# Expanded Clay Aggregate Incorporation in Self-Compacting Concrete through Multi-Performance Evaluation of Fresh, Mechanical and Durability Characteristics

*Usha Rani* Bala[1*], *R.* Bhavani[2], and J. *Gurujawahar*[3]

[1] Research Scholar, Jawaharlal Nehru Technological University, Department of Civil Engineering, Ananthapuram, AP, India
[2]Professor, Jawaharlal Nehru Technological University, Department of Civil Engineering, Ananthapuram, AP, India.
[3] Professor, Annamacharya Institute of Technology and Sciences, Department of Civil Engineering, Tirupati, AP, India

**Abstract.** This study evaluates the feasibility of using expanded clay aggregate (EC) as a sustainable coarse aggregate replacement in self-compacting concrete (SCC). Six SCC mixtures with 0–100% EC replacement were prepared while maintaining a constant binder composition and water-to-binder ratio. Fresh properties were assessed using EFNARC (2005) tests, whereas compressive, split tensile, flexural, and durability properties were evaluated at 7, 28, and 90 days. All mixtures satisfied the EFNARC requirements for workability. The optimum performance was obtained at 20% EC replacement (A1B6), which achieved the highest slump flow (620 mm), compressive strengths of 27.08, 42.46, and 45.75 MPa, split tensile strengths of 3.93, 4.92, and 5.11 MPa, and flexural strengths of 4.45, 5.57, and 5.78 MPa at 7, 28, and 90 days, respectively. The same mixture also exhibited superior resistance to acid and sulphate attack. The improved performance is attributed to the internal curing effect of porous EC particles, while higher replacement levels reduced strength because of increased porosity and lower aggregate stiffness. Overall, 20% EC replacement provides the optimum balance between workability, mechanical performance, and durability for sustainable structural SCC.

**Keywords:** Self-compacting concrete; Expanded clay aggregate; Coarse aggregate replacement; Fresh properties; Mechanical strength; Sulphuric acid resistance; Sulphate resistance

* Corresponding author: ushasscjntua@gmail.com

# 1 Introduction

Self-compacting concrete (SCC) has become the preferred solution for structural elements with congested reinforcement or complex formwork, since it consolidates under self-weight without mechanical vibration [1]. However, these improvements are accompanied by certain limitations, SCC mixtures require elevated powder and paste contents to sustain flowability, which increases both material expenditure and embodied carbon relative to conventionally vibrated concrete. This compromise has encouraged intensive studies of the use of secondary or lightweight materials in place of the natural mix constituents, including a granular product that is produced through pyro-processing of raw clay to generate a cellular, low-density aggregate, which is known as Expanded Clay (EC) aggregate. EC aggregate decreases the self-weight of the coarse-aggregate fraction, enhances thermal insulation and reduces the embodied energy of natural aggregate extraction and remains compatible with the flow requirements of SCC. It has, however, been found to significantly affect fresh-mixture properties and strength development of the hardened-matrix, compared to crushed stone or gravel, and its performance on exposure to acid or sulfates has been comparatively little studied in a single fully graded replacement series.

Existing studies on EC-based lightweight SCC converge on one consistent finding but diverge sharply on another. There is broad agreement that EC aggregate is rheologically compatible with self-compacting flow classes provided paste proportions are adjusted accordingly: Kanagaraj et al. demonstrated this across a full suite of fresh-state indices (slump flow, T500, V-funnel, J-ring) for a self-compactable lightweight geopolymer concrete, corroborating flowability with density and ultrasonic pulse velocity measurements [2,3], and a broader review of structural EC concretes confirms the same trend of improved workability alongside reduced density and elastic modulus as replacement increases [4]. Where studies diverge is on the magnitude and mitigability of the associated strength penalty. In contrast, work on fibre-reinforced self-compacting lightweight concrete shows that this penalty is strongly size-dependent finer maximum EC particle sizes produce measurably better compressive and flexural results through a more homogeneous paste–aggregate interface [5] while surface pre-coating of EC particles with waste-glass powder and ground granulated slag has been shown to recover much of the lost strength without sacrificing flow class [6]. Taken together, these studies indicate that the strength penalty attributed to EC replacement is not intrinsic to the aggregate alone but is contingent on particle size and surface treatment, a distinction rarely made explicit in mix-design guidance.

