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Shaaban, Ibrahim ORCID logoORCID: https://orcid.org/0000-0003-4051-341X and El-Nemr, Amr (2024) Assessment of Special Rubberized Concrete Types Utilizing Portable Non-Destructive Tests. NDT, 3 (2).

http://dx.doi.org/10.3390/ndt2030010

ndt

MDPI

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Assessment of Special Rubberized Concrete Types Utilizing Portable Non-Destructive Tests

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Abstract: Concrete is the second most common material demanded over the world. Recently, a trending issue is the vast tracking in constructing infrastructure to ensure traffic movement and life quality. Concrete types such as self and rolled compacted concrete offer magical solutions ensuring vast infrastructure and life quality. However, these structures must be assessed using non-destructive testing methods to observe the difference between the concrete types. Several studies have used recycled waste, specifically the crumb rubber extracted from old tires, as a potential replacement for natural aggregate in concrete manufacturing. However, limited research has been devoted to nondestructive testing of produced concrete to further evaluate existing concrete elements containing crumb rubber. This study investigates the self and rolled compacted concrete in comparison with normal ones, in addition to using chopped rubber as recycled materials. This study examines the concrete manufactured destructively by evaluating its compressive, tensile, and flexural strength, in addition to impact resistance, and correlates those results with the non-destructive such as Schmit hammer and Ultrasonic Pulse (UPV) for extended utilization of the concrete produced and data publication. The results showed unique performance and a high potential for data contribution to the extensive utilization of self-compacted rubberized concrete and rolled compacted concrete.

Keywords: self copacted concrete (SCC); non-destructive testing; rolled-compacted concrete (RCC); destructive testing; impact resistance; crumb rubber

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Citation: El-Nemr, A.; Shaaban, I.G. Assessment of Special Rubberized Concrete Types Utilizing Portable Non-Destructive Tests. *NDT* **2024**, *2*, 160–189. https://doi.org/10.3390/ndt2030010

Academic Editor: Andrea Benedetto

Received: 24 May 2024
Revised: 12 June 2024
Accepted: 15 June 2024
Published: 21 June 2024

1. Introduction

Car tires are composed of natural and synthetic rubber, sulfur, filler, accelerators, antioxidants, fabrics, steel wires, and other industrial chemicals pursuing the desired requirement [1]. The majority of these constituents are of hydrocarbon origin and heavy metals [2], especially when subjected to very high temperatures during combustion processes. The emissions from such processes are most likely air pollutants such as black carbon [3,4], which cause serious threats to public health and safety [5,6]. Environmental specialists have developed emission factors for exploring human risks to quantify the average rate released from scrap tire combustion into the atmosphere [7–9].

Since concrete is the second most commonly used material worldwide and produces high CO_2 emissions, attention has been paid to replacing natural aggregate with industrial or construction wastes. On the other hand, recent structures introduced several special concrete types to tackle many problems in construction, such as congested reinforcement and complicated shapes. Self-compacted concrete (SCC) is one of the concrete types that requires no external force for compaction and ensures no segregation occurs [10–12]. It efficiently lowers labor costs and skills while reducing the energy consumed for construction [13] and utilizing alternate wastes or byproducts as mineral additives [14]. Nevertheless, the SCC is considered a quasi-brittle material due to the compact microstructure that yields unsatisfactory/poor strength [15]. This behavior might increase when industrial waste is added due to the flowability certainty and concrete heterogeneity [16–19]. Additionally, since vehicle numbers and traffic density have increased significantly in recent years, another concrete type named roller compacted concrete (RCC) was developed. The main properties have zero slumps and provide more rigidity for pavement [20]. The RCC provides many privileges, among other solutions, such as deicing salt resistance, lowering asphalt friction, and durability resistance. It maintains safe, efficient, comfortable pavement, is cost-efficient, and increases life cycles [21,22]. Nevertheless, the concrete pollutant could be much less, as noted by many researchers [23], if the waste were utilized instead of the natural aggregate, whether fine or coarse aggregate.

At the moment, there is still a debate about the best practice of rubberized concrete and whether to replace natural coarse or fine aggregate with crumb rubber for normal (NC). Most agreed that the coarse aggregate replacement with crumb rubber would provide reasonable compressive strength at 25% for NC [24–29]. Recently, special concrete types such as SCC or RCC, including crumb rubber as industrial waste, have been trending [30–32]. However, despite the mentioned privileges, strength reduction is still the main drawback [31,33–35] due to the existence of many pores and the weakening of the interfacial transition zone (ITZ). Several studies [34,36,37] suggested pretreating the crumb rubber with NaOH to roughen the surface and increase the interlocking bonding between the cement matrix and crumb rubber or adding mineral admixtures (such as fly ash, and silica fume, macro, and nano size to reduce porosity) improve compressive strength and microstructure [38]. A few researchers [39–41] revealed that the weakening of ITZ is mainly caused by coarse aggregate reducing the mechanical strength, whether compressive, flexural, or even elastic modulus.

For the trending concrete types such as SCC and RCC, the crumb rubber has revealed different guides on whether to replace coarse or fine aggregate for better strength performance of the concrete. Table 1 [40–64] and Table 2 [65–74] were generated by summing up collected data from the existing literature review showing the replacement of fine, coarse, and combined aggregate with crumb rubber in SCC [39] and RCC. Most researchers agree that replacing the rubber with fine aggregate in the case of SCC would be more beneficial than the coarse or total aggregate. The optimum replacement achieving enhanced mechanical properties would be at 10% by volume. However, none of the addressed researchers in Table 1 except Aslani et al. [47] and Si et al. [58] suggested treatment. The latter explored rubber treatment by soaking it in water for 24 h and in 1 N NaOH solution, stirring it for about 20 min, and then washing it with water before adding it to the SCC mix. Other researchers [54,60,61] concluded that the total aggregate replacement with crumb rubber would perform better by lowering the strength reduction that occurs when adding crumb rubber to the concrete mix, as in the case of fine or coarse aggregate replacement. Similarly, in RCC, most of the researchers [65–74] studied the replacement of fine aggregate or combined (total aggregate). Most investigations have explored the utilization of crumb rubber as fine aggregate replacement. Nevertheless, Keles et al. [65] studied the utilization of total aggregate replacement by crumb rubber. They revealed that the total aggregate replacement would not provide adequate enhancement in strength reduction if the crumb rubber was utilized in mixes. The strength reduction increased to 81% at higher total aggregate replacement. It should be mentioned that most investigations were not treating crumb rubber, which may be the reason for the lower reduction; however, most agreed that the finer aggregate replacement would enhance the strength reduction. Their conclusion does not include investigating the coarse aggregate replacement. On the contrary, Meddah et al. [69] confirm that the treatment of crumb rubber by soaking in 1 N NaOH solution for 24 h and drying at 60 °C for 24 h would enhance strength, while sand coating the rubber with resin for adhesion would reduce the loss of the elastic modulus and strength.

Table 1. Mechanical and flowability characterization of rubberized SCC [39].

Reference	Replacement (%)	Replaced Components	Quantity		Flow-Ability/Passing-Ability	Mechanical Properties @ 28 Days			NDT Handling	Treatment		Remarks
			By Volume	By Weight		Compressive Strength	Flexural Strength	Splitting Tensile Strength		Treated (T) or Untreated (U)	Treatment Type	
Ismail and Hassan [40]	till 50%	FA	x		↓	16–67% ↓	3–42% ↓	1–57% ↓	NA	U		Elastic modulus testing
AbdelAleem and Hassan [41]	till 40%	FA	x		↓	till 68.3% ↓	till 53.15% ↓	till 52% ↓	NA	U		
Ganesan et al. [42]	15, 20%	FA	x		↓	1–13% ↓	9–15% ↑	NA	NA	U		fatigue testing
Bideci et al. [43]	till 15%	CA	x		↓	7–61% ↓	NA	NA	Excellent to very good UPV	U		fracture energy
AbdelAleem et al. [44]	till 30%	FA	x		↓	12–58% ↓	till 31.57% ↓	till 40% ↓	NA	U		Adding fibers increases mechanical properties in general/impact resistance tests.
Ismail and Hassan [45]	till 30%	FA	x		↓	57.9% ↓	31.7% ↓	40.3% ↓	NA	U		impact resistance test
Mishra and Panda [46]	till 20%	CA		x	↑	11–47% ↓	21.32% ↓	23.66% ↓	NA	U		
Aslani et al. [47]	20%	CA	x		↓	29–67% ↓	NA	50.27% ↓	NA	T	water soaked in 24 h	

