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Durability Assessment of Concrete Incorporating Tannery Sludge and Crumb Rubber: Implications for Sustainable Structural Applications

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ABSTRACT
Sustainable valorisation strategies in construction materials are essential to tackle the combined environmental problems caused by increased tannery sludge (TS) generation and end-of-life tire disposal. This study examines the durability and environmental impact of concrete using TS as a partial substitute for Portland limestone cement (PLC) and crumb rubber (CR) as a partial replacement for fine aggregate (TSCRC). Experimental assessments were performed on water absorption, sulfuric acid attack, accelerated carbonation, and heavy metal (chromium) leaching across different curing durations and exposure conditions. The findings demonstrated that water absorption diminished with curing age due to the ongoing densification of the matrix. The control concrete demonstrated the lowest absorption rates, ranging from 3.8% at 7 days to 2.7% at 90 days, while the 5% TS and 10% TS mixtures showed reductions of 4.1% to 3.1% and 4.5% to 3.5%, respectively. Exposure to acid resulted in gradual mechanical deterioration. The depth of carbonation also increased proportionally with higher replacement levels, indicating greater permeability to carbon dioxide. Leachate analysis verified that chromium mobility rose with TS dosage, although concentrations stayed relatively low because of immobilization within the hydration products. The findings collectively suggest that a preliminary replacement range of 5–10% TS and 0–5% CR achieves optimal industrial waste incorporation while ensuring the necessary durability for sustainable concrete purposes.

Keywords: Tannery Sludge, Crumb Rubber, Sustainable Concrete, Durability, Acid Resistance, Carbonation, Leaching

INTRODUCTION

The intensified consumption of natural resources, increased generation of industrial and solid waste, and environmental challenges related to conventional construction practices have escalated the demand for sustainable construction materials (Adesina, 2020). Concrete production requires substantial quantities of Portland cement and natural aggregates and is consequently associated with significant environmental impacts. The incorporation of recycled and waste-derived materials into concrete provides an opportunity to reduce the consumption of virgin resources, divert wastes from disposal, and support circular-economy principles.

Tannery sludge (TS), generated during wastewater treatment in leather-processing industries, has attracted increasing attention as a potential constituent of cement-based construction materials. However, its use requires careful consideration of its chemical composition, particularly chromium-bearing constituents and their potential mobility. Previous stabilization/solidification studies have demonstrated that cementitious binders can reduce the mobility of chromium in tannery sludge (Montañés *et al*., 2014; Oh *et al*., 2014). Recent studies have also investigated tannery sludge as a partial replacement material in concrete and have highlighted the need to balance waste utilization with mechanical performance and environmental safety (Sunmathi *et al*., 2025; Shahadat *et al*., 2026; Mondal & Shiuly, 2026).

Similarly, crumb rubber (CR) derived from end-of-life tires provides an alternative aggregate material while reducing the environmental burden associated with waste-tire disposal. However, its relatively low stiffness, hydrophobic surface, and weak adhesion to cement paste can reduce concrete strength and increase interfacial porosity, particularly at higher replacement levels (Abdulkadir *et al*., 2020; Roychand *et al*., 2021). Nevertheless, controlled incorporation of crumb rubber can provide a useful route for waste-tire recycling and the development of more sustainable cementitious composites.

The simultaneous incorporation of TS and CR provides an opportunity to utilize two problematic waste streams within a single concrete system. However, their combined effects on pore structure, mechanical performance, durability, and contaminant immobilization require systematic investigation. Recent research on tannery sludge has identified significant variability in mechanical, durability, microstructural, and leaching behavior, indicating the need for comprehensive assessment rather than reliance on strength alone (Mondal & Shiuly, 2026).

Accordingly, this study investigates the combined effects of TS and CR on selected durability and environmental properties of concrete. Response Surface Methodology (RSM) is employed to investigate the effects and interactions of the two waste materials and to identify a preliminary mixture range that balances waste utilization, durability performance, and environmental safety (Montgomery, 2020; Myers *et al*., 2016).

Synthesis of Waste Incorporation and Research Gaps

Recent research on industrial waste utilization demonstrates the potential of tannery sludge and crumb rubber as

alternative constituents of cementitious composites. However, the individual benefits they offer come with critical constraints, notably in terms of strength retention, transport properties, durability, and environmental safety.

Studies involving tannery sludge indicate that its incorporation can provide a beneficial filler effect at controlled replacement levels, whereas excessive replacement may reduce the quantity of cementitious material available for hydration and consequently increase porosity and reduce strength. Sunmathi *et al*. (2025) demonstrated the feasibility of incorporating tannery sludge into concrete, while Shahadat *et al*. (2026) investigated the mechanical performance and chromium leaching behavior of concrete containing tannery sludge. Recent review literature has further emphasized the need for comprehensive durability, microstructural, and environmental assessment of tannery-sludge-based construction materials (Mondal & Shiuly, 2026).

Crumb rubber provides a sustainable route for diverting waste tires from disposal; however, its incorporation can adversely affect mechanical performance because of its lower stiffness and weak bonding with cement paste (Abdulkadir *et al*., 2020; Roychand *et al*., 2021). The resulting interfacial transition zone may introduce additional voids and transport pathways, particularly when relatively high rubber content is used.

