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Properties of Concrete Containing Rubber Aggregate Derived From Discarded Tires

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Abstract

This study carried out the experiment to evaluate the effects of different contents and sizes of rubber particles derived from discarded tires used for replacing fine and coarse natural aggregates, on the workability of fresh rubberized concrete and the compressive and flexural strengths of hardened rubberized concrete. The study results showed that the workability of fresh rubberized concrete was improved when replacing natural fine aggregate (sand) with fine rubber particles (2.5-5 mm) at the replacing proportions of 30-50% by volume, and when replacing natural coarse aggregate (crushed stone) with coarse rubber particles (5-20 mm) at the replacing proportions of 10-30% by volume. With respect to the mechanical properties of hardened rubberized concrete, a larger reduction in the compressive and flexural strengths was generally found when the replacing proportions increased and when coarse aggregate rather than fine aggregate was replaced by rubber particles at all replacing proportions (10-50%). However, the study results also indicated that using fine rubber particles for replacing fine natural aggregate at the low replacing proportion (up to 10%) might not cause the significant effect on the compressive and flexural strength of rubberized concrete.

Keywords: Discarded tire rubber, Fine and coarse rubber particle, Rubberized concrete, Workability, Mechanical properties.

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Ethical: This study follows all ethical practices during writing.

Contents

1. Introduction

It has been estimated that 1000 million tires reach the end of their useful life every year. By the year 2030, the number can reach up to 1200 million tires representing almost 5000 million tires (including stock piled) to be discarded on a regular basis [1]. The development and enforcement of regulations and guidance on collection, storage and separation, transport, processing, disposal, and recycling activities for discarded tires in several countries such as USA, Japan, Korea, and Taiwan has brought a number of environmental and economic benefits in those countries [2]. However, in many developing countries including Vietnam, there are lacking of such regulations and guidance in place. In these countries, discarded tires have been largely treated in unsustainable manners. At present, enormous quantities of discarded tires are already stockpiled (whole tire) or landfilled (shredded tire). Such stockpiles pose serious environmental and health threats which could have severe long-term effects if not properly addressed. Improperly stored tires are potential breeding grounds for disease-carrying insects and rodents. Discarded tire landfilling is responsible for a serious ecological threat. Mainly discarded tires disposal areas contribute to the reduction of biodiversity as the tires hold toxic and soluble components. Secondly although discarded tires are difficult to ignite, this risk is always present. Once tires start to burn down due to accidental causes, high temperature takes place and toxic fumes are generated which causes air pollution problem [3] besides the high temperature causes tires to melt, thus producing an oil that will contaminate soil and water [4]. In order to properly dispose of huge amount of discarded tires, use of innovative techniques to recycle them is important. Worldwide, discarded tires have been recycled for different purposes such as energy recovery (use of tire derived fuel in cement kilns, paper mills or power plants); tire pyrolysis for producing gas, oil, and char [5] civil engineering applications (lightweight fill for embankments and retaining walls, leachate drainage material and alternative daily cover at municipal solid waste landfills, insulating layer beneath roads and behind retaining walls, etc.) [6-9].

On the other hand, consumption of natural aggregates (river sand, stone, etc.) for concrete production is rapidly increasing in countries around the world in order to meet the increasing needs of infrastructural development in the recent years. Due to the overexploitation in many countries, the availability of these natural aggregates has been decreasing [10, 11]. The increasing shortage of natural aggregates has created an opportunity for using by-products as fine aggregate. Reuse of waste rubber derived from discarded tires as a partial or full replacement of natural aggregates in construction activities not only reduces demand for exploitation of natural raw materials, but also reduces environmental pollution problems associated with disposal of discarded tires [12]. In this regard, a number of studies on the use of rubber aggregate derived from discarded tire for replacing natural aggregates in concrete have been conducted recently. Rubber aggregates are obtained from discarded tires using two different technologies: mechanical grinding at ambient temperature and/or cryogenic grinding at a temperature below the glass transition temperature [13, 14]. Although previous studies have achieved encouraging results, there are still several aspects related to the effects of replacing volume for traditional aggregates by rubber aggregate and the effects of size and shape of rubber particles on the mechanical properties of concrete, that need to be further studied. This paper presents the results of the first ever study in Vietnam which aims to investigate the effects of different contents and sizes of rubber particles derived from discarded tires used as aggregates for replacing fine and coarse natural aggregates on the workability of fresh rubberized concrete, the compressive and flexural strengths of hardened rubberized concrete.