Table 1. *Cont.*

			Quantity			Mechanical Properties @ 28 Days				Treatment		
Reference	**Replacement (%)**	**Replaced Components**	**By Volume**	**By Weight**	**Flow-Ability/Passing-Ability**	**Compressive Strength**	**Flexural Strength**	**Splitting Tensile Strength**	**NDT Handling**	**Treated (T) or Untreated (U)**	**Treatment Type**	**Remarks**
Uygunoğlu and Topçu [48]	till 50%	FA	x		↓	48–58% ↓	31–55% ↓	NA	UPV 27–34% ↓	U		water absorption/Dry shrinkage
Aslani et al. [49]	till 40%	FA	x		↓	29–67% ↓	NA	13% ↑	NA	U		
Rahmani et al. [50]	till 15%	CA	x		↑	15.5% ↓	NA	NA	NA	U		increase of strength when adding SF up to 8.5%
Etli & Cemalgil [51]	till 20%	FA	x		↓	16.58–29.87% ↓	NA	33.29% ↓	NA	U		
Chen et al. [52]	till 30%	FA	x		↓	↓	NA	NA	NA	U		Toughness resistance and elastic modulus
Raj et al. [53]	till 20%	FA	x		↓	8–40% ↓	12–16% ↓	12–16% ↓	NA	U		Modulus elasticity testing
Mallek et al. [54]	till 15%	FA and CA	x		↓	38% ↓	NA	NA	NA	U		Durability testing: carbonation depth, water absorption, chloride penetration, etc.

Table 1. *Cont.*

Reference	Replacement (%)	Replaced Components	Quantity: By Volume	Quantity: By Weight	Flow-Ability/Passing-Ability	Mechanical Properties @ 28 Days: Compressive Strength	Mechanical Properties @ 28 Days: Flexural Strength	Mechanical Properties @ 28 Days: Splitting Tensile Strength	NDT Handling	Treatment: Treated (T) or Untreated (U)	Treatment: Treatment Type	Remarks
Anil et al. [55]	till 25%	FA		x	↓	NA	NA	NA	NA	U		Shear stresses
Bušić et al. [56]	till 30%	FA	x		↓	35.5–70.9% ↓	15.1–70.7% ↓	NA	NA	U		prediction Models
Yang et al. [57]	till 30%	FA	x		↓	10–40% ↓	NA	NA	NA	U		dynamic action compressive and bending strengths
Si et al. [58]	15, 25%	FA	x		↓	33–52% ↓	NA	19–33% ↓	UPV ↓	T	soaked in 1 N NaOH solution with stirring for about 20 min and washed then after	Durability testing
Khalil et al. [59]	till 40%	FA	x		↓	40% ↓	29% ↓	8.75% ↓	NA	U		Impact resistance
Zaoiai et al. [60]	till 20%	FA and CA		x	↓	≈37% ↓	NA	29–42% ↓	NA	U		shrinkage testing

Table 1. *Cont.*

Reference	Replacement (%)	Replaced Components	Quantity		Flow-Ability/Passing-Ability	Mechanical Properties @ 28 Days			NDT Handling	Treatment		Remarks
			By Volume	By Weight		Compressive Strength	Flexural Strength	Splitting Tensile Strength		Treated (T) or Untreated (U)	Treatment Type	
Güneyisi et al. [61]	till 25%	FA and CA	x			7.0–50.6% ↓	NA	NA	NA	U		
Miličević et al. [62]	10%	FA	x		↓	8% ↑	NA	NA	NA	U		Microstructure analysis
Hesami et al. [63]	till 15%	FA	x		↓	2–4.5% ↓	23.6–33% ↑	27% ↑	UPV ↓	U		
Alaloul et al. [64]	15, 30%	FA	x		↓	≈92% ↓	≈78.9% ↓	≈84.6% ↓	NA	U		

↑—increase; ↓—decrease; NA—not applicable.

Table 2. Mechanical and flowability characterization of rubberized RCC.

			Quantity			Mechanical Properties @ 28 Days				Treatment		
Reference	**Replacement (%)**	**Replaced Components**	**By Volume**	**By Weight**	**Optimum Content**	**Compressive Strength**	**Flexural Strength**	**Splitting Tensile Strength**	**NDT Handling**	**Treated (T) or Untreated (U)**	**Treatment Type**	**Remarks**
Keles et al. [65]	till 30%	FA + CA	x		6.61–8.47%	10–81% ↓	7–74% ↓	8–60% ↓	0.9–24.1% ↓ UPV	U		Elastic modulus testing/ Microstructure
Mohammed et al. [66]	till 30%	FA		x	5.46–6.09%	9.7–36.26% ↓	NA	NA	RN ↓/UPV 3.9–35.05% ↓	U		
Mohammed and Adamu [67]	till 30%	FA	x		5.46–6.09%	23.2% ↓	9.3–39.3%↑	18.7% ↑@ 10%/ 15–29.4% ↓	NA	U		nano-silica addition increases the mechanical properties/elastic modulus testing/Abrasion testing
Adamu et al. [68]	till 15%	FA		x	5.46–6.09%	rubber content ↑ mechanical properties ↓ nana-silica to 2% and fly addition to 50% mechanical properties ↑			NA	U		impact resistance/elastic modulus/abrasion resistance testing/Microstructure

Table 2. *Cont.*

Reference	Replacement (%)	Replaced Components	Quantity		Optimum Content	Mechanical Properties @ 28 Days			NDT Handling	Treatment		Remarks
			By Volume	By Weight		Compressive Strength	Flexural Strength	Splitting Tensile Strength		Treated (T) or Untreated (U)	Treatment Type	
Meddah et al. [69]	till 30%	FA	x		NA	Mechanical properties ↓ when Rubber content ↑			NA	T	soaked in 1 N NaOH solution with stirring for about 24 h and dried at 60 °C in 24 h/adhesion of sand particles on rubber surfaces with resin	The pretreatment of rubber reduces the loss/elastic modulus testing
Fakhri and Saberi [70]	till 35%	FA		x	5.50%	Compressive strength ↑ till 10% rubber and then ↓	Flexural strength ↑ till 5% rubber and then ↓	NA	NA	U		Absorption testing was handled.

Table 2. *Cont.*

Reference	Replacement (%)	Replaced Components	Quantity		Optimum Content	Mechanical Properties @ 28 Days			NDT Handling	Treatment		Remarks
			By Volume	By Weight		Compressive Strength	Flexural Strength	Splitting Tensile Strength		Treated (T) or Untreated (U)	Treatment Type	
Corinaldesi et al. [71]	10, 30%	FA	x		NA	↓	↓	NA	NA	U		Thermal conductivity and microstructure testing/SP affect flexural strength adversely.
Adamu et al. [72]	till 30%	FA	x		5.48–5.95%	8.8–37% ↓	4.94–22.7% ↓/@10% 6.64–11.91% ↑	8.7–27.6% ↓	NA	U		Suggested that the mineral admixture such as fly ash and silica fume added as filler instead of cement to higher strengths except for flexural the strength improvement would be reached at 10% only in all cases/ductility, toughness, and water absorption were measured

Table 2. *Cont.*

Reference	Replacement (%)	Replaced Components	Quantity		Optimum Content	Mechanical Properties @ 28 Days			NDT Handling	Treatment		Remarks
			By Volume	By Weight		Compressive Strength	Flexural Strength	Splitting Tensile Strength		Treated (T) or Untreated (U)	Treatment Type	
Jingfu et al. [73]	5, 100, 120 kg/m^3	FA	x		NA	4.37–14.56% ↓	11.3–22.4% ↑	5–19% ↑	NA	U		Elastic modulus and drying shrinkage are tested.
Adamu et al. [74]	till 30%	FA		x	NA	Compressive strength ↑ till 10% rubber and then ↓	NA	NA	NA	U		Compressive strength improved when nano silica of 2% was added; above 2%, the strength was reduced.

↑—increase; ↓—decrease; NA—not applicable.

As shown in Tables 1 and 2, in most investigations, the SCC and RCC rubberized concrete were tested destructively. The heterogeneity and porosity detection on the concrete matrix was introduced only by nondestructive testing through Ultra Pulse Velocity (UPV). Researchers [48,58,66] showed that the UPV reduced when increasing the rubber crumb in both SCC and RCC, reaching a 35% reduction, which shows the lack of homogeneity and the increase of porosity. Mohammed et al. [66] studied the rebound number in addition to the UPV to correlate the NDT with those destructive tests as compressive strength. The correlation showed a similar behavior reduction in the strength of the concrete produced. Finally, the impact resistance was handled in several studies for rubberized SCC [45,59] and RCC [68,72], and enhancement was noticed at different percentiles of replacement, such as 10% in SCC and RCC with fine aggregate.