A comparable tension exists in the durability literature. Sulfate-exposure studies on lightweight and recycled-aggregate concretes report that internal curing supplied by porous lightweight aggregate can improve sulfate resistance relative to normal-weight concrete by promoting more complete hydration and a denser resulting microstructure [7] a finding that appears to contradict the intuitive expectation that a more porous aggregate should increase vulnerability to aggressive-ion ingress. This apparent contradiction is partially resolved by evidence that degradation under aggressive-liquid exposure is governed more by binder type, pozzolanic content and exposure concentration than by aggregate type per se [8], and by geopolymer-based studies showing that strength loss after prolonged sulfuric-acid exposure, while measurable, remains moderate and is strongly binder-dependent [9]. Field-performance reviews reinforce this binder-dominant interpretation, reporting that properly proportioned lightweight-aggregate concretes can match or exceed the chloride and carbonation resistance of normal-weight concrete in service, despite conservative design

assumptions to the contrary [9]. The unresolved question this body of work leaves open is whether the binder-dominance observed for chloride and carbonation resistance also holds for combined acid/sulfate attack across a finely graded EC replacement series none of the studies above test this directly. The binder proportion adopted in the present study (65% cement, 25% fly ash, 10% silica fume) was previously validated in a companion investigation of the same base SCC system using slag sand as a fine-aggregate replacement, where the identical binder blend, water binder ratio and mixing protocol satisfied EFNARC flow, passing-ability and viscosity criteria retaining this binder here isolates EC content as the sole variable responsible for the trends reported below.

Three limitations emerge from this synthesis. First, the fresh-state, mechanical and durability effects of EC replacement have each been documented, but almost always for a single behavioural domain per study, at a coarse resolution of replacement levels, and often confounded by simultaneous variation in binder chemistry across studies rather than within one dataset [2-6], [8],[9]. Second, the durability literature is internally inconsistent regarding whether aggregate porosity helps performance through internal curing [7] and is largely irrelevant relative to binder effects [8,9], and no study has tested this question across a graded EC series built on a single fixed binder, leaving it unclear which mechanism dominates as replacement level increases. Third, and most critically, no prior work has examined whether the two behavioural regimes fresh-state rheology and hardened-state durability are coupled: it remains unknown whether a non-monotonic slump-flow response at intermediate EC contents corresponds to a disproportionate penalty in acid and sulfate residual-strength retention, or whether the two respond independently of one another. This coupling question cannot be resolved from the existing literature, since no published dataset combines fine-resolution replacement levels, multiple mechanical indices measured at multiple ages, and dual aggressive-media exposure within one internally consistent experimental matrix built on a fixed binder system.

This study addresses that gap by evaluating fresh-state flow, three hardened mechanical properties across three curing ages, and residual strength under two aggressive-media exposures within a single, finely graded EC replacement series (0-100%) produced with a fixed binder. Prior studies have generally reported fresh-state and durability results separately. Here, both are measured against the unmodified reference mixture using retention ratios, allowing direct comparison. This makes it possible to check whether the fresh-state anomaly at moderate EC replacement corresponds to a disproportionate durability loss, or whether the two behave independently. Considering both together gives a clearer picture of EC-based SCC performance than either alone, supporting more informed mix-design decisions for structural and non-structural use.

## 2 Materials

### 2.1 Cement

The basic binder used was Ordinary Portland Cement (OPC, 53 Grade) as per IS 12269. The cement from UltraTech Cement Ltd, India has a specific gravity of 3.12, a fineness of 4.16% and an initial setting time of 110 min and a final setting time of 241 min, which is in agreement to the fine particle-size distribution and rapid early hydration kinetics that are required for the stable flow of SCC.

