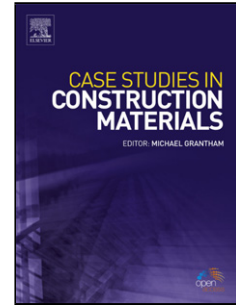


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Rubber Concrete: Mechanical and Dynamical Properties

Najib N. Gerges, Camille A. Issa, Samer A. Fawaz

Najib Gerges is a Professor at the University of Balamand, el-Koura, Lebanon (e-mail: najib.georges@balamand.edu.lb).

Camille Issa is a Professor at the Lebanese American University, Byblos, Lebanon (e corresponding author e-mail: cissa@lau.edu).

Samer A. Fawaz is a Ph.D. candidate (e-mail: samer_fawaz@hotmail.com)

Abstract — The purpose of this paper is to report on an experimental study that explores the effect of using recycled rubber powder as an alternate fine aggregate in concrete mixes. Natural sand in the concrete mixes was partially replaced by 5%, 10%, 15%, and 20%. Physical properties such as the density, the compressive strength, the fresh concrete properties, the split-tension, and the impact load capacity are examined. The results revealed a decrease in the compressive strength of concrete cylinders containing rubber. The dynamic performance of the rubber concrete is of high importance because of its high resilient nature, as the rubber particles that are included in the concrete have a positive effect on the dynamic performance. The conclusions that were derived from this research implicate potential applications where rubberized concrete can be efficiently used. Even though rubberized concrete mixture generally has a reduced compressive strength that may limit its use in certain structural applications, it possesses a number of desirable properties, such as lower density, higher toughness, and higher impact resistance compared to conventional concrete.

Keywords—Rubberized Concrete; Compressive Strength; Splitting Tensile Strength; Impact Load.

I. INTRODUCTION

Countries and cities have been faced with major increasing problems with the disposal of recycled materials, such as rubber, glass, and plastics for several years. The consumption of the world's rubber has nearly reached 24.9 million tons in year 2010. In the U.S. alone, approximately 3.9 million tons of scrap tires are produced every year, out of which 1.36 million tons are recycled and 2.54 million tons are burned or land-filled. In view of the wide and vast market for scrap tires, about a quarter of all scrap tires end-up in landfills numbering to approximately 27 million tires or roughly 6 million tons annually, making-up over 12% of all solid waste. The disposal of the scrap tires materials become very costly once they are sent to landfills; not to mention the wide space that they use in landfills to dispose of, and the hazard that they cause towards the environment. Based on this information, the rubber use in concrete and pavement material provides an environmentally sustainable method for disposing of the millions of tires that are annually generated.

Powdered rubber is a general term or an expression given to recycled rubber that is generated from scrap tires. The production of powder rubber consists of removing the steel and fluff, then using a granulator and/or cracker mill, with the aid of cryogenics or mechanical means, in order to reduce the size of the tire particles.

A well-known fact is that tires can be divided into two major groups: automobile tires and truck tires, and they are different from each other. The description of the rubber source is very important and should always be specified in the literature because it has an influence on the texture and the shape, and consequently, on the characteristics of the concrete that is adjusted by the addition of the specified percentage of the rubber. It is also important to point out that automobile tires and truck tires vary not only in shape, weight and size, but above all, in the ratio of the components of the base mixture. Researchers have considered three wide categories of discarded tire rubber concrete mix design:

1. Chipped Rubber: This type of rubber has dimensions of about 25 to 30 mm and used to replace the coarse aggregates in concrete.
2. Crumb Rubber: The particles of rubber are highly irregular, varying between 3 to 10 mm, and are used to replace the fine aggregates.
3. Powdered Rubber: The particles of the rubber are smaller than 1 mm and consist of the powder formed during the crunch process, fallen from the machinery of the plant that is handling the waste rubber. This type of rubber could be used as filler in concrete due to its size.

On the other hand, and for so many years, material researchers have attempted to make concrete a ductile material. It appears, however, that due to the brittle nature of concrete, the most direct and effective approach in creating damage tolerant concrete structures would be to embed intrinsic tensile ductility into concrete. If concrete behaves like steel in tension (highly ductile), while retaining all other advantages (e.g. high and extreme compressive strength), concrete structures with enhanced serviceability and safety can be readily realized.

This research attempts to provide a solution for this worst limitation of concrete, i.e. brittleness and very low tensile strength. Making concrete a ductile material would also improve the impact strength and toughness of the concrete. Another issue would be to seek ways of making the concrete “green” or environmentally friendly through the choice of materials while retaining the core advantages of the concrete. Ductility is a very desirable structural property because it allows the stress re-distribution and allows warning signs of impending failure. The ductile behavior enables the concrete material to have the capacity to deform and support flexural and tensile loads even after initial cracking. One material that is suggested as a possible replacement of mineral aggregates is rubber from used tires. This research focuses on the effect of replacing the fine aggregates (sand) with powdered rubber. A significant difference between mineral aggregates and tire derived aggregates is that individual particles are much more deformable than those of sand, gravel, or rock. Another significant difference is that the unit weight is much lower; therefore, tire derived aggregates can be considered as lightweight aggregates.

II. LITERATURE OVERVIEW

It is estimated that each person discards one car tire per year in the USA. With a population of over 300 million people, it indicates that every year, there is a total of 300 million tires that need to be disposed of [1–3]. Several innovative ways of using these tires have been developed in the last years, and they include tire derived fuel for cement kilns and boilers [1], and tire derived aggregates used as raw materials for civil engineering projects [3]. However, not all tires are consumed in these beneficial ways and the scrap tires that remain are disposed of in various legal and illegal means (disposal of tires in un-permitted areas). The whole disposal of tires is difficult to landfill because tires tend to float back to the surface with time. Stockpiles of scrap tires result in public health, environmental, and aesthetic problems, in addition to being fire hazards [2].

