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Evaluation of Materials and Performance Characteristics of Tannery Sludge Crumb Rubber Concrete (TSCRC)

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Abstract
This study presents a preliminary evaluation of tannery sludge–crumb rubber concrete (TSCRC) as a sustainable alternative for eco-friendly construction. The research investigated the suitability of treated tannery sludge (TS) and crumb rubber (CR) as partial replacement materials in concrete to promote waste valorisation and reduce the environmental impacts associated with tannery sludge and discarded tyres. Portland limestone cement, aggregates, TS, and CR were characterised using X-ray fluorescence (XRF), X-ray diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR), while fresh concrete performance was assessed through the slump test. Response Surface Methodology based on Central Composite Design (RSM/CCD) was adopted for mix design optimisation. The coarse aggregate satisfied structural requirements, recording an Aggregate Crushing Value of 20.8% and an Aggregate Impact Value of 12.0%, while Portland limestone cement complied with standard specifications. Treated TS exhibited a specific gravity of 2.30 and significant reductions in heavy metal concentrations after washing, with chromium decreasing from 4,750 to 96 mg/kg and lead from 213 to 65 mg/kg, indicating improved environmental suitability. CR had a low specific gravity (1.14), moderate water absorption (2.8%), and low elastic modulus, confirming its role as a lightweight performance modifier. XRF analysis showed that TS contained appreciable amounts of CaO (48.72%), SiO_2 (24.86%), Al_2O_3 (7.64%), and Fe_2O_3 (7.63%), indicating chemical compatibility with Portland limestone cement and limited supplementary cementitious potential. FTIR analysis identified hydroxyl, silicate, carbonate, amide, and metal–oxygen functional groups, confirming the presence of hydration-related minerals and residual chromium-bearing compounds. Slump values decreased from 83 mm for the control mix to 20 mm at the highest TS and CR replacement levels; however, all mixes remained cohesive without segregation or bleeding. The findings confirm that controlled incorporation of treated TS and CR is feasible for sustainable concrete production, promoting waste recycling, resource conservation, and the development of environmentally friendly concrete suitable for structural and non-structural applications.

Keywords: *Tannery sludge–crumb rubber concrete (TSCRC); Sustainable concrete; Waste recycling; Response Surface Methodology; Fourier Transform Infrared Spectroscopy; X-ray Diffraction Analysis.*

1.0 INTRODUCTION

The increasing generation of tannery sludge (TS) and crumb rubber (CR) has intensified the need for sustainable construction materials that promote waste valorization and reduce environmental impacts [14] *Science of the Total Environment*, 2024). The incorporation of TS from leather-processing industries and CR from end-of-life tyres into concrete offers a viable approach to conserving natural resources while mitigating waste-disposal challenges [5]. Although previous studies have demonstrated the feasibility of using TS and CR individually in concrete, concerns remain regarding their influence on workability, mechanical properties, durability, and long-term performance [9],[10]. Moreover, research on their combined utilization within a single cementitious matrix is limited, and their physicochemical interactions, hydration behavior, and microstructural development are not yet fully understood [5]. Although Response Surface Methodology (RSM) and Central Composite Design (CCD) have been widely applied to optimize sustainable cementitious composites, their application to determining the optimal combined replacement levels of tannery sludge and crumb rubber in concrete remains limited [5]. Therefore, this study investigates the physicochemical characteristics of TS and CR, their effects on fresh concrete properties, and their interactions in cementitious systems. The findings provide valuable insights into the development of sustainable Tannery Sludge–Crumb Rubber Concrete (TSCRC) and establish a foundation for further research on its mechanical performance, durability, environmental safety, and practical engineering applications.

2.0 Materials and Methods

2.1 Materials

Response Surface Methodology (RSM) coupled with Central Composite Design (RSM/CCD) was employed as an optimization tool to develop and evaluate tannery sludge–crumb rubber concrete (TSCRC), providing an efficient statistical approach that enhances experimental accuracy while minimizing time and material consumption and it efficiently evaluates the interactive effects of tannery sludge (TS), crumb rubber (CR), and water-cement ratio on concrete properties, reduces the number of experimental runs while maintaining statistical reliability, develops predictive quadratic models, identifies the optimum mix proportions for enhanced performance, and statistically validates the developed models using ANOVA, regression analysis, lack-of-fit tests, and desirability functions.

Portland Limestone Cement (PLC) grade 42.5, conforming to ASTM C150 and IS 269:2015 standards, served as the primary binder. Natural river sand and crushed granite chippings were used as fine and coarse aggregates, respectively, with their physical and grading properties satisfying ASTM C33 requirements. Aggregate characterization included particle size distribution, specific gravity, and moisture content determination. A constant water-to-cement ratio of 0.50 was maintained throughout the study to ensure consistency among mixtures.

Tannery sludge obtained from the Nigerian Institute of Leather and Science Technology (NILEST), Zaria, was dried, ground, and sieved before use as a partial replacement for cement. Silica fume, sieved to 20μm, was incorporated at a fixed replacement level of 30% to enhance the performance of the concrete. Crumb rubber sourced from a certified recycling facility, with particle sizes ranging from 2–3 mm and a specific gravity of 1.05, was utilized as a partial fine aggregate replacement. The physicochemical properties of TS and CR were characterized to evaluate their suitability and compatibility within the cementitious matrix.

2.2 Mineral Admixtures/Super Plasticizers

Mineral admixtures are required in concrete containing crumb rubber and tannery sludge to mitigate losses in strength, durability, and workability. In this study, Fosroc Conplast SP432MS super plasticizer was used to improve workability. The chloride-free admixture complies with BS and ASTM standards, enhances cement dispersion, hydration, and water reduction, and is compatible with various cements and supplementary cementitious materials. Proper storage and trial mixes are necessary to ensure optimal performance and compatibility.

