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Enhancing the Strength and the Environmental Performance of Concrete with Pre-Treated Crumb Rubber and Micro-Silica

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Abstract: Dumped non-biodegradable tires present a significant environmental threat, with overflowing landfills and associated health risks highlighting the urgency of tire waste disposal. Current disposal methods, such as stacking tires in open spaces, exacerbate the problem. The large-scale recycling of tire rubber waste offers environmental benefits. This study examines the effects of pre-treatment using NaOH and micro-silica as a mineral admixture on the mechanical strength of crumb rubber concrete (CRC) with partial replacement of natural sand. Samples of M20 and M30 grade were prepared with varying levels of crumb rubber (CR) replacement and evaluated at 28 days. CRC prepared with pre-treated NaOH solution and micro-silica showed improved workability and strength compared to conventional concrete and untreated CRC, with the highest strength observed for 5% CR replacement using micro-silica. Predictive models and micro-structural analysis validated these findings. Life Cycle Assessment (LCA) using OpenLCA v2.10 software and the ecoinvent database revealed that incorporating micro-silica into CRC did not significantly increase environmental impacts, compared to conventional concrete across different mixes.

Keywords: crumb rubber concrete; pre-treated crumb rubber; micro-structural study; life cycle assessment

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1. Introduction

The world moves on wheels, and a large number of rubber tires are used in vehicles all over the world. Approximately 1000 million discarded tires are produced globally each year, and, by 2030, this number is projected to increase to 1200 million [1]. The projected increase in discarded tires over the next decade presents several challenges and implications for global waste management strategies, underlining the need for sustainable solutions. The implications are as follows: increased landfill pressure exacerbating the existing pressures on landfill capacities worldwide; environmental pollution leading to public health issues spreading vector-borne diseases; chemicals and heavy metals from waste tire rubber that can leach into the soil and groundwater posing environmental risks; tire fires, which are difficult to extinguish, release toxic pollutants into the air; valuable materials wastage, including rubber, steel, and textile fibers; and increased management costs diverting funds from other essential services. Crumb Rubber used in concrete contributes to mitigating these implications by diverting waste from landfills, recovering, and recycling resources, and reducing environmental pollution. The innovative use of crumb rubber in infrastructure leads to the development of more sustainable and resilient urban environments; there are also economic benefits from stimulating new markets for recycled tire products [2,3].

To address the environmental threats posed by non-biodegradable dumped tires, waste management policies also need to be improved and strategically implemented to encourage the recycling of rubber for construction purposes. Some of the policy recommendations which can be taken up as a priority include the following: extended producer responsibility (EPR) to reduce illegal dumping and stockpiling of tires; recycling targets and mandatory content standards to create a stable demand; financial incentives to make it economically viable; research and development support leading to technological innovations; public procurement policies giving preference to projects incorporating recycled rubber; standardization and certification to build trust among stakeholders; awareness and education campaigns to increase the understanding and acceptance of recycled rubber; and infrastructure investment to streamline the recycling process. Thus, crumb rubber concrete represents a promising approach that not only addresses the environmental and logistical challenges posed by tire waste but also offers potential benefits for the construction industry and the broader economy.

Crumb Rubber used in cement concrete is one such waste product used to reduce the global load of used rubber tires [3]. By substituting rubber crumb, created from rubber waste, as a partial replacement for natural fine aggregate in concrete, the utilization of natural sand can be reduced. Through a process known as continual shredding, it is possible to create a granulated rubber crumb, which undergoes the process repeatedly to make the crumb sufficiently small to replace aggregates as fine as sand. Owing to its improved resistance to frost and ice thawing, this type of concrete is used in the construction of reinforced pavements and bridges [2].

The elimination of discarded tire rubber is a serious issue in waste management worldwide. The estimated annual number of leftover waste tires worldwide is 1.2 billion. Additionally, it is estimated that only 4% of tires are employed for structural construction projects, and that 27% of tires are piled up as waste [1–4]. Therefore, attempts have been made to utilize waste tire rubber in structural concrete. The composition of rubber tires consists of 40 to 50% rubber, up to 40% carbon black, and up to 15% low-molecular-weight additives [5]. The primary objective of this study was to develop an environmentally friendly and sustainable material that would benefit humanity [6,7]. However, with the increase in construction activity, high-quality natural resources, such as sand, rock, and aggregates, are quickly running out. Therefore, there is a constant search for substitute materials that can better meet these needs. The characteristics of crumb rubber, when mixed in concrete as a partial fine aggregate replacement, have been examined using a variety of tests to determine the behavior of this combination [8–12]. If feasible, it might aid in reducing natural soil utilization and increasing the usage of leftover crumb rubber.

The term “Crumb Rubber Concrete” (CRC) refers to concrete that has fine aggregates substituted for rubber in various volumes or weight amounts. The use of crumb rubber poses no environmental danger. Therefore, the use of rubber, in the form of crumb rubber, in concrete can be an environmentally friendly and economically feasible way to convert it into a useful resource [4]. CR can partially replace some of the fine aggregates in concrete, giving it properties such as low unit weight, good protection from scraped areas, absorption to shocks and vibrations, and high ductility [13–15]. Higher resilience and durability are also a result of the incorporation of rubber into concrete. A few studies have demonstrated that the toughness, plastic distortion, and crack resistance of rubber samples have increased, while their strength and stiffness are reduced. To improve the overall properties of concrete, such as toughness, durability, and deformation, a percentage of fine aggregate can be replaced with crumb rubber [4–7]. Rajan et al. [16] utilized M30 grade concrete by varying the percentages of crumb rubber, used as a replacement for sand, and studied the chemical bond between rubber and the cement matrix. Salonia et al. [17] reported the efficacy of sand replacement in CRC for geopolymer concrete. NaOH pre-treatment was adopted at 8M concentration. Jokar et al. [1] used natural zeolite as a partial replacement for cement and NaOH solution of 1M concentration. Huang et al. [18] proposed a model based on microporosity theory and a correlation coefficient, and the experimental values were compared with existing models, leading to the conclusion that the model is reliable. Cauana Melo Copetti et al. [19] studied cement with NaOH pre-treatment and using silica fume at proportions of 7.5% and 15%, as a mineral additive. Juan Wang et al. [20] compared and reported similar hydration compounds in Crumb Rubber Concrete as in natural sand concrete. Wu et al. [2] concluded that crumb rubber is not suitable for structural concrete and reported a major loss in the strength of concrete. Rodríguez-Fernández et al. [3] performed a microstructural study on crumb rubber with the addition of asphalt mixtures. Taha et al. [21] used both chipped and crumb rubber tire particles, varying the replacement levels by volume, and reported their mechanical strength and fracture properties. Osama Youssf et al. [22] proposed an empirical model to forecast CRC compressive strength with a mean variation of 10.7%. The bonding between cement mortar and aggregates was found to be improved by pretreatment or by using admixtures. These findings form the premise for the authors to research crumb rubber in concrete and to fix the optimal proportion, pre-treatment, and mineral admixture to be used in the composite in order to obtain the optimum properties of the concrete, establishing this using macro-level tests and morphological studies. There are several methods to treat crumb rubber, such as soaking in NaOH solution, potassium permanganate, hydrogen peroxide, calcium chloride, sulfuric acid, and silane coupling agents [10,23–28]. Among all the treatment methods, the use of NaOH in concrete provides the most optimal and practical solution on a mass scale.

Pre-treating crumb rubber with NaOH solution reduces its inherent water absorption and mitigates the increase in porosity and permeability. Such a treatment also improves the interfacial bonding between crumb rubber particles and the cement matrix, enhancing the overall durability.

Micro-silica, also known as silica fume, is a byproduct of silicon and ferrosilicon alloy production, characterized by its ultrafine particles. When used as a mineral admixture in crumb rubber concrete, micro-silica enhances the concrete's mechanical properties and durability by improving its compressive strength, bond strength, and resistance to abrasion and chemical attack. Incorporating supplementary cementitious materials, such as silica fume, can help to refine the pore structure and improve the durability of crumb rubber concrete. Micro-silica counteracts the increase in porosity and permeability, improving water resistance and mitigating the ingress of harmful substances.