The US government and through the Environmental Protection Agency (EPA), encourages more studies on methods of recycling tires, because of this environmental concern [2]. The use of crumb rubber as a replacement for mineral aggregates in concrete resulted in a vast beneficial use of tires [4, 5]. However, none of the studies have elucidated in any detail the beneficial aspects of crumb rubber and the mechanism by which the properties of crumb rubber reinforced concrete differ from the traditional concrete. Crumb rubber can be a lightweight substitute for mineral aggregates as its density is less than half of that of mineral aggregate. Mineral aggregates have a unit weight or density ranging between 1600 and 2080 kg/m³ while crumb rubber unit weight or density ranges between 640 and 720 kg/m³ [6].

The effect of adding two kinds of crumb rubber and chipped rubber were studied by Khatib and Bayomy [7]. They prepared three groups of concrete mixtures: in group A, crumb rubber was used to replace fine aggregate, while in group B, chipped rubber was used to replace coarse aggregate, and in group C, both types of rubber were used in equal volumes. All the three groups had eight different rubber contents varying between 5 and 100%. It was noticed that there was a decrease in slump with an increase in the rubber content; admixtures made with fine crumb rubber were more workable than those with coarse tire chips or those with a combination of tire chips and crumb rubber.

Hernandez et al. [8] has investigated the dynamic characteristics of rubberized concrete material. The rubberized concrete showed possible advantages in reducing or minimizing the vibration and impact effect due to the unique elasticity properties of the rubber material.

Topcu [9] has examined the physical and mechanical properties of rubberized concretes with initial compressive strength of 20MPa. The amounts of the rubber used in the rubberized concrete were 15%, 30%, and 45% by volume of the total aggregates. This study has concluded that a general reduction in the compressive strength of rubberized concrete has occurred.

As mentioned above, most of the literature review has shown a significant decrease in the mechanical properties of concrete after the addition of tire rubber particles as aggregates. The use of only coarse rubber particles affects the properties of concrete more negatively than do only fine particles. Moreover, the plastic energy capacity of the normal concrete has increased by adding rubber. Due to their high plastic energy capacities, concrete has shown high strains, particularly under the impact effects.

Fattuhi and Clark [10] have proposed that rubberize concrete could possibly be utilized in the following applications:

- 1) In foundation pad for machinery, and in railway stations, where vibrations damping is needed.

- 2) In trench filling and pipe bedding, pile heads, and paving slabs.
- 3) In railway buffers, barriers, and bunkers, where the resistance to impact or blast is required.

Most recently, Gupta et al. [11-12] have extensively explored the effect of the use of a combination of waste rubber and silica fume on the durability and the mechanical properties of the concrete mix. The effect of replacement of fine aggregates by waste rubber fibers with a combination silica fume as of replacement of cement, on the impact resistance of concrete has also been assessed [13].

The main purpose of this study consists of exploring the feasibility of incorporating scrap tires in form of rubber powder as fine aggregates in concrete mixes and to determine its effect on the mechanical properties of the concrete mix. The parameters that were monitored comprised the influence of the rubber content on the mechanical properties of rubberized concrete starting with the 0% rubber content (no rubber) and up to 20% rubber content. The hardened concrete properties like the compressive strength, split tensile strength, and impact load were scrutinized.

Generally, several impact tests procedures have been employed to demonstrate the relative brittleness and impact resistance of concrete and similar construction materials [14-17]. However, none of these tests procedures has been declared a standard test, at least in part due to the lack of statistical data on the variation of the results. In this regard, ACI Committee 544 [18] proposed a drop-weight impact test to evaluate the impact resistance of fiber concrete. The test is widely used since it is simple and economical. Thus, this test was adopted for this study to investigate rubber concrete.

Accordingly, a special impact mechanism (Figure 1) was designed and fabricated according to ACI [18] recommendations relating to the adoption of the drop weight impact test technique. A summary of the impact test is that, the concrete samples are placed on the bottom of the mechanism with a thin layer of petroleum jelly or a heavy grease and placed on the base plate within the positioning lugs with the finished face up (if appropriate) as shown in Figure 2. The positioning bracket is then bolted in place, and the hardened steel ball is placed on top of the specimen within the bracket. The drop hammer is placed with its base upon the steel ball and held there with just enough down pressure to keep it from bouncing off the ball during the test. The base plate is withdrawn to a rigid base, such as a concrete floor or cast concrete block. The hammer is dropped repeatedly, and the number of blows required to cause the first visible crack on the top and to cause ultimate failure are both recorded. Ultimate failure is defined to be the opening of the cracks in the specimen just enough for the pieces of concrete to touch three of the four positioning lugs on the base plate. The results of these tests display a high variability and may vary greatly with the different types of mixtures.