### 2.2 Fly Ash

Class F fly ash of local thermal power plant was used as supplementary cementitious material, fineness=320m2/kg, specific gravity=2.20. The oxide chemistry ($SiO_2$= 60%, $Al_2O_3$ = 25%, $Fe_2O_3$ = 5.5%, CaO =1.0%, $SO_3$ = 0.7%) and low LOI of 1.5% meet the criteria for low calcium pozzolanic materials, which reflect its pozzolanic reactivity and low unburnt-carbon content requirement, to prevent excessive demand of superplasticiser.

### 2.3 Silica Fume

Densified silica fume was added as the second supplementary cementitious material, contributing 92.5% $SiO_2$, a fineness of approximately 20,000 $m^2/kg$, a mean particle size of 0.1 μm, and a bulk density of 550 $kg/m^3$, with a loss on ignition of 1.2%. At this fineness, silica fume particles occupy the interstitial voids between cement grains, refining pore structure through a micro-filler effect while its high amorphous silica content drives secondary pozzolanic reaction with calcium hydroxide, together densifying the paste matrix and improving its resistance to aggressive-ion ingress.

### 2.4 Fine aggregate

The fine aggregate used is natural river sand which fulfils the zone II grading requirement of IS 383:2016 with a fineness modulus of 2.68, specific gravity of 2.65, bulk density of 1580 $kg/m^3$ and water absorption of 0.8%. The grading that is provided here offers continuous particle size distribution throughout the fine fraction that enhances packing density, limits inter-particle friction during flow and reduces the potential for aggregate segregation (a critical requirement for passing ability of SCC).

### 2.5 Coarse Aggregate

Conventional coarse aggregate used was crushed granite which was obtained from a granite quarry near Kadapa, Andhra Pradesh, India and mixed in 10 mm and 20 mm size fraction to achieve good particle packing. The aggregate properties, including specific gravity (2.72), bulk density (1500 $kg/m^3$), water absorption (0.4%), crushing value (18%), impact value (15.5%), flakiness index (12%), and elongation index (11.5%), suggest good mechanical properties and particle shape suitable for structural grade SCC.

### 2.6 Expanded clay aggregate

The conventional coarse aggregate has been replaced by expanded clay lightweight aggregate (LECA) provided by Buildtech Aggregates, Hyderabad, India with six different replacement ratios as described in Section 2.2. The aggregate was obtained by firing the natural clay at a temperature of 1100-1200°C which gives cellular structure in the internal part of the fired mass surrounded by hard ceramic shell and the aggregate had specific gravity of 1.20, bulk density of 800$kg/m^3$, water absorption of 15% and crushing strength of 4.5MPa as per IS 9142 (Part 2):2018.

### 2.7 Super plasticizer and water

The high-range water-reducing admixture (Hrwe) used was a polycarboxylate ether (PCE) based concrete admixture (manufactured by BASF Construction Chemicals, Hyderabad, India) with a specific gravity of 1.08-1.12, pH range of 6.5 – 8.0, chloride content less than 0.1%, and air entrainment less than 2%. The 6% by binder mass was determined from preliminary trial mixtures that met the EFNARC criteria for slump flow, passing ability and segregation resistance.

Mixing and curing water had chemical purity limits that met IS 456:2000 (pH 7.2, TDS 500 mg/L, chloride 150 mg/L, sulphate 200 mg/L, no organic impurities detected) which were within the limits required for no interference with cement hydration and reinforcement durability.

### 2.8. Mix Proportions

The SCC mixtures were proportioned in accordance with EFNARC (2005) guidelines for M30 grade concrete, with reference to IS 10262:2019 for supplementary guidance on constituent proportioning. The total binder content was fixed at 452 kg/m³ across all mixtures, comprising 294 kg/m³ cement (65%), 113 kg/m³ fly ash (25%), and 45 kg/m³ silica fume (10%), at a water-to-binder ratio of 0.35 (158 L/m³). Fine aggregate content was likewise held constant at 887 kg/m³ in all mixtures to isolate the coarse-aggregate fraction as the sole experimental variable.

