mixture that contained river sand and crumb rubber is shown in Figure 3 and Table II.

Tab. II Values of projected lines in grain-size distribution diagrams of aggregate mixtures.

Mixture	Cumulative percentages passing (%) through the sieve openings (mm)											
	0.063	0.09	0.125	0.25	0.5	1	2	4	8	16	31.5	45
P1-P4	0.5	0.6	1.4	4.5	22.5	29.3	36.8	46.0	60.9	97.2	100.0	100.0
P9-P12	0.4	0.6	1.3	4.4	22.0	29.5	37.0	46.0	60.9	97.2	100.0	100.0
P17-P20	0.4	0.5	1.3	4.2	21.0	30.1	37.4	46.1	60.9	97.2	100.0	100.0

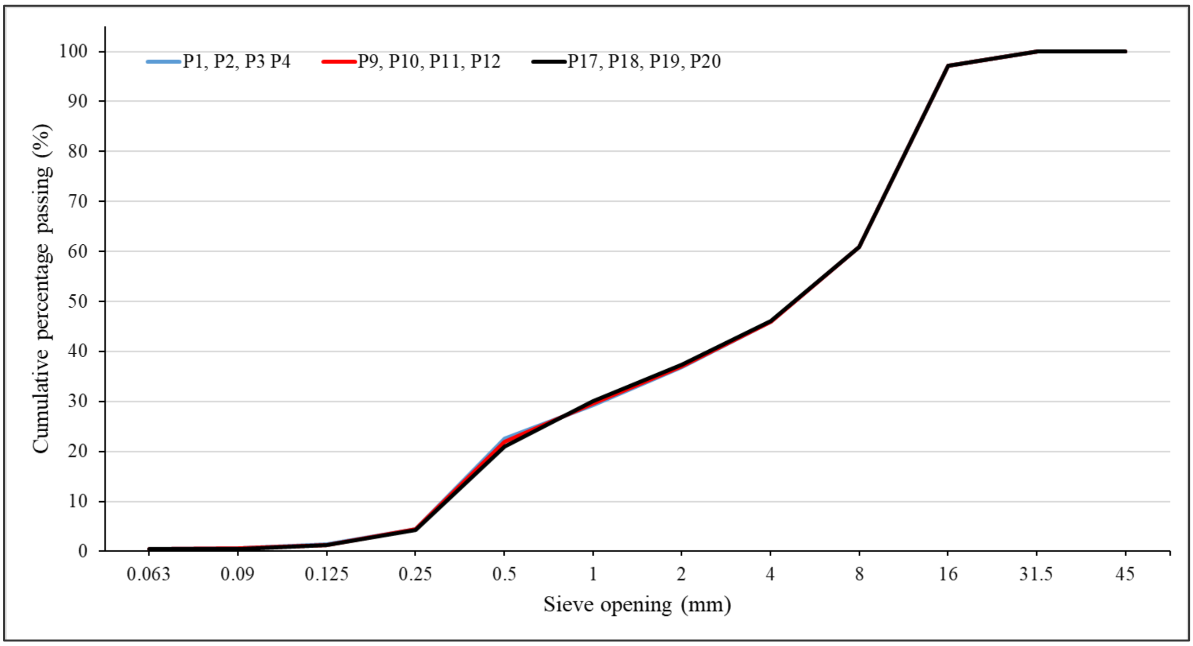


Fig. 3. Grain-size distribution of aggregate mixtures used in concrete mix-design.

Thereby, a total of twelve different concrete mixtures were prepared. The mixing of concrete was conveyed in a 0.150 m^3 laboratory planetary mixer. Mixing time for all concrete mixtures was 90 seconds. Componential materials were added in the following order:

- Mixtures P1, P2, P3, and P4: aggregate, cement, water, and superplasticizer;
- Mixtures P9, P10, P11, and P12: aggregate, crumb rubber (2.5 %), cement, water, and superplasticizer;
- Mixtures P17, P18, P19, and to P20: aggregate, crumb rubber (7.5 %), cement, water, and superplasticizer.

After homogenisation, cube-shaped samples with 150 mm-edge dimensions were casted (in moulds) and left to cure until testing time.

The mix-design of experimental concrete samples with marked quantities of raw materials used per mixture is provided in Figs. 4, 5, 6 and 7.

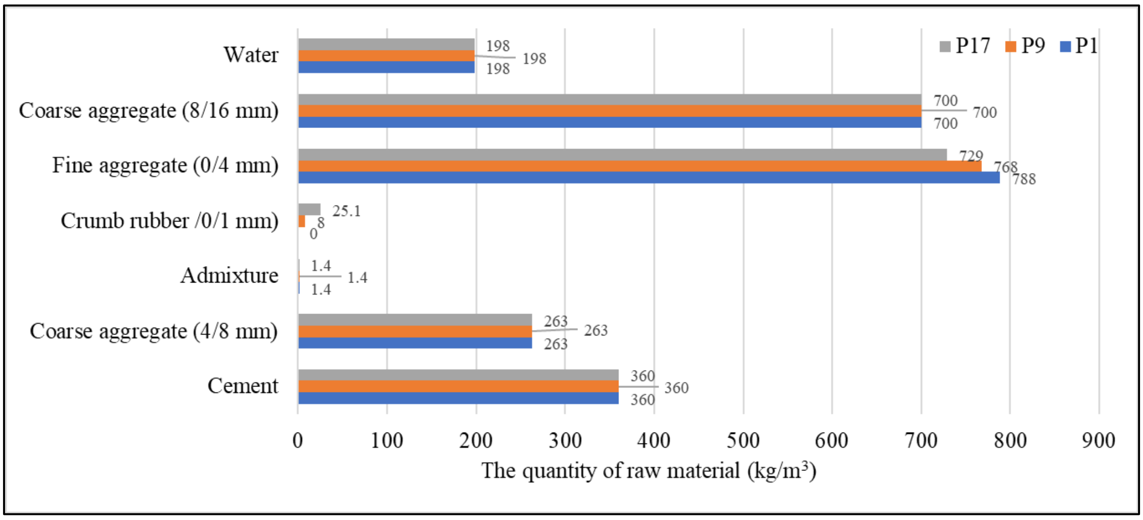


Fig. 4. Mix design of concrete samples P1, P9, and P17 (w/c=0.55).

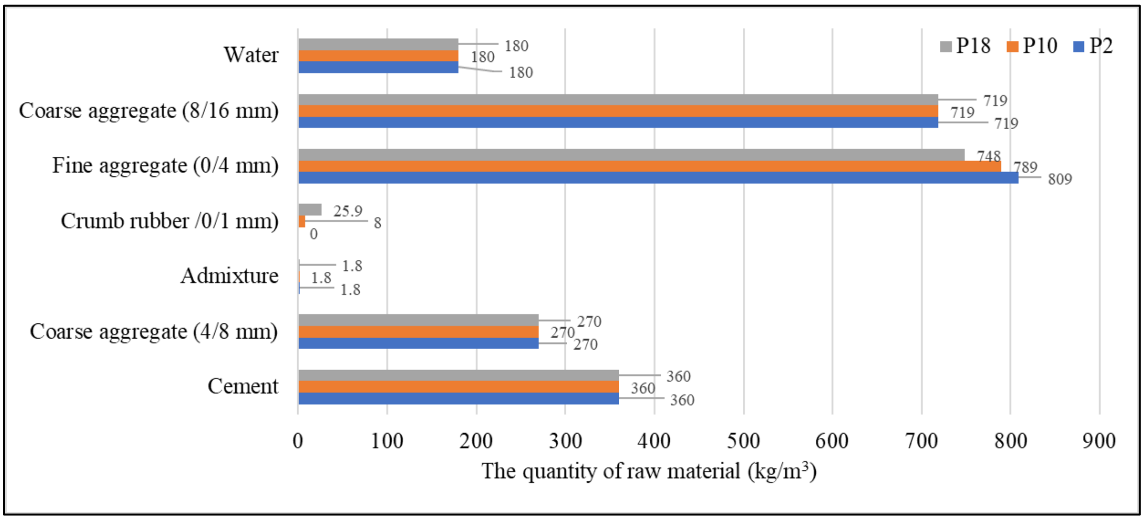


Fig. 5. Mix design of concrete samples P2, P10, and P18 (w/c=0.5).

