

Experimental Investigation of M25 Steel Fibre Reinforced Concrete with 100% Recycled Coarse Aggregate

Sant Prakash Mehta
 B.I.T. Sindri, Jharkhand

ABSTRACT

In recent years, the construction industry has seen a growing trend towards using recycled aggregates (RA) as a more environmentally-friendly and sustainable alternative to natural coarse aggregates, in order to minimize the use of natural aggregates and the environmental effects of construction and demolition waste. The research on the use of 100% recycled coarse aggregates (RCA) along with steel fibre reinforcement is still limited. In this study, recycled aggregate concrete (RAC) has been prepared using 100% of the RAC as the coarse aggregate and the impact of steel fibres on fresh and mechanical properties have been examined. The experimental results suggest that the 100% recycled coarse aggregate can be used for concrete so that the workability of concrete can be improved, as evidenced by the increase of the slump value. However, the addition of steel fibres causes the slump to be reduced by 10.34% to 27.58% as a result of less flowability of the concrete. The mechanical test shows that the replacement of the natural coarse aggregates with recycled coarse aggregates decreases 28 day compressive strength by 45.03% and split tensile strength by 52.86%. The addition of steel fibres is a good countermeasure for these loss of strength and increase the compressive strength and split tensile strength of recycled aggregate concrete by 13.72% and 7.13% at 28 days respectively. The results show that the inclusion of steel fibres greatly improved the mechanical properties of RAC, which makes it a potential and sustainable material to be used in structural applications and enables efficient reuse of construction and demolition waste.

TABLE OF CONTENT

CHAPTER 01: INTRODUCTION	
1.1 General	
1.2 Historical Reinforced Concrete	
1.3 Chemistry within the Fibre Matrix	
1.4 Bridging Action	
1.5 Applications of SFRC	
1.6 Advantages of SFRC	
1.7 Cases of SFRC Projects in India	
1.8 Objectives of the Study	
1.9 Significance of the Study	
CHAPTER 02: LITRATURE REVIEW	
2.1 General	

2.2 Review of Technical Papers	
2.3 Research Gap	
CHAPTER 03: METHODOLOGY	
3.1 General	
3.2 Objectives and Hypotheses	
3.3 Design of Materials and mix	
3.4 Casting, Curing and Specimen Schedule	
3.5 Testing Procedures	
CHAPTER 04: RESULT AND DISCUSSION	
4.1 Workability properties of recycled aggregate concrete	
4.2 Compressive Strength Test	
4.3 Split Tensile Strength Test	
CHAPTER 05: CONCLUSION	
CHAPTER 06 : REFFRENCES	

CHAPTER 1 : INTRODUCTION

1.1 General

The Concrete as a Construal Material. One of the most significant building materials that are applied in building constructions is concrete. In most ways, concrete determines the material nature of the modern infrastructure. Industrial facilities, housing, and roads, as well as the bridges all rely upon its availability, reliability and cost efficiency. However, the substance that has enabled such quick development is now linked with two rising concerns to be worsened by the reserves of natural aggregates, alongside aggregation and reconstruction (C&D) waste. The production of conventional concrete uses vast amounts of natural coarse aggregates, whereas the amount of demolition waste keeps increasing in urbanising centres [30]. The problem, however, is not simply technical, but environmental one as well how to preserve the structural integrity and stability of concrete and at the same time to diminish the ecological footprint that the materials of which it is made leave behind.

Recycled coarse aggregates (RCA) which are made of demolished concrete form one method which has received growing popularity. Properly used, RCA may improve the freeing of natural aggregates and transfer considerable amounts of that which is wasted to the landfill, thus aligning the construction processes with the overall sustainability objectives[25].

However, adding recycled aggregates to it is a source of new mechanical and durability-related issues. Critically, some coarse aggregates that are recycled still contain the adhered mortar of the parent concrete and therefore grow porous and absorb water more and the aggregate strength is low compared to natural aggregates. Due to this fact, concrete with RCA tends to be lower in compressive strength, lower in stiffness, and have increased cracking behaviour [7]. These problems are especially serious in the structural applications where reliability and long-term performance may not be compromised. Integration of steel fibres into the concrete matrix is one of the promising approaches in dealing with these limitations. It is well known that steel-fiber-reinforced concrete (SFRC) has a higher tensile resistance, crack-bridging properties, and post-cracking ductile [5]. By scattering fibres in the matrix, the fibres suppress the crack propagation and help redistribute stresses hence improving the composite behaviour of concrete. The proposal to use recycled aggregates mixed with the steel fibre is thus very interesting: the fibres can partially compensate the

negative mechanical characteristics of the RCA [31], which can give a more environmentally friendlier and at the same time structurally efficient material.

