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Mechanical properties of cement-based composites incorporating eco-friendly aggregate of waste rubber

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Abstract: The purpose of this study is to evaluate the waste tires that harm the environment as aggregate in concrete and to examine the effect on the mechanical properties of concrete. Three different classes (powder, crumb and chips) of waste rubber with seven different ratios (0%, 4%, 8%, 12%, 16%, 20% and 24%) and two different water to cement ratio (0.4 and 0.5) were used in concrete production. In this regard, this study conducted various experiments consisting of 28 and 90 days of the curing process to determine the properties of unit weight, compressive, flexural, and splitting tensile strength, along with ultrasonic pulse velocity (UPV) and dynamic modulus of elasticity. The waste rubber concrete with the highest compressive strength at the end of 90 days is the concrete that includes 4% waste rubber (0.4WR4) with 58.81 MPa. Concrete containing 8% waste rubber has the highest UPV of 5660 m/s after 90 days. The increase in the water/cement ratio from 0.4 to 0.5 and the waste rubber ratio cause deterioration in the mechanical properties of concrete. Although the use of waste rubbers does not bring an increase in strength, it is feasible to produce high strength concretes with 4% and 8% waste rubber substitution ratios. The water/cement ratio and curing time were highly effective on the mechanical properties of rubberized concrete.

Keywords: Rubberized concrete, compressive strength, ultrasonic pulse velocity, flexural strength, splitting tensile strength.

1. Introduction

Every year, millions of tires create a non-negligible amount of solid that is not biodegradable waste in the environment, which poses serious problems worldwide (Pelisser et al., 2011; Yung et al., 2013; Aslani, 2016). Waste rubber is one of the most important wastes, leading to serious environmental problems in the world (Qaidi et al., 2021). The annual world tire waste exceeded 2.9 billion in 2017, solid proof of the severe problems tires cause (Siddika et al., 2019). The automobile industry alone disposes of 1 billion tires as solid waste each year because of the short life cycles of tires (Thakare et al., 2021). By the end of 2030, around 1.2 billion tires will be disposed of annually worldwide (Azevedo et al., 2012). Most of the tire waste is kept in landfills. This poses a grave threat to the environment. Furthermore, the increasing solid waste in landfill sites may also cause firedamp explosions and mosquito outbursts around their vicinities (Siddique and Naik, 2004; Thomas and Gupta, 2015; Figueiredo et al., 2017; Mundo et al., 2018; Hamdi et al., 2021).

Dumping scrap tire wastes into the environment gives rise to severe problems in different ecosystems (Bala and Gupta, 2021). That is because rubber, the recycled material obtained from tire wastes, is steel wires, fine powder, crumb rubber, small chips and other carbon-based products (Ferdous et al., 2021). However, there are potential solutions to minimize the negative effects of tire waste on the environment. One of the most effective solutions is to "upcycle" these wastes in the forms such as crumbs or shredded rubber in construction and other industries (Shu and Huang, 2014; Bideci et al., 2017; Gheni et al., 2017; Bušić et al., 2018; Pham et al., 2018; Alaloul et al., 2021). These materials are used in the building industry as substitutes for natural aggregates used in concrete production (Guo et al., 2014; Onuaguluchi and Panesar, 2014; Elchalakani, 2015; Thomas and Gupta, 2016; Záleská et al., 2019).

The most important factor motivating researchers to focus on potential applications of disposed tires in the concrete industry is the environmental damage caused by the large number of tires released each year (Li et al., 2019). Researchers have recently investigated different application areas for recycled rubber particles in concrete production. The concrete produced using recycled rubber particles is referred to as rubberized concrete (RC) (Alam et al., 2015; Li et al., 2016; Rashad, 2016; Girskas and Nagrockienė, 2017; Xu et al., 2020). RC is concrete containing rubber particles from disposed tires. The wasted tires are replaced here with coarse and fine aggregates (Eltayeb et al., 2021). During the process, tire wastes are recycled in varying sizes, classified as chips rubber (>4mm), crumb rubber (0.5mm – 4mm), and powder rubber (<0.5mm) (Thakur et al., 2020). Researchers have carried out various studies to enhance the behavior of the RC by taking into consideration particle size and the amount of rubber particles (Khaloo et al., 2008; Mohammadi et al., 2016; Bompa et al., 2017; Mendis et al., 2017; Bisht and Ramana, 2019; Mohajerani et al., 2020). The strength of RC decreases with the growing percentage of rubber particles with limited rubber content substituting for building applications (Snelson et al., 2009; Son et al., 2011; Pacheco-Torgal et al., 2012; Gupta et al., 2016; Raffoul et al., 2016; Mousavimehr and Nematzadeh, 2019; Yang et al., 2019). Moreover, the rubber particles' size and texture impact the rubberized concrete's performance since it remarkably affects bonding with the cement paste (Aliabdo et al., 2015; Meddah et al., 2017; Pacheco-Torres et al., 2018; Angelin et al., 2019). In this respect, numerous studies in the literature investigate the impacts of using rubbers as either coarse or fine aggregate in concrete (Guíñez et al., 2024). In previous studies where waste materials were used in concrete production, Keerio et al. (2020) investigated concrete properties by using silica fume instead of cement and fine aggregate instead of waste glass. As a result, it has been reported that the best option for optimum strength is concrete using 10% silica fume instead of cement and 30% waste glass instead of fine aggregate. On the other hand, the number of studies focusing on concrete produced by simultaneously substituting coarse and fine aggregate with tire waste is limited (Aslani and Khan, 2019).

The rubber in the waste tires is used in electricity generation after undergoing a number of processes, and the steel parts are recycled. While the waste tire is divided into parts, some of the rubber and steel in the tire cannot be separated and are directly thrown into the environment. The study aims to prevent this material, which is a direct waste, from polluting the environment and to examine its effect on concrete by using it as an aggregate. In the building industry, waste tires can be used in roof and facade coatings, road construction and floor coverings, concrete and lightweight concrete production. In this direction; different from most studies in the literature, this study has a unique aspect: it uses wasted rubber in three different particle size classes (powder, crumb, and chips) in the concrete instead of coarse and fine aggregates. In the study, various experiments measure the engineering properties of UPV, unit weight, compressive, flexural and splitting tensile strength, and dynamic modulus of elasticity for concretes produced with two different water-to-cement ratios (0.4-0.5) and seven different waste rubber ratios (0%, 4%, 8%, 12%, 16%, 20%, 24%). The curing duration is 28 and 90 days. Furthermore, the study compares the results of UPV-unit weight, flexural strength-compressive strength, compressive strength-splitting tensile strength, and results for each concrete consisting of different water/cement plus waste rubber ratios.

1.1. *Research significance*

Studies in the literature show that chips, crumbs and powder are used alone as aggregates. However, the unique aspect of this study is the use of waste tire rubbers of three different sizes at the same time by substituting them in concrete. Another unique point of the study is that rubber obtained entirely from waste vehicle tires is used as aggregate in concrete production. In other words, in this study, unlike other studies, it was thought that some steel wires contained in waste rubbers may have an effect on the mechanical properties of rubberized concrete. Finally, it aimed to increase the originality of the study by using

0.4 and 0.5 water/cement ratios to see how the water/cement ratio, one of the most important parameters of concrete, affects the mechanical properties of rubberized concrete.

2. Materials and methods

2.1. *Materials*

Portland cement classified as CEM I 42.5 R according to TS EN 197-1 (2012) standard utilizes in this study, and Table 1 displays the specific physical and chemical properties of this cement.

Table 1. Physical and chemical properties of cement.

	CEM I 42.5 R
Chemical compositions (%)	
SiO_2	19.42
Al_2O_3	4.53
Fe_2O_3	3.35
CaO	62.37
MgO	2.51
SO_3	3.04
Na_2O	0.40
K_2O	0.83
CI^-	0.007
Loss on ignition	2.94
Insoluble residue	0.60
Physical characteristics	
Residue on a 32-micron sieve	7.38
Specific gravity	3.10
Specific surface (cm^2/g)	3327
Beginning of setting	2hrs-28min
End of setting	3hrs-30min
Volume expansion (mm)	1.0
Compressive strength (MPa)	
2nd day	29.4
28th day	54.8

Limestone-based crushed stone and crushed sand are used as natural aggregates during concrete production. The properties of the aggregates are in Table 2.

Table 2. Properties of natural aggregates.

	Grain size (mm)	Specific gravity (g/cm^3)	Water absorption (%)
Coarse aggregate	4 – 16	2.66	0.62
Fine aggregate	0 - 4	2.64	0.65

The ideal granulometry curve was obtained according to TS 802 (2016) when coarse and fine aggregate were mixed half and half. The granulometry curve and limit curves of the aggregates are presented in Figure 1.