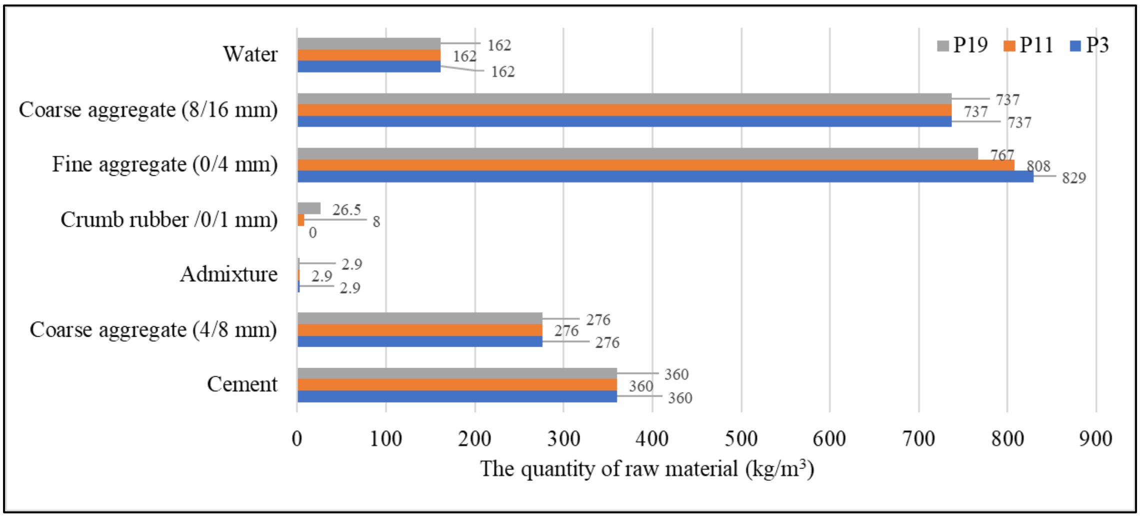


Fig. 6. Mix design of concrete samples P3, P11, and P19 (w/c=0.45).

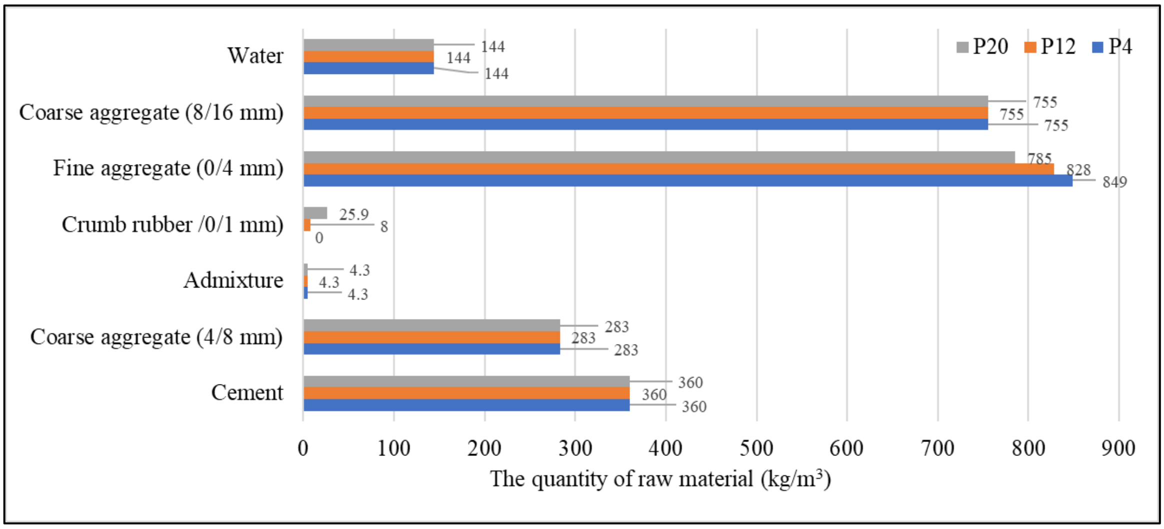


Fig. 7. Mix design of concrete samples P4, P12, and P20 (w/c=0.4).

2.3. Instrumental methods

Experimentally prepared concrete samples were tested on properties both in their fresh state and in their hardened state.

The concrete mixtures were designed to achieve a slump class of S4 (160–210 mm). The consistency of the mixture was tested using the slump test method. The fresh samples were tested 10 minutes after the addition of water to the mixture of raw materials. The amount of chemical admixture was varied in order to achieve a slump of 160–210 mm.

The following properties of concrete in a fresh state were tested: consistency via slump method in accordance with Standard SRPS EN 12350-2:2019 (Testing fresh concrete, Part 2: Slump test); air content in accordance with Standard SRPS EN 12350-8:2019 (Testing fresh concrete, Part 8: Self-compacting concrete, Slump-flow test); and bulk density in accordance with Standard SRPS EN 12350-6:2019 (Testing fresh concrete, Part 6: Density). Testing was conducted after 10, 30, and 60 minutes upon the addition of water to the dry mixture of component materials (showed in Fig. 8).

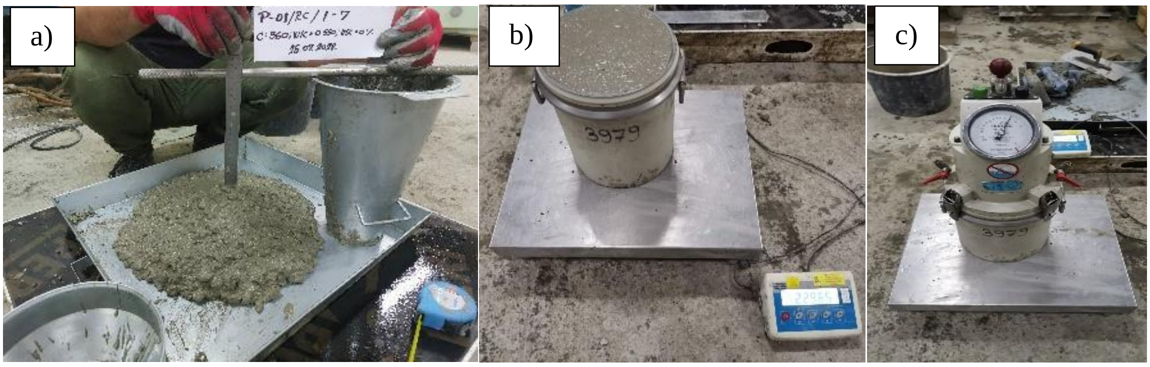


Fig. 8. Testing of the fresh concrete: a) consistency/slump test; b) bulk density; and c) air content.