Ideally, a structural concrete would be able to meet three conditions at the same time. First, it would retain steady mechanical performance that could support the structural grades like M25. Second, it would use recycled materials to a considerable extent so as to minimize the use of virgin aggregates. Third, it would retain service life, and resistance to crack during a service life of the structure. In reality though, these objectives are not always in line. Even though recycled aggregate concrete (RAC) is a source of sustainability, the mechanical behaviour of such concrete- especially tensile, flexural and crack containment properties, is usually inferior to the mechanical properties of standard concrete [7]. This is a weakness that inhibits its application on a widespread basis in structural applications, particularly in areas where moderate strength grades like M25 of reinforced concrete construction are widely applied.

The earlier studies have tried to deal with this challenge in a number of ways. Others have involved the enhancement of the recycled aggregates by pre-treating them with choices like mechanical leaching of attached mortar or coating on the surface [25]. The optimisation of the parameters of mix design such as water- cement ratio, and incorporation of auxiliary cementitious materials have been investigated by others. Though these methods enhance some properties of recycled aggregate concrete, most of the time, they add complexity or cost in processing. In parallel to the above studies, other research lines have also focused on the study of the enhancement of mechanical behaviour of conventional concrete with the help of steel fibres. Regular results of experimental works indicate that steel fibres enhance toughness, energy-absorption, and crack-resistance, especially in flexural loading [31]. More modern studies have just started to explore the recombinant use of fibres and recycled aggregates. However, even as such encouraging results are presented, most of these investigations concentrate on concrete of higher strengths or laboratory based conditions as opposed to the common structure grade of M25 concrete.

The impacts of this unaddressed problem are not limited to laboratory performance. So long as the recycled aggregates are still considered to be inferior in a mechanical sense, their use in the mainstream structural construction is bound to be small. This has both a direct and indirect implication. The construction industry, in its turn, will remain, directly, greatly dependent upon the extraction of natural aggregate, which will create stronger impact on environment degradation and resources draining. The accumulated quota of demolition waste will stay idle in an indirect way, straining landfills and unproductive material flows. The fact that there is no good explanation of the interaction between fibre reinforcement and recycled aggregates in realistic strength grades therefore is a scientific vacuum as well as a formidable challenge to the sustainability of the construction industry [31].

It is against this background that the current paper aims at investigating the behaviour of M 25 -grade steel -fibre reinforced concrete using recycled coarse aggregates. The theoretical basis of the study is based on the conceptual assumption on the composite material theory: concrete, aggregates, and fibre as an integrated structural system. In this system, recycled aggregates as well as influence micro-interface zones and steel fibre are crack arresters and stress-transfer mechanisms. The study and observation of the interactions between these two elements, especially the strength grade so commonly used, might present helpful information on how to create stronger and more sustainable concrete mixtures.

Even though the overall effect of the recycled aggregates on the properties of concrete has already been reported [5] as well as the positive effect of steel fibre contribution to better crack resistance [31], the interaction between those two elements in the framework of concrete M25 grade is scarcely investigated. Concentrations have been placed on compressive strength and less on flexural behaviour, toughness, and crack resistance as many existing works have strongly stressed. Moreover, the interdependence between fibre reinforcement and recycled aggregate properties i.e., interfacial transition zones and left over mortar have not been systematically tested in moderate-strength building concrete. The current study will fill this gap by a study on the mechanical and behavioural response of M25 SFRC using recycled coarse aggregates, hence, not only adds to the scientific knowledge but also of the practical application of sustainable technology of concrete.

1.2 Historical Reinforced Concrete

As it was noted the flexural strength of concrete is approximately 7 to 14 percent of compressive strength of concrete. Due to this significant drawback, concrete should not be used as a tensile and bending load-bearing material. To counter this disadvantage, a reinforcement bar model (rebars) made of steel was proposed, and thus the Reinforced Cement Concrete was created (RCC). In reinforced concrete: Compression stresses are the main ones that concrete can withstand.

Tensile, flexural and shear stress remain resisted by the steel reinforcement

Structural Members reinforcement.

- Beams: The longitudinal bars are resistant to flexural (tensile) stress.
- Stirrups (transverse reinforcement) all response to shear forces.
- Columns: Vertical bars are compression and buckling resistant.
- Ties offer restraint and hold back.

Therefore, RCC has the structural strength of concrete and the tensile strength of steel that is the composite material making it a valuable structure in a wide range of applications.

Nevertheless, traditional steel bars are only used to strengthen concrete in defined points. The cracks have the freedom of developing and spreading through the concrete until they meet a reinforcing bar. It is practically beyond the means, and economically, hardly practicable, to give close, multidirectional reinforcement when it is everywhere. It was due to this failure that an invention of Steel Fibre Reinforced Concrete (SFRC) was invented, in which the fibres are spread throughout the concrete mass.

