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Effect of waste crumb rubber tyre as partial replacement of fine aggregates on fresh and hardened properties of concrete

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Concrete has remained challenging to replace for an extended period due to its inherent strength and minimal maintenance needs over the lifespan of structures, coupled with its versatile applications in various infrastructure projects such as foundations, superstructures, and more. Additionally, concrete components, including fine crushed rock and river sand, are readily accessible in the environment. Recently, waste crumb rubber tyres have emerged as a readily available aggregates option. A True Experimental Research Design method was employed in this study. Concrete was prepared using cement, coarse crushed rock, fine crushed rock, and water, without the use of admixtures, additives, or any other agents, in order to exclusively assess the impact of waste crumb rubber tyres on both fresh and hardened properties. Crumb rubber concrete (CRC) was created by substituting waste crumb rubber tyres for natural fine crushed rock in ratios of 0, 10, 20, 30, and 40% by weight, within the range of 0 to 2.36 mm. Among the CRC samples studied in this research, 10-CRC, which denotes concrete where 10% of the fine aggregates is replaced with waste crumb rubber tyres, exhibited the best performance. This determination was based on its workability, air content, unit weight, compressive and flexural strength, and rate of water absorption.

Key words: Concrete, environment, aggregates, crumb rubber, tyres, fresh, hardened.

INTRODUCTION

Concrete is the most extensively used construction material due to its strength, flexibility, and low maintenance requirements throughout the lifespan of structures. Its components are economically and widely available, making it challenging to replace in various infrastructure applications such as foundations and superstructures. Global concrete production currently stands at around 25 billion tons annually, surpassing the combined production of steel, wood, plastics, and aluminum by weight (TR Construction Omaha, 2020). According to the Pennsylvania Aggregates and Concrete Association (PACA), 70% of the world's population resides in concrete structures for residential purposes (SPECIFY concrete, 2019). However, this widespread use of concrete also leaves the environment vulnerable to associated negative impacts. Increasing attention is

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being drawn to concrete's significant contributions to greenhouse gas (GHG) emissions, which pose a threat to the ozone layer (SPECIFY concrete, 2019).

In the past five years, the construction industry has been increasingly embracing the concept of sustainability. Sustainable construction aims to reduce environmental footprints by incorporating ecological criteria into all phases of construction, from conception to demolition. Sustainability is seen as the key solution to addressing the environmental impacts imposed by the construction industry, as demanded by the public (Cachim et al., 2013). Efforts are underway by both academia and industry practitioners to minimize the environmental impact of concrete production and enhance its carbon sequestration capabilities (Lehne and Preston, 2018).

The United Nations' Sustainable Development Goals 12 and 15 focus on ensuring sustainable consumption and production patterns and protecting terrestrial ecosystems. These goals include promoting the recycling of waste tyres and combating the environmental issues caused by tyre waste. According to the United States Environmental Protection Agency (EPA), there are currently 2 to 3 billion stockpiled tyres in the United States as of 1998, with an annual increase estimated at around 279 million. Waste tyre Rubber (WTR) poses significant environmental challenges, including air, soil, and water pollution. Therefore, recycling tyre waste for economic reuse and cleaner production is crucial for sustainable development (Al-Bared et al., 2018).

Crumb rubber is obtained by crushing end-of-life tyres (ELTs) into small particles comparable in fineness to sand. These "rubber crumbs" can replace a certain portion of fine aggregates used in the concrete mixing process. By doing so, crumb rubber not only provides economic value to waste tyres but also reduces the demand for natural sands (Mills et al., 2018). Typically, waste crumb rubber tyres have been utilized in sizes ranging from 10 to as low as 0.075 mm (Eldin and Senoucci, 1992). In recent years, the term "Crumb rubber concrete" (CRC) has gained prominence as a new construction material with significant potential, created by substituting aggregates with rubber crumbs in concrete mixing. This results in concrete that minimizes environmental harm while still meeting structural requirements (Topcu and Avcular, 1997; Eldin and Senouci, 1994).

Previous studies have experimented with substituting fine aggregates in concrete with rubber ash and other sizes of rubber ranging from less than 0.6 up to 8 mm in various proportions. It was evident that workable levels of concrete were reduced. Zhuoming et al. (2019), Aldahdooh et al. (2016), Aly et al. (2019), Ismail et al. (2018), Jokar et al. (2019), and Girskas and Nagrockienė (2017) all noted that the presence of rubber dust and fluff in crumb rubber, along with its surface roughness, adversely affected workability. Yang et al. (2021), Hossain et al. (2019), AbdelAleem and Hassan (2019), and Onuaguluchi and Panesar (2014) found that workability decreased due to the significant hydrophobicity of crumb rubber particles, causing them to float and further segregate within the concrete mix. However, a few studies have shown that the low water absorption of crumb rubber can improve workability. Similar findings were reported by Khaloo et al. (2008) when substituting natural fine aggregates with crumb rubber in small proportions, that is, less than 20%. Assaggaf et al. (2021) found that the slump of concrete increased with the inclusion of crumb rubber, attributed to the low water absorption of crumb rubber.

Khatib and Bayomy (1999) observed that air content increased with an increase in the amount of rubber aggregates in concrete. It is widely acknowledged in the literature that crumb rubber can replicate a similar portion of air typical of air entrainment by admixtures. Uygunoğlu and Topçu (2010) and Adamu et al. (2017) recorded a 26% increase in air content when substituting fine aggregates with 1.5% weight of crumb rubber. The authors attributed these outcomes to the non-polar tendencies and lighter density of crumb rubber.

The effect of crumb rubber on unit weight was consistent across the literature, with reductions observed for all proportions of crumb rubber ranging from 0 to 100%, and across all sizes. Sukontasukkul et al. (2013) obtained typical results when experimenting with crumb rubber sizes below 600 microns. Guneyisi et al. (2004) and Pastor et al. (2014) found similar results when experimenting with crumb rubber sizes ranging from 0.075 to 12.5 mm.

Abendeh et al. (2016) noted a reduction in compressive strength corresponding to an increase in crumb rubber replacement. They experimented by replacing fine aggregates with sizes ranging from 0.6 to 4.75 mm, commonly in replacement ratios of 0 to 50% at 5 to 10 intervals. Salehuddin et al. (2015) experimented with three portions of 2.5, 5.0, and 7.5% of crumb rubber replacing fine natural aggregates, with water/cement ratios of 0.5 and a crumb rubber size of 2-4 mm. The results showed a decrease in compressive strength due to the lighter density of crumb rubber, as well as the rigid nature of crumb rubber in binding with cement and increased pressure at the interfacial transition zone (ITZ), leading to crack development at vital connection points.