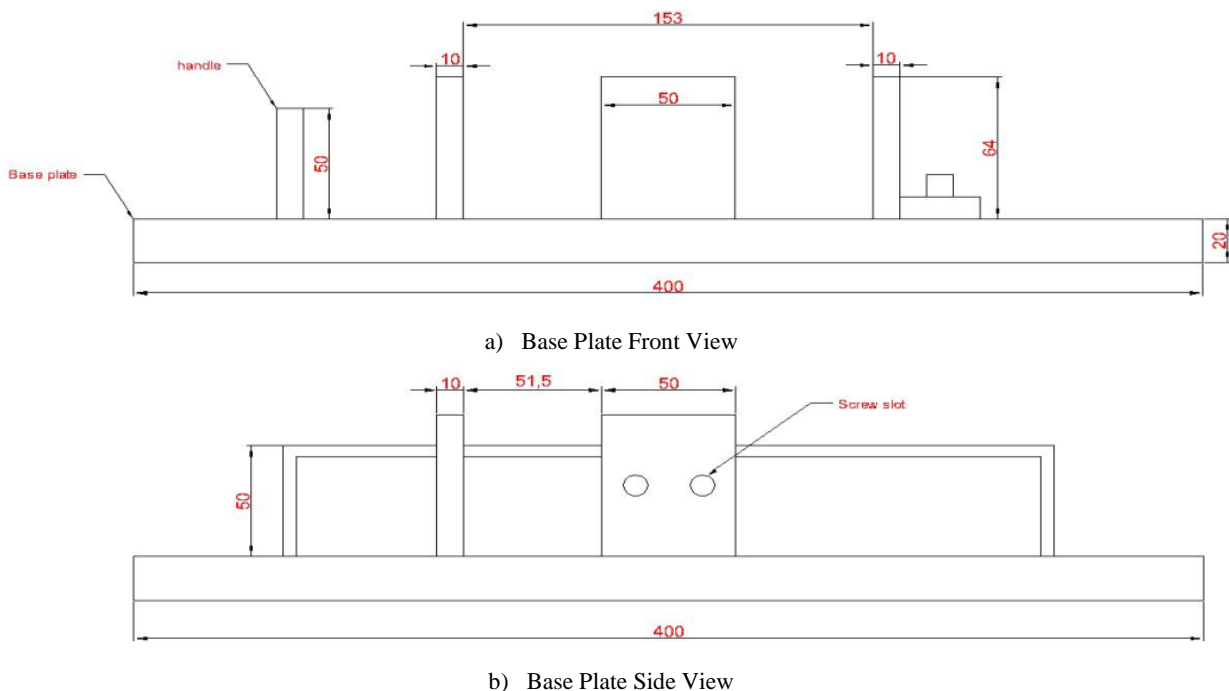


Figure 1: Schematic of Impact Mechanism (Dimensions in mm)



Figure 2 The Fabricated Impact Mechanism

III. EXPERIMENTAL SETUP

In this experimental study, a total of 20 designated concrete mix designs containing 0, 5, 10, 15 and 20 % of partial replacement of fine aggregates with powdered rubber were prepared. Ordinary Portland Cement (OPC) with a specific gravity of 3.15 was used throughout this study. The sand used in the experiment was obtained from a local source with a water absorption rate of 1%. The coarse aggregate that was utilized in the experiment was crushed angular stone aggregates with a maximum size of 20 mm having a specific gravity of 2.67 with a water absorption rate of 0.5%.

The source of the rubber aggregate was recycled tires which were collected from a local tire recycling plant. The gradation of powdered rubber was determined based on the ASTM C136 Standard [19]. The term powdered rubber stands for recycled tire rubber with particle size less than 1mm. A sieve analysis was performed on powdered rubber to fit the sand grain size distribution. The rubber was used without any surface treatment in order to investigate the effect of untreated tire particles on the mechanical properties of concrete. Drinking water with pH value of 7.0 was used in the concrete mix and the curing process of the concrete cylinders. The water was free of acids, organic matters, suspended solids, alkalis, and impurities which when present, may have side effects on the strength of concrete.

Casting of 100 concrete cylinders of 150mm by 300mm was conducted based on ASTM C192 [20]. The cylinders were casted into three layers and each layer was tamped, using a steel rod, moving all around the layer twenty five times. Tamping of the next layer was done without crossing into the previous layer. The surface was finished by rolling the tamping rod over the surface to trim the concrete. The impact resistance of the specimen was determined by using the drop weight method of the Impact Test as recommended by the ACI committee 544 [18]. The size of the specimen recommended is 152mm in diameter and 63.5mm in thickness and the weight of hammer deployed is 4.54 Kg with a drop height of 457mm.

The curing process in concrete prohibits the water in the concrete to disperse and reduce the hydration of cement or to relieve concrete from any water loss. In the curing process, the cylinders mold for the concrete cylinders were covered with plastic sheets (Figure 3) to prevent the evaporation of water. The next day, the concrete cylinders were removed from the mold and placed in a water tank at a controlled temperature for 28 days. Each specimen was labeled with or without rubber and the date of the mix.



Figure 3 Cylinders Covered in Plastic Sheets for Curing

EXPERIMENTAL PROCEDURE

In the mixing process, the concrete was dry mixed using a mechanical mixer; afterwards, water was added gradually and mixed till the homogenous mix obtained. Powdered rubbers mixed with cement and then with aggregate are finally mixed with water in order to prohibit the low specific gravity powdered rubber initially mixed with aggregate from floating to the top of mixture.

The specimens of standard cylinders of 150mm by 300mm were utilized to determine the compressive and split tensile strength of the concrete mix. However, cylinders of 152mm by 63.5mm were utilized to determine the impact load capacity. The mix proportions of different types of percentages of replacement percentage of fine aggregates with powdered rubber are summarized in Table 1.

TABLE 1 MIXTURE PROPORTIONS FOR CONCRETE WITH WASTE TIRE REPLACING SAND

No.	Targeted f'c (M Pa)	Cement (Kg)	Water (Kg)	Gravel (Kg)	W/C	Sand (Kg)	Rubber (Kg)	Rubber (%)
1	30 (Mix 1)	31.68	16.32	87.49	55%	53.32	0	0%
2						50.65	2.67	5%
3						47.99	5.33	10%
4						35.08	8.00	15%
5						42.66	10.66	20%
6	35 (Mix 2)	34.84	16.37	87.5	50%	50.12	0	0%
7						47.61	2.51	5%
8						45.11	5.01	10%
9						42.6	7.52	15%
10						40.1	10.02	20%
11	40 (Mix 3)	38.71	16.43	87.49	45%	46.19	0	0%
12						43.88	2.31	5%
13						41.57	4.62	10%
14						39.26	6.93	15%
15						36.95	9.24	20%
16	50 (Mix 4)	43.55	16.51	87.5	40%	46.19	0	0%
17						39.21	2.06	5%
18						37.14	4.13	10%
19						35.08	6.19	15%
20						33.02	8.25	20%

IV. EXPERIMENTAL RESULTS

Subsequently to when the concrete cylinders have acquired the 28 days strength, three types of experiments were performed to measure the compressive, tensile, and impact load of the specimens. A uniaxial compressive load testing was conducted according to ASTM C39 in order to measure the compressive strength of the concrete cylinders [21]. Prior to testing, the area of the 150mm diameter by 300 mm height cylinders was measured to be incorporated in the computation concrete compressive strength. The cylinders were then placed in the universal testing machine, and according to ASTM C1231 [22], the cylinders should be capped with neoprene pad caps to provide a uniform load distribution during the loading process. The cylinders were then subjected to a steady stress rate varying between 0.2 MPa/sec to 0.4 MPa/sec. Once the maximum load was attained, the loading process automatically stopped, and the values were recorded. Consequently, break patterns were generated due to the failure of the cylinders that have produced cracks in several directions.

