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Effect of Environmentally Sustainable Materials on the Strength behaviour of Self-Curing Concrete

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Abstract: The increasing demand for sustainable construction materials has led to growing interest in the use of recycled aggregates (RA) as partial replacements for natural aggregates in concrete. However, the wider application of RA is still limited due to its higher porosity, greater water absorption, and lower mechanical strength, mainly caused by the presence of adhered old mortar. Although acid treatment has been applied to improve the quality of RA, and internal curing agents such as polyethylene glycol-400 (PEG-400) have been used to enhance cement hydration, the combined effect of these two approaches has not been thoroughly investigated. This study evaluates the influence of HCl-treated RA used together with 1% PEG-400 as a self-curing agent on the fresh and mechanical properties of concrete. The RA were incorporated at replacement levels of 0%, 10%, 20%, 30%, 40%, and 50%. The concrete mixes were assessed at 28 days through slump, compression strength, split tensile strength, flexural strength, and water absorption tests. The results show that concrete performance improved up to 20% replacement of treated RA. The slump increased from 82 mm for the control mix to 93 mm at 20% replacement. When compressive strength increased from 23.5 N/mm² to 25.5 N/mm², split tensile strength from 1.7 N/mm² to 2.3 N/mm², and flexural strength from 2.9 N/mm² to 3.5 N/mm² at the same replacement level. Water absorption also showed a slight reduction, decreasing from 3.42% to 3.20%. However, when the replacement level exceeded 30%, mechanical strengths gradually declined and water absorption increased, reaching 19.2 N/mm² compressive strength and 4.05% absorption at 50% RA. Overall, the findings indicate that the combined use of HCl-treated RA and 1% PEG-400 improves fresh and mechanical performance at moderate replacement levels, with 20% identified as the optimum proportion under the conditions investigated in this study.

Keywords: Recycled Aggregate Concrete, HCl-Treated Aggregates, PEG-400, Mechanical Properties, Water Absorption, Sustainable Concrete

1. Introduction

Concrete remains the backbone of modern construction, but its performance depends heavily on proper curing to achieve the required strength and durability [1]. The conventional curing practices, which depend on continuous water use, are often difficult to maintain, particularly in regions undergoing water scarcity and rapid urban growth [2, 3]. In such conditions, self-curing concrete has gained attention as it reduces evaporation losses and ensures continuous hydration through the incorporation of self-curing agents [4, 5]. This method not only improves the strength behaviour of concrete but besides conserves water, making it a sustainable alternative to traditional curing techniques [6].

While curing is essential, the choice of aggregates also shows an essential part in the overall performance of concrete [7]. The construction industry faces a growing challenge as the removal of normal aggregates leads to resource depletion, environmental poverty, and high energy consumption [8–10]. The RA, achieved from building and demolition waste, provide a sustainable substitute that moderates the demand for ordinary resources then minimizes waste disposal issues [11]. However, their use in concrete is limited because of their higher porosity, residual mortar content, and weaker bonding, which often result in reduced strength and durability compared to natural aggregates [12–14].

To overcome these inadequacies, treatments have been developed to enhance the quality of recycled aggregates before their use in concrete [15, 16]. Some effective approach is hydrochloric acid (HCl) treatment, which removes adhered mortar, improves the surface condition of the aggregates, and strengthens their bond with cement paste [17–19]. In addition, the use of PEG-400 as an internal curing agent provides internal water reservoirs that enhance hydration and improve the overall performance of concrete [4, 5, 20]. The combination of HCl-treated recycled aggregates and PEG-400 therefore offers a promising trail to produce concrete that is both durable and sustainable [21].

The recycled aggregate (RA) concrete has gained significant attention in recent years due to increasing environmental concerns and the urgent need to reduce construction and demolition waste. However, the widespread practical use of RA is still limited because its quality is generally inferior to that of natural aggregates. The presence of adhered old mortar on RA increases their porosity and water absorption while reducing mechanical strength. As a result, the performance of RA concrete is often lower than that of conventional concrete. To address these limitations, several researchers have proposed various treatment techniques, including acid treatment, to improve the quality of RA by removing loose and weak attached mortar. In parallel, internal curing methods using materials such as PEG-400 have been investigated to enhance cement hydration and minimize moisture loss within concrete. These approaches contribute to the formation of a denser microstructure and improved durability characteristics. However, most previous studies have examined aggregate treatment and internal curing separately [22]. Then very limited research has explored the combined effect of chemically treated recycled aggregates and self-curing agents within a single concrete system. Moreover, much of the existing literature primarily focuses on compressive strength, with comparatively less attention given to other important performance indicators such as tensile strength, flexural strength, workability, and water absorption. Consequently, there remains a lack of comprehensive understanding regarding how treated RA interact with internal curing agents and how this combination influences both mechanical and durability properties at different replacement levels. Therefore, a clear research gap exists in developing an integrated approach that simultaneously improves RA quality and enhances internal hydration in concrete. The novelty of the present study lies in the combined use of HCl-treated RA and 1% PEG-400 as a self-curing agent within an optimized mix design. Unlike earlier studies that focused on individual improvement techniques, this research systematically evaluates their combined influence on fresh properties, compressive strength, split tensile strength, flexural strength, and water absorption. In addition, the study identifies an optimum replacement level at which performance exceeds that of conventional concrete while maintaining sustainability benefits. Overall, this research provides practical and scientific insight into how treated RA and internal curing agents can work together to produce stronger, more durable, and environmentally responsible concrete suitable for structural applications.

2. Materials and Methods

2.1 Cement

PPC of grade 53 was used in this research study, conforming to IS 1489-1991 [23]. PPC was selected because of its lower heat of hydration at early ages and its ability to provide higher durability compared to ordinary Portland cement [24]. The physical properties of the cement used in this study are presented in Table 1. The PPC also reached a compressive strength of 41 N/mm², indicating its suitability for producing durable concrete.

2.2 Fine Aggregate

M-sand obtained from a local source was used as sand classified according to Zone II of IS: 383-2016 [25] in this research work. The M-sand was chosen for its consistent particle size distribution and compliance with quality requirements. The physical properties of the fine aggregate used in this study are presented in Table 1.

2.3. Coarse Aggregate

The locally available of gravel size is 20 mm, following to IS 383-2016 [25] specifications, was used in this study. The physical and mechanical properties of the normal coarse aggregate used in this study are presented in Table 1, indicated that the aggregate possessed adequate strength and toughness for structural concrete applications.