Table-1. Major properties of materials

Properties	Unit	Values
1. Portland cement PC40		
Fineness: particles retained on 90 µm sieve	%	0
Specific gravity	g/cm³	3.10
Initial time of setting	Minute	105.00
Final time of setting	Minute	180.00
Compressive strength at 3 days ± 45min	MPa	28.80
Compressive strength at 28 days ± 8 hours	MPa	46.70
2. Fly ash		
Total content of SiO_2, Al_2O_3, Fe_2O_3	%	90.51
Fineness: particles retained on 45 µm sieve	%	23.20
Water absorption	%	2.00
Strength activity index • At 7 days • At 28 days	%	80.10 84.80
3. Sand		
Specific gravity	g/cm³	2.60
Water absorption	%	2.10
Fineness modulus	mm	2.65
4. Crushed stone		
Specific gravity	g/cm³	2.65
Water absorption	%	1.50
Fineness modulus	mm	6.48
5. Rubber		
Specific gravity	g/cm³	1.17
Water absorption	%	0
Particle size • Fine • Coarse	mm	2.50 - 5.00 5.00 - 20.00

2. Experimental Study

2.1. Materials

In this study, the ordinary Portland cement PC 40 and fly ash (FA) were used as the binders. The physical, chemical and mechanical properties of the Portland cement and FA are given in Table 1. The Portland cement PC 40 is produced by the local company named JSC Vicem But Son Cement with its properties determined according to [15-17]. The percentage of cement retained on a 90 μm sieve as specified by Vietnam Standard [15] was 0 %. The FA was obtained from the local power plant (Pha Lai Power Plant in Hai Duong province, Northeast of Vietnam). According to ASTM C618-15 [18] the FA can be classified as a class F fly ash due to its chemical composition. In addition to having pozzolanic properties, this type of FA also has some cementitious properties. The total content of SiO_2, Al_2O_3, and Fe_2O_3 in FA is 90.51%, which is larger than the value given by the ASTM C618-15 standard for class F fly ash. The amount of FA retained on a 45 μm sieve was 23.20%, which is less than the value given in ASTM C618-15 standard [18].

Sand and crushed stone were used as fine and coarse aggregates in the concrete mix, respectively. The major properties of these materials were determined following [19] and given in Table 1. The sand used complies to the description of ASTM C778 [20] and its gradation was in agreement to the requirement of ASTM C33/C33M [21]. In this study, the size of crushed stone was in the range of 5-20 mm. Coarse (5-20 mm) and fine (2.5-5 mm) rubber particles used in the experiment were obtained from mechanical shredding of discarded tires. The physical properties of rubber particles are shown in Table 1.

2.2. Concrete Mix Design

Eleven different mix designs (M0-M10) were considered in this study. The control design (M0), containing no rubber, was determined using the absolute volume method, and consisted of 332 kg of cement, 58.5 kg of FA, 680 kg of sand (fine aggregate), 1200 kg of crushed stone (coarse aggregate), 155 kg of water, 2.73 kg of superplasticizer, and all per cubic meter of mix. The other five mixes (M1-M5) had fine aggregate replaced by fine rubber particle of equal volume, in 10% increments, up to 50% rubber replacement. Similarly, the remaining five mixes (M6-M10) had coarse aggregate replaced by coarse rubber particle of equal volume, in 10% increments, up to 50% rubber replacement.

Table-2. Concrete mix design (calculated for 1m^3 concrete)

Mix ID	Cement	Fly ash	Sand	Crushed stone	Water	Fine rubber particle		Coarse rubber particle		Superplasticizer
	Weight (kg)	Weight (kg)	Weight (kg)	Weight (kg)	Weight (kg)	Weight (kg)	% by volume	Weight (kg)	% by volume	Weight (kg)
M0	332	58.5	680	1200	155	0	0%	0	0%	2.73
M1	332	58.5	612	1200	155	30.18	10%	0	0%	2.73
M2	332	58.5	544	1200	155	60.35	20%	0	0%	2.73
M3	332	58.5	476	1200	155	90.53	30%	0	0%	2.73
M4	332	58.5	408	1200	155	120.71	40%	0	0%	2.73
M5	332	58.5	340	1200	155	150.88	50%	0	0%	2.73
M6	332	58.5	680	1080	155	0	0%	52.27	10%	2.73
M7	332	58.5	680	960	155	0	0%	104.53	20%	2.73
M8	332	58.5	680	840	155	0	0%	156.80	30%	2.73
M9	332	58.5	680	720	155	0	0%	209.07	40%	2.73
M10	332	58.5	680	600	155	0	0%	261.33	50%	2.73

