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Research Article

Engineering properties and SEM analysis of eco-friendly geopolymer mortar produced with crumb rubber

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ABSTRACT

In the present study, the influence of the crumb rubber (CR) utilization as fine aggregate on the engineering properties of fly ash-based geopolymer mortar was experimentally investigated. In this context, the natural sand (NS) used in the production of geopolymer mortars was substituted with the CR, which comes out in the course of applying the retreading process to the end-of-life tires, at the substitution levels of 10%, 20%, 30%, 40%, and 50% by volume. In this way, 6 different geopolymer mixtures, one of which was the control mixture, were designed and produced. Then, the effect of CR on the fresh-state properties like flowability and fresh unit weight and the hardened-state properties like dry unit weight, compressive and flexural strengths of geopolymer mortars were examined. Besides, the properties of CR such as grading, specific gravity, water absorption capacity, fineness modulus as well as surface texture and particle shapes were compared with that of the river sand. In addition, the interfacial transition zone (ITZ) between fine aggregate particles (both NS and CR) and geopolymer paste was viewed using SEM images. When NS was substituted with CR at a 50% level, unit weights decreased significantly, which is considered lightweight mortar; however, no remarkable influence on the flowability was observed. The incorporation of CR, on the other hand, resulted in a reduction in the strength characteristics of the geopolymer mortar. Besides, a weaker ITZ was detected between the CR particles and geopolymer paste. Moreover, the visual appearance of the mixes revealed that the CR particles were well-distributed on the mortar cross-section, namely no bleeding and segregation problems were faced. As a consequence, it can be stated that the geopolymer mortar can be manufactured by substituting the NS with CR provided that it is at specified substitution levels. For instance, the flexural strength of the mortar was more than 3 MPa even at a 40% replacement level while the compressive strength of the geopolymer mortar dropped under 20 MPa at a 20% replacement level.

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1. INTRODUCTION

One of the important problems of the 21st-century world is the growing waste piles. The United Nations Environmental Protection Agency classifies these waste piles as hazardous and non-hazardous waste materials. In this context, waste tires can be regarded as one of the most known and common contaminant materials. Although it is considered a non-hazardous waste material, it has a high potential of being a hazardous waste material, especially in the case of its uncontrolled burning. In addition, the pile of waste tires leads to be a nest for some animals like snakes, rodents, centipedes, etc., thereby, the natural habitat in the region where the waste tire is piled can be degraded. Therefore, recycling or reusing waste tires is an essential issue having importance because the decomposition of the tire rubber through natural ways takes a very long time [1].

As a consequence of this, many recycling and/or reusing methods were developed to decrease the amount of waste tire pile. Controlly burning the waste tires to obtain energy is one of the easiest and most beneficial ways of recycling the waste tires since they provide a high amount of heating energy [2]; however, it is limited or forbidden in many countries by laws due to its negative impact on nature such as releasing contaminant, hazardous, and toxic gases [3, 4]. In addition to burning them, there are alternative ways for recycling and/or reusing the waste tires like retreading them to obtain recapped tires, decomposing them by pyrolysis technique, and recycling them to achieve the materials or to produce tire-based products.

Apart from the aforementioned ways, using the end-of-life tires in civil engineering applications as filling material or aggregate is an innovative, environmentally friendly, and effective way of sweeping these idle tires away. To bring the waste tires into the form that can be used in such civil engineering applications, mechanically granulating is generally applied to the waste tires in order to obtain the idle tires in the sizes, commonly named tire chips and crumb rubber (CR) [5]. Among the civil engineering applications, using the waste tires as aggregate in the ready-mixed concrete sector having a large industrial volume with 160 million tons manufacturing in Turkey, 620 million tons manufacturing in Europe [6], and approximately 4.4 billion tons manufacturing in the world [7] can be regarded as the most effective way to get rid of these idle tires [8, 9].

Many scientists have investigated the influence of the aggregate derived from the waste tire on both fresh and hardened state properties of conventional concrete. However, incorporating rubber-derived aggregates into the geopolymer concrete, which was a material developed by French scientist Joseph Davidovits as an alternative to conventional concrete [10], is a completely new phenomenon, and there are some investigations about the rubber incorporated geopolymer concretes but the rubber percentage amount was limited. The difference between the traditional and geopolymer concretes is the paste phase of the mixture: in the traditional one, the cement (and mineral additives) and water constitute the paste phase while in the geopolymer one, the paste phase consists of aluminosilicate-rich material and alkaline solution. Here, it should be stated that sodium silicate (Na_2SiO_3)-sodium hydroxide (NaOH) and potassium silicate (K_2SiO_3)-potassium hydroxide (KOH) alkaline solution pairs are the pairs commonly used [11]. Thereby, a reaction named polymerization takes place between the aluminosilicate-rich raw materials and alkaline activator solution and as a result, the Si-O-Al-O bonds are formed, providing for the creation of geopolymers [12, 13]. One of the most significant pros of this new concrete concept is the possibility of being used of industrial waste materials like fly ash, blast furnace slag, bottom ash, etc. as the aluminosilicate-rich raw material, in other words, this concrete concept does not require the production of a specific raw material as in the traditional concrete. As a consequence, the production of such material leads to less energy consumption and greenhouse gas emissions, making this material a more energy-efficient and environmentally friendly construction material [13, 14].

There are just a few studies in the literature that evaluate the impact of CR incorporation on the performance of geopolymer mortars. Aly et al. [15], for example, employed waste rubber in the manufacture of geopolymer concrete and investigated the compressive and tensile strengths. Similarly, Aslani et al. [16] investigated the workability and mechanical performances of rubber aggregate-incorporated geopolymer concrete. Niş et al. [17] conducted a study in which the influence of CR incorporation on the mechanical characteristics of the geopolymer concrete and Eren et al. [18] carried out a study in which the possible utilization of CR in the self-compacting geopolymer concrete was investigated. Additionally, Wongsa et al. [19], on the other hand, looked at how CR affected the mechanical and thermal properties of geopolymer mortar, while Moghaddam [20] investigated the influence of sulfuric acid on CR-incorporated fiber-reinforced geopolymer concrete.

The target of the research presented herein is to manufacture a sustainable eco-friendly construction material and investigate its engineering properties. For this reason, an experimental study was carried out towards the reuse potential of the waste tire rubber as fine aggregate in geopolymer mortar production. For this reason, waste tire rubber named CR in fine size, coming out in the course of applying the retreading process to the end-of-life tires was incorporated into the fly ash-based geopolymer mortar instead of natural sand. Hereby, manufacturing an eco-friendly construction material was desired. For this reason, the possible influences of the incorporation of CR on the fundamental engineering properties of the geopolymer mortar were experimentally researched. Moreover, the interfacial transition zone between the fine aggregate particles (both river sand and crumb rubber) and geopolymer paste was also viewed using the scanning electron microscope (SEM) technique.