Following the evaluation of the fresh concrete's characteristics, samples were moulded into cubes with an edge length of 150 mm. Subsequently, the specimens were immersed in water at a temperature of 20 °C until further testing on mechanical and physical properties (compressive strength and bulk density). The mechanical properties of the concrete were observed at three, seven, and twenty-eight-day intervals.

After curing in water for 3, 7, and 28 days, cube-shaped samples with edge dimensions of d=150 mm (Fig. 9a) underwent compressive strength measurements. A digital hydraulic press with a 3000 kN capacity (Fig. 9b) was used for the test. The rate of load progression was 0.6 MPa/s. The test was conducted on the concrete sample up to the force's maximum value. In every sample, the fracture has a consistent form. This test was carried out in compliance with SRPS EN 12390-3:2021 (Testing hardened concrete - Part 3: Compressive strength of test specimens). A photograph of the crushed sample is given in Fig. 9c.

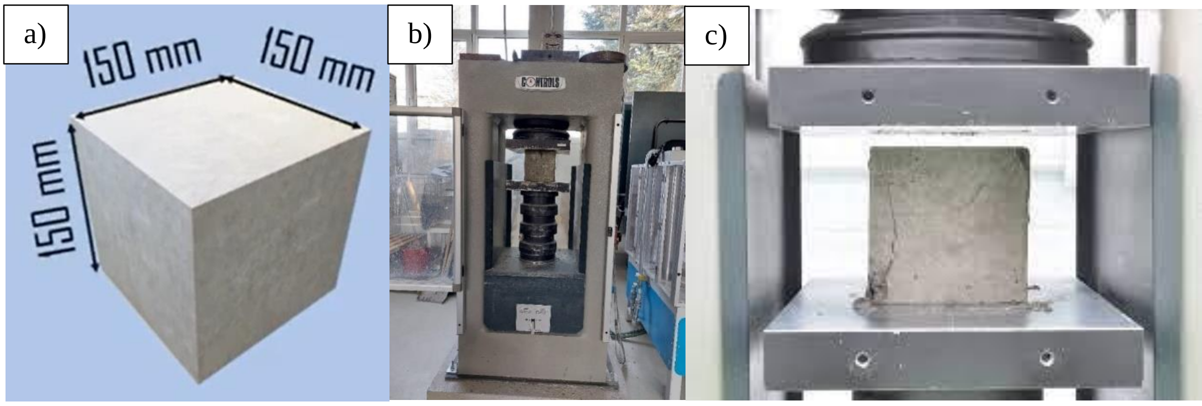


Fig. 9. Compressive strength: a) dimensions and shape of concrete sample; b) digital hydraulic press with 3000 kN capacity; and c) testing of the concrete specimen.

3. Results and discussion

3.1. Properties of fresh concrete

Fresh concrete properties were assessed using the slump test, air content, and bulk density. All mentioned properties were measured after 10, 30, and 60 minutes from the time of adding water to the mixture of dry raw materials for concrete preparation. Tests were conducted on ordinary concrete (OC) and rubberized concrete (RC) with 2.5% and 7.5% rubber, respectively.

Figures 10a–d depict the results of slump test, i.e. consistency of fresh concrete samples.

