REVISTAMATÉRIA V.28 N.4
ISSN 1517-7076 articles e20230206, 2023

Optimal proportional combinations of rubber crumbs and steel slag for enhanced concrete split tensile strength

Amalnathan Alex Rajesh[1], Shanmugamoorthy Senthilkumar[1], Sisupalan Samson[2]

[1]KSR College of Engineering, Civil Engineering. 637215, KSR Kalvi Nilayam, Thiruchengode, Namakkal, Tamilnadu, India.

[2]Veltech Rangarajan Dr Sagunthala R&D Institute of Science and Technology, Department of Civil Engineering. Chennai, Tamilnadu, India.

e-mail: aalexrajeshksr@gmail.com, senthilkumarcivil@ksrce.ac.in, drssamson@veltech.edu.in

ABSTRACT

Waste management is one of the essential issues in the global domain of environmental conservation. The flourishing promotion of the Automobile Industry in India has eventually ended up with an increase in dumped waste material, such as a waste tyre. Steel slag was also added to the improvised concrete mix (CRAC) in a frozen percentage within the cement mantle of the concrete matrix for the stabilization of the binding qualities. It was discovered that an optimal proportional combination of 12% waste rubber tyre crumbs and 9% steel slag proved to be the most techno-economically viable solution for maintaining the mandated qualities of supplied 30MPa or other base values for concrete with reference to a specific purpose due to calcium oxides. The achieved split tensile strength (3.762MPa) validated this ideal proportionate combination as the best and most long-lasting.

Keywords: Spilt-tensile test; recycled material; modified concrete; steel slag; rubber crumb.

1. INTRODUCTION

Material substitution has become the order of the day inasmuch as the natural non-renewable geological sources contributing to most building materials are getting irrecoverably depleted [1]. Rock and sand quarrying have resulted in irreparable damage to the environment, in the form of atmospheric pollution and water resources contamination by airborne dust particles [2]. Extensive industrial processes contribute to environmental degradation by the waste by-product landfills and point source pollution from piped discharges of effluents directly into the flowing streams and static water bodies such as lakes, ponds, and tanks. The novel idea of transforming these waste materials into potentially beneficial building materials and by material substitution within the concrete mix against cement, coarse and fine aggregates, and water would serve the purpose of balancing the demand-supply gap in the construction side [3]. Among umpteen alternate and equivalent materials available for substitution, this study has its focuses on how best the waste disposals of rubber materials and the waste dumping of steel slag as an industrial by-product can be diverted towards obtaining improvised concrete mixes so as to eliminate the chances of pollution and contamination.

NORMAN [4] used Carbon pack material with rubberized concrete. ELDIN and SENOUCI [5] initiated a technical evaluation on rubberized concrete for its versatile suitability for simple pavement laying to building construction in tandem with road formations. TOUTANJI [6] and LEE [7] tried out rubberized concrete with crumbed rubber from waste tyres against coarse aggregates. GOULIAS *et al.* [8] tried crumb rubber fractions as fine aggregate replacers with Portland cement. Brittle failure with high ductility and quick deformations were noted to make a setback in the ultimate concrete quality and strength standards. CHUNG *et al.* [9] and CHOU *et al.* [10] attempted with small-scale applications of rubberized concrete in pavements by substitution against the coarse aggregates [11–13]. Hardening of the improvised concrete upon incorporating wasted rubber was suggested as part of strength imparting. TOPCU [13] scrutinized the result of particle size and content material of tyre rubbers at the mechanical properties of concrete. The researcher conveys into being that, even though the strength has decreased, the plastic potential has progressed considerably. SEGRE and JOEKES [14] labored on the usage of tyre rubber debris as an addition to cement paste. The surface of powdered tyre rubber (debris of maximum size 35 meshes, 500 m) was changed to increase its adhesion to cement paste. GIRISH *et al.* [15] accomplished an investigational study incorporating crumb rubber, as a fine aggregate with Portland

Corresponding Author: Amalnathan Alex Rajesh Received on 14/07/2023 Accepted on 14/09/2023

DOI: https://doi.org/10.1590/1517-7076-RMAT-2023-0206

cement. Test effects illustrated diversifications within the brittle failure of concrete, which simplifies that rubber concrete specimens show symptoms of better ductility overall performance than conventional concrete. Results confirmed more deformation without the entire crumbling of concrete. GRRICK [16] confirmed the analysis of waste tyre-modified concrete used 15% via volume of the coarse aggregate whilst changed via the waste tyre as a two-segment material as tyre fiber and chips dispersed in a concrete mix. The end result is that there may be plastic deformation, an increase in longevity, impact, and cracking resistance. Even though the strength and stiffness of the rubberized sample be decreased. The control concrete collapsed when the top load was reached at the same time as the rubber aggregate concrete had enormous deformation without segregation because of the bridging due to the tyres. NOAMAN *et al.* tested rubber-modified concrete for numerous makes use and had proven ability consequences [17]. The inclusion of rubber particles directs to the degradation of physical properties, predominantly, the compressive strength of the concrete [18]. LI *et al.* [19] initiated rubber concrete the usage of the dry process. The compressive strength of rubberized concrete changed into approximately 90MPa in addition to the Poisson's ratio becoming 5%. BIGNOZZI & SANDROLINI [20] tested the exploit of concrete imitative from shredded rubber from waste tyres for repairing a cracked pavement. They observed that the concrete became greater skid resistant, excessive elasticity, lightweight, and probably might be used for fire protection and sound insulation. BIEL & LEE [21] used recycled tyre rubber in concrete mixes made with $MgCl_2$ cement, in which the aggregate became replaced via crumb rubber up to 20–25% by way of volume. MOHANRAJ *et al*. investigated the properties of Crumb Rubber Concrete, the unit weight of the combination was reduced more or less 6 pcf for each 50 lbs of crumb rubber introduced [22]. TOPÇU [23] endorsed the use of rubberized concrete in instances in which vibration damping is needed. Associated observations have been also made by means of FATTUHI and CLARK [24], who determined that the impact resistance of concrete improved at the same time as rubber aggregates were covered in the concrete mixtures. The growth in resistance turned into imitative from the progressed potential of the material to absorb energy. ELDIN and SENOUCI [5], TOPCU [13] also suggested comparable results. ZHU [25], HERRERA-SOSA *et al.* [26], RIVAS-VÁZQUEZ *et al.* [27] offered the flexural toughness and impact resistance of steel fiber-reinforced light-weight concrete and the outcomes indicate that the excessive compressive strength and density are fine for suitable impact resistance of plain cement concrete and also stated that the incorporation of steel fibers improved the impact resistance significantly. The compressive strength reduced at the same time as the rubber content material accelerated. Guoqiang LI investigated chips and fibers [28]. The tyre surfaces are treated by means of saturated Sodium Hydroxide solution and physical anchorage with the aid of a drilling hole at the middle of the rubber aggregates have been additionally investigated, and they over and executed with that fibers carry out better than chips. Sodium Hydroxide treatment no longer works for large-sized tyre chips with the use of physical anchorage and has a few impacts. A scientific experimental study was achieved currently to enhance the strength and durability of rubber-modified Concrete. Furthermore, the workability of the mixtures fabricated was no longer extensively affected. HE *et al.* [29] investigated the durability (durability is likewise known as energy absorption potential and is usually described as the area beneath the load-deflection curve of a flexural specimen) of a control concrete mixture and TRAC mixtures with 5% and 10% buff rubber by means of volume of coarse aggregate [30]. Based on their studies on the use of rubber shreds and granular rubber in mortar, MUNOZ-SANCHENZ *et al.* [31] accounted that mortar specimens with rubber shreds are able to resist additional load after final load. LOGANATHAN *et al.* [32] reported that failure of concrete specimens with 20, 25, 30, 35, 40, 45, and 60% substitute of fine aggregate with rubber debris took place as a gradual shear that led to a diagonal failure, whereas failure of plain (control) concrete specimens turned into explosive, leaving specimens in numerous portions. ABDULLA *et al.* [33] observed that the dynamic modulus of elasticity and rigidity reduced with an increase in the rubber content material, indicating a much less stiff and much less brittle material. However, LEUNG & GRASLEY [34]., mentioned that the addition of crumb tyre rubber volume fractions as much as 5% in a cement matrix no longer yield a massive variation of the concrete mechanical functions, both maximum stress and elastic modulus [35].