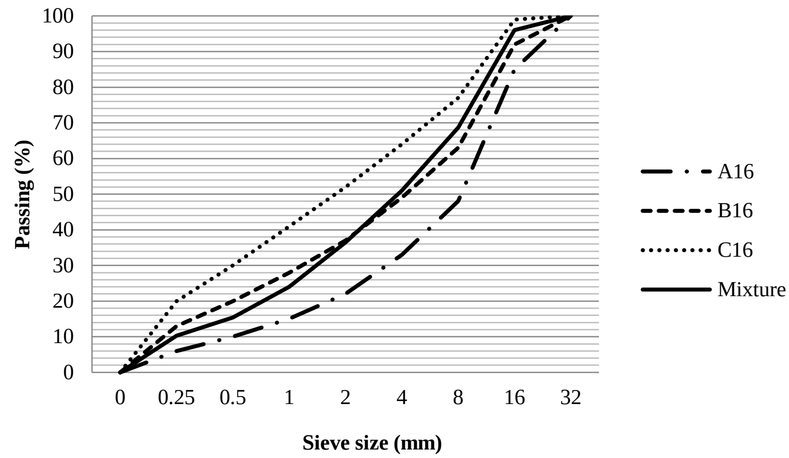

Figure 1. The granulometry curve of the mixture.

Waste tires, which were separated into chips, crumbs and powder, were used as aggregates in the production of rubberized concrete. The size of the chip rubber used instead of coarse aggregate in the study is between 5-16 mm. The dimensions of crumb and powder rubbers used instead of fine aggregate are 0.425-4.75 mm and 0.075-0.475 mm, respectively. Waste rubber has a specific gravity of 1.05 g/cm^3. The study utilized a Polycarboxylate ether-based superplasticizer (SP) (new generation) additive.

2.2. *Concrete design*

This study determined two different water-to-cement ratios, 0.4 and 0.5. In the study, for concrete with each water/cement ratio, 0%, 4%, 8%, 12%, 16%, 20% and 24% waste rubber by volume was used instead of natural aggregate. While selecting these ratios, preliminary experiments were carried out by taking into account the ratios in the literature. The use of waste rubbers at high rates (20% and 24%) was carried out in preliminary experiments. When waste rubbers are used higher than 24%, the workability of the concrete deteriorates and segregation occurs. Therefore, the maximum ratio was determined as 24%. While waste rubbers were used as aggregate, the granulometry curve of the mixture remained constant in each concrete. In this direction, for example, in concrete with 20% waste rubber, chips rubber was used instead of 10% coarse aggregate, and crumb and powder rubber were used by volume instead of 10% fine aggregate. In addition, 1%-3% by volume steel wire adhered to waste rubbers was used in production within the scope of the study. Control concrete is concrete that does not contain rubber aggregate and is represented by 0%. Concrete with 14 different contents was produced within the study's scope. A cement dosage of 400 kg/m^3 was used in all concrete production. Detailed information about concrete mix design and coding are given in Kandil and Bulut (2024).

2.3. *Testing of concretes*

Firstly, all the aggregates were mixed in the mixer for 1 minute. 3/4 of the cement and water were added and mixed for 3 minutes. SP and the remaining water were added to the mixture and all ingredients were mixed for 2 minutes. After the mixtures were compacted, they were placed in the molds. Then, the concretes removed from their molds after 24 hours got cured in water for 28 and 90 days.

The slump values of concrete were determined according to the ASTM C143/C143M (2020) standard. Besides, the unit weight test was performed according to the TS EN 12350-6 (2019) standard. All hardened concrete tests were conducted after 28 and 90 days of curing. The experiments regarding compressive strength determination were applied on cube samples of 15 cm size by the TS EN 12390-3 (2019) standard. The sample visual result of the compressive strength test is given in Figure 2.

Figure 2. Visual of the compressive strength test.

The flexural strength test was performed on 10x10x40 cm prismatic samples according to the TS EN 12390-5 (2019) standard. The center-point loading method was employed to identify the flexural strength of concretes. Subsequently, the splitting tensile strength test was implemented on 10x20 cm samples according to TS EN 12390-6 (2010) standard. Lastly, the UPV test got performed on cube samples of 15x15x15 cm. A transmitter and receiver probe was installed on the sample's parallel surfaces, and the sound's time interval was determined. The ultrasonic gel used UPV test provides an ambient that will enhance sound transmission to be continuous on the surface where the probe contacts the concrete. Then, the speed of sound through concrete was calculated by Equation (1) (Marie, 2016).

$$V=L/t \quad (1)$$

where L denotes the distance (0.15 m) traveled by the sound between the two probes, and t represents the sound transmission time experimentally measured in seconds. Lastly, V is the velocity of sound in m/s. The sample visual result of the UPV test is given in Figure 3. This UPV device used can give a ±17% margin of error in measurement results. Therefore, this situation should be taken into account when evaluating both UPV and dynamic elasticity modulus test results.

Figure 3. Visual of the UPV test.

After finding the ultrasonic pulse velocity of concretes and determining the average rates for each sample, the dynamic modulus of elasticity was calculated according to the ASTM C 597 (2016) standards. The formula displayed in Equation (2) (ASTM C 597, 2016) was utilized for calculating dynamic modulus of elasticity.

$$E_d = \frac{\rho V^2 (1+\mu)(1-2\mu)}{1-\mu} \quad (2)$$

In Equation (2), E_d represents the dynamic modulus of elasticity (MPa) of concrete and ρ denotes the density of concrete (kg/m^3). At the same time, V is the UPV (km/s), and μ is the Poisson's ratio of the concrete.

3. Experimental results and analysis

3.1. *Unit weight*

The unit weight of samples depending the concretes' water to cement and waste rubber ratios, and the outcomes are both in Figure 4 and Figure 5. The experimental results show that substituting waste rubber in the mixtures reduces the unit weights of the samples, regardless of water/cement ratios. Examining the concretes with a water to cement ratio of 0.4 (Figure 4) shown that the control concrete (0.4C) has the highest unit weight with 2410 kg/m^3, and the sample code with 0.4WR24 has the lowest unit weight with 2200 kg/m^3. As the water to cement ratio rises from 0.4 to 0.5, all unit weight values show a decrease.

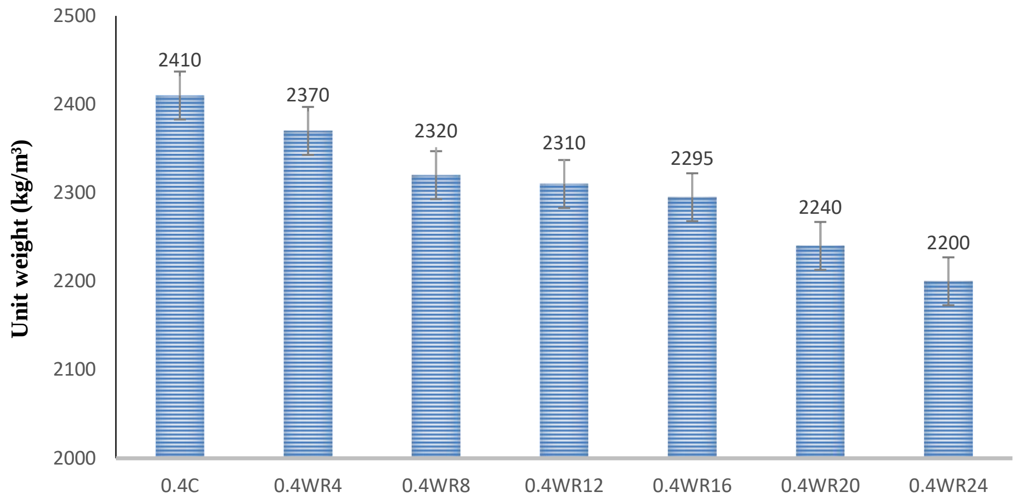

Figure 4. Effect of waste rubber substitution on unit weight of 0.4 w/c concrete.

Figure 5 displays that the highest unit weight value is 2380 kg/m^3. This value belongs to the control concrete (0.5C). On the other side, sample 0.5WR24 has the lowest unit weight value of 2110 kg/m^3, just as observed in the group with a water to cement ratio of 0.4. The percentage in weight losses took place up to 8.71% and 11.34% per unit weight, respectively, for water to cement ratios of 0.4 and 0.5 when adding differential rates of waste rubbers in concrete. Figure 4 and Figure 5 shows that the unit weight of concrete reduce inversely proportional to the waste rubber substitution ratio. In this regard, numerous studies in the literature point out similar results (Gesoğlu et al., 2014; Zhang et al., 2014; Ismail et al., 2016; Hassanli et al., 2017; Alsaif et al., 2018a; Ramdani et al., 2019; Stallings et al., 2019; Wang et al., 2019; Adeboje et al., 2020; Habib et al., 2020).