2.3 Experimental Procedures

2.3.1 Determination of Properties of Basic Ingredients of Concrete

Aggregates and cementitious materials were tested in accordance with relevant BS and EN standards. Fine and coarse aggregates were evaluated for specific gravity, water absorption, density, and strength-related properties (AIV and ACV) as shown in Table 5, while Portland limestone cement was tested for fineness, soundness, consistency, and setting times. Tannery sludge and crumb rubber were also characterized for their physical and chemical properties. (as shown in Table 8 and Table 9)

2.3.2 Workability Test and Fresh Properties Test Methods

2.3.3 Slump Flow Test

The test evaluated the filling ability, flow, and segregation resistance of fresh concrete, particularly its capacity to flow into congested formwork without external vibration. Workability and consistency of the concrete mixes were assessed using the slump test in accordance with ASTM C143 (as shown in Table 2)

2.3.4 Fourier Transform Infrared Spectroscopy (FTIR)

This study examines the organic compounds of the TS using FTIR (Plate 1). This excludes field performance and thermal, electrical, and acoustic properties, while chemical analyses (FTIR and XRF) are used to examine their effect on cement hydration, assessing the material's suitability for sustainable waste utilization.[15]

2.3.5 Leaching Test.

Leaching tests were conducted to assess the potential release of hazardous heavy metals, including Cr, Pb, Cd, Zn, Cu, and Ni, from tannery sludge (TS), as these contaminants may pose significant risks to soil and groundwater if not properly managed [10].

Leaching assessment is essential for evaluating the environmental suitability of TS for incorporation into construction materials such as concrete, bricks, pavement layers, and other cement-based composites, thereby supporting safe waste valorization and circular economy practices [14]. Cement stabilization effectively immobilizes heavy metals through physical encapsulation and chemical binding within hydration products, significantly reducing their mobility and leaching potential and improving the long-term environmental sustainability of tannery sludge crumb rubber concrete (TSCRC), particularly at low TS replacement levels [4].

2.3.6 Oxide Composition in TS, CR, OPCL

The oxide composition test (Table 11) is carried out to determine the chemical constituents present in tannery sludge (TS), crumb rubber (CR), and cement. The test identifies major oxides such as silica (SiO_2), calcium oxide

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(CaO), alumina (Al_2O_3), iron oxide (Fe_2O_3), magnesium oxide (MgO), sulfur trioxide (SO_3), and chromium oxide (Cr_2O_3). These oxides influence the hydration, strength, durability, and environmental performance of concrete mixtures. The test is commonly conducted using X-Ray Fluorescence (XRF), Atomic Absorption Spectroscopy (AAS)(Table 6.0), or Inductively Coupled Plasma (ICP) analysis.

2.3.7 Design of Experiment (DOE) and Development of Mix Matrix

Response Surface Methodology (RSM) was employed using Design-Expert software to develop the Design of Experiments (DOE) and generate the experimental mix matrix. The independent variables considered in the model were Tannery sludge (TS) content, Crumb rubber (CR) content, and curing age. Table 1 summarizes the selected factors and their corresponding levels used in the experimental design.

In Table 1.0, L [1], L [2], L [3], L[4], L[5], and L[6] denote factor levels (dosages) 1, 2, 3, 4, 5, and 6, respectively.

Table 1: Design Factors and Levels (Dosages)

Categoric Factors	Name	Units	Type	Levels	L[1]	L[2] [2]	L[3]	L[4]	L[5]	L[6]
A [Categoric]	TS	%	Nominal	6	0	5	10	15	20	25
B [Categoric]	CR	%	Nominal	5	0	5	10	15	20	-
C [Categoric]	Curing Age	days	Nominal	4	7	28	56	90	-	-

2.3.8 Preparation of TS

Tannery Sludge preparation entailed collecting the tannery sludge, drying it to remove moisture, washing to reduce chromium content, and then crushing and grinding it to achieve a fine, uniform particle size. The material was subsequently sieved to remove impurities and stored in dry conditions before its use as a concrete constituent.

2.3.9 Determination of the Material Properties for TS

The physicochemical properties of Tannery Sludge samples were determined. The physical properties of TS computed include cross-sectional area, thickness & aspect ratio.

2.3.10 Mix Design and Proportioning of TS and CR Concrete

Mixtures were designed based on EFNARC [11] and IS 10262 (2019) with a constant water/cement ratio of 0.50. TS was replaced with PLC between 0 to 25% by weight of cementitious materials (CMs), & CR was added between 0 to 20% by weight of Fine Aggregates.

2.3.11 Mix Preparation/Casting Specimens for Tests on TSCRC.

60 mixtures were prepared for fresh TSCRC, and their respective ingredients are presented in Table 2 Fresh samples were used for casting specimens for different categories of tests on hardened Concrete.

Table 2: Mix Proportions of TSCRC Ingredients

Mix ID	Mix PROPORTION	OPLC (kg/m³)	TS (kg/m³)	CR (kg/m³)	W/C Ratio	Water (kg/m³)	SP (kg/m³)	FA (kg/m³)	CA (kg/m³)
M1	(Control)	100	0	0.0	0.45	55	1.0	45	30
M2	0TS5CR	100	0	5.0	0.45	55	1.0	45	30
M3	0TS10CR	100	0	10.0	0.45	55	1.0	45	30
M4	0TS15CR	100	0	15.0	0.45	55	1.0	45	30
M5	0TS20CR	100	0	20.0	0.45	55	1.0	45	30
M6	0TS25CR	100	0	25.0	0.45	55	1.0	45	30
M7	5TS0CR	95	5	0.0	0.45	52.25	1.0	42.75	28.50
M8	5TS5CR	95	5	5.0	0.45	52.25	1.0	42.75	28.50
M9	5TS10CR	95	5	10.0	0.45	52.25	1.0	42.75	28.50
M10	5TS15CR	95	5	15.0	0.45	52.25	1.0	42.75	28.50
M11	5TS20CR	95	5	20.0	0.45	52.25	1.0	42.75	28.50
M12	5TS25CR	95	5	25.0	0.45	52.25	1.0	42.75	28.50
M13	10TS0CR	90	10	0.0	0.45	49.50	1.0	40.50	27.00
M14	10TS5CR	90	10	5.0	0.45	49.50	1.0	40.50	27.00
M15	10TS10CR	90	10	10.0	0.45	49.50	1.0	40.50	27.00
M16	10TS15CR	90	10	15.0	0.45	49.50	1.0	40.50	27.00
M17	10TS20CR	90	10	20.0	0.45	49.50	1.0	40.50	27.00
M18	10TS25CR	90	10	25.0	0.45	49.50	1.0	40.50	27.00