Industrial, agricultural, and domestic waste can be effectively converted into useable inputs for other pertinent purposes, such as the replacement of construction materials, the application of manures to cultivated fields, and the promotion of kitchen gardening or terrace gardening employing kitchen rubbish wastes. In accordance with these null assumptions, the current study made an effort to utilize waste materials that would otherwise be disposed of in landfills, such as rubber tyre scraps and slag from industrial operations, by exploring potential material substitution options as alternatives for concrete ingredients.

2. MATERIALS AND SAMPLE PREPARATION

Cement-Portland cement of 53 Grade, Fine aggregate-Natural River Sand, Coarse aggregate-Natural aggregates, Admixtures-Waste tyre crumbs obtained from four-wheelers and steel slag, Water-Potable water [36].

Table 1: Material properties of fine aggregate, rubber crumbs and coarse aggregates.

PROPERTIES	FINE AGGREGATE		COARSE AGGREGATE
	SAND	WASTE RUBBER CRUMBS	
Specific Gravity	2.63	1.14	2.61
Fineness Modulus (%)	4.91	5.35	7.42
Water Absorption (%)	2.00	1.14	1.00

Steel Industry slag:

Steel slag contains Calcium Oxide 48%, Silicon Dioxide 13%, Ferric Oxide 16%, Manganese Oxide 6.5%, Magnesium Oxide 7.2%, Aluminum Oxide 1.18%, Phosphorous 0.85%, and Metallic 0.77% [37].

Physical properties of steel slags are as follows: Abrasion value 27%, Volume of Voids 0.3%, Specific gravity 3.41%, Water absorption 0.7%, Crushing value 29.1%, Impact value 17%, loose bulk density 1849 kg/m^3, compacted bulk density 2148 kg/m^3, and Fineness modulus 3.10 [38].

Rubber crumb aggregate: The properties are shown in Table 1 and the mix design of concrete was carried out according to Indian Standards [39].

3. EXPERIMENTAL STUDY

Split tensile strength also known as indirect tensile strength has been tested on a concrete cylinder of size 100 mm length and 200 mm diameter. Now and again cylinder of size 150 × 300 mm has additionally been used for testing the split tensile strength of concrete [40]. Likewise, of compressive strength, the load is applied at the cross-sectional area, the failure load of the cylinder is noted, and the tensile strength has been calculated by dividing the tensile load through the lateral area where the load is applied. The components used to calculate the tensile strength is given below. Figure 1 depicts the test setup.

Split Tensile Strength in MPa = $2P / \pi DL$

Where P = load in N

D = Cylinder dia in mm

L = Cylinder length in mm

Figure 1: Split tensile strength.

4. RESULTS AND DISCUSSION

4.1. Split tensile strength

On parallel trials with the compressive strength attained by a concrete mix, its ability to withstand the tensile stresses is also equally important. However, the universal notion is that concrete is weak in tensile strength, but compressive strength alone has been referred to as the strength criterion in practical cases. Once a concrete mix, conventional or modified with material substitution gets curd after the nominal curing spell of 28 days, it is taken granted that nearly 90 to 95% of the mix strength is attainable however due to the standardized practice assessing the mix proportions for the basic ingredients namely cement, fine aggregates, and coarse aggregates. Many times, it has been observed that at the end of 28 days, even the conventional concrete mix can achieve its strength by more than 20 to 30% compared to the mix design strength. Experimentation trials now also established that the improvised concrete mixes always cross the comparable strength of conventional concrete mix if optimal proportional combinations of the substitute materials can be made. By and large, the universal rule is that once compressive strength is attained more than the design mix strength after the practically accepted nominal curing spell of 28 days. The conventional concrete or improvised concrete mix is taken for granted and the split tensile strength, as well as the flexural strength, will also be at satisfactory levels.

The test for the assessment of tensile strength involves the preparation of a cylindrical specimen with prescribed dimension 150 mm × 300 mm. The split tensile strength has been carried out for the experimental treatments towards for the compressive strength with a minimum of three specimens as the treatment replications. Table 2 present the experimentally assessed split tensile strength values for the prenominal curing spell of 7 and 14 days towards by the nominal curing spell of 28 days and extended to 56 days as the post-nominal curing spell. Table 2 furnishes the observed values of the tensile strength after the nominal curing spell of 28 days with respect to the experimental substitution combination of waster tyre crumbs with the percentage of a combination of the steel slag against the cement mantle. The family of curves obtained depicts the variations in split tensile strength for improvised concrete with respect to the different curing spells for given substitution percentage variations of waste rubber crumb at a frozen 9% steel slag the family of curves clearly indicates relatively higher values of split tensile strength can be attained at any instance of curing spell compared to the conventional concrete mix. As regards the compressive strength versus incremental additions of waste tyre rubber crumbs for 9% frozen value of steel slag, the experimentation was supported by a regression analysis depicting the tensile strength values as a parabolic function of the combinational proportions of waste tyre rubber crumbs for

Table 2: Tensile strengths (f_t) of concrete with different mixtures.