The amount of cement, FA, water, and superplasticizer were all held constant, to reduce the number of variables and maintain a water-to-cement ratio of 0.47 for all mixes. The weights of aggregates and rubber in each mix can be found in Table 2.

2.3. Specimen Preparation and Test Setup

a. Slump Test

In order to evaluate the effect of rubber particles derived from discarded tires replacing natural aggregates on the workability of fresh rubberized concrete, slump tests were performed for all mixes (Table 2) according to Vietnam Standard [22].

b. Compressive Strength Test

The compressive strength tests were performed for all mixes according to Vietnam Standard [23] in order to evaluate the effect of fine and coarse aggregate replacement with fine and coarse rubber particles, respectively, on the compressive strength of hardened concrete. Mix proportions used to prepare specimens for the compressive strength tests were those presented in Table 2. One set of three cubic specimens with a side of 150 mm was realized for each mixture studied. Specimens were cast using appropriate moulds placed on a vibration table for 60 seconds in order to obtain a more homogeneous distribution of rubber particles in concrete mix. After casting, the moulds were left to cure for 24 hours. Once hardened, specimens were accurately demoulded, placed in a curing room at a relative humidity of 75% and a temperature of 27 ± 2 °C until testing time. The compressive tests were then carried out for both 7 and 28 day aged specimens by an oil-pressure machine under loading control with a capacity of 3,000 kN and the loading rate of 0.4 MPa/s.

c. Flexural Strength Test

The flexural strength tests were also performed for all mixes according to Vietnam Standard [24] in order to evaluate the effect of fine and coarse aggregate replacement with fine and coarse rubber particles, respectively on the flexural strength of hardened concrete. Employed mix proportions for preparing specimens for the flexural strength tests were the same presented in Table 2. One set of three specimens with measuring 150 × 150 × 600 mm was cast for each mix design. The casting and curing procedures were similar to those reported above for the compressive strength tests. For the flexural strength test, three specimens from each mix design were tested by one-point loading configuration with a span of 10 cm using testing machine with a capacity of 10 kN and the loading rate of 0.06 MPa/s. All tests were carried out 28 days after casting.