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Mix ID	Mix PROPORTION	OPLC (kg/m³)	TS (kg/m³)	CR (kg/m³)	W/C Ratio	Water (kg/m³)	SP (kg/m³)	FA (kg/m³)	CA (kg/m³)
M19	15TS0CR	85	15	0.0	0.45	46.75	1.0	38.25	25.00
M20	15TS5CR	85	15	5.0	0.45	46.75	1.0	38.25	25.00
M21	15TS10CR	85	15	10.0	0.45	46.75	1.0	38.25	25.00
M22	15TS15CR	85	15	15.0	0.45	46.75	1.0	38.25	25.00
M23	15TS20CR	85	15	20.0	0.45	46.75	1.0	38.25	25.00
M24	15TS25CR	85	15	25.0	0.45	46.75	1.0	38.25	25.00
M25	20TS0CR	80	20	0.0	0.45	44.00	1.0	36.00	24.00
M26	20TS5CR	80	20	5.0	0.45	44.00	1.0	36.00	24.00
M27	20TS10CR	80	20	10.0	0.45	44.00	1.0	36.00	24.00
M28	20TS15CR	80	20	15.0	0.45	44.00	1.0	36.00	24.00
M29	20TS20CR	80	20	20.0	0.45	44.00	1.0	36.00	24.00
M30	20TS25CR	80	20	25.0	0.45	44.00	1.0	36.00	24.00

2.3.12 Determination of Fresh Properties of TSCRC

Concrete properties were determined based on EFNARC [11]. Fresh TSCRC mixtures were tested for filling ability (slump flow).

2.3.13 Slump flow spread

The slump flow spread test was performed to evaluate the flowability of Tannery Sludge–Crumb Rubber Concrete (TSCRC) and its ability to deform under its own weight without the need for external compaction. The slump flow time (T_{500}) was measured as the elapsed time between lifting the slump cone from the base plate and the instant the flowing concrete first reached the 500 mm diameter circle marked on the base plate.

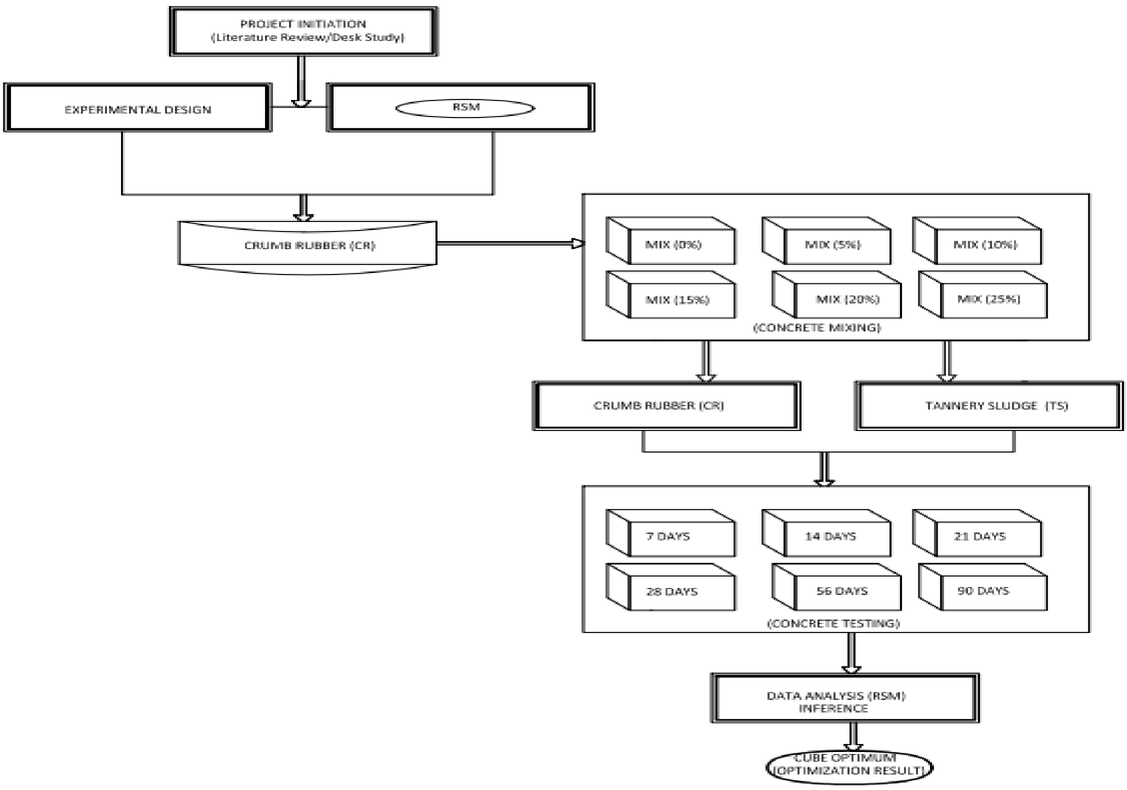

Figure 1: Flow chart of the methodology

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3.0 Results and Discussion

3.1 Preliminary properties of the Constituent Materials

3.1.1 Sieve Analysis of Fine and Coarse Aggregates

Sieve analysis of fine and coarse aggregates was conducted following ASTM C136 / BS 812-103.1 to determine particle size distribution. Oven-dried samples were sieved through standard apertures, and the retained masses were used to calculate percentage passing. The results were applied to generate grading curves, determine fineness modulus, and evaluate aggregate suitability for concrete. The particle size distribution is presented in Table 3 and Figure 2.