Table 1 The properties of the constituent materials used in this study

Properties	Cement	FA	NCA	RA	HCl treated RA	PEG 400
Specific gravity	3.12	2.59	2.67	2.45	2.52	1.12
Standard consistency (%)	32.3	-	-	-	-	-
Initial setting time (min)	38	-	-	-	-	-
Final setting time (min)	459	-	-	-	-	-
Bulk density (kg/m^3)	-	1653	1735	1580	1640	-
Water absorption (%)	-	2.25	0.43	4.20	2.80	-
Fineness modulus	-	2.47	6.49	6.30	6.35	-
Impact value (%)	-	-	21.7	28.5	24.8	-
Crushing value (%)	-	-	23.63	30.2	26.4	-
pH	-	-	-	-	-	7.5
Molecular weight	-	-	-	-	-	400 g/mole

2.4 Water

The clean drinkable water, allowed after impurities, existed used for both mixing and preserving of the concrete. The water complied with IS 456-2000 [26] standards, having a pH of 7.3, which falls within the permissible range of 6.5 to 8.0. It was ensured that the water had no adverse effect on the properties of the concrete.

2.5 Self-Curing Agent (PEG-400)

PEG-400 was used as the self-curing agent in this investigation. The specified percentage refers to the as-supplied liquid form of PEG-400, which was used directly as received from the manufacturer without any correction for active content. The selection of the 1% dosage was based on previous research findings, which indicate that PEG-400 in the range of 0.5% to 2% by weight of cement is effective in enhancing internal curing while maintaining mechanical performance. Based on literature evidence and preliminary trial mixes conducted in this study, 1% was found to provide an optimal balance between strength development, workability, and internal moisture retention. The higher dosages were not adopted to avoid potential retardation of hydration and possible reduction in strength. When PEG-400 was dissolved in a portion of the mixing water prior to its addition to ensure uniform dispersion throughout the concrete matrix. As PEG-400 was introduced in liquid form, its volume was considered part of the total mixing liquid. However, no separate reduction in mixing water was made, since the quantity used was relatively small and did not significantly affect the effective water–cement ratio. The total mixing water content was maintained constant across all mixes to ensure consistency and enable reliable comparison of results [4, 5, 27]. The physical properties of the PEG-400 used in this study are presented in Table 1.

2.6. Recycled Aggregate (RA)

The recycled aggregates (RA) used in this investigation were sourced from demolished reinforced concrete structural elements obtained from a local construction and demolition waste processing facility. According to supplier documentation and site verification, the parent concrete was approximately of M25–M30 structural grade, which is commonly used in building construction. The demolished concrete was estimated to be more than 10 years old, ensuring that the parent material had fully matured prior to crushing and reuse. Before processing, the demolition waste was carefully sorted both manually and mechanically to remove contaminants such as reinforcing steel, wood, plastics, glass, soil, and other foreign materials. The cleaned concrete debris was then crushed using a jaw crusher and subsequently sieved to obtain the required 20 mm nominal size coarse aggregate fraction. Only clean, well-graded aggregate particles were selected for use in the experimental program. Due to the presence of adhered mortar on the surface of the recycled aggregates, the RA exhibited slightly lower specific gravity and higher water absorption compared to natural coarse aggregates. These properties were determined through standard laboratory tests and are recognized as typical indicators of adhered mortar content in recycled aggregates. In addition, abrasion resistance and aggregate impact values were evaluated and found to be within permissible limits for structural concrete applications. The physical and mechanical properties of the RA used in this study are presented in Table 1.

2.7 HCL Treatment of RA

To improve the quality of RA by reducing adhered mortar and surface impurities, a dilute hydrochloric acid (HCl) treatment was adopted. A 0.1 M HCl solution was selected based on findings reported in previous studies, which indicate that low-concentration acid treatment effectively removes a portion of the adhered mortar without causing significant damage to the natural aggregate core. The higher acid concentrations may result in excessive surface degradation and potential strength reduction; therefore, a mild concentration of 0.1 M was chosen to achieve controlled surface modification. The immersion duration of 24 hours was selected to ensure sufficient interaction between the acid solution and the adhered cement paste, allowing partial dissolution of loose mortar and calcium hydroxide deposits. The RA were immersed in the acid solution using a liquid-to-solid ratio of 3:1 by volume to ensure complete submergence and uniform exposure of all particles. The solution was not renewed during the 24-hour treatment period, as the selected ratio provided adequate reaction capacity for the quantity of aggregates treated. After the treatment period, the aggregates were thoroughly rinsed several times with clean tap water to remove residual acid and dissolved reaction products. The rinsing was continued until the pH of the final rinse water reached near-neutral conditions. The final rinse pH was measured using a digital pH meter and recorded in the range of 6.8–7.2, confirming effective removal of residual acidity. The treated aggregates were then air-dried to saturated surface dry condition before being used in concrete production. This controlled HCl treatment procedure improved the surface characteristics of the RA while preventing excessive degradation, thereby enhancing the reliability and reproducibility of the experimental work [28, 29] and methodology flow schematic diagram for presented in Figure.1. The physical and mechanical properties of the HCl-treated RA used in this study are presented in Table 1.

2.8 Aggregate Gradation & Particle Size Distribution

To eliminate the effect of aggregate gradation on strength performance, a detailed sieve analysis was carried out for both natural aggregate and treated RA in accordance with relevant standard procedures. The particle size distribution curves of both aggregates are presented in Figure.2.

