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AN EXPERIMENTAL INVESTIGATION ON SELF COMPACTING CONCRETE (SCC) BY RUBBER CREATE AND FLY ASH

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ABSTRACT
This study explores the use of rubber chips (RC) derived from Waste tires can be used in self-compacting concrete (SCC) to partially replace coarse particles, aiming to address environmental concerns related to rubber waste and reduce reliance on natural aggregates. Following IS 10262:2019 and EFNARC requirements, a total of 25 SCC mixes of M30 grade were prepared, containing fly ash (FA) at 0–20% as a partial cement replacement and RC at 0–20%. The experimental program assessed durability features (water absorption, porosity, and chloride ion penetration), mechanical qualities (compressive, flexural, and splitting tensile strength), and new attributes (flowability and passage ability). The results showed that combinations like M30-FA10-RC10 performed best, maintaining adequate strength and workability up to 10% RC paired with 10–15% FA. FA contributed positively to matrix densification and durability, mitigating the adverse effects of rubber on porosity and permeability. However, higher RC levels led to a decline in mechanical performance and increased porosity due to the weak rubber–cement interface and hydrophobic nature of rubber particles. The findings confirm that the combined use of FA and limited RC content can produce sustainable SCC with satisfactory performance, promoting both material efficiency and waste valorization in construction application.
KEYWORDS: Rubber chips, fly ash, flowability, compressive strength, flexural strength, water absorption, durability, porosity.

1. INTRODUCTION

A high-tech, high-performance concrete known as SCC has been dubbed over the last 20 years, the concrete technology's "most revolutionary step" due to its impact on the economic and environmental sustainability of the construction sector [1]. It has gained popularity in the concrete industry recently because of its many technical and financial benefits. One of the biggest benefits is that the formwork's exceptional filling ability allows it to hold large reinforcement without vibrating [2]. In the 1980s, it was founded in Japan. It has a greater deformation capacity, filling rate, resistance to high segregation, and self-strengthening without vibration or segregation under its own weight than conventional concrete. It may also lower the block of steel reinforcing area [3]. Furthermore, the SCC displays superior flexural and tensile strength than traditional concrete because to its dense microstructure and increased region where individual particles transition in the interfacial space [4]. The fine or coarse aggregates can be partially replaced with rubber particles, depending on their size. The addition of rubber to concrete has both positive and negative effects on its properties. For example, it loses strength and stiffness [5]. Because of its ductility and light weight, self-compacting rubberized concrete (SCRC) offers the construction industry a number of potential advantages. According to previous studies, chemical admixtures can be used to create viable RC without adding more water [6]. Concrete that contains rubber is known as crumb RC (CRC). Natural sand can be preserved and other environmental advantages can result from using recycled tire rubber waste in concrete [7]. Rubber waste can be utilized in place of some or all of the coarse or fine aggregate. It can also be added to Portland cement as an additive. According to a recent study, the mechanical properties of crumb rubber as fine aggregates are superior to those of chipped rubber as coarse aggregate [8]. According to reports, using FA or CR in SCC has several benefits, such as lower concrete costs, increased material and environmental sustainability, and better waste management. However, because of their detrimental impacts, their primary drawbacks

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include a decrease in SCC's mechanical qualities and durability [9].

Materials such as steel fibers, polypropylene fibers, FA, BA, and MK have all been used in a number of SCC tests. However, the use of BA in combination with MK and GF in SCC was limited to a few trials. Few studies focus on acidic effects on SCC and microstructural analysis [10]. Furthermore, because SCC provides a uniform distribution in both fibers and non-fiber shaped rubber particles, prior research indicates that it might provide higher rubber fiber dispersion [11]. However, most tests have used SCC reinforced with steel fibers and/or polypropylene, despite their high cost and substantial CO2 emissions during manufacturing from non-renewable resources [12]. The flowability of SCC was separated into three flowable classes: overall zones, balancing zones, and predominance zones. These three flowable classes indicated three features: the velocity and regularity of flow, the condition of new features, and the balance between free and around-impediments flows [13]. The amount of waste tires that are disposed of would be reduced and a supply of ecologically friendly concrete would be produced if used tire rubber was used to construct concrete. From an engineering perspective, adding used tires to concrete could result in a material with improved dynamic qualities, including ductility and carbonation resistance, as well as durability [14]. In addition to increasing concrete's durability, recycling tires into particles and incorporating them into concrete can also substitute fine aggregate, lessening the environmental harm caused by sand mining operations [15].

However, the main problem limiting the assessment of concrete's fatigue performance is the dispersion of fatigue life. This issue also affects the SCRC. The fatigue life is analyzed using the probability statistics method in order to resolve this issue [16]. Response surface methodology (RSM) was used in a prior study to create a mixed design model for self-compressing engineering cement composite (SC-ECC). Additionally, they maximize elasticity and energy absorption to enhance the ECC blend [17]. In its fresh form, ECC is typically made to have SC qualities. In its fresh state, ECC that is SC-ECC exhibits adequate segregation resistance, filling capacity, passing capacity, and flowability [18]. According to reports, adding more superplasticizer to the SCC reduces surface voids, which restricts impregnant penetration and causes a somewhat higher chloride penetration [19]. Numerous studies concur that adding rubber to concrete has several benefits, including improved abrasion resistance, decreased water absorption, decreased spalling danger, and, most importantly, increased ductility and damping behavior. Additionally, all published studies agree that tires' mechanical qualities deteriorate as the percentage of waste tire rubber increases [20].

This study's main objective is to experimentally assess the fresh, mechanical, and durability properties of SCC by adding different proportions of waste RC (0%, 5%, 10%, 15%, and 20%) as partial substitutes for natural coarse aggregates. FA is also used as an additional cementitious material at replacement levels of 0%, 5%, 10%, 15%, and 20% by weight of cement. This dual replacement strategy aims to enhance the sustainability of SCC by reducing dependency on virgin materials while promoting the reuse of industrial and solid wastes. Additionally, the role of chemical admixtures, particularly polycarboxylate-based superplasticizers, will be examined to ensure the modified mixes retain their required self-compacting properties. The findings of this study should provide important information for creating environmentally friendly SCC mixtures that satisfy durability and structural standards, promoting more sustainable and green building methods.

2. MOTIVATION

The growing need for sustainable construction practices and effective waste management has encouraged the development of environmentally friendly alternatives in concrete technology. SCC, widely valued for its superior workability, reduced labor demands, and excellent surface finish, still poses challenges due to its high cement content and material costs. At the same time, non-biodegradable waste rubber tire disposal has grown to be a serious environmental issue. In addition to aiding in trash recycling, adding RC to concrete as a partial substitute for natural coarse aggregates improves the material's ductility and energy-absorbing qualities. However, the inclusion of rubber can adversely affect strength and rheology, requiring careful mix proportioning. In parallel, using industrial by-products to replace some of the cement like FA offers a viable strategy to reduce cement usage, lower carbon emissions, and enhance long-term durability. Nevertheless, FA can also influence setting time and early strength development. Thus, the requirement to thoroughly assess the combined effects of RC and FA inclusion on the mechanical, fresh, and durability properties of SCC is what drives this investigation. The goal is to develop optimized, eco-efficient SCC mixtures that meet performance standards while contributing to sustainable and circular construction practices.

3. Methodology

This experimental study examines the effects of FA and RC on the fresh, hardened, and durability properties of SCC when used as partial substitutes for cement and coarse aggregate, respectively. The primary objective is to optimize the mix design parameters and determine the performance impact of varying FA (0%, 5%, 10%, 15%, and 20%) and RC (0%, 5%, 10%, 15%, and 20%) content. A total of

25 SCC mix variations are prepared based on a factorial approach involving combinations of FA and RC replacements. The mixes are categorized into three groups,

- Control Mix: Conventional SCC mix without any replacements (FA = 0%, RC = 0%)
- FA–Rubber Modified Mixes: SCC mixes incorporating varying FA and RC proportions
- Admixture-Adjusted Mixes: Selected trial mixes tested with adjusted superplasticizer dosage and optional viscosity-modifying agents to enhance rheology and stability

The mix designs follow guidelines from EFNARC and IS: 10262–2019 [21-22], ensuring compliance with SCC requirements for workability, stability, and mechanical performance. All constituent materials are carefully selected and batched by weight to maintain uniformity across mixes. Fresh property tests include V-Funnel and L-Box tests to evaluate flowability and passing ability. Hardened properties are assessed through, Compressive Strength, Split Tensile Strength, and Flexural Strength at standard curing ages (e.g., 7, 28 days). Durability performance is evaluated by conducting, Water Absorption, porosity and Chloride Ion Penetration tests. The purpose of the testing protocol is to document the combined impacts of FA and RC replacements on the long-term durability, strength development, and structural integrity of SCC.