3.1.2 Grain Size Analysis of Fine and Coarse Aggregates

Results of grain size analysis for fine & coarse aggregates were presented in particle size distribution graphs of Figures 2 & 3, respectively.

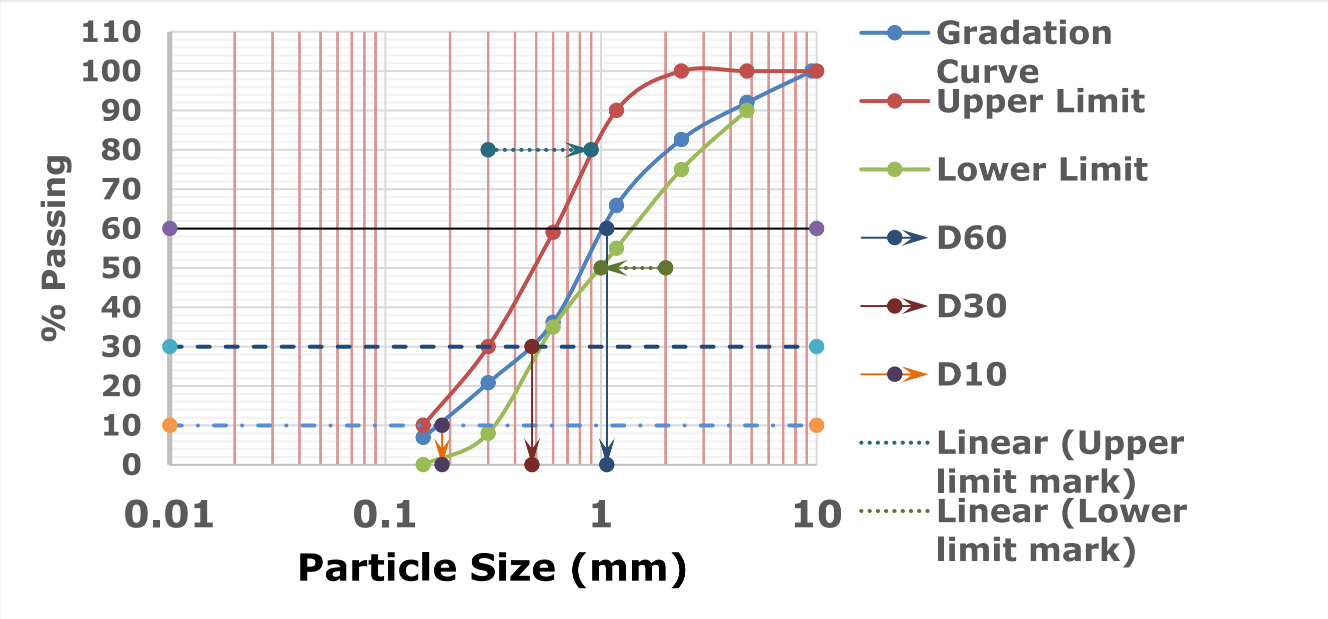

Figure 2.: Gradation of natural (fine) aggregate

The sieve analysis results show that the fine aggregate falls within Zone II grading limits, classifying it as medium sand suitable for general concrete production. The grading satisfies standard requirements, confirming its suitability for concrete applications. The log-normal particle size distribution curve shows a gradual reduction in particle size with decreasing sieve openings. For crumb rubber (CR), most particles are concentrated within the medium-to-fine size range, with the highest retention at the 1.18 mm sieve and very little material passing the 0.15 mm sieve. The cumulative retention increased steadily while the percentage passing decreased accordingly. Overall, the crumb rubber was found to be predominantly fine and well graded, falling within Zone IV classification, making it suitable as a partial replacement for fine aggregate in concrete.