Although concrete is known to be weak in resisting direct tension, it is important to measure its tensile strength due to the cracking that has developed from the applied loading or other kinds of effects. The split-cylinder test was conducted for the cylinder specimens, according to ASTM C496 [23] to determine the tensile strength of concrete since uniaxial tension is difficult to be conducted. Concrete cylinders 300mm by 150mm were placed horizontally between the platens of the compression testing machine (Figure 4). The steel strips were placed between the horizontal cylinders and the platens of the machine in order to provide a uniform distribution of the applied load and to lessen the stresses at the surface of application, as shown in Figure 5. The compressive load was applied and increased gradually along the total length of the cylinder until failure has occurred. The failure occurred along the vertical diameter of cylinder which caused it to split into two halves, due to the indirect tension stresses, as shown in Figure 6.

Therefore, the splitting tensile strength (f'_{ct}) of the specimen was calculated using the following equation:

$$f'_{ct} = \frac{2P}{\pi DL} \quad (1)$$

Where

P = load at failure (N)

L = length of the cylinder (mm)

D = Diameter of the cylinder (mm)



Figure 4 Cylinder Placed in the Steel Strips

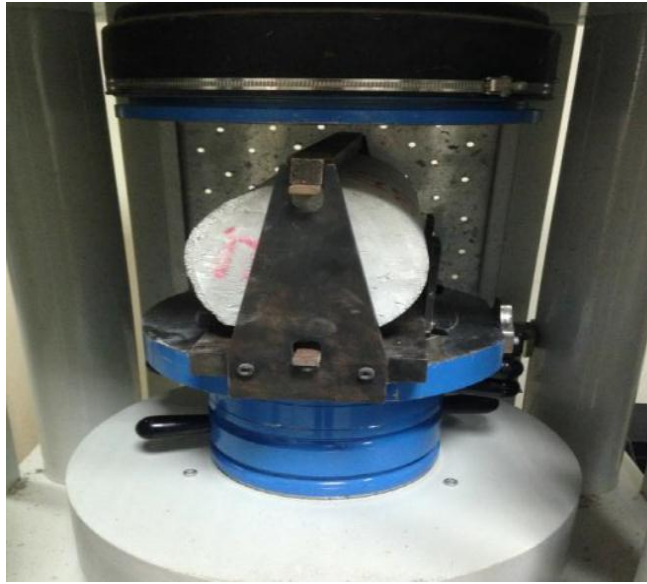


Figure 5 Tensile Testing Machine



Figure 6 Tensile Testing

The simplest of the impact tests is the “repeated impact” drop-weight test. This test yields the number of impact blows delivered by a drop hammer that is accumulated until the first visible crack occurs and until the test specimen is forced to separate by continued impacting. This number offers a qualitative estimate of the energy absorbed by the specimen at the levels of the specified distress level (Figures 7, 8, and 9). The impact energy (IE) exposed to by the specimen is calculated using the following equation:

$$IE = N m g h \quad (2)$$

Where:

- IE = impact energy (N m)
- N = the number of blows
- m = mass of the drop hammer (kg)
- g = gravitational acceleration = 9.81 m/sec²
- h = height of drop hammer (m)



Figure 7 Rubberized Concrete Impact Failure



Figure 8 Plain Concrete Impact Failure



Figure 9: Portion of the Specimens Subsequently to Impact Load Failure

V. ANALYSIS OF RESULTS

As previously mentioned, one of the main goals of this study is to achieve an optimal powder rubber ratio for the partial replacement of the fine aggregates in the concrete mix design with an ultimate objective to increase the ameliorative effects on the impact resistance and make it suitable for specific engineering applications. The limit of the compressive strength of the concrete depends on both, the strength of the matrix and the particle tensile strength of the aggregates. The strength of the concrete is usually

related to the mix content and the water to cement ratio. The 28 days compressive strengths of the concrete mixes are shown in Table 2. The comparison between the calculated compressive strength and the experimental results as a function of sand replacement with powdered rubber is graphically summarized in Figures 10 through 13.

TABLE 2 CONNCRETE CYLINDERS COMPRESSIVE STRENGTH RESULTS

Rubber (%)	MIX1	f' _c (MPa)	Avg. MPa	MIX2	f' _c (MPa)	Avg. MPa	MIX3	f' _c (MPa)	Avg. MPa	MIX4	f' _c (MPa)	Avg. MPa
	No.			No.			No.			No.		
0%	1	32.16 28.68	30.42	6	36.90 37.47	37.19	11	42.27 44.56	43.42	16	50.65 52.43	51.54
5%	2	15.41 16.88	16.15	7	27.46 26.3	26.88	12	32.40 33.73	30.07	17	40.09 39.8	39.95
10%	3	13.55 14.08	13.82	8	25.76 22.5	24.13	13	28.40 27.90	28.15	18	35.45 33.80	34.63
15%	4	12.55 11.20	11.88	9	20.36 18.70	19.53	14	22.58 21.67	22.13	19	25.28 22.63	23.96
20%	5	9.40 8.54	8.97	10	14.50 12.80	13.65	15	15.70 16.90	16.30	20	18.31 19.55	18.93