Table 1. Chemical compositions and physical properties of class F fly ash

Chemical composition, %									Physical properties	
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	LOI*	Specific gravity	Specific surface area
1.69	55.46	26.33	6.71	2.42	0.05	1.08	4.22	1.2	2.00	2.018 m^2/g

*: LOI: loss on ignition.

Table 2. Chemical compositions of sodium hydroxide (NaOH)

Chemical composition, %				
NaOH (sodium hydroxide)	Na_2CO_3 (sodium carbonate)	NaCl (sodium chloride)	Fe (iron)	Specific gravity
≥98.0	≤0.5	≤0.02	≤0.001	1.254

Table 3. Chemical compositions and physical properties of sodium silicate (Na_2SiO_3)

Chemical composition, %		Density, g/ml	Module	Bome, °B
Na_2O (sodium oxide)	SiO_2 (silica)			
9.03	27.08	1.367	2.93	38.68

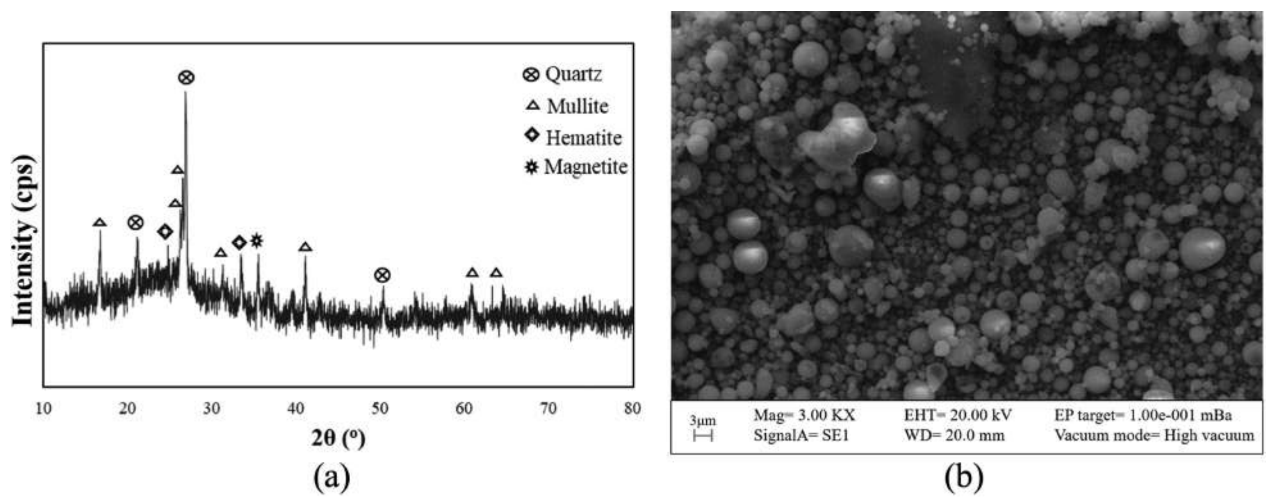

Figure 1. **(a)** X-ray diffraction (XRD) analysis result of fly ash and **(b)** scanning electron microscope (SEM) image of its particles

2. MATERIALS AND METHODS

2.1. Materials

Fly ash conforming to ASTM C311 [21] and regarded as class F according to ASTM C618 [22] was employed as an aluminosilicate-rich raw material in the production of geopolymer mortars. The chemical compositions and physical properties of fly ash, which was procured from the Çatalağzı thermal power plant in Zonguldak province of Turkey, are presented in Table 1. In addition, the X-ray diffraction (XRD) analysis result of fly ash is indicated in Figure 1a, and the image of its particles taken by scanning electron microscope (SEM) is demonstrated in Figure 1b. The main themes presented in these figures are components constituting the fly ash and particle sizes and shapes of fly ash. In regard to Figure 1a, it can be stated that the peak point in the intensity occurred at quartz crystal since the fly ash highly consists of SiO_2. On other hand, it can be seen in Figure 1b that the fly ash consists of generally particles smaller than 3 μm. Also, it should be emphasized that the particles of the FA are in a spherical shape.

As an alkaline activator, NaOH and Na_2SiO_3 pair with a ratio of 1-to-2 was used. The chemical compositions and properties of NaOH in spherical pellet form in white color and Na_2SiO_3 in the liquid form in light yellow color