The coarse-aggregate fraction, equivalent to 1010 kg/m³ for the reference mixture (A1), was replaced volumetrically with EC lightweight aggregate at 0%, 20%, 40%, 60%, 80% and 100% (mixture A1B6-A1B10, respectively). The superplasticiser was added at 6% of the binder mass (27.1 kg/m³) which is the same proportion as recommended by the EFNARC to optimise the mix for the use of superplasticiser.

## 3 Experimental Programme

### 3.1 Fresh Properties

The experimental programme was designed to investigate the fresh-state properties, mechanical development and chemical durability of the EC-modified SCC mixes for the entire replacement range. The fresh properties of fresh concrete were evaluated as soon as possible after mixing, according to the EFNARC guidelines for self-compacting concrete. The mechanical properties of hardened-state were then evaluated at 7, 28, and 90 days, and the chemical properties were evaluated by exposing water-cured specimens to two aggressive media. The overall testing sequence is summarised schematically in Figure 3.

### 3.2. Mechanical Properties

#### *3.2.1 Compressive strength*.

Compressive strength was determined on 150 mm cubes tested in accordance with IS 516:2013. Three specimens were cast per mixture at each curing age (7, 28, and 90 days), giving a total of 54 cubes across the test matrix. Specimens were surface-dried immediately

before testing in a calibrated compression testing machine, and the mean of the three replicate values at each age and mix was adopted as the representative compressive strength.

#### *3.2.2 Splitting tensile strength.*

The 150 mm × 300 mm cylinder was used to split tensile resistance in accordance with IS 516:2013 and the same replication scheme, was used. There were 54 cylinders tested. Three replications were made for each age, the cylinders were surface dried and loaded diametrically to failure in a calibrated testing frame and the average of the three replications is reported as the splitting tensile strength for each age.

#### *3.2.3 Flexural strength*

The flexural property was measured on 100 mm × 100 mm × 500 mm prisms of each mixture at three curing ages subjected to two-point bending tests as per IS 516:2013, each with three specimens. There were 54 beams tested. The peak load for each specimen was recorded and the modulus of rupture calculated and the average of three replicates was regarded as the representative flexural strength.

### 3.3 Chemical Durability

Durability was evaluated by exposing 28-day water-cured cube specimens to two aggressive media. Three replicate cubes per mixture went into 5% sulphuric acid ($H_2SO_4$), another three into 5% magnesium sulphate ($MgSO_4$), and three water-cured cubes were held back as the reference set for each assessment age. Across all six mixtures, this gave 36 cubes for acid exposure, 36 for sulfate exposure. Compressive strength was measured at 28 and 90 days of immersion in line with IS 516:1959, and strength loss at each age was calculated as a percentage of the corresponding water-cured reference value.

## 4. Results and Discussion

### 4.1 Fresh properties

The slump flow and $T_{50}$ slump flow results variation is shown graph in Figure 1. The slump flow of SCC was found to vary with the addition of expanded clay (EC) aggregate, showing the highest value at 20% replacement of expanded clay aggregate (620 mm) and the lowest value (554 mm) in the control mix. At replacement levels greater than this, the slump flow dropped slightly at intermediate replacement levels and rose to 596 mm at full EC replacement. This response is caused by two antagonistic mechanisms. The lesser density of EC particles reduces interlocking of aggregates and helps to move the cement paste, improving its flowability. On the other hand, at intermediate replacement levels, the porous structure of EC will take up some of the mixing water, so there will be less free water in the EC matrix, which will temporarily lower the flow. On the other hand, the $T_{50}$ slump flow time showed a constant decrease from 4.96 s to 4.44 s as the EC content increased, suggesting a gradual decrease in plastic viscosity and enhancement of flow kinetics. For all the mixtures, their filling ability and flow stability were found to be adequate and within the requirements set by EFNARC (2005) throughout the investigated range of replacement without any significant changes in these properties.