Ultrasonic Pulse Velocity (UPV) is an important test that can provide information on the homogeneity and uniformity of concrete, as well as the presence of voids and cracks. The number of cracks, cavities, and voids in a concrete sample affects its quality. UPV is a non-destructive test that can be performed before measuring compressive strength on the same samples. The replacement of fine aggregates by crumb rubber led to a decrease in flexural strength by 18% compared to normal aggregates concrete, with this decrease becoming more significant as replacement levels increase up to 50%

(Silva et al., 2018). All common chemical reactions in concrete are accelerated by moisture. The main connection between durability and the rate of water absorption in Crumb rubber concrete (CRC) is significant.

According to the literature, the exploratory outcomes of Bravo and De Brito (2012) support that further water absorption occurs as the amount of crumb rubber increases. Thomas et al. (2014) concluded that water absorption depends on the size and quantity of crumb rubber, along with the water-to-binder ratio of the mix. They have mentioned the presence of voids that appear upon replacing fine aggregates with crumb rubber as a contributing factor to the increased absorption recorded. Some researchers found that water absorption reduced up to a certain limit before increasing again (Wang et al., 2019; Thomas and Gupta, 2015; Bisht and Ramana, 2017; Salehuddin et al., 2015; Mohammed and Azmi, 2011). Incorporating different sizes of crumb rubber developed the degree of aggregates (Si et al., 2017), causing a denser microstructure, which promoted favorable sorptivity.

In this research, the fresh and hardened properties of concrete made with waste crumb rubber tyres were studied. The properties of concrete in the plastic state are rarely studied despite their influence on the ultimate results in the hardened state. The hardened properties considered in this research are useful in determining the mechanical strength and serviceability of the concrete discussed.

This study researched the slump and vebe, unit weight, air content, compressive strength, flexural strength, ultrasonic pulse velocity (UPV), and rate of water absorption properties of concrete made with waste crumb rubber tyre. The ultimate goal is to create concrete with this waste material (crumb rubber) that can meet standard grade concrete requirements. The research monitored the effect of waste crumb rubber tyre working as a fine aggregate in proportions of 0, 10, 20, 30, and 40% on various properties of concrete. To this end, no admixtures, agents, or additives of any kind were used in preparing the concrete. The results obtained show that 10-CRC was the best performing crumb rubber concrete across all properties observed in this research.

MATERIALS AND METHODS

The basic materials used in this research were cement, coarse limestone rock, fine limestone rock, water, and crumb rubber. The cement used was CEM II/BS 42.5N, and potable water was used to mix the constituents together. The source of the natural aggregates used was Besparmak Mountains, North Cyprus. These aggregates were physically observed and found to be angular in shape. Tests for moisture content were performed according to ASTM C566-19, and specific gravity and absorption capacity were tested according to ASTM C127-15 and ASTM C128-15, respectively.

Crumb rubber, that is, waste tyre rubber, reduced to sizes 4.75 to 0.075 mm (Siddique and Naik, 2004; Kardos, 2011), was obtained from Rubberland Kauçuk Granür Recycling Industry, Haspolat, North Cyprus. The waste tyrerubber was processed through ambient grinding to obtain the crumb rubber. The specific gravity of the crumb rubber was determined according to ASTM C188. The angular-ameboid shape of the crumb rubber was discovered with the aid of a stereomicroscope (Figure 1).

Figure 1. Crumb rubber image obtained from stereomicroscope.

Mix proportioning

The constituents of the control concrete were assigned according to the Building Research Establishment (BRE) method (1997). 10, 20, 30, and 40-CRC were derived by mass replacement of natural fine crushed rock with crumb rubber in percentages of 10, 20, 30, and 40%, respectively (Table 1). The share of aggregates for mixing concrete was determined according to ASTM C136M-19 and C33M-18 (Figure 2 and Table 2). The mixer used was a Bentoneira 125L drum mixer with the following specifications: V ~ 230, Hz ~ 50, kW ~ 0.90, A ~ 3.2. The specimen type for hardened tests was 150 mm cubes. The necessary equipment included a vibrating table, metal tray, and scoop. The method of mixing was as follows: The mixer was switched on, then coarse aggregates were added and tilted to about 60º and rotated for 1 min. Fine crushed rock followed afterwards for a period of 1 min (30 s each when adding crumb rubber).

Then cement was poured and rotated for 1 min. Finally, water was added, and the drum was lowered to the mixing angle. It continued mixing for 5 min, bringing the total mixing time to 8 min. A vibrating table was used to vibrate plastic cube molds of fresh concrete, and curing was administered according to ASTM C192M-19. Three specimens were prepared for each reported value when

Table 1. Physical tests on constituents.

Aggregates type/property	Coarse aggregates	Fine aggregates	Crumb rubber
Specific gravity	2.73	2.75	1.25
Moisture content (%)	0.40	2.17	0.06
Absorption capacity (%)	0.73	1.57	Negligible
Bulk density (kg/m^3)	1370.16 for loose, 1489.13 for compacted	-	-

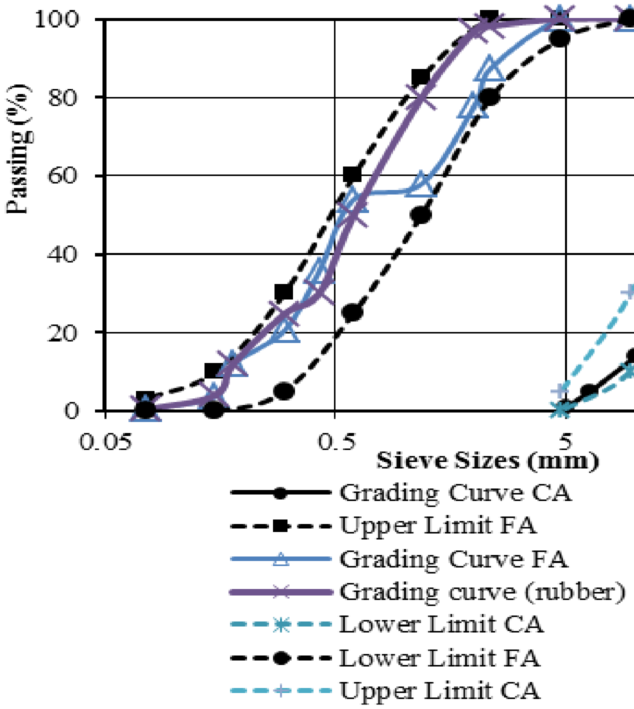

Figure 2. Particle size distribution of aggregates.

testing hardened concrete. Table 3 shows the physical test of constituents.