However, the ultrafine nature of micro-silica particles poses a health risk if inhaled, potentially leading to respiratory issues. Workers handling micro-silica need to take precautions to avoid inhalation. The production of silicon and ferrosilicon alloys, from which micro-silica is derived, is energy-intensive and contributes to CO_2 emissions. Fly ash, blast furnace slag, rice husk ash, natural pozzolans such as volcanic ash, calcined clay, and diatomaceous earth, biochar, and recycled glass powder are other promising options for sustainable alternatives. However, in selecting sustainable alternatives, it is crucial to consider their availability and cost. Micro-silica offers a balance of improved concrete performance, availability, and cost. Further continued research in this area is required, in order to identify and optimize such materials for widespread use in the construction industry. As a mineral additive, micro-silica was used in the current project at 10% replacement of cement. The goal of this research project was to create CRC by employing crumb rubber as a partial replacement for fine aggregate (FA). The concrete was created by replacing 5%, 10%, 15%, and 20% of the fine aggregate weight with untreated crumb rubber, pre-treated Crumb Rubber and CRC with a mineral admixture, and it was tested to determine the mechanical properties vis à vis concrete specimens without Crumb Rubber. Several predictive models have been proposed for determining the compressive strength of crumb rubber concrete. As part of this project, the compressive strength results obtained were compared with three such models to validate the experimental results and the reported findings. The microstructural properties of CRC were studied [29] and analyzed, and the findings were presented in the report.

Finally, a Life Cycle Assessment (LCA) was conducted for conventional and crumb rubber concrete. Conducting LCAs for construction materials is crucial for evaluating their environmental footprint, aiding informed decision-making, and promoting sustainable practices within the construction industry. LCA techniques have been previously employed to evaluate the environmental impact of construction activities (Means and Guggemos 2015) [30]. Saleem et al. (2018) [31] conducted a comparative analysis of the environmental impacts associated with four distinct building facades—aluminum, glass, brick, and granite—using LCA methodology. The assessment was carried out using SimaPro software (version 8.0), revealing granite as the most sustainable facade choice.

2. Results and Discussion

2.1. Results for Trial Mixes at M20 and M30 Grade

The compressive strengths of the concrete mixtures made to the M20 and M30 grades were assessed for seven days. The replacement rates of fine aggregates with crumb rubber by weight were 5%, 10%, 15%, and 20%. M20 and M30 represent the concrete grades; M20CR0 and M30CR0 denote the controlled mixes; UCR denotes untreated concrete; TCR denotes NaOH-treated crumb rubber; UCRM denotes the addition of micro-silica as an admixture in untreated crumb rubber concrete; and 0, 5, 10, 15, and 20 denote the percentages of sand replaced by weight with crumb rubber. When 10% treated crumb rubber was utilized, the compressive strength of the concrete was 5.97% and 5.5% lower, respectively, than it would have been with regular concrete. Table 1 lists the results of the trial mix tests for the compressive strength of concrete at the grades M20 and M30.

Table 1. Trial mix test results for M20 and M30 grade concrete.

Type of Concrete	M20CR0	M30CR0	M20UCR10	M30UCR10	M20TCR10	M30TCR10
Compressive * Strength (MPa)	18.95	28.00	17.60	25.43	17.82	26.46

* When the cubes were tested after 7 d of curing, the concrete should have attained 65% of its target compressive strength. After seven days of curing, the acceptable compressive strength range of M20 concrete was 17.55 N/mm^2, and, for M30 grade concrete, it was 24.86 N/mm^2.

2.2. Workability

The workability test was performed to determine the slump values of concrete grades M20 and M30. Table 2 contains the slump values for various percentages of M20 and M30 grade concrete.

Table 2. Slump values for the M20 and M30 grades of concrete.

Type of concrete	M20CR0	M20UCR5	M20UCR10	M20UCR15	M20UCR20	M20TCRN5	M20TCRN10	M20TCRN15	M20TCRN20	M20UCRM5	M20UCRM10	M20UCRM15	M20UCRM20
Slump value (mm)	72	90	98	106	120	65	79	86	90	62	70	92	95
Type of concrete	M30CR0	M30UCR5	M30UCR10	M30UCR15	M30UCR20	M30TCRN5	M20TCRN10	M30TCRN15	M30TCRN20	M30UCRM5	M30UCRM10	M30UCRM15	M30UCRM20
Slump value (mm)	64	80	87	99	113	60	70	82	87	55	60	74	88

As per IS 456-2000, the workability of concrete should be 50 mm–100 mm, for medium workability used for normal reinforced concrete and 100 mm–150 mm, for high workability used for heavily reinforced sections.

2.3. Mechanical Strength of Crumb Rubber Concrete

2.3.1. Compressive Strength

The compressive strength results of the M20 and M30 grade concretes for different percentages are shown in Tables 3 and 4 respectively. After 28 days, the compression strengths of all combinations were assessed. For M20 grade, the compressive strength increased by 1.4% when 5% untreated crumb rubber was used as a replacement by weight, along with micro-silica, but the strength decreased by 4.9%, 14.4%, and 30% when 10%, 15%, and 20% crumb rubber were used. For M30 grade, when crumb rubber was used as the replacement, along with micro-silica, the compressive strength increased when 5% rubber was used and decreased when 10%, 15%, and 20% rubber were used, respectively, by 11%, 30%, and 38%. A loss in strength was observed for all the proportions of crumb rubber when pre-treated with NaOH. However, the strength increased, in comparison with that of a specimen in which untreated crumb rubber was used. A substantial recovery of strength loss due to NaOH pretreatment was observed for 5% replacement, at 10.5% and 2.43% for M20 and M30 grades, respectively.

Table 3. M20 grade concrete's compressive strength results.

Type of Specimen	Compressive Strength (Mpa)	Predictive Model l (Mpa)	Predictive Model 2 (Mpa)	Predictive Model 3 (Mpa)
M20CRO	28	28	28	28
M20UCR5	25.6	25.85	23.09	30.8
M20UCR10	242	23.89	19.69	24.97
M20UCR15	20.37	22.10	14.94	20.24
M20UCR20	14	20.48	9.26	16.4
M20TCR05	27.32	25.85	24.64	30.8
M20TCR10	25	23.89	20.34	24.97
M20TCR15	23.26	22.10	17.06	20.24
M20TCR20	17.14	20.48	11.33	16.4
M20UCRM05	28.4	25.85	25.62	30.8
M20UCRM10	26.62	23.89	21.65	24.97
M20UCRM15	24.04	22.10	17.63	20.24
M20UCRM20	19.58	20.48	12.94	16.4

Table 4. M30 grade compressive strength results.

Type of Specimen	Compressive Strength MPa	Predictive Model 1 (Mpa)	Predictive Model 2 (Mpa)	Predictive Model 3 (Mpa)
M30CR0	38	38.00	38	38
M30UCR5	29	35.85	26.16	30.8
M30UCR10	25.43	33.89	20.69	24.97
M30UCR15	22.7	32.10	16.65	20.24
M30UCR20	21	30.48	13.88	16.4
M30TCR05	34	35.85	30.67	30.8
M30TCR10	28.46	33.89	23.15	24.97
M30TCR15	23.5	32.10	17.24	20.24
M30TCR20	21.85	30.48	14.45	16.4
M30UCRM05	39.2	35.85	35.36	30.8
M30UCRM10	33.73	33.89	27.44	24.97
M30UCRM15	26.58	32.10	19.49	20.24
M30UCRM20	23.34	30.48	15.43	16.4

2.3.2. Tensile Strength

The split tensile strength results of the M20 and M30 grade concrete for different percentages are depicted in Figures 1 and 2. After 28 days, the split tensile strengths of all combinations were assessed. For M20 grade and M30 grade concrete with 5% crumb rubber and added micro-silica, the tensile strength improved by 1%. However, in all other combinations, i.e., when 10%, 15%, and 20% crumb rubber were used, the split tensile strength declined at varying levels.

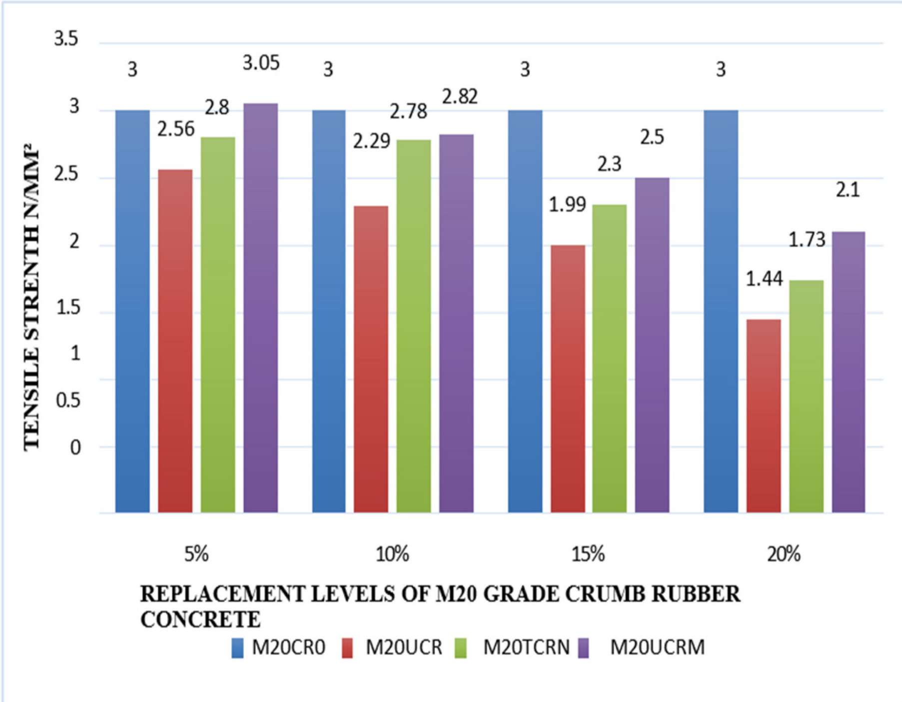

Figure 1. Tensile strength of M20 grade CRC.