SPECIFICATIONS	SPECIMEN ID	7 DAYS N/mm²	14 DAYS N/mm²	28 DAYS N/mm²	56 DAYS N/mm²
CRAC (crumb rubber aggregate concrete)	RFA 0	3.12	3.19	3.23	3.36
	RFA 1	3.35	3.43	3.58	3.85
	RFA 2	3.42	3.51	3.62	3.89
	RFA 3	3.29	3.31	3.40	3.62
	RFA 4	3.12	3.02	3.25	3.31
	RFA 5	2.76	2.87	3.00	3.04
SSIC (steel slag infused concrete)	SS 0	3.12	3.19	3.23	3.36
	SS 3	3.25	3.52	3.65	3.87
	SS 6	3.35	3.65	3.88	3.9
	SS 9	3.43	3.72	3.96	3.98
	SS 12	3.29	3.54	3.80	3.86
	SS 15	3.18	3.36	3.62	3.7
CRACS (crumb rubber aggregate concrete infused with steel slag)	SS 0 + RFA 0	3.12	3.19	3.23	3.36
	SS 9 + RFA 1	3.28	3.46	3.59	3.76
	SS 9 + RFA 2	3.35	3.60	3.76	3.84
	SS 9 + RFA 3	3.46	3.63	3.81	3.92
	SS 9 + RFA 4	3.36	3.49	3.62	3.80
	SS 9 + RFA 5	3.15	3.21	3.51	3.76

a standardized reference value of 9% steel slag. However the trend line of variations was found to be parabolic in line with the compressive strength endorsements, with the identification of a maximum split tensile strength corresponding to an optimal combination of substitution materials as the critical point of choice from the point of technical feasibility, however, the trend line started declining after reaching this point of inflection and it has allowed cutting the mix design tensile strength for the conventional concrete mix, considering this point has the point of tolerance from the economic viability angle.

4.1.1. Split tensile strength vs. the curing spells with incremental addition of waste rubber crumbs alone against fine aggregate

Figure 2 depicts the variations in the split tensile strength attained gradually passing through the successive curing spells of time for the analysis the curing spells were distinguished as pre-nominal (7 & 14 days), nominal (28 days) and post-nominal (56 days). The family of curves indicates the levels of split tensile strength for the proportional combination of waste rubber tyre crumbs alone for the control concrete mix and the material substituted improvised mix.

From the tabular values and the family of curves thus obtained it can be seen that the split tensile strength gradually increases with respect to the curing spells irrespective of the control or treatments at the same time irrespective of the curing spells the treatment combination of T2 / RFA2 with 6% addition of rubber crumb waste have yielded the maximum tensile strength in the range of 3.42MPa to 3.85MPa from 7 days to 56 days curing span. Therefore, the tensile strength values gradually decreased when the percentage addition of rubber crumbs was increased and the optimal proportional combination of waste rubber tire crumbs alone in replacing the cement mantle shall be limited to 9% only. From the standard practice of comparing the attainment of tensile strength after the nominal curing spell of 28 days, this treatment combination of rubber crumbs against cement yielded a maximum tensile strength of 3.62, and afterward, for any addition of rubber crumbs alone, the tensile strength gradually decreased to 2.87MPa when the percentage addition was 15%. The same trend was endorsed during the pre-nominal curing spell of 14 days and a post-nominal curing test period of 56 days. At 28 days spell the split tensile strength attained for 9% addition of rubber crumbs was observed at 3.62MPa against 3.89MPa at the end of 56 days. When compared to the CHOU *et al.* [10] literature the experimental results increased 9%.

4.1.2. Split tensile strength vs. the curing spells with incremental addition of steel slag alone against cement mantle

Even though the tabular values and the corresponding family of curves indicated the same trend of the relationship between tensile strength and percentage addition of steel slag for different curing spells, the treatment T3/SS9 corresponding to 9% addition of steel slag produced the maximum tensile strength values in the range of 3.43MPa to 3.98MPa corresponding to curing spell range of 7 to 56 days. Hence the optimal proportional combination of steel slag addition is frozen at 9% only. Then for this frozen 9% steel slag addition, the treatment

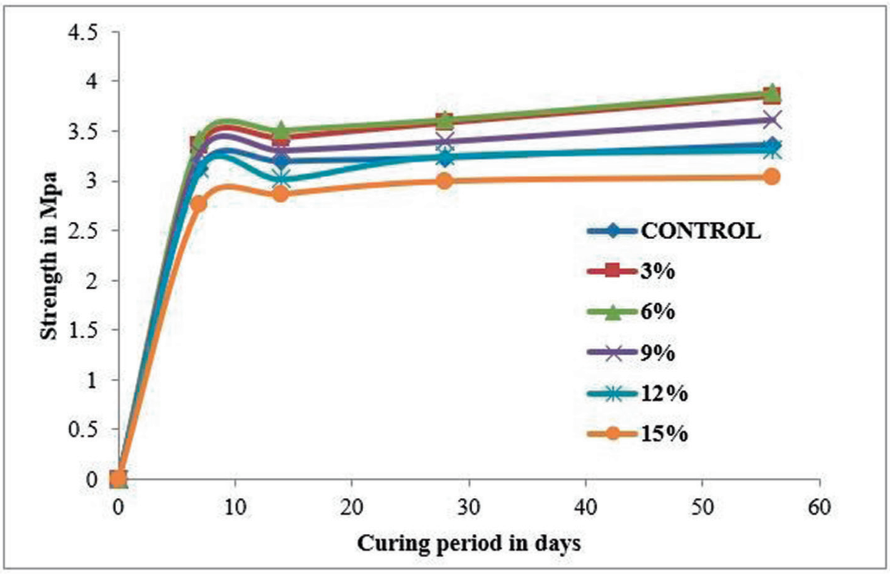

Figure 2: A family of curves (rubber crumbs against fine aggregate) for split tensile strength vs. curing spell in days.

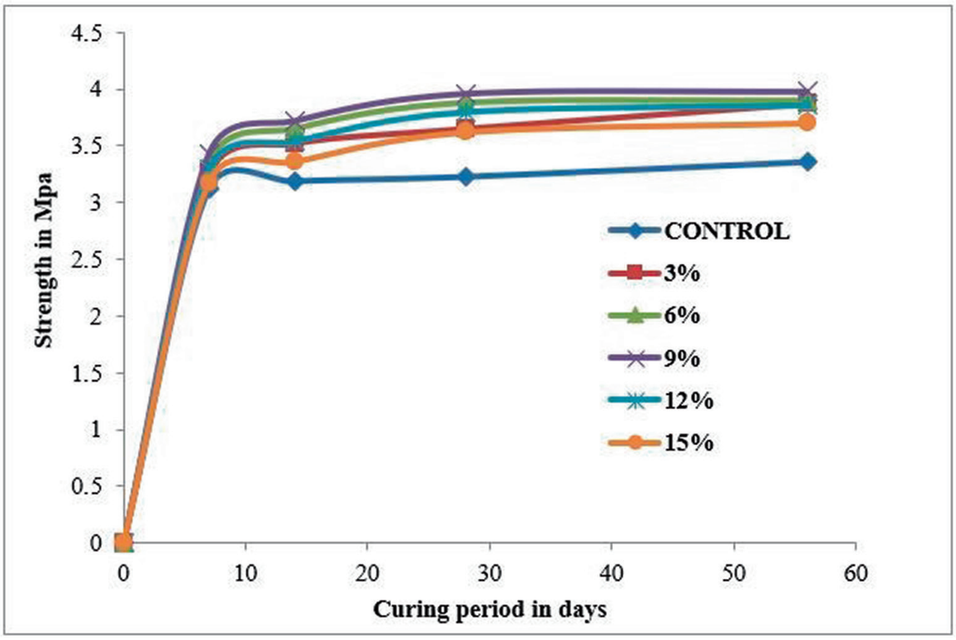

Figure 3: A family of curves (steel slag against cement) for split tensile strength vs. curing spell in days.

variation was made with combinations of rubber crumbs from 3% to 15% in steps of 3% addition. The values depicted in Figure 3.

