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Original Research Paper

Investigating the Viability of Rubber Crumbs from Waste Tyres as Partial Replacement for Coarse Aggregates in Concrete

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Abstract: The number of waste tyres is on the increase, because of the growing use of transport vehicles. Almost one trillion waste tyres are generated in the world annually. Established methods of disposal, recycling and re-use of waste tyres have failed to keep pace with generation, proven to be ineffective, cost-intensive and in some cases environmentally unsustainable. This study aims to investigate the effects of utilizing crumbs from discarded rubber as a partial replacement for coarse aggregates in concrete. Rubber crumbs of 10 – 20mm nominal size were produced manually from waste tyres. The rubber crumbs were used to replace 10%, 20% and 30% of coarse aggregates in design concrete of 20N/mm2 target compressive strength. The effects of this material on the slump, water absorption and compressive strength of concrete were examined. The inclusion of rubber crumbs resulted in a decline in the slump of concrete up to 10% relative to the control specimen. Water absorption increased marginally at 10% replacement compared to the control specimen and recorded a maximum value of 0.77% with 30% replacement after 28 days of curing. The compressive strength of the concrete was negatively affected by the rubber crumbs. The maximum value of 13.9N/mm2 was attained at 10% replacement after 28 days of curing. Rubberized concrete with 10% replacement of coarse aggregates can be used for non-structural concrete members such as roof slabs, non–load–bearing partition walls, and roadside barriers. Chemical treatment of rubber crumbs to improve surface adhesion properties should be encouraged.

Keywords: Waste Tyre Recycling, Rubber Crumbs in Concrete, Coarse Aggregate Replacement, Rubberized Concrete Performance, Compressive Strength of Concrete.

1. Introduction

The increase in urbanization, civilization and industrialization has led to numerous use of vehicles as the most prominent means of transportation in Uganda and as such leads to huge numbers of discarded waste tyres in the country. Discarded tyre rubber crumbs are waste materials that pose huge environmental hazards to the surroundings where they are deposited and their disposal has become a global problem [1]. In many countries, burying waste tyres is a common disposal method, which shortens the service life of the burial ground and causes a very serious threat to ecology. Therefore, effectively reusing waste tyres is an urgent and important issue for saving energy and protecting the environment [2]. The filtration of rainwater harvested by deposits of natural sand and gravel is being lost within the tyre-buried zone because of contamination [3] [4] [5]. Hence, authorities are imposing stringent restrictions and policies on the extraction of natural aggregates and their crushing to prevent pollution [6].

Discarded rubber tyre is a very good additive to concrete to make it retain its tensile strength and durability. Concrete, an artificial stone-like mass, is a composite material that is created by mixing binding material (cement or lime) along with the aggregate (sand, gravel, stone, brick chips, etc.), water, admixtures, etc., in specific proportions. The proportions used in mixing determine the quality and strength of the concrete. During the hardening and curing process, concrete also tends to shrink and crack [7]. Utilizing cement kilns to recycle used tyres into carbon black is a viable method, despite the potential financial and environmental challenges [6]. Another approach is incorporating recycled rubber into construction materials, replacing traditional aggregates, or using crumb rubber disposals as asphalt modifiers. Combining old tyre rubber with cement-based materials and substituting rubber crumbs for mineral aggregates in concrete can help reduce environmental pollution [8]. Research suggests that coarsely ground rubber particles in concrete lead to stronger bonds with the matrix, resulting in rubberized concrete with higher compressive strength and better adhesion to cement paste [7].

Discarded tyres pose environmental challenges, particularly in nations like Uganda, where their non-biodegradable nature leads to landfilling issues and ecological harm [9] [10]. To address these concerns, various research projects have explored using rubber waste as aggregate replacements in concrete for building construction and infrastructure, such as roads. In road pavement construction, modifying asphalt with crumb rubber from used tyres offers a sustainable solution. The crumb rubber, composed of synthetic and natural rubber hydrocarbon, exhibits superior resilience, durability, viscosity, and a high softening point [11]. Crumb rubber modifiers (CRMs) can replace fine and/or coarse aggregates in asphalt mixes or serve as a binder modifier. The increasing production of waste tyres worldwide poses a significant environmental threat due to their non-biodegradable nature and improper disposal, with approximately 700,000 to 850,000 scrap tyres being added to the waste stream annually [12] [13].