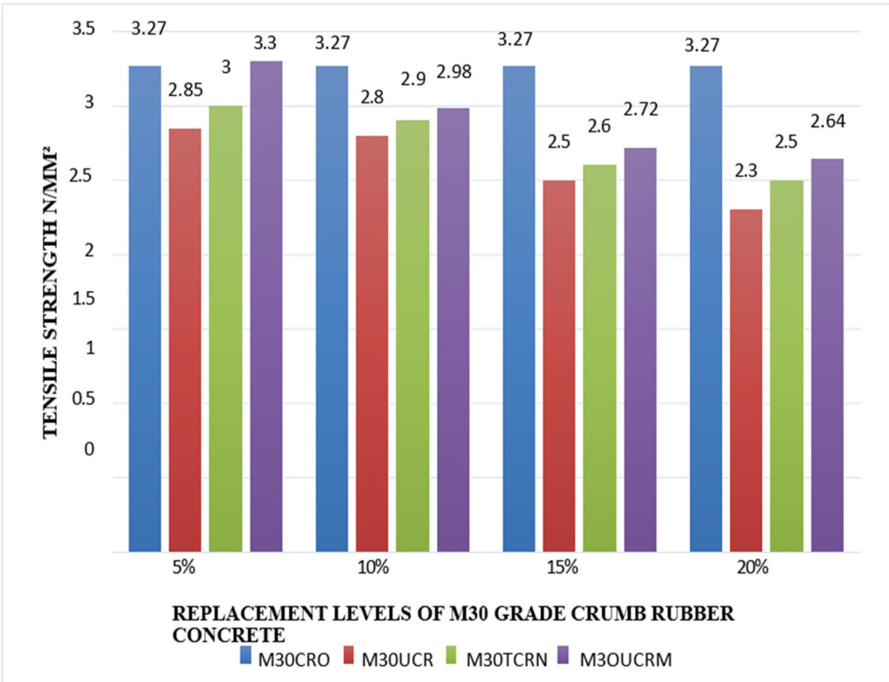

Figure 2. Tensile strength of M30 grade CRC.

2.4. Mechanical Performance Results Analysis

The experimental results of the M20 grade and M30 grade CRC were compared with three predictive models, and a summary of the results is shown in Tables 3 and 4.

2.4.1. Predictive Compressive Strength of M20 Grade Concrete

The experimental results vis à vis the predictive models are depicted for M20UCR, M20TCR, and M20UCRM with varying partial replacements of fine aggregates at 5%, 10%, 15%, and 20% in Figures 3–5, respectively.

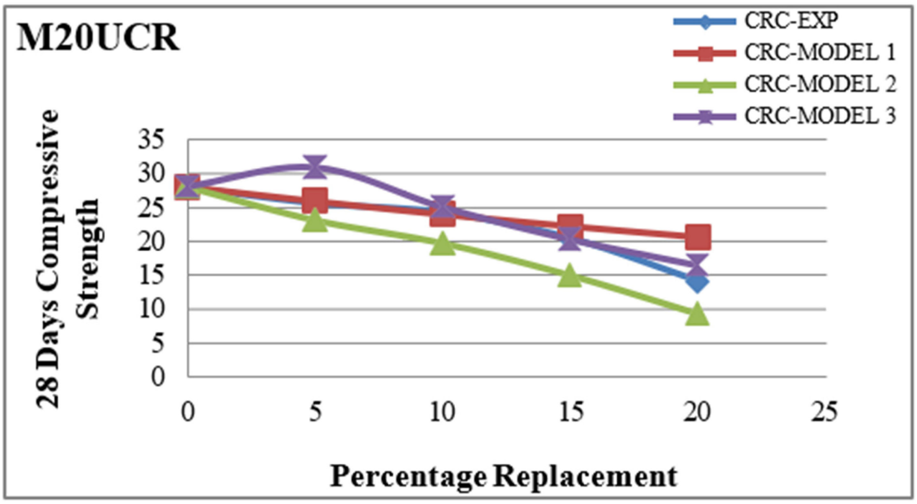

Figure 3. M20UCR results.

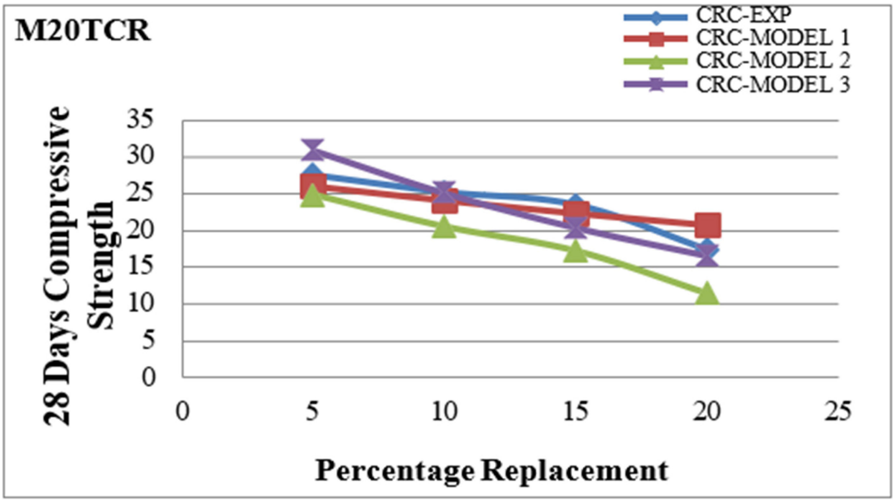

Figure 4. M20TCR results.

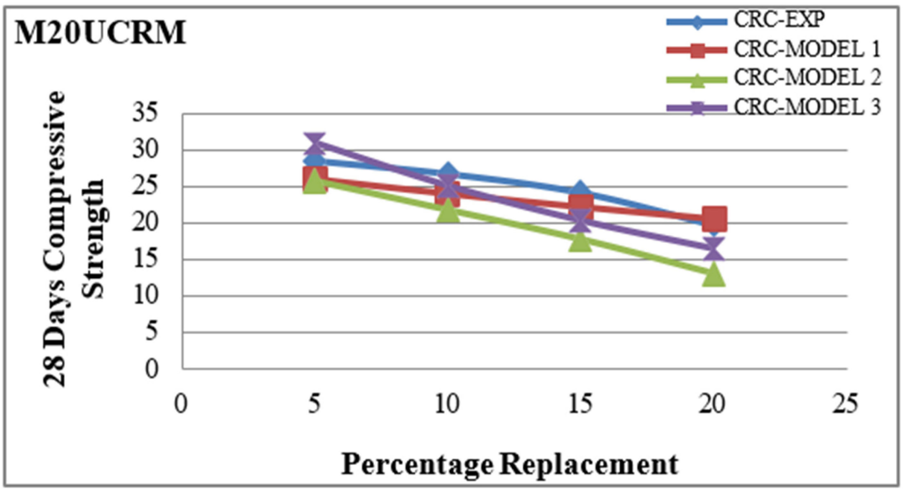

Figure 5. M20UCRM results.