1.3 Chemistry within the Fibre Matrix.

The tensile cracking strain of cement matrix compares much lower than the final strain of steel fibres. Assuming that a fibre-reinforced composite is loaded: The cement matrix is first cracked. The fracture of steel fibres does not occur instantly. Even after cracking the composite still exhibits tensile stress. As a result: The maximum stress and maximum strain of fibre composite are larger compared to the plain concrete. Several micro-cracks are formed, rather than a large one, in the inelastic range (between the time of first cracking up to the peak load). This process enhances post-cracking and ductility of the material.

CRACK ARRESTING MECHANISM

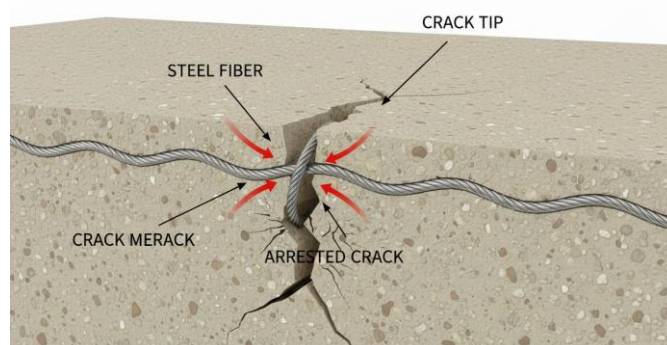


Fig. 1 Fibre mechanisms

1.4 Bridging Action

The pull-out resistance of the steel fibres is very important in determining the level of efficiency. In case of a crack formation caused by an SFRC member: Crossover of steel fibres takes place over the cracks. The fibres pass tensile strains between fractured areas. Post cracks are strengthened by resistance to fibres pull-out.

Effects of Bridging Action:

- Strength ultimate increased tensile
- Greater toughness
- Increased form of absorption energy Ratio.
- Better impact resistance

- Damage tolerance is considered to be one of the most significant advantages of SFRC.

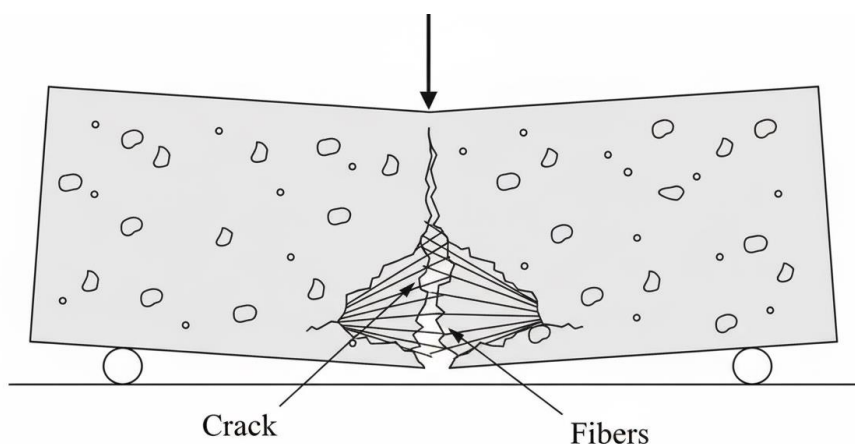


Fig. 2 Fibre pull-out

According to Bayasi and Kaiser (2001), the damage tolerance factor was defined as: Flexural ratio of residual flexural resistance to ultimate flexural capacity. The factor of damage tolerance at a volume fraction of 2% of steel fibre was obtained to be about 93 which is high at that rate implying high post-cracking load bearing capacity.

1.5 Applications of SFRC

SFRC is widely used in:

- Prolongation and stabilizing of rock slopes as well as excavation aiding (rock and soil anchor systems).
- Warehouse flooring, foundations, and slabs.
- Punaluu Abutment and Channel Lining protection.
- Marine (dry docks, piers, bulkheads, seawalls) rehabilitation.
- Making repairs on reinforced concrete in chemical plants and bridges.
- Managerial basement tunnel and mine foundations.

1.6 Advantages of SFRC

The benefit of the Steel Fibre Reinforced Concrete is:

- Eradicates storage, handling, and location of traditional reinforcement cages.
- Decreases the production cycle and augments productivity.
- Conserves time in the manufacture, transportation and location of reinforcements.
- Enhances the resistance to impact in construction and control.
- Increases load-bearing ability and minimizes the spalling damages.
- Enhances durability
- Eliminates sealing harm caused by the non-existence of customary reinforcement cages.
- Increase the corrosion resistance and reduces the spalling.
- Improves the control of crack due to the distribution of micro-cracks.
- Provides tensile resistance in any detail of the concrete mass.
- ails against crushing forces.
- Avoids wastage of material through abrasion.
- Will decrease cracks water migration.