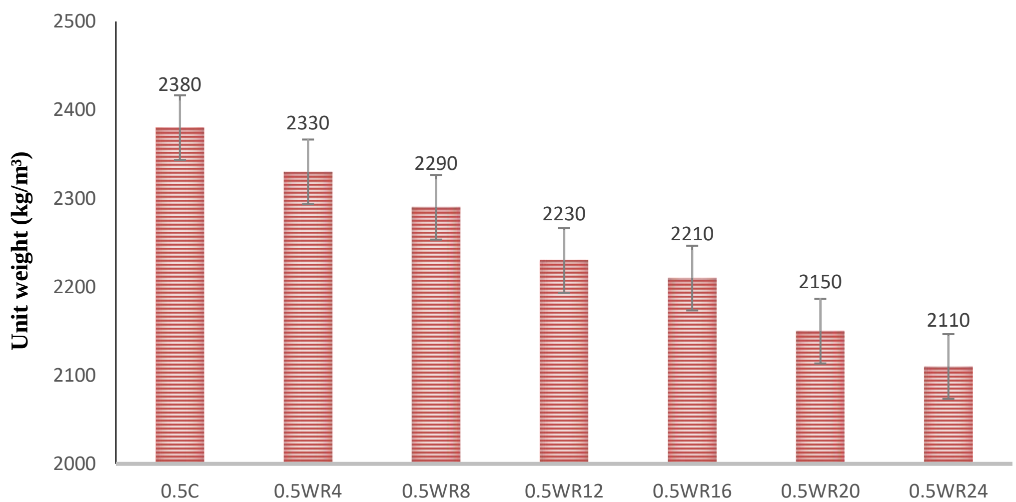

Figure 5. Effect of waste rubber substitution on unit weight of 0.5 w/c concrete.

The main reason for the decrease in unit weight values is that the specific gravity (1.05 g/cm^3) of waste rubbers substituted with natural aggregates is less than the specific gravity of normal aggregates (2.67 g/cm^3) (Gupta et al., 2014; Holmes et al., 2014; Lv et al., 2015; Moustafa and ElGawady, 2015; Bisht and Ramana, 2017; Assaggaf et al., 2021; Ferdous et al., 2021). Another reason is the decrease in the unit weight of concrete owing to air compression in the rough surface texture of waste rubbers (Khatib and Bayomy, 1999; Su et al., 2015). Besides, the unit weight values may decrease due to the hydrophobic behavior of the waste rubber and the very low adherence between the cement matrix and the rubber, which increases the porosity (Ganjian et al., 2009; Gonen, 2018). Studies also state that the decrease in the unit weight of fresh RC stems from the mixing time and the mixing system (Bravo and Brito, 2012; Güneyisi et al., 2016). This study also revealed that the water/cement ratio significantly affects the unit weight values of concretes with waste rubber (Kundan and Sharma, 2021). In fact, when 20% waste rubber was used in the concrete, a 4% reduce in unit weight value occurred due to the water to cement ratio increasing from 0.4 to 0.5.

3.2. *Compressive strength*

Figure 6 and Figure 7 shows the results of the compressive strength test. The concretes' compressive strength decreased for 28 days and 90 days with respect to the control. The strength loss increases with higher waste rubber substitutions into the production of concretes. Checking the samples with a water to cement ratio of 0.4 (Figure 6) demonstrates that the concrete with the highest 28-day compressive strength is the control concrete. The compressive strength of control concrete (0.4C) is 61.46 MPa. On the other side, sample 0.4WR24 has the lowest 28-day compressive strength, around 22 MPa.

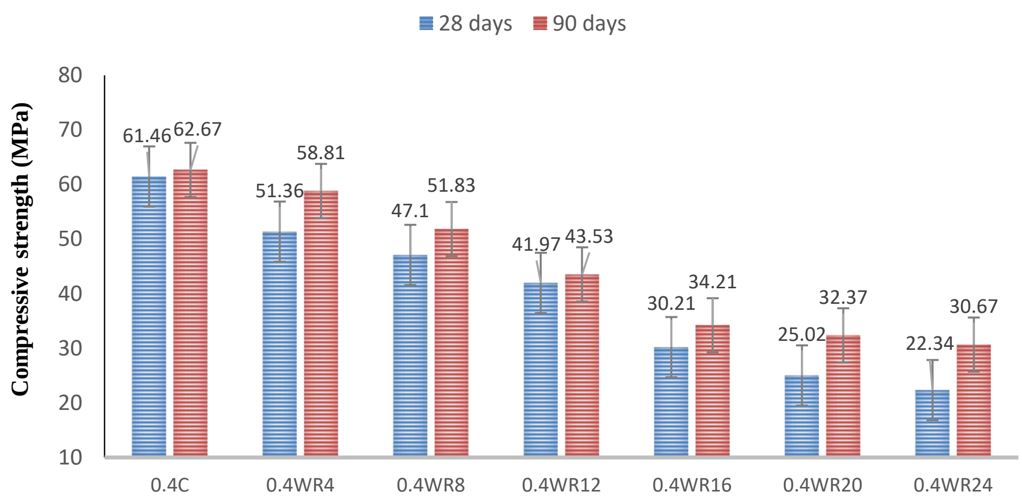

Figure 6. Effect of waste rubber substitution on compressive strength of 0.4 w/c concrete.

Examining the compressive strength values of the concretes shows approximately 51% to 64% strength loss occurred according to control concrete due to the rise in the waste rubber ratio up to 24%. Among the concretes produced using waste rubber, the concrete with the highest 28-day compressive strength has 51.36 MPa strength. This concrete is 0.4WR4 representing that the concrete has a 4% waste rubber substitute ratio. A similar trend is visible among the 90-day compressive strength results. This study specifically and uniquely reveals that high-strenght concretes of 50 MPa (and above) can be produced when 4% and 8% waste rubber ratios are used in concrete with a water to cement ratio of 0.4. Bisht and Ramana (2017) show the highest 28-day compressive strength is reached with the sample having a 4% crumb rubber substitute. The compressive strength amounts to 33 MPa in the 0.4 water/cement ratio. This study, deviating from the majority of the literature, utilized waste rubber as fine and coarse aggregate. As a result, the study shows the 28-day compressive strength value is even less than the sample 0.4WR12 with the same water to cement ratio of 0.4. The compressive strength of 0.4WR12 is 41.97 MPa. This study also shows that at the end of 90 days of curing, the compressive strength value obtained for sample 0.4WR4 is very close to the strength of the control when employing a 4% waste rubber substitution ratio. While the compressive strength of 0.4WR4 is 58.81 MPa, it is 62.67 MPa for the control concrete (0.4C), closing the difference in the 28-day results (10 MPa). Incorporating both water/cement ratios and curing duration parameters in regards to compressive strength values, the study results indicate that the ideal waste rubber ratio is 4%. As in Figure 7, the highest 28 and 90-day compressive strengths are 48.5 MPa and 51.49 MPa, respectively in the control concrete (0.5C).

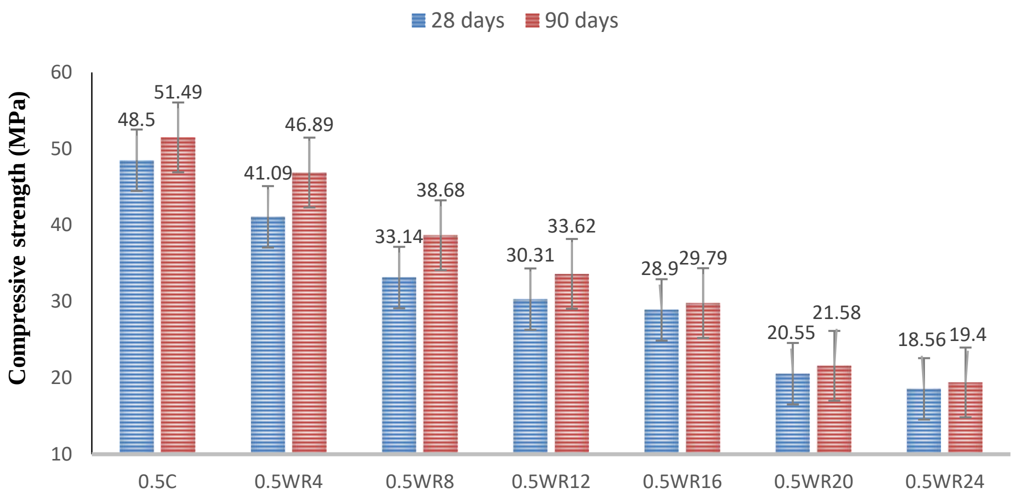

Figure 7. Effect of waste rubber substitution on compressive strength of 0.5 w/c concrete.