Experimental procedure

The consistency of concrete was determined by the Vebe consistometer. The apparatus consisted of a hollow conical frustum placed in a larger upright cylinder, a clear glass disk attached to a swivel arm, a vibrating table, and a timer. The testing procedure was as follows: The sheet metal slump cone was placed into the cylindrical container within the consistometer. Fresh concrete was poured into the cone in four layers, with each layer being one-fourth of the cone's height. After pouring each layer, the cone was subjected to twenty-five tamps using the tamping rod's rounded end.

Strokes were uniformly distributed, with minimal penetration into the underlying layer. Excess concrete was struck off with a trowel to ensure the cone was precisely filled and leveled. The cone is then removed, and the slump is recorded as the Vebe slump (Figure 3a). The clear glass disk is raised to a maximum height of 0 cm and then released to mold the concrete in the cylindrical container (Figure 3b). The metered rod reading is taken as the first drop of the Vebe rod (Figure 3c). Afterwards, the vibrating table is turned on. Once a mortar ring appears on the sides of the transparent glass disk, the time on the stop-clock is recorded as the Vebe time (Figure 3d). When carrying out the Vebe test on concrete specimens, moldability and pliability are evaluated by measuring Vebe slump and the first drop of the Vebe rod. Other fresh properties such as slump, amount of air, and unit weight are evaluated using ASTM standards: ASTM C143M-20, ASTM C231M, and ASTM C138M-17a, respectively.

In testing for the pulse velocity of concrete, 150 mm concrete cubes are obtained and properly dried. These specimens are marked, and jelly is applied at the point of contact. The device is calibrated with a metal weight of known velocity. Then, the transducers are placed on opposite sides of the concrete cube, and the time taken for the pulse to travel from one end to the other is recorded in microseconds.

$$\text{Pulse velocity}\left(\frac{mm}{\mu s}.\right)=\frac{\text{Width of Structure }(mm)}{\text{Time taken by pulse to go through }(\mu s)}$$

Final results are converted to km/s;1 mm/µs = 1 km/s.

The compressive strength was measured as follows: In testing for compressive strength, the same concrete cubes used in the

Table 2. Mix design.

Specimen	w/c ratio	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Crumb rubber (kg/m^3)	Coarse aggregates (kg/m^3)
Control	0.41	237.50	580.00	578.90	(-)	985.60
10-CRC	0.41	237.50	580.00	521.01	57.89	985.60
20-CRC	0.41	237.50	580.00	463.12	115.78	985.60
30-CRC	0.41	237.50	580.00	405.23	173.67	985.60
40-CRC	0.41	237.50	580.00	347.34	231.56	985.60

10-CRC that is, concrete made by replacing 10% mass of fine aggregates with corresponding mass of crumb rubber.

Table 3. Fresh concrete data.

Fresh concrete parameter	Cont.	10-CRC	20-CRC	30-CRC	40-CRC
Slump (mm)	175.00	140.00	80.00	65.00	45.00
Vebe time (s)	1.40	3.00	5.25	11.00	17.00
Vebe slump (mm)	30.00	60.00	55.00	15.00	~
First drop of Vebe Rod (mm)	45.00	105.00	75.00	35.00	15.00
Air content (%)	0.60	1.20	1.60	2.00	2.40
volume of water to expel excess air (cm^3)	13.73	86.07	172.50	213.03	343.99
Unit weight (kg/m^3)	2361.25	2279.38	2177.50	2088.75	1943.63

aforementioned nondestructive test are subjected to a compression load in acompression-flexural testing machine. The specimens were properly dried and placed on the plane according to the provided guides (Figure 3).

The plane was free of any specks or grit before testing. Compression force was applied accordingly until fracture. The compressive strength is measured in MPa. The flexural strength recorded in this research is measured according to ASTM C78M-21. The rate of water absorption for concrete is determined according to ASTM C642-21.

RESULTS AND DISCUSSION

Effect of crumb rubber on fresh and hardened properties of concrete

Crumb rubber effect on workability

Crumb rubber reduced slump and increased vebe time, as seen in Figures 4 and 5, respectively. Every 10% increase in crumb rubber reduced slump by 15 to 75% across all crumb rubber concrete mixes, with respect to control concrete.

The reason is that crumb rubber does not dissolve easily in water, and only through mechanical means, such as the electric mixer, can the crumb rubber diffuse within the concrete mix, with minimal isolation that reduces workable levels.

Additionally, crumb rubber has a tendency to float, inhibiting the flowing nature of concrete when the slump cone is released for it to spread. The majority of studies reported a similar decrease in this regard. The attribution of slump reduction is due to the roughness of crumb rubber surface compared to mineral aggregates (Alsaif et al., 2018). Moreover, fine impurities such as rubber dust and fluff hampered workability (Alsaif et al., 2018; Chen et al., 2019). Vebe time rose gradually with an increase in crumb rubber content up to 20%, and then steeply for 30-CRC and 40-CRC (Figure 6). For 10-CRC, it increased by 114.29%. For 20-CRC, it increased by 275%. For 30-CRC, it increased by 685.71%, and for 40-CRC, it increased by 1114.29%. In Tables 4 and 5, the stickiness of control concrete caused it to adhere to the base and walls of the Vebe bucket, preventing the mass of concrete from slumping (Marar and Eren, 2011). This caused a higher percentage slump for 10-CRC and 20-CRC compared to control concrete. A higher Vebe slump in 10 and 20-CRC than in control concrete emphasizes the moldability of concrete enhanced by crumb rubber. Raising the glass plate to zero

Figure 3. (a) Vebe slump (b) Glass disk raised to 0cm height (c) Depth of first drop of Vebe rod (d) Mortar ring appears on the sides of the transparent glass disk.