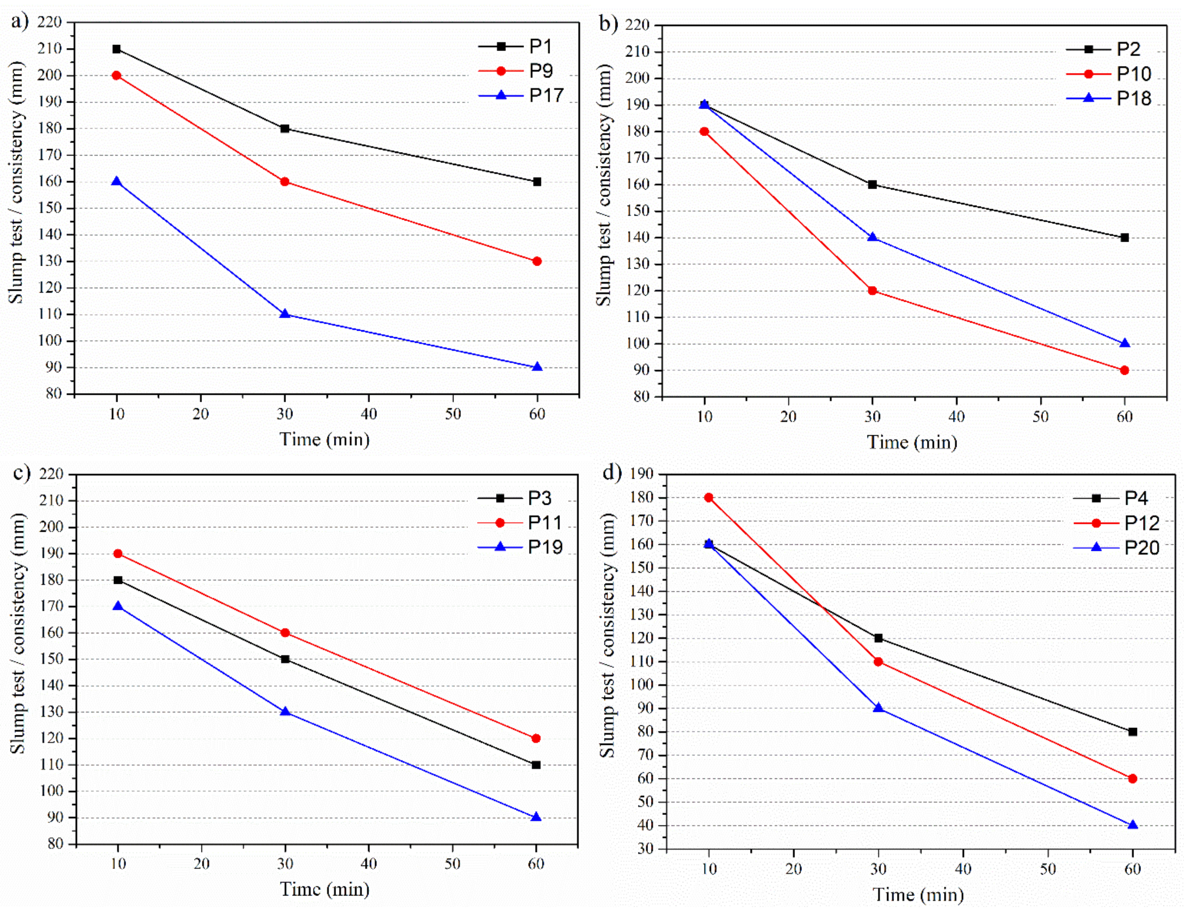


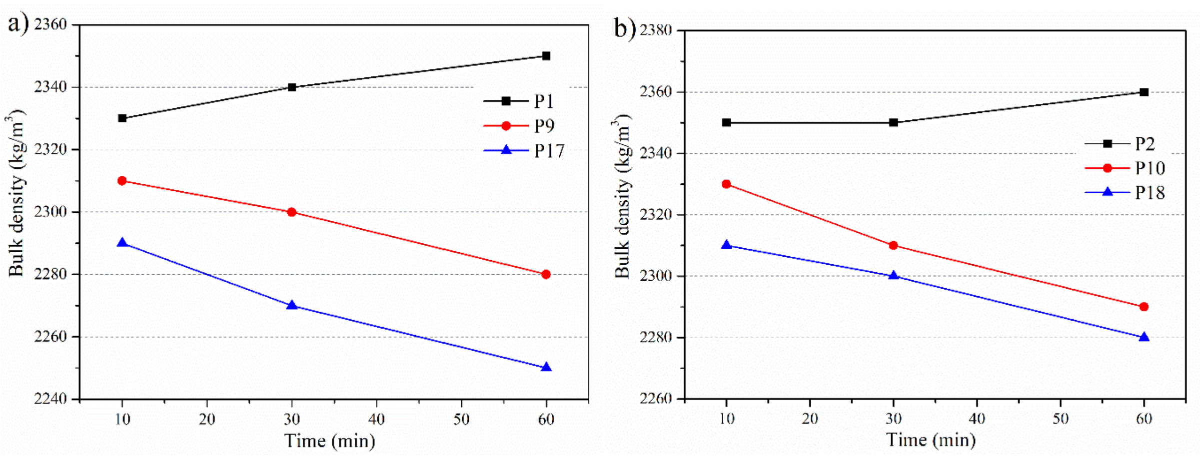
Fig. 10. Consistency of fresh concrete via slump test: a) OC-P1, RC-P9, and RC- P17 (w/c=0.55); b) OC-P2, RC-P10, and RC- P18 (w/c=0.5); c) OC-P3, RC-P11, and RC- P19 (w/c=0.45); and d) OC-P4, RC-P12, and RC-P20 (w/c=0.4).

In the case of w/c = 0.55, the consistencies of the concrete samples with CR addition (P9 and P17) were lower than the consistency of OC (P1) at all three measuring points in time (10, 30, and 60 min), as it can be seen in Fig. 10a. The consistency of RC-P10 (w/c = 0.5) was lower than that of ordinary concrete (P2), as it can be seen in Fig. 10b. Concrete P18 had the same starting consistency as P2 (at 10 minutes), but consistencies measured at 30 and 60 minutes were lower than that of P2. The third group of samples with w/c = 0.45 (Fig. 10c) showed the highest values of consistency which were obtained for the P11 sample. RC with 7.5% of rubber (P19) had lower consistency values than its ordinary concrete counterpart (P3). A similar disposition of obtained values was observed for the fourth group of concretes (Fig. 10d). This group had the lowest w/c ratio (0.4). It also exhibited comparatively lower values of consistencies in comparison with the three initial groups of concrete.

Most investigations [33–36] highlight the fact that workability (consistency of a fresh concrete) is decreasing as the amount of crumb rubber is increasing. This can be explained by the fact that highly hydrophobic and very light CR particles tend to "float," which results in the segregation of concrete. Alsaif et al. [37] discovered that the consistency of fresh concrete (tested using the slump method) deteriorated as the amount of CR increased due to the rough surface of the CR grains. Since there is more internal friction between the larger CR particles, moving fresh concrete is made difficult because more energy is required to overcome the friction [38]. Fine impurities (rubber dust) can also potentially impair the workability and mobility of fresh concrete [39, 40]. Because of the low bulk density of rubber, fresh concrete with CR also often has a lower bulk density than regular concrete. Namely, there is an inverse link between the bulk density of concrete and the amount of CR in the concrete. Thomas and Gupta [41] showed that high-strength concrete generated by replacing 2.5–20 % of the fine aggregate fraction with CR has a bulk density reduction of 0-9.6 % when compared to control concrete without CR. Su et al. [42] found that finer CR particles influence a certain reduction in the bulk density of the tested samples. In this experiment, the addition of crumb rubber led to a decrease in the consistency (workability) of fresh concrete over a period of 60 minutes. However, the addition of 2.5 % of crumb rubber particles improved workability in the case of a 0.45 w/c ratio.

According to the results obtained upon assessing the consistency of fresh concretes (P1-P4, P9-P11, and P17-P20) using the slump test method, it was observed that after 10 minutes of mixing, all tested concrete samples belong to consistency class S4 (160–210 mm). After 30 minutes, the consistency of the tested concrete is decreasing. Namely, concretes with w/c = 0.55, 0.50, and 0.45 belong to consistency classes S3 and S4 (obtained values vary from 130 to 180 mm), while concretes with w/c = 0.40 belong to consistency classes S2 and S3. After 60 minutes, the consistency of tested concrete is decreasing for all concretes, as they all belong to the consistency classes S2 and S3, except concretes with w/c = 0.40, which belong to the consistency classes S1-S2 (obtained values are from 40 to 80 mm).

Bulk densities in fresh state of ordinary concrete (OC) and rubber concrete (RC) with 2.5% and 7.5% rubber particles are presented in Fig. 11a-d.



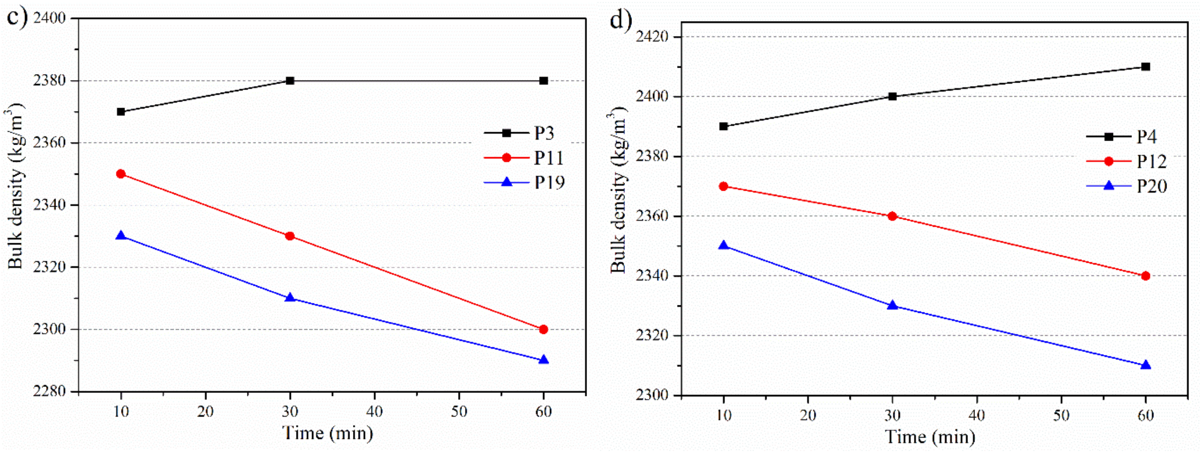
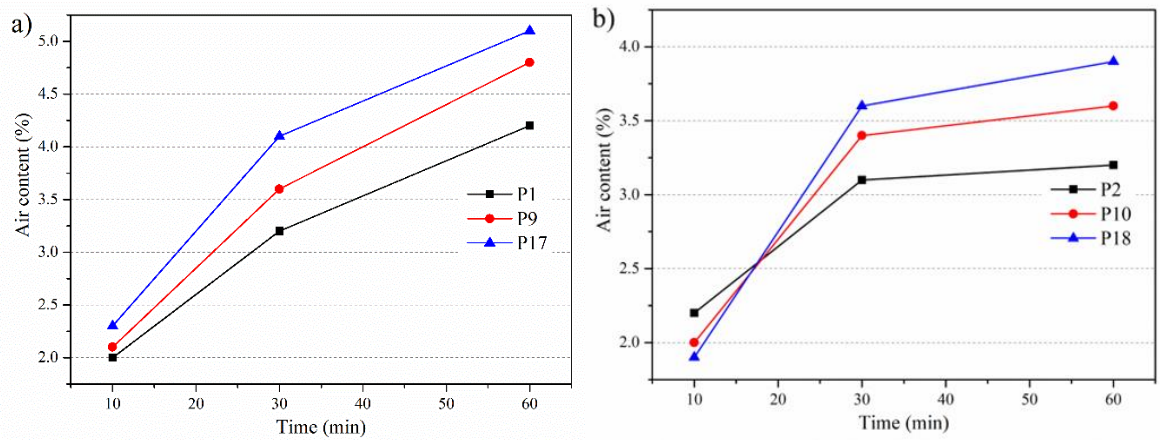