Figure 1 illustrates the full experimental workflow — from material selection and mix design to fresh property testing, mechanical evaluation, and durability assessment. The results are analyzed to identify optimal replacement levels and admixture strategies for achieving balanced performance in sustainable SCC formulations.

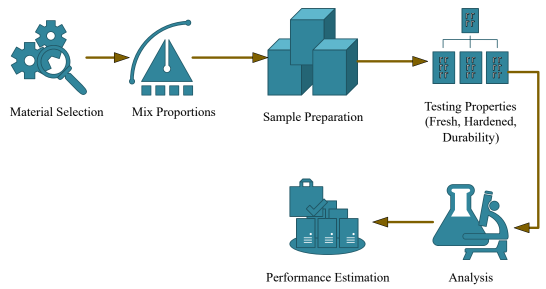

Fig 1. Proposed Flow for the Investigation of SCC

3.1 MATERIALS SELECTION

The materials used in this study were carefully chosen to meet SCC's fresh and hardened property standards while also promoting sustainability goals by utilizing waste and additional cementitious resources. The materials listed below were utilized,

3.1.1 Cement

OPC of Grade 43, conforming to the specifications of IS 8112:1989, was used as the primary binder. It was uniform in color, free from lumps, and stored in dry conditions to prevent moisture absorption.

3.1.2 FA

As a by-product of a thermal power plant, low-calcium (Class F) FA was utilized in different weight percentages (0%, 5%, 10%, 15%, and 20%) to partially substitute cement in the cementitious content. It enhances the long-term strength and durability of SCC and conforms with IS 3812 (Part 1):2003.

3.1.3 Fine Aggregate

The fine aggregate was clean, well-graded natural river sand from Zone I, in accordance with IS 383:1970. To get rid of silt, clay, and organic contaminants, the sand was cleaned and sieved. Using standard testing, its fineness modulus and specific gravity were ascertained.

3.1.4 Coarse Aggregate

In accordance with IS 383:1970, crushed natural stone coarse aggregates with a nominal maximum size of 20 mm were utilized. These aggregates were angular in shape and clean, providing mechanical interlock and structural strength to the SCC mix.

3.1.5 RC

Coarse aggregate was partially substituted with recycled waste tire RC at different weight percentages (0%, 5%, 10%, 15%, and 20%). The RC were irregular in shape and had particle sizes similar to the natural coarse aggregate. Their incorporation aimed to enhance the impact resistance, flexibility, and sustainability of the concrete, while simultaneously resolving environmental issues surrounding the disposal of tire waste. Visual representation of rubber chips is provided in Figure 2.

Fig 2. Rubber chip Samples

3.1.6 Chemical Admixture

To obtain the necessary flow properties of SCC at a low water–cementitious ratio, Cera Hyperplast XR-W40, a high-range water-reducing admixture based on polycarboxylate ether (PCE) and supplied by Cera-Chem Pvt. Ltd., Chennai, was utilized. It improves the mix's stability, workability, and dispersion—all of which are essential for self-compaction.

3.1.7 Water

According to IS 456:2000 guidelines, concrete samples were mixed and cured using potable tap water that was free of organic materials, oils, and other contaminants.

3.2 MIX PROPORTIONS

In this work, the mix design for SCC was developed to reach M30 grade strength by partially substituting recycled RC and FA for cement and coarse aggregate, respectively, with sustainable materials. To guarantee sufficient flowability and resistance to segregation, SCC needs a larger volume of fine particles and a smaller volume of coarse aggregates than conventional concrete. The mix design was developed using a trial-and-error approach, following the guidelines provided in EFNARC, IS 10262:2019, and IS 456:2000.

For all combinations, a fixed water-to-cementitious material ratio (w/cm) of 0.375 was used. The concrete was able to fill formwork and pass through crowded reinforcement under its own weight thanks to the addition of a polycarboxylate ether-based superplasticizer, which was dosed at 0.4% by weight of the total cementitious material. OPC and FA are both included in the mix, with FA substituting OPC at mass percentages of 0%, 5%, 10%, 15%, and 20% of the total binder content. Fine aggregates comprised approximately 38–40% of the total mix volume, ensuring adequate paste volume for flow. Waste tire RC was used to partially replace coarse aggregates at weight percentages of 0%, 5%, 10%, 15%, and 20% of the total coarse aggregate content. The mix was designed for moderate exposure conditions and was intended to be placed using pumping methods. A total of 25 mix combinations were developed to account for the dual variations in FA and RC contents. The behavior of the fresh concrete was evaluated for each mix, and then the hardened qualities including flexural, split tensile, and compressive strength were evaluated. Durability performance was also investigated using tests for water absorption, porosity, and chloride ion penetration.

3.2.1 Initial Mix Design Inputs and Volume Calculations

The main input parameters utilized to create the mix design of M30-grade SCC are listed in Table 1. A volume-based strategy was used, using RC as a partial coarse aggregate replacement and FA as a partial cementitious replacement.

Table 1. Mix Design Specifications for M30 Grade SCC

Parameter	Value
Grade of Concrete	M30
Cementitious Binder	OPC + FA
Nominal Maximum Aggregate Size	20 mm
Workability	Self-Compacting
Exposure Condition	Moderate
Placement Method	Pumping
Chemical Admixture	Superplasticizer (Polycarboxylate)
Water-to-Binder Ratio (w/cm)	0.375 (constant)
Specific Gravity of Cement	3.15
Specific Gravity of FA	2.2 (typical)
Specific Gravity of Water	1
Specific Gravity of Fine Aggregate	2.65
Specific Gravity of Coarse Agg.	2.7
Air Content (assumed)	2%
Superplasticizer Dosage	0.4% by weight of cementitious binder

3.2.2 Fine and Coarse Aggregate Proportions and Rubber Replacement

This section includes determination of fine and coarse aggregate proportions as per EFNARC guidelines and introduces rubber chip replacement in varying percentages by weight of coarse aggregate.

Step 5: Fine and Coarse Aggregate Proportions

As per EFNARC, for SCC mixes, the fine aggregate proportion is typically 60%of the total aggregate volume. In this design, a 60% fine aggregate ratio is adopted:

- Volume of fine aggregate:

$$V_{FA} = 0.60 \times 0.6141 = 0.36846\, m^3$$

- Volume of coarse aggregate:

$$V_{CA} = 0.40 \times 0.6141 = 0.24564 m^3$$

Step 6: Mass of Aggregates

- **Fine aggregate mass :**

$$M_{FA} = V_{FA} \times SG_{FA} \times 1000$$
$$= 0.36846 \times 2.65 \times 1000 = 976.419\, kg/m^3 \quad (5)$$

- **Coarse aggregate mass:**

$$M_{CA} = V_{CA} \times SG_{CA} \times 1000$$
$$= 0.24564 \times 2.70 \times 1000 = 663.228\, kg/m^3 \quad (6)$$

Step 7: Rubber Replacement Method

Coarse aggregate is partially replaced by rubber chips by weight, keeping the total aggregate weight constant. Replacement is done by weight of coarse aggregate, keeping the total,

$$(CA + rubber) = 663.228\, kg/m^3$$

Calculate the replacement amounts for:

$$RC5 \rightarrow 5\%\ rubber\ replacement$$
$$RC10 \rightarrow 10\%\ rubber\ replacement$$
$$RC15 \rightarrow 15\%\ rubber\ replacement$$
$$RC20 \rightarrow 20\%\ rubber\ replacement$$

$$M_{CA(base)} = 663.228 kg / m^3$$
$$M_{rubber} = R\% \times M_{/ CA(base)} \quad (7)$$

Where, R% indicates the rubber replacement percentage.

$$M_{CA(final)} = M_{CA(base)} - M_{rubber} \quad (8)$$

- *M30-RC0 (0% rubber)*
  Coarse aggregate = 663.228 kg
  Rubber chips = 0 kg
- *M30-RC5 (5% rubber)*
  $$M_{rubber} = 0.05 \times 663.228 = 33.1614$$
  $$M_{CA(final)} = 663.228 - 33.1614 = 6$$
  Coarse aggregate = 630.06 kg
  Rubber chips = 33.1614 kg
- *M30-RC10 (10% rubber)*
  $$M_{rubber} = 0.10 \times 663.228 = 66.32 kg$$
  $$M_{CA(final)} = 663.228 - 66.32 = 59$$
  Coarse aggregate = 596.908 kg
  Rubber chips = 66.32 kg
- *M30-RC15 (15% rubber)*
  $$M_{rubber} = 0.15 \times 663.228 = 99.48 k$$
  $$M_{CA(final)} = 663.228 - 99.48 = 56$$
  Coarse aggregate = 563.75 kg
  Rubber chips = 99.48 kg
- *M30-RC20 (20% rubber)*
  $$M_{rubber} = 0.2 \times 663.228 = 132.65 kg$$
  $$M_{CA(final)} = 663.228 - 132.65 = 53$$
  Coarse aggregate = 530.58 kg
  Rubber chips = 132.65 kg

3.2.3 Final Mix Proportions for M30 SCC with Varying Rubber Replacement

The table 2 summarizes the final mix proportions including all materials (cement, FA, aggregates, water, admixture, and RC) for each mix variation.