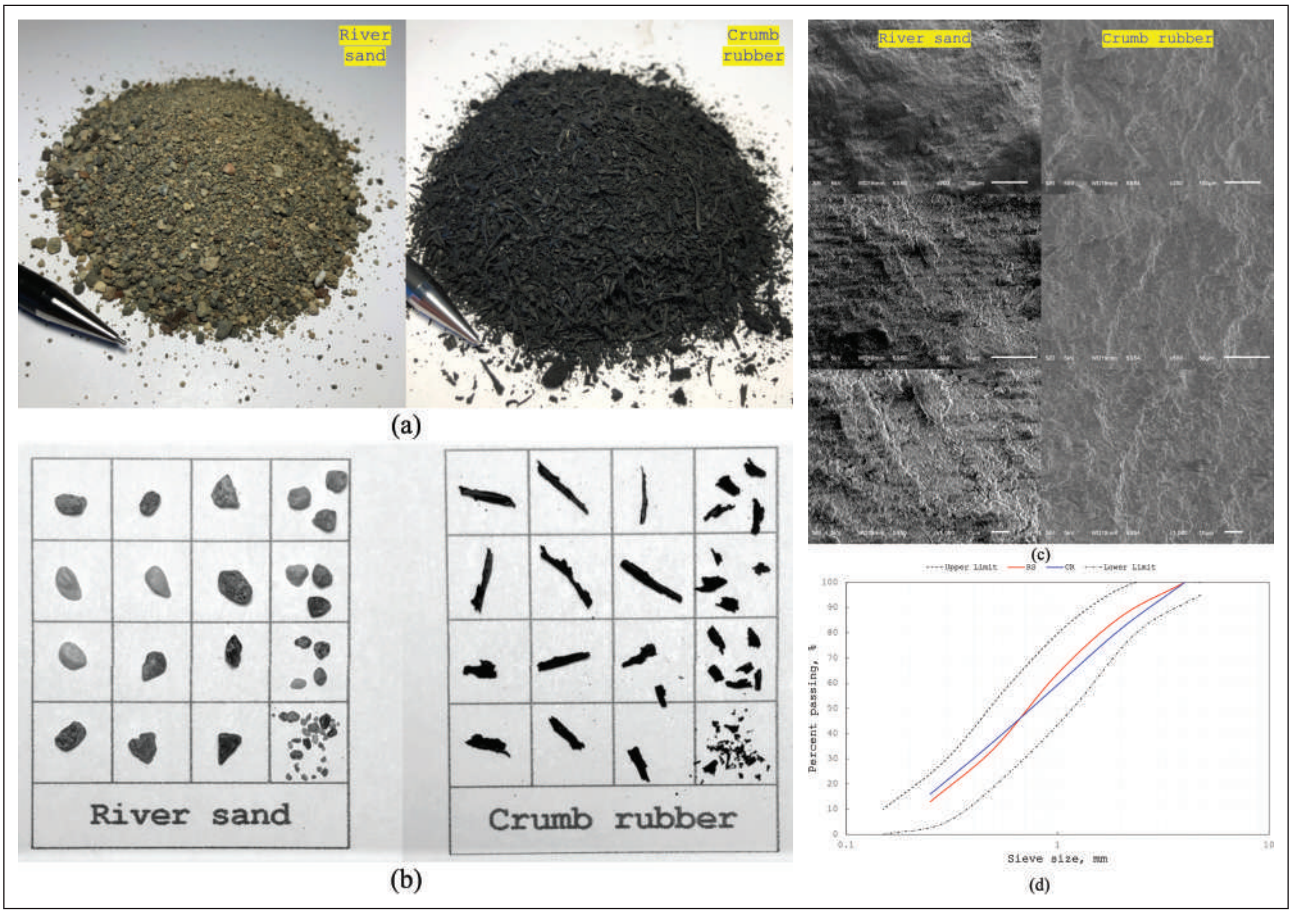

Figure 2. River sand and crumb rubber: **(a)** general photographic views, **(b)** photographic view of particles, **(c)** SEM images, and **(d)** sieve analysis results.

are presented in Tables 2 and 3, respectively. The NaOH pellets used to prepare the NaOH solution with a 12-M concentration had a purity of more than 98%. In addition to this, Na_2SiO_3 solution comprising of liquid and solid materials with respectively roughly 61.5% and 38.5% had a silica-to-sodium oxide ratio (SiO_2/Na_2O) of about 2.5.

As the last material, the superplasticizer with a commercial name of MGlenium 51 having a specific gravity of 1.07 was used to achieve geopolymer mixtures with sufficient flowability.

In the production of the geopolymer mortars of the present study, river sand (RS) with a maximum particle size of 4 mm and specific gravity of 2.74 was used. However, the waste tire rubber aggregate named crumb rubber (CR) having a specific gravity of 0.55 was substituted in some mixtures with river sand. The general photographic views of these two fine aggregates are given in Figure 2a whereas their particle shapes and sizes are shown in Figure 2b and their SEM images are indicated in Figure 2c. In addition, sieve analysis results (determined in accordance with ASTM C136 [23]) of RS and CR compared with the upper and lower limits for fine aggregate (proposed by ASTM C33 [24]) are shown in Figure 2d. The fineness modulus values of RS and CR were respectively 2.03 and 2.06. On the other hand, the water content and absorption values of RS were respectively about 0.94 and 2.31, whereas that of the CR were 0 which means the CR used in this study did not contain water and had no water absorption capability. As can be seen in Figures 2a and 2b, the CR consists of flaky and elongated particles. As the size of the particles decreases, the CR particles become angular and/or partly rounded. Besides, the CR particles are substantially softer than the RS particles, thus the elastic modulus of CR is less than that of the RS, which makes such materials structural unstable material. However, such characteristics may be useful for absorbing the energy such as impact energy, sound energy, heat energy, etc.

2.2. Mixture Proportions and Production

The mixtures in the present study were designed at a Na_2SiO_3-to-NaOH ratio of 2.0 and alkaline activator-to-aluminosilicate-rich raw material ratio of 0.5. The alkaline activator content and powder material (aluminosilicate-rich raw material) dosage were designated as 300 kg/m^3 and 600 kg/m^3, respectively. The superplasticizer content for the control mixture with sufficient flowability

Table 4. Mixture proportions for the rubberized geopolymer mortars, kg/m^3

Mixture name	FA	NH	NS	RS	CRSL, %	CR	SP
Plain mix	600	100	200	1231.1	0	–	21
Rubberized mix 1				1108.0	10	24.7	
Rubberized mix 2				984.9	20	49.4	
Rubberized mix 3				861.8	30	74.1	
Rubberized mix 4				738.7	40	98.9	
Rubberized mix 5				615.6	50	123.6	

FA: Fly ash; NH: Sodium hydroxide; NS: Sodium silicate; RS: River sand; CRSL: Crumb rubber substitution level; CR: crumb rubber; SP: superplasticizer.

was determined as 3.5% of powder material by mass after many trial batches. Since the rheological behavior of such materials is significantly influenced by variation in the superplasticizer content, all the mixtures in the present study were produced at a superplasticizer content of 3.5%. In the production of the plain geopolymer mixture, only the RS was used as fine aggregate; however, in the production of the geopolymer mixture containing crumb rubber, the RS was partially replaced with the CR at the levels of 10%, 20%, 30%, 40%, and 50% by volume. In this way, 6 geopolymer mortar mixtures were produced in total. Table 4 presents the detailed proportions of the geopolymer mortar ingredients.

Alkaline activator-to-fly ash ratio (Na_2SiO_3-to-NaOH), alkali activator molarity, fly ash dosage, and alkali activator content selected within the scope of the study carried out by Ekmen et al. [25], which is one of the most comprehensive studies in this context, in which the effects of the above-mentioned parameters on the fresh and hardened properties of geopolymer mortars were taken into consideration. Ekmen et al. [25] investigated the fresh and hardened properties of fly ash-based geopolymer mortars with 2 activator-to-fly ash ratios, 3 Na_2SiO_3-to-NaOH ratios, and 3 alkali activator molarities. Considering the consistency and strength findings obtained from this study, the mixture proportions in the current study were determined.