Despite the growing body of research on tannery sludge and crumb rubber, their simultaneous incorporation into a single concrete system remains insufficiently investigated. The combined materials may influence cement hydration, pore-network development, interfacial bonding, contaminant immobilization, and durability in different and potentially interacting ways.

This research gap justifies a systematic multi-response assessment of TSCRC concrete. RSM provides a suitable framework for evaluating the individual, interaction, and quadratic effects of TS and CR and for identifying a practical replacement range based on multiple performance criteria (Montgomery, 2020; Myers *et al*., 2016).

MATERIALS AND METHODS

Materials

Portland Limestone Cement

Portland Limestone Cement (PLC) grade 42.5, conforming to ASTM C150 and IS 269:2015 standards, served as the primary binder. The cement had a reported specific gravity of 3.15 and a Blaine specific surface area of 3400 cm²/g. The cement was used as received and stored under dry conditions before batching.

Tannery Sludge Processing

Tannery sludge was obtained from the Nigerian Institute of Leather and Science Technology tannery. The sludge was oven-dried at 105 ± 5 °C for 24 h to reduce moisture content, then mechanically pulverized using a laboratory ball mill. The processed material was passed through a 75-µm sieve to obtain a relatively uniform fine material.

X-ray fluorescence analysis indicated the presence of mineral constituents, including calcium- and silicon-bearing compounds, together with chromium-bearing constituents. The fine particle characteristics of the processed sludge provide the potential for filler action within the cementitious matrix. However, excessive TS replacement can reduce the effective cement content and consequently affect hydration and matrix densification.

Crumb Rubber Grading

Crumb rubber was obtained from processed waste automobile tires. The particles used in the study had a nominal size range of approximately 0.60–2.36mm. Particle-size distribution was determined by sieve analysis. The specific gravity and bulk density of the crumb rubber were 1.15 and 480 kg/m³, respectively.

Crumb rubber was incorporated as a partial replacement for fine aggregate. Because CR has a substantially lower density than natural sand and a hydrophobic surface, its replacement basis must be stated consistently as either mass or volume. The replacement basis used for the final experimental batching should therefore correspond exactly to the laboratory batch records.

Aggregates and Admixture

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. 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. The ACV test assessed the aggregate's resistance to crushing under a gradually applied compressive load by measuring the percentage of material passing the 2.36 mm sieve. Crushed granite with a nominal maximum size of 20 mm was used as coarse aggregate.

Fosroc Conplast SP432MS superplasticizer was used to achieve the required workability and reduce water demand, particularly for mixtures containing higher proportions of TS and CR. The admixture had a reported specific gravity of 1.22 ± 0.03 at 25 °C and was used in accordance with the manufacturer's recommendations,

Plate 1: Showing the materials pictures used in the laboratory

Experimental Design and Mix Proportions

Response Surface Methodology (RSM) was employed to investigate the effects of tannery sludge and crumb rubber and their interactions. A Central Composite Design (CCD) was used to develop response models and identify a preliminary optimum mixture range (Montgomery, 2020; Myers *et al*., 2016).

Tannery sludge was investigated at replacement levels ranging from 0 to 25%, while crumb rubber was investigated at replacement levels extending from 0 to 20%. The control mixture contained neither TS nor CR. The experimental programme therefore comprised a control concrete and modified TSCRC mixtures containing different combinations of TS and CR.

Water-to-Binder Ratio (W/c)

The water-to-binder ratio (w/c) of 0.45 was maintained at the predetermined design value for the experimental batches.

Mix Proportions

The mix proportions were established for 1 m³ of concrete. Cement, TS, fine aggregate, coarse aggregate, water, superplasticizer, and CR were proportioned according to the experimental design.

Table 1: The Experimental Mix Proportions

Mix ID	Mix PROPORTION	OPLC (kg/m^3)	TS (kg/m^3)	CR (kg/m^3)	W/C Ratio	Water (kg/m^3)	SP (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)
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
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

Mixing, Casting, and Curing

Mixing Procedure

The dry constituents consisting of Portland Limestone Cement, TS, natural sand, and coarse aggregate were initially homogenized in a laboratory pan mixer for approximately 2 min. Crumb rubber was subsequently introduced gradually and dry-mixed for a further 2 minutes to promote uniform distribution and minimize agglomeration.

Approximately half of the mixing water containing the dissolved superplasticizer was then introduced over approximately 1 minute, followed by the remaining water. Wet mixing continued for approximately 3 minutes.

Casting and Compaction

Fresh concrete was cast into steel molds in two approximately equal layers. Each layer was compacted using a vibration table for 30 blows to minimize entrapped air and achieve adequate consolidation.

Curing

After casting, specimens were covered with wet burlap and polyethylene sheets and maintained under controlled laboratory conditions at approximately 20 ± 2 °C for 24 ± 2 h. After demolding, specimens were immersed in lime-saturated water maintained at approximately 23 ± 2 °C until the designated testing ages of 7, 14, 28, 56, and 90 days.

Concrete Mixtures

The experimental program comprised a control concrete without tannery sludge or crumb rubber and modified TSCRC mixtures incorporating varying proportions of both materials. Tannery sludge (TS) was incorporated as a partial cement

replacement, while crumb rubber (CR) was used as a partial substitute for fine aggregate.