4.1.3. Split tensile strength vs. the curing spells with the combined addition of waste rubber crumbs with frozen % of steel slag

For the optimal proportional combinations of rubber crumbs from 3 to 15% in steps of 3% alongside the frozen value of 9% steel slag with cement, the tabular data and the family of curves depicted the same trend as above. However, the combined effect of 9% steel slag and 9% waste rubber crumbs produced the maximum tensile strength of 3.81MPa at the end of 28 days curing spell. Hence by this notion the optimal proportional combinations of waste rubber crumb and fine aggregates respectively. This optimal proportional combination is only a first approximation of getting a rough idea of how much the percentage combination of waste rubber crumbs with steel slag in attaining relatively higher split tensile strengths compared to the control concrete mix. However, further endorsement should be done keeping the nominal 28-day curing spell as the reference point at which the optimal proportional combinations of both steel slag and waste rubber crumbs can be finalized based on the points of inflection and tolerance corresponding to split tensile strength Vs. Incremental additions of steel slag and rubber crumbs. The values depicted in Figure 4.

4.2. Regression modeling

4.2.1. Split tensile strength vs. percentage addition of crumb rubber aggregates at the end of 28 days nominal curing spell

Table 2 and Figure 5 depict the tensile stress variations with respect to the stipulated curing test spells with respect to incremental additions of crumb rubber replacing the fine aggregates. However, the discussion is restricted only to the nominal curing spell of 28 days in as much as the strength attainments cross over 90% of the expected strength after this spell, as a universal notion. From Table 2 the experimentally observed values of the split tensile strength with respect to incremental additions of crumb rubber alone in steps of 3% ranging from 3 to 15%, indicating the maximum split tensile strength could be obtained at 6% addition only. Thereafter the strength attained shows a decreasing trend.

This trend of the point of inflection at which the maximum strength was attained was also endorsed by the regression analysis pertaining to 90% data correlation, as given by the model equation. $V = -0.007x^2 + 0.089x + 3.29$, which indicates a parabolic curve fitting for prediction of split tensile strength with varying values of the percentage incremental additions of crumb rubber in partial substitution replacement of the fine aggregates in

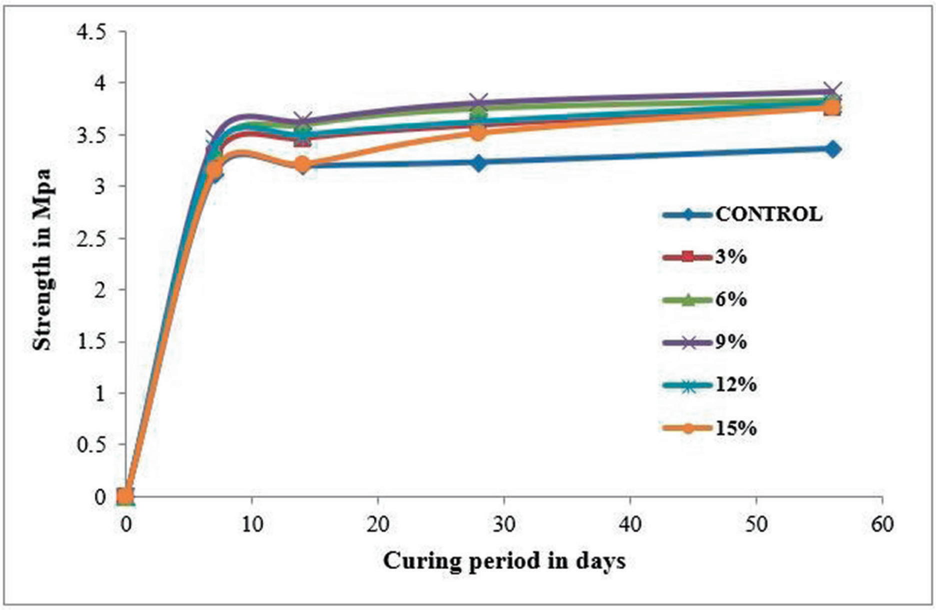

Figure 4: A family of curves (rubber crumbs + steel slag against fine aggregate and cement) for split tensile strength vs. curing spell in days.

concrete. The point of inflection is given by dy/dx = 0. Accordingly, at this change point (point of inflection) the limiting percentage additions of crumb rubber could be predicted as 6.35%, i.e., is closer to the observed value of 6% with a reduction percentage error of 5.8% only. Hence it can be safely endorsed from the technical feasibility point of that we can limit the percentage replacement of fine aggregates with 6% addition of crumb rubber, to yield a maximum split tensile strength of 3.573MPa by prediction against an observed value of 3.62MPa with 6% addition of crumb rubber.

The nature of attainment of maximum split tensile strength with respect to the prenominal curing spells (7 & 14 days) and the post-nominal curing spell (56 days) was also modelled with the regression analysis at correlation levels of data exceeding 90% as the best fit. The trends indicated by curing spells other than nominal 28 days were also found to be in close approximation with the 28 days curing spell, with the percentage errors limited to less than 5% the prediction by interpolation within the range 7 to 56 days curing spells for which the data were observed, were also supported by the regression modelling equations furnished alongside the Figure 5(a–d). However, extrapolation of the split tensile strength attainable beyond the range of observations exceeding 56 days can be done with the regression equation pertaining to the nominal curing spell of 28 days itself without much error (since more than 90% of split tensile strength is expected to be attained at the end of 28 days itself and further strength attainment for any number of extended days of curing will be very gradual and 100% strength may be reached within a year).

4.2.2. Split tensile strength vs. addition of steel slag (against cement) at the end of 28 days nominal curing spells

Since the process of other and equivalent material substitutions replacing partly the basic ingredients of concrete involves complicated interactions, the acceptance of this foreign matter to get incorporated within the conventional concrete matrix shall be experimentally approached on a trial-and-error basis. Since the concept of material substitution has yet to win over the confidence of all levels of civil engineering personnel, in the initial stages of research and development additional supporting materials can also be added for ensuring the bondage between the mantles of the concrete matrix. In the present investigation, the same rule has been applied by considering the addition of a certain percentage of steel slag in partial replacement with the cement mantle tried the reason is that the rubber crumbs are degradable over time and the disintegration of the rubber molecules at later stages may cause destabilization at the whole concrete matrix.