From the limitations observed, this research paper will develop a concrete mix design incorporating discarded tyre rubber crumbs as coarse aggregates in the concrete mix. It will also determine the change in the concrete properties such as slump, water absorption rate and comprehensive strength. This research paper aimed at incorporating discarded tyre rubber in the concrete mix to improve the waterproofing in roof slabs. It is also aimed at obtaining good quality concrete at a lower cost and addresses the problem of environmental pollution and economic options for construction as the cost of coarse aggregate skyrockets daily in Uganda.

2. Literature Review

The concrete specimens were prepared from Multipurpose 32.5 Portland Pozzolana Cement conforming to BS EN 196-6:2018 [14] and US EAS 18 -1:2017 [15]. Natural fine and coarse aggregates were obtained from local sources within Ishaka-Bushenyi, Uganda. The rubber crumbs were derived from waste tyres obtained from waste disposal sites within Ishaka-Bushenyi. They were produced manually by cutting and shredding waste tyres into the required sizes of 10 – 20 mm using a sharp blade. The surface of the rubber crumbs was scrubbed with a metallic wire brush to roughen its surface texture.

3. Methodology

Mix design is the process of determining the required and specified characteristics of a concrete mixture. The study proposed concrete with a characteristic strength of 20 N/mm2 after 28 days.

Rubber aggregate in concrete mixes of grade M-20 will be used to obtain the waterproof slab as the minimum grade ratio for roof slabs is BS: 8110-1:1997 [18]. Mix design for the proposed concrete specimens was done using the British DoE (Department of Environment) Mix Design Method. Figure 3 is a flowchart summarizing the procedures for the British DoE (Department of Environment) Mix Design Method.