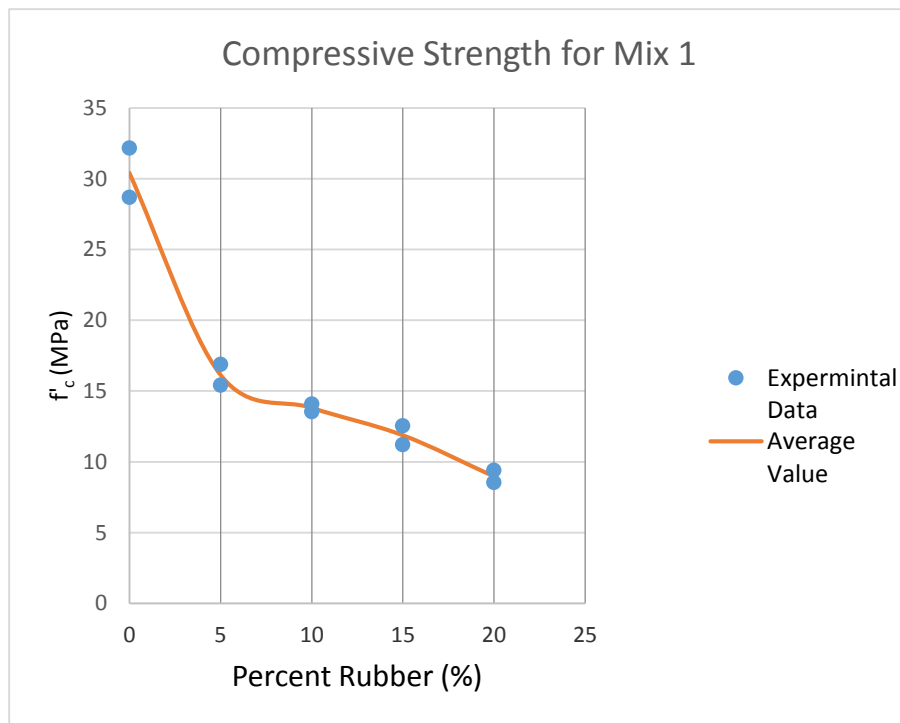


Figure 10 Average Compressive Strength for Mix 1

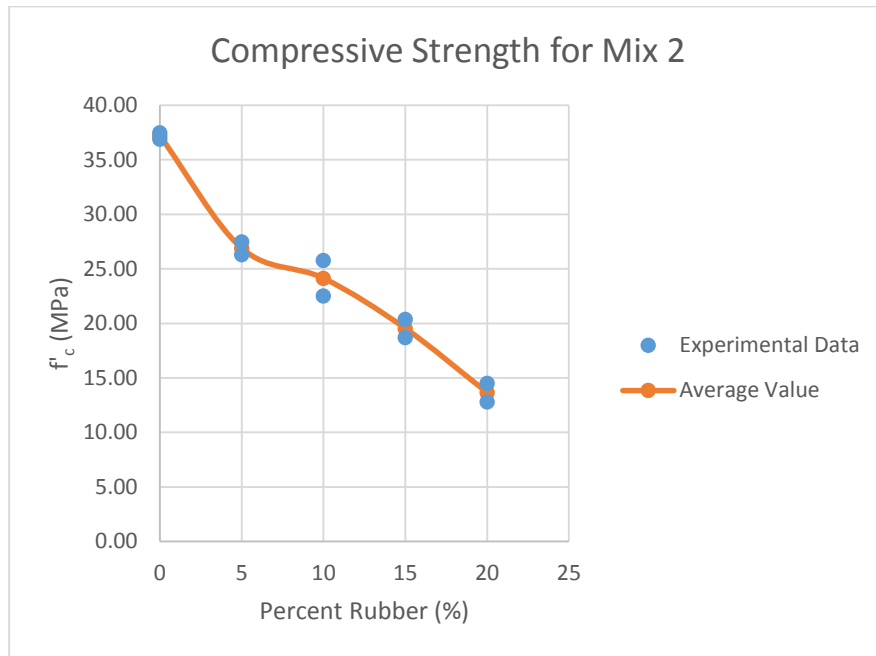


Figure 11 Average Compressive Strength for Mix 2

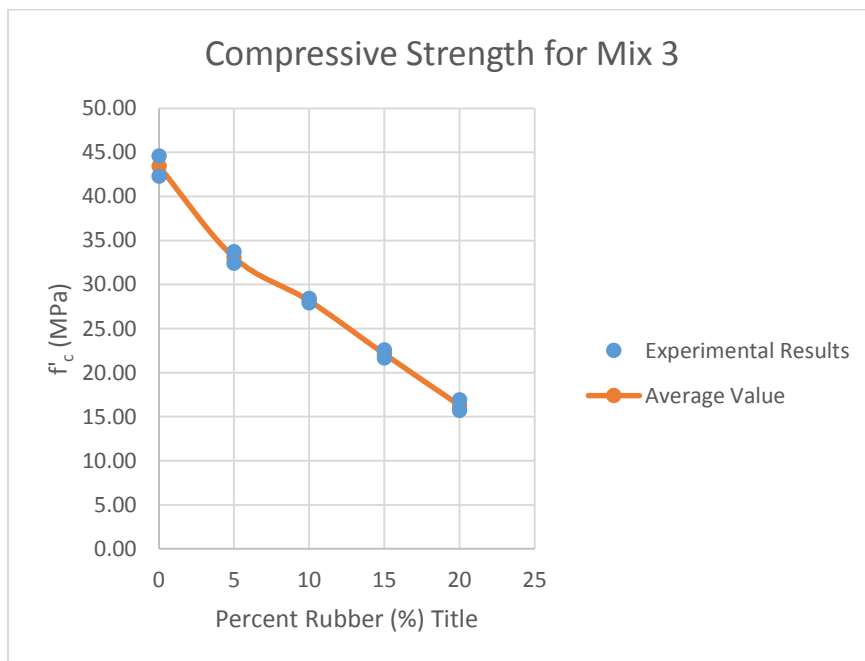


Figure 12 Average Compressive Strength for Mix 3

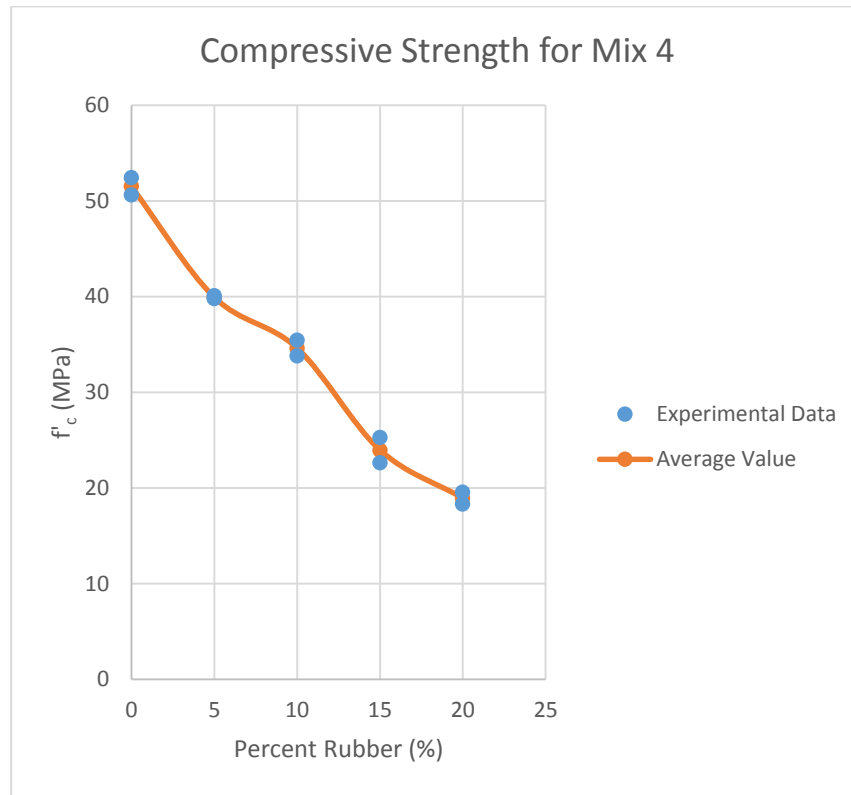


Figure 13 Average Compressive Strength for Mix 4

The 28 days splitting tensile strength of the powder rubber concrete cylinders with varying percentage replacement of powder rubber of fine aggregates in normal concrete are tabulated in Table 3. The concrete cylinders without rubber failed by splitting into two halves during the splitting tensile tests as shown in Figure 14, whereas the rubberized concrete cylinders displayed a more cohesive behavior that is failing without splitting as shown in Figure 15.

TABLE 3 SPLITTING TENSILE STRENGTH (f'_{ct}) RESULTS

Rubber (%)	MIX1	f_{ct} (MPa)	Avg. MPa	MIX2	f_{ct} (MPa)	Avg. MPa	MIX3	f_{ct} (MPa)	Avg. MPa	MIX4	f_{ct} (MPa)	Avg. MPa
	No.			No.			No.			No.		
0%	1	3.152 2.91	3.031	6	3.59 3.68	3.635	11	4.221 4.456	4.339	16	5.435 5.134	5.285
5%	2	2.433 2.55	2.492	7	2.73 2.62	2.675	12	3.541 3.244	3.393	17	4.307 4.166	4.327
10%	3	1.825 1.773	1.799	8	2.524 2.455	2.49	13	3.178 3.251	3.215	18	3.782 3.529	3.656
15%	4	1.755 1.822	1.789	9	2.234 2.356	2.295	14	2.883 2.791	2.837	19	3.173 2.856	3.015
20%	5	1.275 1.362	1.319	10	2.188 1.943	2.066	15	2.364 2.415	2.39	20	2.316 2.405	2.361



Figure 14 Non-Rubberized Concrete Cylinders Splitting into Two Halves.



Figure 15: Rubberized Concrete Cylinders without Splitting After Failure

The replacement of sand by powdered rubber has increased the occurrence of concrete to crack starting under the impact drop load. The failure occurs rapidly in rubberized concrete. Therefore, it could be deduced that the rubber with small size (no particle bridging) has a little effect in delaying the crack spirit in concrete. All the specimens are split into separate parts under the effect of the impact