Beside, the lowest 28 and 90-day compressive strength values are 18.56 MPa and 19.4 MPa in sample 0.5WR24, respectively. It is similar to what has been observed in the group of concretes having a water to cement ratio of 0.4. Approximately 62% strength loss occurred for the rise in the waste rubber ratio up to 24%, in compressive strength of the concretes of a water to cement ratio of 0.5. Sample 0.5WR4 has the highest 28-day compressive strength among the concretes using waste rubber, and its compressive strength amounts to 41.09 MPa. Similar trends are also prevalent in the 90-day compressive strength results. All compressive strength values dramatically decreased as the water to cement ratio increased from 0.4 to 0.5. For instance, the 28-day compressive strength of sample 0.4WR8 is 47.1 MPa.

Plus, the compressive strength of sample 0.5WR8 decreases by approximately 30% and down to around 33.14 MPa. Moreover, the 90-day compressive strength of sample 0.4WR4 is 58.81 MPa, while this strength with sample 0.5WR4 concrete decreases by approximately 20%, down to 46.89 MPa. These results show the effect of the water to cement ratio on the compressive strength of waste rubber substituted concrete (Chen et al., 2019). Figure 6 and Figure7 displays that the compressive strength of samples goes down as the waste rubber ratio rises. Numerous studies focusing on the mechanical properties of concrete samples containing varying waste rubber ratios suggest that the compressive strength decreases with the rise in the rubber ratio (Dong et al., 2013; Dehdezi et al., 2015; Rivas-Vázquez et al., 2015; Salehuddin et al., 2015; Hesami et al., 2016; Marie, 2016; Aslani and Khan, 2019).

As for the decrease in the compressive strength of waste rubber substituted concrete samples, the prevalent idea is that rubber particles in the cement paste make it relatively softer than the conventional cement paste. The softening causes accelerated cracking while loading the rubber aggregates and ultimately leads to rapid deterioration of the concrete (Taha et al., 2008; Bisht and Ramana, 2017). The relatively weak bond between rubber aggregates and cement paste can also result in non-uniform stress distribution (Aslani, 2016; Thomas and Gupta, 2016). In consequence of the rise in the use of waste rubber in concrete, a rubber-rubber interface region less resistant to breakage emerges. This interface region, in turn, negatively affects the strength (Mohammadi et al., 2014). Besides, waste rubbers' lower specific gravity and hydrophobicity (compared to normal aggregate) cause the rubber particles to move above during the vibration process. Therefore, a higher rubber concentration is formed on the upper surface, giving rise to a concrete structure with a lack of homogeneity and high strength (Toutanji, 1996; Xue and Shinozuka, 2013; Gupta et al., 2014; Duarte et al., 2016).

3.3. *Flexural strength*

Figure 8 and Figure 9 displays the results acquired from the flexural strength test. Compared to control, the flexural strengths of the concretes at 28 days and 90 days decreased due to the increased use of waste rubber. As in Figure 8, the concrete with a water to cement ratio of 0.4 was the control concrete (0.4C) owing to the highest flexural strength evaluated as 10.06 MPa at 28 days. As the waste rubber replacement rised to 24%, sample 0.4WR24 showed the lowest value with a flexural strength of 2.48 MPa. The flexural strength of the sample coded 0.4WR4 reached the highest value with 8.98 MPa among the waste rubber substituted concretes. The results of flexural strength tests at 90-day were also similar. The 90-day flexural strength of all waste rubber substituted concretes, including control concrete, is higher than the 28-day. The flexural strength results highlight the optimal ratio of waste rubber for this study as 4% when evaluating results according to all parameters. The 28-days and 90-day flexural strength values of concrete with 4% waste rubber replacement are not significantly lower than the control.

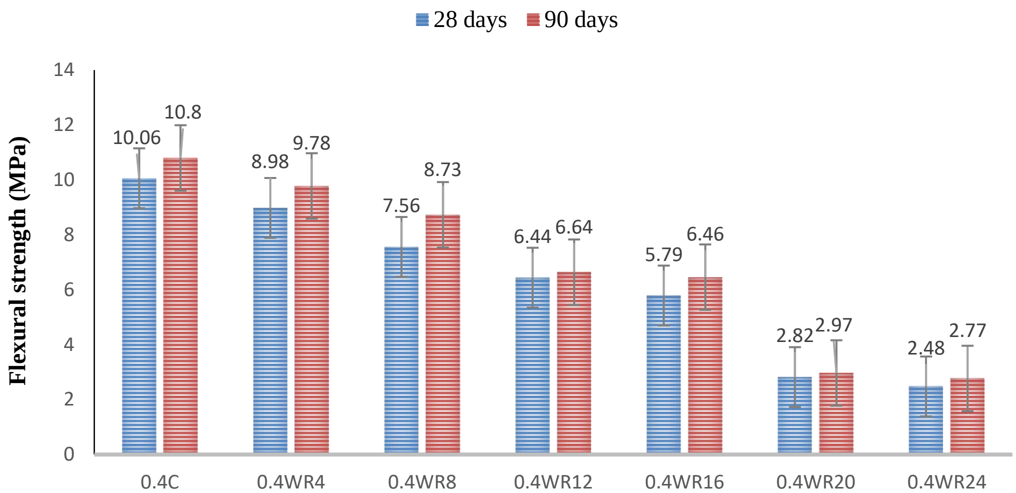

Figure 8. Effect of waste rubber substitution on flexural strength of 0.4 w/c concrete.

In Figure 9, the control (0.5C) has the peak flexural strength at 28 and 90 days with 8.4 MPa and 9.7 MPa flexural strength values, respectively. Comparatively, the sample with the code 0.5WR24 representing 24% waste rubber substituted concrete has the lowest flexural strength values at 28 and 90 days, 2.28 MPa and 2.47 MPa, respectively. With a flexural strength of 7.38 MPa, sample 0.5WR4 has the peak 28-day compressive strength value among the concretes with waste rubber. A similar trend is also evident in flexural strength results obtained after the 90-days of curing.

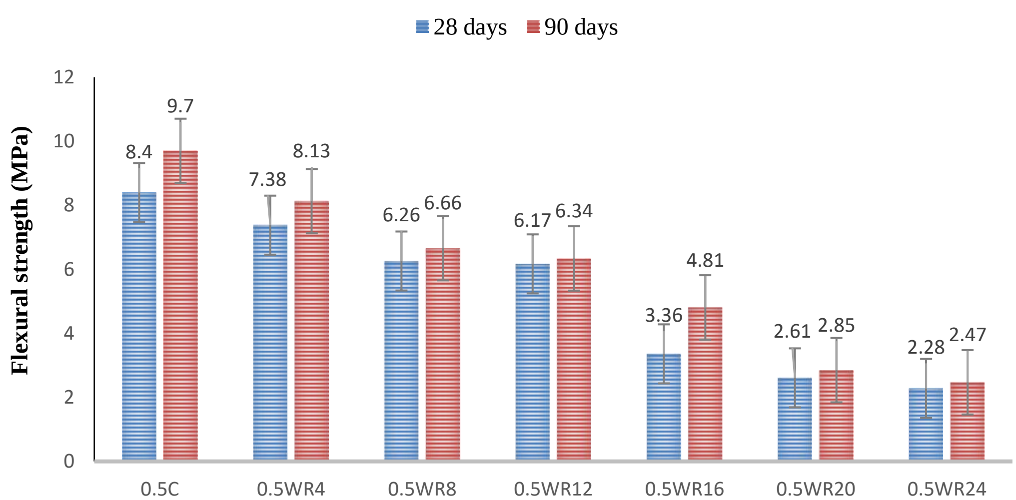

Figure 9. Effect of waste rubber substitution on flexural strength of 0.5 w/c concrete.