The investigated replacement levels extended from low to relatively high proportions to permit evaluation of the individual and combined effects of the two waste materials. The resulting durability and environmental properties were compared with those of the control mixture to identify replacement levels providing a favorable balance between waste utilization and performance.

Experimental Methods and Test Procedures

Water Absorption

Water absorption was determined to indicate the accessible pore structure and potential for moisture ingress. Lower absorption was interpreted as indicative of a less permeable and more compact matrix.

The test was based on BS 1881-122:2011+A1:2020, *Testing concrete—Method for determination of water absorption*. The standard specifically addresses the determination of water absorption of concrete specimens. Because the present study used laboratory-cast cubes, the procedure was applied as an adapted laboratory method.

We tested hardened concrete specimens at the designated curing ages. The specimens were oven-dried to approximately constant mass, cooled, weighed, immersed in water, and reweighed after saturation. Water absorption was calculated from the increase in specimen mass relative to its dry mass.

The percentage Water absorption was calculated as:

Water absorption (%) = $[(M_2 - M_1) / M_1] \times 100$ (1)

where M_1 is the dry mass, and M_2 is the saturated mass.

Acid Resistance

Acid resistance was evaluated to determine the susceptibility of TSCRC concrete to deterioration under sulfuric acid exposure. The assessment was based on changes in residual compressive strength and mass following immersion in a 5% H_2SO_4 solution.

The test was conducted as an adapted laboratory immersion procedure. BS EN 12390-7:2019 was not used as the acid-resistance standard because that standard specifies determination of the density of hardened concrete. Similarly, BS EN 13529 was not used because it concerns resistance to severe chemical attack of surface-protection systems for concrete.

Concrete cubes were immersed in 5% H_2SO_4 solution for the specified exposure periods. At each exposure age, specimens were removed, rinsed where appropriate, surface-dried, and tested for mass and residual compressive strength.

Percentage strength loss was calculated as:

Strength loss (%) = $[(f_0 - f_a) / f_0] \times 100$ (2)

Where: f_0 is the compressive strength of the corresponding unexposed specimen and f_a is the residual compressive strength after acid exposure.

Percentage mass loss was calculated as:

Mass loss (%) = $[(M_0 - M_a) / M_0] \times 100$ (3)

where M_0 is the initial mass before acid exposure, and M_a is the mass after the specified exposure period. Because the exposure solution was sulfuric acid, the results are described throughout this manuscript as acid resistance or sulfuric-acid resistance, rather than sulfate resistance.

Carbonation Resistance

Carbonation resistance was assessed by determining the depth of carbonation following accelerated exposure to carbon dioxide.

The test procedure was based on BS EN 12390-12:2020, *Testing hardened concrete—Determination of the carbonation resistance of concrete—Accelerated carbonation method*. The present investigation used the specified laboratory chamber conditions of approximately 3% CO_2, 25 °C, and 65% relative humidity. Because the exposure conditions and durations used in this study were not identical to all reference conditions specified by the standard, the procedure is described as based on/adapted from BS EN 12390-12:2020, rather than as full compliance with the standard.

Upon reaching the designated exposure ages, the specimens were split, and a 1% phenolphthalein indicator solution was applied to the freshly fractured surfaces. The uncolored regions were delineated as the carbonated zones, with carbonation depths quantified at representative locations. The carbonation depth was determined as the average penetration distance measured perpendicularly from the initially exposed boundary. Where applicable, the resulting carbonation depth was expressed using:

$$d_c = \frac{(d1+d2+d3+\cdots.dn)}{n} \quad (4)$$

Where d_1,d_2,d_3 are the carbonation depths measured in mm, **n** is the number of depths, d_c is the average depth. The carbonation coefficient was then calculated and expressed using:

$$K = d_c / \sqrt{t} \quad (5)$$

Where: **K** is the carbonation coefficient, d_c is carbonation depth in mm, and **t** is the exposure time in days. Lower carbonation coefficients indicate greater resistance to CO_2 ingress under the specified exposure conditions. The carbonation coefficient has units of mm/√day.

Heavy-metal Leaching

Heavy-metal leaching was assessed to evaluate the environmental stability of TSCRC concrete and the ability of the cementitious matrix to immobilize potentially hazardous constituents associated with tannery sludge. The leaching assessment was based on the Toxicity Characteristic Leaching Procedure (TCLP), U.S. EPA Method 1311.

Crushed hardened concrete samples were subjected to the TCLP extraction procedure. The resulting leachates were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) for chromium and other selected heavy metals.The leaching results are reported for specimens after 90 days of curing. The concentrations of Cr, Pb, Cd, and Ni were used to assess contaminant release and the apparent immobilization performance of the cementitious matrix

RESULTS AND DISCUSSION

Water Absorption Performance

The water absorption values for the control and modified mixtures incorporating different levels of tannery sludge (TS) and crumb rubber (CR) are presented in Figure 1.