1.7 Cases of SFRC Projects in India.

Among the prominent projects that SFRC has been applied are : Chamera Dam, Uri Dam, Srisaillam Dam, Tehri Dam, Ranganadi Dam, Mumbai-Pune Expressway

1.8 Objectives of the Study

The main objective of this exploration is to evaluate the performance of M25 grade steel-fiber-reinforced concrete in terms of recycled coarse aggregates as well as to conclude whether fiber reinforcement can eliminate the mechanical deficiencies that come along with recycled aggregates. In particular, the paper attempts to:

- Determine the mechanical performance of M25 concrete supplemented with recycled coarse aggregates with regards to compressive strength and split tensile strength.
- Compare the effect of steel-fiber reinforced concrete on the crack resistance, toughness and post-cracking behavior.
- Test the response of steel fibers in contact with recycled aggregates in the concrete packing and, in particular, the crack propagation and load-transfer element(s).
- Compare the performance of recycled aggregate steel-fiber-reinforced concrete (SFRC) against the performance of conventional concrete in order to determine whether the structural grade performance is possible without necessarily utilizing natural aggregates.
- Establish useful recommendations on sustainable concrete design particularly on strength grades commonly used in the construction of reinforced concrete.

1.9 Significance of the Study

The topicality of this question is where sustainability and structural performance interconnect. Academically, the research helps in the continuous debate on the use of alternative materials in the conventional concrete systems without the degradation of reliability. Practically, the results can guide engineers and practitioners about the practicability of the mixed recycled aggregates and steel fibers in normal buildings. Such combinations would be able to reduce the natural aggregate consumption, promote recycling of demolition waste materials and improve the crack resistance on structural concrete elements in case they were successful.

CHAPTER 2 : LITERATURE REVIEW

2.1 General

The recycled materials used in the production of concrete have experienced significant momentum in the last few years which is mainly influenced by the growth and rise in environmental concerns, urbanization and exhaustion of natural aggregate sources. Construction industry is among the biggest consumers of natural material and the production of construction and demolition waste has become a big challenge to its sustainability. In this respect, recycled coarse aggregate (RCA) created out of removed concrete buildings is a feasible means of making a positive impact on the environment. But the intrinsic weaknesses of RCA, including increased water uptake, reduced densities and poorer interfacial transition areas can tend to lead to lower performances in mechanical actions than those of traditional concrete. To overcome these disadvantages, the addition of steel fibers has become a powerful solution to improve the properties of strength, ductility, and durability of recycled aggregate concrete [36][8].

2.2 Review of Technical Papers

In the study conducted by Saravanan and Nirmala (2025), the results are an experimental investigation on the ideas of concrete with 100% recycled coarse aggregate and steel fibers. Their research discovered that although compressive strength slightly decreases relative to the conventional concrete, the strength levels met the structural requirements mandates. More to the point, the incorporation of steel fibers lead to tensile strength as well as post-cracking behavior increasing dramatically. The fibers served to prevent crack propagation by bridging the micro-cracks, and increasing the retention of cracks, which led to high ductility and energy absorption properties [22].

Similarly, Zhang, Li, Li, Zhao, and Cheng (2024) also studied the mechanical properties of fully recycled aggregate reinforced by polypropylene fiber and steel. Their findings showed that steel fibers significantly affect compressive, flexural and splitting tensile strength and polypropylene fiber affects plastic shrinkage cracking control. The research highlighted that hybrid fiber can offer synergism advantages, resulting in enhanced toughness, crack resistance and the structural performance in general [36].

You et al. (2023) were interested in the impact of steel fiber content and morphology on the mechanical properties of recycled aggregate concrete. Their study has shown that the strength properties optimize with increase in the fiber volume fraction to a certain optimal level (which most often remains between 1 percent and 1.5 percent). This is the maximum point in which workability of concrete is negatively influenced because of fiber clustering and less flowability. Furthermore, the paper reported that the shape, aspect ratio, and texture of the steel fibers greatly affect the bonding process with the cementitious matrix and recycled aggregates [35].

Gao, Zhu, Gu, and Yang (2023) evaluated the flexural performance of steel fiber reinforced recycled aggregate concrete beam. They found that, inclusion of steel fibers can significantly improve load-carrying capability, crack distribution and deflection behaviour. The recycled aggregates used led to a minor decrease in stiffness but combination with fibers offset this limitation, improving toughness and ductility [8].

Subsequent research in the Journal of Building Engineering (2024) explored mechanical and durability properties of SFRAC. The findings showed significant increases in flexural strength, abrasiveness and sulfate attack resistance. Such improvements are especially necessary in buildings which are subjected to hostile climate conditions [17].

In yet another important discovery, the researchers of Structures (2025) created both analytical and empirical models to model the post-cracking behavior of steel fiber reinforced recycled aggregate concrete. They have found that crack width is greatly reduced by the introduction of steel fibers providing also better serviceability performance [28].

Khan et al. (2025) investigated the performance of fiber-reinforced recycles aggregate concrete under high temperatures. Their findings showed that steel fibers can increase the fire resistance of concrete and improve the ability to retain residual strength following the exposure to high temperatures [18].