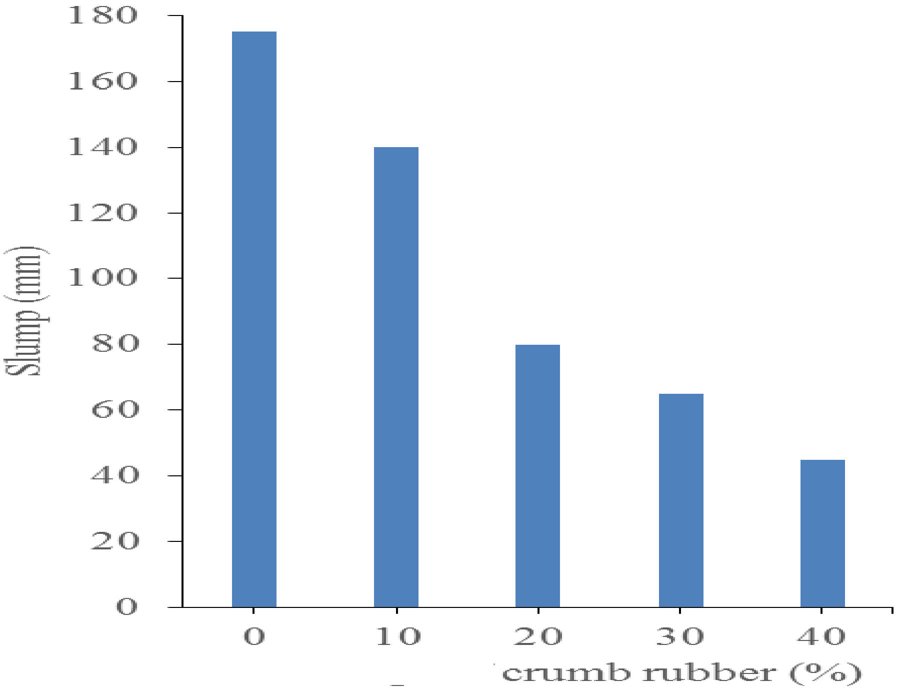

Figure 4. Slump of CRC.

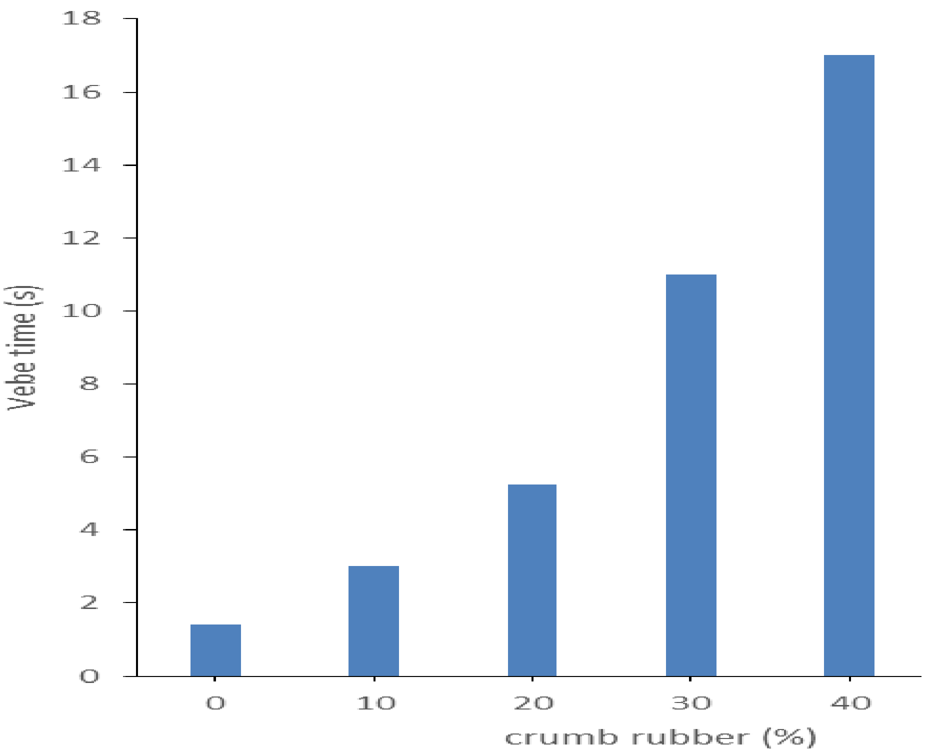

Figure 5. Vebe time of concrete mixes.

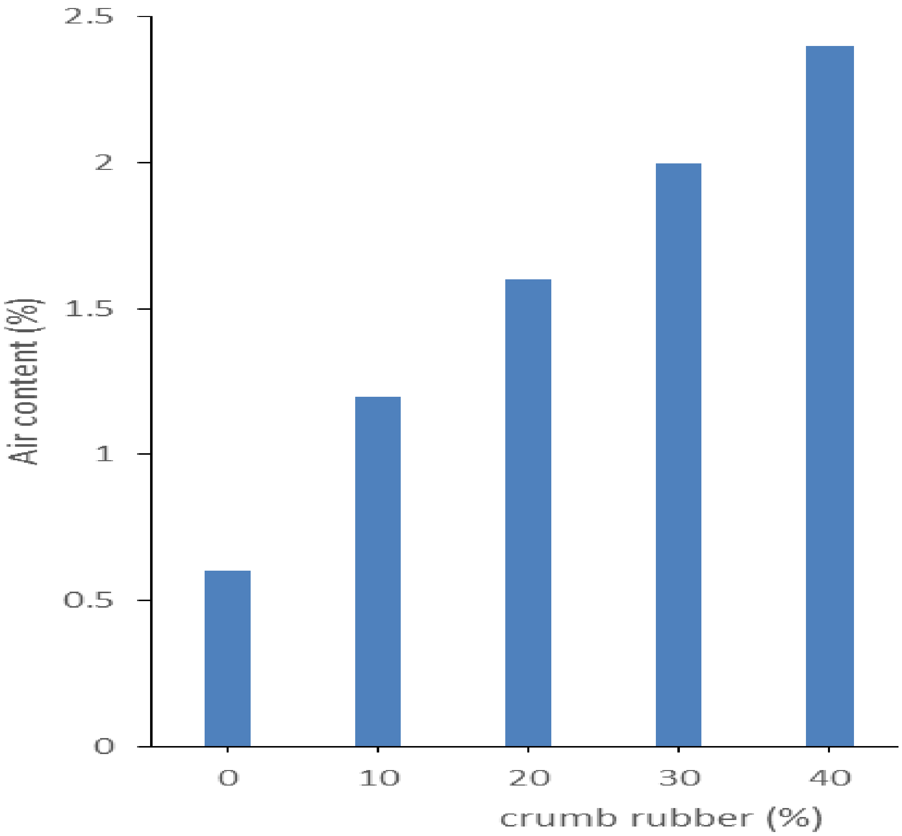

Figure 6. Crumb rubber concrete (CRC) air content.