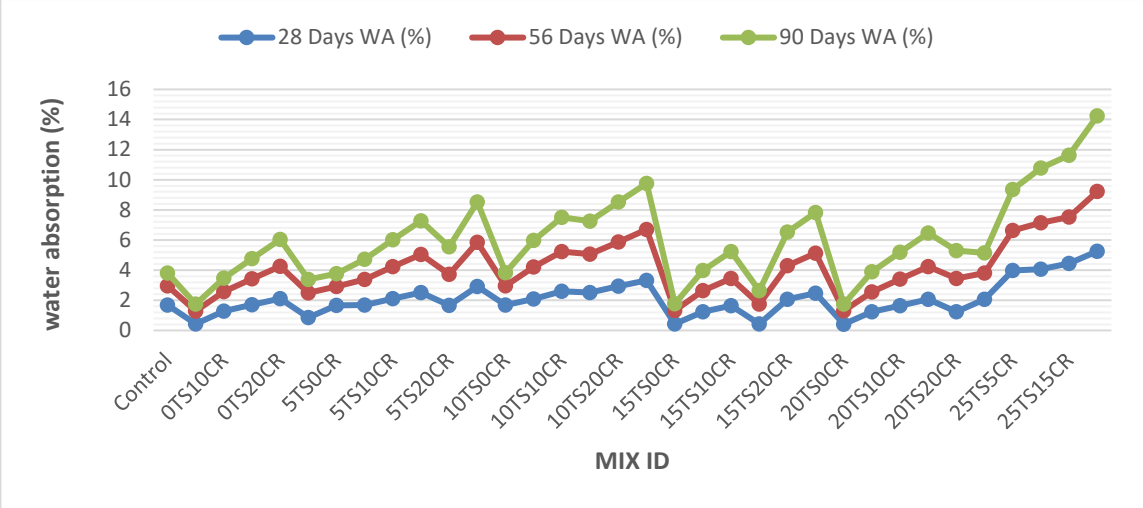

Figure 1: Showing the Water Absorption (%) Results

Water absorption is an important durability indicator because it provides information concerning the accessible pore structure and potential pathways for moisture ingress. Lower water absorption indicates a less connected pore network and improved resistance to moisture transport.

The water absorption values for the control and TSCRC mixtures are presented in Figure 1. Water absorption generally decreased with increasing curing age, which can be attributed to continued cement hydration, pore refinement, and progressive densification of the cementitious matrix.

The control mixture recorded the lowest absorption, decreasing from approximately 3.8% at 7 days to 2.7% at 90 days. The 5% TS mixture decreased from approximately 4.1% to 3.1%, whereas the 10% TS mixture decreased from approximately 4.5% to 3.5% over the same period.

The relatively higher absorption observed in mixtures containing increased TS and CR contents indicates greater pore connectivity and a less compact matrix. At low-to-moderate TS contents, the fine sludge particles may contribute to particle packing and filler action. At higher TS replacement levels, however, cement dilution can reduce the quantity of hydration products available for matrix densification.

Increasing CR content may also increase water-accessible porosity because the hydrophobic rubber surface and relatively weak rubber–cement bond can promote interfacial voids and discontinuities within the matrix. Similar concerns regarding the mechanical and transport effects of waste-tire rubber have been reported in the literature (Abdulkadir *et al*., 2020; Roychand *et al*., 2021).

Overall, the results indicate that curing age improved water-absorption performance across the investigated mixtures, whereas excessive TS and CR incorporation tended to increase absorption. The results therefore support controlled TS incorporation, particularly within the lower replacement range.

Acid Resistance of TSCRC

The acid resistance tests were conducted according to BS EN 12390-12 and BS EN 13529, respectively. Water-cured concrete specimens were immersed in a 5% H_2SO_4 solution for 28, 56, and 90 days, after which percentage mass loss and residual compressive strength were determined to assess durability under aggressive chemical exposure.