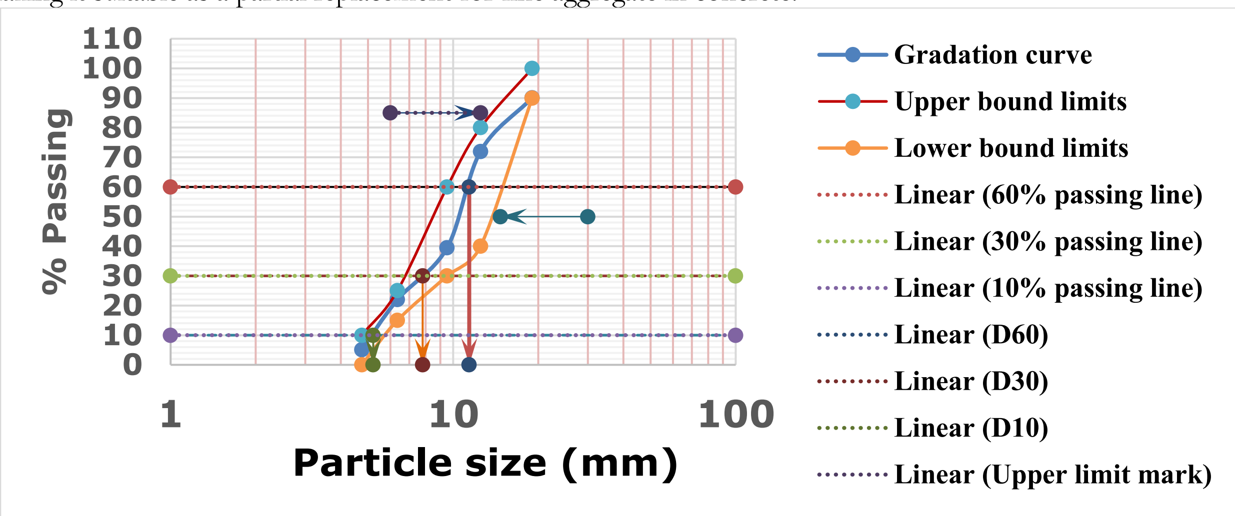

Figure 3: Gradation of coarse aggregate

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The fine aggregate particles fall within the Zone II range specified by BS 882 (1992) & EN 12620: 2002 +A1:2008, and as such are categorized as medium sand with a fineness modulus (FM) of 3.95. The coarse aggregates of 20mm maximum nominal size were also found to meet the grading requirements of the above-named codes. Therefore, all the aggregates were suitable to produce Concrete.

3.2 Results of Specific Gravity, Water Absorption, Density, AIV & ACV

Table 3.0 presents the physical properties of the aggregates, tannery sludge (TS), crumb rubber (CR), and chemical admixtures used in the study. Fine and coarse aggregates recorded specific gravities of 2.60 and 2.66, respectively, while TS and CR showed lower values of 1.10 and 0.91, all within acceptable ranges reported in the literature. Water absorption values of 1.06% for fine aggregate and 0.30% for coarse aggregate indicate low porosity. The densities of fine and coarse aggregates were 1360 and 1475 kg/m³, respectively, whereas TS and CR had lower densities. Aggregate strength tests yielded Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) of 16.0% and 16.7%, confirming that the aggregates are strong and suitable for concrete production in accordance with AASHTO standards.

3.2.1 Aggregate Crushing Value (ACV) Test and Aggregate Impact Value (AIV) Test

The mechanical properties of the coarse aggregates were evaluated using the Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV) tests (as shown in Table 3) in accordance with BS 812-110 and BS 812-112, respectively. The ACV test assessed the aggregates' resistance to crushing under a gradually applied compressive load by measuring the percentage of material passing the 2.36 mm sieve. The AIV test determined the toughness and impact resistance of the aggregates based on the proportion of fines generated after repeated hammer impacts. Collectively, these tests provide important indicators of aggregate strength, durability, and suitability for concrete production.

Table 3: Physical Properties of the Coarse Aggregate

Physical Property	**Laboratory Value**	**Standard Requirement**	**Specification**
Specific gravity	2.74	2.6-2.9	ASTM C136
Aggregate Crushing Value	20.8	≤30	BS 812
Aggregate Impact Value	12.0	≤30	BS 812

Table 4: Materials Characteristics Used for TSCRC Mix Design

S/N	**Materials**	**Size(mm)**	**Specific gravity**	**Water Absorption**	**Bulk Density**	**Fineness Modulus**
1	Fine aggregate (uncrushed natural)	4.75	2.61	1.06	1360 kg/m³	2.45
2	Coarse aggregate (crushed)	20	2.63	0.85	1475 kg/m³	6.8
3	Tannery Sludge	0.020	1.10	-	1.05 g/cm³	-
4	Crumb Rubber	60	0.91	-	0.90 g/cm³	6.0

3.2.2 Physico-Chemical Properties of Tannery Sludge

Table 5: Physico-Chemical Properties of Tannery Sludge

Property	**Description / Value**
Colour and Texture	Dark brown in appearance with a fine- to medium-grained granular structure
Moisture Content	20 % in untreated sludge; affects handling and concrete mix design
Specific Gravity	2.3
Chromium Content	Approximately 2.3% (dry weight basis); critical for environmental safety and long-term durability
Loss on Ignition (LOI)	Indicates organic matter content; can influence cement hydration and overall performance of cementitious systems

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3.3.3 FAAS Results for Washed Tannery Sludge (Leachate Test)

Table 6: FAAS Results for Washed Tannery Sludge
Air-dried sludge → acid digestion (HNO_3/HCl) → FAAS analysis. Units: mg/kg (dry weight)

Heavy Metal	Unwashed Sludge	Washed Sludge	WHO Guideline (Soil/Reuse)	Nigerian Guideline (FMEnv/NESREA)	Compliance Status
Chromium (Cr)	4,750	96	100	100	Satisfactory
Lead (Pb)	213	65	100	85	Satisfactory
Cadmium (Cd)	12.12	2.8	3	3	Marginal
Nickel (Ni)	135	51	50	70	Slightly above WHO
Zinc (Zn)	986	413	300	421	WHO exceeded
Copper (Cu)	330	115	100	140	WHO exceeded
Iron (Fe)	9,240	6,845	-	-	—
Manganese (Mn)	415	268	200	500	WHO exceeded

Guidelines compiled from WHO soil quality references and FMEnv/NESREA environmental standards commonly cited in Nigerian environmental studies.

3.3.4 Results of Portland Limestone Cement

Table 7: Consistency and Setting Time of Cement

S/N	Parameter	Result	Standard requirement	Remark
1	Specific gravity	3.12	2.6-3.15 BS EN 1097-3(1998)	Satisfactory
2	Fineness (%)	3.0	≤10 BS EN 196-2(2013)	Satisfactory
3	Standard Consistency (%)	31	26-33 BS EN 196-3(2016)	Satisfactory
4	Initial Setting Time	90 min.	45minutes (Min)EN 196-3(2016)	Satisfactory
5	Final Setting Time	152min.	375 minutes (Max) EN 196-3 (2016)	Satisfactory

Table 7 presents the properties of Portland Limestone Cement (PLC), including consistency, setting time, fineness, and soundness. The cement achieved a standard consistency of 32% and setting times of 90 minutes (initial) and 152 minutes (final), all within standard specifications. The fineness test showed 92.3% passing the 75μm sieve, indicating adequate fineness, while the soundness test recorded 10 mm expansion, which is within the permissible limit. The cement satisfied relevant standards and was confirmed suitable for concrete production.