Table 4. 7-day mechanical strength results.

Mix ID	Max load (KN)	Compressive strength (MPa)	Max load (KN)	Flexural strength (MPa)	Dry density (kg/m^3)
Control	854.00	37.90	11.23	5.62	2453.33
10-CRC	725.00	32.20	8.33	4.15	2349.63
20-CRC	441.00	19.60	6.27	3.13	2228.15
30-CRC	456.00	20.30	5.90	2.94	2212.35
40-CRC	346.00	15.38	5.70	2.85	2103.70

Table 5. 28-day mechanical strength results.

Mix ID	Max load (KN)	Compressive strength (MPa)	Max load (KN)	Flexural strength (MPa)	Dry density (kg/m^3)
Control	1307.00	58.10	12.25	6.10	2361.48
10-CRC	912.30	40.50	9.00	4.49	2295.80
20-CRC	633.67	28.20	7.73	3.86	2135.80
30-CRC	587.33	26.10	7.00	3.49	2096.30
40-CRC	512.33	22.77	6.23	3.12	2163.95

mm height and releasing it, the height of the first drop of the Vebe rod on the fresh sample of control concrete was 45 mm. It increased by 133.33 and 66.67% for 10 and 20-CRC respectively, compared to control concrete.

For 30 and 40-CRC, it decreased by 22.22 and 66.67% respectively, with respect to control concrete. This showed that CRC, particularly 10 and 20-CRC in this instance, were more pliable than control concrete. The actual cement content in control concrete caused a bond of attraction with the glass plate, which reduced the first drop height (Table 3).

Effect of crumb rubber on air content

Figure 6 showed a proportionate rise in air content with replacement levels. For the control mix, air content was recorded at 0.60%. It increased rather sharply by 100.00% for 10-CRC, and continued steadily at 166.67% for 20-CRC, 233.33% for 30-CRC, and 300.00% for 40-CRC, with respect to control concrete. This rise in air content is beneficial in concrete for freeze-thaw reasons. It is attributed to the segregation in freshly mixed concrete containing crumb rubber, which led to visible bubbles in 10-CRC. At higher replacement levels, such as 30-CRC and 40-CRC, there were visible pockets of air like cheese holes that developed even after adequate tamping as per the standards. Segregation increased with the content of crumb rubber, as evidenced by the amount of water needed to expel excess air from the chamber (Table 3).

A similar trend occurred where Khatib and Bayomy (1999) discovered 4% air content by weight of concrete for the highest percentage replacement of fine aggregate by crumb rubber, which was 50%. Neville and Brooks (2010) prescribed 4% as the maximum ideal limit for freeze-thaw, making 50% the highest ideal amount of crumb rubber replacement when considering freeze-thaw design. However, the lesser amount of air at the maximum replacement ratios recorded in this research is due to replacement by mass, compared to replacement by volume as in the aforementioned studies. The authors have named the non-polar nature of rubber aggregates as a probable cause of the high air content introduced into concrete, coupled with lightly dense rubber aggregates which culminate in a lighter unit weight of crumb rubber concrete (Kumar and Lamba, 2017; Assaggaf et al., 2021). Crumb rubber has the ability to repel water, attract air, and thus, introduce bubbles into the concrete (Mutar et al., 2018).

Effect of crumb rubber on unit weight

In Figure 7, crumb rubber reduced the unit weight proportionately by 4 to 7% at every 10% increase in replacement level. Control concrete recorded a unit weight of 2361.25 kg/m^3. It reduced by 3.47% in the case of 10-CRC, 7.78% for 20-CRC, 11.54% for 30-CRC and 17.69% for 40-CRC, with respect to control concrete. This reduction is attributed to the lighter density of the crumb rubber particles compared to finely crushed limestone rock. The crumb rubber used in this research had a density slightly less than half of the fine mineral aggregates with respect to the density of water. The lighter density of crumb rubber, nearly equal to the density of water, caused a lower weight per unit volume of fresh concrete. Other studies have found similar range reductions across varying intervals (Kumar and Lamba, 2017).

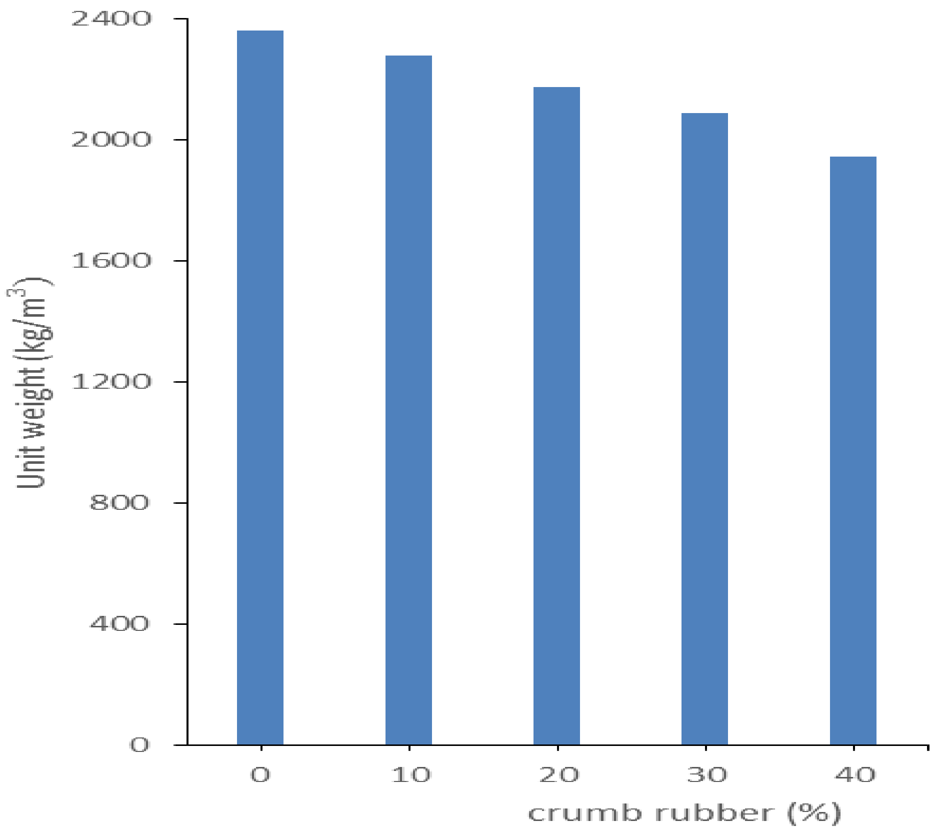

Figure 7. Crumb Rubber Concrete (CRC) unit weight.