One article that was published by Springer (2025) was based on low-carbon construction materials, using the addition of different proportions of recycled aggregates. The results showed that steel fibres are very suitable in curbing the cracking caused by the shrinkage effect, and limiting micro-cracks, thus enhancing durability and sustainability [27].

Moreover, a study of the triaxial performance of steel fiber reinforced recycling aggregated concrete found out the enhanced strength, deformation ability and failure resistance because of confinement effect caused by steel fibers [17].

Recently, more than that, Adisa, Oshadare, and Yusuf (2026) examined the application of steel fibers obtained as a waste of tires to use them in recycled forms as reinforcement in concrete. They showed that these fibers can be effectively used to enhance tensile strength and achieve sustainability through the use of waste materials [1].

Nevertheless, despite the remarkable achievements achieved in this area, there is still a number of gaps in research. High strength or generalized concrete mixes have used majority of the studies undertaken with little consideration being given those who specifically use M25 grade steel fiber reinforced recycled aggregate concrete. Additionally, it has no standard mix design procedures and guidelines especially in Indian conditions. Further studies are needed to determine the workability, longevity, and in-field performance of SFRAC.

2.3 Research Gap

Through a close examination of the available literature on the recycled aggregate concrete (RAC) and steel fiber reinforced concrete (SFRC) one may find that the two fields have grown mostly independently and only a few scattered attempts have been made at integrating the two domains in a systematic and application based way. Although it seems unanimously agreed that recycle coarse aggregates (RCA) have a negative impact on compressive strength, stiffness and tensile resistance, as a consequence of weak interfacial transition zone (ITZ) and increased porosity, there has been also much evidence to the effect that steel fibers partially counter this shortcoming, by crack-bridging and stress redistribution effects. Nevertheless, even with this perceived complementary, the literature falls short to provide a direct, cohesive vision of the amount of enhancement that is doable under what material circumstances and at what practical proportions of mixture-particularly in the commonly used structural grades of M25.

The limitation due to the current literature is that there are no systematic experimental designs to isolate the combined action of RCA and steel fiber contents in a controlled and consistent mix design. Numerous studies explore either RCA replacement, or fiber addition, but when the two variables are joint, the experimental matrices tend to be small, non-uniform, biased towards extreme conditions. An example is a few studies on high-strength concrete (M40 and higher) or high fiber contents that are beyond practical levels, which would not be necessarily applicable to actual construction work. On the other hand, research on the medium strength concrete- especially M25- commonly found in structural members like beams, slabs and columns, is quite limited and does not go in great detail with regard to parametric variation.

The other problem that rebars itself is the confounding factor of the supplementary contents, including silica fume, fly ash, or polymer modifiers. Although these materials are certainly beneficial to some properties of RAC, they frequently mask the individual effects of RCA and fiber reinforcement. Consequently, it cannot be easy to identify which of the fiber action, densification of the matrix, or the chemical modification are present. Such ambiguity restricts the capacity to generate design-based inferences particularly to those practitioners who need simple, practical solutions without having to involve several such additives.

In addition, the current literature generally places more focus on compressive strength as the major measure of performance, and the focus on tensile strength, flexural behavior, and ductile was relatively less significant. It is a large downside, especially where fiber-reinforced methods are concerned, where compressive strength is under no longer the key benefits; instead, control of cracks, absorption of energy, and post-cracking characteristics are also the benefits. The lack of an all-inclusive assessment plan, including workability (slump), compressive strength, split tensile strength, and flexural strength of the material under consistent testing mechanisms reduces the overall picture of material behavior. The effect on strengthening between RCA-induced weak and fiber-induced strengthening is therefore not well comprehended.

Inconsistency is also evident in the way studies are tested. The curing regimes, sizes of specimen, rates of loading, and with or without moisture conditioning regularly result in results that are not easily comparable. The lesson learned is that in other instances, non-conformance to the routine testing leads to the creation of other doubts that makes it even more difficult to generalize the results of various studies. This variability shows that there is a necessity in having a standardized methodology of experiment based on standard codes, including Indian Standards, in order to come up with data that is reproducible and comparable.

In addition to the flaws in its methodology, the literature shows conflicting results of the effectiveness of steel fibers in RAC. Though a number of studies have shown a remarkable increase in tensile and flexural strength as fiber addition is added, some have shown reduced returns after a point in terms of fiber addition, especially in mixes with a high percentage of RCA. Excessive fiber contents will result in poor workability, fiber clustering, and poor compaction in selected instances, which will counter the desired good. These inconsistencies lead to the fact that there exists an optimal fiber content, and the dependence of this optimal degree on the level of RCA replenishment, but it is not a clear-cut relation which is not quantified and proved in case of moderate-strength concrete.