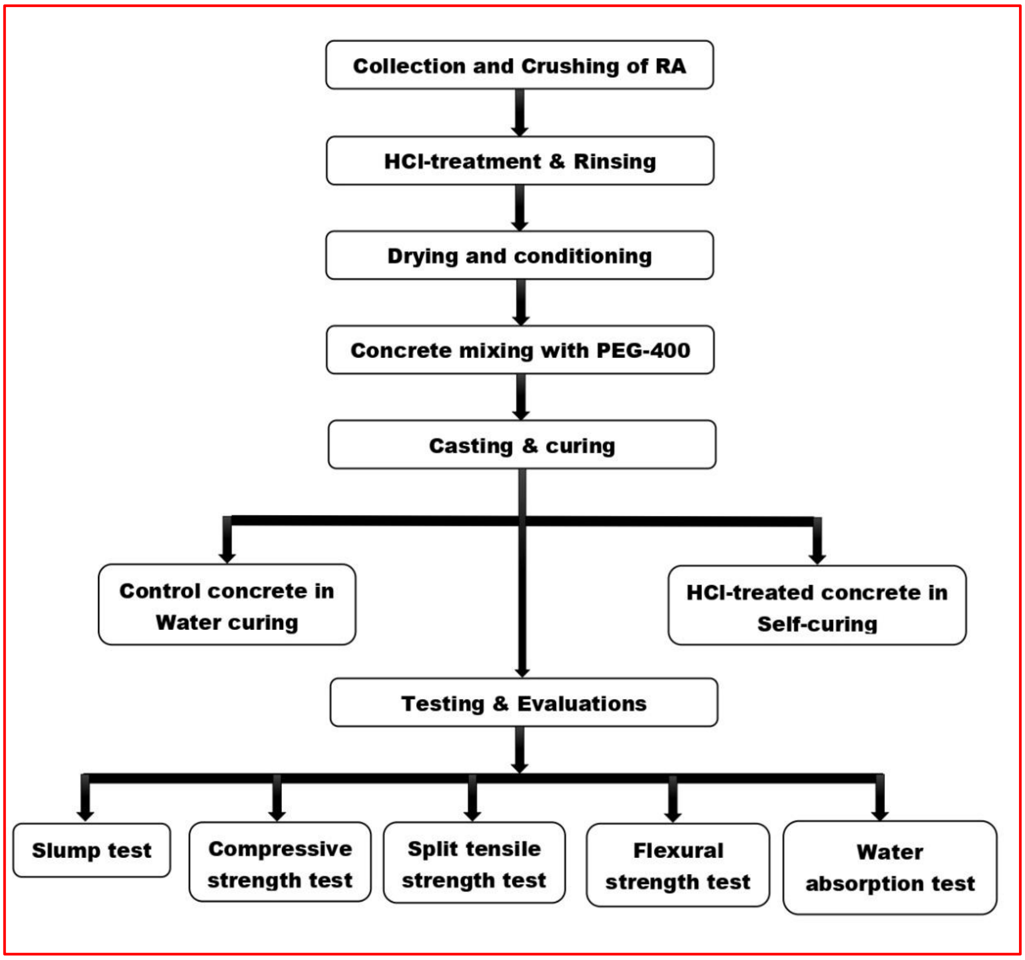

Figure 1. Methodology

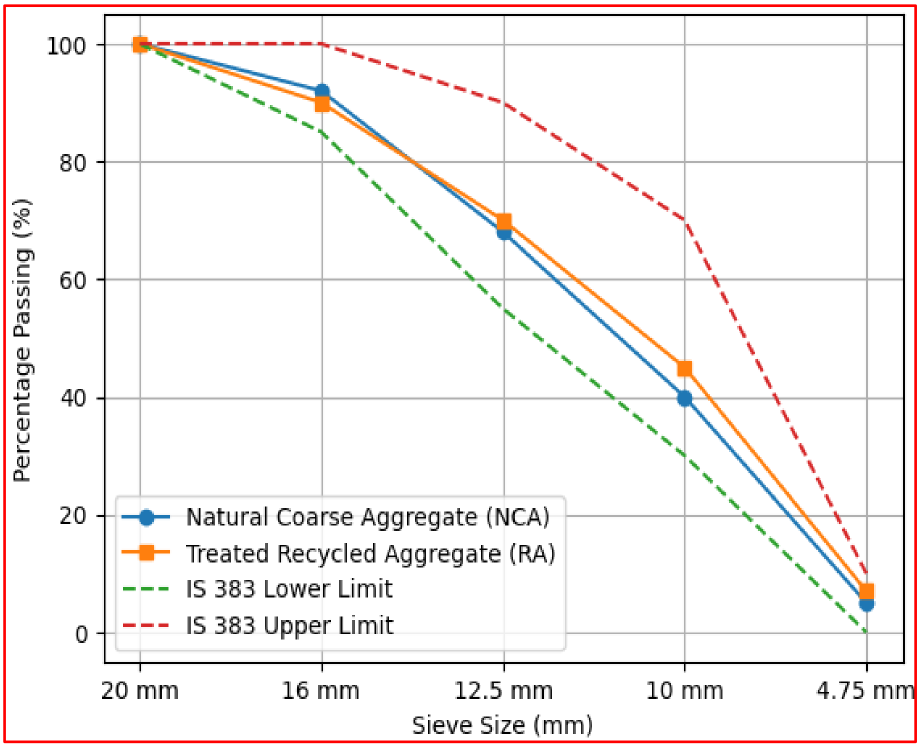

Figure 2. Grading curves for Natural aggregate and Treated RA

The results show that both natural aggregate and treated RA satisfy the permissible grading limits specified for 20 mm nominal size coarse aggregates. In order to ensure that variations in strength were not affected by differences in aggregate gradation, the combined coarse aggregate grading was maintained identical across all concrete mixes. For mixtures incorporating treated RA, replacement was performed on a weight basis while preserving the overall particle size distribution of the control mix. The proportions of each size fraction were carefully adjusted so that the blended grading curve of the coarse aggregates in all mixes closely matched the control grading envelope. By maintaining a consistent combined coarse aggregate grading for all mixtures, the potential influence of gradation-driven strength differences was minimized. Therefore, any observed variations in mechanical properties can be primarily attributed to the intrinsic characteristics of the treated RA and the self-curing system, rather than to differences in aggregate size distribution.