With all the above-listed crumb rubber utilization, some privileges, especially in different types of special concrete, such as RCC, while some setbacks reduce their utilization in large percentiles, as in SCC. Nevertheless, the crumb rubber provides ductility and energy absorption capacity improvement, reducing the brittleness nature of concrete and CR improving ductile behavior. However, very few of these studies correlate mechanical characterization with NDT. The main objective of this research is to seek a comparison between the special types of concrete NC (normal concrete), SCC, RCC, and without crumb rubber replacement fine or coarse or total aggregate, whichever provides the best performance or rubberized concrete as per the literature review. The testing program includes mechanical characterization and developed equipment to assess the impact resistance, in addition to the correlation between the mechanical characterization and those reading from Schmidt hammer and UPV as NDT testing portable devices.

2. Materials and Methods

In this study, seven mixes each two mixes; control and rubberized one concerned the special types of concrete such as SCC and RCC, while NC consists of 3 mixes. The best-optimized strength achieved in the NC rubberized concrete was at 25% coarse aggregate replacement [24–29], while for SCC 10 percent of total aggregate volume showed the best performance [39–64]. Finally, the RCC rubberized concrete showed optimized compressive strength at 10% fine aggregate replacement by crumb rubber [65,74].

2.1. Cement

The cement type utilized was normal Portland cement with a grade of 42.5 N. Table 3 provides the chemical composition of cement. As per the manufacturer's datasheet, the air Blaine fineness for the cement was 3780 cm^2/kg and had a specific gravity of 3.15.

Table 3. Physical and chemical composition of cement.

Components	Cement, (%)
SiO_2	25.3
Al_2O_3	6.64
Fe_2O_3	6.68
CaO	58.44
MgO	2.29
P_2O_5	0
K_2O	0.25
Na_2O	0.66
SO_3	2.04
Cl	0.06
TiO_2	-
SrO_2	-
Mn_2O_3	-
LOI	4

2.2. Fine and Coarse Aggregates

Figure 1 shows the grain size distribution of coarse, fine, and crumb rubber aggregates. The figure encountered the upper and lower bound assigned by ASTM C33 [75]. The natural coarse used here in this study was a nominal maximum aggregate size of 20 mm. The specific gravity was determined for both coarse and fine aggregate and valued at 2.57 and 2.65, respectively. Similarly, the absorption and moisture content of the fine and coarse aggregate used was 1.10, 0.5, 1.11, and 0.26%. The crushing and impact values are limited to less than 25%, as ECP 203 [76] and BS 882 [77]. The values were 19.8 and 17.8%.

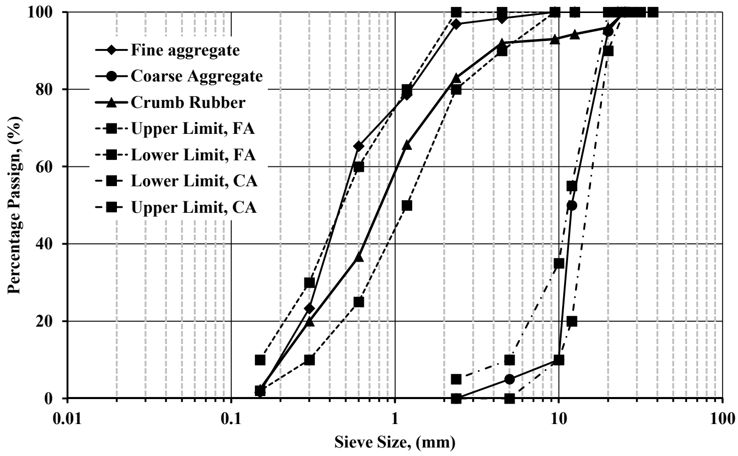


Figure 1. Sieve size grade distribution of coarse, fine, and crumb rubber aggregate.

2.3. Crumb Rubber

The crumb rubber included the shredded tire wastes of cars, and the size ranges between 20 to 0.75 mm for coarse replacement and 4.75 to 0.15 mm for fine aggregate replacement, as shown in Figure 1, through the sieve analysis. The sizes both are bound within the upper and lower limits assigned by ASTM C33 [75]. Figure 2 shows the materials from crumb rubber and aggregates before casting the specimens. The specific gravity of crumb rubber is 1.51.

Figure 2. Material from crumb rubber and aggregates of fine and coarse.

2.4. Superplasticizer

Viscosity for self-compacted concrete was maintained using the Viscocrete achieving effective workability. The chemical admixture was provided by Sika Inc., Elobour City, Egypt as per ASTM C1017 [78] and ASTM C494 [79], Its chemical basis is modified polycarboxylate.

3. Specimens Preparation

Table 4 shows the mix design portions for rubberized and control mixes in NC, SCC, and RCC assigned. A total of 42 cube specimens dimensioned 150 mm, 21-cylinder specimens of diameter 150 mm and height 300 mm, while 21 prism specimens of length 500 mm, height, and width of 100 mm were cast to evaluate the compressive, flexural, and splitting tensile strength, respectively. 7 extra cylinders (diameter 150 mm × height 300 mm) were cast to cut into 60 mm height for obtaining three samples evaluating the impact resistance test for each mix. The molds were tightened, cleaned, and coated with oil film for demolding after hardening. A vibrating table was utilized hen at RCC and NC; however, the SCC did not require any vibrating due to its flowability. The specimens were de-molded after 24 h from the cast and cured at an ambient room temperature of 21 ± 1 °C. The crumb rubber was treated in two methods: one using soaking in NaOH solution for 24 h (1 N) and then washing before utilizing, and the other, which was limited only to NC for trail purposes, using the cement content with some of the water mix to coat the rubber first before being used onto the mixing portions. The former was adopted in all mixes as most researchers [34,36,37] agreed that the NaOH with (1 N concentration) roughened the rubber surface and helped in strengthening the ITZ and cement matrix.

Table 4. Portions of concrete ingredients.

Mix ID	w/c	Water (kg/m^3)	Cement (kg/m^3)	Nano Silica Fume (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate (kg/m^3)	Rubber (kg/m^3)	Treatment	Fly ash (kg/m^3)	Superplasticizer (Kg/M^3)	Viscosity (kg/m^3)	Remarks
NC-CR0	0.5	182.5	365	0	730	1096	0		0	0	0	
NC-CR1	0.5	182.5	365	0	730	830	122.61	NaOH treatment 24 h (1 N)	0	0	0	25% CA by volume
NC-CR2	0.5	182.5	365	0	730	830	122.61	Cement paste	0	0	0	
SCC-CR0	0.4	180	450	0	800	950	0		0	5.85	0.9	
SCC-CR1	0.4	180	450	0	729	860	77.23	NaOH treatment 24 h (1 N)	0	5.85	0.9	10% of the total aggregate volume
RCC-CR0	0.7199	96.90	134.6	2.4	1300	833	0		102.5	0	0	
RCC-CR1	0.7199	96.90	134.6	2.4	1170	833	56.42	NaOH treatment 24 h (1 N)	102.5	0	0	10% FA by volume

NC: Normal concrete; SCC: Self-compacted concrete; RCC: Rolled compacted concrete; CR: crumb rubber; 0: no crumb rubber; 1: optimum crumb rubber percentile according to literature; 2: treatment method.

4. Testing Method

Most tests handled were systematic tests for hardened concrete, such as compressive, flexural, and splitting tensile tests. Usually, workability is the main issue in NC. As the RCC used the method of modified proctor test to determine the optimum water content then, it is expected that the sump would stiff as the value of zero, which compiles with RCC standards set by ACI, 327 [80] and Dale et al. [81]. On the other hand, various tests were handled to ensure the self-compacted concrete and self-flowability. Therefore, several tests were handled as per standard. ElNemr and Shaltout [82] sum up these tests, and Table 5 shows the limits of the six assigned tests by ECP 203 [76] that should be handled over trials. In contrast, Table 6 sums up all the tests used to evaluate the fresh concrete properties, with a brief description of the test procedure. Finally, Table 7 sums up the testing handled in the hardened state from compressive, flexural, and splitting tensile strengths, in addition to the impact resistance, as shown in Figure 3. Further, the non-destructive test was correlated with those destructive tests using portable devices such as Schmidt hammer and UPV, as shown in Figure 4.

(**a**) (**b**) (**c**) (**d**)

Figure 3. Shows the testing of the cube, prism, and cylinder specimens for (**a**) compressive, (**b**) Flexural, (**c**) Splitting tensile strengths, and (**d**) impact resistance.

(**a**) (**b**)

Figure 4. Portable nondestructive testing devices, such as (**a**) Schmidt Hammer and (**b**) UPV, are utilized to correlate destructive and nondestructive testing.