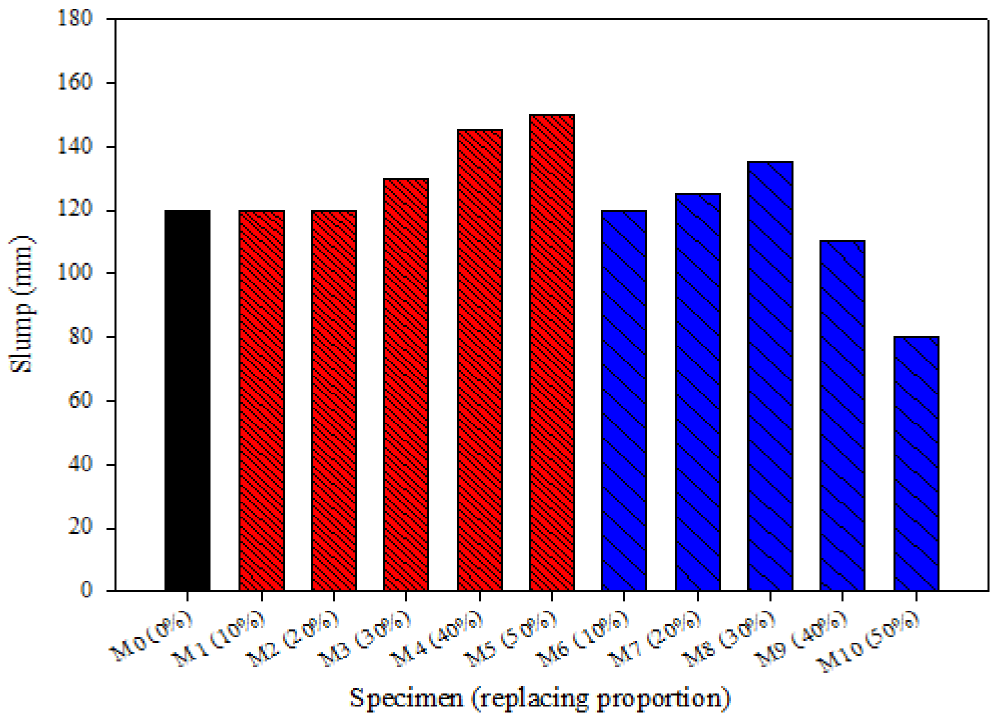

Figure-1. Impact of proportion and size of rubber particles replacing fine and coarse aggregates on slump of fresh rubberized concrete

3. Results and Discussions

3.1. Workability of Fresh Rubberized Concrete

The results of slump tests are shown in Figure 1. When sand (fine aggregate) was replaced by fine rubber particle at the low proportions (10% and 20% by volume), it can be seen that the slumps or workability of fresh rubberized concrete were not changed much compared to that of the control mix (M0). At the higher replacing proportions (30%, 40% and 50% by volume), the slumps relatively increased. Our results are in good agreement with those reported by previous studies [25-29] where the workability of fresh rubberized concrete increased with increasing rubber contents. For instances, Aiello and Leuzzi [26] showed that the workability of rubberized concrete was slightly improved when coarse or fine aggregates were partially replaced with rubber shreds. They reported that the control concrete exhibited a fluid behavior, while the rubberized concrete showed a hyper-fluid behavior. Similarly, Balaha, et al. [25] used ground waste tire rubber for partial replacement of natural sand at the proportions of 0%, 5%, 10%, 15% and 20%, by volume and they reported that the workability increased as rubber sand content increased. However, it is worth to note that the other studies reported contrary results with the decreased workability as rubber aggregates included in the concrete mixture [30-33].

When crushed stone (coarse aggregate) was partially replaced by coarse rubber particle at the low and medium proportions (10%, 20%, and 30% by volume), it was observed that the slumps slightly increased in comparing to that of the control mix. However, when the replacing proportion increased to 40%, the slump slightly decreased. Especially, at the replacing proportion of 50%, the slump was found to be decreased significantly. This can be explained that when coarse rubber particles were used at high proportion, the contacts among coarse rubber particles and among rubber particles with other aggregates increased leading to the increase in the inter-particle friction between rubber particles and other aggregates, thus reduce the workability of fresh rubberized concrete. Our slump test results for the case of coarse rubber particle replacing coarse aggregate are also similar to those reported by the other studies [1, 34-40]. Turgut and Yesilata [35] partially replaced sand in concrete block mixtures with rubber aggregate at the proportions ranging from 10% to 70% with an increment of 10%, by volume. Their results showed that the workability increased with the inclusion of rubber aggregate up to 40%, whereas the inclusion of 50-70% rubber aggregate caused the decreased workability. Pacheco-Torgal, et al. [1] reported that when rubber chips used to partially replace for coarse aggregate, the slump increased with increasing volume of rubber aggregates up to the replacing proportion of 15%, and the slump decreased as the replacing proportions were larger than 15% by volume. Compared results on the workability of fresh rubberized concrete between this study and other studies suggest that the workability may be largely dependent on the specific characteristics of the rubber aggregates used in the concrete mixture. Therefore, future studies should focus more on the characteristics of rubber aggregates (size, shape, pretreatment of rubber aggregates, etc.) that influence the workability of rubberized concrete.