The 90-day flexural strengths of the control concrete and waste-replaced concrete with a 0.5 water to cement ratio were over than the 28-day flexural strengths. Flexural strength values decreased as the water to cement ratio increased from 0.4 to 0.5. For example, while the 28-day flexural strength of sample 0.4WR16 was 5.79 MPa, sample 0.5WR16's flexural strength decreased by approximately 42% to 3.36 MPa. While the 90-day flexural strength of sample 0.4WR8 was 8.73 MPa, sample 0.5WR8's flexural strength decreased by about 24% and reached 6.66 MPa. The remarkable effect of the water/cement ratio on the flexural strength of waste rubber substituted concretes was also observed in the study of Elchalakani (2015). The decrease in the flexural strength of concrete with the increasing waste-rubber ratio has also been stated in the studies (Ganjian et al., 2009; Aiello and Leuzzi, 2010; Al-Tayeb et al., 2012; Thomas et al., 2014; Noor et al., 2015; Mohammadi et al., 2016; Hilal, 2017; Angelin et al., 2019; Mousavimehr and Nematzadeh, 2019; Wang et al., 2019). The weak bond between cement and rubber is a highly effective impact on the decrease in flexural strength owing to the use of waste rubber in concrete (Batayneh et al., 2008; Roychand et al., 2020). This weak bond decreases the flexural strength more stingingly than it does the compressive strength (Khaloo et al., 2008; Najim and Hall, 2012; Dehdezi et al., 2015; Moustafa and ElGawady, 2015). Separation of the cement-rubber matrix is another factor responsible for reducing flexural strength in rubberized concrete (Khorrami et al., 2010). The fact that the waste rubber pieces can be easily removed from the concrete after the specimens exposed to the flexural strength test was broken confirmed this situation.

The water/cement ratio was very effective on both compressive and flexural strength results. In fact, increasing the water/cement ratio from 0.4 to 0.5 reduced the strength more than adding 4% waste rubber.

3.4. *Splitting tensile strength*

Figure 10 and Figure 11 presents the results of the test. Both Figures show that the splitting tensile strength of concretes decreases with the increase in waste rubber replacement ratio, without considering water to cement ratio and curing time. Figure 10 (concrete containing 0.4 water/cement ratio) shows the highest splitting tensile strength among 28-day concretes is in the control concrete (0.4C) with 5.41 MPa. The minimum splitting tensile strength is 1.90 MPa for the concrete with 24% waste rubber aggregate substitute (0.4WR24). A similar behaviour is also visible in the 90-day splitting tensile strength test results. As the ratio of waste rubber replacement increased to 24%, resulted in a 58% to 65% reduction in splitting tensile strength as regards the control. The increase in the splitting tensile strength of concretes in 90-days varied between 3% and 26% compared to the 28-days concretes.

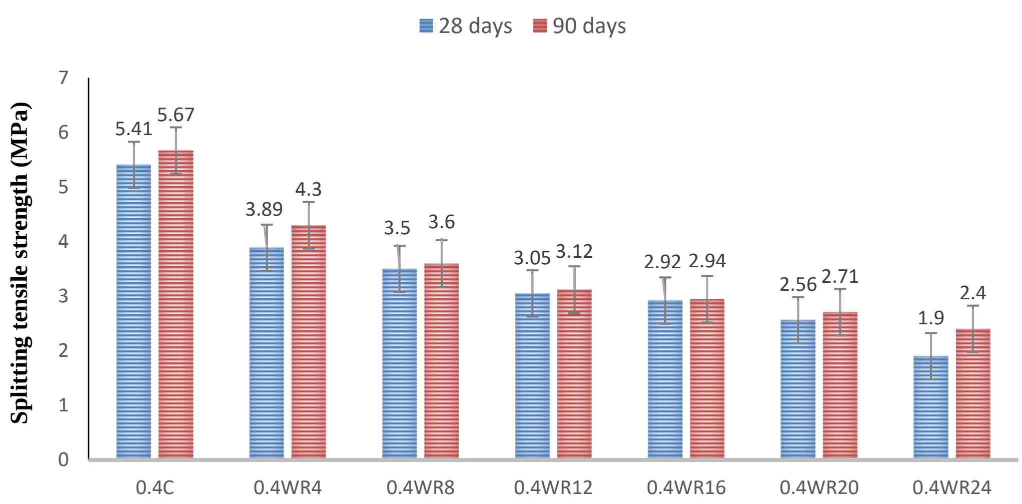

Figure 10. Effect of waste rubber substitution on splitting tensile strength of 0.4 w/c concrete.

Figure 11 shows the samples with a 0.5 water to cement ratio. Accordingly, the highest 28-day splitting tensile strength among concretes is the control concrete (0.5C) with 4.55 MPa. The minimum splitting tensile strength is the one having 24% waste rubber aggregate replacement, and its tensile strength is 1.60 MPa. Similar behavior is observed in the 90-day splitting tensile strength results. As regards the control concrete, the ratio of waste rubber replacement increased to 24%, resulting in a 65% reduction in splitting tensile strength. It's concluded that the increase in splitting tensile strength of 90-day concretes varied between 5% and 22%.

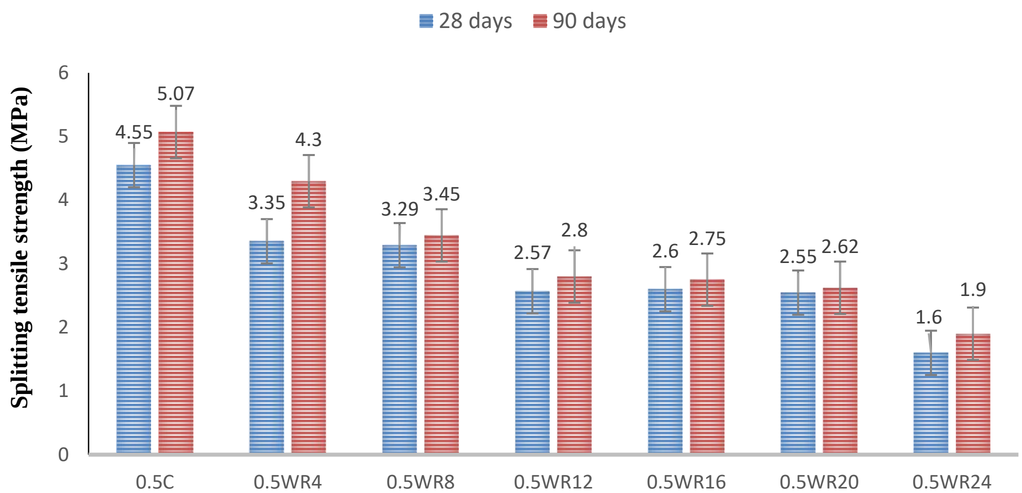

Figure 11. Effect of waste rubber substitution on splitting tensile strength of 0.5 w/c concrete.

When Figure 10 and Figure 11 are examined together, it is seen that the reduce in splitting tensile strength reached 21% as a result of increasing the water to cement ratio from 0.4 to 0.5. There are many investigations in the literature that using waste rubber instead of aggregate in concrete reduces the splitting tensile strength of concrete (Siddique and Naik, 2004; Najim and Hall, 2010; Pacheco-Torgal et al., 2012; Li et al., 2014; Lv et al., 2015; Li et al. 2016; Rashad, 2016). The reasons for this situation can be given under three main headings. Firstly; unlike hardened cement paste, soft rubber particles tend to deform under load, which can accelerate the formation of microcracks in concrete (Alsaif et al., 2018b). Under continuous loading, cracks develop rapidly in the interfacial transition zone (ITZ) between waste rubber aggregates and cement paste, resulting in a decrease in mechanical properties (Gonen, 2018). Secondly; in contrast to chemical reactions that result in strong bonds between cement paste and aggregates (Thomas et al., 2016), the weak chemical interaction between cement paste and rubber particles results in poor adhesion in ITZ (Rivas-Vázquez et al., 2015). Finally, the presence of high air content in concretes containing waste rubber may adversely affect the splitting tensile strength (Gonen, 2018; Gupta et al., 2018).

3.5. *Ultrasonic pulse velocity*

Figure 12 and Figure 13 shows the results of the ultrasonic pulse velocity test (UPV). According to the graphs, the UPV of the concretes reduced with the increase in the ratio of waste rubber replacement. In addition, there was an rise in the UPV of the concretes owing to increasing curing times from 28 days to 90 days. In Figure 12 (representing concretes containing a 0.4 water/cement ratio), the highest UPV among samples cured for 28-days is 5405 m/s in the control concrete (0.4C). The lowest UPV is 4747 m/s, and this value belongs to a sample having a 24% ratio of waste rubber replacement (0.4WR24). There is a similar pattern for 90-day concretes as well. Due to the rise in the waste rubber replacement ratio up to 24%, there is a reduction in the UPV values. The reductions varied from 12% to 15%. This study shows that the decline in UPV is 2% compared to control concrete for sample 0.4WR4, which has the least waste rubber replacement rate of 4%. Accordingly, using waste rubber instead of aggregate in concrete did not significantly reduce the UPV. The study indicated that the increase in UPVs of 90-day samples, independent of the waste rubber ratio, can reach up to 8% compared to 28-day samples.