Crumb rubber effect on compressive strength

In Figure 8, compressive strength decreased with the increase in crumb rubber content. At 7 days, compressive strength decreased by 15.04% for 10-CRC, 48.28% for 20-CRC, 46.44% for 30-CRC, and 59.42% for 40-CRC, compared to control concrete. At mature age, compressive strength decreased by 30.29% for 10-CRC, 51.46% for 20-CRC, 55.08% for 30-CRC, and 60.81% for 40-CRC, relative to control concrete. It is noteworthy that crumb rubber exhibited significantly higher strength percentages after 7 days compared to control concrete. The reduced maturity observed after 7 days until 28 days is attributed to the effective absorption of cement paste by crumb rubber within the concrete matrix, which is essential for the continuous production of hydration compounds during the 28-day curing period.

Another reason for the decrease in compressive strength is the replacement of sand with lightly dense crumb rubber. Figure 8 illustrated a 30 to 60% reduction in compressive strength with 10 to 40% replacement by crumb rubber. This is consistent with findings by Thomas et al. (2014), who reported reductions of 41.2 to 52.9%, 44.9 to 48.7%, and 49.9 to 53.4% for w/c ratios of 0.3, 0.4, and 0.5, respectively, for 15 to 20% replacement of fine aggregate with crumb rubber by weight. It is evident from the literature that the interface between crumb rubber and cement mortar produced an interfacial transition zone (ITZ) that differed significantly from the ITZ formed between natural aggregates and cement mortar. There was a poor state of rigid existence between rubber and cement particles, generating regions of high stress concentrations at the interfacial transition zone (ITZ), leading to crack formation within that zone. This results in the least resistance to load deformation (Salehuddin et al., 2015). Additionally, 70% of the cracks that occur in concrete are ITZ cracks, which are the main points of propagation for crack development (Department of Civil Engineering, 2014).

Effect of crumb rubber on ultrasonic pulse velocity (UPV)

In Figure 9, UPV exhibited a minimal decrease with 10-CRC, followed by a steep decline with 20-CRC, and a gradual decrease with higher replacement levels up to 40-CRC. At 28 days, UPV decreased by 0.22% for 10-CRC, 12.50% for 20-CRC, 16.38% for 30-CRC, and 17.67% for 40-CRC, relative to control concrete. The decline in UPV is attributed to the detrimental effects of crumb rubber on concrete, including the formation of

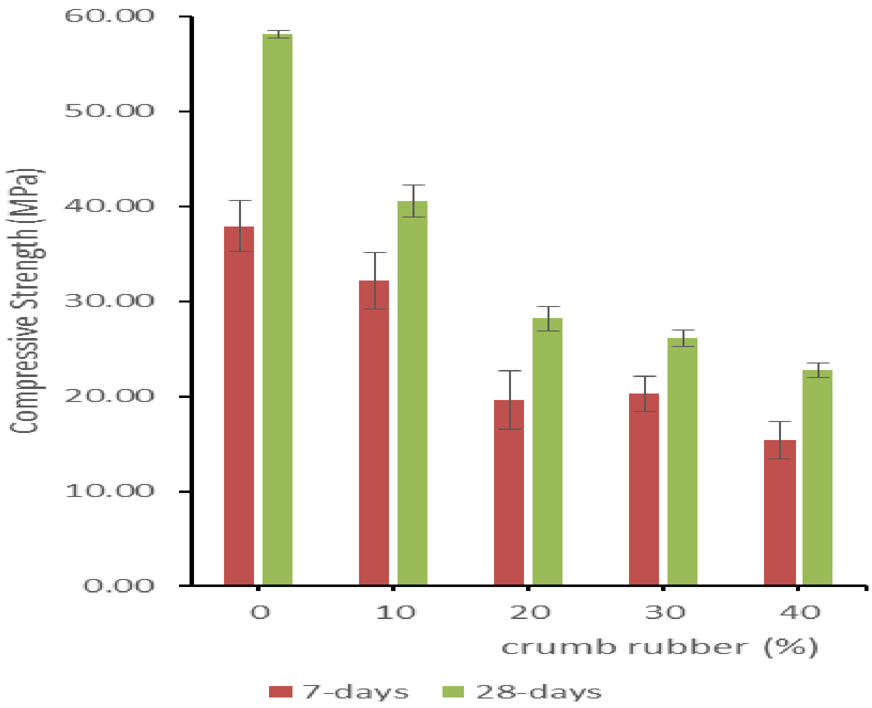

Figure 8. Compressive strength of CRC.