The experimental compressive strength values for M20UCR are in alignment with Predictive Model 1 and Predictive Model 3. The compressive strength results obtained at 10% and 15% are almost the same as the predicted values obtained using Model 3. However, the experimental results for the 5% and 20% replacements are lower than the predicted results from Model 3 and vary by a percentage of 20% and 17%, respectively. The compressive strength results obtained at 5% and 10% are almost the same as the predicted values obtained using Model 1. The experimental results for the 15% and 20% replacements are lower than the Predictive Model 1 and vary by a percentage of 8% to 16%. In the case of M20TCR, similar to M20UCR, the experimental compressive strength values are in alignment with Predictive Model 1 and Predictive Model-3. The compressive strength results obtained for 5%, 10%, and 15% are almost the same as the predicted values obtained using Model 1. However, the experimental results for the 20% replacement are lower than the predicted results obtained using Model 1 and vary by a percentage of 19%. The compressive strength results obtained for the 10% and 20% replacements are almost the same as the predicted values obtained using Model 3. The experimental results at 5% are lower than the results from Predictive Model 3, and, at 15% replacement, it is higher and varies by a percentage of 12% to 15%. The experimental compressive strength values for M30UCRM are in alignment with Predictive Model 1 and Predictive Model 3. The compressive strength results obtained at 15% and 20% are almost the same as the predicted values obtained using Model 1. However, the experimental results for the 5% and 10% replacements are higher than the predicted results from Model 1 and vary by a percentage of 8% to 10%, respectively. The experimental results, in comparison with Model 3, are higher across all the replacement percentages by a varying increment, starting from 6%, increasing to 16%, and lowering at 5%. To summarize, in all three cases, i.e., M20UCR, M20TCR, and M20UCRM, the experimental compressive strength values are in closer alignment with Predictive Model 1 and Predictive Model 3. In addition, the results for the 5% and 10% replacements are comparable with these models. The results are not found to be in alignment in all three cases, i.e., M20UCR, M20TCR, and M20UCRM, with Model 2, as the experimental results are lower by a varying percentage of 9% to 33%.

2.4.2. Predictive Compressive Strength of M30 Grade Concrete

The experimental results vis à vis the predictive models are depicted for M30UCR, M30TCR, and M30UCRM with varying partial replacements of fine aggregates, at 5%, 10%, 15%, and 20%, in Figures 6–8, respectively.

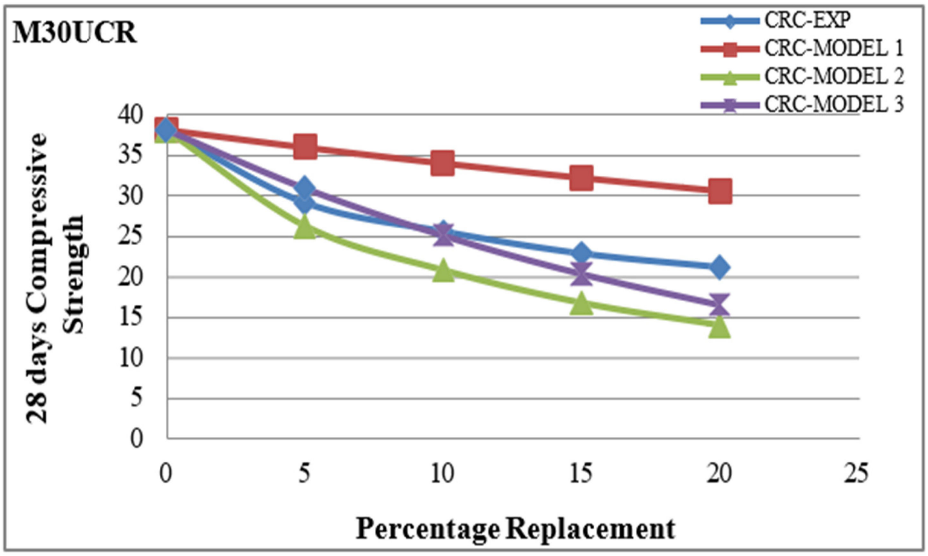

Figure 6. M30UCR results.

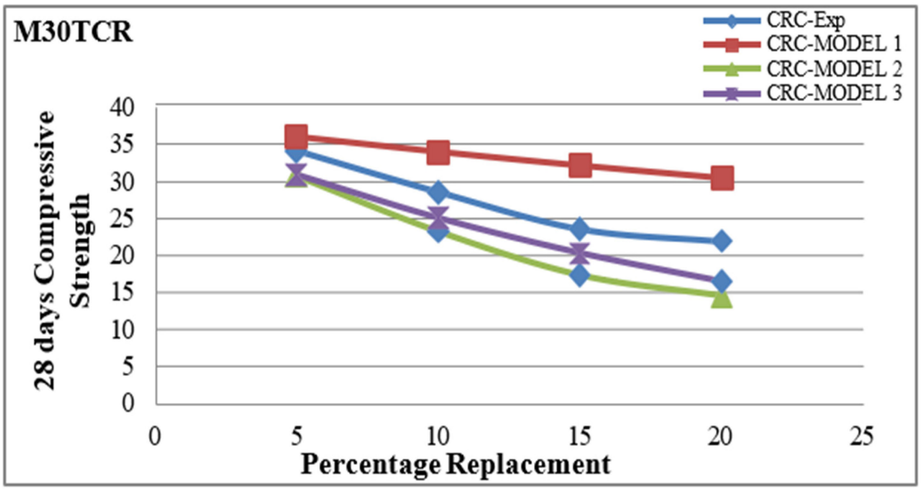

Figure 7. M30TCR results.

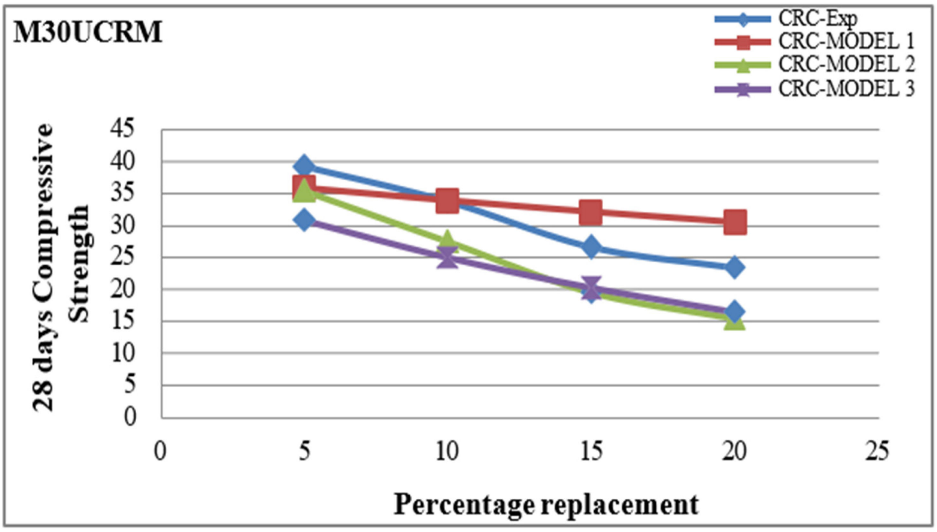

Figure 8. M30UCRM results.

For M30UCR, the experimental compressive strength values are in alignment with those of Predictive Model 2 and Predictive Model 3. The compressive strength results obtained for the 5% and 10% replacements were almost the same as the predicted values obtained using Model 3. However, the experimental results at 15% and 20% replacement were higher than those of Model-3 and vary by a percentage of 10% to 21%, respectively. The experimental results, in comparison with Model 2, were higher across all the replacement percentages by a varying increment ranging from 9% to 33%. The results were not found to be in alignment with Model 1, as the experimental results were lower by a varying percentage from 23% to 45%. For M30TCR, the compressive strength results obtained for the 5% replacement were almost the same as the predicted values obtained using Model 1. However, the experimental results for the 10%, 15%, and 20% replacements were lower by varying percentages ranging from 19% to 39%. The experimental results, in comparison with Model 2, were higher across all the replacement percentages by a varying increment, ranging from 9% to 33%. The experimental results, in comparison with Model 3, were higher across all the replacement percentages by a varying increment, ranging from 9% to 25%. In the case of M30UCRM, the experimental compressive strength value for the 10% replacement agreed with Predictive Model 1. The experimental results for the 5% replacement were higher than the predicted results from Model 1 and varied by a percentage of 8%, and, for the 15% and 20% replacements, the experimental results were lower than Model 1 by varying percentages ranging from 20% to 30%. The experimental results, in comparison with Model 2, were higher across all the replacement percentages by a varying increment ranging from 9% to 33%. The experimental results, in comparison with Model 3, were higher across all the replacement percentages by a varying increment ranging from 21% to 30%.

The predictive models did not consider the treatment methods and were based on the volumetric partial replacement percentages of crumb rubber in concrete. The predictive models can be refined further by considering the treatment methods and types of admixtures for a more refined and accurate prediction of compressive strength. Very few predictive models are available in the literature for the splittensile strength of crumb rubber concrete, which is a case for further study.