Table 2. Final Mix Proportions for M30 SCC (kg/m³)

Mix ID	OPC (kg)	Fly Ash (kg)	Fine Agg (kg)	Coarse Agg (kg)	Rubber Chips (kg)	Water (kg)	SP (kg)	w/cm
M30-FA0-RC0	493	0	976.419	663.23	0	185	1.97	0.375
M30-FA0-RC5	493	0	976.419	630.06	33.16	185	1.97	0.375
M30-FA0-RC10	493	0	976.419	596.91	66.32	185	1.97	0.375
M30-FA0-RC15	493	0	976.419	563.75	99.48	185	1.97	0.375
M30-FA0-RC20	493	0	976.419	530.58	132.65	185	1.97	0.375
M30-FA5-RC0	468.35	24.65	976.419	663.23	0	185	1.97	0.375
M30-FA5-RC5	468.35	24.65	976.419	630.06	33.16	185	1.97	0.375
M30-FA5-RC10	468.35	24.65	976.419	596.91	66.32	185	1.97	0.375
M30-FA5-	468.	24.65	976.419	563.75	99.48	185	1.97	0.3

RC15	35							75
M30-FA5-RC20	468.35	24.65	976.419	530.58	132.65	185	1.97	0.375
M30-FA10-RC0	443.7	49.3	976.419	663.23	0	185	1.97	0.375
M30-FA10-RC5	443.7	49.3	976.419	630.06	33.16	185	1.97	0.375
M30-FA10-RC10	443.7	49.3	976.419	596.91	66.32	185	1.97	0.375
M30-FA10-RC15	443.7	49.3	976.419	563.75	99.48	185	1.97	0.375
M30-FA10-RC20	443.7	49.3	976.419	530.58	132.65	185	1.97	0.375
M30-FA15-RC0	419.05	73.95	976.419	663.23	0	185	1.97	0.375
M30-FA15-RC5	419.05	73.95	976.419	630.06	33.16	185	1.97	0.375
M30-FA15-RC10	419.05	73.95	976.419	596.91	66.32	185	1.97	0.375
M30-FA15-RC15	419.05	73.95	976.419	563.75	99.48	185	1.97	0.375
M30-FA15-RC20	419.05	73.95	976.419	530.58	132.65	185	1.97	0.375
M30-FA20-RC0	394.4	98.6	976.419	663.23	0	185	1.97	0.375
M30-FA20-RC5	394.4	98.6	976.419	630.06	33.16	185	1.97	0.375
M30-FA20-RC10	394.4	98.6	976.419	596.91	66.32	185	1.97	0.375
M30-FA20-RC15	394.4	98.6	976.419	563.75	99.48	185	1.97	0.375
M30-FA20-RC20	394.4	98.6	976.419	530.58	132.65	185	1.97	0.375

3.3 SAMPLE PREPARATION

3.3.1 Moulding and Casting Procedure

In this experimental study, SCC specimens were prepared by incorporating two key variables: partial replacement of OPC with FA at levels of 0%, 5%, 10%, 15%, and 20%, and substitution of natural coarse aggregate (NCA) with waste RC at corresponding percentages of 0%, 5%, 10%, 15%, and 20%. A total of 25 mix combinations were developed and tested.

Concrete mixing was carried out in a tilting drum mixer to ensure uniform distribution of all constituents. The SCC mixes were designed for self-consolidation, eliminating the need for external vibration. Fresh concrete was neither compacted or tamped before being put straight into molds that had already been cleaned, ensuring that the rheological properties of SCC could be properly evaluated. Compressive strength and split tensile strength tests were conducted using cube molds of 150 mm by 150 mm by 150 mm. For the assessment of flexural strength, beam molds with dimensions of 1200 mm by 230 mm by 230 mm were utilized. To make demoulding easier, the inside surfaces of the cast iron molds were machine-finished and lightly oiled. After casting, the specimens were allowed to rest undisturbed for 24 hours at room temperature. Subsequently, they were demoulded and transferred to clean water tanks for curing. Curing was performed for 7 and 28 days, in accordance with IS: 10262–2019 recommendations. Before testing, all specimens were surface-dried and conditioned at ambient room temperature for 24 hours.

3.4 TESTING PROPERTIES

To evaluate the fresh and hardened qualities of SCC with different amounts of FA and waste RC replacements, the cast and cured specimens were put through a battery of standardized tests. To guarantee consistency and dependability, the testing methods were carried out in compliance with the applicable IS and EFNARC criteria.

3.4.1 Fresh Properties

The flowability, filling ability, and passing ability of SCC were the main criteria used to assess its performance in its fresh state. These characteristics are crucial for mixes that comprise unusual ingredients like FA and RC. In this research, fresh concrete properties were examined using the following two EFNARC-recommended tests:

3.4.1.1 V-Funnel Test (Flow Time)

Following EFNARC recommendations, the V-Funnel test was performed to assess the flowability and segregation resistance of the SCC mixtures. The experiment was conducted on a number of mixes with different proportions of RC (0%, 5%, 10%, 15%, and 20%) as a partial substitute for natural coarse aggregate and FA (0%, 5%, 10%, 15%, and 20%) as a partial substitute for OPC [24]. Prior to each trial, the V-Funnel apparatus was carefully positioned on a stable and perfectly level surface to avoid any tilt that could affect the flow results. The internal surfaces of the funnel were moistened using a damp sponge or cloth to prevent fresh concrete from sticking to the sides and to ensure a smooth flow. Freshly mixed SCC, prepared using a tilting drum mixer, and was immediately poured into the funnel in a continuous motion, ensuring the funnel was completely filled without introducing any voids or entrapped air. No compaction or vibration was applied during the filling process, in order to simulate true self-compacting behavior. The bottom trap door was immediately opened after the funnel was filled, and the amount of time needed for the concrete to completely drain through the funnel was timed using a stopwatch. The beginning flow time was noted at this moment, denoted as T_0. Following this, a second reading was taken by refilling the funnel with the same SCC mix and allowing it to stand undisturbed for a period of five minutes. Following the rest period, the trap door was opened once more, and the amount of time it took for the concrete to completely discharge was measured and noted as the delayed flow time, or T_5. These steps were carefully repeated for each mix variation to ensure consistency and accuracy. The difference between T_5 and T_0 was also analyzed to assess the mix's resistance to segregation. The impact of FA and RC incorporation on the novel rheological characteristics of SCC, specifically its flow behavior via confined apertures, could be investigated thanks to this thorough testing process. Figure 3 shows the V-funnel test apparatus.

Fig 3. V-funnel test equipment (Rectangular section Equipment)

3.4.1.2 L-Box Test

To evaluate the filling capacity and passing ability of SCC mixes containing different proportions of waste RC (0%, 5%, 10%, 15%, and 20%) as a partial replacement for natural coarse aggregates, and FA (0% to 20%) as a partial cement replacement, the L-Box test was performed as per EFNARC guidelines. This test gives information about the deformability and blockage resistance of SCC by simulating its flow via reinforcement in crowded areas.

The L-Box apparatus comprises a vertical section connected to a horizontal channel. The horizontal section is fitted with steel rebar obstructions designed to replicate the conditions of reinforcement congestion in real structural elements. Prior to each test, the internal surfaces of both the vertical and horizontal sections were lightly moistened to reduce surface friction and ensure smooth flow of concrete. Fresh SCC was then poured into the vertical section of the L-Box using a scoop to avoid segregation. The mix was allowed to rest for approximately one minute to settle and eliminate entrapped air. The concrete was then allowed to flow horizontally through the reinforcement bars by carefully opening the sliding gate that separated the vertical and horizontal sections. Two height measurements were made after the flow stopped: h_1 is the height of the concrete that was still present in the vertical part near the obstruction bars. The concrete's height at the horizontal channel's far end is denoted by h_2. The blocking ratio (h_2/h_1) was calculated to assess the passing ability. According to EFNARC, a blocking ratio between 0.80 and 1.00 indicates good passing performance, with lower values reflecting higher viscosity or blockage, and values near 1.00 indicating excellent flow but a possible risk of segregation if excessively fluid.