Hence by lateral thinking to compensate for any negative impact by adding rubber crumbs alone within the fine aggregate mantle, a certain percentage of steel slag within the cement mantle is expected to counteract

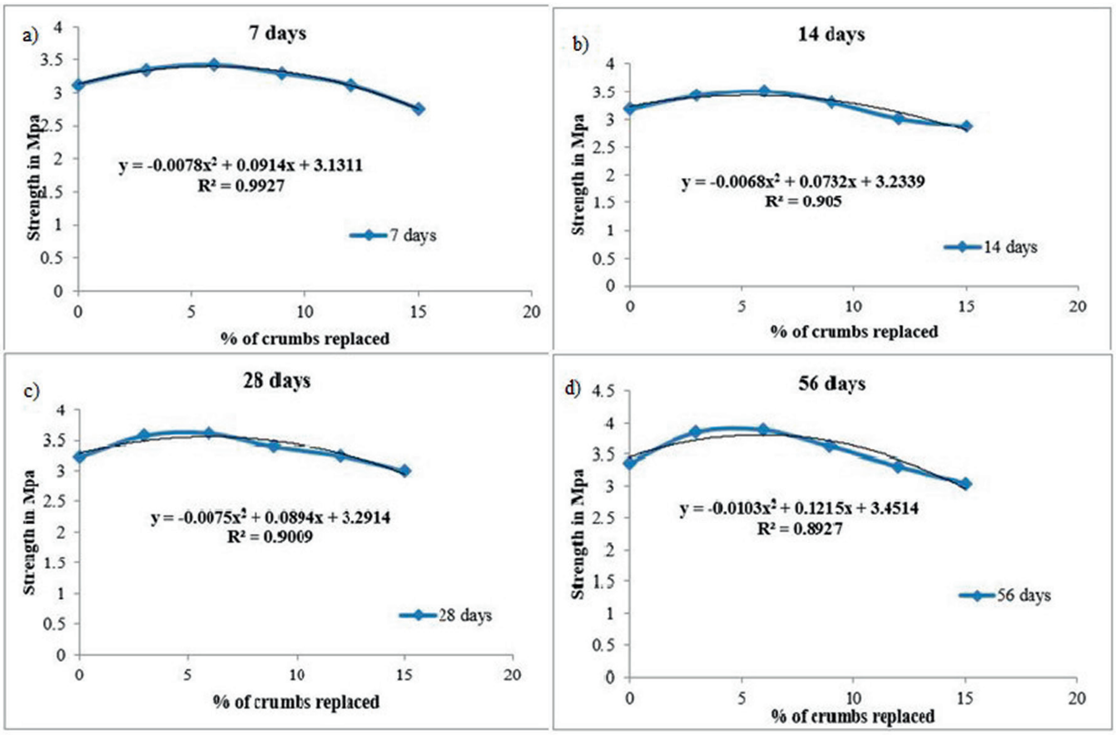

Figure 5: a) A trend of split tensile strength vs. % of rubber crumbs for 7 days curing spell, b) A trend of split tensile strength vs. % of rubber crumbs for 14 days curing spell, c) A trend of split tensile strength vs. % of rubber crumbs for 28 days curing spell, d) A trend of split tensile strength vs. % of rubber crumbs for 56 days curing spell.

and maintain the bond established after the desired curing spell of 28 days or more. Accordingly, the impulse of adding incremental proportions of steel slag with cement was also tried on the response related to the attainment of the desired levels of split tensile strength. To start with the steel slag was added to cement as an optimal percentage of steel slag addition to which only different combinational proportions of rubber crumbs within the fine aggregate mantle can be tried. Tables and Figure 6(a–d) furnish the trend of split tensile strength attainable at different combinational proportions of steel slag replacing cement by weight or volume with respect to different curing spells. For discussion purposes, in line with the addition of rubber crumbs alone in the fine aggregate mantle, the 28-day nominal curing spell was considered.

Steel slag was also added in the incremental addition range of 3 to 15% in steps of 3%. From the tables and the figure the general trend observed was it could be safer to add up to 9% steel slag with the cement mantle to counterbalance the interactive destabilization due to the fine aggregate mantle comprising degradable rubber crumbs. The endorsement of steel slag addition is also limited to the consideration of 28-day nominal curing spells at which more than 90% of tensile strength can be obtained. The regression model as an outcome of the experimental trials with data correlation exceeding 90% is presented as a prediction equation for the split tensile strength attainable (y) against the incremental increases in the proportional additions of steel slag (x). The model equation for both interpolation and extrapolation of split tensile strength by prediction is given by $y = -.009x2 + 0.159x + 3.241$ (for the standard nominal curing spell of 28 days). By and large, the tabular data recorded and the regression trends obtained as shown in the figures, indicated a gradual increase in split tensile strength up to 9% addition of steel slag, thereafter registering a declining trend. The point of inflection can be obtained by using $dy/dx = 0$. Accordingly, the optimal proportional combination of steel slag alone can be frozen at 9% addition corresponding to a maximum split tensile strength of around 4MPa.

From the regression model equation, the point of inflection was obtained as 8.83% of steel slag that can be safely rounded up to 9% due to the flatness of the curve even slightly beyond 9% steel slag. Then the predictable maximum strength was given as 3.94MPa which is closely approaching the rounded value of 4MPa. This regression model prediction equation can be safely used without much error for predicting the values of the split tensile strength in MPa corresponding to any curing spells and any percentage addition of steel slag as interpolation within the data range of 7 to 56 days curing spell or extending beyond 56 days for extrapolation. However, for both cases of predicting the attainable safe value of the split tensile strength, we considered only the point