The L-box ratio and U-box height difference (ΔH) is shown in Figure 2. The L-box ratio rose steadily for each successive increase in EC replacement with the highest ratio being 0.835 for the complete EC replacement mixture, demonstrating increasing passing ability. Lower density of the expanded clay aggregate led to less interlocking between the particles and better flowability of the concrete through narrow spaces, which allowed for smoother flow between the reinforcement bars.

The U-box ΔH, on the other hand, declined from 28.6 mm to the lowest point of 23.5 mm at 60% EC replacement and was not significantly different from this thereafter. This action is caused by the absorption of moisture by the porous EC particles and the decrease in aggregate density. The positive influence of the decreased particle weight took precedence over the increased water absorption, thus increasing the resistance to flow at intermediate replacement levels, at the higher EC content. All mixtures met the EFNARC (2005) acceptance criteria, indicating good passing ability and filling throughout the range of replacement mixtures studied.

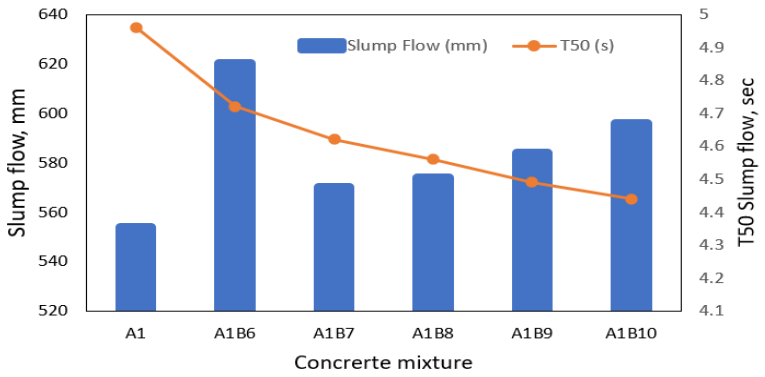


**Fig. 1.** Effect of expanded clay aggregate (EC) replacement on the slump flow and $T_{50}$ slump flow time of SCC.

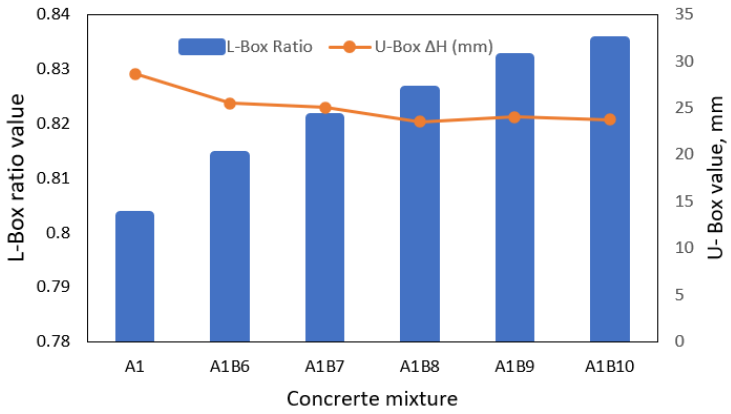

**Fig. 2.** Effect of expanded clay aggregate (EC) replacement on the L-box ratio and U-box of SCC

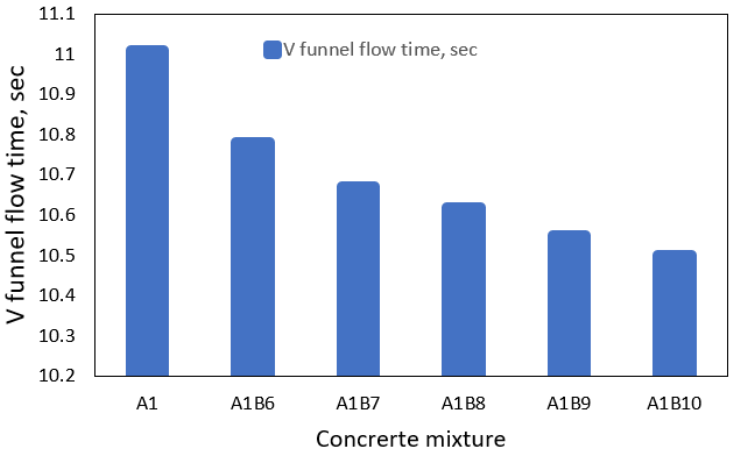


**Fig. 3.** Effect of expanded clay aggregate (EC) replacement on the V-funnel flow time of SCC

## 4.2 Mechanical Properties

### *4.2.1 Compressive Strength*

The compressive strength results are shown in Figure 4. The strength increased with EC replacement up to 20% (A1B6) with maximum strength of 27.08, 42.46 and 45.75 MPa after seven, 28 and 90 days respectively. This improvement is due to the internal curing effect of the porous EC particles, which result in continued hydration and enhancement of the cement matrix. When the replacement rate exceeds 20%, the durability of the material will gradually decrease due to the lower stiffness and higher porosity of EC. However, good strength development was observed in all the mixtures and 20% EC was found to be the optimum replacement level.

### *4.2.2 Split Tensile Strength*

The split tensile strength results are shown in Figure 5. The maximum tensile strength was found at 20% EC replacement (A1B6), with 3.93, 4.92 and 5.11 MPa at 7, 28 and 90 days respectively, like in the case of compressive strength. This improvement is credited to the improved internal curing, which provides continued hydration and strengthens aggregate–paste bond. Above 20% replacement, tensile strength started to decrease as the higher porosity, coupled with lower strength of lightweight aggregate, led to a lower resistance to cracking. However, the optimum replacement level was determined to be 20% EC and all of the mixtures performed well in terms of tensile properties.