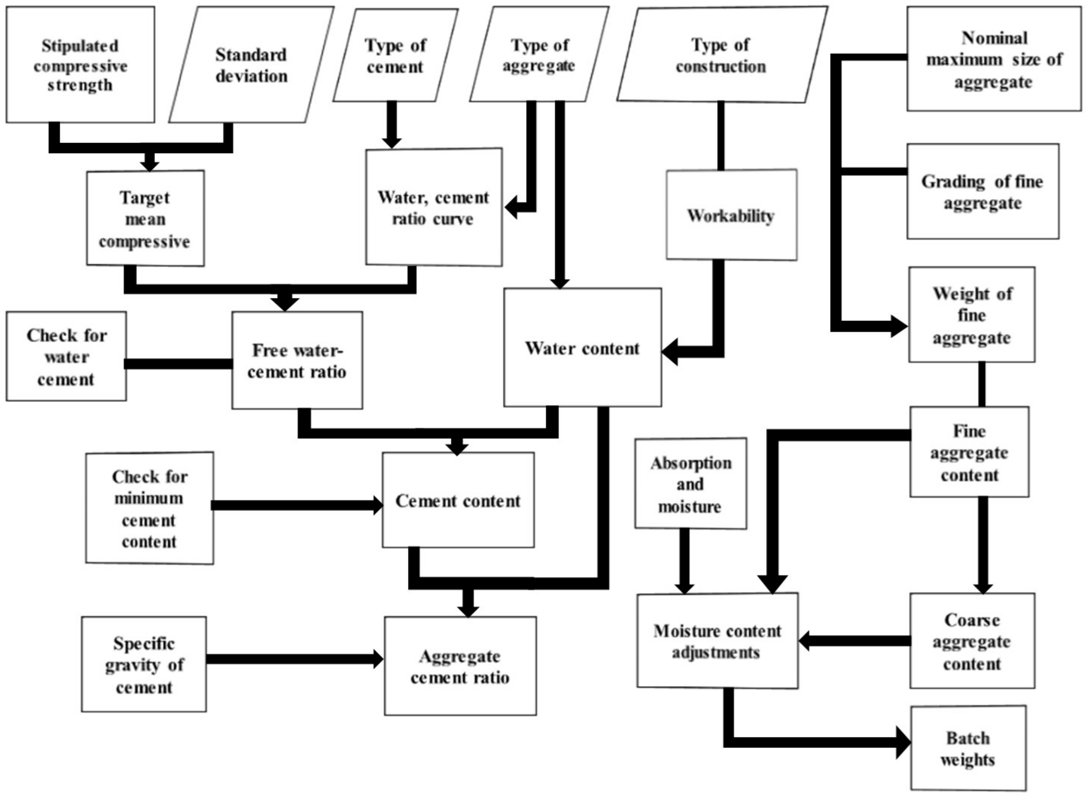


Figure 3. Flowchart of Procedures for the British DoE Mix Design Method

1) Mixing and Batching
   Batching and mixing of the designed concrete mixes was done according to BS 1881 – 125: 2013 [17]. The batching was done by weight. For each concrete batch, the cement and the water were weighed to an accuracy of ±0.5%, and the aggregates were weighed to an accuracy of ±1%. The rubber crumbs were introduced as replacements for coarse aggregates in the range of 10%, 20%, and 30%. Manual mixing was adopted for this study. The concrete batch will be mixed on a non-absorbent surface using a shovel, trowel or similar tool, at ambient temperature.

2) Slump
   This test will be carried out following BS EN 12350-2:2019 [18]. The fresh concrete is then placed in a mould shaped like the frustum of a cone and compacted. The workability of the concrete is measured by the distance the concrete has slumped when the cone-shaped mould is withdrawn upwards.

3) Casting
   Plastic cube mold dimensions of 100x100x100mm conforming to BS EN 12390-1:2019 [19], were used for compressive strength, density and water absorption tests. All the cube molds are cleaned and properly oiled before casting. The molds are inspected to ensure that they are not broken which could possibly lead to slurry leakage and deformation of the shape of the

concrete cube. For each category, the cleaned and oiled molds were filled with concrete in three (3) layers all well compacted after a tamping rod was used to tamp each layer 25 times. The specimens are left in the molds covered with a jute bag for 24 hours.

4) Curing
The concrete cubes were de-moulded and placed in a curing tank containing clean water conforming to BS 1348 - 2:1980 [20]. Specimens were tested after 7 days, 14 days and 28 days respectively.

5) Water absorption test
This test will be performed following BS 1881 – 122:2011 [21]. The absorption test shall be made when the age of the concrete is 7 days, 14 days and 28 days. The concrete specimens will be dried in an oven for 72 ± 2 hrs, after which they will be cooled for 24 ± 2 hrs in an airtight vessel. The mass of each specimen will be obtained and recorded (m1) immediately after cooling before it is immersed in a water tank with a 25mm ±5mm depth of water atop the specimen. The specimens will remain immersed in water for 30 ± 0.5 mins after which it is removed and all excess water wiped off from its surface using a dry, soft and absorbent cloth. The mass of the specimen is obtained and recorded (m2). The water absorption is calculated as follows:

$$Water\ absorption\ (\%) = \frac{m_2 - m_1}{m_1} \text{ x } 100 \tag{1}$$

Where,
m_1 = mass of dry concrete specimen in kg
m_2 = mass of water – immersed concrete specimen in kg

6) Compressive strength
This test was performed following BS EN 12390-3:2019 [22] on concrete specimens at 7, 14 and 28 days of curing time. A compression testing machine was used to apply a steady direct load to the concrete specimen until it reached the failure point. The compressive strength of the concrete specimen was calculated from the maximum load sustained.

The compressive strength is given by the formula:

$$f_c = \frac{F}{A_c} \tag{2}$$

Where,
fc is the compressive strength in megapascals (MPa) or Newtons per square millimetre (N/mm^2)
F is the maximum load at failure in, N
Ac is the cross-sectional area of the specimen on which the compressive force acts, in mm2
The compressive strength shall be expressed to the nearest 0.1 MPa (N/ mm2).

4. Finding and Discussion

4.1. Preparation of Rubber Crumbs Results

The discarded car tyres were obtained from the Ishaka town disposal site and were shredded with a sharp knife and hard wire brush to reduce the sizes to 10-20 mm and make their surface texture rough respectively. The Auto sieve machine was used to properly grade the rubber crumbs to the required size of 10-20mm. The sequential preparation method is shown in Figure 2a-h.