Fig 11. Bulk densities (in fresh state): a) OC-P1, RC-P9, and RC- P17 (w/c=0.55); b) OC-P2, RC-P10, and RC- P18 (w/c=0.5); c) OC-P3, RC-P11, and RC- P19 (w/c=0.45); and d) OC-P4, RC-P12, and RC-P20 (w/c=0.4).

When the bulk densities of fresh OC and RC concretes were compared to their regular concrete equivalents, it was found that all concrete samples containing rubber in 2.5 and 7.5 weight percent had bulk densities that were 20 to 40 kg/m^3 lower. After 10, 30, and 60 minutes from mixing the components, bulk densities for regular concrete (P1, P2, P3, and P4) exhibit a trend of increasing, while bulk densities for rubberized concrete (P9-P12 and P17-P20) are decreasing. Thereby, the addition of crumb rubber caused a decrease in bulk density. Concretes with 2.5% of CR addition had higher bulk densities than concretes with 7.5% of CR addition.

A number of factors, notably the air content, affect the bulk density of fresh concrete, which is an indicator of how compact the concrete mixture is. The bulk density of fresh concrete decreases as the air content increases and vice versa. Furthermore, the bulk density of fresh concrete increases as the water-to-cement ratio lowers (w/c = 0.55, 0.5, 0.45, and 0.40). During 60 minutes from adding water to the mixture, the bulk density values of the ordinary concrete increase for all w/c ratios. After 10, 30, and 60 minutes from the time water is added, the bulk density of fresh concrete drops for concrete with 2.5% of CR (P9, P10, P11, and P12) and 7.5% of CR (P17, P18, P19, and P20).

Measured air contents of ordinary concrete (OC) and rubber concrete (RC) with 2.5 % and 7.5 % of crumb recycled rubber are presented in Fig. 12a-d.



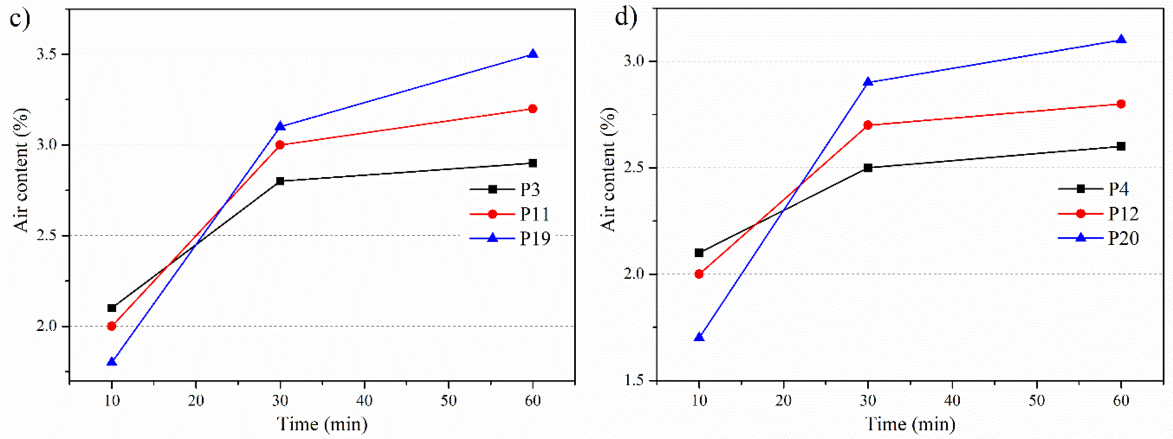


Fig 12. Air content: a) OC-P1, RC-P9, and RC- P17 (w/c=0.55); b) OC-P2, RC-P10, and RC-P18 (w/c=0.5); c) OC-P3, RC-P11, and RC- P19 (w/c=0.45); and d) OC-P4, RC-P12, and RC-P20 (w/c=0.4).

In the case of the first group of concrete samples (Fig. 12a), in which the w/c ratio is 0.55, rubberized concretes P9 and P17 have higher air content at all measuring time points (10, 30, and 60 min) than ordinary concrete (P1). When the w/c ratio is 0.5, rubberized concretes (P10 and P18) show lower values of air content than OC at 10 minutes. At 30 and 60 minutes, the air content of P2 is lower than those of P10 and P18 (Fig. 12b). The disposition of air content values on diagrams for concretes with w/c=0.45 and w/c=0.4 (Fig. 12c and Fig. 12d) are the same as in the previous case. Also, the air content values are decreasing with a decrease in the w/c ratio, meaning that the lowest air content values are achieved for concretes P4, P12, and P20.

Depending on the w/c ratio utilized, rubberized concrete with 2.5 % and 7.5 % of CR addition had a larger air content than regular concrete. For example, the increase in air content for concrete mixtures with w/c = 0.55 was 38 %, 71 %, and 105 % for P9 (2.5 % of CR); 83 %, 129 %, and 155 % for P10 (7.5 % of CR). In contrast to the results obtained in concrete combinations with w/c = 0.55, the air content decreases for the remaining concrete mixtures with 2.5 % and 7.5 % of CR and with w/c = 0.5, 0.45, and 0.4. The friction between the cement paste and the rubber particles, which have air micropores, is thought to be the reason for the increased air content in fresh concrete. Using the RapidAir 457 digital microscope on hardened concrete samples, this assumption will be evaluated in further research. The approach given in SRPS EN 480-11 standard (Admixtures for concrete, mortar and grout - Test methods - Part 11: Determination of air void characteristics in hardened concrete) will be used to validate the total air content and micropore spacing.

3.2. Properties of hardened concrete

Bulk density of concrete in its hardened state determines how effectively the mechanical performances and strength of the obtained samples are related to one other. The calculated volume mass values provide an estimate of the mechanical characteristics of the hardened concrete and give an insight at the internal porosity of the concrete structure. The bulk density of hardened concrete (measured in dry condition) was monitored for a period of 3, 7, and 28 days, as shown in Figures 13a–d.