During the tests, visual observations were also recorded to identify signs of segregation, arching, or material build-up near the reinforcing bars. As rubber chip content increased, a minor but consistent reduction in the blocking ratio was noted. This trend suggested a slight loss in passing efficiency, potentially due to the lower density and altered shape of rubber chips, which may influence particle interaction and reduce the stiffness of the mix. This test was repeated for all combinations of rubber and fly ash replacement to study their combined effects on SCC’s ability to flow through confined spaces. Figure 4 illustrates the L-Box apparatus and experimental setup used in this study.

Fig 4. L-Box test equipment and set-up

3.4.2 Hardened Properties

3.4.2.1 Compressive strength

The compressive strength of SCC with different amounts of waste RC and FA was evaluated using standardized testing in compliance with IS 516:1959 [25]. The test's objective was to assess how these partial replacements affected M30-grade SCC's structural performance. The predefined mix proportions were used to cast standard 150 mm × 150 mm × 150 mm cube specimens for each concrete mix, which included combinations of 0%, 5%, 10%, 15%, and 20% RC replacement for natural coarse aggregate and 0%, 5%, 10%, 15%, and 20% FA replacement for OPC. All specimens were left in the molds for a full day at room temperature following casting. Following a meticulous demolded process, they were moved to clean water tanks to cure for seven to twenty-eight days.

A UTM was used to test the specimens at the conclusion of each cure phase. The specimens were positioned in the center between the UTM's compression platens after surface moisture had been removed prior to testing [26]. Until the specimen failed, a constant loading rate of 140 kg/cm² per minute was used. After recording the highest load at failure, the compressive strength was computed using equation (9),

$$f_c = L/a \tag{9}$$

Where, f_c indicates the Compressive strength of concrete (in MPa or N/mm^2), L shows the highest load applied at failure in N and a shows the specimen's loaded area (in mm^2).This procedure was repeated for all mix variations to capture the compressive strength trends across different replacement levels. Because of the chips' worse stiffness, elasticity, and weaker bond with the cement matrix, it was found that adding more RC somewhat reduced compressive strength. For some applications, such as pavements and non-load-bearing parts, mixtures containing up to 10% rubber replacement and 10% to 15% FA were still viable since they maintained adequate strength and satisfied the minimal structural criteria. Figure 5 shows the setup for the compressive strength test.

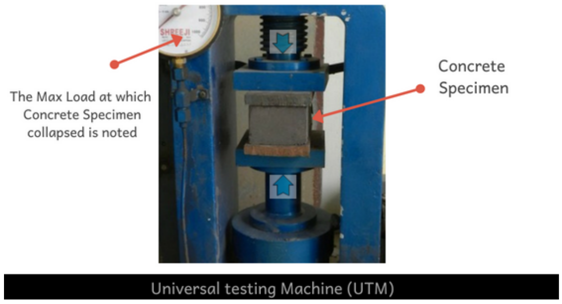

Fig 5. Compressive strength testing machine

3.4.2.2 Flexural strength

The flexural strength of SCC with varying percentages of RC as partial substitutes for natural coarse aggregate and FA as partial cementitious material was assessed in order to assess the structural ductility and bending resistance of the mixes. According to IS: 516-1959, the test was carried out utilizing the one-point loading technique. For each mix variation, beam specimens measuring 1200 mm × 230 mm × 230 mm were cast using the established SCC mix proportions, including five levels of RC replacements (0%, 5%, 10%, 15%, and 20%) and FA replacements (0%, 5%, 10%, 15%, and 20%). 24 hours after casting, the beams were demolded, and they were then immersed in water for 7 and 28 days to curing.

For the flexural strength tests, a UTM [27] with a 1000 KN capacity was used. Prior to testing, each beam's mid-span had a dial gauge installed to track vertical deflection when load was applied. The beams were positioned on two steel rollers, ensuring proper alignment, and were subjected to a gradual load applied at the center of the span until cracking and ultimate failure occurred. Throughout the testing process, observations were made about the method of collapse and the beginning and spread of cracks. This provided insights into the influence of RC and FA on the fracture behavior, ductility, and energy absorption capacity of the SCC. The flexural strength (f_s) was calculated using the following formula (10),

$$Flexural\ strength\ = \frac{L\,m}{w\,d^2}$$

(10)

Where, L indicates the ultimate load (N), m indicates the span length (mm), w indicates the width of the beam (mm) and d indicates the depth of the beam (mm). According to the test results, the flexural strength gradually decreased as the amount of rubber chips increased. This decrease was ascribed to the rubber particles' decreased rigidity and decreased interlock when compared to traditional aggregates. However, SCC mixes with up to 10% rubber replacement, particularly when combined with 10–15% fly ash, maintained adequate flexural capacity, suggesting suitability for structural applications requiring flexibility, such as pavements and slabs under moderate bending stresses. Figure 6 depicts the experimental configuration used to measure flexural strength.

Fig 6. Flexural strength testing machine

3.4.2.3 Splitting tensile strength

The splitting tensile strength test [28] was conducted in compliance with ASTM C496 to evaluate the indirect tensile strength of SCC that included different percentages of RC as a partial replacement for natural coarse aggregate and FA as a partial replacement for cement. This test is essential for assessing the material's overall tensile performance under indirect loading as well as its resistance to cracking. For this test, concrete specimens were made into cylinders that were 200 mm tall and 100 mm in diameter. Each mix variation, involving five levels of RC replacement (0%, 5%, 10%, 15%, and 20%) and corresponding FA replacements (0%, 5%, 10%, 15%, and 20%), was used to cast three identical cylindrical samples. The specimens were demoulded after 24 hours and cured in clean water for 7 and 28 days, as per standard practice.

A 2000 KN capacity automatic compression testing machine was used for the test. To provide even load distribution and avoid stress concentration, thin plywood strips or padding were positioned horizontally between each cylindrical specimen and the compression platens. Until failure, the load was applied steadily and gradually along the cylinder's vertical diameter. The beginning and spread of cracks were observed during the test, providing information about the tensile fracture mechanisms of SCC with RC and FA. The following formula (11) was used to calculate the concrete's splitting tensile strength,

$$f_{st} = \frac{2L}{\pi d m}$$

(11)

Where, f_{st} indicates Splitting tensile strength (MPa), L indicates Maximum applied load (N), d Diameter of the specimen (mm) and m indicates the Diameter of the specimen (mm). The findings showed that, in general, the tensile strength dropped as the amount of RC increased because rubber is less able to connect and is more pliable than traditional aggregates. However, mixes containing up to 10% RC, especially when coupled with moderate FA replacements (10–15%), retained satisfactory tensile performance, demonstrating potential for structural applications requiring enhanced crack resistance and ductility. Figure 7 shows the setup for the splitting tensile strength test.

Fig 7. Splitting tensile strength testing machine

3.4.3 Durability Properties

3.4.3.1 Water absorption Test

A water absorption test was conducted in order to evaluate the durability performance of SCC that included FA as a partial cementitious material and RC as a replacement for coarse aggregate [29]. The porosity, permeability, and general resistance of the concrete to water intrusion—all of which are critical markers of long-term durability—are reliably indicated by this test. The test was carried out in compliance with BS 1881: Part 122 and ASTM C642-13 guidelines. For each mix variation (with 0%, 5%, 10%, 15%, and 20% RC replacement, and corresponding FA replacements), cylindrical specimens measuring 75 mm in diameter and 75 mm in height were created after 28 days of curing. The specimens were oven-dried at 100°C to 110°C after curing, until they reached a consistent bulk. M1 (dry mass) was the documented value for this stable dry mass. The specimens were then left at room temperature for 48 hours while submerged in water. The specimens were immediately weighed again to determine the saturated mass, or M2, after being submerged and surface-dried with a cloth to eliminate any remaining moisture. Equation (12) was used to get the percentage of water absorption.

$$Water\ Absorption(\%) = \left(\frac{M_2 - M_1}{M_1} \right) \times 100 \quad (12)$$

The influence of RC and FA on the interior pore structure of SCC was successfully demonstrated by this test. The findings showed that mixes containing larger proportions of RC had higher water absorption values. This behavior was attributed to the porous and non-polar (hydrophobic) nature of rubber particles, which led to greater interconnected voids in the matrix and a reduction in density and compactness. While FA typically improves microstructure by filling voids due to its finer particle size, its positive effects were partially offset at higher rubber contents. Thus, the water absorption test served as a key parameter for understanding the durability implications of incorporating waste rubber and FA in SCC.