(a) Disposal Site of Discarded Tyres

(b) Shredding the Car Tyres

(c) Scrubbing the Rubber Surface

(d) Rough Surface Texture

(e) Improvised Hard Wire Brush

(f) Cutting Rubber Crumbs

(g) Grading of Rubber Crumbs

(h) Auto Sieving Machine

Figure 2. Sequential Preparation Method

4.2. Concrete Mix Design Results

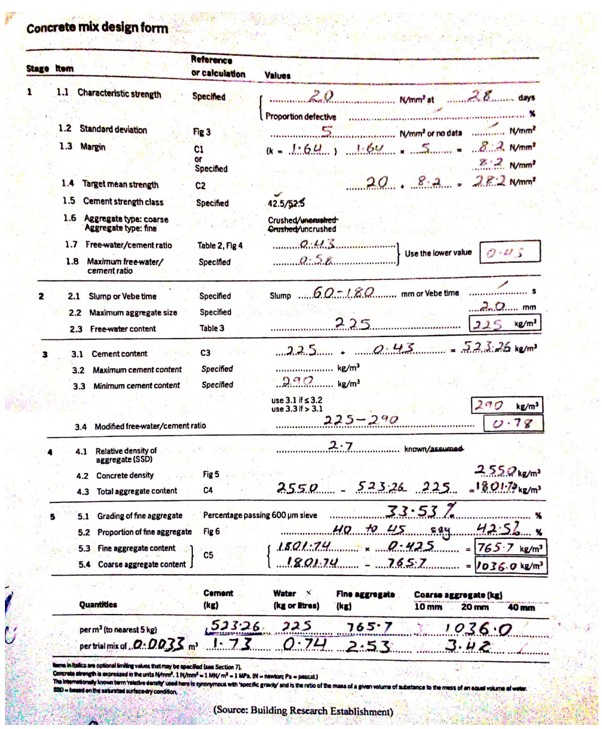
The results of the concrete mix design are shown in Table 1. The target compressive strength of 20N/mm2 was considered during the concrete mix design development. Table 2 displays the mix design ratios and quantities used to produce the concrete specimens. Figure 3 is the worksheet used in the design development.

Table 1. Results of Concrete Mix Design

Materials	**Values**
Target slump	60-180 mm
Cement class	42.5N
Characteristic strength at 28 days, fc	20N/mm^2
Defectiveness k = 5%	1.64
Standard deviation, s	5N/mm^2
Target mean strength, fm = fck + ks (20+(1.64x5))	28.2N/mm^2
Free Water to Cement Ratio	0.43
Free water Content (kg/m3)	225kg/m^3
Cement Content	523.26kg/m^3
Bulk density = free water + cement content + total aggregates	2550kg/m^3
Total Aggregates = concrete density - (cement content +free water content) = 2550-(523.26+255)	1801.74kg/m^3
Proportion of the fine aggregates, (42.5% of the total aggregates)	765.7kg/m^3

Table 2. The Mix Design Quantities and Ratio

Material	**Quantities (g)**	**Quantities (%)**	**Ratio**
Cement	523260	20.52	1
Water	2250	8.82	0.43
Fine aggregate	765700	30.03	1.5
coarse aggregate	1036000	40.63	2.0
TOTAL (concrete density)	**2549960**	**100.00**	**5**


Concrete mix design form

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	20 N/mm² at 28 days; Proportion defective ... %
	1.2 Standard deviation	Fig 3	5 N/mm² or no data ... N/mm²
	1.3 Margin	C1 or Specified	(k = 1.64) 1.64 × 5 = 8.2 N/mm²; 8.2 N/mm²
	1.4 Target mean strength	C2	20 + 8.2 = 28.2 N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse / Aggregate type: fine		Crushed/~~uncrushed~~; ~~Crushed~~/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.43 } Use the lower value 0.43
	1.8 Maximum free-water/cement ratio	Specified	0.58
2	2.1 Slump or Vebe time	Specified	Slump 60-180 mm or Vebe time ... s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	225 → 225 kg/m³
3	3.1 Cement content	C3	225 ÷ 0.43 = 523.26 kg/m³
	3.2 Maximum cement content	*Specified*	... kg/m³
	3.3 Minimum cement content	*Specified*	290 kg/m³; use 3.1 if ≤ 3.2, use 3.3 if > 3.1 → 290 kg/m³
	3.4 Modified free-water/cement ratio		225 − 290 → 0.78
4	4.1 Relative density of aggregate (SSD)		2.7 known/~~assumed~~
	4.2 Concrete density	Fig 5	2550 kg/m³
	4.3 Total aggregate content	C4	2550 − 523.26 225 = 1801.74 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 μm sieve	33.53 %
	5.2 Proportion of fine aggregate	Fig 6	40 to 45 say 42.5 %
	5.3 Fine aggregate content	C5	1801.74 × 0.425 = 765.7 kg/m³
	5.4 Coarse aggregate content	C5	1801.74 − 765.7 = 1036.0 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm / 20 mm / 40 mm
per m³ (to nearest 5 kg)	523.26	225	765.7	1036.0
per trial mix of 0.0033 m³	1.73	0.74	2.53	3.42