The same mixing procedure was applied to all geopolymer mortars during the production. This procedure consisted of two states: in the first stage, the alkaline activator solution was prepared and in the second stage, the geopolymer mortar was produced. First, the NaOH solution with 12-M concentration was prepared, and then, it was mixed with Na_2SiO_3 solution before almost 24-h of the beginning of the second stage. This solution was kept in a beaker till it was used in the production of geopolymer mortars. The second stage of the production procedure began by mixing the alkaline activator solution with fly ash in a mixer for about 3 minutes. Subsequently, the superplasticizer was poured into the mixer, and it was allowed to revolve for 2 minutes more. Thereafter, the RS in the plain mortar mixture and RS and CR mixture in the other mortars were gradually added to the mixer, and it was permitted to rotate the mixer extra 3 minutes after all fine aggregates were poured. Thereby, the production process of the geopolymer mortars was completed. The fresh-state properties of the geopolymer mortars were determined in terms of flowability measured by the flow table test, and fresh unit weight once the production process finished. After the fresh-state properties were determined, the mixtures were poured into the steel molds in two layers, of each which was vibrated for 30 seconds using a vibrating table. A heat curing of 60 °C for 24 hours was applied to the specimens taken and then, the demoulded specimens were kept in the laboratory condition where the temperature was 23±2 °C for the following 2 days. The specimens in the steel molds were put into the oven to be exposed to the heat curing regime and all the specimens were covered with a plastic bag to prevent water evaporation in the alkali solution during the heat curing. After the 3-day curing regime, the hardened-state tests were performed. Herein, it should be noted that one of the most important issues to be resolved regarding the applicability of geopolymer mortars is the high-heat curing required for the geopolymerization process and its application time. The main purpose of recent studies is to manufacture geopolymer mortar or concrete at lower curing temperatures as much as possible with application time. In terms of energy efficiency, 60°C as the curing temperature and 24 hours as the curing duration were selected according to research in the literature on the issue.

2.3. Testing Methods

The test apparatus shown in Figure 3a was employed to measure the flowability of the geopolymer mortar mixtures and ASTM C1437 [26] was followed during the application of the flow table test. During the determination of both fresh and hardened (1-day and 3-day) unit weights of the mixtures, ASTM C138 [27] was followed. A closed-loop testing machine shown in Figure 3b was used to perform the 3-day flexural strength test in regard to the ASTM C348 [28]. The 3-day compressive strength of the geopolymer mortar mixtures was determined per ASTM C109 [29] and ASTM C597 [30] was followed during measuring the 3-day UPV values of the mixtures as typically indicated in Figure 3c.

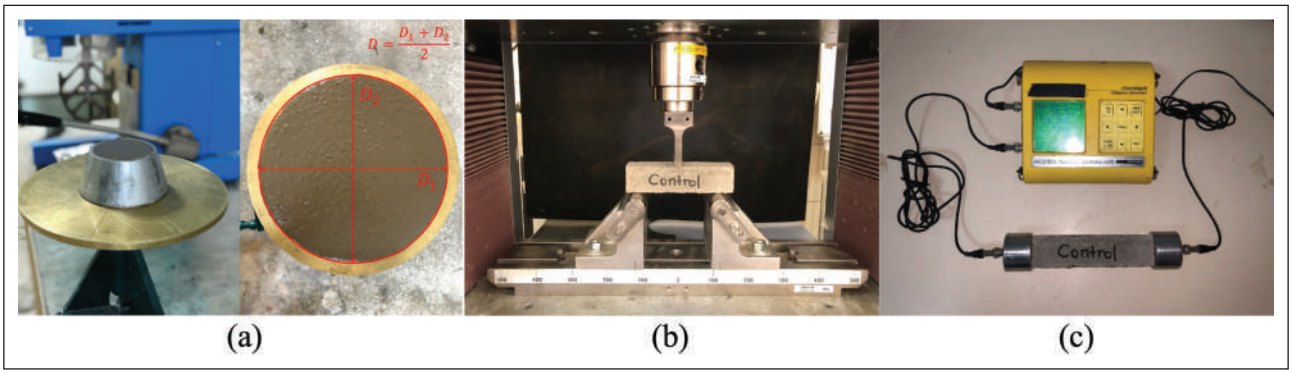

Figure 3. **(a)** Test apparatus of flow table test and measuring the flow diameter, **(b)** test device used in the measurement of flexural strength, and **(c)** UPV test device.

3. RESULTS AND DISCUSSION

3.1. Flowability Results

Based on the flow table test, the flowability of the mortars can be described in terms of mm or percentage. It should be noted that when the flowability is presented in mm the perfect flowability is 200 mm while when it is given in percentage this 200-mm flowability is defined as 100% flowability. The plain geopolymer mortar produced in this study had a flowing diameter of 210 mm which means 110% flowability. On the other hand, it was observed that substituting the RS with CR did not influence the flowability of geopolymer mortars. All the mixtures produced in the current study had a flowing diameter of 210 mm (namely 110% flowability). Since the CR particles have almost no water absorption capability, incorporating the CR into the geopolymer mortar did not affect the flowability characteristics of the mixtures. Besides, the CR particles that can be considered flaky and elongated may play a blockage role during the flowing but since the table is rammed 25 times in 15 seconds during performing the test, this role of the CR particles may have been minimized and/or eliminated. However, it should be stated that this finding is not consistent with the results reported in the literature. For example, when Aslani et al. [16] increased the crumb rubber replacement level from 10% to 20%, they observed a small decrease in the slump flow diameter values. In addition, Wongsa et al. [19] investigated how the crumb rubber incorporation influences the flowability, mechanical, and thermal properties of geopolymer mortar. They found that adding crumb rubber to geopolymer mortar mixtures made them less workable. On the other hand, Moghaddam et al. [20] reported a minor improvement in the flowability of geopolymer concrete after replacing natural sand with spherical crumb rubber derived from old tires. Similarly, Zhong et al. [31] achieved an enhancement in the workability of the geopolymer mortar from a general perspective. For this reason, the findings presented in the current study will contribute to the literature in this context.

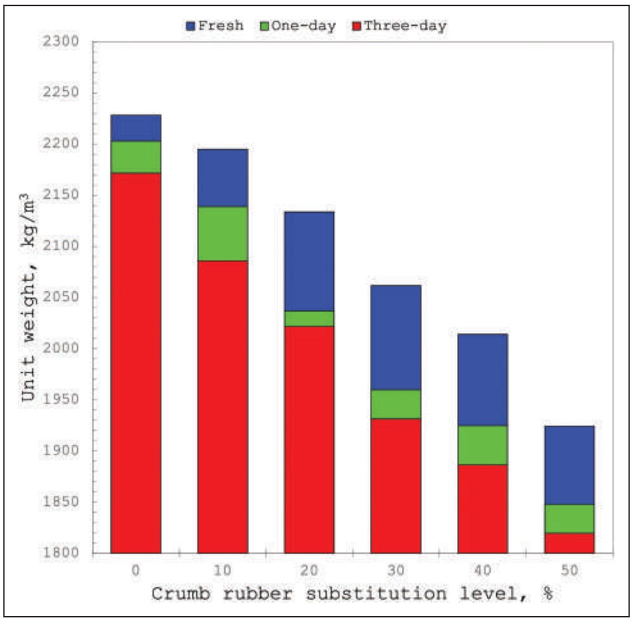

Figure 4. The variation in both fresh and dry unit weights of rubberized geopolymer mortars