3.3.5 Material Properties of Crumb Rubber.

Table 8.0 presents CR material properties. The peak applied load has a magnitude of 5.89N. The TS has tensile stress, strain, elongation & elastic modulus (E_{TSCRC}) of 18.81MPa, 18.04%, 7.23 mm, and 1.02 MPa, respectively.

Table 8: Physical Properties of Crumb Rubber

S/N	Property	Typical Values
1	Appearance	Granular, black
2	Particle Size	4.75 mm
3	Specific Gravity	1.14
4	Bulk density (kg/m³)	456
5	Water Absorption (%)	2.8
6	Elastic Modulus (MPa)	4.5
7	Hardness (Shore A)	58
8	Thermal Conductivity (W/m·K)	0.19
9	Colour & Texture	Black, granular, or powdery
10	Odour	Mild rubber smell

Table 9: Physical Properties of Tannery Shredded Waste

S/N	Physical Properties	Tannery Sludge
1	Shape	Irregular
2	Appearance	Greenish blue

S/N	Physical Properties	Tannery Sludge
3	Water absorption (%)	0.15
4	Moisture content (%)	0.10
5	Density (kg/m³)	240.9
6	Bulking point (%)	10
7	Specific gravity	2.6

Crumb rubber is obtained from recycled tires, ground into particles ranging from 0.1 to 5 mm. Composition includes polyisoprene, styrene-butadiene rubber, carbon black, oils, and minor metal traces.

3.3.6 Fourier Transform Infrared Spectroscopy (FTIR) Results.

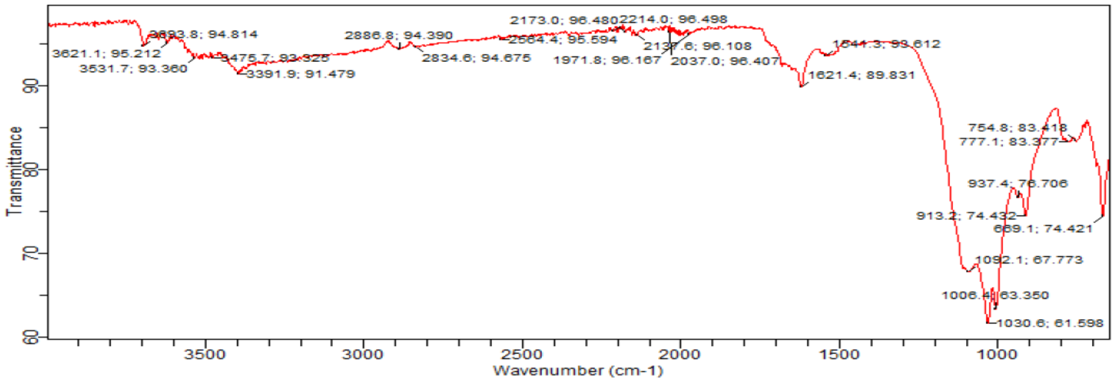

Plate 1: Fourier Transform Infrared Spectrum

Plate 1.0: The FTIR spectrum of tannery sludge reveals the presence of hydroxyl, amide, carbonate, silicate, and metal–oxygen functional groups, indicating a complex composition of organic residues, lime-derived carbonates, mineral phases, and chromium-bearing compounds. These functional groups influence the physicochemical behavior of the sludge when incorporated into cementitious systems.

3.3.7 X-Ray Diffraction Test Result:

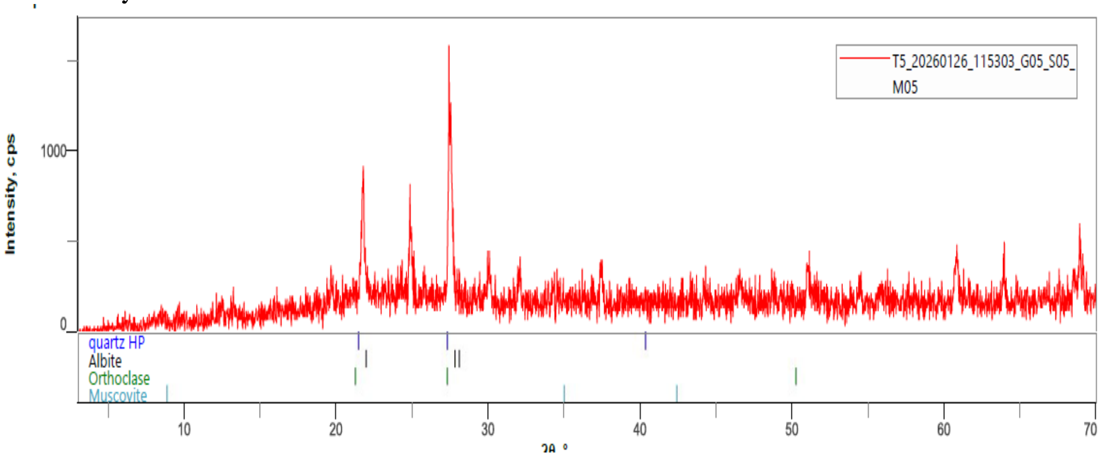

Plate 2: X-ray diffraction (XRD) of TS

Table 10: Tannery sludge X-ray diffraction analysis result (XRD)