force. No visible cracks were noticed in each of the separated parts and no dislocated dolomite particles were found across the fractured surface. This may be due to the good bond between the mortar and the dolomite. Therefore, the favorable crack path is across the dolomite particles not around the surface of the particles. There is no particle bridging found in the case of rubberized concrete because the small size of the powder rubber. The results of the Impact strength and number of blows are shown in Table 4.

TABLE 4 ACI DROP WEIGHT IMPACT TEST RESULTS

Rubber (%)	MIX1	N Blows	Energy NM	MIX2	N Blows	Energy NM	MIX3	N Blows	Energy NM	MIX4	N Blows	Energy NM
	No.			No.			No.			No.		
0%	1	59	1190	6	77	1553.42	11	93	1876.2	16	27	544.71
5%	2	36	726.27	7	50	1008.71	12	60	1210.46	17	112	2259.52
10%	3	29	585.05	8	40	806.979	13	49	988.54	18	73	1472.72
15%	4	23	464	9	33	665.75	14	38	766.62	19	61	1230.63
20%	5	18	363.13	10	25	504.36	15	31	625.4	20	43	867.49

VI. CONCLUSIONS

After extensively exploring this topic and studying different aspects of rubber concrete properties and behavior, a series of conclusions were derived:

1. Partial fine aggregates replacement in concrete mix by powdered rubber leads to a reduction in the density of the final product, because the specific gravity of rubber used was less than that of fine aggregates.
2. Decreasing in the rubberized concrete strength (compressive and tensile strength) with the increasing powdered rubber content in the mixture is always detected as shown in Figures 16 and 17. The strength reduction may be attributed to two reasons. First, because the rubber particles are much softer (elastically deformable) than the surrounding mineral materials, and on loading, cracks are initiated quickly around the rubber particles in the mix, which accelerates the failure of the rubber–cement matrix. Second, soft rubber particles may behave as voids in the concrete matrix, due to the lack of adhesion between the rubber particles and the cement paste.