3.2. Unit Weight Results

The change in both fresh and dry unit weight of the geopolymer mortars with respect to the CR substitution level is indicated in Figure 4. The fresh unit weight of the plain geopolymer mortar was about 2228 kg/m^3, whereas a systematic decrease in the fresh unit weight was observed by gradually substituting the RS with the CR. The fresh unit weights ranging between 2195 kg/m^3 and 1924 kg/m^3 were obtained for the geopolymer mortars containing CR. As expected, the CR incorporation into the geopolymer mortar led to a decrease in the unit weight of the mixtures because of its lighter weight than the RS. The highest decrease of 14% was observed when the RS was substituted with the CR at 50%. The drying of the geopolymer mortar mixtures resulted in weight loss as is expected. There were decreases to be ranging from about 1.0% to 5.0% in the unit weights of the mortars after 1 day. On the other hand, after 3 days, re-

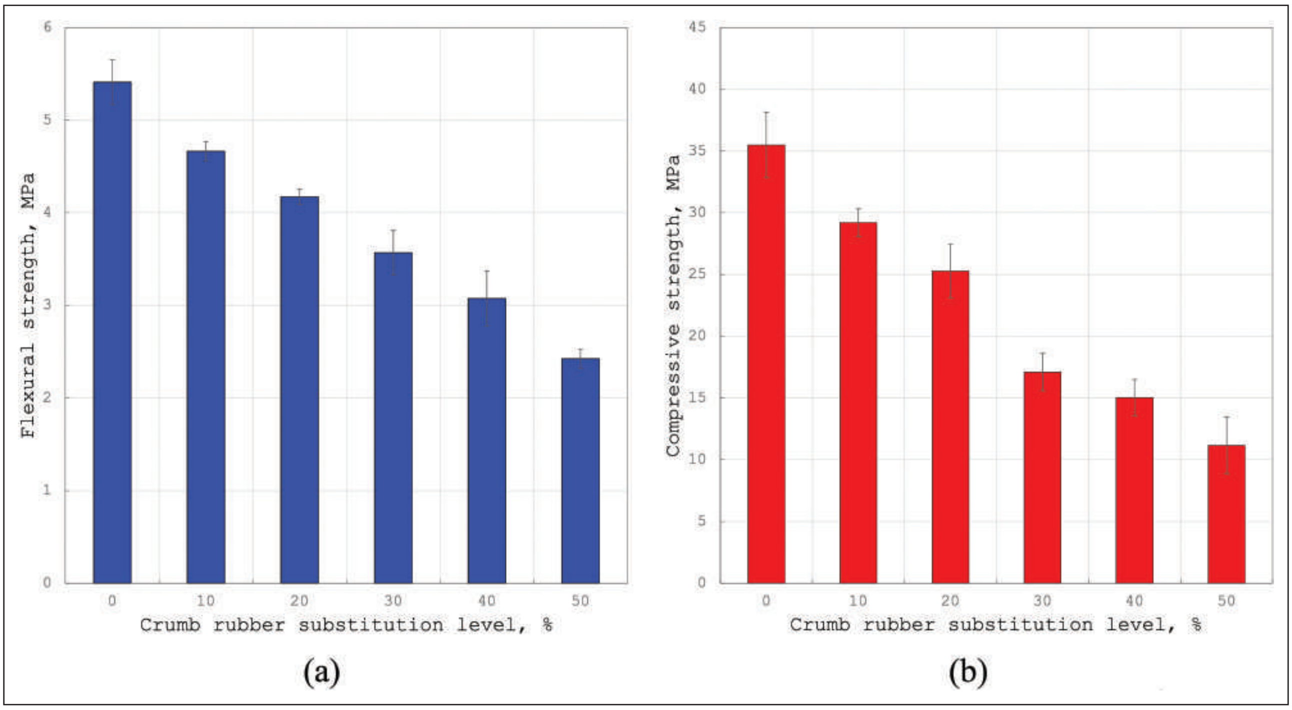

Figure 5. The variations in **(a)** flexural strength and **(b)** compressive strength of rubberized geopolymer mortars.

ductions between about 2.5% and 6.5% in the unit weights were observed. The lowest unit weight after the 3 days was obtained in the mixture produced with 50% CR as about 1820 kg/m^3 and on the same day, the control mixture had a unit weight of 2172 kg/m^3. TS EN 206-1 [32] regards the concrete having a unit weight (but oven-dry) of less than 2000 kg/m^3 and more than 800 kg/m^3 as lightweight concrete. Similarly, ACI Committee 213R-03 [33] classified the concretes as lightweight concrete when their unit weight (but air-dry) is less than 1950 kg/m^3. Since the geopolymer concretes (or mortars) have not been covered by any standard yet, these criteria can be taken into consideration to describe the geopolymer concretes (or mortars) based on the unit weight. In this context, it can be stated that the geopolymer mortar mixtures produced with 30%, 40%, and 50% CR can be definitely considered the lightweight geopolymer mortar when the 3-day unit weights were taken into consideration. Aslani et al. [16] and Wongsa et al. [19] characterized the geopolymer mortars incorporating crumb rubber manufactured in their studies as lightweight. Azmi et al. [34] reported a systematical reduction in the unit weight of the geopolymer concretes when the crumb rubber replacement level gradually increased from 0% to 20%. Besides, it should be stated that there are a limited number of studies in which the unit weight of the geopolymer mortar incorporating crumb rubber was investigated.

3.3. Flexural and Compressive Strengths

The variations occurring in flexural and compressive strengths of the geopolymer mortars because of the CR incorporation are shown in Figures 5a and 5b, respectively. The 3-day average flexural strength value of the control geopolymer mortar was about 5.41 MPa, and there was observed to be a systematical decrease in the average flexural strength of the mortars by substituting the RS with the CR and increasing the substitution level. The lowest 3-day average flexural strength value of 2.42 MPa was observed in the geopolymer mortar produced with a 50% CR substitution level. The reduction rates in the 3-day average flexural strength due to the CR incorporation were about 14%, 23%, 34%, 43%, and 55% when the substitution levels were 10%, 20%, 30%, 40%, and 50%, respectively. Wongsa et al. [19] investigated the properties of two types of geopolymer mortars: one was fully produced with RS and the other one was fully produced with CR. They reported a more than 75% reduction in the 28-day flexural strength when the RS was fully replaced with the CR. However, Zhong et al. [31] reported a slight increase in the flexural strength of the geopolymer mortar when the RS was replaced with the CR at the substitution level of 5% and a decrease after this substitution level.