No.	2θ, °	Phase Name	Chemical Formula
1	21.748(18)	quartz HP: 1 0 0, Albite: 2 0 -1	Si O₂,Na ((Al Si3)…
2	24.86(2)	Unknown	
3	27.477(6)	quartz HP: 1 0 1, Albite: 2 0 -2	Si O₂,Na ((Al Si3)…
4	30.03(6)	Albite: 0 2 -2	Na ((Al Si3) O8)
5	37.382(16)	Albite: 3 1 0, Orthoclase: 1 5 0	Na ((Al Si3) O8),…
6	50.96(5)	quartz HP: 0 0 3, Albite: 4 -2 0,…	Si O2,Na ((Al Si3)…
7	54.456(5)	Unknown	
8	60.725(18)	Albite: 3 7 -2	Na ((Al Si3) O8)
9	63.885(15)	Albite: 5 1 -4	Na ((Al Si3) O8)

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No.	2θ, °	Phase Name	Chemical Formula
10	68.954(10)	Unknown	

Plate 2.0: X-ray diffraction (XRD) pattern of the material. The diffraction peaks indicate that quartz (SiO_2) is the dominant phase, with secondary contributions from albite ($NaAlSi_3O_8$) and minor orthoclase feldspar ($KAlSi_3O_8$). Peaks at 2θ ≈ 24.86°, 54.46°, and 68.95° remain unidentified, likely corresponding to trace, amorphous, or poorly crystalline phases.

3.4.8 Oxide Composition Results (XRF)

Table 11: Showing the Oxide Composition of Crumb Rubber

Component	Content (%)	Component	Content (%)
SiO_2	22.501	BaO	0.025
Cr_2O_3	0.02	Al_2O_3	8.047
MnO	0.147	Ta_2O_5	0.01
Fe_2O_3	3.211	TiO_2	0.341
CoO	0.058	ZnO	0.448
NiO	0.001	Ag_2O	0.006
CuO	0.362	Cl	6.302
Nb_2O_5	0.009	ZrO_2	0.02
WO_3	0.003	SnO_2	0.663
P_2O_5	20.332	PbO	0.009
CaO	4.274	MgO	11.703
K_2O	20.776	SrO	0.341
SO_3	0.72	Rb_2O	0.004

Table 12: Showing the oxide Composition (PLC, TS)

Oxide(%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Cr_2O_3	LOI	Total
Cement	20.5	5.21	3.78	67.81	2.32	0.31	0.62	2.41	-		
TS	24.86	7.64	7.63	48.72	3.90	0.51	0.84	2.01	1.11	-	99.98

3.5 Properties of Fresh TSCRC

3.5.1 Slump test results

Figure 4 and Table 13. show the results of the slump flow spread variation for the 30 experimental runs with different TS and CR blends. The slump test results indicate that tannery sludge (TS) and crumb rubber (CR) significantly affect the workability of fresh concrete. Increasing CR content consistently reduced slump due to its low density, irregular shape, and hydrophobic nature, which increases internal friction and reduces flowability. Moderate TS content (5–10%) improved workability by enhancing particle packing and paste lubrication, while higher TS levels (15–20%) reduced slump because of increased water demand and surface area. The combined use of high TS and CR contents resulted in generally low-slump concrete mixes.

Table 13: Summary Mix designation for Slump Test result

Mix ID	TS%CR (%)	SP (%)	W/C	Slump Flow (mm)
M1	Control	1.0	0.45	83
M2	0TS5CR	1.0	0.45	70
M3	0TS10CR	1.0	0.45	60
M4	0TS15CR	1.0	0.45	50
M5	0TS20CR	1.0	0.45	40
M6	0TS25CR	1.0	0.45	30
M7	5TS5CR	1.0	0.45	35
M8	5TS10CR	1.0	0.45	30
M9	5TS15CR	1.0	0.45	28
M10	5TS20CR	1.0	0.45	25
M11	5TS25CR	1.0	0.45	20
M12	10TS0CR	1.0	0.45	32
M13	10TS5CR	1.0	0.45	30

Mix ID	TS%CR (%)	SP (%)	W/C	Slump Flow (mm)
M14	10TS10CR	1.0	0.45	28
M15	10TS15CR	1.0	0.45	35
M16	10TS20CR	1.0	0.45	25
M17	10TS25CR	1.0	0.45	20
M18	15TS0CR	1.0	0.45	30
M19	15TS5CR	1.0	0.45	28
M20	15TS10CR	1.0	0.45	26
M21	15TS15CR	1.0	0.45	40
M22	15TS20CR	1.0	0.45	25
M23	15TS25CR	1.0	0.45	35
M24	20TS0CR	1.0	0.45	60
M25	20TS5CR	1.0	0.45	45
M26	20TS10CR	1.0	0.45	40
M27	20TS15CR	1.0	0.45	38
M28	20TS20CR	1.0	0.45	35
M29	25TS0CR	1.0	0.45	60
M30	25TS5CR	1.0	0.45	35