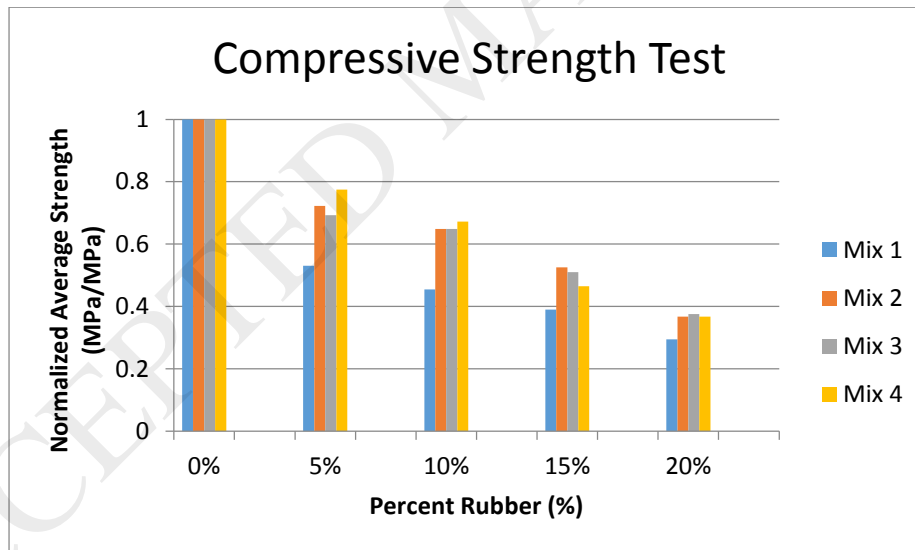


Figure 16 Normalized Concrete Compressive Strength with Plain Concrete Mix.

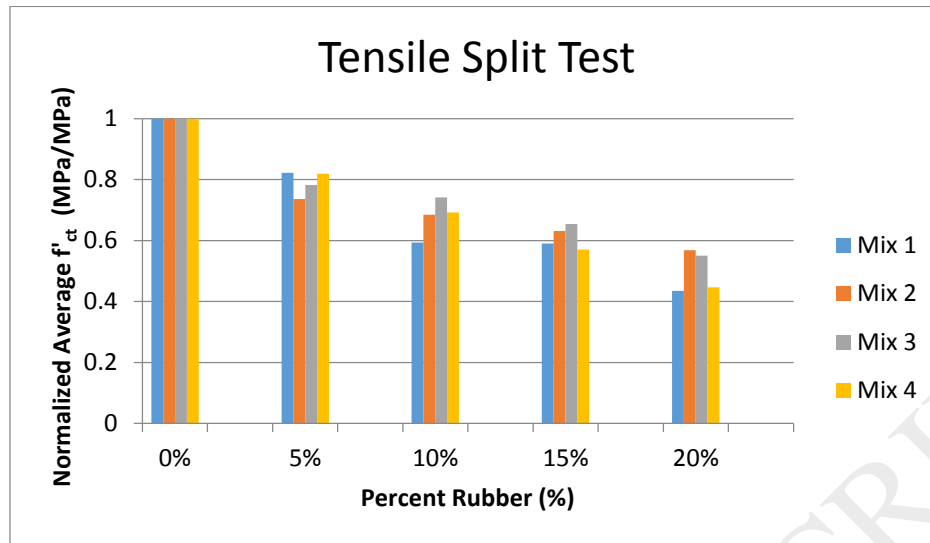


Figure 17 Normalized Concrete Tensile Strength with Plain Concrete Mix.

3. For a design mix strength ranging between 30 MPa and 50 MPa, the reduction in the compressive strength is consistent and almost at a constant ratio with the increase in the percent of powdered rubber. The reduction in strength is an average of 30, 35, 50, and 63 % against a powdered rubber replacement of fine aggregates at 5, 10, 15, and 20 %, respectively.
4. The addition of powdered rubber yields a slight improvement in the concrete tensile strength at all rubber percentages but still results in less improvement compared to the compressive strength reduction rate.
5. The addition of powdered rubber to the concrete mix results in a negative effect on the modulus of elasticity. The decrease of elasticity reflects the capability of rubberized concrete to behave in an elastic manner when loaded in tension, thus improving the failure manners of typical concrete.
6. Rubberized concrete exhibits enhanced energy absorption since the concrete did not undergo a typical brittle failure yet it encountered a ductile, plastic failure mode. Actually, according to Figure 18, concrete of compressive strength of 50 MPa, definitely displays a much better resiliency for rubberized concrete than plain concrete. This is not true for concrete of compressive strengths below 50 MPa, which displays a consistent reduction in resiliency.