Table 5. Upper and lower limits of the rheological tests on SCC as Per ECP 203 [76].

The Rheological Test	Units	Limits	
		Min.	**Max.**
Slump Flow (diameter)	mm	600	800
Time for reaching slump flow with a diameter of 500 mm ($T_{50\ cm}$)	s	2	5
J-ring slump flow (diameter)	mm	0	20
V-funnel after immediate mixing (t_o)	s	6	12
V-funnel after 5 min from mixing ($t_{5min.}$)	s	t_o	t_o + 3
L-box (H_2/H_1)	ratio	0.80	1.0

Table 6. Rheological tests as per standards for NC, SCC, and RCC [82].

<table>
<tr><th>Concrete Type</th><th>Testing</th><th>The Codes Guidelines and Standards</th><th>Equations</th><th>Description</th></tr>
<tr><td>NC</td><td>slump</td><td rowspan="2">ASTM C143 [83]</td><td>NA</td><td>Normal slump test</td></tr>
<tr><td>RCC</td><td>slump</td><td>NA</td><td>Normal slump test to ensure zero or stiff slump</td></tr>
<tr><td rowspan="6">Rheological SCC</td><td>Slump flow test</td><td rowspan="2">ECP 203 [76]
ASTM C1611 [84]</td><td>$D_{slump\ flow} = \frac{D_1+D_2}{2}$
where D_1 and D_2 are the slump diameters perpendicularly to each other.</td><td>Fresh concrete is placed into the frustum on the rigid plate. The frustum is then removed so that the freshly mixed concrete would flow into a diameter range between 600 and 800 mm.</td></tr>
<tr><td>Slump flow time at $T_{50\ cm}$</td><td></td><td>Fresh concrete is poured inside the frustum. The time elapsed for the slump flow to reach a diameter of 500 mm engraved on the rigid plate is measured in seconds.</td></tr>
<tr><td>J-ring flow</td><td>ASTM C1621 [85]</td><td>$D_{J-ring} = \frac{D_1+D_2}{2}$</td><td>The test examines the ability of concrete to pass (pass ability) through a reinforcement diameter of 16 mm and spacing of 59 mm.</td></tr>
<tr><td>V-funnel</td><td rowspan="2">EN 12350-9 [86]</td><td></td><td>The V-funnel measures the time elapsed for falling the concrete into the cylinder, which is denoted by (t_o).</td></tr>
<tr><td>V-funnel after 5 min</td><td></td><td>The freshly mixed concrete was left for 5 min. The time elapsed is measured for falling the concrete into the cylinder is calculated from (t_o) till (t_o + 3)</td></tr>
<tr><td>L-Box test</td><td>EN 12350-10 [87]</td><td>$PL = \frac{H_2}{H_1}$
where H_1 is the concrete height in the vertical section, while H_2 is the horizontal end of the section</td><td>The passing ability of SCC is measured passing by the concrete's weight through tight openings including congested reinforcement at certain spacing.</td></tr>
</table>

Table 7. Mechanical properties tests as per standards for NC, SCC, and RCC [82].

Concrete Type	Testing	The Codes Guidelines and Standards	Description
Mechanical properties	Compressive strength	EGP 203 [76]	Cubes were loaded in compression at 240 kg/cm^2 per minute pacing rate until the specimens failed.
	Flexural Strength		Prisms were loaded in compression onto the longitudinal direction at a 24 kg/cm^2 per minute pacing rate.
	Splitting Tensile Strength		Cylinders were loaded in compression longitudinally at a 12 to 24 kg/cm^2 per minute pacing rate.
	Impact resistance	BS 812: Part 112 [88], ACI 544.2R [89], Eren et al. [90]	A specimen of 150-mm-diameter and 60-mm-thick cylinders was tested by a drop-weight modified [88–90] to obtain the number of the average blows causing the first crack and final fracture at 28 days of age.

For the UPV, the quality of the concrete, as well as the homogeneity, were evaluated through the ASTM C597 [91] assigned table that correlates the velocity with concrete quality, as shown in Table 8.

Table 8. Ultrasonic pulse velocity classifications of concrete [91].

S/N	UPV Range of Values (m/s)	Concrete Classification/Quality Rating
1	UPV > 4500	Excellent
2	4500 > UPV > 3500	Good
3	3500 > UPV > 3000	Medium
4	3000 > UPV > 2000	Doubtful
5	UPV < 2000	Very weak

5. Results and Discussion

This section addresses the rheological and mechanical properties of the tested mixes. The results generated for a device for testing the impact resistance were discussed. In addition to the results of rebound number and UPV correlated with those, destructive testing was also used.

5.1. Slump

The slump of rubberized NC showed relevant workability as the natural coarse aggregate was replaced by 25% crumb rubber. The method of crumb rubber treatment is in the workability. Treatment using the NaOH with (1 N) concentration or coating the crumb rubber with cement paste would decrease the workability, as shown in Figure 5. The SCC has many tests to provide a flowable concrete that requires no compaction. Table 9 provides the six tests that are handled to maintain the adequate rheological properties of the SCC concrete. From the table, the rheological tests range among the limits assigned in Table 5 for both mixes, SCC-CR0 and SCC-CR1, those without or with crumb rubber. For RCC, the slump should be zero as the optimum water content is maintained through the ACI 327 [80] method of design. As per the literature; see Tables 1 and 2, the flowability is reduced by increasing the crumb rubber. Figure 5 shows the same trend among the mixes in addition to the lower compaction degree maintained due to the natural replacement of fine and coarse aggregate. The reduction in slump ranges between 4.3 to 8.69% for NC and 6% for SCC. These values are minor reduction values (less than 10%) and are not considered to have a great influence on the workability of the concrete. The crumb rubber is usually shaped in an angular form, which is similar to that of natural aggregate. This might be the reason for the slight reduction in workability, in addition to the roughness of crumb rubber using NaOH solution. This should be further addressed in the rubberized SCC behavior as the NaOH should influence the workability negatively as the surface roughened.

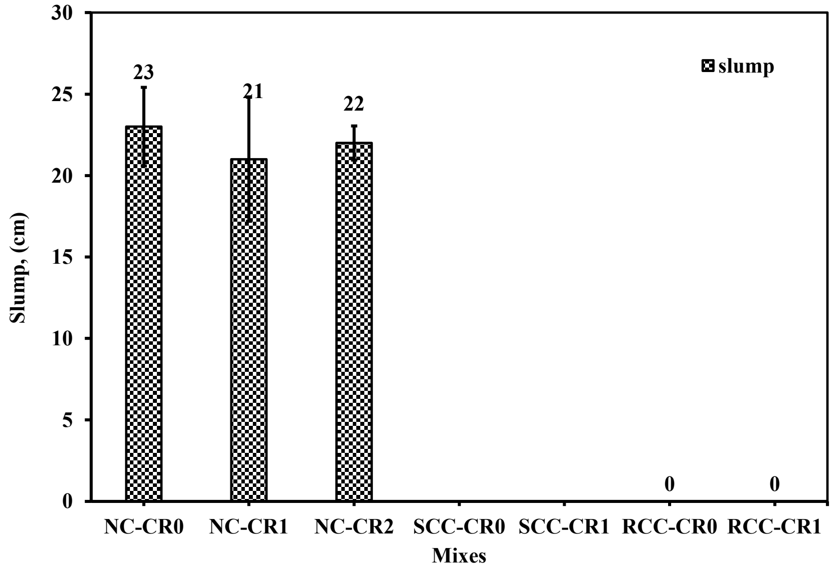


Figure 5. Slump among the mixes.

Table 9. Results of rheological tests on SCC mixes.

The Rheological Test	**Units**	**Test Values**	
		SCC-CR0	**SCC-CR1**
Slump Flow (diameter)	mm	700	650
Time for reaching slump flow with a diameter of 500 mm ($T_{50\ cm}$)	s	2.5	3
J-ring slump flow (diameter)	mm	12	10
V-funnel after immediate mixing (t_o)	s	8	9
V-funnel after 5 min from mixing ($t_{5min.}$)	s	10	11
L-box (H_2/H_1)	ratio	0.9	0.87

The reduction in slump flow and slump or the flowability and passing ability by the crumb rubber replacement is attributed to a rough texture and angularity of the crumb rubber, as stated by Reda-Taha et al. [92] and adopted by many other researchers. Thus, it is expected to raise the interparticle friction by entrapping more air through their roughened surface and controlling the flowability of the mixture. Bibm & Ermco [93] stated that the increase of crumb rubber by 30% (i.e., from 0) could influence the segregation degree by four times. However, Naito et al. [94] have another view relevant to the air-entrapped increase from the high compressibility of rubber particles, which may result in an artificial amount of air measured through the standard ASTM C231 [95] test method.