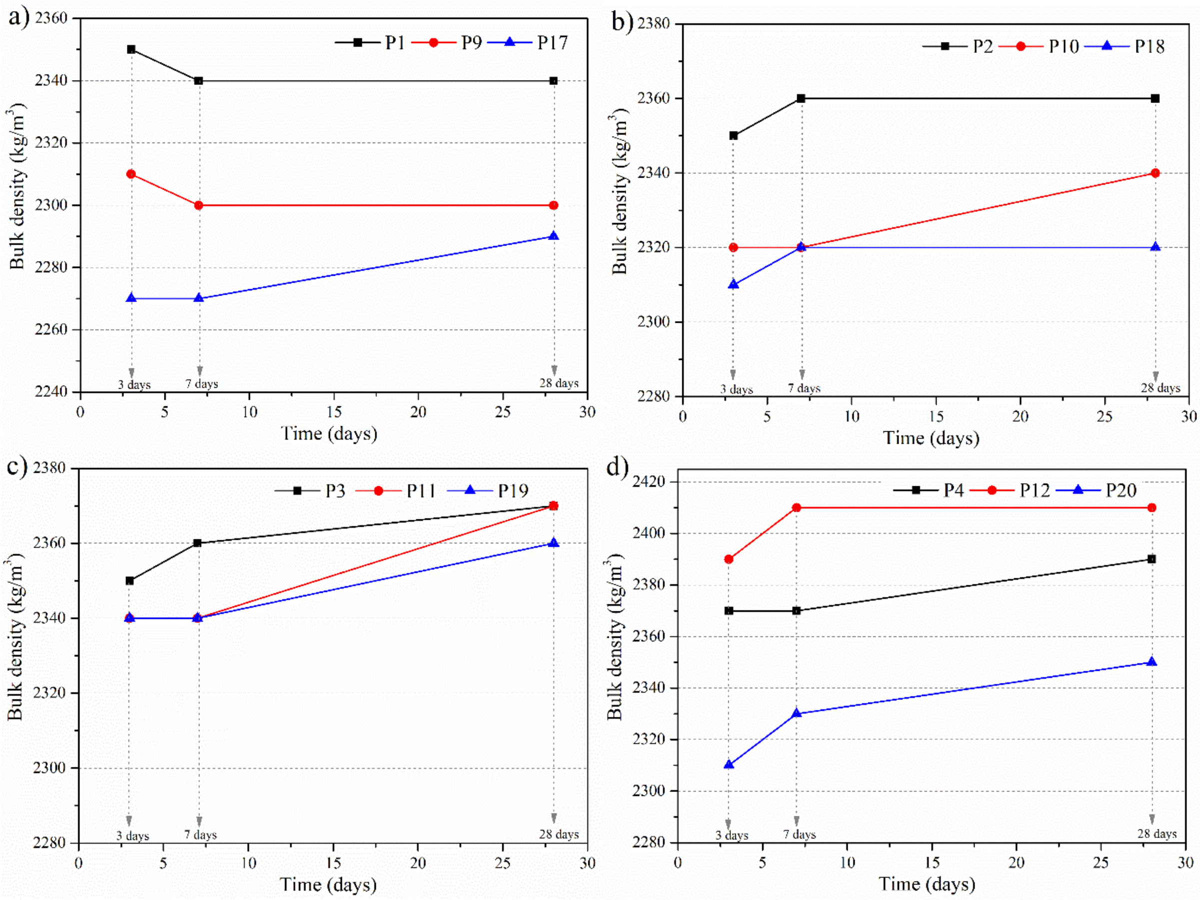


Fig 13. Bulk densities (in hardened state): a) OC-P1, RC-P9, and RC- P17 (w/c=0.55); b) OC-P2, RC-P10, and RC- P18 (w/c=0.5); c) OC-P3, RC-P11, and RC- P19 (w/c=0.45); and d) OC-P4, RC-P12, and RC-P20 (w/c=0.4).

The overall bulk density values of ordinary concrete (P1, P2, and P3) were higher than those of rubberized concrete, except in the case of P4. Bulk densities of P12 (RC with 2.5% of crumb rubber addition) were higher than bulk densities for ordinary concrete measured at 3, 7, and 28 days. For w/c = 0.55 (Fig. 13a), bulk density values of P1 and P9 decreased from the 3rd to the 7th day and then remained the same until the 28th day. The bulk density of P17 did not change during the initial seven days. Later, it showed an increasing trend and reached its maximum on the 28th day. In the case of w/c = 0.5 (Fig. 13b), bulk densities of P2 and P18 increased from the 3rd to the 7th day, after which they remained constant. Concrete P10 exhibited the same bulk density values for the initial 7 days. Its bulk densities started to increase afterwards. The bulk density of OC-P3 (Fig. 13c) showed an increasing trend during the entire 28-day period. RC-P11 and RC-P19 exhibited an increase in bulk density values after the 7th day of curing. Reversely, bulk density values of P4 started increasing after the seventh day (Fig. 13d). Bulk densities of rubberized concrete P20 showed a trend of increasing during the entire 28-day period. Bulk density values of P12 increased during the initial 7-day period and then remained constant.

The decrease in bulk density values upon the addition of crumb rubber is in agreement with the literature. For instance, authors [43] that investigated the properties of concrete, which included three different proportions of CR (2.5 %, 5.0 %, and 7.5 %) in place of fine aggregate, registered a decrease in bulk densities for all three concrete compositions with CR. In the mentioned investigation, the size distribution of the CR particles was 2–4 mm, with a water-to-cement ratio of w/c = 0.5. It was highlighted that an increase in the amount of crumb rubber induced a decrease in bulk density and consequently, a decrease in the compressive strength of each concrete sample. Thereby, rubber applied as a sand replacement was assumed to be the source of the compressive strength decrease because CR has a smaller bulk density than sand. Furthermore, the same authors [43] found that the interphase transition zone (ITZ) between cement mortar and rubber particles was weaker than the same zone between cement mortar and natural aggregates. The difference in stiffness between the cement and rubber particles generates a significant stress concentration at the ITZ, leading to the formation of microcracks.

Experimentally prepared concrete samples were tested for compressive strength after 3, 7 and 28 days of curing. The acquired results are presented as diagrams in Figures 14a-d.