2.5. Microstructural Analysis

2.5.1. Scanning Electron Microscopy (SEM) Analysis

Images of the M20 grade specimens M20UCR10, M20TCRN10, and M20UCR20, using the APREOSEM equipment, were captured in the scale range of 500 µm to 500 nm. The SEM analysis of the concrete samples with 10% and 20% treated and untreated rubber (Figures 9–12) did not seem to have undergone any substantial modifications following the NaOH treatment. In both cases, the microcracks were verifiable. Cauana Melo Copetti et al. [19] reported similar outcomes. It was discovered, through a comparison of the hydration products' morphology in rubber concrete, that, following the typical 28-day curing, the morphology of the hydration products created between the normal concrete and CRC were similar and comparable, except that the CRC density was lower and the amount of hydration products was larger.

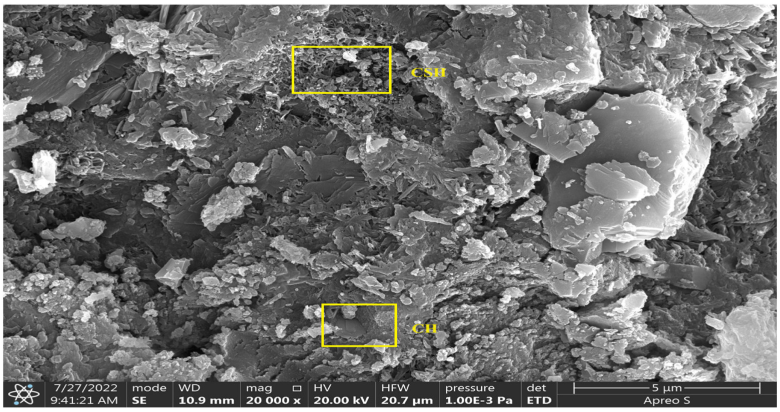

Figure 9. SEM analysis of M20UCR10 at 5 µm.

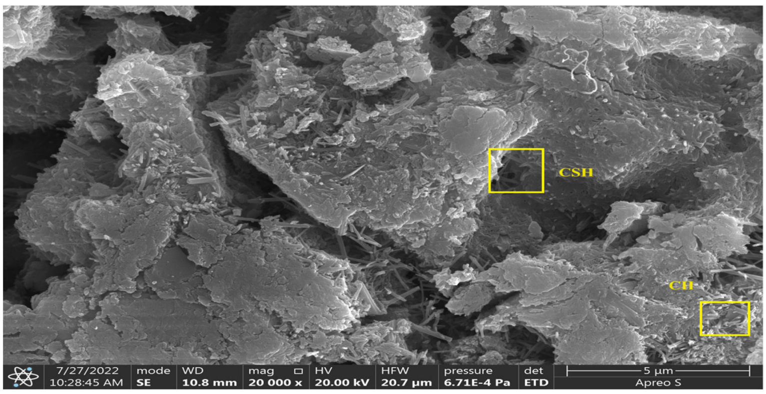

Figure 10. SEM analysis of M20TCR10 at 5 µm.

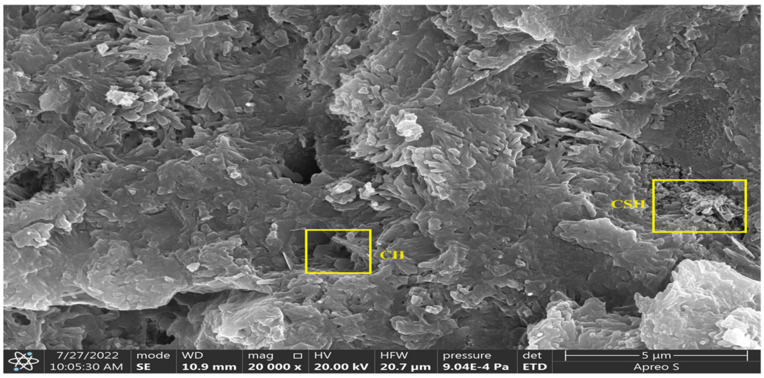

Figure 11. SEM analysis of M20UCR20 at 5 µm.

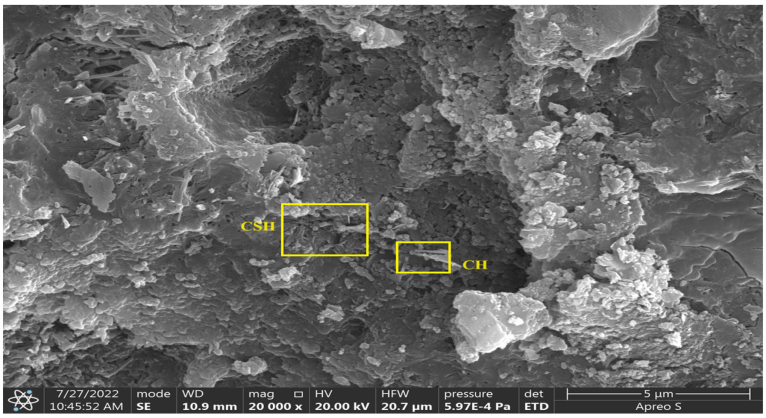

Figure 12. SEM analysis of M20TCR20 at 5 µm.

2.5.2. Energy Dispersive X-ray Spectroscopy (EDS)

The images obtained for the M20 grade samples from EDS are presented in Figures 13 and 14. The Ca/Si ratios for M20UCR10, M20UCR20, M20TCR10, and M20TCR20 were 2.44, 2.47, 2.28, and 2.39, respectively. The results were within the hydration products' acceptable range of 0.8 to 2.5.

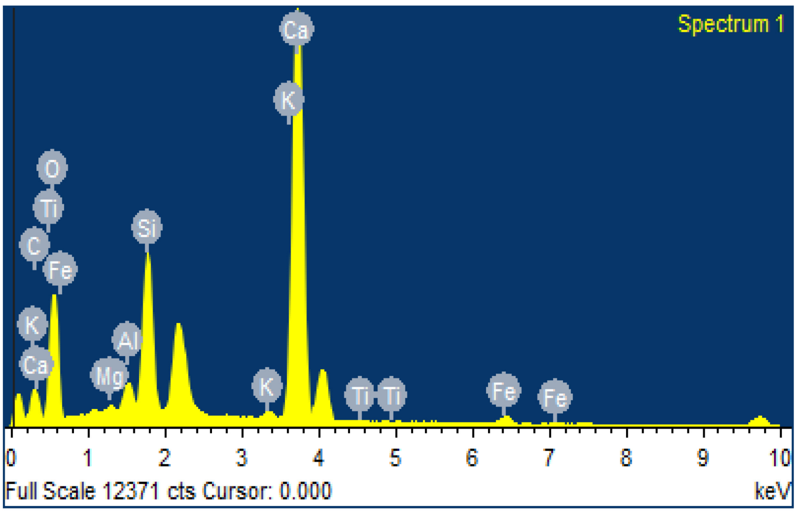

Figure 13. EDS image of M20UCR10.

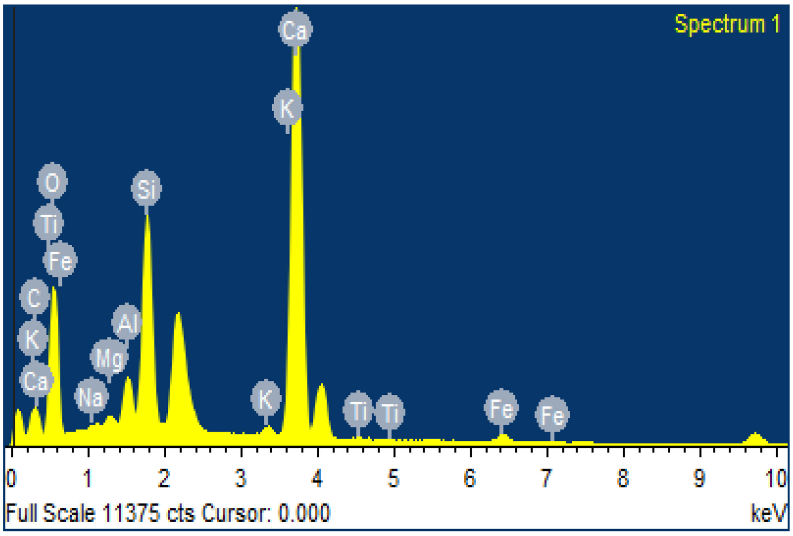

Figure 14. EDS image of M20TCR10.

2.5.3. X-ray Diffraction (XRD)

XRD was used to identify the phases of the concrete samples. Because morphological and elemental analyses alone could not reliably identify such secondary deposits, XRD was employed. The XRD peaks (d-spacing) and 2θ values were analyzed, using ORIGINPRO v2024, for the specimens M20UCR10, M20TCR10, M20UCR20, and M20TCR20, and the hydration compounds were identified based on the standard values. The analysis results are shown in Figure 15.