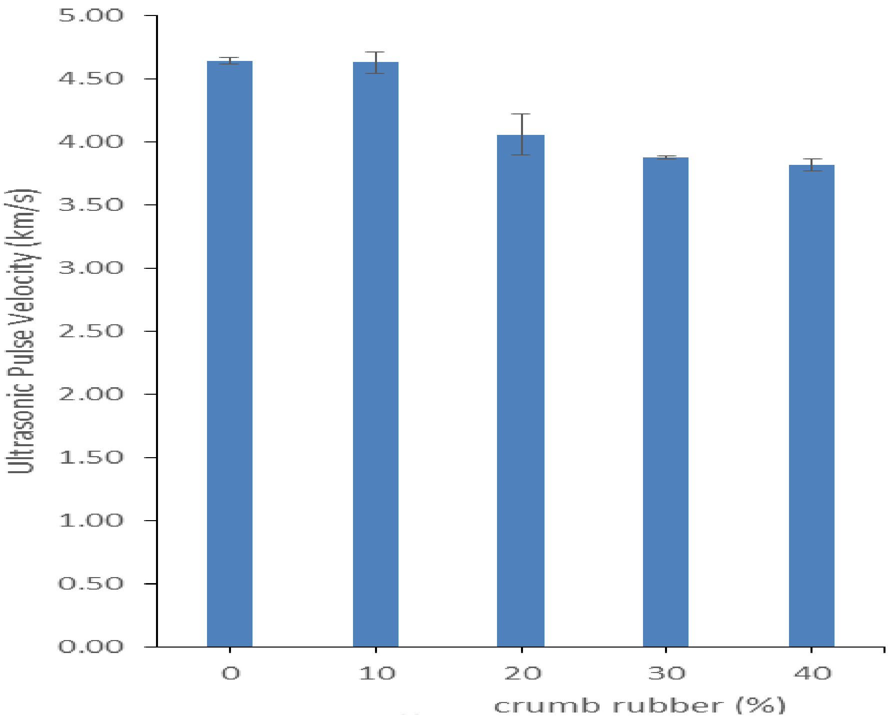

Figure 9. Ultrasonic pulse velocity of CRC at 28-days.

blisters, delamination, air voids, micro-cracks, and visible cracks. Crumb rubber acts as an impurity that increases interference between transducers when present in larger quantities within the concrete matrix. Jafari and Toufigh

Table 6. UPV grading.

Pulse velocity (km/s)	Concrete quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

Source: Civil Engineering Portal (2022).

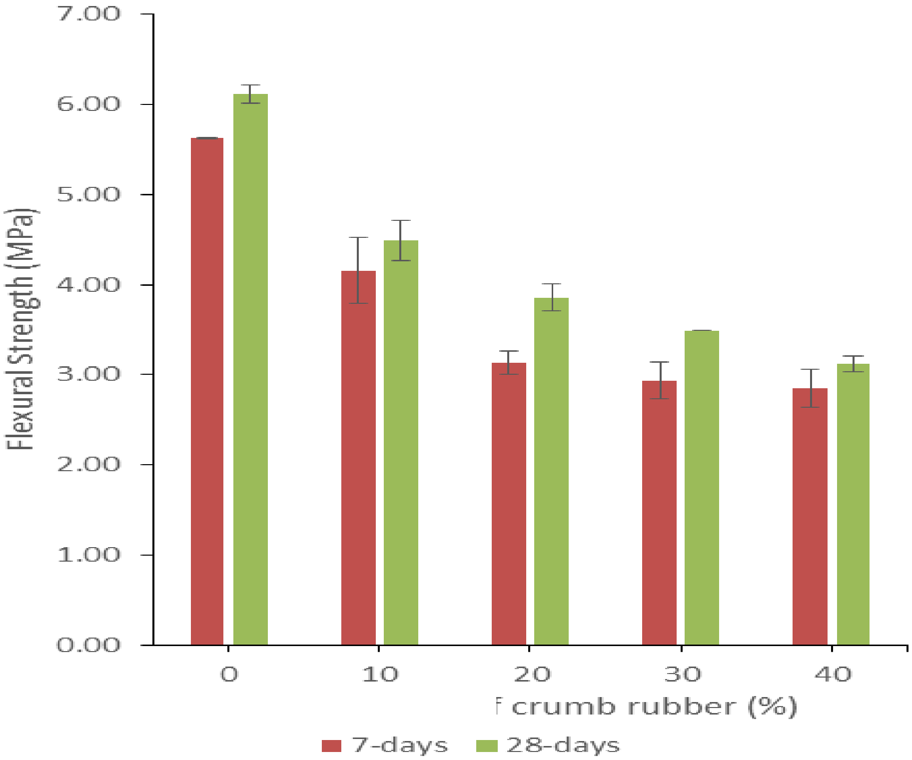

Figure 10. CRC flexural strength.

(2017) investigated the substitution of fine aggregates with crumb rubber (4 mm in size) at replacement ratios of 0, 10, 20, and 30% and observed a decrease in UPV as the replacement ratio increased. Table 6 shows the UPV grading.

Effect of crumb rubber on flexural strength

Similar to compressive strength, flexural strength decreased with increasing amounts of crumb rubber (Figure 10). At 7 days, flexural strength decreased by 26.16% for 10-CRC, 44.31% for 20-CRC, 47.69% for 30-CRC, and 49.29% for 40-CRC, relative to control concrete. At maturity, flexural strength decreased by 26.39% for 10-CRC, 36.72% for 20-CRC, 42.79% for 30-CRC, and 48.85% for 40-CRC, with respect to control concrete. This reduction is attributed to crack formation at the interface between cement mortar and crumb rubber particles in the bending plane. During testing, crumb rubber concrete (CRC) beams exhibited increasing ductility with higher crumb rubber content, allowing for concrete deformation without significant rupture. Despite the reduction in strength, the ratio of flexural to compressive strength remained higher in crumb rubber concrete compared to natural aggregate concrete. The ratios of flexural to compressive strength for concrete comprising 10, 20, 30, and 40% crumb rubber were higher than those of natural aggregate concrete by 0.59, 3.19, 2.87, and 3.20%, respectively. Al-Attar et al. (2022) observed a similar trend, with ratios of flexural to compressive strength for concrete containing 10, 20, and 30% crumb rubber higher than those of natural aggregate concrete by 2.95, 4.23, and 1.48%, respectively.