2.9 Mix proportion

In this experimental work, six different concrete mixes were prepared with a grade of concrete M20 and mix proportion was considered of 1:1.51:3.00 with a w/c ratio of 0.45, as per guidelines of IS: 10262-2009 [30]. When all materials were batched by weight using a calibrated digital weighing balance to ensure accuracy and consistency. A pan mixer with a capacity of 100 kg per batch was used, and approximately 60 kg of concrete was prepared for each mix. Initially, the coarse and fine aggregates were introduced into the mixer and dry mixed for one minute. Subsequently, cement and other binder materials were added and dry mixed for an additional two minutes to achieve uniform distribution. About 70% of the total mixing water was then added gradually and mixed for two minutes. The remaining 30% of the mixing water, containing pre-dissolved PEG-400, was slowly introduced into the rotating mixer. Final mixing was continued for three more minutes to obtain a homogeneous and uniform concrete mixture, resulting in a total mixing time of approximately eight minutes. The PEG-400 was incorporated at a dosage of 1% by weight of cement. To ensure proper dispersion and to avoid localized concentration within the mix, PEG-400 was completely dissolved in a portion of the mixing water before being added to the concrete. The direct addition of PEG-400 without dilution was avoided. This procedure ensured uniform distribution of the self-curing agent throughout the concrete matrix and enhanced the effectiveness of internal curing. After casting, all specimens were demoulded after 24 ± 2 hours. The conventional concrete specimens were subjected to standard water curing, whereas the SCC specimens were stored under controlled laboratory conditions without any external water curing. The environmental conditions were maintained at a temperature of 27 ± 2°C and a relative humidity of 65 ± 5% for a curing period of 28 days [5, 31, 32]. In total, 57 specimens were prepared for this research work, consisting of 21 cubes, 18 cylinders, and 18 prisms. As shown in Figure.3, indicates to preparation process of the sustainable concrete using the selected materials. The detailed mix proportion of essential materials are presented in Table 2.

Table 2. Mix proportions based on the selected sustainable materials

Mix id	% of RA	Cement (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	HCL treated RA (Kg/m^3)	Water (Kg/m^3)	PEG-400 (Kg/m^3)
SCR-0	0	420.51	635.23	1265.21	---	190	---
SCR-1	10	420.51	635.23	1138.69	126.52	190	4.20
SCR-2	20	420.51	635.23	1012.17	253.04	190	4.20
SCR-3	30	420.51	635.23	885.65	379.56	190	4.20
SCR-4	40	420.51	635.23	759.13	506.08	190	4.20
SCR-5	50	420.51	635.23	632.61	632.60	190	4.20

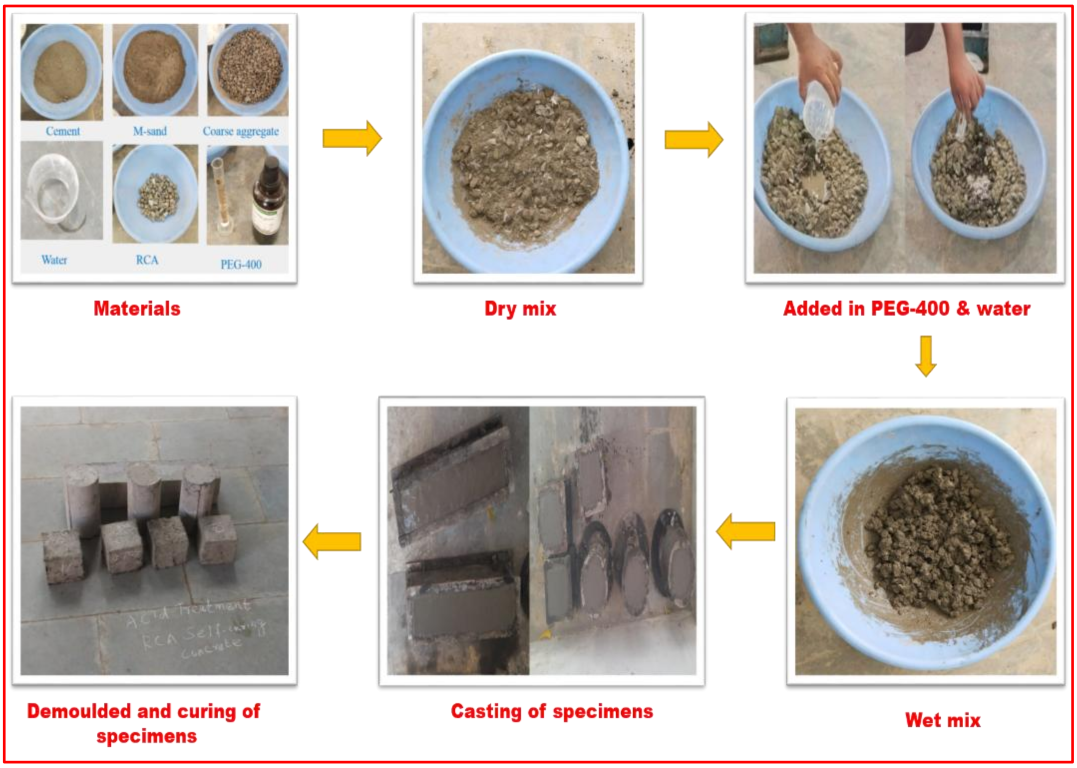

Figure 3. Mixing and Casting of Specimens

3. Experimental Testing

The workability of the prepared concrete mixes was evaluated by the slump test to evaluate their workability using their slump cone test for selected sustainable materials. All mechanical tests were conducted in accordance with the relevant IS specifications to ensure reliability and reproducibility of the results. The compression strength was performed as per IS 516:2018 using cube specimens of size 100 mm × 100 mm × 100 mm, and the specimens were tested at 28 days of age. Prior to testing, the specimen surfaces were cleaned to remove any loose particles, and the cubes were placed centrally in the compression testing machine such that the load was applied perpendicular to the casting direction. The load was applied at a uniform rate of 0.6 ± 0.2 MPa/s until failure, and the compression strength was calculated by dividing the maximum load by the cross-sectional area of the specimen. The tensile strength test was carried out in accordance with IS 5816:1999 using cylindrical specimens of 100 mm diameter and 200 mm height, tested at 28 days. Before testing, thin plywood strips of approximately 3 mm thickness were placed between the specimen and the loading platens to ensure uniform load distribution and to minimize stress concentration. The load was applied continuously without shock at a rate corresponding to 1.2 to 2.4 MPa/min until failure occurred along the vertical diameter, and the split tensile strength was calculated using the standard expression. The flexural strength test was conducted as per IS 516:2018 using prism specimens of size 100 mm × 100 mm × 500 mm at 28 days of age. A two-point loading arrangement with an effective span of 400 mm was adopted. The load was applied at a constant rate of stress increase of approximately 0.1 MPa/s until failure, and the modulus of rupture was computed based on the maximum load recorded during testing. All testing machines were periodically calibrated using certified calibration devices to ensure accuracy, and the exact age of each specimen was calculated from the date and time of casting to the time of testing [33]. All mechanical tests were performed using standard equipment of 200-TON capacity CTM for cube and cylinder testing and a 400 KN capacity UTM for flexural strength evaluation.