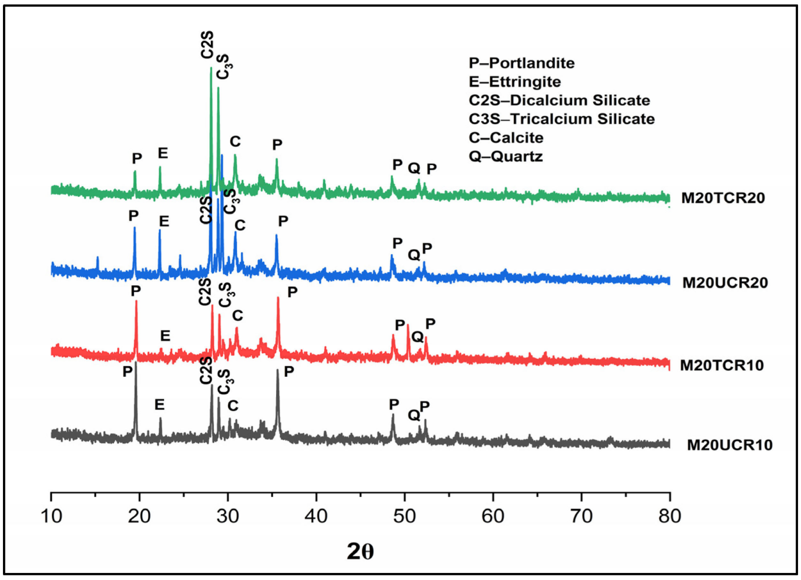

Figure 15. XRD images of M20 grade specimens.

2.6. Life Cycle Assessment

Environmental impact values for various indicators used in the Intergovernmental Panel on Climate Change (IPCC), Life Cycle Impact Assessment (LCIA)IPCC method for M20 grade concrete, M30 grade concrete, and various mixes are presented in Tables 5 and 6, respectively. The results clearly indicate that the M30 CRC had a higher impact than the M20 CRC across all impact categories. It is also evident that the usage of NaOH solution for pretreatment marginally increased the environmental impacts in comparison to the untreated CRC samples and untreated CRC samples with micro-silica as an admixture.

Table 5. Environmental impacts of M20 CRC.

Climate Change	Impact Category	Impact Results for Different Mixes (kg CO^2-Eq)						
		M20	**M20UCR05**	**M20UCR10**	**M20TCR05**	**M20TCR10**	**M20UCRM05**	**M20UCRM10**
Biogenic	Global temperature change potential (GTP100)	0.735	0.732	0.730	1.318	1.901	0.739	0.737
	Global temperature change potential (GTP50)	1.625	1.620	1.616	2.916	4.207	1.635	1.630
	Global warming potential (GWP100)	4.220	4.207	4.194	7.571	10.922	4.245	4.232
	Global warming potential (GWP20)	12.456	12.418	12.381	22.348	32.239	12.530	12.493
	Global warming potential (GWP500)	1.125	1.122	1.118	2.019	2.912	1.132	1.129
	Including SLCFs–global temperature change potential (GTP100)	0.848	0.846	0.843	1.460	2.071	0.857	0.855
	Including SLCFs–global warming potential (GWP100)	4.951	4.938	4.925	8.484	12.016	5.007	4.993
	Including SLCFs–global warming potential (GWP20)	14.703	14.664	14.625	25.152	35.601	14.870	14.831
Fossil	Global temperature change potential (GTP100)	28,361.222	28,343.005	28,324.788	29,572.413	30,783.604	28,424.162	28,405.945
	Global temperature change potential (GTP50)	28,483.160	28,464.617	28,446.074	29,720.447	30,957.734	28,547.163	28,528.620
	Global warming potential (GWP100)	28,810.785	28,791.407	28,772.029	30,116.885	31,422.984	28,877.644	28,858.266
	Global warming potential (GWP20)	29,858.862	29,836.798	29,814.734	31,385.469	32,912.075	29,934.858	29,912.795
	Global warming potential (GWP500)	28,393.752	28,375.473	28,357.193	29,612.276	30,830.799	28,456.983	28,438.704
	Including SLCFs–global temperature change potential (GTP100)	28,417.762	28,399.421	28,381.079	29,631.014	30,844.266	28,480.987	28,462.645
	Including SLCFs–global warming potential (GWP100)	28,928.114	28,908.479	28,888.843	30,238.493	31,548.872	28,995.566	28,975.930
	Including SLCFs–global warming potential (GWP20)	30,125.204	30,102.556	30,079.908	31,661.527	33,197.850	30,202.546	30,179.898
Land Use	Land use–global temperature change potential (GTP100)	17.505	17.497	17.488	20.038	22.571	17.535	17.526
	Land use–global temperature change potential (GTP50)	17.507	17.498	17.490	20.041	22.575	17.537	17.528
	Land use–global warming potential (GWP100)	17.512	17.503	17.494	20.049	22.587	17.541	17.533
	Land use–global warming potential (GWP20)	17.526	17.518	17.509	20.076	22.625	17.557	17.548
	Land use–global warming potential (GWP500)	17.506	17.497	17.489	20.040	22.573	17.536	17.527
	Land use, including SLCFs–global temperature change potential (GTP100)	17.514	17.505	17.496	20.053	22.593	17.544	17.535
	Land use, including SLCFs–global warming potential (GWP100)	17.529	17.520	17.512	20.080	22.631	17.559	17.551
	Land use, including SLCFs–global warming potential (GWP20)	17.566	17.557	17.548	20.146	22.725	17.597	17.588

Table 6. Environmental impacts of M30 CRC.

Climate Change	Impact Category	Impact Results for Different Mixes (kg CO^2-Eq)						
		M30	**M30UCR05**	**M30UCR10**	**M30TCR05**	**M30TCR10**	**M30UCRM05**	**M30UCRM10**
Biogenic	Global temperature change potential (GTP100)	0.731	0.728	0.726	1.371	2.011	0.735	0.732
	Global temperature change potential (GTP50)	1.617	1.611	1.606	3.033	4.449	1.626	1.621
	Global warming potential (GWP100)	4.197	4.183	4.169	7.874	11.551	4.222	4.208
	Global warming potential (GWP20)	12.390	12.348	12.307	23.244	34.098	12.462	12.420
	Global warming potential (GWP500)	1.119	1.116	1.112	2.100	3.080	1.126	1.122
	Including SLCFs–global temperature change potential (GTP100)	0.845	0.842	0.840	1.516	2.187	0.854	0.851
	Including SLCFs–global warming potential (GWP100)	4.932	4.917	4.903	8.808	12.684	4.987	4.972
	Including SLCFs–global warming potential (GWP20)	14.646	14.603	14.560	26.112	37.577	14.812	14.769
Fossil	Global temperature change potential (GTP100)	28,736.166	28,716.113	28,696.060	30,064.887	31,393.608	28,798.324	28,778.271
	Global l temperature change potential (GTP50)	28,859.791	28,839.379	28,818.968	30,217.141	31,574.491	28,922.997	28,902.585
	Global warming potential (GWP100)	29,191.901	29,170.570	29,149.239	30,624.741	32,057.581	29,257.927	29,236.596
	Global warming potential (GWP20)	30,254.340	30,230.053	30,205.766	31,929.088	33,603.835	30,329.386	30,305.099
	Global warming potential (GWP500)	28,769.120	28,748.998	28,728.876	30,105.885	31,442.651	28,831.567	28,811.445
	Including SLCFs–global temperature change potential (GTP100)	28,792.962	28,772.772	28,752.583	30,123.944	31,454.926	28,855.397	28,835.208
	Including SLCFs–global warming potential (GWP100)	29,309.762	29,288.147	29,266.533	30,747.296	32,184.830	29,376.365	29,354.750
	Including SLCFs–global warming potential (GWP20)	30,521.890	30,496.960	30,472.029	32,207.295	33,892.700	30,598.247	30,573.317
Land Use	Land use–global temperature change potential (GTP100)	17.093	17.084	17.074	19.872	22.651	17.123	17.113
	Land use–global temperature change potential (GTP50)	17.095	17.085	17.076	19.875	22.655	17.124	17.115
	Land use–global warming potential (GWP100)	17.099	17.090	17.080	19.884	22.668	17.129	17.119
	Land use–global warming potential (GWP20)	17.114	17.105	17.095	19.911	22.707	17.144	17.134
	Land use–global warming potential (GWP500)	17.094	17.084	17.075	19.873	22.653	17.123	17.114
	Land use, including SLCFs–global temperature change potential (GTP100)	17.102	17.092	17.083	19.888	22.673	17.131	17.122
	Land use, including SLCFs–global warming potential (GWP100)	17.117	17.107	17.098	19.916	22.715	17.147	17.137
	Land use, including SLCFs–global warming potential (GWP20)	17.154	17.144	17.135	19.984	22.814	17.185	17.175

3. Materials and Methods

3.1. Cement

The widespread preference for Ordinary Portland Cement (OPC) grade 53 in building construction is rooted in its superior mechanical properties and versatility, such as high early strength, enhanced durability, economic efficiency, wide range of applications, compatibility with additives, building code compliance, and consistent quality, which makes it suitable for a broad range of applications. Hence, in this study, OPC 53 grade cement, confirming to IS 12269 (1989) [32], was used. The properties of the cement, namely specific gravity, standard consistency, fineness, and initial setting time were determined [33], and the results are listed in Table 7.