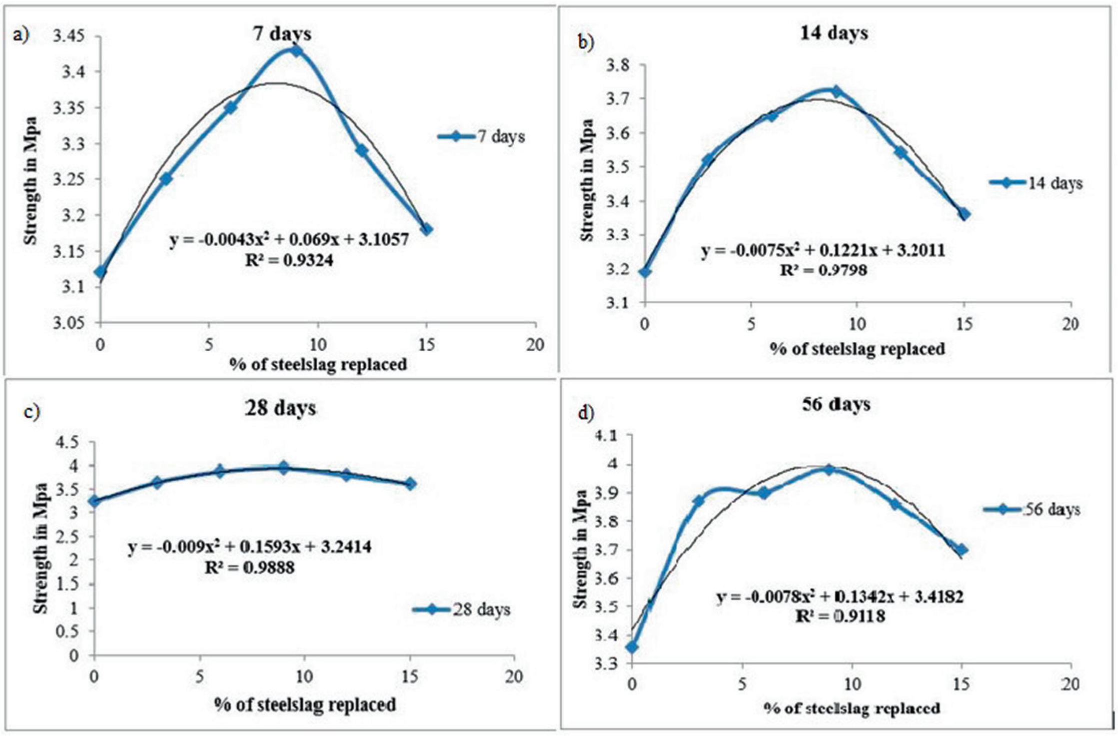

Figure 6: a) A trend of split tensile strength vs. % of steel slag for 7 days curing spell b) A trend of split tensile strength vs. % of steel slag for 14 days curing spell, c) A trend of split tensile strength vs. % of steel slag for 28 days curing spell, d) A trend of split tensile strength vs. % of steel slag for 56 days curing spell.

of inflection and not up to the point of tolerance that may indicate economic viability. Since the combination of different proportions of rubber crumbs with a frozen percentage of steel slag was tried, the point of inflection and the point of tolerance can be considered for techno-economic plausibility.

4.2.3. Impact of optimal proportional combinations of both crumb rubber and steel slag on the split tensile strength response

Figures 7(a–d) furnishes the variations in the split tensile strength of the improvised concrete mix in a combination of both the frozen percentage of steel slag and varying proportions of crumb rubber in the range of 3 to 15% in incremental steps of 3%. In this discussion also we consider the split tensile strengths attainable with respect to the nominal curing spell of 28 days, but in addition to the technical feasibility with the point of inflection, the economic viability indicated by the point of tolerance will also be considered. The data observed indicated relatively higher values of (3.51 to 3.81MPa) split tensile strength at all proportional combinations of rubber crumbs alongside the 9% frozen value of steel slag addition, compared to the conventional concrete mix at 3.23MPa. By and large, irrespective of the curing spells the maximum split tensile strength could be observed from the table values or predicted from the regression curves at an optimal proportional combination of 9% crumb rubber with 9% steel slag the strength values centering around 3.81MPa. The regression analysis at a data correlation level more than the 95% best fitting, indicated a point of inflection of the maximum strength attainable closer to 3.8MPa (against the addition of 9% both steel slag and crumb rubber) and point of tolerance i.e. permissible at 3.5MPa (against 9% addition of steel slag with 15% crumb rubber). Since we consider both the technical feasibility and economic viability for obtaining the split tensile strengths more than attainable by the control concrete mix, both the point of inflection and tolerance are to be considered with an open choice of adding crumb rubber in the range of 9 to 15% for a frozen proportion of 9% steel slag the empirical regression model equations for prediction of attainable split tensile strengths also endorsed this optimal combination of 9%crumb rubber. Alongside 9% steel slag for technical safety and 15% crumb rubber with 9% of steel slag for cost-effectiveness.

Accordingly, we consider the regression model equation for 28days as curing spell obtained as $y = -0.007x2 + 0.127x + 3.251$ where, y is the split tensile strength predicted, as applicable for both interpolations within the observed data range of curing spells 7 to 56 days and for extrapolation of the strength beyond 56 days. The technical point of inflection is given by $dy/dx = 0$. Accordingly, the point of inflection was reckoned as

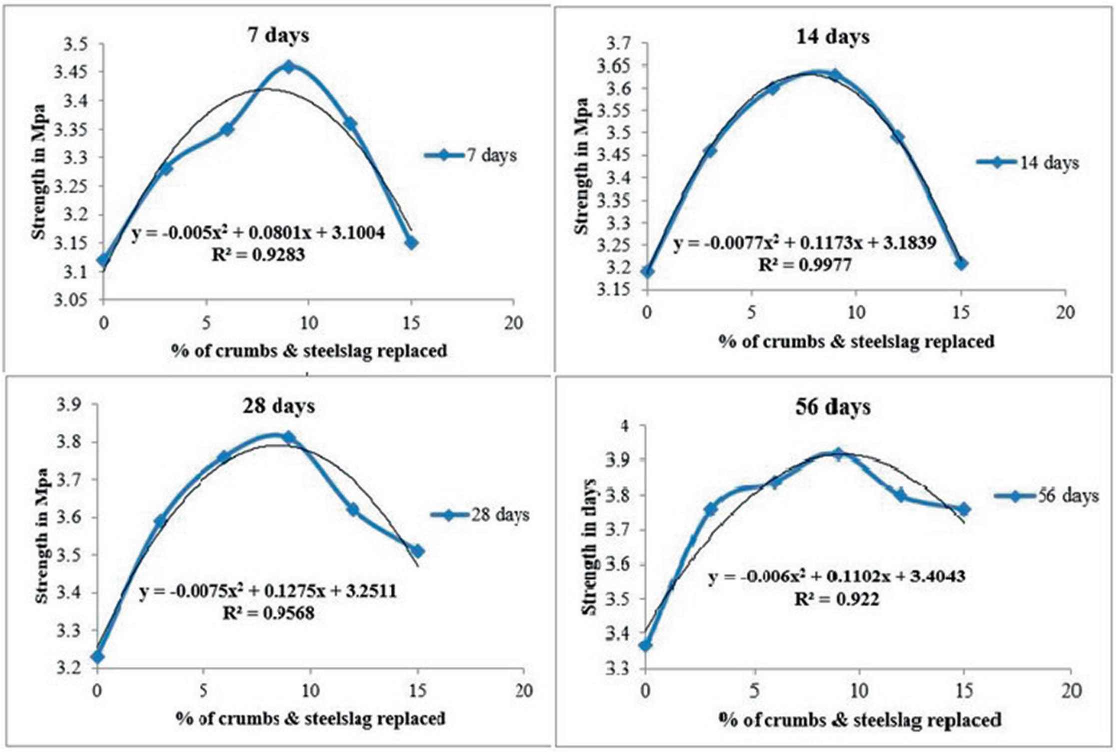

Figure 7: a) A trend of split tensile strength vs. % of rubber crumbs + steel slag for 7 days curing spell, b) A trend of split tensile strength vs. % of rubber crumbs + steel slag for 14 days curing spell, c) A trend of split tensile strength vs. % of rubber crumbs + steel slag for 28 days curing spell, d) A trend of split tensile strength vs. % of rubber crumbs + steel slag for 56 days curing spell.