Percentage Residual Strength

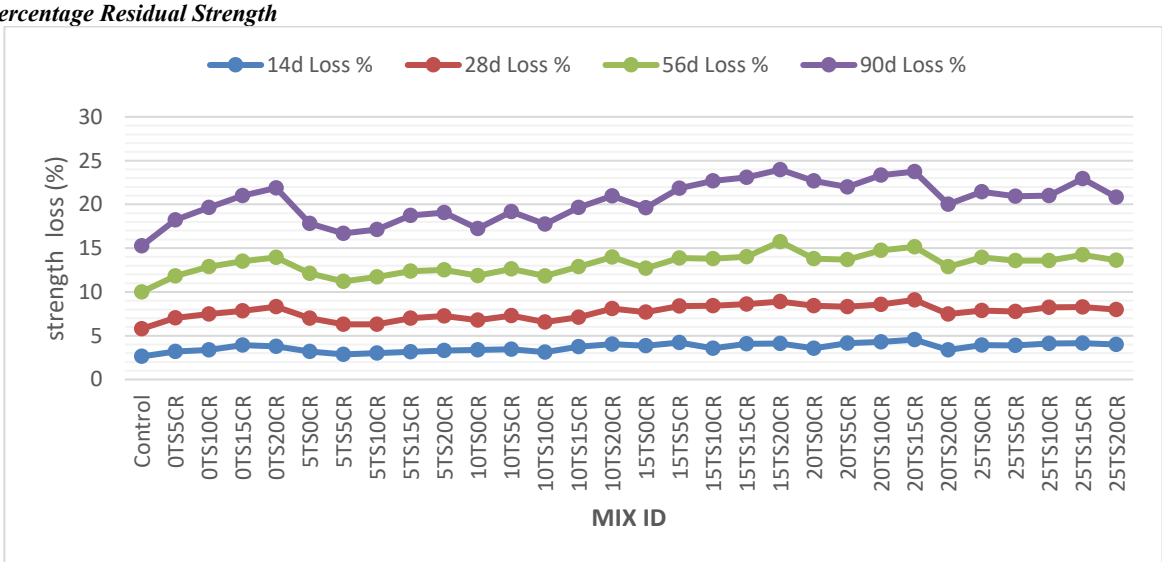

Figure 2: Percentage Compressive Strength Loss of TSCRC Concrete Mixtures

Acid Resistance of TSCRC Concrete

Acid resistance was evaluated based on visual deterioration, mass loss, and residual compressive strength following immersion in a sulfuric acid solution for 28, 56, and 90 days. The results revealed progressive deterioration of the concrete mixtures with increasing exposure duration, although the extent of degradation varied with tannery sludge (TS) and crumb rubber (CR) contents.

As illustrated in Figure 2, the 90-day strength loss ranged from 7.21% to 61.69%. The mixture containing 10% TS and 0% CR (10TS0CR) exhibited the lowest strength loss (7.21%), followed by the 5% TS–5% CR mixture (5TS5CR), which recorded an 8.71% loss. These results indicate comparatively better resistance to sulfuric acid attack than the other investigated mixtures. In contrast, the 15% TS–20% CR mixture exhibited the highest strength loss (61.69%), followed by the 20% TS–15% CR and 20% TS–10% CR mixtures, with losses of 48.26% and 45.02%, respectively.

The observed deterioration may be attributed to the acid-induced dissolution of calcium-bearing hydration products, particularly calcium hydroxide and calcium-rich phases of calcium silicate hydrate (C–S–H), which can weaken the cementitious matrix and increase its susceptibility to material loss. Higher CR contents may further contribute to deterioration through weak rubber–matrix interfacial transition zones and associated pore pathways that facilitate acid ingress. At elevated TS replacement levels, cement dilution may also reduce the quantity of hydration products available to sustain the integrity of the matrix under aggressive exposure.

Overall, the findings suggest that moderate TS incorporation combined with limited CR replacement can provide comparatively better resistance to sulfuric acid attack, whereas higher combined replacement levels may substantially compromise durability. Among the investigated mixtures, 10TS0CR and 5TS5CR demonstrated the most favourable strength retention after 90 days of exposure.

Percentage Weight Loss

The study analyzed weight loss to determine how much concrete surfaces degraded because of sulfate exposure 28,56, and 90days in aggressive environments, including sulfate or acid attack. As a result, the weight loss accurately reflects how much material will be lost because of erosion, dissolution, or degradation.

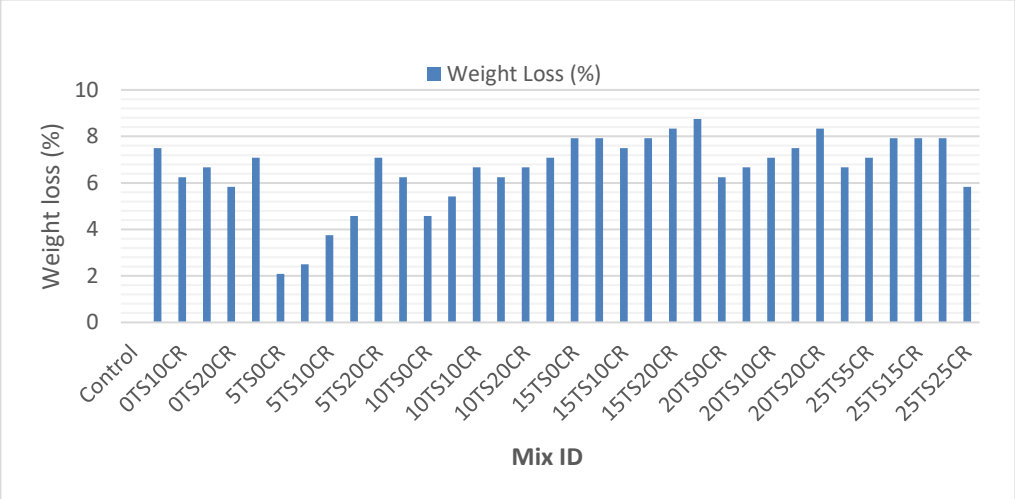

Figure 3: Percentage Weight Loss of TSCRC After Acid Exposure

Mass loss was used as an additional indicator of physical deterioration following acid exposure. The percentage mass loss was calculated from the difference between the initial mass and the mass measured following exposure.

The 90-day results indicate that mass loss increased with increasing combined TS and CR contents, ranging from approximately 2.08% to 8.75%. The lowest mass loss occurred in the 5% TS–0% CR mixture (2.08%), followed by the 5% TS–5% CR mixture (2.50%). The highest reported mass loss was approximately 8.75% for the 15% TS–25% CR mixture.

The increase in mass loss at higher replacement levels indicates greater physical and chemical deterioration. The results are consistent with the strength-retention results, which indicate that low-to-moderate replacement levels provide comparatively better resistance to acid-induced deterioration.