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

(Source: Building Research Establishment)

Figure 3. Worksheet for the Concrete Mix Design

4.3. Batching

From the concrete mix design, the batch quantities as per the trial mix volume of 0.0033m3 were determined. The batching of the quantities was done using a weighing scale. The quantities of cement, sand, coarse aggregates and rubber crumbs weights were obtained accordingly and displayed in Table 3. Figure 4a and 4b shows the batching and weighing procedure. Figure 4c shows the weighed-out quantities of the materials ready for mixing.

Table 3. Batch Quantities as Per Trial Mix Volume

Partial Replacement of Coarse Aggregates with Rubber Crumbs Per Trial Mix (0.0033m³)		
Percentage of replacement (%)	Coarse aggregate (g)	Rubber crumb (g)
0%	3419	0
10%	3077	342
20%	2735	684
30%	2393	1026

(a) (b) (c)

Figure 4. Batching and Weighing Procedure with Weighed-Out Material
(a) Batching Of Materials on Weighing Balance
(b) Riffle Box Used in Batching
(c) Batches Of Material in Different Portions Ready For Mixing

4.4. Slump

The slump of concrete is an important characteristic that is utilized to gauge the consistency or workability of fresh concrete. The procedure for the slump test is shown in Figure 5. The results of the slump tests for the various percentage replacements of rubber crumbs are displayed in Table 4.

Table 4. Slump Values of Rubberized Concretes

Rubber crumbs replacement (%)	Slump value (mm)
0	50mm
10	49mm
20	47mm
30	45mm

(a) Oiled Slump Mold

(b) Placing Concrete

(c) Removing the Slump Cone

(d) Measuring the Slump Value

Figure 5. Procedure for Slump Test

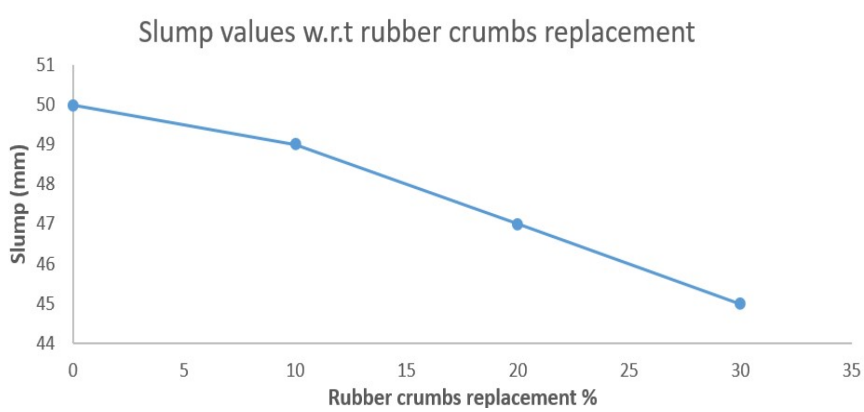


Figure 6. Slump Values of Concrete with Rubber Crumbs

There is a noticeable decrease in slump values due to an increase in the percentage of rubber crumbs in all samples of the concrete mix as shown in Figure 6. In the control concrete mix, the slump was recorded as 50mm and when the coarse aggregates were replaced with 10% rubber crumbs then the slump declined to 49mm. The slump reduced relative to the control mix by 2%, 6% and 10% with replacement levels of 10%, 20% and 30%. Although the downward trend of slump continued until the 30% replacement of rubber crumbs, it was still in the range of moderate workability. This slump behavior is due to the rough texture of the rubber aggregates, the considerable inter-granular friction and the low density of the rubber crumbs [23] [24] [25].