Table 7. Properties of cement.

#	Tests on Cement	Results	Acceptable Range	IS Code
1	Fineness modulus	2	<10	IS 4031, 1996
2	Specific gravity	3.15	3.1–3.16	IS 2720-part 3
3	Standard consistency	28.5%	26–33%	IS 4031, 1988
4	Initial setting time	32 min	>30 mins	IS 4031, 1988

3.2. Fine Aggregate

River sand, locally available after being sifted and cleansed, was used to remove potential organic and inorganic components. To remove large and undesirable organic debris, the sand was sieved with a 4.75 mm mesh. The fineness modulus [34–36] and specific gravity of the sand used were 2.41 and 2.44, respectively; the details are listed in Table 8.

Table 8. Properties of fine aggregate.

#	Test on Fine Aggregate	Result	Acceptable Range	IS Code
1	Fineness modulus	2.41	2.0–3.5	IS 383, 1970
2	Specific gravity	2.44	2.5–3.0	IS 2386, 1963

3.3. Coarse Aggregate

Coarse aggregate that passed through a 20 mm sieve and was retained on a 16 mm sieve was used. The fineness modulus [34,35] and specific gravity of the coarse aggregate used were 7.18 and 3.0, respectively; the details are listed in Table 9.

Table 9. Properties of coarse aggregate.

#	Tests on Coarse Aggregate	Result	Acceptable Range	IS Code
1	Fineness modulus	7.18	5.5–8.0	IS 383, 1970
2	Specific gravity	3	2.5–3.0	IS 2386, 1963

3.4. Water

Potable water suitable for human consumption was used for the mixing of the concrete.

3.5. Crumb Rubber

Tires from vehicles and trucks were used to make recycled crumb rubber. During recycling, the steel and tire cords were removed from the tire rubber, leaving it to have a granular consistency. The rubber particle size was further reduced by mechanical grinding, employing equipment such as granulators, hammer mills, or grinding mills, or by using cryogenic grinding, wherein rubber is cooled using liquid nitrogen to a low temperature until it becomes brittle and is then fractured into small particles using mechanical impact. Crumb rubber produced by mechanical grinding was used for this research work, with a rough surface texture that can improve mechanical interlock with the cement matrix and, hence, the strength of concrete. However, the mechanical grinding process produces a wider range of particle sizes, necessitating thorough sieving for uniformity. Color (black alone or black and white) and other characteristics, such as the size and classification of the particles, are modified. The crumb rubber employed in this study passed through a sieve with a mesh size of 2.36 mm but was retained on a mesh size of 1.18 mm, with a specific gravity of 1.154. The properties of the Crumb Rubber are listed in Table 10.

Table 10. Properties of Crumb rubber.

#	Property	Value
1	Color	Black
2	Size	Passing through a 2.36 mm and retained using a 1.18 mm sieve
3	Fineness modulus	2.4
4	Specific gravity	1.154

3.6. NaOH Crystals

The pretreatment procedure used in the current study involved soaking crumb rubber in 5 M concentrated NaOH for 20 min. Crumb rubber treated with NaOH for longer than 30 min has a negative impact on the mechanical qualities of crumb rubber [37]. In research contexts where the effectiveness of NaOH concentrations on the pre-treatment of crumb rubber is evaluated for use in concrete, typically a systematic experimental approach is adopted to arrive at the suitable concentration. Initially 10M concentrated NaOH was used; however, due to the high alkalinity of 10M NaOH, the strength of the samples after 7 days curing to assess early strength gain was not adequate. Subsequently, the results, when 5 M NaOH was used for pre-treatment, resulted in an acceptable 60–70% of the strength gain expected at 28 days. Hence, 5 M NaOH solution was used for the pre-treatment of Crumb Rubber. The treated crumb rubber was then rinsed with tap water and allowed to air-dry for 24 h, making it suitable for use in concrete. Figure 16 depicts the NaOH crystals used for the study.

Figure 16. NaOH crystals.

3.7. Powdered Micro-Silica

The use of micro-silica offers several advantages, including an increase in strength, a decrease in thermal cracking owing to the heat generated by the hydration of cement, and an improved resistance to sulfates and acid attacks [15]. As a mineral additive, micro-silica, in the current project, takes the place of cement. By cement weight, 10% of the original material was replaced. Figure 17 depicts the micro-silica used for the study. According to the literature, a replacement of up to 15% of silica fume by weight of the cement can produce the best compressive and tensile strengths. The 28-day compressive strength test results revealed improved strength when 10% silica fume was used in place of cement by weight for this study. The properties of the micro-silica used are listed in Table 11.

Figure 17. Micro-silica.

Table 11. Properties of Micro-silica.

Properties	Color	Diameter	Bulk Density	Specific Gravity
	Grey	<1 mm	130–600 Kg/m^3	2.2–2.3

3.8. Replacement Ratio Selection and Notations

The density of concrete mixtures is influenced by the aggregate components. There is greater motivation to look for new options because of the high cost of transporting sand and its scarcity. The replacement rates of fine aggregates with crumb rubber by weight were 5%, 10%, 15%, and 20%. M20 and M30 represent the concrete grades; M20CR0 and M30CR0 denote the controlled mixes; UCR denotes untreated concrete; TCR denotes NaOH-treated crumb rubber; UCRM denotes the addition of micro-silica as an admixture in untreated crumb rubber concrete; and 0, 5, 10, 15, and 20 denote the percentages of sand replaced by weight with crumb rubber. The replacement of fine aggregate was restricted to a maximum of 20% to evaluate the utilization of CRC in RCC structural elements of foundations, beams, columns, walls, and slabs.

3.9. Concrete Mix Design

The ratios of cement to fine aggregate to coarse aggregate considered were 1:1.5:3 and 1:1.63:2.8, while the water/cement ratios considered were 0.55 and 0.45 for M20 grade and M30 grade concrete, respectively [38]. The workability test on concrete was performed as per IS 7320 [39]. Casting, curing, compressive strength and split tensile strength tests on concrete were performed according to IS codes 456 [40] and IS516 [41].

3.10. Crumb Rubber Concrete Mechanical Performance Predictive Models

3.10.1. Predictive Model 1

This model was proposed by Reda Taha et al. [21] to predict the compressive strength of crumb rubber concrete. The reduction in compressive strength was directly proportional to the tire crumb rubber content. The model predicts the 28-day compressive strength of rubber concrete, f_{RC}, based on the level of aggregate replacement by tire particles, R, which is represented as follows:

$$f_{RC} = f_c - 0.4496R + 0.004R^2 - 1.65 \times 10^{-5} \times R^3$$

where f_{RC} is the predicted 28-day compressive strength of rubber concrete; f_c is the 28-day compressive strength of concrete without tire rubber particles; and R is the replacement percentage of the aggregate with crumb rubber tire particles.

3.10.2. Predictive Model 2

This model, called the Strength Reduction Factor model, was proposed by Huang et al. [18]. It is based on the macro porosity theory and has a correlation coefficient of R^2 = 0.854, where the experimental values were compared with other proposed models and concluded to be more reliable and accurate. However, the effects of crumb rubber particle size and shape were not considered in this model.

$$\mathrm{SRFC}\ (V_R) = (1 - \alpha \mathrm{vR}) \times 10^{-\beta \mathrm{VR}}$$

where SRFc is the Strength Reduction Factor, α is the solid material quantity parameter ($\alpha = 0.281$), β is the experimental parameter ($\beta = 0.773$), and V_R is the crumb rubber volume fraction.