Carbonation Resistance of TSCRC

The carbonation results indicated that carbonation depth increased with increasing tannery sludge (TS) and crumb rubber (CR) contents, suggesting a reduction in the resistance of the concrete mixtures to carbon dioxide (CO_2) penetration at higher replacement levels. The control mixture exhibited the lowest carbonation depths, measuring approximately 1.8, 2.5, and 3.4 mm after 28, 56, and 90 days of exposure, respectively. In comparison, modified mixtures exhibited greater carbonation penetration. One mixture recorded an increase from approximately 2.2 mm at 28 days to 4.3 mm at 90 days, while another increased from approximately 2.8 to 5.6 mm over the same period.

Carbonation resistance was evaluated using the accelerated carbonation test in accordance with BS EN 14630. Concrete cubes were exposed for 28, 56, and 90 days, after which carbonation depth was determined using a 1% phenolphthalein solution. The indicator identifies the boundary between carbonated and uncarbonated concrete through a colour change associated with reduced alkalinity. Lower carbonation depths indicate greater resistance to CO_2 ingress and, consequently, improved potential durability. The observed increase in carbonation depth at higher TS and CR contents may be attributed to increased pore connectivity, cement dilution, and the development of relatively weak interfacial zones around rubber particles. These features may facilitate CO_2 transport and accelerate the neutralisation of alkaline hydration products. For reinforced concrete, deeper

carbonation may increase the risk of reinforcement corrosion by reducing the alkalinity required to maintain the passive protective layer around steel. Therefore, limiting TS and CR replacement levels may be beneficial where carbonation resistance is a primary durability requirement.

Plate 2: Showing a concrete cube showing reaction to carbonation depth.

The increase in carbonation depth can be associated with increased pore connectivity and reduced alkalinity resulting from cement replacement. Carbon dioxide can penetrate more easily through interconnected pores, where it reacts with alkaline hydration products.

High CR content contributes to increased interfacial porosity. The resulting increase in transport pathways explains the greater carbonation depths recorded for high replacement mixtures.

For reinforced concrete applications, this behavior is important because carbonation reduces the alkalinity of concrete and can increase the risk of reinforcement corrosion. Therefore, low replacement levels are recommended where carbonation resistance is a major design requirement.

Durability testing evaluated the carbonation and acid resistance of TS–CR concrete compared with the control mix. Figure 4 presents the mean carbonation depths measured after 28,56, and 90 days of exposure, indicating the resistance of the different mixes to CO_2 ingress.

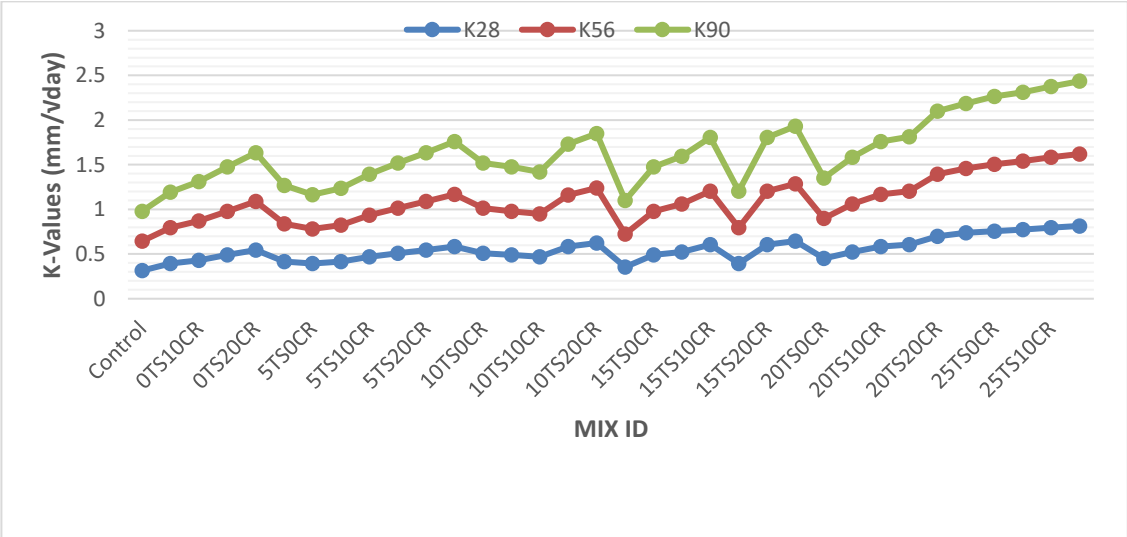

Figure 4: Carbonation Coefficient values for the various TSCRC mixes after 28, 56, and 90 days of exposure to 3% CO_2.

Figure 4 presents the variation in carbonation coefficients at 28, 56, and 90 days for the control and TSCRC concrete mixtures. The results show a clear increase in the K-values with increasing tannery sludge (TS) and crumb rubber (CR) contents, although some fluctuations occur among individual mixtures. Mixtures containing elevated amounts of TS and CR typically exhibited considerably higher carbonation coefficients compared to the control mixture, notably at 90 days.

Carbonation depth increased with increasing exposure duration and generally increased with increasing TS and CR contents. This behavior indicates that higher replacement levels produced matrices that were more susceptible to CO_2 ingress under the specified accelerated exposure conditions.