5.2. Density

The density showed trending behavior, as shown in Figure 6. The figure presents the density in both 7 and 28 days. The density increases with age except for those of RCC-CR1, as the crumb rubber has a lighter weight through its low specific gravity. The compaction is taking more place in the RCC-CR1, closing the porosity as seen later on in the UPV. Nevertheless, the density of those with crumb rubber is less than that without crumb rubber, as shown through the mixes. The reduction of NC-CR1 and NC-CR2 reference to the control (NC-CR1) is about 5 to 8% within 7 and 28 days of age. Similarly, the SCC mixes showed a range of 2 to 3%.

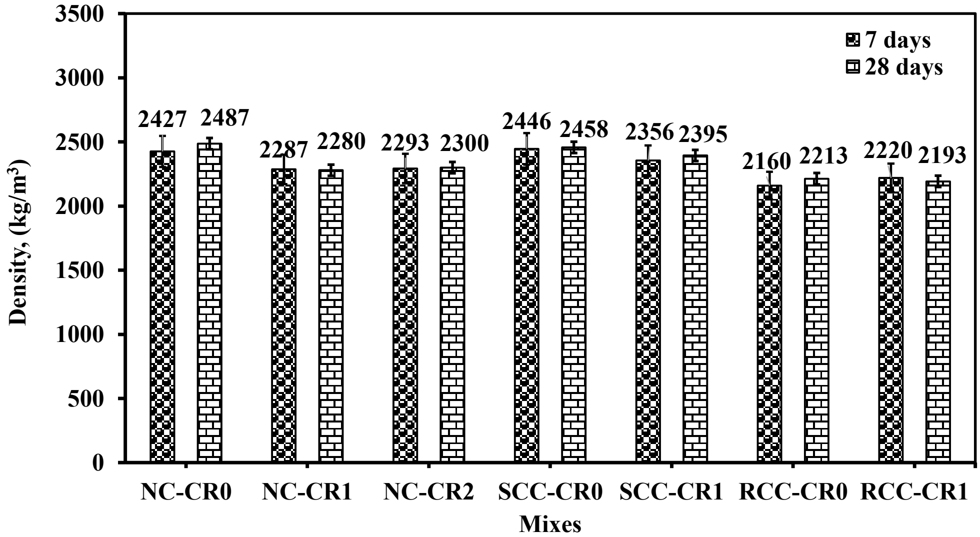


Figure 6. Density of the mixes.

This behavior is aligned with those mentioned in the literature [24–29,40–74], and the reasoning is mostly about the specific gravity while replacing it with volume or by weight method. These would affect the density, which would align with the influence of the compressive strength as it provides a quick overview of the porosity availability in the concrete mix, which negatively impacts the compressive strength of the produced concrete. In all forms, the volume and weight replacement change would be slight due to the occupation of the greater amount of crumb rubber in replacement of fine or coarse aggregate.

5.3. Mechanical Properties

5.3.1. Compressive Strength

The compressive strength of the mixes is presented in Figure 7. The same trend of density was noticed in the compressive strength of the cube specimen with crumb rubber as in the case of natural aggregate. The development between 7 and 28 days was nearly about 74% on average through all the mixes. Nevertheless, the compressive strength of mixes NC-CR1 and NC-CR2 is about 10 to 15% less than the control mix (NC-CR0) at both 7 and 28 days. Similarly, the compressive strength of the mixes SCC-CR1 and RCC-CR1 is reduced by 10 and 15.67% than the control mixes, SCC-CR0 and RCC-CR0, at 7 and 28 days of age.

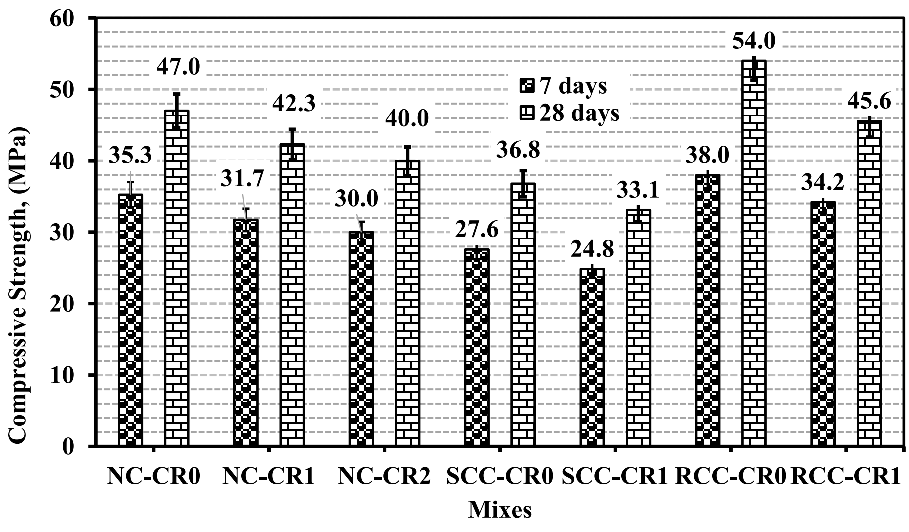


Figure 7. Compressive strength results of the mixes.

These results were aligned with the literature review [40–74]. NC [24–29] showed that the optimum reduction would be achieved at 25% with NaOH coarse aggregate replacement. As stated in the literature, the reason for the reduction in strength is the weakened ITZ within the concrete matrix between the crumb rubber and cement matric. This behavior is noticed mainly in SCC-CR1 in which the crumb rubber size was fine (less than 4.75 m). As the crumb rubber size decreased, the surface area that covered the crumb rubber by cement area increased, and thus, the weakening of ITZ was higher and more pronounced. This is because the optimum amount of replacement in the case of SCC is 10% for fine aggregate, not higher than 10% (see Figures 11, 21, and 14 in [55,65,67]). On the contrary, the RCC showed scatter behavior when fine aggregate was replaced by crumb rubber [65–74]. Keles et al. [65] showed a reduction of 10% when replacing the total aggregate with 10% crumb rubber.

5.3.2. Flexural Strength

Figure 8 shows the flexural strength results of the mixes. A similar trend is deduced as those in compressive strength. The reduction in flexural strength is nearly 10% to 15% for NC and 10% for SCC, while RCC reached 15.67% from their control mixes (NC-CR0, SCC-CR0, RCC-CR0). The difference between the method treatments did not significantly affect the flexural strength as the flexural value was 7.5 MPa for the mix NC-CR1 while the value was 7.0 MP factor for the mix NC-CR2, which was nearly 5.55%. This value can be considered negligible.

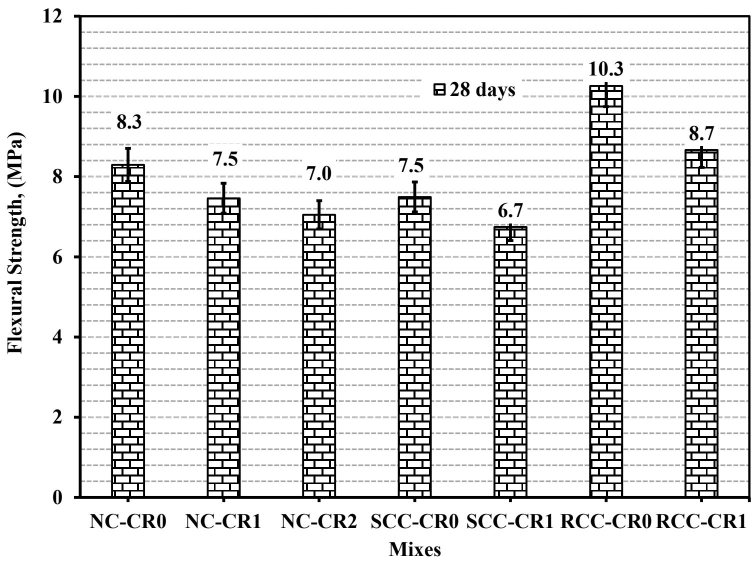


Figure 8. Flexural strength results of the mixes.

The flexural strength was addressed by most researchers in NC [24–29], SCC [40–42,44–46,48,53,56,59,63,64], and especially RCC [65,67–73] as it represents more of the bending capacity that the pavement can handle for the vehicle traffic as per ACI 327 [80] which recommends ranges between 3.5 to 7 MPa according to the traffic capacity. The results agree that the reduction of the flexural strength occurs when increasing the crumb rubber percentile. Meddah et al. [69] announced that the treatment of the crumb rubber would differ in the performance of the flexural strength in terms of canceling the reduction; however, the results revealed some enhancement in the loss of flexural strength for the RCC.more investigation is required in the area of treated crumb rubber and SCC.