3.4.3.2 Porosity Test

To assess the permeability and internal pore structure of SCC with different concentrations of RC and FA, the porosity test—also known as the volume of permeable voids test—was conducted. This characteristic is critical to comprehending the durability performance of the concrete, especially under harsh climatic conditions. The test procedure was conducted in accordance with the guidelines of ASTM C642-13, using cylindrical specimens measuring 75 mm in diameter and 75 mm in height, previously employed for the water absorption test. These specimens were subjected to a sequence of mass measurements that reflect different moisture states of the concrete:

The samples were oven-dried between 100°C and 110°C until their mass remained constant, at which point it was designated as M_1. The specimens were allowed to dry before being submerged in water for 48 hours at room temperature. After being taken out, their surfaces were carefully cleaned to get rid of any remaining water, and the saturated surface-dry mass, or M_2, was measured once more. Following complete submersion in water, the specimens were weighed, and the submerged mass was noted as M_3. The following formula (13) was used to determine the % porosity (volume of permeable voids) using these values.

$$Porosity(\%) = \left(\frac{M_2 - M_1}{M_2 - M_3} \right) \times 100 \quad (13)$$

This test offered crucial insights into the interconnected voids present within the concrete matrix—voids that contribute to water penetration, chloride ingress, freeze-thaw vulnerability, and overall durability loss. According to the test results, porosity rose in tandem with the amount of RC. This pattern is explained by the fact that RC are porous, elastic, and non-bonding, which prevent dense packing and lessen the cementitious matrix's capacity to compact well around the particles. Although FA tends to reduce porosity by refining the pore structure through pozzolanic action, its mitigating influence was less effective at higher RC percentages. Thus, the porosity test was instrumental in identifying optimal replacement levels that balance sustainability with long-term performance in SCC.

3.4.3.3 Chloride Ion Penetration Test

The Rapid Chloride Ion Penetration Test (RCPT) [30] was carried out in compliance with European Standard XP P 18-462 to assess the chloride resistance and long-term durability of SCC that incorporates FA as a cementitious replacement and RC as a partial coarse aggregate. This test is widely recognized for assessing the permeability of concrete to chloride ions, which is critical for predicting deterioration in marine environments and deicing salt exposure zones.

For every SCC mix modification, cylindrical concrete specimens measuring 100 mm in diameter and 50 mm in height were cast, and they were allowed to cure for 28 days in clean water. To replicate a fully saturated internal pore structure, the samples underwent a vacuum saturation procedure after curing. Initially, the specimens were placed under vacuum for 4 hours, followed by 68 hours of immersion in 0.1 M NaOH solution to ensure complete saturation. For the RCPT setup, a two-cell diffusion apparatus was used: The anodic cell was filled with 0.1 M NaOH solution. A mixture of 0.1 M NaOH and 1 M NaCl solution was present in the cathodic cell. To hasten the migration of chloride ions through the material, a steady 20 V voltage was supplied across the two cells for eighteen hours. The concrete specimens were split longitudinally at the conclusion of the test period, and 0.1 M $AgNO_3$ solution was sprayed on the inside surface. This made it possible to visually identify chloride penetration: Areas impacted by chloride ions were shown by a white precipitate (AgCl). Areas devoid of chloride were indicated by a brown layer (AgO). Next, a digital caliper was used to quantify the depth of chloride penetration (Xe) from the surface with a precision of ±0.02 mm. Using equation (14), the apparent chloride diffusion coefficient (d_{app}) was calculated.

$$d_{app} = \frac{S \times U \times d}{Y \times E \times \Delta F} \times \frac{X_e - \left(\beta \times \sqrt{X_e}\right)}{\Delta u} \quad (14)$$

$$\beta = dse^{-1}\left(1 - 2 \times \frac{C_e}{C_t}\right) \times \sqrt{\frac{S \times U \times d}{Y \times E \times \Delta F}}$$
(15)

Where, S denoted as the universal gas constant $(8.314 J/mol \cdot K)$, Y indicates the Valency of chloride ion (1), U indicates the Temperature in Kelvin, E indicates the Faraday's constant ($96480 J/V \cdot mol$, d denoted as the Thickness of specimen in m, ΔF indicates the Applied voltage (20 V), X_e indicates the Measured chloride penetration depth in m, Δu represents the Duration of test in $\sec$, dse^{-1} indicates the Inverse error function, C_e denoted as the Free chloride concentration at depth X_e (mol/L), C_t is the Chloride concentration in cathodic cell (mol/L). The results revealed that chloride penetration depth increased with higher rubber chip content, indicating a reduction in the concrete's resistance to chloride ingress. Because rubber is porous, elastic, and hydrophobic, it contributes to a more permeable microstructure, which is largely responsible for this tendency. However, mixes with up to 10% rubber replacement showed acceptable diffusion performance and can be considered for non-critical structural applications where chloride exposure is moderate.

4 RESULT ANALYSIS

The results obtained from the experimental investigations were thoroughly analyzed to evaluate the impact of incorporating varying percentages of RC (0%, 5%, 10%, 15%, and 20%) as partial replacements for coarse aggregates, alongside different levels of FA (0% to 20%) as a cementitious substitute. The study examined key performance indicators of SCC, including fresh properties, mechanical strengths, and durability characteristics. This section presents a comprehensive interpretation of how the combined influence of RC and FA affects workability, strength development, and resistance to environmental factors. The analysis highlights the trends observed across different mix variations, identifying optimal replacement levels that balance sustainability with performance.

4.1 Fresh Properties Analysis

4.1.1 Evaluation of Flow Time

The V-Funnel test was used to evaluate the flow time and segregation resistance of SCC mixes that included different amounts of RC to partially replace natural coarse aggregates and FA to partially replace cement. The results, presented in Table 3, include the initial flow time (T_0), delayed flow time after 5 minutes (T_5), the difference (T_5–T_0), and the corresponding segregation risk. Across all fly ash levels, the trend indicated that increasing RC content consistently led to higher T_0 and T_5 values, reflecting a reduction in flowability. This was attributed to the irregular shape, low density, and poor cohesion of rubber chips, which tend to increase internal friction in the mix. However, the addition of fly ash up to 15% showed a compensatory effect, reducing viscosity and improving matrix cohesion due to its finer particles and pozzolanic activity.

- Low RC replacement levels (0–5%), across all FA levels, maintained flow times well within EFNARC recommendations (T_0 = 8–12 s, T_5–T_0 ≤ 3 s) with no segregation risk.
- At 10% RC, the mixes still displayed satisfactory flow characteristics, though T_5–T_0 values approached the 2.2–2.3 s range, indicating a low segregation risk.
- 15% RC replacement began to show moderate flow retardation, with T_5–T_0 values reaching 3.0 s or more, suggesting moderate segregation risks, particularly in mixes with lower FA content.
- 20% RC mixes, especially without or with low FA content, exhibited T_5–T_0 differences exceeding 3.5 s, indicating high segregation risk, which may compromise the mix's stability and uniformity during placement.

Notably, mixes with 15–20% FA showed improved resistance to segregation even at higher RC contents due to better particle packing and improved paste quality, although high RC levels still posed challenges. In summary, the optimal flow behavior was observed in SCC mixes containing up to 10% RC and 10–15% FA, balancing workability with stability. Beyond these levels, segregation tendencies increase, especially in the absence of adequate binder support from FA.

Table 3. Results of the V-Funnel Test for SCC Mixtures with Different FA and RC Contents

Mix ID	T_0 [s]	T_5 [s]	T_5 - T_0 [s]	Segregation Risk
M30-FA0-RC0	9.2	10.8	1.6	No
M30-FA0-RC5	9.8	11.6	1.8	No
M30-FA0-RC10	10.4	12.7	2.3	Low
M30-FA0-RC15	11.2	14.5	3.3	Moderate
M30-FA0-RC20	11.8	15.4	3.6	High
M30-FA5-RC0	8.9	10.4	1.5	No
M30-FA5-RC5	9.5	11.2	1.7	No
M30-FA5-RC10	10.1	12.3	2.2	Low

M30-FA5-RC15	11	14	3	Moderate
M30-FA5-RC20	11.6	15	3.4	High
M30-FA10-RC0	8.6	10	1.4	No
M30-FA10-RC5	9.2	10.8	1.6	No
M30-FA10-RC10	9.8	12	2.2	Low
M30-FA10-RC15	10.7	13.7	3	Moderate
M30-FA10-RC20	11.3	14.8	3.5	High
M30-FA15-RC0	8.4	9.7	1.3	No
M30-FA15-RC5	9	10.5	1.5	No
M30-FA15-RC10	9.6	11.7	2.1	Low
M30-FA15-RC15	10.5	13.5	3	Moderate
M30-FA15-RC20	11.1	14.6	3.5	Moderate-High
M30-FA20-RC0	8.5	9.9	1.4	Low
M30-FA20-RC5	9.1	10.7	1.6	Low
M30-FA20-RC10	9.7	11.9	2.2	Moderate
M30-FA20-RC15	10.6	13.6	3	High
M30-FA20-RC20	11.2	14.7	3.5	High