The control mixture exhibited the lowest carbonation depths, with representative values of approximately 1.8, 2.5, and 3.4 mm at 28, 56, and 90 days, respectively.Modified mixtures exhibited greater carbonation penetration. One low-to-moderate replacement mixture increased from approximately 2.2 mm at 28 days to 4.3 mm at 90 days, while another mixture increased from approximately 2.8 mm to 5.6 mm over the same period.The increase in carbonation depth can be attributed to changes in pore connectivity and the reduction in cement content associated with replacement by TS. Greater pore connectivity facilitates CO_2 transport into the cementitious matrix, where carbon dioxide reacts with alkaline hydration products.

Higher CR contents may additionally contribute to interfacial porosity because of the relatively weak bonding between rubber particles and cement paste. Consequently, mixtures with elevated TS and CR contents generally exhibited greater carbonation coefficients.

At 28 days, the carbonation coefficient values were approximately 0.3–0.8 mm/√day. At 56 days, the values

increased to approximately 0.6–1.6 mm/√day, while the 90-day values showed the greatest variation, reaching approximately 2.4 mm/√day in the higher-replacement mixtures.

Overall, the results indicate that low-to-moderate TS contents combined with limited CR contents provide comparatively better carbonation resistance. Where reinforced-concrete applications are considered, the increased carbonation susceptibility at higher replacement levels should be taken into account because carbonation can reduce concrete alkalinity and potentially increase the risk of reinforcement de-passivation.

Heavy-metals Leaching Behavior of TSCRC

The leaching test was conducted to evaluate the chemical stability of tannery sludge–crumb rubber concrete (TSCRC) by measuring the release of soluble constituents under environmental exposure. Lower leaching rates indicate greater resistance to degradation, enhanced matrix stability, and improved long-term durability. The environmental performance of TSCRC was evaluated through chromium leaching analysis because tannery sludge may contain chromium compounds.

Heavy-metal leaching was evaluated to assess the environmental stability of TSCRC concrete and the effectiveness of the cementitious matrix in immobilizing potentially hazardous constituents.

The results show an overall increase in heavy-metal concentrations with increasing TS content, confirming that TS is the principal source of the investigated metal constituents. Chromium, the principal contaminant of concern associated with tannery sludge, increased from approximately 0.0020 mg/L in the control to approximately 0.0186 mg/L at 25% TS. Representative chromium concentrations were approximately 0.0080 and 0.0120 mg/L at 10% and 15% TS, respectively.

Nickel exhibited a more pronounced increase, reaching approximately 0.055 mg/L at the highest investigated TS and CR combination. Lead and cadmium exhibited comparatively lower concentrations throughout the mixtures.

The influence of CR was less pronounced and showed some variation among mixtures. This behavior may be related to changes in matrix porosity and the rubber–cement interfacial transition zone, which can affect contaminant transport pathways.

The relatively low measured concentrations indicate that the cementitious matrix substantially restricted the mobility of the investigated heavy metals under the specified leaching conditions. Such immobilization may occur through a combination of physical encapsulation and chemical interaction with cement hydration products. Previous stabilization/solidification research has similarly demonstrated the potential of cementitious matrices to reduce chromium mobility in tannery sludge (Montañés *et al*., 2014; Oh *et al*., 2014; Shen *et al*., 2017).

Although the measured concentrations were low, environmental suitability should not be inferred solely from comparison with a general regulatory threshold unless the applicable jurisdiction, regulatory framework, and analytical basis are explicitly specified. Long-term leaching assessment is therefore recommended before extensive structural application.

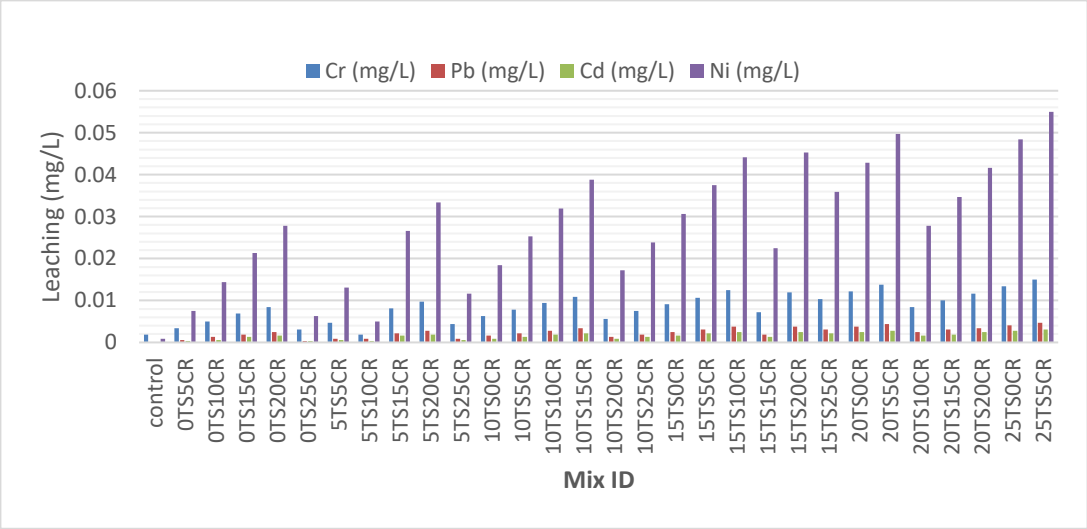

Figure 5: Showing leaching characteristics of TSCRC concrete after 90 days of curing.