5.3.3. Splitting Tensile Strength

Tensile strength is a crucial property, especially in RCC concrete and SCC, in some cases of complicated structures. This strength property ensures the minimization of the cracking or crack control of the structure element in question, especially if it is water-tightened structures such as tanks or swimming pools. Figure 9 revealed the splitting tensile strength for the mixes. Similar trending was deduced in the flexural and compressive strength, with lower values representing around d 10 to 15% of the compressive strengths observed for the mixes. The reduction is taking place due to a similar reason: the weakening of the ITZ between the cement matrix and the crumb rubber.

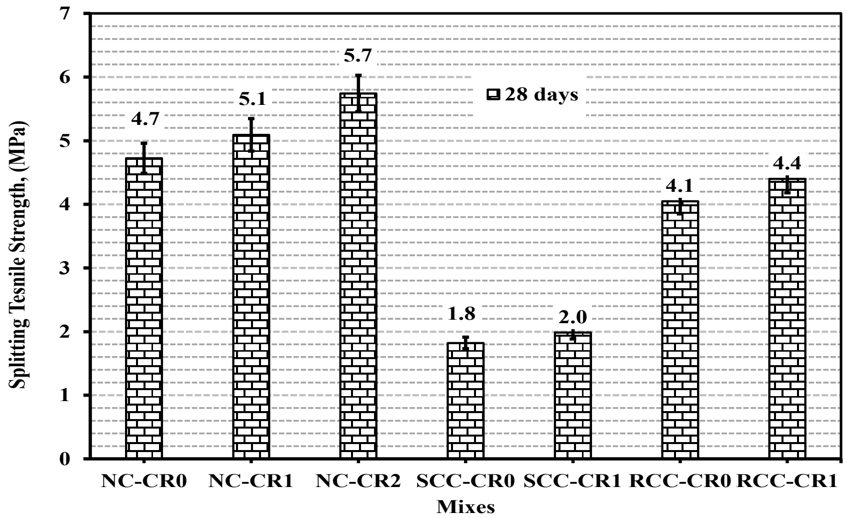


Figure 9. Splitting tensile strength results in the mixes.

The literature should also provide discrepancies in the analysis considering the tensile strength while using crumb rubber for NC [24–29], SCC [40,41,44–47,49,51,53,58–60,63,64], and RCC [65,67–69,72,73]. The splitting tensile strengths showed a relevant reduction to that available in this study at the level of crumb rubber replacement, whether it was fine or coarse or combined crumb rubber. The reason for the splitting tensile strength is due to the low stiffens of rubber relevant to the natural aggregate, which influences the tensile and flexural strength, in addition to the bond between the cement matrix and crumb rubber, especially the rubber is not treated as at most studies [44–47,67–69]. Aslani et al. [47] and Si et al. [58] discussed utilizing the crumb rubber after treating and testing tensile strengths. Their results aligned with the reduction of tensile strength as the crumb rubber replacement increased, reaching the replacement of 25% and the reduction in tensile strength to 50% in SCC. It should be mentioned that there was a difference between the treatment methods, from soaking in water to using NaOH solution. Thus, as expected, the reduction reached 50% for the treatment of those utilizing the waste soaking. Meddah et al. [69] addressed similar results when studying the compressive strengths of RCC with the utilization of crumb rubber as fine aggregate replacement. Their results revealed a range of about 25% reduction in values for those treated using NaOH solution. Indeed, increasing the percentage of aggregate replacement by crumb rubber would reduce the strength, as observed [69].

5.3.4. Relationship between Strengths

The relationship between the compressive strength and both flexural and tensile strengths is clear in Figure 10. The flexural strength of mixes with or without crumb rubber showed a relevant ratio to that of the compressive strengths of about 18%, on average, which is considered within the range of 15 to 23% [76,77]. On the contrary, the tensile strength showed a performance of around 10% on average compared to the compressive strength. It should be mentioned that the range is usually between 10 and 15% [76,77], which is considered adequate, taking into consideration that some mixes with crumb rubber replacement are considered within the average.

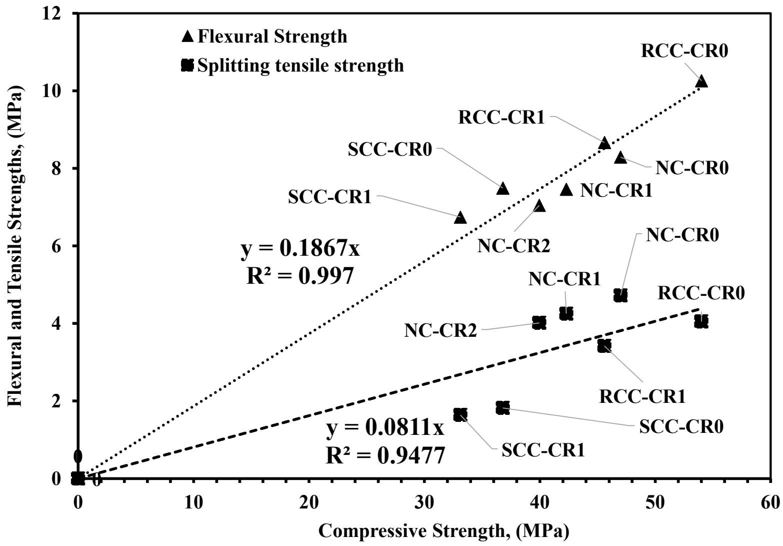
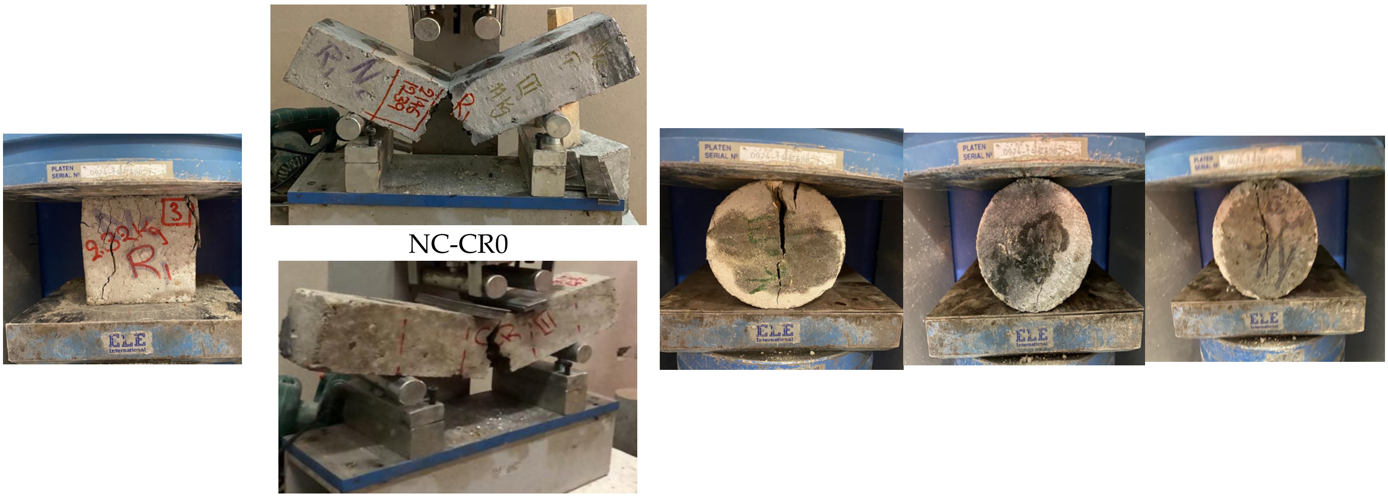


Figure 10. Relationship between the strengths.