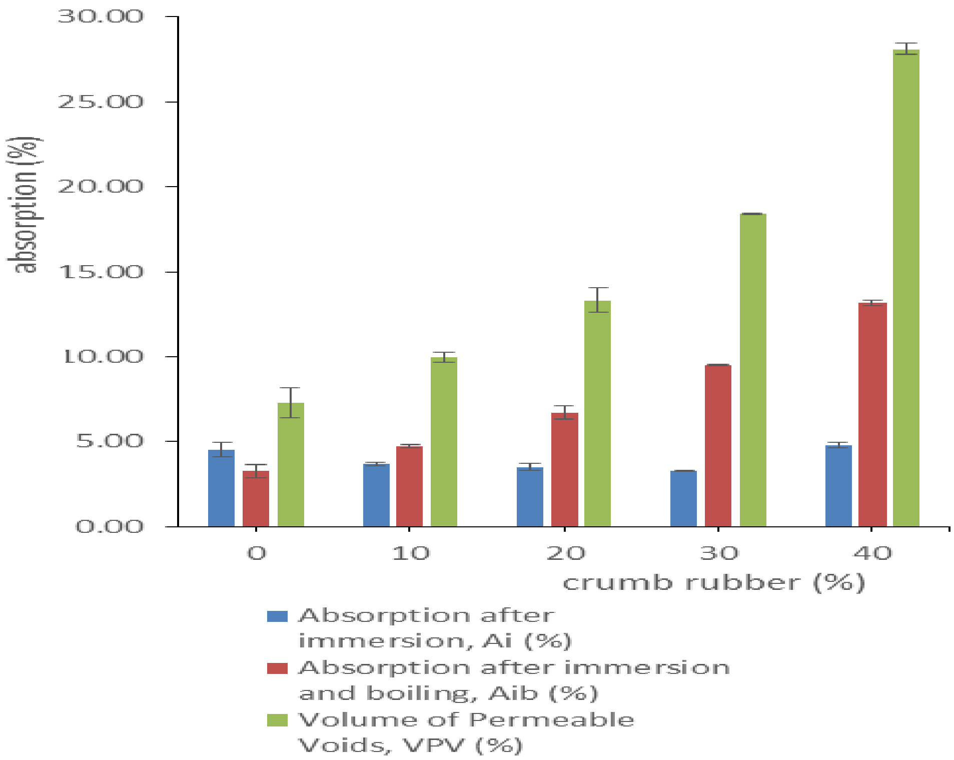

Figure 11. Rate of water absorption, of CRC.

Table 7. Volume of permeable voids chart.

Type	Ratio (%)
Water-tight	4.4 - 7.9
Compact	6.4 - 10.9
Moderate	9.9 - 13.5
Permeable	11.4 - 16.4
Pervious	12.7 - 21.9

Source: Paulini (2019).

Crumb rubber effect on rate of water absorption

Figure 11 shows that absorption after immersion (Ai), and absorption after immersion and boiling (Aib), with volume of permeable voids (VPV) increased with crumb rubber, compared to control concrete (Table 7). Control concrete recorded 2.24:3.27:7.30% for Ai:Aib:VPV respectively. At first instance of 10-CRC, it increased by 65.18:44.65:36.30% for Ai:Aib:VPV respectively, compared to control concrete. At next instance of 20-CRC, it increased by 56.70:105.50:82.47% for Ai:Aib:VPV respectively, compared to control concrete. Then for next instance of 30-CRC, it increased by 48.21:191.13:152.19% for Ai:Aib:VPV respectively, compared to control concrete. Finally, for 40-CRC, it increased by 113.84:302.75:285.21% for Ai:Aib:VPV respectively, compared to control concrete. In this research, when measuring absorption after immersion (Ai), it was discovered that at first instance of crumb rubber content 10%, absorption rose, but at 20 and 30%, there was a little decline before rising tremendously at 40%. At the first instance, the poor adhesions between pastes of cement and crumb rubber led to the jump in water absorption. However, on increasing the crumb rubber content to, 20 through to 30%, the melted crumb rubber (procedure 7.1 and 7.2, ASTM C642-21) somewhat helped in lacing the surface crevices of the concrete matrix. On cooling, crumb rubber crystallizes (hardens), this limits ingress of water into the crumb rubber concrete matrix after immersion, but not beyond control concrete. Subsequently, it rose highest with 40-CRC. When observing absorption after immersion and boiling in this research, it was discovered that during immersion and boiling of the concrete cube in water, as the water goes into a rolling boil, the pressure of the bubbles (water vapor) causes the crumb rubber lacing the concrete matrix to shrink, penetrating through the matrix to the tiniest veins of the concrete. This leads to increased percentage gain in weight C (7.3, ASTM C642-21), compared to control concrete.

Hence, the increasing trend in absorption after immersion and boiling compared to control concrete (Figure 11). It has been shown that, in low-pressure environments, (CRC) can be nearly as durable as control concrete, depending on the percentage of crumb rubber replacement. However, in high-pressure environments, (CRC) is generally less preferable compared to control concrete. The rate of water absorption test provides insights into the possible voids that can be introduced into concrete. Concrete typically contains pores, which hold some significance. From gel pores containing C-S-H gel as small as 0.005 microns, to larger pores, such as capillary pores and permeable pores, with common sizes of 0.082 to 0.121 microns and 0.1 to 1 micron respectively? Figure 11 shows that despite the increase in the volume of permeable voids, 10-CRC is within the admissible ranges of conventional normal weight concrete, that is, <16% (CCAA, 2009). Pore information about any concrete can determine its required compaction and compatibility for the intended purpose (Department of Civil Engineering, 2014). Figure 11 shows water absorption after immersion and boiling increases with increasing ratios of crumb rubber, consistent with past research (Aliabdo et al., 2015; Salehuddin et al., 2015; Pham et al., 2019). It has been suggested that for optimal absorption, it is suitable to limit the replacement with crumb rubber to a maximum of 15%. At this dosage, the difference between oven-dry mass A and apparent immersed mass B was minimal.

Conclusion

This study experimentally investigated the effect of waste crumb rubber tyre as a partial replacement of fine aggregates on the fresh and hardened properties of concrete. Based on the findings, 10-CRC emerged as the best performing crumb rubber concrete across the fresh and hardened properties studied in this research, making it the most ideal option. Considering its favorable characteristics such as workability, unit weight, air content, compressive strength, flexural strength, pulse velocity, and rate of water absorption demonstrated in this research, 10-CRC appears suitable for various construction purposes.

Further research could explore the permeability of crumb rubber concrete with the use of natural pozzolanic admixtures, particularly those of volcanic origin. Additionally, investigating the size and development of pores within the crumb rubber concrete through porosimetry could provide valuable insights.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Nomenclature

A	Amperes
CRC	Crumb rubber concrete
FA	Fine aggregates
g	grams
Hz	Hertz
kg/m^3	Kilogram per cubic meter
kW	Kilowatts
L	Liter
mm	millimeter
V	Volts
w/c	water to cement ratio
w/b	water to binder ratio
Ai	Absorption after immersion
Aib	Absorption after immersion and boiling
VPV	Volume of Permeable Voids