This study is aimed to fill these gaps with a rigorous and systematically designed experimental program that specifically addresses the strength class of concrete, M25, since the strength is both practically relevant and not well-explored in this regard. Through the use of a controlled mixture of factors by using a comprehensive mix matrix with varying RCA replacement (0 to 100 percent) and varying amounts of steel fiber contents (0 to 2 percent by volume), the research isolates the effects of each factor and the interaction between the two factors. In comparison with other studies that rely on additional materials or non-standard conditions, the presently used approach keeps the base mix design constant, empowering the results of the observed variation in performance to be directly linked to the variables of interest.

Conceptually, the study is based on the framework of fiber-reinforced composite where steel fibers serve as discrete elements of reinforcement which span cracks and provide transfer of stress across weak interfaces. This is especially applicable in the case of RAC, where the ITZ between RCA and cement matrix is weaker by its nature because of the remaining mortar and microstructural discontinuities. The tensile and flexural strength of fibers as well as ductility and toughness of the material in the sense of the ductile nature of the material are anticipated to be augmented with the aid of the enhancement in load transfer across this interface. Nevertheless, the level to which this mechanism could offset the RCA-induced deficits particularly at increased levels of replacement has not been adequately measured, which is a major concern of the current study.

By doing this, the present study furthers and deviates the previous studies. It is an expansion of the existing knowledge; it consists of uniting many performance measures, namely, workability, compressive strength, split tensile strength, and flexural strength, in one and coherent scheme. Meanwhile, it is bound to the previous literature, focusing on the pragmatic mix proportions, standardized testing protocols and statistically sound analysis, making the results more reliable and relevant to generalization.

Finally, the research should not stop at the individual observation but should pass to the comprehensive comprehension of the behavior of material with the goal of determining the obvious patterns and eliminating inconsistencies in the literature. The research will aim to deliver design-relevant information by determining the relationships between the RCA content, fiber dosage and mechanical performance that can be used to encourage the wider implementation of the sustainable concrete technologies in structural practice.

CHAPTER 3 : METHODOLOGY

3.1 General

This paper takes a controlled experimental and systematic approach to determine the mechanical behavior of M25-grade steel fiber reinforced concrete with recycled coarse aggregates (RCA). The methodology is well designed to extract and determine the effect of RCA replacement and steel fiber inclusion on the concrete performance, especially compressive, tensile, and flexural behavior. In the beginning, a control mix with M25 grade concrete is developed based on the IS 10262:2019 with the necessary target mean strength and workability considerations being achieved at the base mix. The choice of M25 grade is not arbitrary, but rather it is a commonly used structural concrete grade in the real world construction and thus contributes to the relevance of the findings. Natural coarse aggregate is gradually substituted by recycled coarse aggregate on a mass basis through five levels 0%, 25, 50, 75 and 100. The gradation can be used to gain a clear insight into the effect of the gradual increase of RCA content on the mechanical response of concrete.

Special consideration is taken to the preparation of RCA, cleaning, adhered contaminants removal, and pre-soaking to consider its increased water absorption properties. This is a very important step because the presence of adhered mortar in RCA has a great influence on interfacial transition zone (ITZ) which ultimately determines the strength and durability.

Hooked-end steel fibers are added to the mix in order to counteract the inherent weak posed by the recycled aggregates. Different volume fractions of fibers (0, 0.5, 1.0, 1.5 and 2.0) are used with the fibers being of a length of 50 mm and diameter of 1 mm (aspect ratio of 50) [6]. These ratios are chosen by first-mover experimental results that indicate that the fiber content in this range can have a strong effect on crack resistance, toughness and post-cracking behavior without making the mix unworkable. The interaction effect of RCA replacement and fiber dosage leads to the formation of a comprehensive experimental plan, allowing the assessment of the effect of both independent and interaction effects. An elaborate batching matrix is drawn so that all mix combinations are consistent and repeatable.

A mixer of concrete is used to provide homogenous mix of the materials. The mixing process is a controlled process: dry mixing of cement and aggregates is performed, and then gradually water is added. Steel fibers are added gradually in the process of mixing so that they do not clump or form balls, which would otherwise cause uneven mechanical characteristics. Fresh concrete workability is evaluated by slump test as per IS 1199:2018 and any significant decrease in workability with the addition of fibers or RCA content is noted with care.

Specimens are poured in conventional moulds in relation to various mechanical tests. Cube ($150 \times 150 \times 150$ mm), cylindrical (150 mm diameter $\times$ 300 mm height) and prismatic beam ($100 \times 100 \times 500$ mm) are the specimen types used in compressive strength testing, split tensile strength testing, and flexural strength testing, respectively. In the casting process, the concrete is put in sections and the concrete is either tamped or vibrated to ensure that the entrapped air is as minimal as possible and the density is even. Surface finishing is done in a way that prevents irregularities that can lead to test results.