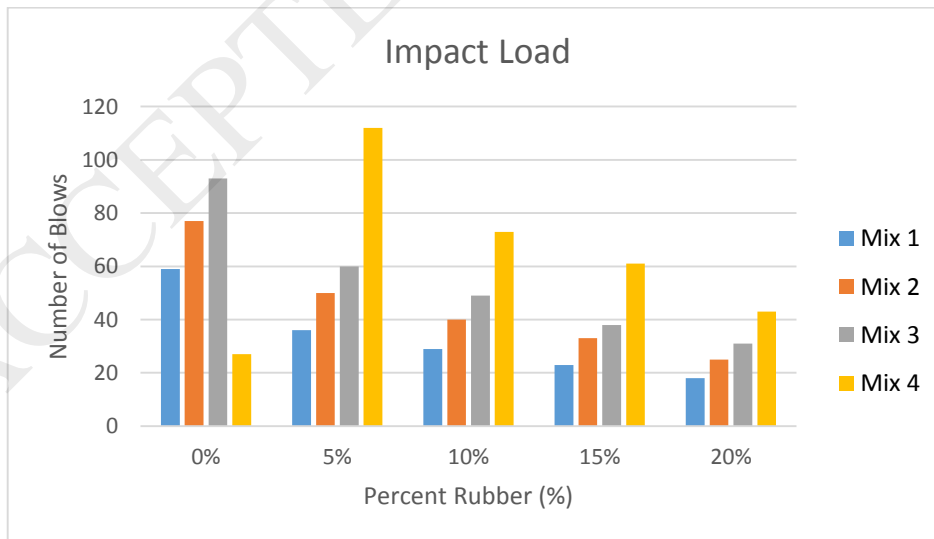


Figure 18: Impact Load Blows as a Function of Rubber Replacement.

Rubberized concrete can be used efficiently. Even though the rubberized concrete mixture has generally a reduced compressive strength that may limit its use in certain structural applications, it possesses a number of desirable properties, such as lower density, higher toughness, and higher impact resistance, compared to conventional concrete.

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Compliance with Ethical Standards

There was no external funding for this study.

REFERENCES

1. Texas Commission on Environmental Quality (2010), Tracking the fate of scrap tires in Texas: an audit report, Tech. Rep. SFR-078/08.
2. United States Environmental Protection Agency. Office of Solid Waste (1991), Markets for scrap tires, Policy Planning and Evaluation PM-221, United States Environmental Protection Agency.
3. Rubber Manufacturers Association (2009), Scrap tire Markets in the United States, 9th Biennial Report, Rubber Manufacturers Association of Tyre Rubber Particles in Slag
4. Modified Cement Mortars, Proceeding of the 11th International Congress on the Chemistry of Cement (ICCC).
5. V. Petr and T. G. Rozgonyi (2005), Rubberized concrete composition and method of making the same, US Patent Application, US 20050096412 A1.
6. Maryland Department of the Environment's Scrap Tire Program (2008), "Guidance manual for engineering uses of scrap tires", Geosyntec Project ME0012-11, Maryland Department of the Environment's Scrap Tire Program.
7. Z. K. Khatib and F. M. Bayomy, "Rubberized Portland cement concrete," Journal of Materials in Civil Engineering, vol. 11, no. 3, pp. 206–213, 1999.
8. F. Hernandez-Olivaresa, G. Barluenga, M. Bollati, and B. Witoszek (2002), "Static and dynamic behaviour of recycled tyre rubber-filled concrete", Cement and Concrete Research, vol. 32, 1587 – 1596.
9. I.B. Topcu (1995), "The properties of rubberized concretes", Cement and Concrete Research, Vol. 25, no. 2, pp. 304–310.
10. N. I. Fattuhi and L. A. Clark (1996), "Cement-based materials containing shredded scrap truck tyre rubber", Construction and Building Materials, vol. 10, no. 4, pp. 229–236.
11. Gupta, T., Chaudhary, S., and Shrama, R. K. (2014), "Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate", Construction and Building Materials, Vol 73, pp. 562-574.
12. Gupta, T., Chaudhary, S., and Shrama, R. K. (2016), "Mechanical and durability properties of waste rubber fiber concrete with and without silica fume", Journal of Cleaner Production, Vol. 112, pp. 702-711.
13. Gupta, T., Shrama, R. K., and Chaudhary, S. (2015), "Impact resistance of concrete containing waste rubber fiber and silica fume", International Journal of Impact Engineering, Vol. 83, pp. 76-87.

14. Barr, B. and Baghli, A. (1988), "A repeated drop-weight impact testing apparatus for concrete", Magazine of Concrete Research Vol. 40, No. 144, pp. 167-176.
15. Kishi, N., Konno, H., Ikeda, K., and Matsuoka, K. G., (2002), "Prototype impact tests on ultimate impact resistance of PC rock sheds", International Journal of Impact Engineering, Vol. 27, No. 9, pp. 969-985.
16. Mindess, S. and Cheng, Y., (1993), "Perforation of plain and fibre reinforced concretes subjected to low-velocity impact loading", Cement and Concrete Research, Vol. 23, No.1, pp. 83-92.
17. Ong, K. C. G., Basheerkhan, M., and Paramasivam, P., (1999), "Resistance of fiber concrete slabs to low velocity projectile impact", Cement and Concrete Composites, Vol. 21, Issue 5-6, pp. 391-401.
18. ACI Committee 544, "State-of-the-Art Report on Fiber Reinforced Concrete," 544.1R-10, American Concrete Institute, Farmington Hills, MI, USA, 2010.
19. ASTM International (2009), "ASTM Standard C136 / C136M: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," ASTM International, West Conshohocken, Pa, USA
20. ASTM International (2009), "ASTM Standard C192/ C192M: Standard practice for making and curing concrete test specimens in the laboratory," ASTM International, West Conshohocken, Pa, USA.
21. ASTM International (2009), "ASTM Standard C39/ C39M: Standard test method for compressive strength of cylindrical concrete specimens," ASTM International, West Conshohocken, Pa, USA.
22. ASTM International (2009), "ASTM Standard C1231/ C1231M: Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Cylindrical Concrete Specimens," ASTM International, West Conshohocken, Pa, USA.
23. ASTM International (2009), ASTM Standard C496/ C496M: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, Pa, USA.