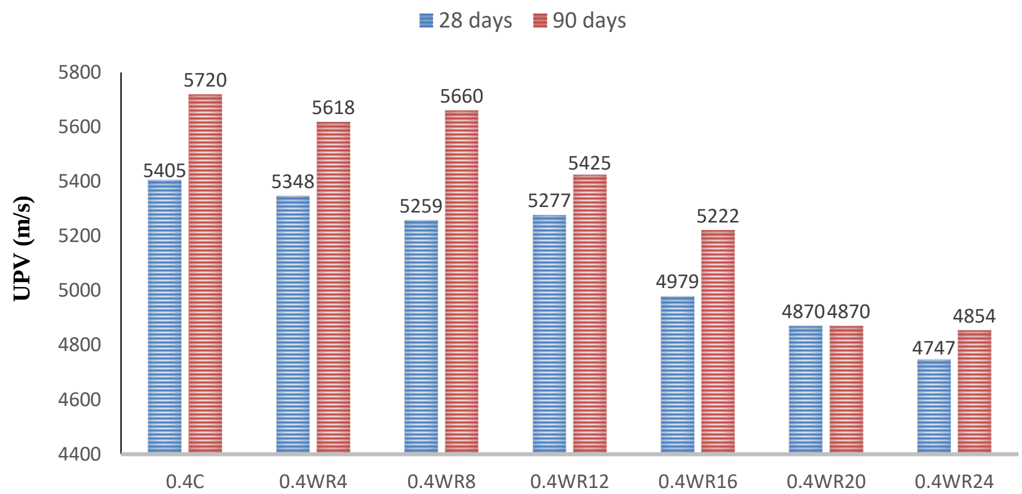

Figure 12. Effect of waste rubber substitution on UPV of 0.4 w/c concrete.

Figure 13 (displaying concretes with a water to cement ratio of 0.5) shows the highest UPV among the 28-day concretes is 5085 m/s, and it again belongs to the control concrete (0.5C). The lowest UPV value is 4464 m/s among rubberized concrete with 24% waste rubber replacement (0.5WR24). There is also a similar trend for 90-day samples. Increasing the waste rubber replacement rate to 24% caused a 13% decrease in the UPV. Similar to concrete with a water to cement ratio of 0.4, the UPV of sample 0.5WR4 reduced by 2% as regards control concrete. The rise in UPV of 90-day samples, independent of the waste rubber ratios, could reach up to 5% compared to 28-day samples.

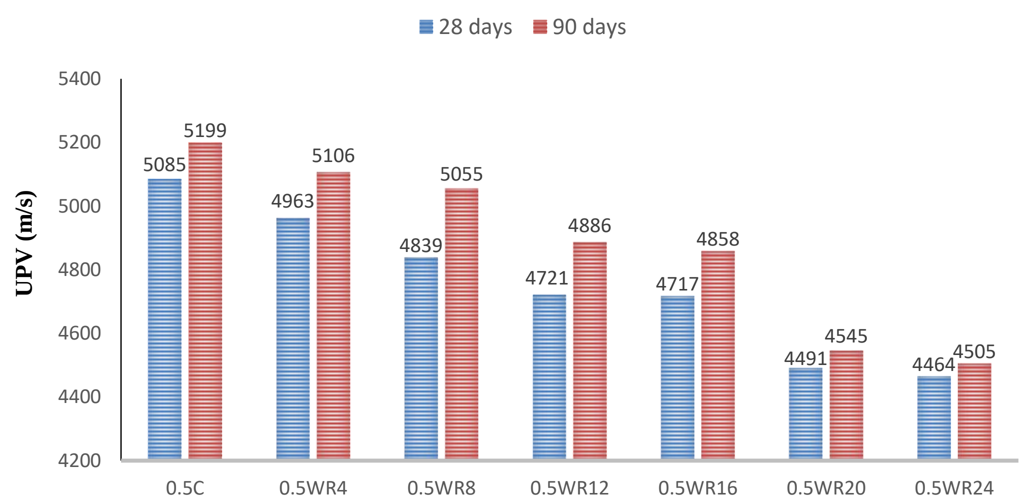

Figure 13. Effect of waste rubber substitution on UPV of 0.5 w/c concrete.

Examining Figure 12 and Figure 13 together indicates the decrease in the UPV (due to increasing the water to cement ratio from 0.4 to 0.5) for concretes ranges from 5% to 11%. Different researchers in the literature (Gupta et al. 2014; Assaggaf et al., 2021) point out that the sound-absorbing capacity of concrete proportionally increases with the rising waste rubber amount in concrete. That is because the porosity in the concrete structure increases, and the unit weight of the concrete declines. In a study (Marie, 2016), a decrease of 7% took place in the UPV of concrete when replaced 20% of crumb rubber was with fine aggregate. The drop was from 5500 m/s to 5100 m/s. The findings of this study show the decrease in UPV values in the concrete containing a 20% ratio of waste rubber was around 13%. The decline in ultrasonic pulse velocity is parallel with the findings in the literature. The IS 13311 (1992) standard classifies concretes with a UPV of more than 4500 m/s as excellent-quality concrete. Moreover, concretes with a UPV of 3500-4500 m/s are graded as good-quality concrete. Among the concretes produced according to this standard, all concretes are classified as excellent quality concretes (except for concrete with a water to cement ratio of 0.5, with 20% and 24% waste rubber substitutes). Concretes with 20% and 24% waste rubber substitutes were in the good quality class. In this study, it has been proven that good or excellent quality concrete can be produced in terms of UPV test, when up to 24% of waste rubber is used in concrete by replacing both fine and coarse aggregates.

3.6. *Dynamic modulus of elasticity*

For determining the dynamic modulus of elasticity, the density values and UPV obtained from concretes were used and incorporated them into Equation (2). For the entire calculation, the poisson ratio is supposed to be 0.2 (Rao et al., 2016; Thomaz, 2021). Figure 14 and Figure 15 shows the dynamic modulus of elasticity of concretes. Both Figures indicate that concretes' dynamic modulus of elasticities reduced with the increase in the waste rubber substitution ratios. In addition, as a result of rise the curing times from 28 days to 90 days, it was determined that there was an increase in the dynamic modulus of elasticity of the concretes. Figure 14 show that the sample with the highest dynamic modulus of elasticity among the 28-days concretes is the control concrete (0.4C) with 63.4 GPa. Additionally, the minimum dynamic modulus of the elasticity sample is 0.4WR24, which has a 24% rubber substitution rate and 44.6 GPa dynamic elasticity. As rising the waste rubber replacement ratio from 0% to 24%, reductions of up to 30% to 34% (compared to control concrete) in the dynamic modulus of elasticity occurred. The experimental results show that the increase in dynamic modulus of elasticity of concretes cured for 90-days could reach up to 11% compared to 28-days, regardless of the rubber ratio.

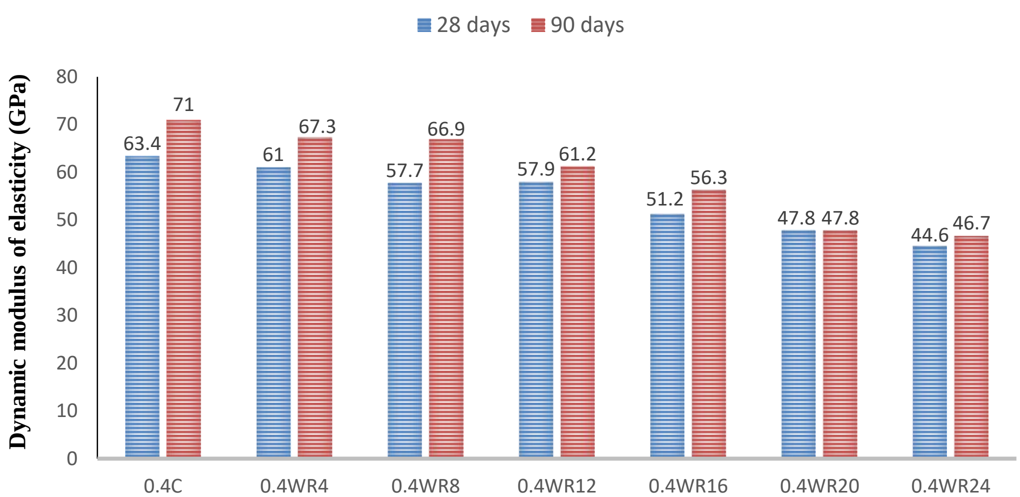

Figure 14. Effect of waste rubber substitution on dynamic modulus of elasticity of 0.4 w/c concrete.

Figure 15 show concrete with a 0.5 water to cement ratio. For 28 days of curing, the highest dynamic modulus of elasticity was 55.4 GPa belongs to the control (0.5C) and the lowest dynamic modulus of elasticity has 37.8 GPa belongs to the sample 0.5WR24. Similar trends are also predominant in the samples cured for 90-days. As regards the control concrete, the dynamic modulus of elasticity of samples declined by 33% owing to the increasing the waste rubber replacement rate to 24%. The experiments indicate that the rise in dynamic modulus of elasticity of samples can reach up to 9% when comparing the 28-day and 90-day curing results. The growth occurs regardless of the ratio of waste rubber substitution.