4.1.2 Evaluation of passing ability

The L-Box test was used to evaluate the passing ability of SCC that included different ratios of FA and RC. The ability of the mix to pass through crowded areas without becoming blocked is simulated in this test. The evaluation focused on the blocking ratio (h_2/h_1), where h_1 is the vertical height of concrete behind the rebar and h_2 is the final height after passing through the reinforcement. A blocking ratio close to 1.0 indicates excellent passing ability, while lower values indicate increased resistance or potential blocking. The data from Table 4 shows that,

- Mixes without rubber (RC = 0%) consistently exhibited excellent passing ability, with blocking ratios ranging from 0.95 to 0.98, across all FA levels. This demonstrates the beneficial effect of fly ash in enhancing flow characteristics and deformability.
- For mixes with 5% rubber replacement, the blocking ratio remained high (≥ 0.93), indicating very good to excellent passing ability even as rubber was introduced.
- As the RC content increased to 10% and 15%, a gradual decline in the blocking ratio was observed. The ratio dropped to around 0.89–0.88, which was still within the acceptable EFNARC range (0.80–1.00), but signaled a slight increase in interparticle friction and flow restriction due to rubber chip presence.
- At 20% RC replacement, the blocking ratio decreased further, falling between 0.81 and 0.84 for most mixes—classified as borderline acceptable. This decline reflects the adverse effects of rubber chips on particle interlock, deformability, and smooth flow, particularly under confinement.
- Importantly, fly ash incorporation had a mitigating effect on the passing ability. Mixes with 15–20% FA maintained better blocking ratios at higher RC levels compared to mixes with lower FA content. The enhanced workability and cohesiveness imparted by fly ash improved the mix's ability to pass through reinforcement even in the presence of rubber particles.

The optimal balance between deformability and obstruction-free flow was achieved in SCC mixes containing up to 10% RC and 15% FA, offering excellent or good passing performance. Beyond these levels, although the SCC remained within acceptable limits, caution is advised due to increased risk of blockage under heavily reinforced conditions.

Table 4. Results of the L-Box Test for SCC Mixtures with FA and RC

Mix ID	**h_1 (mm)**	**h_2 (mm)**	**Blocking Ratio (h_2/h_1)**	**Passing Ability**
M30-FA0-RC0	200	190	0.95	Excellent
M30-FA0-RC5	200	186	0.93	Very Good

M30-FA0-RC10	200	178	0.89	Good
M30-FA0-RC15	200	170	0.85	Acceptable
M30-FA0-RC20	200	162	0.81	Borderline Acceptable
M30-FA5-RC0	200	192	0.96	Excellent
M30-FA5-RC5	200	188	0.94	Very Good
M30-FA5-RC10	200	180	0.9	Good
M30-FA5-RC15	200	172	0.86	Acceptable
M30-FA5-RC20	200	164	0.82	Borderline Acceptable
M30-FA10-RC0	200	194	0.97	Excellent
M30-FA10-RC5	200	190	0.95	Excellent
M30-FA10-RC10	200	182	0.91	Good
M30-FA10-RC15	200	174	0.87	Acceptable
M30-FA10-RC20	200	166	0.83	Borderline Acceptable
M30-FA15-RC0	200	196	0.98	Excellent
M30-FA15-RC5	200	192	0.96	Excellent
M30-FA15-RC10	200	184	0.92	Good
M30-FA15-RC15	200	176	0.88	Acceptable
M30-FA15-RC20	200	168	0.84	Borderline Acceptable
M30-FA20-RC0	200	195	0.975	Excellent
M30-FA20-RC5	200	191	0.955	Excellent
M30-FA20-RC10	200	183	0.915	Good
M30-FA20-RC15	200	175	0.875	Acceptable
M30-FA20-RC20	200	167	0.835	Borderline Acceptable

4.2 Hardened Properties Analysis

4.2.1 Evaluation of Compressive strength

SCC mixes with different proportions of FA and RC as partial substitutes for cement and coarse aggregates, respectively, were evaluated for compressive strength at 7 and 28 days. Rubber's elastic and low-bonding properties negatively impacted the integrity of the concrete matrix, as seen by Table 5 and Figure 8, which show that strength values generally declined as rubber content increased. However, the inclusion of fly ash up to 10% appeared to mitigate this loss to a certain extent, enhancing the pozzolanic reaction and contributing to a denser matrix.

At 7 days, compressive strengths ranged from 27 MPa (M30-FA0-RC0) to 12.5 MPa (M30-FA20-RC20). The maximum strength of 39.5 MPa was recorded for M30-FA10-RC0 at 28 days, indicating that a 10% FA component provided the best mechanical performance in rubber-free mixes. On the contrary, the lowest strength of 25 MPa was observed for M30-FA20-RC20. Notably, mixes with up to 10% rubber content still maintained compressive strengths above 30 MPa at 28 days, making them potentially viable for moderate structural applications. These results demonstrate that while rubber inclusion leads to a reduction in compressive strength, the combined effect of FA (particularly up to 10%) can compensate for the loss and contribute to a more sustainable yet structurally reliable concrete.

Table 5. Compressive Strength of SCC Mixes with Different FA and RC Content

Compressive strength (MPa)		
Mix ID	**7-days**	**28-days**
M30-FA0-RC0	27	38
M30-FA0-RC5	25	35.5
M30-FA0-RC10	23	33
M30-FA0-RC15	20	30
M30-FA0-RC20	18	27
M30-FA5-RC0	26	39
M30-FA5-RC5	24.5	36.5
M30-FA5-RC10	22.5	34

M30-FA5-RC15	19.5	31
M30-FA5-RC20	17.5	28
M30-FA10-RC0	25	39.5
M30-FA10-RC5	23.5	37
M30-FA10-RC10	21.5	34.5
M30-FA10-RC15	18.5	31.5
M30-FA10-RC20	16.5	28.5
M30-FA15-RC0	23	38
M30-FA15-RC5	21.5	35.5
M30-FA15-RC10	19.5	33
M30-FA15-RC15	16.5	30
M30-FA15-RC20	14.5	27
M30-FA20-RC0	21	36
M30-FA20-RC5	19.5	33.5
M30-FA20-RC10	17.5	31
M30-FA20-RC15	14.5	28
M30-FA20-RC20	12.5	25

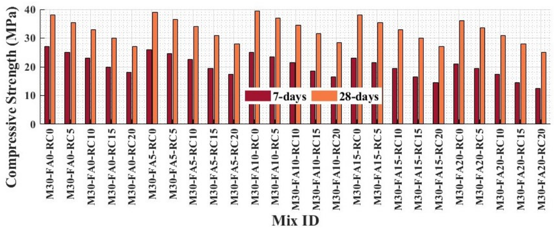

Fig 8. Variation of Compressive Strength at 7 and 28 Days for SCC with Different FA and RC Content

4.2.2 Evaluation of Flexural strength

At 7 and 28 days, the SCC mixes with different proportions of RC and FA were tested for flexural strength. At 28 days, the control mix (M30-FA0-RC0) had the maximum flexural strength, measuring 5.3 MPa, as indicated in Table 6 and Figure 9. All FA levels showed a progressive decrease in flexural strength as the RC content increased. This decrease in the concrete matrix's ability to transfer load efficiently and resist cracking is ascribed to the rubber particles' poor interfacial bonding and decreased stiffness. However, mixes with up to 10% RC substitution showed acceptable strength for structural applications, particularly in non-load-bearing or flexible elements. The presence of fly ash appeared to improve the performance slightly, especially at 10–15% FA content, likely due to its filler effect and pozzolanic reaction, which refined the pore structure and enhanced the matrix continuity. Overall, mixes such as M30-FA10-RC0 and M30-FA10-RC5 displayed commendable results, with 28-day flexural strengths of 5.5 MPa and 5.3 MPa respectively, showing the beneficial synergy between fly ash and moderate RC replacement.

Table 6. Flexural strength of SCC mixes with varying percentages of FA and RC at 7 and 28 days.