From the results of the compressive, flexural, and tensile strength, it seems that most reasoning is the same, while more exploration is needed. The reduction or enhancement of each strength has its reason. For instance, it was revealed that the ion charges on the surface rubber with the water added during the mixing process could cause repulsion forces, which help in standing still of the workability, and the changes nearly would be related to the crumb rubber aggregate shape whether angular or have a tendency towards flakiness or elongation [60]. Thus, this repulsion forms a thickness of ITZ between the cement matrix and aggregates. This consequently would lead to more weak layers and lower bonding between the ingredients of concrete, which is pronounced when the load applied in compression performs premature failure, which is clear in low compressive strength [60], as shown in Figure 11a. The microcrack seems to have occurred between the aggregate and paste, which prematurely failed inside the cube before the fracture occurred. Nevertheless, the flexural strength showed a slight reduction as a result of the nature of crumb rubber, especially if its shape is elongated, not more angular, and therefore, the post-cracking behavior, as well as the distribution of cracks along the bottom face of the prism specimens, would be more pronounced than plain concrete with natural aggregate resisting more flexural loading [67], as shown in Figure 11b. While in tensile, the failure takes the direction of loading, activating the Poisson effect for plain concrete, providing a crack parallel to the loading direction. However, with crumb rubber, the crack propagation is usually delayed, and the crack width increases gradually based on the rough surface of crumb rubber in case of being treated with NaOH [67], as shown in Figure 11c. This behavior is denoted by the inelastic action of crumb rubber, which in turn increases the ductility by absorbing more strain energy and reduces the brittleness along with the possessed deformation.

Indeed, the homogeneity of the concrete while adding the crumb rubber is still in question, especially if the crumb rubber is not compatible with sand and natural aggregate specific with their low specific gravity, strength, stiffness, and capacity, which could be the reason for strength reduction [65,66]. This heterogeneity leads to an increase in pore volume and air content due to the hydrophobic nature of crumb rubber. This, in turn, accumulates stresses, causing stress construction across the pores and connecting the microcracks released between the pores, reducing the strength [65,67].



NC-CR1 (**a**) NC-CR1 (**b**) NC-CR0 NC-CR1 (**c**) NC-CR2

Figure 11. Failure of (**a**) cube, (**b**) prism, and (**c**) cylinder specimens for evaluating compressive, flexural, and splitting tensile strengths.

5.3.5. Impact Resistance

Impact resistance is a crucial parameter, especially when talking about RCC. The crumb rubber provides more toughness, although its low stiffness is presented in elastic modulus. It should be mentioned that the crumb rubber behaves inelastically, and this could contribute to a larger stress-strain curve. This, in turn, would manage a higher area under the curve, impacting a high level of toughness. Thus, when added to concrete, it is expected to provide similar or nearly approximate behavior. The impact resistance was measured through the induced first crack and total fracture of the cylindrical specimen of height 60 mm. This corresponds to the number of blows in which the hammer was utilized for testing. The values encountered here in this study were at 28 days of age only.

Table 10 provides the impact resistance result for NC, SCC, and RCC of the mixes in terms of the number of blows at the first crack and fractured state. The number of blows ranges between 143 and 173 in general. The SCC mixes showed fewer blows than NC concrete and RCC; however, the mixes with crumb rubber showed higher values of the number of blows at the first crack and fracture. The difference between the first crack and fracture in the number of blows is calculated in Table 10. From the table, it can be noticed that the difference between the first crack and fracture is shown, and some indication of the post-cracking resistance would be provided while ensuring the increase of ductility and reduction of brittleness. For the concrete produced [44,45,52,59,68,72]. Figure 12a–d provide the last shape of fracture and first crack for NC mixes and fracture of mix RCC-CR1.

Table 10. Average number of blows at the first crack and fracture at 28 days of age.

Mix ID	No of Blows Corresponding to the First Crack (N_1)	No of Blows Corresponding to the Fracture (N_2)	$N_2 - N_1$
NC-CR0	150	152	2
NC-CR1	169	173	4
NC-CR2	165	168	3
SCC-CR0	143	145	2
SCC-CR1	165	168	3
RCC-CR0	148	151	3
RCC-CR1	157	161	4

(**a**) (**b**) (**c**) (**d**)

Figure 12. Specimen tested through impact with the modified device (**a**) first crack for NC-CR0, (**b**) fracture for RCC-CR0, (**c**) fracture due to impact testing for NC, and (**d**) fracture of RCC-CR1.

5.4. Non-Destructive Testing

5.4.1. Rebound Number

The Schmidt hammer is one of the portable hardness-based devices that can be used to evaluate compressive strength through the hardness of concrete surface; however, correlation must be considered for the rubberized concrete before utilizing it on existing structures. Very few researchers have performed the rebound test for correlation purposes [66]. Mohammed et al. [66] ensured the linearity of the rebound number versus the compressive strength. Similarly, here in this study, it was found that the relationship between the compressive strength of the mixes, although the difference in replacement and concrete type, is linear, as shown in Figure 13.

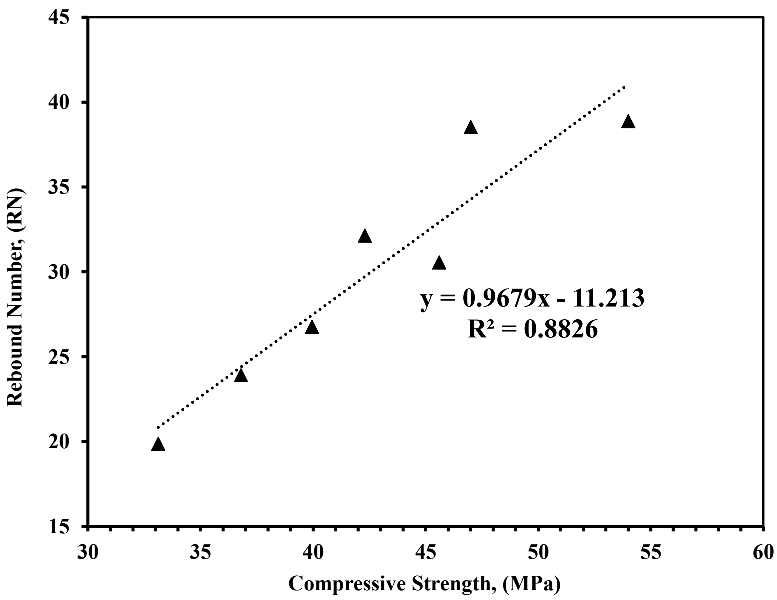
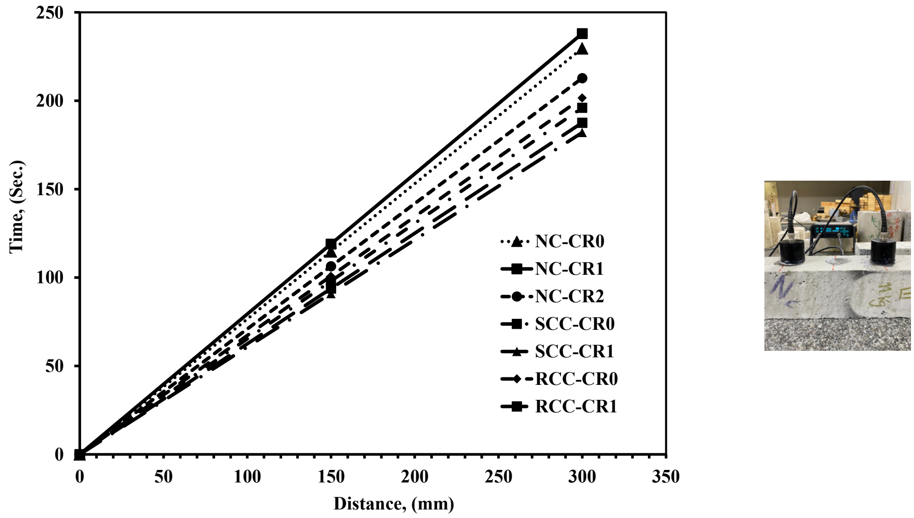


Figure 13. Rebound number against the compressive strength of the mixes.

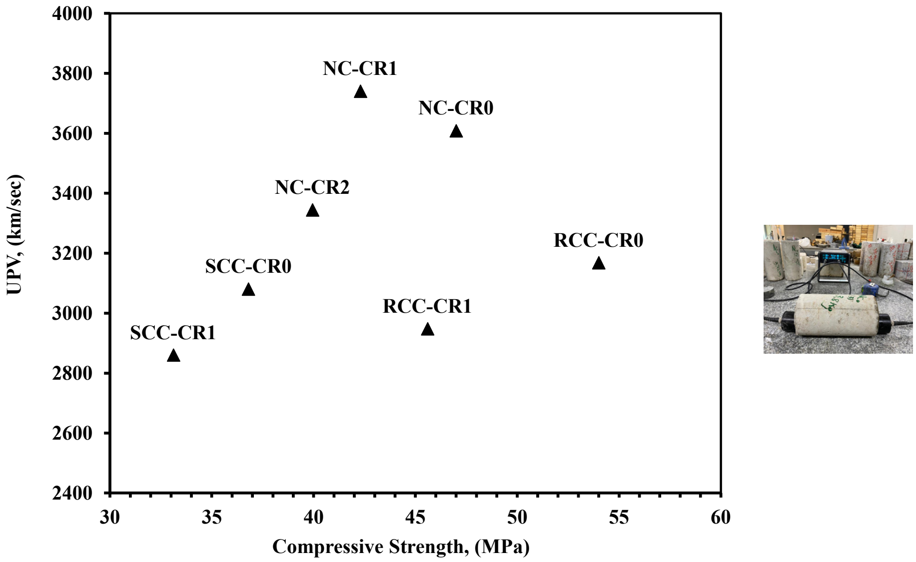
As shown from the relationship between the Rebound number and compressive strength in Figure 13, the values might be reduced for mixes with crumb rubber, and the coefficient of determination (R2) is as high as 0.88, showing adequate measuring and significance of the data measured (coefficient of correlation, r = 0.94). However, this reduction was caused by air being trapped while mixing the crumb rubber with concrete ingredients. Other explanatory related to the energy absorbed caused some internal echo impact without rebounding them back onto the rebound scale.