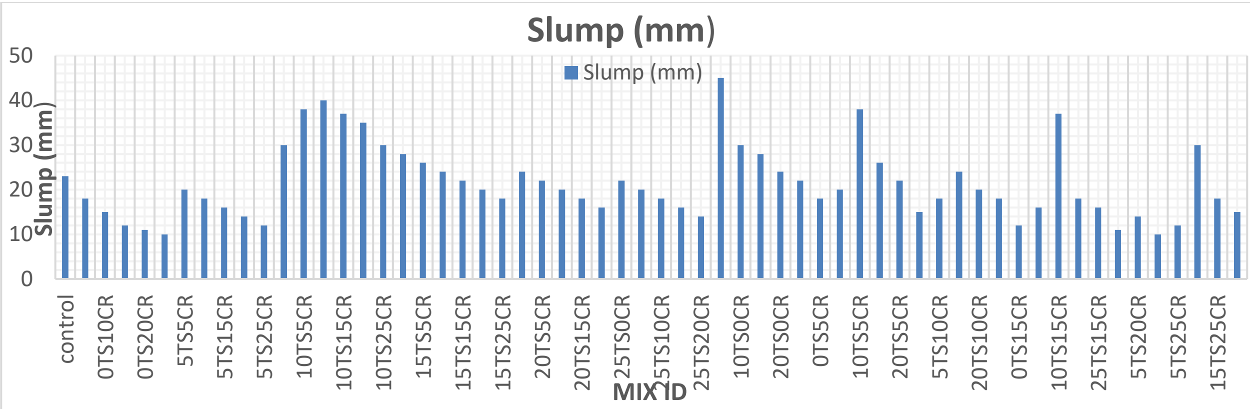

Figure 4: Presentation of Slump Flow Test Results

Discussion of Slump Test Results

The slump results showed a progressive reduction in workability with increasing tannery sludge (TS) and crumb rubber (CR) contents. The control mixture recorded the highest slump (83 mm), which decreased to approximately 70, 60, 50, and 40 mm as CR increased from 5% to 20% at 0% TS. This reduction is attributed to the higher water demand and irregular particle characteristics of TS, together with the low density and hydrophobic nature of CR, which increase internal friction and restrict paste flow. The response-surface model indicated that CR had a stronger negative effect on slump than TS. Nevertheless, mixtures containing 5–10% TS and ≤5% CR provided a reasonable balance between waste incorporation and workability, particularly with the use of a suitable superplasticizer.

4.0 Conclusions

Based on the findings of this study, the following conclusions were drawn:

i. Portland limestone cement (PLC) satisfied the relevant standard requirements, with a specific gravity of 3.15, confirming its suitability for TSCRC production in accordance with ASTM D854.

ii. Fine and coarse aggregates met the grading requirements of BS EN 882 (1992) and EN 12620 (2002),[6], [7]
while their specific gravity values (2.60 and 2.66, respectively) and densities were within acceptable limits for structural concrete.

iii. Aggregate quality tests showed satisfactory performance, with an Aggregate Impact Value (AIV) of 12.0% and an Aggregate Crushing Value (ACV) of 20.8%, indicating adequate resistance to impact and crushing loads.

iv. Physicochemical characterization confirmed that tannery sludge (TS) and crumb rubber (CR) are suitable constituent materials for eco-concrete production. TS exhibited limited pozzolanic activity, contributing

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mainly to pore refinement and matrix densification, while CR acted as a lightweight, hydrophobic, and non-reactive performance modifier.

v. The combined incorporation of TS and CR enhanced the sustainability potential of concrete through physical and microstructural improvements rather than significant chemical interactions.

vi. Fourier Transform Infrared Spectroscopy (FTIR) confirmed the formation of characteristic cement hydration products in all concrete mixtures. The presence of C–S–H gel and $CaCO_3$ absorption bands after curing indicates that normal cement hydration occurred, while additional bands observed in the TSCRC mixtures confirmed the incorporation of crumb rubber and the stabilization of metallic constituents from tannery sludge within the cementitious matrix.

vii. Tannery sludge (TS) contains major oxides, including CaO, SiO_2, Al_2O_3, and Fe_2O_3, which are compatible with Portland cement chemistry and can participate in or coexist with cement hydration reactions. X-ray Diffraction (XRD) analysis further revealed that TS exhibits a mixed crystalline–amorphous structure with limited pozzolanic potential, whereas crumb rubber (CR) is predominantly amorphous and chemically inert. These findings indicate that TS and CR act primarily as supplementary and performance-modifying materials rather than as active cementitious constituents.

viii. The application of Response Surface Methodology (RSM) coupled with CCD using Design-Expert 13 was employed because it is a statistically robust optimization technique that evaluates the combined effects of tannery sludge, crumb rubber, and water-cement ratio, develops reliable predictive models, and identifies the optimum concrete mix with fewer experimental runs than conventional experimental methods, which successfully developed and optimized 30 TS–CR concrete mixtures under EFNARC guidelines and IS 10262 (2019), providing a robust experimental framework for evaluating the fresh, mechanical, and microstructural performance of Tannery Sludge–Crumb Rubber Concrete (TSCRC).

5.0 Recommendations

Based on the findings of this study, the following recommendations are made:

i. Adopt optimized replacement levels of 5–10% tannery sludge (TS) as cement replacement and 0- 5% crumb rubber (CR) as an additive to achieve an optimal balance between fresh TSCRC properties.

ii. Utilize TS and CR in eco-concrete production, as material characterization, FTIR, and XRD analyses confirmed their compatibility with cementitious matrices and demonstrated their potential for sustainable waste valorization and natural resource conservation.

iii. Conduct full-scale field trials to validate the structural performance and service-life behavior of optimized TSCRC under practical construction conditions, and to quantify the environmental benefits, carbon footprint reduction, and cost-effectiveness of TSCRC compared with conventional concrete.

iv. Evaluate pre-treatment techniques for tannery sludge and crumb rubber to further improve their interaction with the cementitious matrix and enhance overall concrete performance, and develop engineering guidelines and standard specifications for the design, production, and application of TSCRC to facilitate its adoption in sustainable construction practices

6.0 Contribution to Knowledge:

This study contributes to knowledge by:

i. Establishing the engineering performance of Tannery Sludge–Crumb Rubber Concrete (TSCRC) as a sustainable construction material.

ii. Providing an optimized TSCRC mix (approximately ≤5% TS and ≤5% CR) that balances strength, durability, and environmental sustainability.

iii. Developing empirical RSM models that can predict the performance of TSCRC and assist engineers in mix design.

iv. Providing evidence that hazardous tannery sludge can be safely immobilized within a cementitious matrix, thereby reducing environmental disposal problems while promoting circular economy practices and expanding the body of knowledge on hybrid waste-material concrete by correlating microstructural characteristics with mechanical and durability performance.

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