Flexural Strength (MPa)		
Mix ID	**7-days**	**28-days**
M30-FA0-RC0	3.8	5.3
M30-FA0-RC5	3.6	5.1
M30-FA0-RC10	3.4	4.8
M30-FA0-RC15	3	4.5
M30-FA0-RC20	2.7	4
M30-FA5-RC0	3.7	5.4
M30-FA5-RC5	3.5	5.2
M30-FA5-RC10	3.2	4.9
M30-FA5-RC15	2.9	4.6
M30-FA5-RC20	2.6	4.1
M30-FA10-RC0	3.6	5.5
M30-FA10-RC5	3.4	5.3
M30-FA10-RC10	3.1	5
M30-FA10-RC15	2.8	4.7
M30-FA10-RC20	2.5	4.2
M30-FA15-RC0	3.4	5.3
M30-FA15-RC5	3.2	5.1
M30-FA15-RC10	2.9	4.8
M30-FA15-RC15	2.5	4.5
M30-FA15-RC20	2.2	4
M30-FA20-RC0	3.2	5
M30-FA20-RC5	3	4.8
M30-FA20-RC10	2.7	4.6
M30-FA20-RC15	2.4	4.2
M30-FA20-RC20	2	3.8

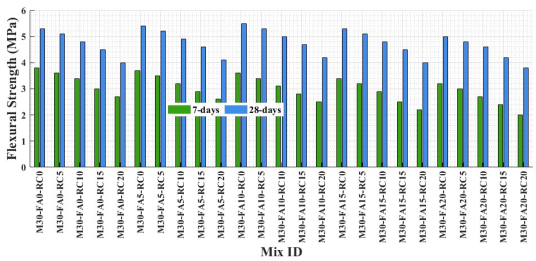

Fig 9. Variation of flexural strength for different SCC mixes with RC and FA content at 7 and 28 days

4.2.3 Evaluation of splitting tensile strength

Table 7 and Figure 10 show the results of the splitting tensile strength test for SCC mixes with different proportions of RC and FA. Both at 7 and 28 days of curing, the data show a continuous pattern of decreasing tensile strength as RC content increases. This decrease is explained by the rubber particles' poor bonding properties and decreased stiffness, which impair the concrete matrix's resistance to tensile stresses. At 28 days, the reference mix (M30-FA0-RC0) attained the highest tensile strength of 3.3 MPa, while the mix with 20% RC and 20% FA (M30-FA20-RC20) showed the lowest value of 2.3 MPa, indicating a 30.3% strength loss. The incorporation of fly ash at moderate levels (5–15%) slightly improved the tensile strength over the control for lower RC content, likely due to improved particle packing and pozzolanic activity enhancing matrix cohesion.

However, despite the decrease, all mixes with up to 10% RC and FA combinations still maintained acceptable splitting tensile strength values suitable for non-load-bearing or semi-structural applications, especially where improved ductility and impact resistance are desired. The trend also suggests that tensile strength performance is more sensitive to RC content than to FA substitution.

Table 7. Splitting Tensile Strength of SCC Mixtures at 7 and 28 Days

Splitting Tensile Strength (MPa)		
Mix ID	**7-days**	**28-days**
M30-FA0-RC0	2.3	3.3
M30-FA0-RC5	2.2	3.1
M30-FA0-RC10	2	2.9
M30-FA0-RC15	1.8	2.7
M30-FA0-RC20	1.6	2.4
M30-FA5-RC0	2.4	3.4
M30-FA5-RC5	2.2	3.2
M30-FA5-RC10	2	3
M30-FA5-RC15	1.8	2.8
M30-FA5-RC20	1.6	2.5
M30-FA10-RC0	2.5	3.5
M30-FA10-RC5	2.3	3.3
M30-FA10-RC10	2.1	3.1
M30-FA10-RC15	1.9	2.9
M30-FA10-RC20	1.7	2.6
M30-FA15-RC0	2.4	3.4
M30-FA15-RC5	2.2	3.2
M30-FA15-RC10	2	3
M30-FA15-RC15	1.8	2.7
M30-FA15-RC20	1.5	2.4
M30-FA20-RC0	2.3	3.2
M30-FA20-RC5	2.1	3
M30-FA20-RC10	1.9	2.8
M30-FA20-RC15	1.6	2.6
M30-FA20-RC20	1.4	2.3

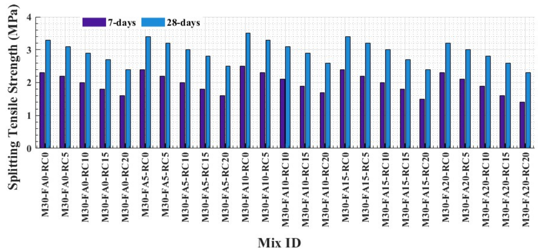

Fig 10. Splitting Tensile Strength Development of SCC with Varying FA and RC Content

4.3 Durability Properties Analysis

4.3.1 Evaluation of Water absorption

One important determinant of concrete's porosity and possible resilience to moisture exposure is water absorption. Table 8 and figure 11, shows the experimental results revealed a consistent trend across all SCC mixes: an increase in RC content generally led to higher water absorption values, while FA incorporation mitigated this rise to a certain extent due to its pozzolanic action and finer particle packing. At 7 and 28 days, mixes with 0% rubber content (e.g., M30-FA0-RC0 and M30-FA10-RC0) exhibited the lowest water absorption values (4.5% and 4.0% at 7 days, reducing to 3.8% and 3.2% at 28 days, respectively). The greatest RC content and FA-free M30-FA0-RC20, on the other hand, showed maximum absorption values of 6.2% at 7 days and 5.4% at 28 days, amply demonstrating the detrimental effects of RC on the pore structure.

Among mixes incorporating fly ash, M30-FA10-RC0 stood out with the lowest absorption values (4.0% at 7 days and 3.2% at 28 days), reflecting the beneficial effect of 10% FA in reducing permeability. Even in rubberized mixes, FA significantly reduced water absorption—for instance, M30-FA15-RC10 had 4.8% (7 days) and 4.1% (28 days), compared to 5.2% and 4.5% in the corresponding M30-FA0-RC10. Overall, the combined use of fly ash and controlled rubber content (≤10%) led to acceptable absorption levels, preserving durability. Water absorption increased proportionally with RC content due to its hydrophobic and porous nature, while FA contributed positively by densifying the microstructure and refining pores.

Table 8. Water absorption (%) of SCC mixes at 7 and 28 days for varying FA and RC contents

Water Absorption (% by mass)		
Mix ID	**7-days**	**28-days**
M30-FA0-RC0	4.5	3.8

M30-FA0-RC5	4.8	4.1
M30-FA0-RC10	5.2	4.5
M30-FA0-RC15	5.7	5
M30-FA0-RC20	6.2	5.4
M30-FA5-RC0	4.2	3.5
M30-FA5-RC5	4.5	3.8
M30-FA5-RC10	4.9	4.2
M30-FA5-RC15	5.4	4.7
M30-FA5-RC20	5.8	5.1
M30-FA10-RC0	4	3.2
M30-FA10-RC5	4.3	3.6
M30-FA10-RC10	4.7	4
M30-FA10-RC15	5.2	4.5
M30-FA10-RC20	5.6	4.9
M30-FA15-RC0	4.1	3.3
M30-FA15-RC5	4.4	3.7
M30-FA15-RC10	4.8	4.1
M30-FA15-RC15	5.3	4.6
M30-FA15-RC20	5.7	5
M30-FA20-RC0	4.3	3.6
M30-FA20-RC5	4.6	3.9
M30-FA20-RC10	5	4.3
M30-FA20-RC15	5.5	4.8
M30-FA20-RC20	6	5.2

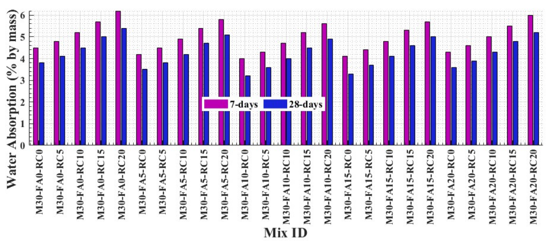

Fig 11. Water absorption behavior of SCC mixes with varying FA and RC contents at 7 and 28 days.

4.3.2 Evaluation of Porosity

Porosity is a crucial microstructural factor that affects SCC's durability and mechanical strength. The test results in Table 9 and Figure 12 make it evident that porosity rises as RC content increases. This is because rubber particles have a low density and high deformability, which causes voids and lowers compaction efficiency. Conversely, FA incorporation leads to a reduction in porosity, owing to its pozzolanic reaction and filler effect that refines the pore structure.