#### *4.2.3 Flexural Strength*

The flexural strength results are given in Figure 6. The highest flexural strengths were achieved at the 20% EC replacement (A1B6) with 4.45 MPa (7 days), 5.57 MPa (28 days) and 5.78 MPa (90 days). This improvement is attributed to the enhanced internal curing phenomenon that provides continued hydration and thus better bond between the cement matrix and aggregate. When replaced with more than 20% the flexural strength gradually decreased as the presence of more porous aggregates with lower stiffness led to a less capacity to withstand crack propagation during bending. However, good flexural properties were achieved for all the mixtures with 20% EC being the best replacement ratio.

### 4.3 Durability Properties

#### *4.3.1 Sulphuric Acide attack*

The acid exposure residual compressive strength data are presented in Figure 7. A1B6 was the winner of this test as well, with 32.31 MPa and 30.42 MPa after it was immersed for 28 and 90 days. This works in conjunction with the effect of internal curing on the matrix: The denser and less porous the microstructure, the slower the penetration of the acids and the later the initiation of decalcification of the C-S-H gel. Beyond that point, however, the porosity of the aggregate begins to work against durability – increased pathways for acidic species to move through the matrix, increased deterioration rates. However, no strength loss is observed outside acceptable limits throughout all the mixtures, suggesting that pore refinement is the major reason for the acid resistance of these mixes rather than the EC aggregate.

#### *4.3.2 Magnesium Sulphate attack*

Figure 8 report the residual compressive strength data obtained following the sulphate exposure, and the trend is similar to that revealed under acid attack. Again the best results were achieved by A1B6 with 37.57 MPa and 36.14 MPa at 28 and 90 days respectively. Again, the internal curing takes the strain here, by simultaneously improving the pore structure and decreasing the connectivity of the matrix, slowing down the penetration of the sulphate ions and preventing the expansive gypsum and ettringite formation that would otherwise cause damage to the concrete from within. When replacement is greater than 20%, the porosity of the lightweight aggregate allows for more rapid ingress of sulphates which in turn creates expansive stresses, which erode any remaining strength. However, strength retention is still high at all replacement levels tested, giving a good indication that using expanded clay aggregate in limited amounts is compatible with durable, sulphate-resistant lightweight SCC.