The results indicate an overall increase in the concentrations of Cr, Pb, Cd, and Ni with increasing tannery sludge (TS) content, confirming that TS is the primary contributor to the heavy-metal loading in the mixtures. The influence of crumb rubber (CR) was comparatively smaller and, in some cases, non-linear. This may be associated with variations in matrix porosity and the rubber–cement interfacial transition zone.

Comparative Assessment of Durability Performance

The combined durability results indicate that TSCRC performance is governed by the interaction of cement replacement, aggregate replacement, matrix densification, and interfacial characteristics.

Low-to-moderate TS incorporation may provide a beneficial filler effect because of the fine particle characteristics of the processed sludge. However, excessive TS replacement reduces the effective cement content and may limit the development of hydration products required for a dense matrix.

Crumb rubber provides environmental benefits through waste-tire recycling but introduces a hydrophobic and relatively flexible phase into the concrete. At low replacement levels, the surrounding cementitious matrix can accommodate this phase more effectively. At higher levels, weak rubber–cement bonding and interfacial voids become increasingly important.

The results consistently indicate that lower TS and CR contents provide comparatively better durability performance, whereas higher combined replacement levels tend to increase water absorption, carbonation susceptibility, acid-induced deterioration, and mass loss.
The observed trends are consistent with previous research showing that high rubber replacement can adversely affect the mechanical and transport properties of cementitious composites, while controlled replacement can provide a useful balance between waste utilization and engineering performance (Abdulkadir *et al*., 2020; Roychand *et al*., 2021).

Conclusion
Based on the combined assessment of water absorption, chloride ion penetration, sulfate and acid resistance, carbonation, microstructure, and chromium leaching, the study identified 5–10% tannery sludge (TS) and 0–5% crumb rubber (CR) as the preliminary optimum replacement range for TSCRC intended for structural applications. The conclusions are as follows:

i. Waste utilization: Tannery sludge and crumb rubber can be incorporated into concrete as partial replacements of cement and fine aggregate, respectively, providing a potential route for beneficial utilization of problematic waste streams.
ii. Water absorption: Water absorption decreased with curing age but tended to increase with increasing TS and CR contents, indicating greater pore connectivity at higher replacement levels.
iii. Acid resistance: Low-to-moderate replacement levels exhibited comparatively lower strength and mass losses under sulfuric acid exposure. Higher combined TS and CR contents resulted in substantially greater deterioration.
iv. Carbonation resistance: Carbonation depth and carbonation coefficient increased with exposure duration and increased TS and CR contents. Higher replacement levels therefore exhibited greater susceptibility to carbonation under the specified accelerated conditions.
v. Environmental performance: Increasing TS content increased the concentrations of chromium and other investigated heavy metals in the leachate. Nevertheless, the measured concentrations remained relatively low under the specified test conditions, indicating substantial restriction of contaminant mobility by the cementitious matrix.
vi. Preliminary optimum range: Considering the investigated durability and environmental responses, 5–10% TS combined with 0–5% CR represents a preliminary favorable range.

Recommendations
The following recommendations are made:

i. Mix design and curing: The water-to-binder ratio should be established and reported from the verified batching records, with adequate curing maintained to promote hydration and matrix densification.
ii. Durability: Excessive TS and CR replacement levels should be avoided where long-term resistance to moisture ingress, carbonation, and chemical attack is critical.
iii. Exposure conditions: TSCRC mixtures containing relatively high replacement levels should not be recommended for severe exposure environments without additional durability validation or protective measures.
iv. Environmental safety: Periodic leaching assessments should be conducted, particularly for mixtures containing higher TS contents, to monitor chromium and other potentially hazardous constituents.
v. Long-term performance: Further studies should investigate extended carbonation, acid resistance, water transport, chloride transport, freeze–thaw performance where relevant, and long-term contaminant release.
vi. Experimental verification: The final mixture proportions, replacement basis, water-to-binder ratio, and RSM design matrix should be verified against the original laboratory batching records before publication.
vii. Recommended preliminary range: For the present dataset, 5–10% TS and 0–5% CR may be considered a preliminary design window for further investigation, subject to the intended exposure condition, structural requirements, and additional experimental validation.

Contributions to Knowledge
This study contributes to knowledge by:
Novel Sustainable Waste Utilization (TSCRC)
The study successfully demonstrates the technical feasibility of co-utilizing industrial by-products, tannery sludge (TS), as a partial cement replacement and crumb rubber (CR) as a fine aggregate replacement within a single concrete composite (TSCRC). This provides a viable route for sustainable waste management in structural applications.

Definition of an Optimum Design Window
The research establishes a quantifiable, optimal replacement range of 5–10% TS combined with 0–5% CR. This serves as a baseline design window for future structural concrete formulations, balancing waste valorization with structural integrity.

Empirical Mapping of Durability and Structural Limits
The study maps how increasing TS and CR contents lead to greater pore connectivity and higher water absorption, highlighting the trade-offs of high waste incorporation. It establishes empirical boundaries, showing that low-to-moderate replacement levels perform adequately under sulfuric acid exposure, whereas higher combined contents drastically increase susceptibility to carbonation and chemical deterioration.

Environmental Safety and Contaminant Immobilization Insights
The research provides critical data confirming that while higher TS content increases the concentration of leachable chromium and heavy metals, the cementitious matrix effectively restricts contaminant mobility, keeping leachate concentrations relatively low under standard test conditions

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