4. Result and Discussion

4.1 Workability

The slump test results for all mixes are presented in Table 3. The control mix (SCR-0), produced without PEG-400 and without RA, exhibited a slump value of 82 mm. Upon incorporation of 1% PEG-400 and HCl-treated RA, variations in workability were observed depending on the replacement level. The recorded slump values were 85 mm for SCR-1 (10% RA), 93 mm for SCR-2 (20% RA), 80 mm for SCR-3 (30% RA), 75 mm for SCR-4 (40% RA), and 72 mm for SCR-5 (50% RA). As shown in Figure.4, a noticeable improvement in slump was observed at lower replacement levels, particularly at 10% and 20% treated RA. The maximum slump of 93 mm was achieved at 20% replacement. This enhancement in workability can be attributed to the combined effect of PEG-400 and the acid treatment of RA. When PEG-400 likely contributed to improved particle lubrication and internal moisture retention, thereby enhancing flow characteristics. Simultaneously, HCl treatment may have removed loosely adhered mortar and surface impurities, resulting in relatively cleaner aggregate surfaces and improved paste–aggregate interaction at lower replacement levels. Beyond 20% replacement, a gradual reduction in slump was observed. At 30%, 40%, and 50% RA content, the slump decreased to 80 mm, 75 mm, and 72 mm, respectively. This decline can be explained by the intrinsic characteristics of recycled aggregates. Despite acid treatment, recycled aggregates generally possess higher surface roughness and residual porosity compared to natural aggregates. As the RA content increases, internal friction among particles rises and a greater portion of mixing water is absorbed into the aggregate pores. Consequently, the amount of free water available for lubrication decreases, leading to reduced workability. Although PEG-400 aids in internal moisture retention, it cannot fully compensate for the increased water demand associated with higher RA content. Therefore, the mixes tend to become relatively stiffer at elevated replacement levels. From a practical perspective, all mixes exhibited slump values ranging from 72 mm to 93 mm, which fall within the acceptable range for medium-workability concrete suitable for general structural applications [12, 14, 16]. The results suggest that replacement levels up to approximately 20% can maintain or slightly enhance workability without additional modifications. At higher replacement levels, minor adjustments in water content or admixture dosage may be necessary to achieve the desired consistency. Overall, the findings demonstrate that the combined use of HCl-treated RA and 1% PEG-400 can produce workable concrete. Nevertheless, careful control of recycled aggregate content is essential to ensure consistent fresh-state performance.

4.2 Compression Test

The compression strength results for all mixes are presented in Table 3. The control mix (SCR-0), produced without PEG-400 and without RA, achieved a 28-day compression strength of 23.5 N/mm². With the incorporation of 1% PEG-400 and HCl-treated RA, the compression strength initially increased and then gradually decreased as the replacement level increased.

Table 3. Test results on sustainable concrete for selected materials

Mix id	PEG-400 (%)	HCL treated RA (%)	Slump in (mm)	Compressive strength (N/mm²)	Split tensile strength (N/mm²)	Flexural strength (N/mm²)	Water absorption (%)
SCR-0	0	0	82	23.5	1.7	2.9	3.42
SCR-1	1	10	85	24.1	2.1	3.3	3.28
SCR-2	1	20	93	25.5	2.3	3.5	3.20
SCR-3	1	30	80	22.3	1.5	2.7	3.60
SCR-4	1	40	75	21.5	1.3	2.5	3.82
SCR-5	1	50	72	19.2	1.1	2.2	4.05