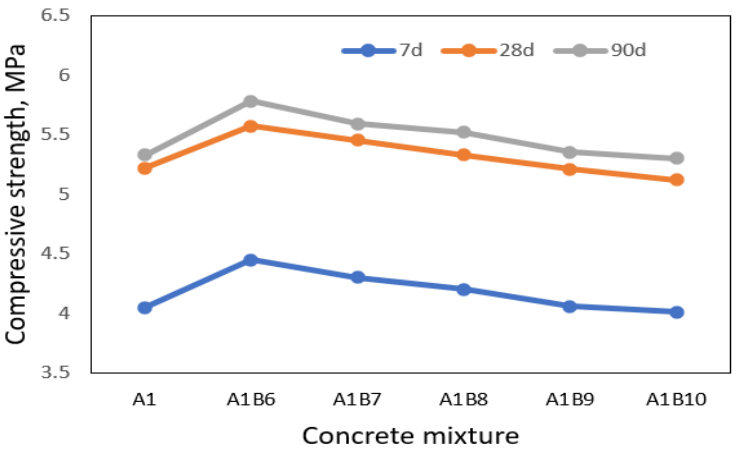


**Figure 4** Effect of expanded clay aggregate (EC) replacement on the compressive strength of SCC at different curing ages.

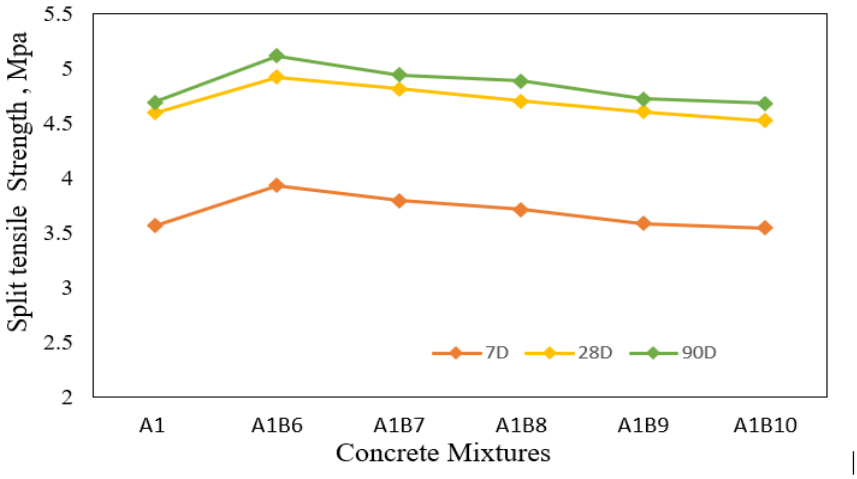


**Figure 5** Effect of expanded clay aggregate (EC) replacement on the split tensile strength of SCC at different curing ages.

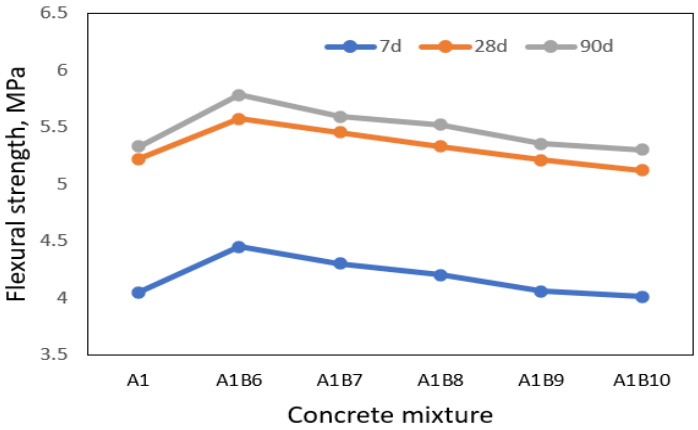


**Figure 6.** Effect of expanded clay aggregate (EC) replacement on the flexural strength of SCC at different curing ages.