Similarly, the compressive strength results revealed that incorporating the CR into the geopolymer mortar led to a decrease in the compressive strength. Also, increasing the CR substitution level yielded a systematic decrease in the compressive strength, see Figure 5b. The 3-day average compressive strength of the control geopolymer mortar was about 35.5% and incorporating 10% CR into the geopolymer mortar resulted in a nearly 18% decrease in the 3-day average compressive strength. Increasing the CR

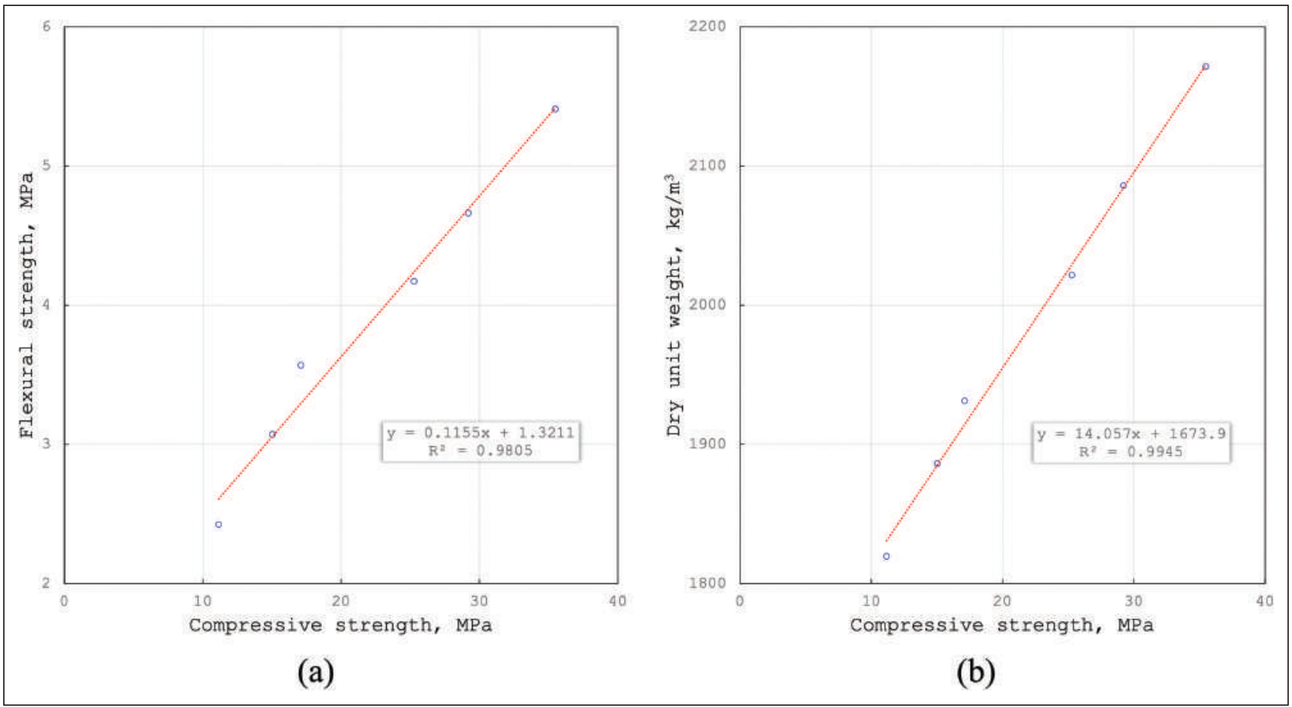

Figure 6. Correlation between **(a)** flexural and compressive strengths and **(b)** dry unit weight and compressive strength of rubberized geopolymer mortars.

substitution level from 10% to 50% diminished the compressive strength to 11.2 MPa. The results achieved from the study herein comply with the limited number of studies reported in the literature. For example, both Wongsa et al. [19] and Zhong et al. [31] reported a decrease in the 7-day and 28-day compressive strengths of the geopolymer mortar by substituting the natural sand with CR. In a similar manner, Azmi et al. [34] observed a nearly 65–75% decrease in the 7-day and 28-day compressive strengths at the CR substitution level of 20%.

One of the main reasons for the decrease in the strengths (both compressive and flexural) is that the interfacial transition zone occurring between geopolymer paste and rubber aggregate is larger than that occurring between the natural aggregate. Besides, the soft structure of the rubber aggregate will exhibit higher strain performance under loading compared to hardened geopolymer paste and natural aggregate. This means that in places where rubber aggregate is present, hardened geopolymer paste and/or natural aggregates will carry the most of the load, and the rubber aggregate will participate in the load-bearing role at even high strain levels, but at these strain levels, the hardened geopolymer paste has already cracked and the integrity of the mortar has deteriorated. Therefore, incorporating the rubber aggregate into the geopolymer mortar negatively influences its compressive strength.

Moreover, in Figure 6a, the correlation between the flexural and compressive strengths of the geopolymer mortars produced in the current study is presented. By taking into consideration the coefficient of determination (R^2) value given in this figure, it can be stated that there is a strong relationship and correlation between the flexural and compressive strengths of the geopolymer mortars of this study. A similar correlation was observed between the dry unit weight and compressive strength of the geopolymer mortars produced in this study as shown in Figure 6b. When the R^2 value given in this figure is considered, it can be stated that there is a directly proportional and strong relationship between the 3-day dry unit weight and compressive strength values.

3.4. UPV Values

The change in the UPV values of the geopolymer mortars depending on the CR substitution level is indicated in Figure 7a. The control mixture, which does not contain CR, had a UPV value of 3027 m/s. Since there is no qualifying scale for the cement-based and/or geopolymer mortars, the classification for the concrete given by Hwang et al. [35] can be used in this context to get an idea about the quality of the mortars produced in this study and to establish a relationship between the other engineering properties and UPV values. According to this classification, the geopolymer mortar produced in this study can be regarded as moderate-quality mortar. However, incorporating the CR into the geopolymer mortar caused decreases in the UPV values, correspondingly in the quality of mortar. The main reason behind this situation is the macro-scale porosity formations in the geopolymer mortar. Such porous structures in the