3.10.3. Predictive Model 3

This model was proposed by Youssf et al. [22] to predict the compressive strength of CRC. The authors considered a dataset of 148 for the CRC compressive strength to verify the proposed model. The compressive strength was proposed in an exponential form and the advantage was that, when the rubber content Rt equals zero (no rubber), the concrete's compressive strength was not affected ($e^0 = 1.0$). Thus, the model formula proposed is as follows:

$$f'_{CRC} = f'_{C}\ [e^{-4.2\mathrm{Rt}}]$$

where f'_{C} is the compressive strength of the control concrete (without rubber); f'_{CRC} is the compressive strength of the crumb rubber concrete; and R_t is the rubber content by volume of the total aggregates.

3.11. Microstructural Characterization

The identification of point-to-point variations in the composition, structure, and microstructure of a material is a crucial component of characterization in materials research. To maximize the performance of all materials, it is essential to understand how elements and phases are distributed in the structures. These studies sought to identify changes in the microstructures, deterioration processes, and their effects on the mechanical characteristics of both types of concrete [42,43].

3.11.1. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) uses a high-energy electron beam to sweep across a sample surface, in a manner similar to a raster scan. The atoms and electrons of the sample interact, resulting in signals that provide details about the surface topography, composition, and other characteristics of the sample. In SEM, two signals, that is, secondary electrons (SE) and back-scattered electrons (BSE), are primarily measured to gather distinct data about the material. While back-scattered electron (BSE) images provide compositional information that can be distinguished by their atomic numbers, secondary electron (SE) images provide information on the topography of the samples. The brighter an element or phase in a BSE image, the greater its atomic number, according to this rule. However, the composition or constituents of BSE are not specified. Thus, Energy Dispersive X-ray Spectroscopy (EDS) analysis is required. The majority of the secondary electron (SEI) images and energy dispersive spectrometry (EDS) analyses were used for concrete examination.

3.11.2. Energy Dispersive X-ray Spectroscopy

Another well-known method for examining the chemical makeup of materials in SEM is energy dispersive spectrometry. The EDS detector is typically linked to SEM instruments and produces chemical component spectra for quantification.

The presence of desirable and undesirable compounds across the cement hydration phases was ascertained using the EDS report, and the acceptable limits [42] are listed in Table 12.

Table 12. Hydrated products range.

Hydration Products	Acceptable Range
C S H (Calcium Silicate Hydrate)	$0.8 \leq Ca/Si \leq 2.5$, $(Al + Fe)/Ca \leq 0.2$
Calcium Hydroxide (CH)	$0.8 \leq Ca/Si \leq 2.5$, $(Al + Fe)/Ca \leq 0.2$
Monosulphate (Afm)	$0.8 \leq Ca/Si \leq 2.5$, $(Al + Fe)/Ca \leq 0.2$

3.11.3. X-ray Diffraction (XRD)

When used to analyze crystalline materials, X-ray diffraction (XRD) is a useful technique that can provide details on crystallinity, phases, preferred crystal orientation, and other structural factors. To determine the phases, a search of the standard database was conducted after the production of X-ray diffraction peaks by the constructive interference of a monochromatic beam of X-rays dispersed at precise angles from each set of lattice planes in a sample. The expected XRD peaks and d-spacing values [44,45] are listed in Table 13.

Table 13. XRD peaks and d-spacing values.

Mineral	Chemical Formula	2-Theta (°)	d-Spacing (% Intensity)
Quartz	SiO_2	26.634	3.344 (100.0)
		20.853	4.256 (38.8)
		36.536	2.457 (1.7)
Portlandite	$Ca(OH)_2$	34.102	2.627 (100.0)
		18.008	4.922 (72.0)
		28.672	3.111 (27.0)
Hatrurite	Ca_3SiO_5	32.193	2.778 (100.0)
		29.357	3.040 (87.6)
		32.504	2.752 (87.4)
Larnite	Ca_2SiO_4	32.169	2.780 (100)
		32.597	2.745 (79.9)
		32.074	2.788 (77.6)
Gismondine	$CaAl_2Si_2O_8$	20.775	4.272 (100)
		12.131	7.290 (99.5)
		28.004	3.184 (71.8)
Brownmillerite	$Ca_2(Al,Fe)_2O_5$	33.876	2.472 (100)
		12.198	7.250 (45)
		50.229	1.815 (45)
Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12}\ 26H_2O$	9.091	9.720 (100)
		15.784	5.610 (74)
		22.944	3.873 (31)
Vesuvianite	$Ca_{19}Fe(Al_{6.48}Fe_{1.52})Al_4(SiO_4)_{10}$	32.402	2.761 (100)
		32.463	2.7566 (83)
		34.463	2.6026 (64.8)

3.12. Life Cycle Assessment

The LCA conducted in this study used OpenLCA v2.10 software and the ecoinvent database (v2.2 and v3.10). Exploring alternative Life Cycle Assessment (LCA) methodologies and tools can enrich insights into the environmental impact of crumb rubber concrete. SimaPro and GaBi offer extensive databases and advanced modelling capabilities, potentially highlighting different environmental aspects. The LCA software tool Chain Management by Life Cycle Assessment (CMLCA) focuses on supply chain impacts, offering a unique perspective on upstream and downstream effects. Another LCA tool, Footprint Expert, specializing in carbon and water footprint assessments, could provide a more focused view on specific environmental impacts. Lastly, considering sector-specific LCA approaches might reveal unique insights relevant to specific applications of crumb rubber concrete.

A Life Cycle Assessment (LCA) was performed on conventional and crumb rubber concrete and the the Life Cycle Impact Assessment (LCIA) method chosen was Ecoinvent IPCC 2021. The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme and the World Meteorological Organization [46]. IPCC assessments furnish governments at all tiers with scientific data for crafting climate policies. These assessments serve as pivotal inputs for global efforts to combat climate change through international negotiations. Drafting and reviewing IPCC reports occurs in multiple stages, ensuring objectivity and transparency throughout the process.

4. Conclusions

In this investigation, treated and untreated crumb rubber were used to partially replace sand in concrete mixtures. The study's findings lead to the following conclusions:

- Substituting 5% crumb rubber for M20 and M30 grade concrete and adding micro-silica resulted in the highest compressive and split tensile strengths. Conversely, when 20% crumb rubber replaced untreated concrete, the lowest strengths were observed.
- A 5 M aqueous solution of NaOH was found to be optimal for the pre-treatment of CRC.
- A reduction in the slump was observed in CRC samples that underwent NaOH pre-treatment and micro-silica addition; however, the values stayed within the acceptable range, as per IS 456 provisions.
- The predictive models, focusing on crumb rubber's volumetric replacement in concrete, overlooked treatment methods. Including these methods and admixture types could refine the models for more accurate compressive strength predictions.
- According to SEM images, silica fume in concrete helped to fill gaps caused by rubber particle growth, reducing void volume and porosity while increasing density. This resulted in enhanced mechanical properties of the concrete.
- Lower Ca/Si ratios, as per the EDS results, signified a higher presence of the CSH gel, with low Ca/Si ratio calcium silicate hydrates showing greater stability, compared to high Ca/Si ratio ones. The treated samples M20TCR10 and M20TCR20 exhibited lower Ca/Si ratios than the untreated samples, indicating a higher percentage of CSH and correlating with the improved strength observed in the treated samples.
- According to the XRD results, different phases of the crystalline structure of CRC were observed. The highest peaks in the XRD results corresponded to the tricalcium silicate (C3S) and dicalcium silicate (C2S) phases, suggesting high strength in the concrete.
- The comparative LCA analysis between crumb rubber concrete and conventional concrete across different M20 and M30 mixes indicated that incorporating micro-silica into crumb rubber concrete did not result in a significant rise in environmental impacts. However, treating crumb rubber with sodium hydroxide solution led to a slight increase in environmental impacts.
- The feasibility and economic viability of scaling up crumb rubber concrete production for widespread adoption in the construction sector hinges on a complex array of factors. Despite challenges, the potential environmental advantages and the prospect of enhancing concrete properties may stimulate innovation and investment in this domain.

5. Scope for Future Research

- The inclusion of pre-treated crumb rubber and micro-silica in concrete mixtures has shown promise in enhanced workability and strength. Building on these results, several other innovative methods and technologies, like incorporating nano-sized particles and applying a nano-coating on crumb rubber particles, could be studied further to improve these properties.
- Using computational models to optimize the particle size distribution and packing density, involving adjusting the proportions of crumb rubber, micro-silica, and other components, could potentially improve these properties for a more viable and sustainable option.
- To explore the lifecycle environmental benefits of crumb rubber concrete in specific applications like road construction or building facades, a comparative LCA study can be designed, utilizing a tool like SimaPro for a comprehensive environmental impact assessment.

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