4.5. Water Absorption

Water absorption is vital for assessing the durability of concrete in various environments, especially in humid or wet conditions. Higher water absorption can lead to increased vulnerability to cracking failure, freeze-thaw damage, and corrosion of reinforcement. Water absorption is linked to other concrete properties like porosity, permeability, and strength [26] [27]. The results of water absorption at various replacement percentages for different curing times are displayed in Table 5 and Figure 7.

Table 5. Results of Water Absorption Tests

Rubber Crumbs Replacement (%)	Curing Time (Days)	Water Absorption (%)
0	7	0.67
	14	0.71
	28	0.39
10	7	1.31
	14	1.06
	28	0.40
20	7	0.82
	14	0.71
	28	0.53
30	7	0.77
	14	0.91
	28	0.77

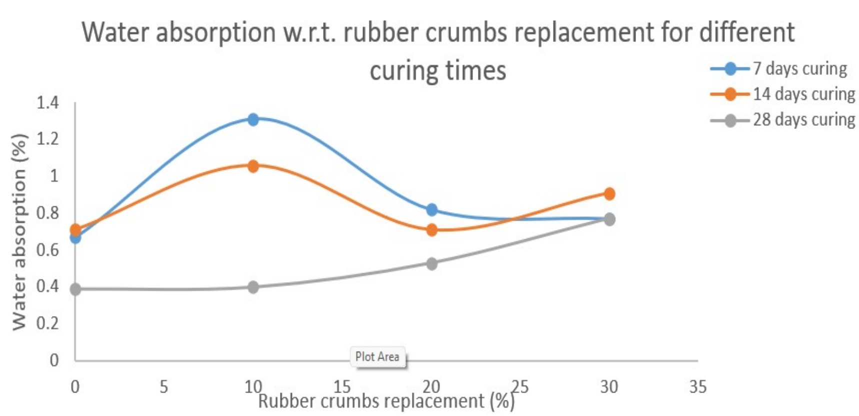


Figure 7. Water Absorption of Concrete Specimens

From Figure 7, water absorption increased with the inclusion of rubber crumbs in all curing durations. The water absorption is at its peak for 10% replacement and identical to the control specimen with 30% replacement of coarse aggregates with rubber crumbs after 7 days of curing. Specimens with 30% rubber crumbs replacement recorded the highest water absorption of 0.91% after 14 days of curing. The water absorption was reduced after curing for 14 and 28 days by 19% and 70% respectively with a 10% replacement of rubber crumbs compared to the control specimen. This could be attributed to hydration reactions which occur in the concrete matrix as curing time extends. The products of these hydration reactions, close up the pore spaces that exist initially in the concrete matrix. The increase in water absorption at 10%, 20% and 30% rubber crumbs replacement compared to the control mix after 28 days of curing was 2.6%, 36% and 97% respectively. The water absorption value of 0.40% at 10% rubber crumbs replacement after 28 days of curing aligns with the value attained by the control specimen with 0% rubber crumbs replacement.

4.6. Compressive Strength

Compressive strength is a fundamental property that is thoroughly studied in research works related to rubberized concrete. Compressive strength can be defined as the capacity of concrete to withstand loads before failure. Of the many tests applied to the concrete, the compressive strength test is the most important, as it gives an idea about the characteristics of the concrete [28].

Concrete specimens were placed in a MATEST CO89PN140 compressive test machine (Figure 8). The load was applied to the concrete specimens at the rate of 0.25Nmm-2s-1 until failure occurred. The maximum load sustained by the specimen and the compressive strength of the concrete were read off from the liquid crystal display (LCD) screen on the machine.

Figure 8. Concrete Specimen: Compressive Test Machine Used to Test the Compressive Strength 0f Rubberized Concrete

Figure 9. Concrete Specimen: Failed Rubberized Concrete Cube

The failed cubic concrete specimen after the determination of compressive strength is shown in Figure 9. Average values of the compressive strength of the specimens. The reported compressive strength was the average of the three specimens tested per curing interval.