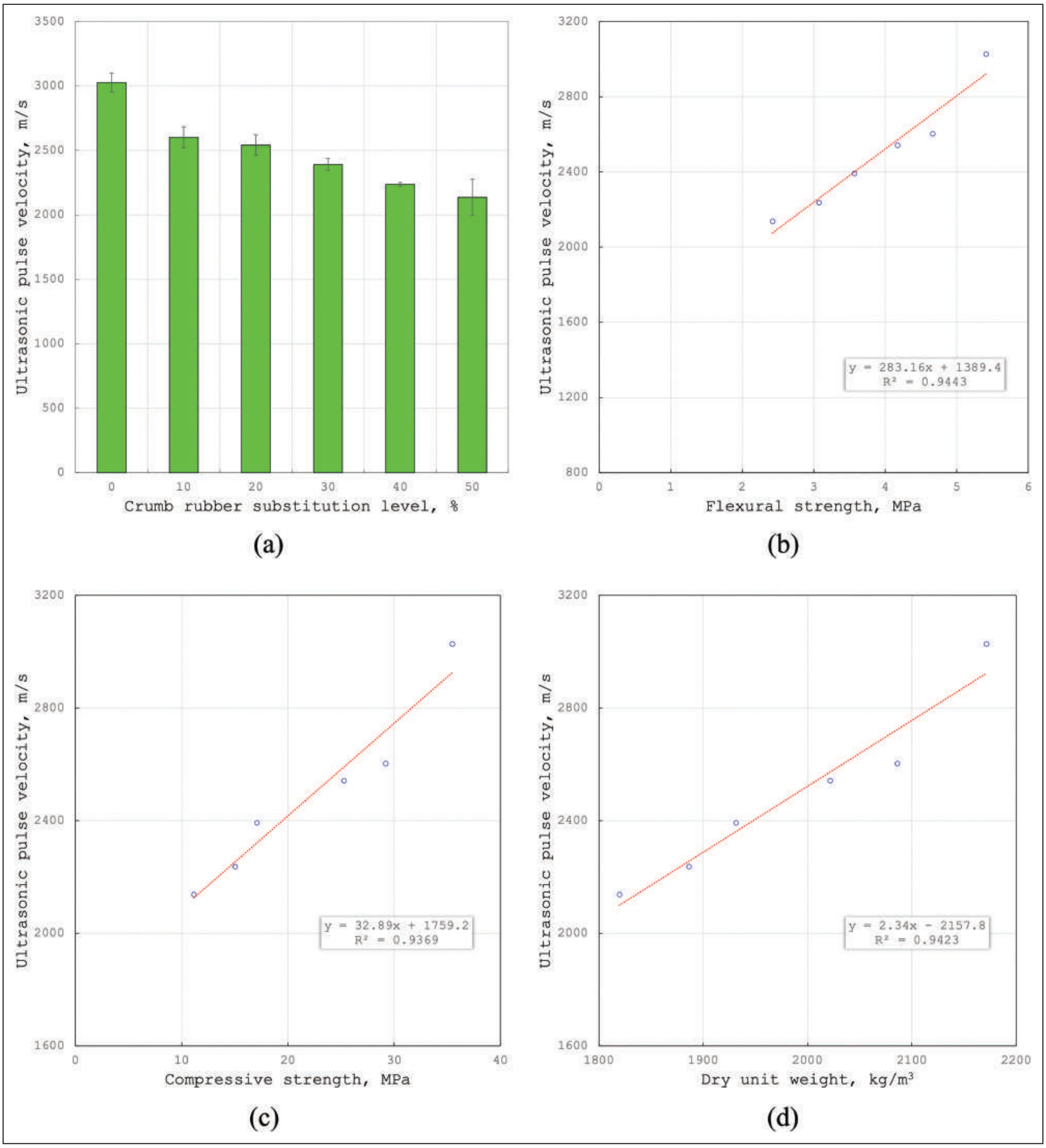

Figure 7. **(a)** Variation in UPV values of the geopolymer mortars due to the CR incorporation and the correlation between the UPV values and **(b)** flexural strength, **(c)** compressive strength, and **(d)** dry unit weight.

hardened mortar prevent and/or delay the transferring of the ultrasonic waves from the transmitter to the receiver. For this reason, there is to be a decrease in the UPV values. But it should be also stated that the decrease in UPV values of geopolymer mortar due to the CR incorporation may be also caused by the nature of the rubber. As it is well-known, the rubber material is a perfect isolation material for waves having any frequency. Therefore, the ultrasonic pulse waves may have been absorbed by the rubber particles during the transfer from the transmitter to the receiver. As can be seen in Figure 7a, the geopolymer mortars produced with CR had UPV values of less than 3000 m/s and more than 2100 m/s. About 30% reduction in the UPV value of geopolymer mortar was observed when the 50% of RS was substi-