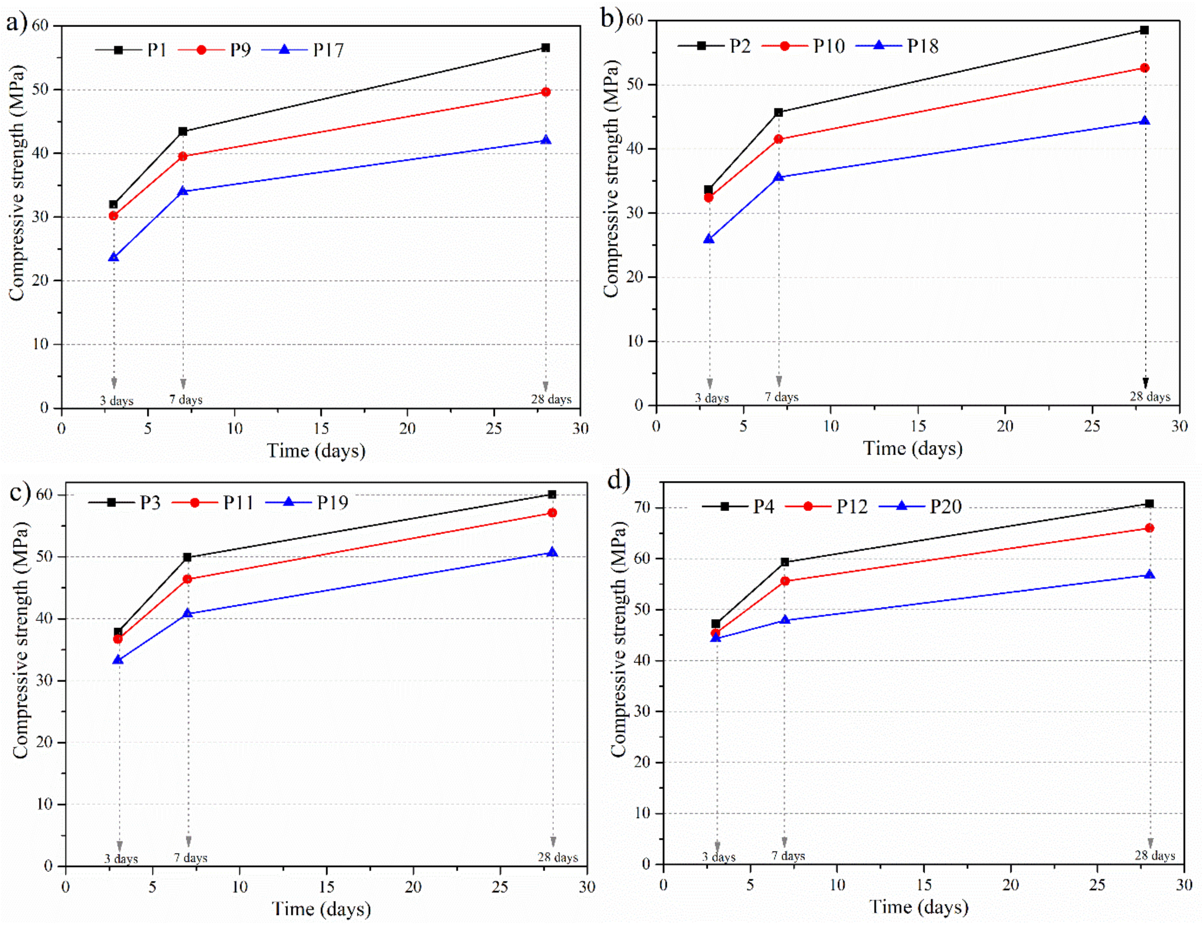


Fig 14. Compressive strengths: a) OC-P1, RC-P9, and RC- P17 (w/c=0.55); b) OC-P2, RC-P10, and RC- P18 (w/c=0.5); c) OC-P3, RC-P11, and RC- P19 (w/c=0.45); and d) OC-P4, RC-P12, and RC-P20 (w/c=0.4).

The compressive strengths of all experimentally produced concretes increased over a period of 28 days, as it was expected. Thereby, the addition of fine-sized rubber did not interfere with the binding agent (cement) or caused a retardation in the hydration route and mechanism. Crumb rubber is inert, and it does not participate in cement chemistry processes. The compressive strength values for ordinary concrete (P1–P4 samples) were higher than those of rubberized concretes (Fig. 14a–d). Initial, 3-day strengths were similar for P1 and P9, P2 and P10, and P3 and P11 samples, respectively. In the case of w/c ration 0.4, all three samples (P4, P12, and P20) have similar values for initial compressive strengths.

The final compressive strengths achieved for ordinary and rubberized concretes were as follows: 56.6 MPa and 49.6 MPa for P1 and P9, respectively; 58.5 MPa and 52.6 MPa for P2 and P10, respectively; 60.1 MPa and 57.1 MPa for P3 and P11, respectively; and 70.8 MPa and 66 MPa for P4 and P12, respectively. Thereby, rubberized concretes with a 2.5 % addition of CR (P9, P10, P11, and P12) exhibited a very small decrease in compressive strength in comparison to ordinary concrete. The difference was 13%, 11 %, 5 %, and 7 % for P9, P10, P11, and P12 concretes, respectively. According to the obtained compressive strength values, all of these experimentally designed rubberized concretes belong to a group of structural concretes.

Fig. 15 illustrates compressive strengths measured after 28 days as a function of the water-to-cement ratio for ordinary concrete (OC) and rubberized concrete (RC) with 2.5 % and 7.5 % of crumb rubber addition, respectively.

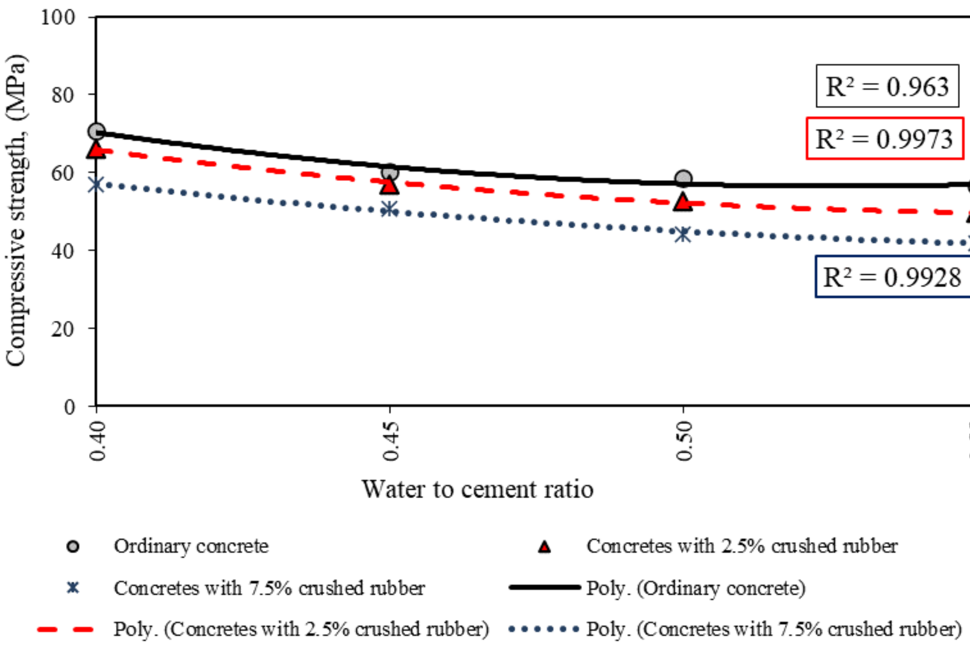


Fig. 15. Compressive strength at 28 days as a function of the w/c ratio.

From Fig. 15, it can be seen that an increase in the water-to-cement ratio causes a decrease in the final 28-day strength. An increased amount of water in the mix design leads to increased porosity and microstructural voids that are not ideal for the development of high-strength construction materials.

4. Conclusions

The reference ordinary concretes (P1-P4) used in this investigation were prepared with a water-to-cement ratio of w/c=0.55, 0.5, 0.45, and 0.4. The physico-mechanical properties of concrete specimens made with 2.5 % (P9-P12) and 7.5 % (P17-P20) replacement of the fine aggregate with recycled crumb rubber (CR) were mutually compared and juxtaposed to ordinary concrete samples. It was determined that a fine aggregate fraction in concrete can be successfully substituted with waste raw material such as recycled crumb rubber. Other main conclusions are summarized below:

- The addition of crumb rubber led to a decrease in the consistency (workability) of fresh concrete over a period of 60 minutes. However, the addition of 2.5 % of crumb rubber particles improved workability in the case of mix-design with a 0.45 w/c ratio.
- The air content values are decreasing with a decrease in the w/c ratio, meaning that the lowest air content values are achieved for concretes P4, P12, and P20. Depending on the w/c ratio utilized, rubberized concrete with 2.5 % and 7.5 % of CR addition had a larger air content than regular concrete.
- The addition of crumb rubber caused a decrease in bulk density (in fresh state). Concretes with 2.5 % of RC addition had higher bulk densities than concretes with 7.5 % of CR addition.
- The overall bulk density values of ordinary concrete (P1, P2, and P3) were higher than those of rubberized concrete, except in the case of P4. Bulk densities of P12 (RC with 2.5 % of crumb rubber addition) were higher than bulk densities for ordinary concrete measured at 3, 7, and 28 days.
- The final compressive strengths achieved for ordinary and rubberized concretes were in range from 49.6 MPa to 70.8 MPa. Rubberized concretes with a 2.5 % addition of CR (P9, P10, P11, and P12) exhibited a very small decrease in compressive strength in comparison to ordinary concrete. The difference was 13 %, 11 %, 5 %, and 7 % for P9, P10, P11, and P12 concretes, respectively.
- According to the obtained compressive strength values, all of these experimentally designed rubberized concretes belong to a group of structural concretes (concrete structural elements in residential construction and prefabricated concrete elements such as curbs, slabs, sound insulation panels, etc.).