Specimens are left undisturbed after casting and then after 24 hours, they are demoulded and placed in a curing tank. The curing is performed in drink water at 27°C , as recommended in the IS 516:1959. Specimens are cured after 7, 28, 56, and 90 days and a range of early-age and long-term development of strength is gained by the study. The presented longer curing regime applies especially to recycled aggregate concrete, in which the strength gain can vary compared to traditional mixes due to internal curing effects and slow hydration.

Mechanical testing is done in compliance with Indian Standard procedures. Compressive strength tests are conducted on cube specimens under the compression testing machine that is calibrated with a load applied in the form of uniformly loading the compressive testing machine until the specimen fails. The loading rate is as per code recommendations to achieve similarity and comparability. Peak failure load is recorded and compressive strength is calculated with the help of standard formulas.

In split tensile strength, the cylindrical specimens are tested according to the IS 5816:1999, under which the load is applied in the direction of the diameter of the cylinder. The test is an indirect measure of tensile strength which is especially significant in the determination of crack resistance in fiber-reinforced concrete. The steel fibers are supposed to affect the initiation and propagation of crack and hence this test will be very important in the study.

In accordance with IS 516:1959 flexural strength testing is performed on beam specimens under a two point loading situation. The test measures the modulus of rupture and gives the information on the performance of bending and ductility of the concrete. Since steel fiber is mainly used to improve post-cracking performance, flexural testing is the core of comprehending the role of steel fibers in structural performance.

Calibration of all the testing equipment is done before experimentation in order to be accurate. The rates of load applications, alignment of the specimen and data recording strictly follow Indian Standards. In the case where certain parameters are not clearly stipulated in the code, uniform experimental conditions are observed on all specimens so that they can be compared.

The taken data, the peak loads and associated stresses are systematically taken and given the standard equations. Analysis of variance (ANOVA) is used to statistically analyze the relationship between RCA replacement levels and fiber content and mechanical properties. A comparison is made against the control mix in order to measure the differences in performance. The trends are drawn in graphs and the best combinations of RCA and fiber content are identified.

A minimum of three specimens is used in testing each mix and each age to provide reliability and average values are reported. Standard deviation and variability are also analyzed in order to examine consistency. Stringent quality control measures are applied during the study such as proper batching, correct curing conditions and proper handling of specimens. All the material handling, mixing, and testing stages are subject to safety measures.

3.2 Objectives and Hypotheses

• Objectives

The main objective of the study is to come up with an in-depth knowledge on the interaction between recycled coarse aggregates and steel fibers in an M25 concrete matrix and the effect of the interaction in terms of mechanical performance. In particular, the research aims to:

Measure the impact of RCA replacement (100%) on compressive strength, split tensile strength and flexural strength of M25 concrete.

Determine the effectiveness of steel fibers (02%, by volume) in increasing tensile resistance, crack control and overall structural behavior of recycled aggregate concrete.

Analyze the joint effect of RCA and fiber reinforcement, determining the possibility of the effective compensation of the mechanical shortcomings added to the recycled aggregates by the addition of fiber.

Identify the best RCA content and fiber dosage combinations that will balance strength, ductility and workability.

Achieve statistically significant correlation between mix parameters and mechanical performance with the help of thorough data analysis.

• Hypotheses

The following hypotheses serve as the guidance of the study and were developed according to the existing literature and theoretical knowledge:

H1: The percentage composition of recycled coarse aggregate will result in the decrease in compressive strength, tensile strength, and workability because of the weak interfacial transition zone and increased water absorption properties of RCA.

H2: The addition of the steel fibers will lower the workability but greatly enhance tensile strength, flexural strength and crack resistance especially in mixes high in RCA content.

H3: There is an optimum fiber dosage (probably 0.5-2 percent volume), beyond which the advantageous effect of fiber reinforcement like better toughness and ductility will be maximized without excessive loss of workability or compaction problems.

3.3 Design of Materials and mix.

The choice and description of constituent materials are the key factors that define the mechanical and durability behavior of concrete, especially the use of recycled coarse aggregates (RCA) and steel fibers. All materials used in the current study are well chosen, tested and balanced to the relevant Indian Standards, as well as taking into consideration the natural variability created by the recycled aggregates and fiber reinforcement.

• Cement

The primary binder is ordinary Portland Cement (OPC) that is in compliance with IS 12269 (Grade 43). The selection of the 43-grade cement is because of its popularity in industrial structural concrete works, especially in the moderate strength grade of M25. The cement is specified according to IS 4031 (Part 1-15) before mix design; this is done to make sure that the cement meets the standard requirements. Some of the important properties considered are fineness, standard consistency, initial and final setting time, specific gravity. Cement fineness is kept high above 300 m² /kg, needed to achieve satisfactory reactivity and strength development. Setting times are checked to be within acceptable limits to enable enough working time during mixing and casting which is critical in fiber-reinforced mixes since handling is more demanding.