9.07% crumb rubber in the fine aggregate mantle with the frozen 9% addition of steel slag in the cement mantle. Now corresponding to this combination percentage of crumb rubber the maximum split tensile strength attainable was predicted as 3.82MPa which is higher than 3.2MPa registered for the conventional concrete matrix. However, this technical feasibility shall also be relaxed considering the point of tolerance up to which the additions of steel slag and crumb rubber on economically viable in producing cost-effective concrete mixes. From decreasing trend of the regression curve substituting the base value of 3.23MPa for conventional concrete, the economically extendable proportion of crumb rubber with a frozen 9% of steel slag addition could be predicted as a solution to the parabolic equation ax2 + bx + c = y with its twin routes as

$$X = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

where, b = 0.127, a = –0.007, and c = 3.251. Accordingly, we get the predicted value of the optimal proportional combination of crumb rubber alongside 9% of steel slag as 14.28% then can be rounded off to 15% to coincide with the base control value of 3.23MPa. However, considering a safer value of the strength within the economics region of tolerance we can limit the addition to a maximum of 12% crumb rubber only, maintaining the ultimate tensile strength value as 3.76MPa, i.e., still 16% higher than the base control mix value 3.23MPa. Hence from the combined criteria of technical feasibility and economic viability we can conclude that the percentage addition of crumb rubber can be limited to 9% if we are interested in getting the maximum possible split tensile strength only, and it can be relaxed up to 12% addition if we are interested in getting a cost-effective concrete mix that can maintain the split tensile strength still more than that for the conventional concrete mix (In both cases the frozen value of steel slag is at 9%).

5. CONCLUSIONS

1. It is a universal rule that if the compressive strength of the control or the improvised concrete mix reaches the maximum in the test period of 28 days, the other tests for tensile or flexural strength will also fall in line with the compressive strength as the best indicator. It is understood that the strength criteria by split tensile

strength will closely follow the trend of variations indicated by the compressive strength. However, in this investigation, for additional anchorage of the encouraging results for the improvised concrete mix, further endorsements were tried with split tensile and flexural strength. The investigation focused on the split tensile strength of concrete, comparing an improvised concrete mix with a conventional one. The findings indicated that the improvised concrete mix exhibited significant improvements, particularly when combining steel slag and rubber crumb in specific proportions.

2. At the optimal combination, the improvised mix approached a split tensile strength of 4MPa. This result was notable when compared to the conventional concrete mix, which only achieved a strength of 3.25MPa. Even at the point of tolerance for the conventional mix, where 15% rubber crumb was used in conjunction with frozen 9% steel slag, the strength reached 3.5MPa. It is worth mentioning that this value exceeded what could be achieved within the 28-day universal curing test period. The findings underscore the enhanced performance of the improvised concrete mix. By incorporating 12% rubber crumb with an appropriate proportion of steel slag, a substantial improvement in split tensile strength was observed. These results demonstrate the potential of the improvised mix to outperform the conventional mix in terms of split tensile strength and provide insights for further research and development in the field of concrete technology.

6. ACKNOWLEDGMENTS

The authors would like to express their heartfelt thanks to KSR College of Engineering for providing infrastructural facilities to carry out this research successfully.

7. BIBLIOGRAPHY

[1] LAI, M.H., CHEN, Z.H., WANG, Y.H., *et al.*, "Effect of fillers on the mechanical properties and durability of steel slag concrete", *Construction & Building Materials*, v. 335, n. 127495, pp. 127495, 2022. doi: http://dx.doi.org/10.1016/j.conbuildmat.2022.127495

[2] FAIRBURN, B., LARSON, J. "Experience with asphalt rubber concrete: an overview and future direction", In: *National Seminar on Asphalt Rubber*, pp. 417–431, Cansas City, Missouri, 2001.

[3] PALANISAMY, S.P., MAHESWARAN, G., ANNAAMALAI, M.G.L., "Steel slag to improve the high strength of concrete", *International Journal of Chemtech Research*, v. 7, pp. 2499–2505, 2015.

[4] NORMAN, D.T., *Rubber grade carbon blocks*, Texas, Product Development Witco Corporation, Concarb Division Houston, 1992.

[5] ELDIN, N.N., SENOUCI, A., "Rubber-tyre particles as concrete aggregate", *Journal of Materials in Civil Engineering*, v. 5, n. 2, pp. 478–496, 1993. doi: http://dx.doi.org/10.1061/(ASCE)0899-1561(1993)5:4(478)

[6] TOUTANJI, H.A., "The use of rubber tyre particles in concrete to replace mineral aggregate", *Cement and Concrete Composites*, v. 18, n. 2, pp. 135–139, 1996. doi: http://dx.doi.org/10.1016/0958-9465(95)00010-0

[7] LEE, H.S., LEE, H., MOON, J.S., *et al.*, "Development of tire added latex concrete", *Materials Journal*, v. 95, n. 4, pp. 356–364, 1998.

[8] GOULIAS, D.G., HOOTON, R.D., ALI, A., "Evaluation of rubber filled concrete and correlation between destructive and non-destructive testing results", *Cement, Concrete, and Aggregates*, v. 20, n. 1, pp. 140–144, 1998. doi: http://dx.doi.org/10.1520/CCA10447J

[9] CHUNG, K., HONG, Y., "Introductory behavior of rubber concrete", *Journal of Applied Polymer Science*, v. 72, n. 1, pp. 35–40, 1999. doi: http://dx.doi.org/10.1002/(SICI)1097-4628(19990404)72:1<35::AID-APP3>3.0.CO,2-B

[10] CHOU, L.H., LU, C.K., CHANG, J.R., *et al.*, "Use of waste rubber as concrete additive", *Waste Management & Research*, v. 25, n. 1, pp. 68–76, 2007. doi: http://dx.doi.org/10.1177/0734242X07067448. PubMed PMID: 17346009.

[11] JIE, X.U., YAO, Z., YANG, G., HAN, Q., "Research on crumb rubber concrete: From a multi-scale review", *Construction and Building Materials*, v. 232, pp. 117282, 2020.

[12] PATTUSAMY, L., RAJENDRAN, M., SHANMUGAMOORTHY, S., *et al.*, "Confinement effectiveness of 2900psi concrete using the extract of Euphorbia tortilis cactus as a natural additive", *Matéria (Rio de Janeiro)*, v. 28, n. 1, pp. e20220233, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2022-0233

[13] TOPCU, I.B., "The properties of rubberised concrete", *Cement and Concrete Research*, v. 25, n. 2, pp. 304–310, 1995. doi: http://dx.doi.org/10.1016/0008-8846(95)00014-3

[14] SEGRE, N., JOEKES, I., "Use of tire rubber particles as addition to cement paste", *Cement and Concrete Research*, v. 30, n. 9, pp. 1421–1425, 2000. doi: http://dx.doi.org/10.1016/S0008-8846(00)00373-2

[15] GIRISH, S., RITU, G., “Beneficial effects of steel slag on concrete”, *International Journal of Recent Research Aspects*, v. 2, n. 2, pp. 51–57, 2015.

[16] GRRICK, G. “Analysis of waste tire modified concrete”, In: *2004 ME Graduate Student Conference*, Louisiana State University, 2004.

[17] NOAMAN, A.T., BAKAR, B.A., AKIL, H.M., “The effect of combination between crumb rubber and steel fiber on impact energy of concrete beams”, *Procedia Engineering*, v. 125, pp. 825–831, 2015.