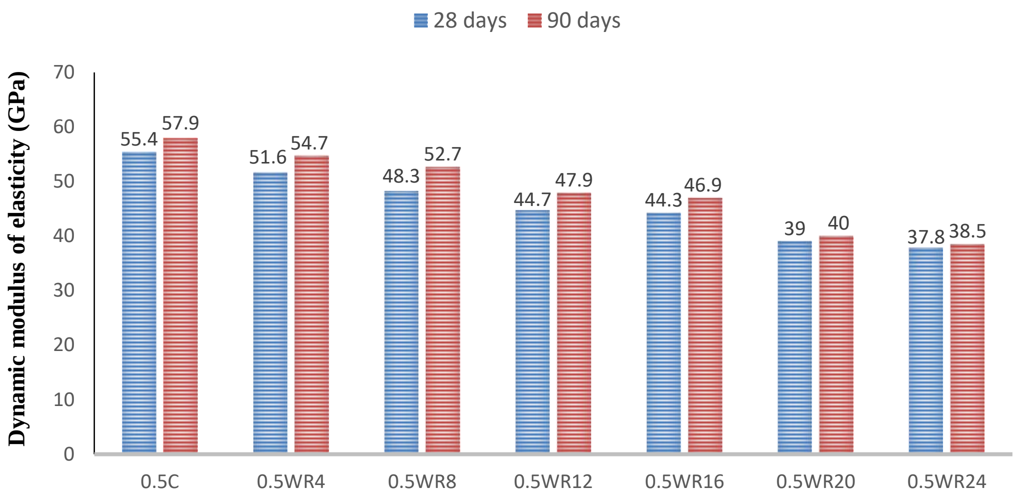

Figure 15. Effect of waste rubber substitution on dynamic modulus of elasticity of 0.5 w/c concrete.

Scrutinizing Figure 14 and Figure 15 together reveals that the reduce in dynamic modulus of elasticity of samples ranges from 12% to 22% as the water to cement ratio rose from 0.4 to 0.5. Various research shows that the dynamic modulus of elasticity of concrete decreases as the ratio of waste rubber replacement or the water/cement ratio rises (Hernández-Olivares, 2002; Najim and Hall, 2012; Li, 2017). Gupta et al. (2014) point out that the dynamic modulus of elasticity decreased by 14% when the water to cement ratio went up from 0.45 to 0.55 in rubberized concretes. Furthermore, the dynamic modulus of elasticity of concretes including 20% waste rubber decreased by 42% when compared to the samples without waste rubber. In this regard, this study reaches conclusions similar to those of the existing literature.

3.7. *Relationship between unit weight-UPV results*

Figure 16 shows the relationship between unit weight and UPV of concretes having a water to cement ratio of 0.4. Controlling the unit weight-UPV graph of concretes cured for 28-days, it is seen that the concrete with a unit weight of 2200 kg/m^3 represents the concrete with a 24% ratio of waste rubber replacement. UPV value of this concrete is the lowest value with 4747 m/s. At this point, the rise in the rate of waste rubber substitution, which has a relatively lower unit weight than the concrete components, gives the concrete a more spacious and less dense internal structure, which in turn reduces ultrasonic pulse velocity. A similar trend is present in the unit weight versus UPV relationship for samples cured 90-days. The R^2 values obtained in the relation between unit weight and UPV are 0.8872 and 0.8609, respectively for samples cured 28-day and 90-day. The R^2 outcomes are close to 1, indicating an important relationship between the two variables.

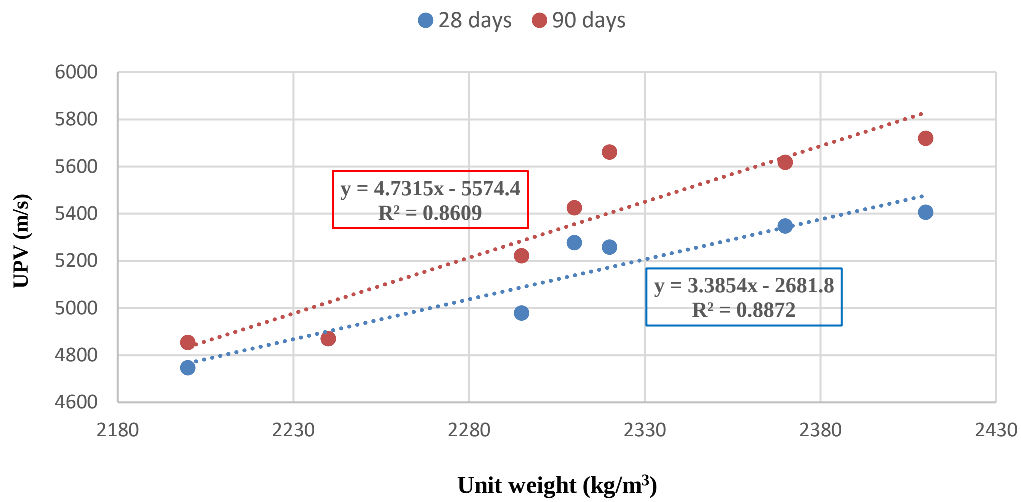

Figure 16. The relationship between unit weight-UPV of concretes with a water/cement ratio of 0.4.

Figure 17 presents the relationship between unit weights and UPV of samples having a water to cement ratio of 0.5. The samples' unit weight and UPV reduce as the ratio of waste rubber replacement increases. The R^2 values with unit weight and UPV are 0.9845 and 0.9581, respectively, for samples cured at 28-day and 90-day. The relationship between unit weight and UPV is remarkably stronger than the samples containing a water/cement ratio of 0.4.

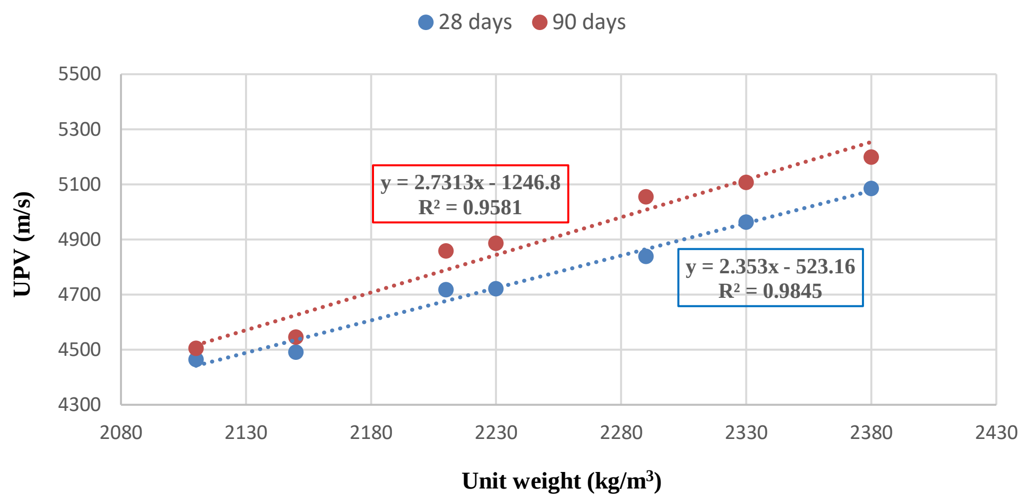

Figure 17. The relationship between unit weight-UPV of concretes with a water/cement ratio of 0.5.

3.8. *Relationship between compressive and flexural strength*

Figure 18 and Figure 19 displays the relationship between compressive and flexural strength based upon the water to cement ratio.

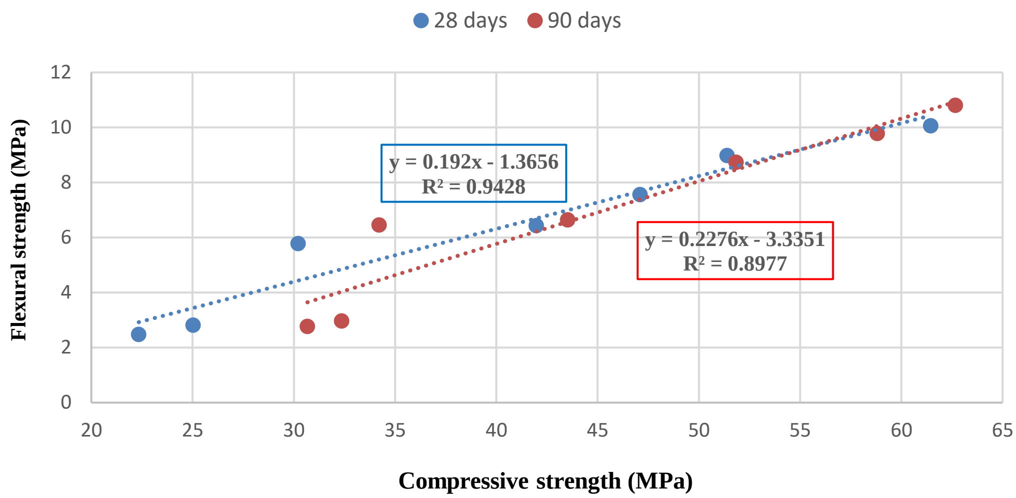

Figure 18. The relationship between compressive and flexural strength of concretes with a water/cement ratio of 0.4.