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5. References

1. A. Mohajerani, L. Burnett, et al., Resour. Conserv. Recycl. 155 (2020) 104679.
2. European Commission https://ec.europa.eu › statistics-explained › index.php (Accessed 24.04.2024)
3. https://leap.unep.org/en/countries/rs/national-legislation/regulation-manner-and-procedure-waste-tire-management (Accessed 24.04.2024)
4. X. Shu, B. Huang, Constr. Build. Mater. 67 (2014) 217.
5. S. Surehali, A. Singh, et al., Develop. Built Environ. 14 (2023) 100171.
6. Y. Li, J. Chai, et al. Buildings 12 (2022) 1975.
7. A. Singh, S.N. Spak, et al. Atmos. Environ. 104 (2015) 273–283.
8. P.T. Lekkas. Discarded Tyre Rubber as Concrete Aggregate: A Possible Outlet for Used Tyres. https://journal.gnest.org/publication/617. (Accessed 24.04.2024)
9. M. Sheraz, Q. Yuan, et al. SN Appl. Sci. 5 (2023) 119.
10. V. H. Nanjegowda, K. P. Biligiri, Resour. Conserv. Recycl. 155 (2020) 104655.
11. A. Al-Attar, H. M. Hamada, et al. Mater. Today Proc. 53 (2022) A1–A17.
12. M. Ul Islam, J. Li, et al. J. Clean. Prod. 374 (2022) 133998.
13. L. Liu, C. Wang, et al. J. Clean. Prod. 392 (2023) 136270.
14. S. Kazmi, M. Munir, Y. Wu Resour. Conserv. Recycl. 167 (2021) 105353.
15. A. Bala, S. Gupta, Construct. Build. Mater. 299 (2021) 123939.
16. B. Angjusheva, V. Ducman, E. Fidanchevski, Sci. Sint. 54 (2022) 359.
17. A. Richardson, K. Coventry, G. Ward, J. Clean. Prod. 23 (2012) 96.
18. S. Martinović, M.Vlahović, T. Volkov Husović, Sci. Sint. 55 (2023) 71.
19. B. Thomas, R. Gupta, Energy Rev. 54 (2016) 1323.
20. H. Zhu, J. Liang, et al. Construct. Build. Mater. 189 (2018) 42–53.
21. A. Abou-Chakra, G. Blanc, et al. Mater. Today Commun. 35 (2023) 105750.
22. M. Liu, J. Lu, et al. J. Build. Eng. 65 (2023) 105718.
23. P. Meyyappan, A. Selvasofia, et al. Mater. Today Proc. 74 (2023) 985.
24. H. Li, W. Long, et al. Cem. Concr. Compos. 138 (2023) 104963.
25. V. González Molina, A. Parra Parra, P. Antonio Márquez, et al., Sci. Sint. 54 (2022) 249.
26. Y. Zhu, et al. Cem. Concr. Compos. 35 (2013) 32.
27. M.K. Ismail, A.A.A. Hassan, ACI Mater J, 114 (2017) 581.
28. K. Strukar, T. Kalman Šipoš, I. Miličević, R. Bušić, Eng Struct 188 (2019) 452.
29. P.K. Dehdezi, S. Erdem, M.A. Blankson, Compos B Eng, 79 (2015) 451.
30. Z. Ghizdăveț, B.M. Ștefan, D. Nastac, O. Vasile, M. Bratu, Constr Build Mater, 124 (2016) 755.
31. I. Mohammadi, H. Khabbaz, K. Vessalas, Constr Build Mater 71 (2014) 456.
32. A. Kashani, T. D. Ngo et al. Construct. Build. Mater. 171 (2018) 467.
33. G. Yang, X. Chen, S. Guo, W. Xuan, KSCE J Civ Eng, 23 (2019) 3669.
34. F. Hossain, M. Shahjalal, K. Islam, M. Tiznobaik, M. Alam, Const. Build. Mater 225 (2019) 983.
35. B. Abdel Aleem, A. Hassan, Constr Build Mater, 229 (2019) 116861.
36. O. Onuaguluchi, D.K. Panesar, J Clean Prod, 82 (2014) 125.
37. A. Alsaif, L. Koutas, S. Bernal, M. Guadagnini, K. Pilakoutas, Constr Build Mater 172 (2018) 533.
38. G. Ossola, A. Wojcik, Cement Concr Compos. 52 (2014) 34-41.
39. X. Jin, X. Yang, Y. Jiang, Y. Li, Constr. Build.Mater. 427 (2024) 136234.
40. Z. Chen, L. Li, Z. Xiong, J Clean Prod 209 (2019) 1354.
41. B.S. Thomas, R. Chandra Gupta, J Clean Prod, 113 (2016) 86.
42. H. Su, J. Yang, T.C. Ling, G.S. Ghataora, S. Dirar, J Clean Prod, 91 (2015) 288.

43. S. Salehuddin, N. Rahim, N. Ibrahim, S. Tajri, M. Abidin, Appl Mech Mater, 754 (2015) 427.

Сажетак: *Све већа количина отпадних аутомобилских гума постаје озбљан еколошки проблем. Током протеклих деценија, рециклирана гума је темељно проучавано ради употребе у системима за хидроизолацију и као сировина за производњу асфалта. Глобално, бетон је најраспрострањенији грађевински материјал. Око 7% емисије* CO_2 *настаје из производње цемента. Сврха овог истраживања је да се процени да ли је изводљиво коришћење комбинације рецилиране аутомобилске гуме и Портланд цемента као композитног материјала за примену у грађевинарству. Отпадне аутомобилске гуме (уситњене на 0/1 mm) коришћене су као замена за фини агрегат (у 2,5 и 7,5%), заједно са Портланд цементом и природним каменом као агрегатом. Испитивање својстава у свежем (тест слегања, запреминска маса, садржај ваздуха) и очврслом стању (насипна густина, чврстоћа на притисак) спроведено је на узорцима бетона са додатком отпадне гуме. Чврстоћа на притисак се смањила повећањем садржаја гуме за све коришћене водо-цементне факторе (0,55-0,4). Додатак гуме финих димензија зрна није узроковао успоравање механизма хидратације. Према добијеним вредностима притисне чврстоће сви експериментално пројектовани бетони са додтаком рециклиране гуме спадају у групу конструктивних бетона.*

Кључне речи*: Грађевински материјал; Алтернативне сировине; Рециклажа; Цементни композит; Отпадна гума; Физичко-механичка својства.*