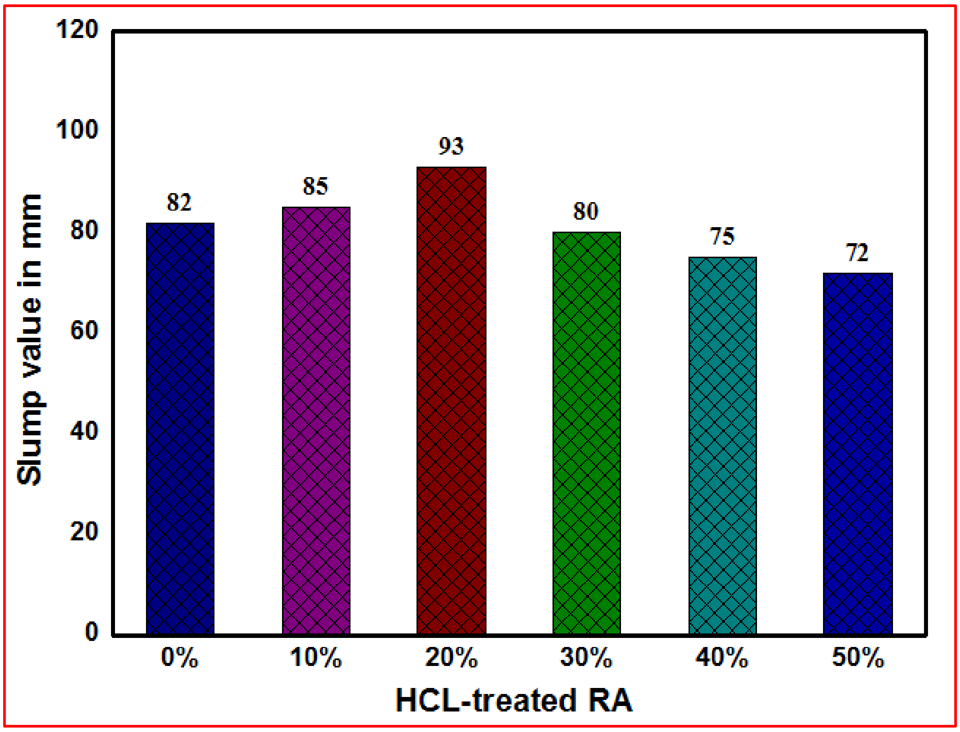

Figure 4. Results for Slump cone test

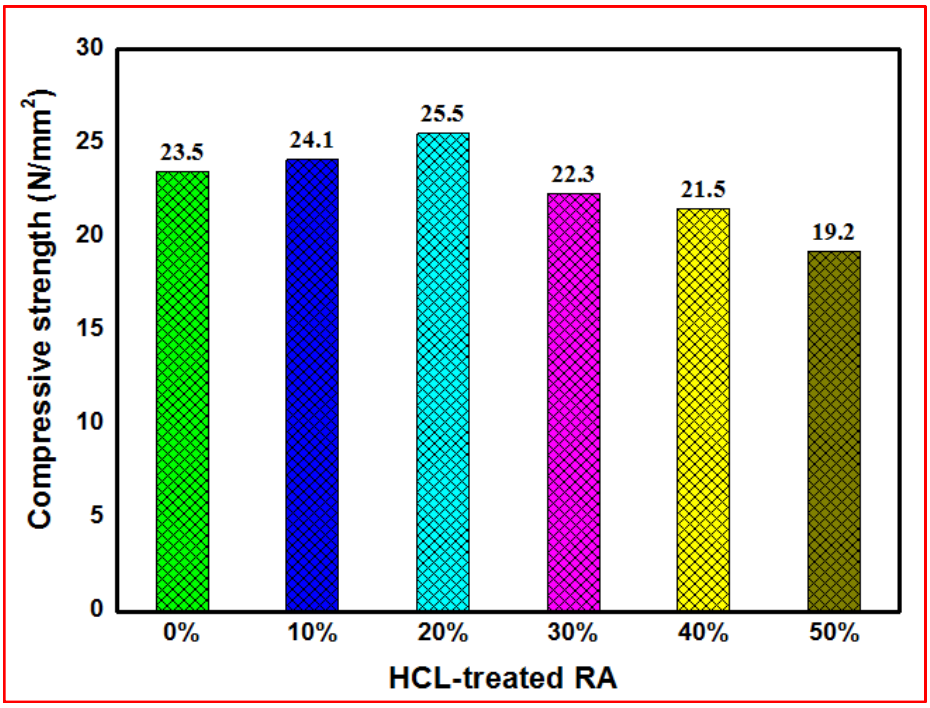

Figure 5. Results for Compressive strength test

The measured strengths were 24.1 N/mm² for SCR-1 (10% RA), 25.5 N/mm² for SCR-2 (20% RA), 22.3 N/mm² for SCR-3 (30% RA), 21.5 N/mm² for SCR-4 (40% RA), and 19.2 N/mm² for SCR-5 (50% RA). As shown in Figure.5, the compression strength improved compared to the control mix up to a replacement level of 20%. The highest strength, 25.5 N/mm², was recorded for SCR-2, representing a noticeable enhancement over the conventional mix. This improvement can be attributed to the combined influence of acid treatment and internal curing provided by PEG-400. The HCl treatment likely removed loosely adhered and weak residual mortar from the RA, resulting in improved surface quality and better bonding between the aggregate and the newly formed cement paste. At the same time, PEG-400 contributed to internal moisture retention, promoting more complete cement hydration. The enhanced hydration generally leads to a denser and more compact microstructure, which directly supports improved compression strength. However, beyond 20%

replacement, a consistent decline in compression strength was observed. At 30%, 40%, and 50% RA content, the strength gradually decreased. This reduction is primarily associated with the essential properties of RA. Despite acid treatment, RA still contain residual adhered mortar, which is more porous and mechanically weaker than natural aggregates. As the recycled aggregate content increases, the overall stiffness and integrity of the concrete matrix are reduced. Furthermore, the ITZ between RA and new cement paste may remain comparatively weaker, particularly at higher replacement levels, contributing to reduced load-carrying capacity. Although PEG-400 enhances hydration and helps limit internal micro cracking, its beneficial effect is not sufficient to completely offset the mechanical limitations introduced by high RA content. Consequently, at replacement levels exceeding 30%, the adverse effects of increased porosity and reduced aggregate strength become more pronounced, leading to lower compression strength values [18, 19, 21].

From a practical perspective, mixes up to 40% replacement still achieved strengths above 20 N/mm², satisfying the minimum requirement for M20 grade concrete. Nevertheless, the optimum performance was clearly observed at 20% replacement, where improved strength was achieved without compromising durability or sustainability objectives. Overall, the findings suggest that HCl-treated RA can be effectively incorporated in concrete when combined with 1% PEG-400, particularly at moderate replacement levels. The careful optimization of RA content is essential to balance mechanical performance and sustainable material utilization.

4.3 Split Tensile Test

The tensile strength results for all mixes are presented in Table 3. The control mix (SCR-0), prepared without PEG-400 and without RA, achieved a 28-day tensile strength value of 1.7 N/mm². With the incorporation of 1% PEG-400 and HCl-treated RA, the tensile strength initially increased and then decreased as the replacement level increased. The measured strengths were 2.1 N/mm² for SCR-1 (10% RA), 2.3 N/mm² for SCR-2 (20% RA), 1.5 N/mm² for SCR-3 (30% RA), 1.3 N/mm² for SCR-4 (40% RA), and 1.1 N/mm² for SCR-5 (50% RA). As shown in Figure.6, a clear improvement in tensile strength was observed up to 20% replacement.

The highest value, 2.3 N/mm², was recorded at 20% RA, representing a significant increase compared to the control mix. This enhancement can be attributed to the combined influence of acid treatment and internal curing. The HCl treatment likely improved the surface condition of the RA by removing weak and loosely adhered old mortar, thereby enhancing the bond between the aggregate and the new cement paste. At the same time, PEG-400 contributed to improved internal moisture retention, promoting more complete cement hydration. Since tensile strength is highly sensitive to micro cracks and the quality of the ITZ, improved bonding and a denser microstructure directly contribute to better tensile performance. However, when the RA content exceeded 20%, a marked reduction in tensile strength was observed.