[18] LI, G., STUBBLEFIELD, M.A., GARRICK, G., *et al*., “Development of waste tire modified concrete”, *Cement and Concrete Research*, v. 34, n. 12, pp. 2283–2289, 2004. doi: http://dx.doi.org/10.1016/j.cemconres.2004.04.013

[19] LI, Z., LI, F., LI, J.S.L., “Properties of concrete incorporating rubber tyre particles”, *Magazine of Concrete Research*, v. 50, n. 4, pp. 297–304, 1998. doi: http://dx.doi.org/10.1680/macr.1998.50.4.297

[20] BIGNOZZI, M.C., SANDROLINI, F., “Tyre rubber waste recycling in self-compacting concrete”, *Cement and Concrete Research*, v. 36, n. 4, pp. 735–739, 2006. doi: http://dx.doi.org/10.1016/j.cemconres.2005.12.011

[21] BIEL, T.D., LEE, H., “Magnesium oxychloride cement concrete with recycled tire rubber”, *Transportation Research Record: Journal of the Transportation Research Board*, v. 1561, n. 1, pp. 6–12, 1996. doi: http://dx.doi.org/10.1177/0361198196156100102

[22] MOHANRAJ, R., SENTHILKUMAR, S., GOEL, P., *et al.*, “A state-of-the-art review of Euphorbia Tortilis cactus as a bio-additive for sustainable construction materials”, *Materials Today: Proceedings*, doi: https://doi.org/10.1016/j.matpr.2023.03.762. [in press].

[23] TOPÇU, I.B., AVCULAR, N., “Collision behaviours of rubberized concrete”, *Cement and Concrete Research*, v. 27, n. 12, pp. 1893–1898, 1997. doi: http://dx.doi.org/10.1016/S0008-8846(97)00204-4

[24] FATTUHI, N.I., CLARK, L.A., “Cement-based materials containing shredded scrap truck tyre rubber”, *Construction & Building Materials*, v. 10, n. 4, pp. 229–236, 1996. doi: http://dx.doi.org/10.1016/0950-0618(96)00004-9

[25] ZHU, A.H., “Florida’s experience utilizing crumb tyre rubber in road pavements”, In: *National Seminar on Asphalt Rubber*, pp. 499–535, Cansas City, Missouri, 1999.

[26] HERRERA-SOSA, E.S., MARTÍNEZ-BARRERA, G., BARRERA-DÍAZ, C., *et al*., “Waste tire particles and gamma radiation as modifiers of the mechanical properties of concrete”, *Advances in Materials Science and Engineering*, v. 2014, pp. 1–7, 2014. doi: http://dx.doi.org/10.1155/2014/327856

[27] RIVAS-VÁZQUEZ, L., SUÁREZ-ORDUÑA, R., HERNÁNDEZ-TORRES, J., *et al*., “Effect of the surface treatment of recycled rubber on the mechanical strength of composite concrete/rubber”, *Materials and Structures*, v. 48, n. 9, pp. 2809–2814, 2015. doi: http://dx.doi.org/10.1617/s11527-014-0355-y

[28] LI, G., WANG, Z., LEUNG, C.K., *et al*., “Properties of rubberized concrete modified by using silane coupling agent and carboxylated SBR”, *Journal of Cleaner Production*, v. 112, pp. 797–807, 2015. doi: http://dx.doi.org/10.1016/j.jclepro.2015.06.099

[29] HE, L., MA, Y., LIU, Q., *et al*., “Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete”, *Construction & Building Materials*, v. 120, pp. 403–407, 2016. doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.05.025

[30] ABD-ELAAL, E.-S., ARABY, S., MILLS, J.E., *et al*., “Novel approach to improve crumb rubber concrete strength using thermal treatment”, *Construction & Building Materials*, v. 229, pp. 116901, 2019. doi: http://dx.doi.org/10.1016/j.conbuildmat.2019.116901

[31] MUÑOZ-SÁNCHEZ, B., ARÉVALO-CABALLERO, M.J., PACHECO-MENOR, M.C., “Influence of acetic acid and calcium hydroxide treatments of rubber waste on the properties of rubberized mortars”, *Materials and Structures*, v. 50, n. 1, pp. 75, 2017. doi: http://dx.doi.org/10.1617/s11527-016-0912-7

[32] LOGANATHAN, P., MOHANRAJ, R., SENTHILKUMAR, S., *et al*., “Mechanical performance of ETC RC beam with U-framed AFRP laminates under a static load condition”, *Revista de la Construcción*, v. 21, n. 3, pp. 679–691, 2022. doi: http://dx.doi.org/10.7764/RDLC.21.3.678

[33] ABDULLA, A.I., AHMED, S.H.J.E., “Effect of rubber treated by acidic solution on some mechanical properties of rubberize cement mortar”, *Eng. Technol. J.*, v. 29, n. 13, pp. 2793–2806, 2011.

[34] LEUNG, C.K., GRASLEY, Z.C., “Effect of micrometric and nanometric viscoelastic inclusions on mechanical damping behavior of cementitious composites”, *Construction & Building Materials*, v. 35, pp. 444–451, 2012. doi: http://dx.doi.org/10.1016/j.conbuildmat.2012.04.021

[35] EMAM, E., YEHIA, S., "Experimental study on enhanced crumb rubber concrete", *International Journal of Scientific and Engineering Research*, v. 9, pp. 1240–1247, 2018.

[36] MOHAMMADI, H., KHABBAZ, H., VESSALAS, K., "In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements", *Construction & Building Materials*, v. 71, pp. 456–471, 2014. doi: http://dx.doi.org/10.1016/j.conbuildmat.2014.08.085.

[37] VELUMANI, M., MOHANRAJ, R., KRISHNASAMY, R., *et al*., "Durability evaluation of cactus-infused M25 grade concrete as a bio-admixture", *Periodica Polytechnica. Civil Engineering*, v. 67, n. 4, pp. 1066–1079, 2023.

[38] SHANMUGASUNDARAM, S., MOHANRAJ, R., SENTHILKUMAR, S., *et al*., "Torsional performance of reinforced concrete beam with carbon fiber and aramid fiber laminates", *Revista de la Construcción*, v. 21, n. 2, pp. 329–337, 2022. doi: http://dx.doi.org/10.7764/RDLC.21.2.329

[39] HADZIMA-NYARKO, M., NYARKO, E.K., ADEMOVIC´, N., *et al*., "Modelling the influence of waste rubber on compressive strength of concrete by artificial neural networks", *Materials (Basel)*, v. 12, n. 4, pp. 561, 2019. doi: http://dx.doi.org/10.3390/ma12040561. PubMed PMID: 30781883.

[40] MOHANRAJ, E.K., MALATHY, R., RAVISANKAR, K.L., "Utilization of industrial waste materials in concrete-filled steel tubular columns", *Matéria (Rio de Janeiro)*, v. 27, n. 2, pp. e13188, 2022. doi: http://dx.doi.org/10.1590/s1517-707620220002.1388