There is a directly proportional relationship between the samples' compressive strength and flexural strength. The R^2 values obtained for the samples having a water to cement ratio of 0.4 are 0.9428 and 0.8977, respectively, in 28-day and 90-day curing duration. The R^2 values for the concretes with a water to cement ratio of 0.5 are 0.8894 and 0.9830, respectively in the 28-day and 90-day cure. Therefore, the statistical correlation is higher in the samples having a higher water/cement ratio.

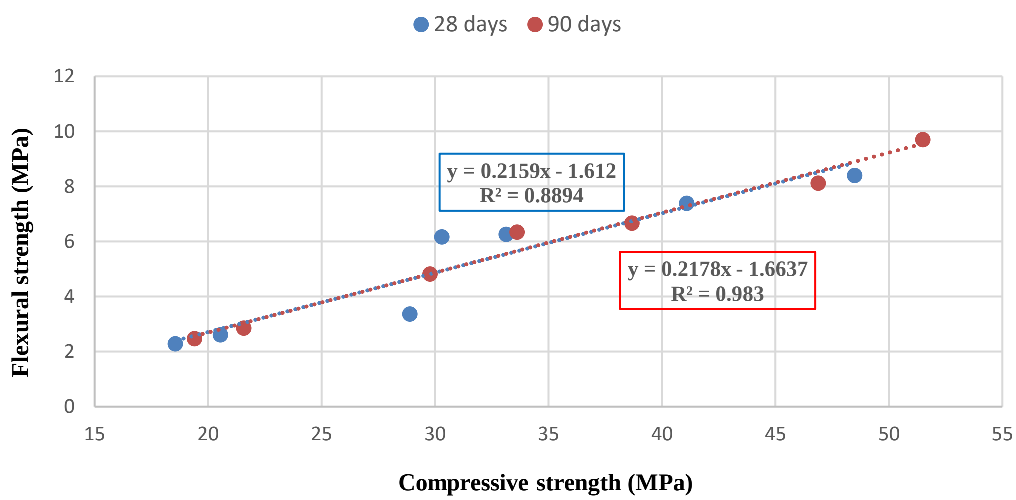

Figure 19. The relationship between compressive and flexural strength of concretes with a water/cement ratio of 0.5.

3.9. *Relationship between compressive and splitting tensile strength*

Figure 20 and Figure 21 present the relationship between compressive strength and splitting tensile strength based on the samples' water/cement ratio.

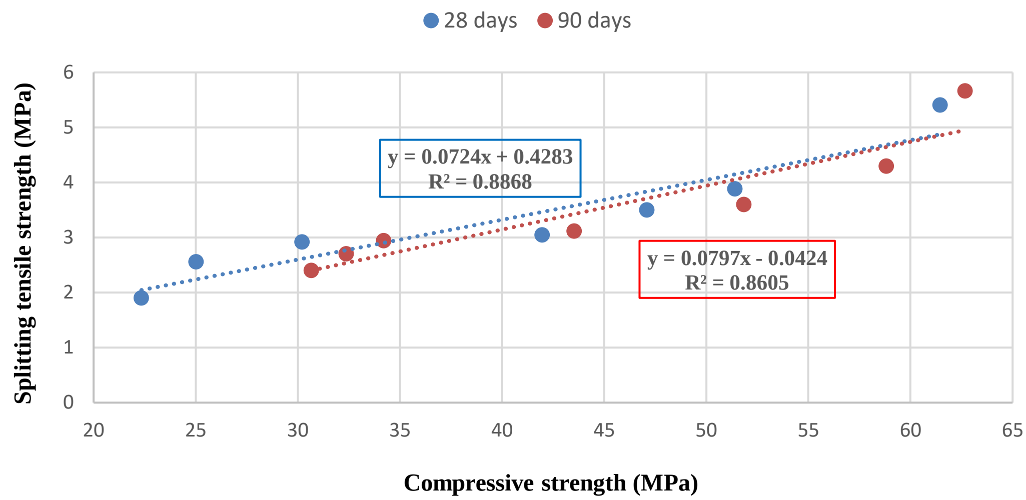

Figure 20. The relationship between compressive and splitting tensile strength of concretes with a water/cement ratio of 0.4.

The Figures shows that the splitting tensile strength rised linearly with the compressive strength. So, there is a positive relationship between them. The R^2 values obtained for the two strength types vary from 0.8605 to 0.9242, hinge on the water to cement ratio and curing time (28 days-90 days). In the end, the experimental results point to significant relationships between the two variables.

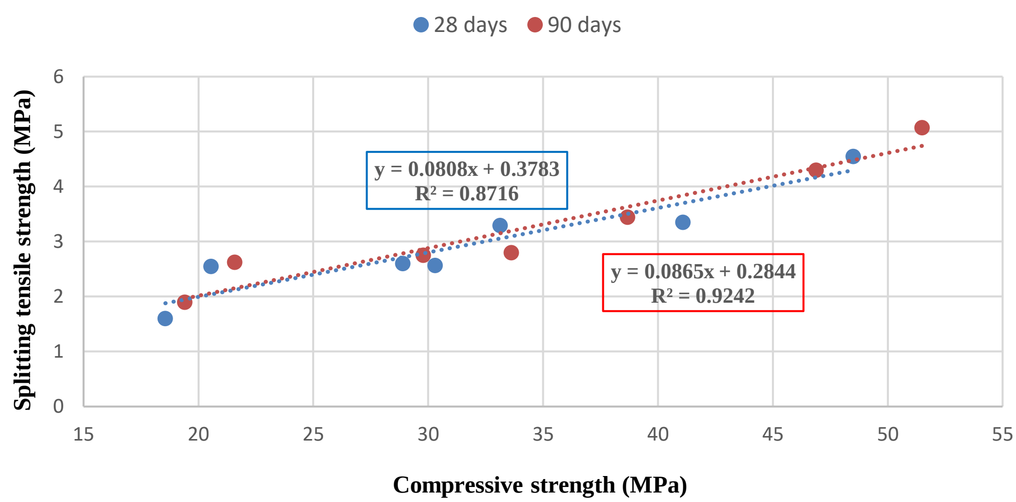

Figure 21. The relationship between compressive and splitting tensile strength of concretes with a water/cement ratio of 0.5.

4. Conclusions

The purpose of this study, unlike the literature, is to examine the mechanical properties of concretes with different curing times and water/cement ratios in three different classes (chips rubber, crumb rubber, and powder rubber) instead of both fine and coarse aggregates. The general conclusions obtained as a result of the study are as follows;

1. The rise in the ratio of waste rubber substitution and the water to cement ratio (from 0.4 to 0.5) causes the unit weight values of the concretes to decline.

2. As regards the control concrete, the study finds that an increase in the proportion of waste rubbers replaced as aggregate results in the compressive strengths decreasing. Nevertheless, high-strength concretes can still be produced when the ratio of waste rubber addition is 4% and 8% while the water to cement ratio is 0.4. In this case, the strength level of concrete reaches beyond 50 MPa. On the other side, significant decreases in all compressive strengths take place due to an rise in the water to cement ratio.
3. The concretes' reduced splitting tensile and flexural strength is attributable to the increasing waste rubber replacement rate during production.
4. The test results about UPV demonstrate that producing excellent quality concrete is possible even with waste rubber replacement ratios of up to 24%. More extended curing periods point to the fact that the dynamic modulus of elasticity of the concretes rises over time. The increase is pronounced in concretes, which have an 8% ratio of waste rubber replacement.
5. The relationships (especially unit weight-UPV of concretes with a water/cement ratio of 0.5) show a strong and positive correlation. Besides, the R^2 values are near 1.
6. This study further demonstrates that water to cement ratio and curing time are highly influential on the mechanical properties of RC.
7. This article finally determines that the ideal waste rubber ratio in concrete production is 4%.
8. For future researches on the use of waste rubber in concrete; It is recommended to examine the fracture energy and durability (chloride permeability test, water penetration depth, shrinkage, carbonation) properties of concretes.

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Graphical Abstract