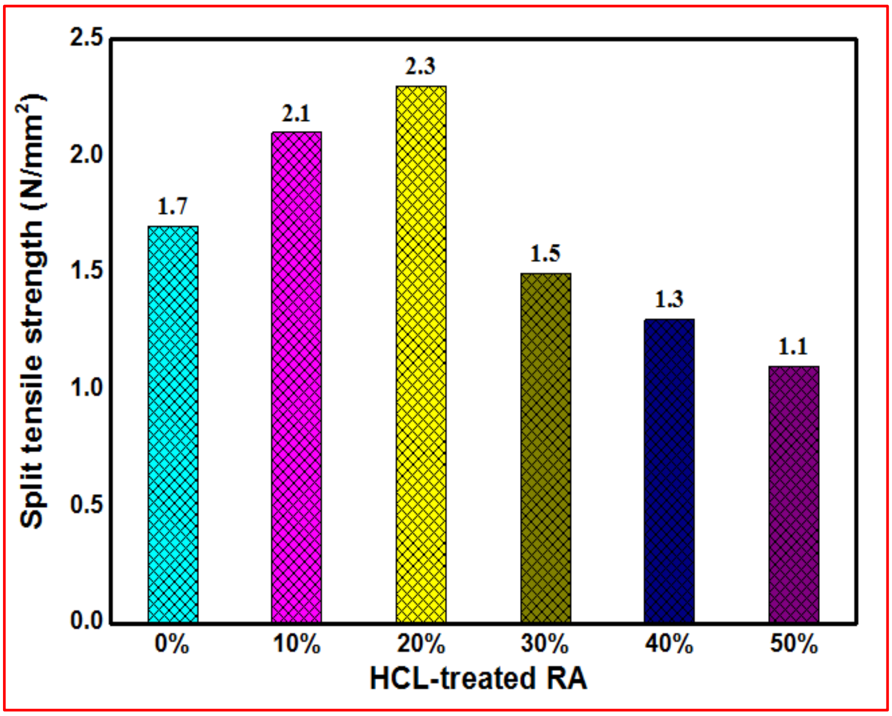

Figure 6. Results for Split tensile strength test

At 30%, 40%, and 50% replacement levels, the strength decreased progressively. This decline is mainly associated with the intrinsic characteristics of recycled aggregates. When the even after acid treatment, some residual adhered mortar remains, which is generally more porous and mechanically weaker than natural aggregate. As the RA content increases, the proportion of weaker zones within the concrete also increases, making it more susceptible to crack initiation and propagation under tensile loading. Although PEG-400 enhances hydration and may help reduce internal micro cracking, its beneficial effect becomes insufficient at higher replacement levels where the weaker aggregate structure governs the mechanical response. This explains the significant drop in tensile strength beyond 30% replacement. From a practical perspective, replacement levels up to 20% appear to improve tensile performance while contributing to sustainable material utilization.

In contrast, higher replacement levels may adversely affect cracking resistance and structural reliability unless additional mix modifications are introduced [4, 7, 11]. Overall, the findings indicate that HCl-treated RA can be effectively used in combination with 1% PEG-400 at moderate replacement levels. When careful optimization of RA content is therefore essential to maintain adequate tensile strength while achieving environmental and sustainability benefits.

4.4 Flexural Strength Test

The flexural strength results for all mixes are presented in Table 3. The control mix (SCR-0), prepared without PEG-400 and without RA, achieved a 28-day flexural strength of 2.9 N/mm². With the incorporation of 1% PEG-400 and HCl-treated RA, the flexural strength initially increased and then gradually decreased as the replacement level increased. The measured strengths were 3.3 N/mm² for SCR-1 (10% RA), 3.5 N/mm² for SCR-2 (20% RA), 2.7 N/mm² for SCR-3 (30% RA), 2.5 N/mm² for SCR-4 (40% RA), and 2.2 N/mm² for SCR-5 (50% RA). As shown in Figure.7, a clear improvement in flexural strength was observed up to 20% replacement. The highest value, 3.5 N/mm², was recorded at 20% RA, indicating a noticeable enhancement compared to the control mix. This improvement can be attributed to the combined effects of acid treatment and internal curing. The HCl treatment likely improved the surface condition of the RA by removing weak and loosely adhered old mortar, resulting in better bonding between the aggregates and the newly formed cement paste. Simultaneously, PEG-400 contributed to internal moisture retention, promoting more complete cement hydration. Improved hydration leads to a denser cement matrix and stronger interfacial transition zones, both of which play a critical role in resisting bending stresses. However, when the RA content exceeded 20%, a steady reduction in flexural strength was observed. At 30%, 40%, and 50% replacement levels, the strength decreased progressively. This decline is primarily associated with the inherent characteristics of RA. Despite acid treatment, some residual adhered mortar remains, which is generally more porous and mechanically weaker than natural aggregates. As the proportion of RA increases, the overall stiffness of the concrete decreases, making it more susceptible to crack initiation and propagation under flexural loading. Although PEG-400 enhances hydration and may help limit micro crack formation, its beneficial effect becomes less significant at higher replacement levels where the weaker aggregate structure governs the mechanical response.