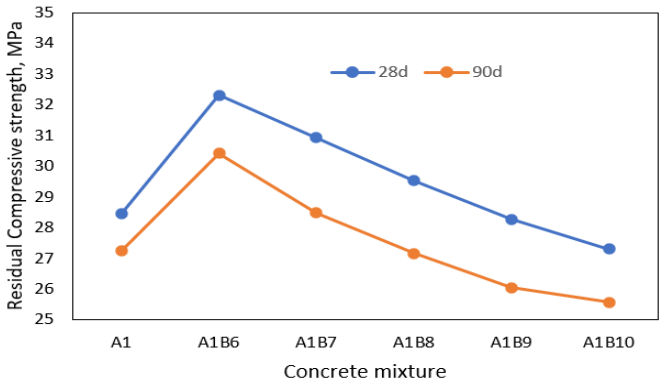


**Figure 7.** Effect of expanded clay aggregate (EC) replacement on the residual compressive strength of SCC after sulphuric acid ($H_2SO_4$) exposure.

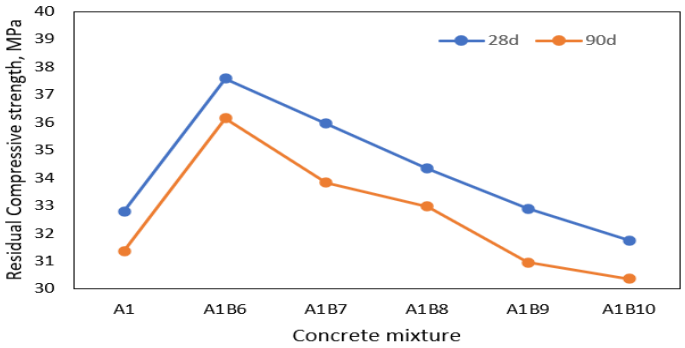


**Figure 8.** Effect of expanded clay aggregate (EC) replacement on the residual compressive strength of SCC after magnesium sulphate ($MgSO_4$) exposure.

## 5 Conclusions

Based on the experimental investigation, the following conclusions are drawn:

- All SCC mixtures satisfied the EFNARC (2005) requirements for slump flow, $T_{50}$ slump flow, V-funnel, L-box, and U-box tests, confirming that EC incorporation did not compromise workability or segregation resistance across the replacement range.
- A1B6 also demonstrated the best mechanical performance, with compressive strengths of 27.08, 42.46, and 45.75 MPa, split tensile strengths of 3.93, 4.92, and 5.11 MPa, and flexural strengths of 4.45, 5.57, and 5.78 MPa at 7, 28, and 90 days, respectively. This improvement is primarily associated with the internal curing capacity of EC, which promotes continued hydration and improves the quality of the aggregate–paste interface.
- This enhancement is mainly related to the internal curing capacity of EC that enables the hydration of cement to be maintained for a prolonged duration and enhances the quality of the aggregate paste bond. The same mixture showed to be the most durable with residual compressive strength at 28 days of 32.31 MPa after exposure to sulphuric acid and 37.57 MPa after exposure to magnesium sulphate, and at 90 days residual compressive strength was 30.42 MPa after sulphuric acid exposure and 36.14 MPa after magnesium sulphate exposure.
- It is believed to be due to the formation of a denser cementitious matrix and lower permeability. Overall experimental results showed that 20% EC replacement is the optimum dosage for obtaining sustainable self-compacting concrete, as it is most suitable to obtain the combination of properties concerning workability, mechanical properties and durability..

## Future scope

- Evaluate long-term durability under chloride ingress, carbonation, and freeze–thaw exposure.
- Conduct microstructural analysis (SEM, XRD, MIP) to clarify the internal curing mechanism.
- Assess structural-scale performance of EC-based SCC members under service loading.
- Develop predictive models for estimating fresh, mechanical, and durability properties.
- Perform life cycle and cost–benefit assessment to quantify sustainability gains.
- Explore hybridization with supplementary cementitious materials or fibres, followed by field-scale validation.

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**Data Availability:** Data is available upon request

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