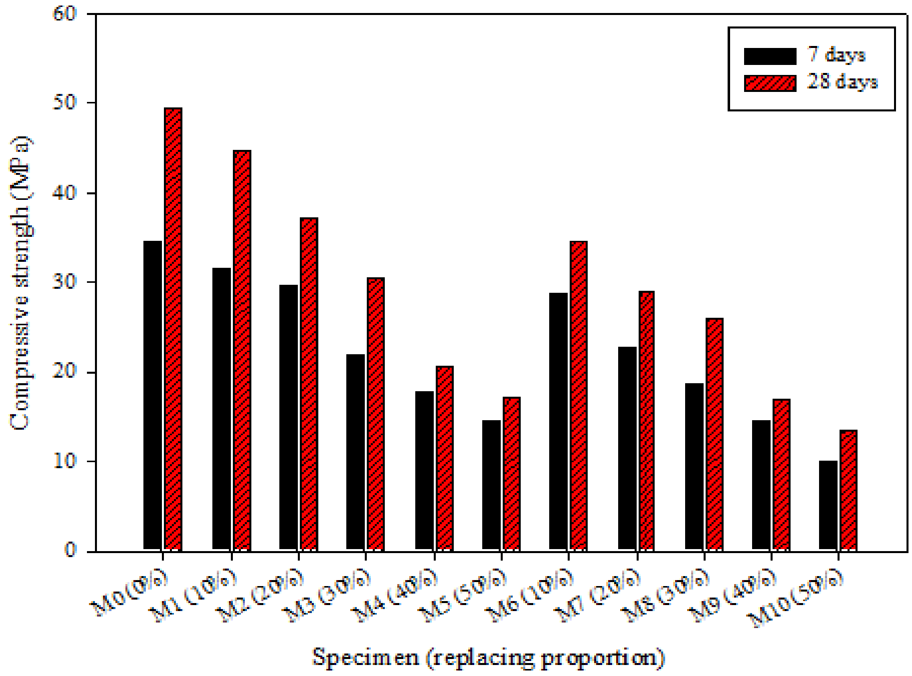

Figure-2. Impact of replacing proportion and size of rubber particles on compressive strength of hardened rubberized concrete

3.2. Mechanical Properties of Hardened Rubberized Concrete

a. Compressive Strength

The 7-day and 28-day compressive strengths as a function of different replacing proportions of rubber particles with different sizes are presented in Figure 2. As expected, the compressive strength increased with curing time for the control specimen (M0) and other specimens (M1-M10) at all replacing proportions. The compressive strength of the control specimen was evaluated as 34.5 and 49.5 MPa at 7 and 28 days, respectively. The test results indicated that there was a significant reduction in the compressive strength of rubberized concrete as the rubber content increased in comparison to that of the control specimen at both 7 and 28 days.

Table-3. Reduction (%) in compressive strength of rubberized concrete compared to plain concrete

	Cured time (day)	Specimen (Proportion of natural aggregates replaced with rubber particles, % by volume)					
		M0 (0%)	M1 (10%)	M2 (20%)	M3 (30%)	M4 (40%)	M5 (50%)
Reduction (%) in compressive strength of rubberized concrete using fine rubber particle to replace fine aggregate	7	0	8.7	14.2	36.5	48.4	57.7
	28	0	9.7	24.8	38.2	58.4	65.5
		M0 (0%)	M6 (10%)	M7 (20%)	M8 (30%)	M9 (40%)	M10 (50%)
Reduction (%) in compressive strength of rubberized concrete using coarse rubber particle to replace coarse aggregate	7	0	16.2	34.2	45.8	58.0	71.0
	28	0	30.3	41.4	47.5	65.7	72.7

It is found that depending on the proportion and size of replacing rubber particles, the degree of reduction in the compressive strength was different (Table 3). At the replacing proportion of 10%, the reduction in the compressive strength of the specimens containing fine rubber particles at 7 and 28 days were 8.7 and 9.7%, respectively; whilst the counterpart for the specimens containing coarse rubber particles at 7 and 28 days were 16.2 and 30.3%, respectively. This suggests that using coarse rubber particles lowered the compressive strength of rubberized concrete more than the case of using fine rubber particles. When the replacing proportions increased to 20, 30, and 40% by volume, the compressive strengths also decreased accordingly, however, the degrees of reduction between two cases (the specimens containing fine and coarse rubber particles) at the same replacing proportions gradually became smaller than that at the replacing proportion of 10%, especially for the specimens at the curing time of 28 days. The replacing proportion of 50% caused the largest reductions in the compressive strength of specimens containing fine and coarse rubber particles at both 7 and 28 days. The test results imply that using fine rubber particles, instead of fine natural aggregate, at the low replacing proportion (up to 10%) might not cause the significant effect on the compressive strength of rubberized concrete. Overall, our results agreed well with previous studies which reported that the inclusion of increasing rubber contents caused progressive losses in the compressive strength of rubberized concrete and the replacement of coarse aggregate in the concrete mixture lowered the compressive strength more than that of fine aggregate [26, 31, 40-44].