Table 6. Results of Compressive Strength Tests

Rubber crumbs replacement (%)	Curing time (days)	Average compressive strength (MPa)
	7 days	
0%		14.844
10%		10.194
20%		5.371
30%		5.043
	14 days	
0%		17.74
10%		9.722
20%		10.48
30%		4.023
	28 days	
0%		25.879
10%		13.904
20%		7.027
30%		6.325

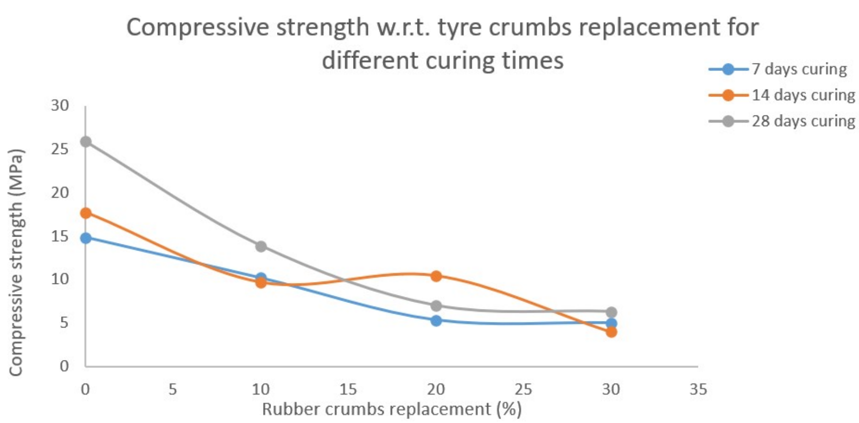


Figure 10. Compressive Strength of Concrete Specimens

The compressive strength values of rubberized concrete measured in the laboratory are presented in Figure 9. By increasing the percentage of rubber crumbs, the compressive strength of mixtures trends negatively at each curing age. This observation aligns with the study of [29]. Rubberized concrete attained its highest compressive strength with 10% replacement of coarse aggregates. Compressive strength at 10%, 20% and 30% replacement ratios declined sharply relative to the control mixture by 46%, 73% and 76% after 28 days of curing.

The poor strength performance of rubberized concrete is due to (i) Poor adherence of rubber crumbs to the cement paste. This results in the formation of cracks when non–uniform stresses are applied. (ii) An aggregate's mechanical and physical properties influence the compressive strength of concrete. The presence of rubber with its intrinsic weaker properties will negatively affect the strength of concrete. (iii) With its low specific gravity and poor adhesion, rubber aggregates tend to segregate from other concrete components during the placing and vibration of fresh concrete. This causes a non – non-homogenous concrete mix and consequently reduced compressive strength [30] [31].

5. Conclusion

This study considered the utilization of rubber crumbs from discarded rubber tyres as coarse aggregates in concrete. Rubber crumbs were produced from waste tyres using a manual process and were introduced as 10%, 20% and 30% replacement of coarse aggregates in concrete. The tests performed on the concrete include slump, water absorption and compressive strength.

From the results of the tests, the following conclusions were drawn:

1. The slump reduced relative to the control mix by 2%, 6% and 10% with replacement levels of 10%, 20% and 30%. Although the downward trend of slump continued until the 30% replacement of rubber crumbs, the concrete was of moderate workability. The morphology of rubber crumb aggregates greatly affected the slump of the concrete.
2. The replacement of coarse aggregates with rubber crumbs resulted in an increase in water absorption. The water absorption was at its lowest relative to the control mix at a 10% replacement level after 28 days of curing. The increase in water absorption at 10%, 20% and 30% rubber crumbs replacement compared to the control mix after 28 days of curing was 2.6%, 36% and 97% respectively. The water absorption value of 0.40% at 10% rubber crumbs replacement after 28 days of curing aligns with the value attained by the control specimen with 0% rubber crumbs replacement. The water absorption at a 30% replacement level was still adequate for use in concrete roof slabs.
3. There is a negative effect on compressive strength with the introduction of rubber crumbs in concrete notwithstanding the curing age. Compressive strength at 10%, 20%, and 30% replacement ratios declined sharply relative to the control mixture by 46%, 73% and 76% after 28 days of curing. The poor compressive strength performance of rubberized concrete is due to the physical and mechanical properties of rubber crumbs which are inferior to natural aggregates.

Rubber crumbs' surface texture should be emphasized to increase the bonding properties of rubber with the general materials in concrete. This can be achieved by immersing them in chemicals that will act to roughen the surface texture of the rubber crumbs.

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