At 7 and 28 days, the lowest porosity values were recorded in M30-FA10-RC0 (12% and 10%), demonstrating the positive role of 10% fly ash replacement in improving the concrete's compactness. In contrast, the highest porosity values were observed in M30-FA0-RC20 (15.5% and 13.5%), highlighting the detrimental effect of 20% rubber inclusion without any pozzolanic compensation. As the fly ash content increased, there was a progressive improvement in porosity, particularly evident at higher curing ages. For instance, M30-FA15-RC10 and M30-FA20-RC10 mixes exhibited reduced porosity values of 13.2% and 13.7% (7 days) and 11.1% and 11.7% (28 days) respectively, compared to 14% and 12% for M30-FA0-RC10. Overall, the findings show that a porosity content of 10–15% fly ash and ≤10% rubber produced the best results, providing a compromise between increased durability and strength retention. The data also confirm that longer curing periods help to further reduce porosity due to ongoing hydration and pozzolanic activity.

Table 9. Porosity (% by volume) of SCC mixes incorporating FA and RC at 7 and 28 days.

Porosity (% by volume)		
Mix ID	**7-days**	**28-days**
M30-FA0-RC0	13	11
M30-FA0-RC5	13.5	11.5
M30-FA0-RC10	14	12
M30-FA0-RC15	14.8	12.8
M30-FA0-RC20	15.5	13.5
M30-FA5-RC0	12.5	10.5
M30-FA5-RC5	13	11
M30-FA5-RC10	13.5	11.5
M30-FA5-RC15	14.3	12.3
M30-FA5-RC20	15	13
M30-FA10-RC0	12	10
M30-FA10-RC5	12.5	10.5
M30-FA10-RC10	13	11
M30-FA10-RC15	13.8	11.8
M30-FA10-RC20	14.5	12.5
M30-FA15-RC0	12.3	10.2
M30-FA15-RC5	12.7	10.6
M30-FA15-RC10	13.2	11.1
M30-FA15-RC15	14	11.9
M30-FA15-RC20	14.7	12.6
M30-FA20-RC0	12.8	10.8
M30-FA20-RC5	13.2	11.2
M30-FA20-RC10	13.7	11.7
M30-FA20-RC15	14.5	12.5
M30-FA20-RC20	15.2	13.2

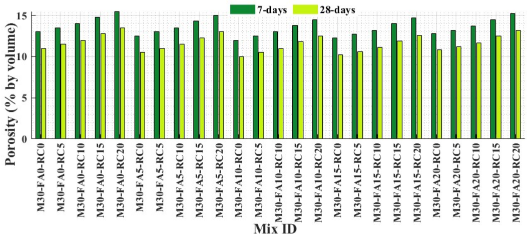

Fig 12. Variation of porosity in SCC mixes with different FA and RC contents at 7 and 28 days.

4.3.3 Effect of Chloride diffusion depth

A crucial indicator of concrete's endurance, especially under harsh maritime or de-icing conditions, is chloride ion diffusion. Figure 13 and Table 9 demonstrate the findings, which reveal that the addition of RC enhances the chloride diffusion depth while the addition of FA decreases it.

For the control mix (M30-FA0-RC0), chloride penetration depths were recorded at 14 mm (7 days) and 12 mm (28 days). As the RC content increased to 20%, the depth increased significantly to 21 mm and 19 mm, respectively. The main causes of this increase are the RC particles' reduced binding capacity and increased porosity, which create interconnected voids that facilitate chloride ingress. In contrast, mixes incorporating FA exhibited markedly reduced chloride diffusion depths. For instance, M30-FA15-RC0 and M30-FA10-RC0 showed the lowest depths of 11 mm & 9 mm and 12 mm & 10 mm at 7 and 28 days, respectively. This enhancement results from FA's pozzolanic reaction, which densifies the matrix and refines the pore structure, preventing the flow of chloride ions. Even in the presence of RC, FA significantly mitigated the chloride ingress. For example, M30-FA15-RC20 and M30-FA10-RC20 mixes recorded lower diffusion depths of 18 mm and 16 mm, compared to 21 mm and 19 mm for the non-fly ash counterpart (M30-FA0-RC20) at corresponding ages. Overall, the test results confirm that:

- RC addition alone increases chloride diffusivity, compromising durability.
- FA addition improves resistance to chloride penetration, particularly at 10–15% replacement levels.
- Longer curing (28 days) consistently improves resistance, suggesting continued matrix densification over time.

These findings emphasize that an optimal blend of FA (10–15%) with moderate RC content (≤10%) can yield SCC mixes with enhanced durability against chloride-induced corrosion.

Table 9. Chloride diffusion depth (mm) of SCC mixes with varying FA and rubber chip content at 7 and 28 days.

Chloride Diffusion Depths (mm)		
Mix ID	**7-days**	**28-days**
M30-FA0-RC0	14	12
M30-FA0-RC5	15	13
M30-FA0-RC10	17	15
M30-FA0-RC15	19	17
M30-FA0-RC20	21	19
M30-FA5-RC0	13	11
M30-FA5-RC5	14	12
M30-FA5-RC10	16	14
M30-FA5-RC15	18	16
M30-FA5-RC20	20	18
M30-FA10-RC0	12	10
M30-FA10-RC5	13	11
M30-FA10-RC10	15	13
M30-FA10-RC15	17	15
M30-FA10-RC20	19	17
M30-FA15-RC0	11	9
M30-FA15-RC5	12	10
M30-FA15-RC10	14	12
M30-FA15-RC15	16	14
M30-FA15-RC20	18	16
M30-FA20-RC0	12	10
M30-FA20-RC5	13	11
M30-FA20-RC10	15	13
M30-FA20-RC15	17	15
M30-FA20-RC20	19	17

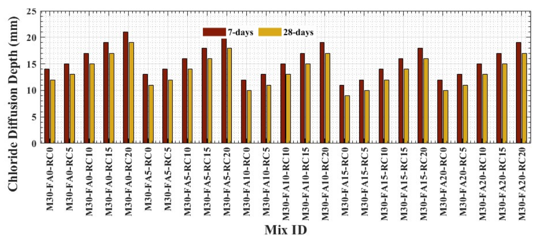

Fig 13. Variation in chloride diffusion depth for SCC mixes incorporating FA and RC at 7 and 28 days

4.4 DISCUSSION

The experimental investigation revealed that the inclusion of FA and RC significantly influenced both fresh and hardened properties of SCC. According to the L-box test, mixes with 10–15% FA and up to 10% RC maintained acceptable flow characteristics, while FA improved flowability due to its spherical particles and pozzolanic reactivity. The irregular shape and low stiffness of RC caused passing ability to decrease with increasing RC content. Compressive strength was highest in mixes with 10–15% FA and no RC (e.g., M30-FA10-RC0), while increasing RC content led to a steady decline in strength due to weaker interfacial bonding and poor stiffness. Flexural and splitting tensile strengths followed similar trends, with peak values observed in FA-rich, RC-free mixes, confirming the negative influence of RC on tensile performance Water absorption, porosity, and chloride diffusion depth were among the durability attributes that improved with increasing RC content. However, FA inclusion, which decreased permeability through matrix densification, greatly enhanced these values. Mixes like M30-FA10-RC10 and M30-FA15-RC5 demonstrated a balanced performance, achieving adequate workability, strength above 30 MPa, and enhanced durability, indicating their suitability for sustainable SCC applications in non-structural and moderately loaded structural elements.

5. CONCLUSION

This study suggested a sustainable way to improve the sustainability of SCC for M30 grade combinations by substituting discarded tire RC at different percentages (0%–20%) for natural coarse aggregates. EFNARC and IS 10262:2019 guidelines were followed in the development of the SCC mixes, which were then assessed for their mechanical (compressive, flexural, and tensile strength), fresh (flowability, passing ability), and durability (water absorption, porosity, and chloride ion penetration) qualities. The results showed that SCC mixes with up to 10% RC maintained adequate workability, strength, and durability, making them feasible for non-structural and moderately loaded structural applications. However, at replacement levels beyond 10%, a noticeable decline in performance was observed due to poor rubber–cement bonding and the hydrophobic, porous nature of rubber particles. Chloride diffusion depth increased significantly with higher RC content, indicating reduced durability in aggressive environments.

The approach offers key advantages, including effective utilization of rubber waste, reduced natural aggregate consumption, and minimized environmental impact, while achieving satisfactory structural performance at optimized RC levels. However, limitations arise from reduced mechanical strength and increased porosity at higher rubber contents, restricting its use in high-performance or durability-critical structures. For future work, the influence of rubber chip size on fresh, mechanical, and durability properties will be investigated to determine optimal gradation for improved bonding and matrix integration. Additionally, advanced surface treatments and hybrid reinforcement strategies may be explored to further enhance the applicability of rubberized SCC in sustainable construction practices.

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