5.4.2. UPV

The ultrasonic wave velocity (UPV) is a portable device that can be used to evaluate compressive strength based on the density of the concrete. Figure 14a,b show the measure of UPV directly and indirectly. From Figure 14a, although the reduction is clear from the steep slope at control mixes (NC-CR0, SCC-CR0, and RCC-CR0) to light inclined towards the horizontal curve, the velocity obtained could be within the medium quality margin for concrete. This behavior ensures that the crumb behavior could reduce the performance of concrete but not significantly. Porosity might be the main reason for this reduction; however, the curves showed good homogeneity between the concrete ingredients despite the difference in their physical and mechanical properties as well as the behavior of the materials. Figure 14b shows the UPV values that were measured directly, and as clear, the values are a bit higher than those measured indirectly (Figure 14a). The UPV values confirm the existence of the porosity and ensure the correlation between the compressive strength and UPV values for further utilization in evaluating existing structures. It is very important to notice that no relationship can be deduced between the compressive strength of the mixes and UP values due to the different concrete types and mixes used in this study.



(a)



(b)

Figure 14. UPV for the mixes created using two methods: (**a**) indirectly and (**b**) directly.

Several researchers [43,48,58,63,65,66] have investigated UPV, especially in rubberized concrete, ensuring the good quality that might maintained while utilizing the crumb rubber, contrary to most reasoning about increasing porosity and losing homogeneity with concrete ingredients. Some investigations [43,65] stated that fine aggregate replacement with crumb rubber to 15% maintained excellent to very good, and others stated that the reduction in UPV might achieve 34% at 50% fine aggregate replacement [48,58,63]. The latter can reach very good to good according to their results [63]. Keles et al. [65] stated that the reduction in UPV is lightly significant to the extent it can be negligible as it optimally reached a 24.1% reduction relevant to the control mix. Mohammed et al. [66] reasoned that the lowering of UPV values by air entrapping increased while mixing, reducing the contribution of hydration (pozzolanic) reaction at an early age. This behavior slows the C-S-Hgeland, causing pore filling, leading to more discontinuities, reduction in strength, and lowering the UPV values. It should be mentioned that Mohammed et al. [66] found the best correlation between the UPV and the compressive strength by using an exponential model with a coefficient of determination $R^2 > 0.65$, contrary to the findings of this study, which ensured that no relationship can be deduced.

5.4.3. Dynamic Modulus of Elasticity (DMOE)

The results of the dynamic modulus of elasticity (DMOE) for all mixes are presented in Table 11. The dynamic modulus of elasticity (DMOE) was calculated using Equation (1)

$$E_D = (UPV)^2 \left(\frac{\rho(1+\mu)(1-2\mu)}{1-\mu}\right) \tag{1}$$

where E_D is the dynamic elastic modulus at 28 days in GPa, ρ is the 28 days hardened density (unit weight) in kg/m^3, and μ is the dynamic Poisson ratio. The value of μ was assumed to be 0.25 for the DMOE calculation.

Table 11. DMOE values are calculated through Equation (1).

Mix ID	DMOE
NC-CR0	26.97
NC-CR1	26.57
NC-CR2	21.43
SCC-CR0	19.43
SCC-CR1	16.32
RCC-CR0	18.51
RCC-CR1	15.88

Table 11 shows the reduction in DMOE among the mixes with crumb rubber relevant to their control mixes in each concrete type, NC, SCC, and RCC. The reduction is attributed to the increases of crumb rubber in the mix, accompanied by the increase in porosity, which in turn increases the wave path length through the ultrasonic wave travels and, therefore, reduces the UPV values. Figure 15 shows the relationship between the DMOE and the compressive strength. No relationship was deduced due to the scatter relevant to the concrete type and percentile replacement. From the literature review, most researchers [43,48,58,63,65] obtain the UPV values and do not go further in the analysis except Mohammed et al. [66], who reported that the relationship between the DMOE and compressive strength is expressed in the exponential model at the coefficient of determination (R^2) of greater than 0.80. They also obtained a relationship between the compressive strength as dependent values with a related independent variable such as the rebound number and UPV values. Further investigation is required for DMOE and other relationships to be deduced between nondestructive testing and destructive ones or several concrete types and additional practice.

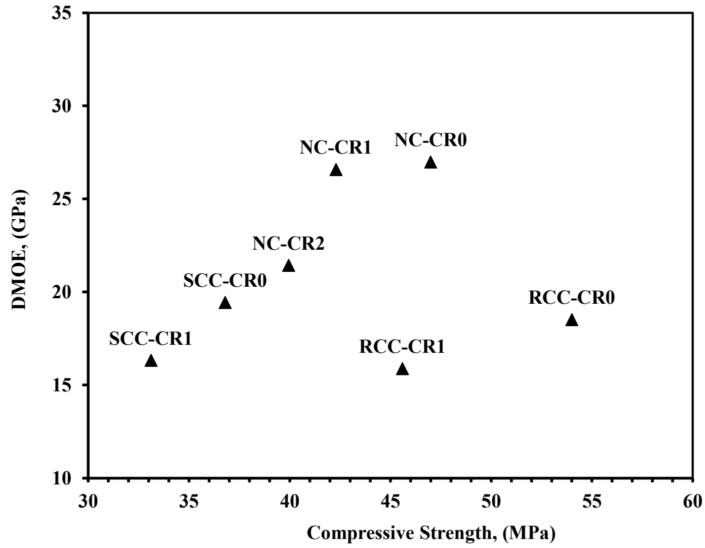


Figure 15. DMOE against the compressive strength of mixes.

6. Conclusions

Based on the experimental program carried out and the analysis of results, the following conclusions were drawn.

- The optimum percentile of crumb rubber was deduced for each concrete type: NC, SCC, and RCC. The difference in the percentile replacement and whether to replace fine, coarse, or total aggregate is attributed to the difference in the design and their basis. For instance, SCC relies mainly on rheological properties when designing its concrete mixes, while RCC uses the optimum water content.
- The crumb rubber reduces the strength properties of the concrete, regardless of the type of concrete used: NC, RCCor, or even SCC.
- The optimum percentile of replacement is for NC 25% of coarse aggregate, for SCC 10% of fine aggregate, and for RCC 10% of the total aggregate.
- Densities are not affected significantly by the replacement with crumb rubber as the volume would be occupied if even the specific gravity is different.
- Slumps will not be influenced or can be negligible in significance as the shape of crumb rubber would shape workability more than its characteristics.
- Compressive, flexural, and tensile strengths reduced at the optimum percentile of replacement due to the weakening of ITZ between the cement matrix and the aggregate; crumb rubber and aggregate, in addition to the existence of the air content that generated from the entrapped air while mixing when utilizing crumb rubber, increasing the porosity and therefore reduces the strength.
- For flexural and tensile strengths, the reduction is not significant as the crumb rubber acts as a fiber-bridging arch, preventing the crack width from increasing and propagating more.
- The impact of rubberized concrete tends towards reducing the brittleness of concrete and increasing its ductility.
- Treatment of crumb rubber is essential in most cases to roughen the surface and increase the bond at ITZ between the cement matrix, crumb rubber, and aggregate.
- The correlation between the rebound number and compressive strength is linear and can be deduced for rubberized concrete, but the opposite is not possible for UPV and DMOE concrete.
- Homogeneity of the rubberized concrete is ensured through the UPV, although the deduced porosity that appears in the reduction of the UPV is relevant to the control mixes.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration, funding acquisition, A.E.-N. and I.G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available upon request.

Acknowledgments: Many thanks to the GUC laboratory, overseen by the technician Ali Mohammed and the student Hady Ayman, who supported us while we performed this experimental work.

Conflicts of Interest: The authors declare no conflicts of interest.

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