There are several possible reasons for the reduction in the compressive strength of rubberized concrete which largely influenced by the physical and mechanical properties of constituent aggregates. First, it could be attributed to the physical properties of rubber particles which are less stiff than cement paste. This could lead to the deformability of rubber particles compared with surrounding cement paste that resulted in the rapid development of cracks around rubber particles in a fashion similar to that occurring with air voids in normal concrete [41, 45, 46]. The second reason for the decrease in the compressive strength is the poor bond between rubber particles and cement paste in comparing to the bond between natural aggregates and cement paste. Corinaldesi, et al. [47] and Raj, et al. [48] indicated that the low strength of rubberized concrete is due to the weak interface or transition zone between rubber particles and cement paste. Such a weak interface could initially cause micro-cracks which eventually grow to macro-cracks, and result in the failure of rubberized concrete specimen under compression. Our test results showed the surfaces of the failed specimens having quite clean rubber particles with little cement paste attached which implies the poor bond between rubber particles and cement paste. The third reason for the reduction in the compressive strength of rubberized concrete might be associated with the low specific gravity of rubber, coupled with the poor bond of rubber particles with other aggregates, which might make rubber particles moving upwards during vibration in the casting process and concentrating at the top layer of the specimen. This could result in a non-homogeneous distribution of rubber particles and other aggregates, and therefore reduce the strength of the specimen. The other reason for the decreased compressive strength could be the increased matrix porosity or weakness points in rubberized concrete matrix which largely depending on the size, density, and hardness of aggregates as explained by the previous studies [45, 49, 50].

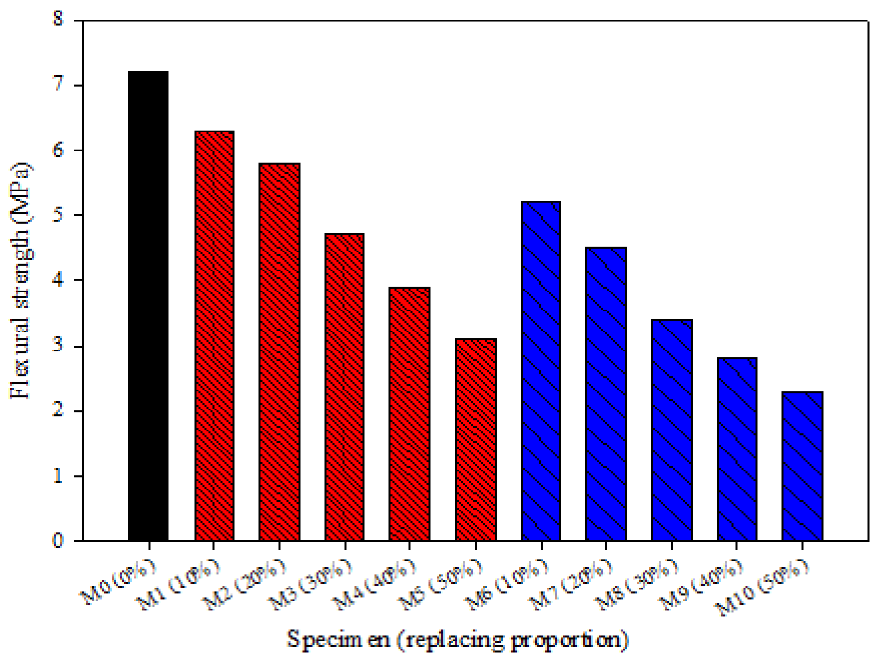

Figure-3. Impacts of replacing proportion and size of rubber particles on flexural strength at 28 days of hardened rubberized concrete

b. Flexural Strength

The influences of different replacing proportions and different sizes of rubber particles on the 28-day flexural strengths of rubberized concrete are presented in Figure 3. The flexural strength at 28 days of the control specimen was 7.2 MPa. Similar to the case of the compressive strength, the test results indicated that there were significant reductions in the flexural strength of rubberized concrete specimens compared to the control specimen when replacing proportions increased.