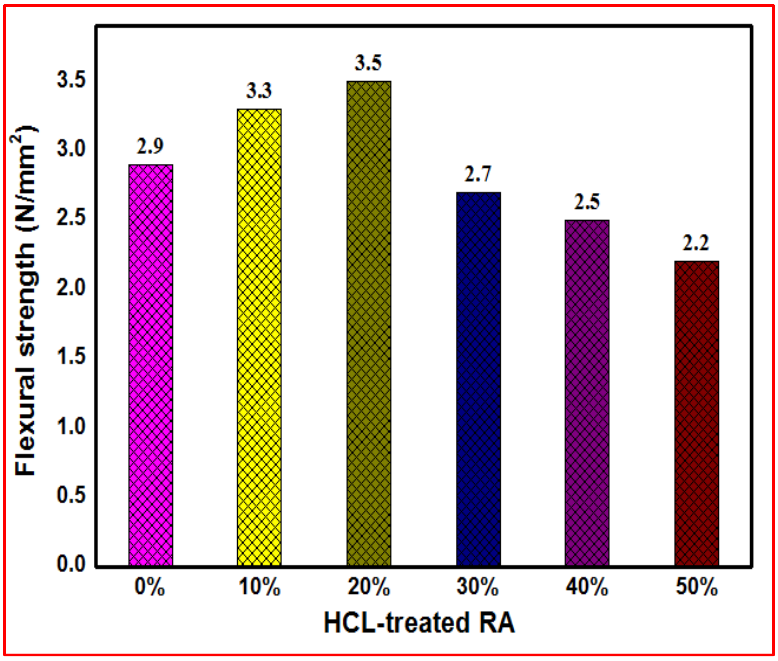

Figure 7. Results for flexural strength test

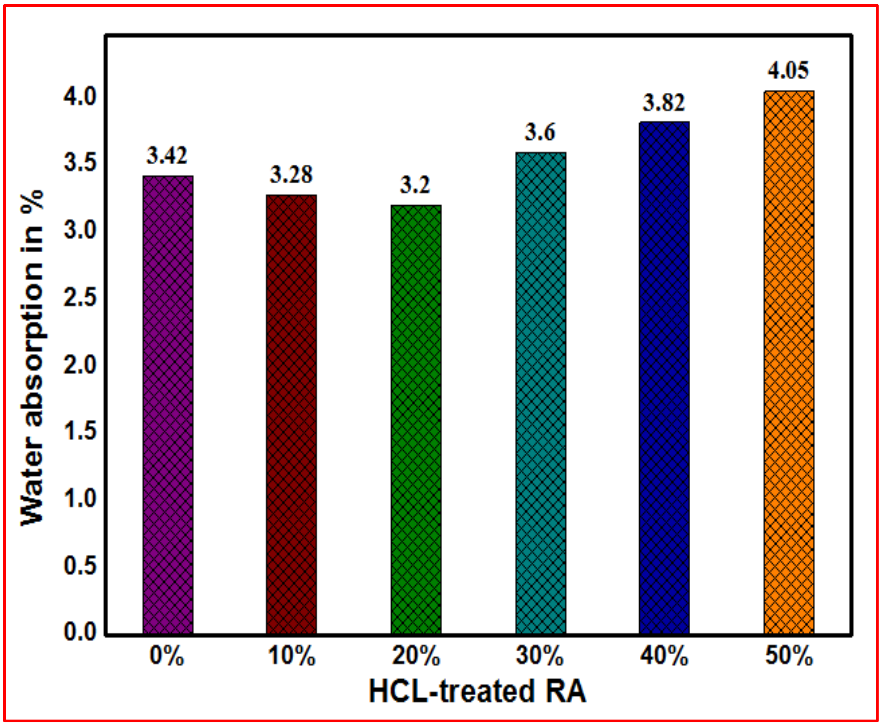

Figure 8. Results for Water absorption test

This explains the noticeable reduction in flexural strength beyond 30% replacement [3, 4, 9]. From a practical perspective, replacement levels up to 20% not only maintain but improve flexural performance while contributing to sustainable material utilization. In contrast, higher replacement levels may require further optimization of the mix design if flexural strength is a critical performance requirement. Overall, the results demonstrate that HCl-treated RA can be effectively incorporated in concrete with 1% PEG-400 at moderate replacement levels. They are careful control of RA content is essential to achieve a balanced combination of mechanical performance and sustainability.

4.5 Water Absorption Test

The water absorption results for all mixes are presented in Table 3. The control mix (SCR-0), produced without PEG-400 and without RA, presented a 28-day water absorption value of 3.42%. With the incorporation of 1% PEG-400 and HCl-treated RA, a discrete variation in absorption behaviour was observed depending on the replacement level. The measured values were 3.28% for SCR-1 (10% RA), 3.20% for SCR-2 (20% RA), 3.60% for SCR-3 (30% RA), 3.82% for SCR-4 (40% RA), and 4.05% for SCR-5 (50% RA). As shown in Figure.8, a slight reduction in water absorption was observed at lower replacement levels (10% and 20%) compared to the control mix. The lowest absorption value, 3.20%, was recorded at 20% RA. This improvement can be attributed to the combined influence of acid treatment and internal curing. The HCl treatment likely enhanced the surface condition of the RA by removing weak and loosely adhered old mortar, thereby reducing surface defects and improving aggregate quality. Simultaneously, PEG-400 contributed to improved internal moisture retention, promoting more complete cement hydration. The enhanced hydration typically leads to a denser and more compact microstructure, which reduces capillary porosity and limits water ingress. However, when the RA content exceeded 20%, water absorption increased progressively. At 30%, 40%, and 50% replacement levels, the absorption values design steadily. This increase is primarily associated with the inherent characteristics of RA. Despite acid treatment, RA still retain some residual adhered mortar, which is generally more porous than natural aggregate. As the proportion of RA increases, the overall porosity of the concrete matrix also increases, creating additional pathways for water penetration. Although PEG-400 supports hydration and contributes to matrix densification, its beneficial effect becomes less significant at higher replacement levels where the porous nature of recycled aggregates governs the behaviour. Consequently, beyond 30% replacement, the increase in water absorption becomes more pronounced [31, 18, 12]. From a durability perspective, all mixes exhibited water absorption values below 5%, indicating acceptable performance for general structural applications. The results suggest that replacement levels up to 20% can slightly enhance resistance to water penetration while contributing to sustainable material utilization. In contrast, higher replacement levels may require additional mix optimization if long-term durability is a critical requirement. Overall, the findings establish that HCl-treated RA can be effectively utilized in combination with 1% PEG-400 at moderate replacement levels to produce concrete with controlled and acceptable water absorption characteristics.

5. Conclusion

This study evaluated the influence of HCl-treated RA combined with 1% PEG-400 as a self-curing agent on the fresh, mechanical, and durability properties of concrete. The results indicate that concrete performance is strongly dependent on the percentage of RA replacement. The workability improved initially, with the maximum slump value of 93 mm recorded at 20% RA replacement (SCR-2), compared to the control mix. This improvement can be attributed to enhanced particle interaction and improved internal moisture retention resulting from acid treatment and PEG-400 incorporation. Similarly, the highest compressive strength of 25.5 N/mm² was achieved at 20% replacement, exceeding the control mix strength of 23.5 N/mm², which reflects improved interfacial transition zone characteristics and enhanced hydration due to the internal curing effect. The split tensile and flexural strengths followed a similar trend, increasing up to 20% replacement and declining beyond 30% because of increased porosity and the presence of weaker adhered mortar in RA. The water absorption slightly decreased at 10–20% replacement levels, indicating improved matrix densification, but increased progressively at higher RA contents. Nevertheless, all mixes exhibited water absorption values below 5%, meeting durability requirements for conventional structural applications. Overall, optimum performance was observed at 20% HCl-treated RA with 1% PEG-400, providing a balanced combination of strength, workability, and durability. However, the study is limited to short-term mechanical and water absorption evaluations, and further investigation on long-term durability behaviour and microstructural characteristics is recommended.

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Authors Contribution Statement

Dhavamanidoss Sakthidoss: Validation, Supervision, Methodology. Ganesan Sundaramoorthy: Writing – Original Draft, Investigation, Data analysis. D. Maruthachalam: Supervision, Project administration, Funding acquisition. P. Hema: Supervision, Project administration. S.P.M. Kannan: Writing – Review & Editing. T.C. Manjunath: Writing – Review & Editing. S. Gopikumar: Conceptualization, Methodology. All the authors have read and agreed to the published version of the manuscript.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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