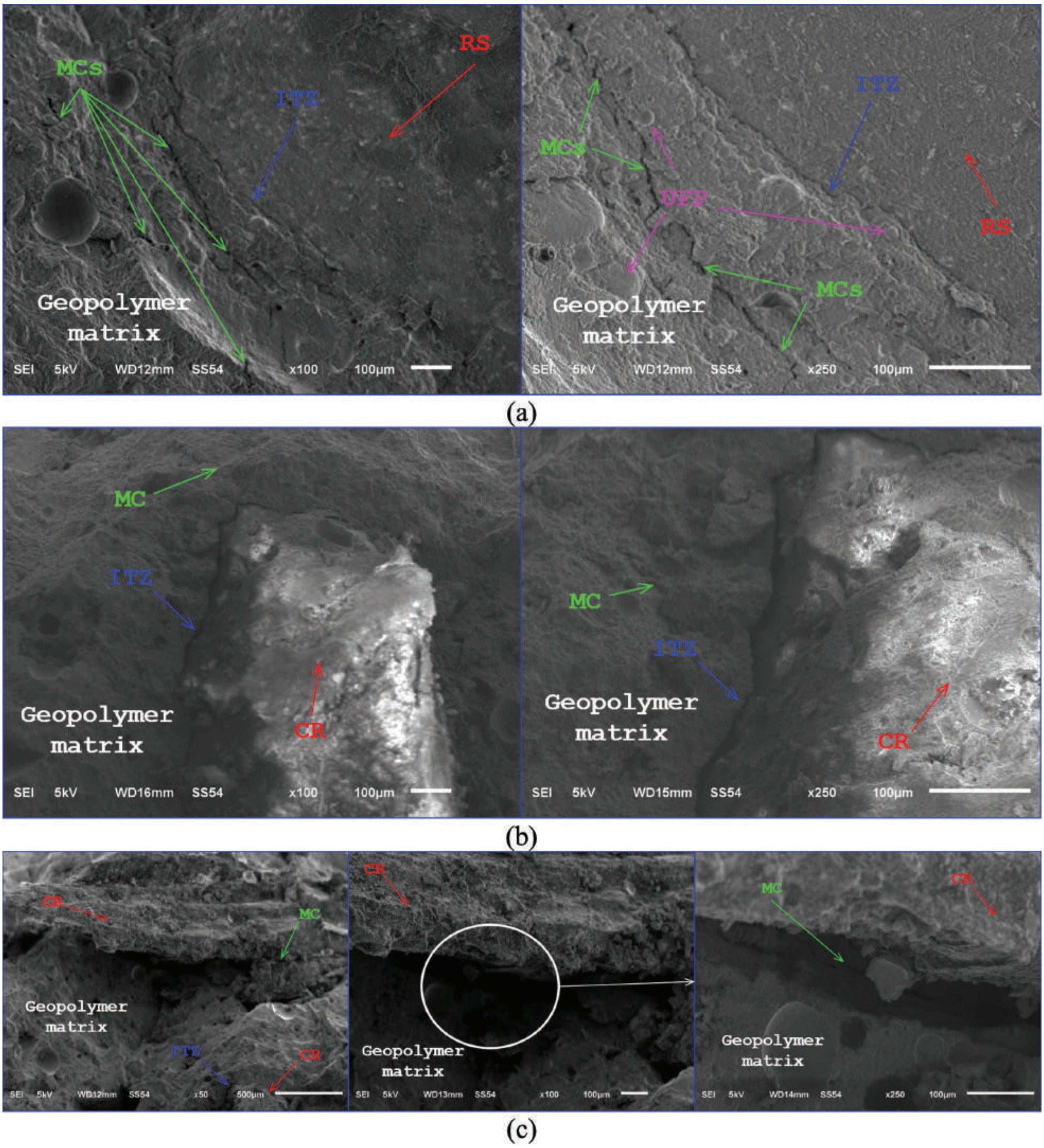

Figure 8. SEM images of **(a)** control geopolymer mortar mixture and **(b)** and **(c)** rubberized geopolymer mortar mixtures.

tuted with CR. In this context, the rubberized geopolymer mortars produced in the present study can be considered poor-quality mortars with respect to the classification presented by Hwang et al. [35].

On the other hand, in order to establish the relationship between the engineering properties of the geopolymer mortars and their UPV values, a binary correlation was used. In this regard, Figures 7b, 7c, and 7d indicate the correlations between UPV values and flexural strength, compressive strength, and dry unit weight, respectively. When the correlations between the UPV values and the aforementioned properties of the geopolymer mortars are investigated, it will be seen that there are strong relationships with the R2 values of more than 0.93 between the UPV values and the flexural strength, compressive strength, and dry unit weight of the geopolymer mortars. This does not only show how

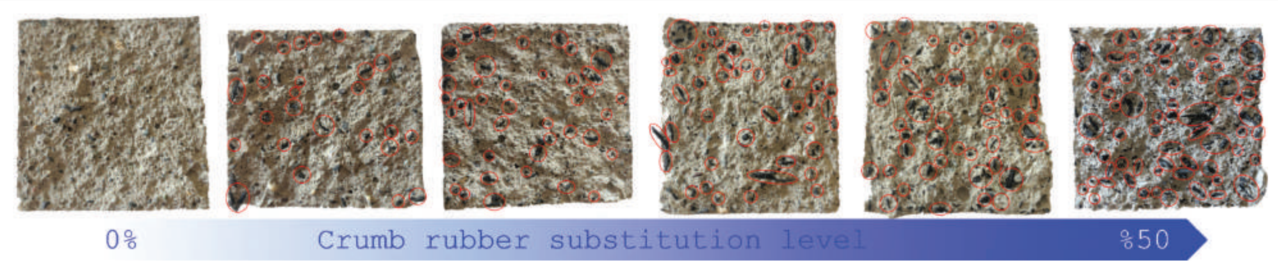

Figure 9. Cross-sections of hardened geopolymer mortar mixtures.

the interactive relations between these properties are well but also indicates that the experimental program conducted in this research has been properly carried out.

3.5. SEM Analysis and Visual Observation

Here, the SEM images of both control and rubberized geopolymer mortars are presented and discussed. Two SEM images (x100 and x250 zoom-in) of the control geopolymer mortar are given in Figure 8a. Similarly, the SEM images presented in the same zoom-in of the rubberized geopolymer mortar are given in Figure 8b; however, in addition to this, three SEM images (x50, x100, and x250 zoom-in) of another rubberized geopolymer mortar are presented in Figure 8c. When the SEM images of the control mixture are investigated, a distinct ITZ between the geopolymer paste and RS particle (as shown with blue arrows) can be noticed. Besides, there are detected to be microcracks (as shown with green arrows) and unreacted and partially reacted fly ash particles on the geopolymer matrix (as indicated with pink arrows). In a similar way, when the SEM images of rubberized geopolymer mortars are investigated, more distinct ITZs between the geopolymer paste and CR particles will be sighted. The ITZ between the CR and the geopolymer paste is more distent in the SEM pictures than it is between the RS and the geopolymer paste. Such distinct ITZ formations decrease the interlock between the particle and paste, thus resulting in lower mechanical performances. Furthermore, SEM scans revealed certain gap areas around the CR particles (Fig. 8c). Such gap regions around the fine particles reduce the permeability resistance of the geopolymer mortars.

In addition to the observation based on the microscopic scale, the CR distributions on the cross-section of the geopolymer mortars were visually observed. One of the difficulties faced during the production of such types of mortars is the bleeding in the mortar and relevantly the inhomogeneous distribution of rubber particles and segregation issues. Since the CR particles are lighter than the geopolymer paste, they have a tendency to move up, leading to the separation of the geopolymer paste and CR particles. As a result, in such types of materials, there occurs a layer consisting of CR particles and paste at the top of the cross-section, and there occurs another paste layer immediately below this layer. Such problems need a very sensitive mixture design. Figure 9 is presented to display the bleeding detection and distribution of rubber particles on the cross-section of mortars produced in the present study. When the cross-sections of the geopolymer mortars illustrated in this figure are investigated, it will be seen that these layers did not occur in any mortar mixtures, and besides, the visually detected CR particles are homogeneously distributed on the mortar cross-sections. In other words, it can be stated that no bleeding and relevant segregation problems were observed in the mortar mixtures produced in the current study.

4. CONCLUSIONS

Based on the findings given above, the following conclusions can be done:

- The flowability of geopolymer mortar was not affected by CR incorporation and increasing its substitution level.
- Substituting the RS with CR and increasing its level systematically decreased the unit weight of the geopolymer mortar. After a 30% substitution level, lightweight geopolymer mortar was achieved. As the geopolymer mortars dried, there was a unit weight loss ranging from 1% to 5% for the first day and ranging from 0.5% to 2.5% for the following two days.
- Incorporating the CR into the geopolymer mortar led to a reduction in both flexural and compressive strengths.
- UPV values of the geopolymer mortars decreased by incorporating the CR since the CR particles cause a porous structure in the hardened mortar and have a wave absorption nature.
- The binary correlation results revealed that there is a strong relationship between the investigated engineering properties.
- SEM images showed that the ITZ occurring between the CR particles and geopolymer matrix is more distinct than that occurring between the RS particles and geopolymer matrix.
- Visually inspection of the cross-sections of the rubberized geopolymer mortars indicated that no bleeding and relevant segregation problems occurred and the CR particles are homogeneously distributed on the mortar cross-sections.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The author declared that this study has received no financial support.

PEER-REVIEW

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