Table-4. Reduction (%) in flexural strength at 28 days of rubberized concrete compared to plain concrete

	Specimen (Proportion of natural aggregates replaced with rubber particles, % by volume)					
	M0 (0%)	**M1 (10%)**	**M2 (20%)**	**M3 (30%)**	**M4 (40%)**	**M5 (50%)**
Reduction (%) in flexural strength of rubberized concrete using fine rubber particle to replace fine aggregate	0	12.5	19.4	34.7	45.8	56.9
	M0 (0%)	M6 (10%)	M7 (20%)	M8 (30%)	M9 (40%)	M10 (50%)
Reduction (%) in flexural strength of rubberized concrete using coarse rubber particle to replace coarse aggregate	0	27.8	37.5	52.8	61.1	68.1

The degree of reduction in the flexural strength was also largely influenced by the size of replacing rubber particles as shown in Table 4. As expected, a smaller reduction of the flexural strength was observed when fine aggregate was replaced by fine rubber particle, compared to the case of coarse rubber particle, for all replacing proportions. This could be attributed to the filling effect of fine rubber particles that increase the compactness of rubberized concrete specimens, reduce the stress singularity at internal voids, and thus reduce the likelihood of fracture [51]. The test results suggest that using fine rubber particles for replacing fine natural aggregate at the low replacing proportion (up to 10%) might not cause the significant effect on the flexural strength of rubberized concrete which similar to the case of the compressive strength.

Similar test results were reported by the previous studies [26, 41, 51]. For instances, Aiello and Leuzzi [26] reported that rubberized concrete with the inclusion of 50% and 75% by volume of coarse aggregate replacement presented 28% decrease in the flexural strength compared to plain concrete. Whereas, rubberized concrete obtained with 50% and 75% by volume of fine aggregate replacement showed a decrease in the flexural strength of about 5.8% and 7.3%, respectively compared to plain concrete. However, it is worth to note that the other studies have reported quite different results compared to ours with the increased flexural strength of rubberized concrete when rubber aggregate used to replace fine aggregate at the low replacing proportions (mainly less than 20% by volume), and the decreased flexural strength at the high replacing proportions. For instances, Yilmaz and Degirmenci [42] reported that rubberized concrete specimens using tire rubber (in the form of fibers) up to 20% by volume showed the higher flexural strength than control specimens, and the flexural strength decreased as rubber contents increased from 20-30%. Gupta, et al. [52] reported that the flexural strength of rubberized concrete containing rubber ash decreased as the content of rubber ash increased, whereas the flexural strength of modified concrete (containing 10% rubber ash and a varying content of rubber fibers) increased with the increasing content of rubber fibers. These studies showed that the increased flexural strength of rubberized concrete associated with the use of tire rubber in the form of fibers. This further suggests that future studies should focus on the characteristics of the rubber aggregates that enhance the flexural strength of rubberized concrete.

4. Conclusions

This study has conducted the experiment to investigate the properties of fresh and hardened rubberized concrete made by replacing natural aggregates with rubber particles derived from discarded tires having similar sizes of replaced natural aggregates. The major findings of this study can be summarized as the following:

- The workability of fresh rubberized concrete improved when replacing natural fine aggregate with fine rubber particles at the replacing proportions of 30-50% by volume, and when replacing natural coarse aggregate with coarse rubber particles at the replacing proportions of 10-30% by volume;
- With respect to the mechanical properties of hardened rubberized concrete, a larger reduction in the compressive and flexural strengths was generally observed when replacing proportions increased, and especially when coarse aggregate rather than fine aggregate was replaced by rubber particles at all replacing proportions (10-50% by volume).
- Using fine rubber particles for replacing fine natural aggregate at the low replacing proportion (up to 10%) might not cause the significant effect on the compressive and flexural strength of rubberized concrete.

Based on the findings of this study, further studies are recommended to verify the workability and the mechanical properties of rubberized concrete mixtures prepared by partially replacing both natural coarse and fine aggregates, and to evaluate effects of specific characteristics (e.g. size, shape, pretreatment) of rubber aggregates on the workability and the mechanical properties of rubberized concrete, especially characteristics that could increase the mechanical properties of rubberized concrete.

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