Fig. 3 Cement

- **Fine Aggregate**

As a fine aggregate, natural river sand that is compliant with IS 383:2016 is applied. The sand falls in Zone II grading which is mostly deemed to be the best in the pursuit of workability and strength balance. Fineness modulus is kept between a range of 2.6 to 3.0 meaning using a medium gradation that is applicable in structural concrete. The fine aggregate water absorption is maintained at a low level of less than 3 percent reducing variation in effective water-cement ratio. Sieve analysis is done to check the compliance of the grading and specific gravity and bulk density are obtained Resistance to ensure correct proportioning of the mix.

This research especially emphasizes the use of well-graded natural sand in this research because it can compensate the fluctuation caused by recycled coarse aggregates, and it also leads to a higher packing density in the concrete matrix.



Fig. 4 Sand

- **Coarse Aggregates**

There are two categories of coarse aggregates, namely natural coarse aggregate and recycled coarse aggregate. The natural aggregate is crushed limestone with a nominal size range of 4.75 20 mm which aligns with the provisions of the IS 383:2016. It is low-grade and has low water absorption and high mechanical strength.

The coarse aggregate recycled is obtained by crushing of concrete rubble that has been demolished due to structures with original compressive strengths of 30-50 Mpa. This makes the concrete quality of the parent reasonably high, which is known to have a positive effect on the performance of RCA. This crushed material is then sieved to get the required size fraction and then manually checked to exclude impurities like wood, plastic and loose mortar fragments.

Both NCA and RCA are tested as per the IS 2386 (Part I-IV) on important physical and mechanical properties such as: Specific gravity, Water absorption, Bulk density, Aggregate crushing value, Los Angeles abrasion value.

The characteristic features of NCA and RCA are identified by the measured properties. Natural aggregates have a definite gravity of about 2.65 and water absorption less than 2 percentage which is dense and relatively impermeable. Conversely, RCA exhibits less specific gravity of 2.4-2.5 and much greater water absorption (4-6%), which is largely attributed to the presence of mortar that sticks to it. The Los Angeles abrasion value is kept to acceptable values (not more than 30 percent in the case of NCA and not more than 40 percent in the case of RCA as a practical limit), and sufficient to wear and mechanical degradation is guaranteed.

These variations are essential, because with their help one can impact directly interfacial transition zone (ITZ), porosity and general mechanical behavior of concrete.



Fig. 5 Natural Aggregate

- **Water**

Both mixing and curing are done using potable water that complies with IS 3025. Pure water is used so that there are no undesirable chemical reactions which may cause problems with hydration or durability in the long run. Water quality is checked regularly during the course of the experiment to remove the variability in outcomes.

- **Chemical Admixture**

In order to reduce the decrease in the workability due to the addition of both RCA and steel fibers, a polycarboxylate ether-based superplasticizer is added to the mix. The admixture has the same functionality as ASTM C494 Type F (high-range water reducer) and is compatible with OPC. The dosage 1 percent weight of cement is taken at first but the actual dosage is established by trial mixes.

The main aim of the superplasticizer application is to obtain a slump target of about 75 ± 25 mm that is deemed appropriate in casting and compaction of fiber-reinforced concrete. Chemical admixtures are especially significant in the present research as steel fibers have a tendency to lower the workability by raising the internal friction and inhibiting flow.



Fig. 6 superplasticizer

- **Steel Fibers**

The discrete reinforcement in the concrete matrix is done with hooked-end steel fibers. The fibers comply with ASTM A820M Type I requirements and have the following features:

Length: 50 mm

Diameter: 1 mm

Aspect ratio: ~ 50

Tensile strength: >1100 MPa

The hooked-end structure increases mechanical anchorage in the cement matrix, which increases the capability of the fiber to bridge cracks and share stresses. Volume fractions of 0, 0.5, 1, 1.5 and 2 are used, which enables a thorough analysis of the effect of the fibers in a broad spectrum.

The dosage range is chosen on the basis of previous studies that have shown that fiber contents in the 1 percent to 2 percent range generally provide maximum tensile strength, toughness, and post-cracking characteristics and higher dosages can result in workability and fiber agglomeration. The study is thus meant to find out the balance point at which the benefits in terms of mechanics are maximized without affecting constructability.



Fig. 7 Steel Fibre

- **Recycled Coarse Aggregate Pre-treatment.**

The most important part of the methodology is the pre-treatment of RCA to control the high absorption of RCA. In this experiment, RCA is dried to saturated surface-dry (SSD) and then mixed. This happens by immersing the aggregates in water overnight and then drying off the surface which contains surplus free water.

The implementation of SSD condition has two important functions. First, it eliminates the uptake of mixing water during batching, so that RCA would experience lower effective water-cement ratio and negatively impact workability and hydration. Second, it guarantees that the results of the work are consistent within various batches, allowing the results to be compared reliably.

The RCA is not subjected to any further chemical or mechanical processing, including acid washing, coating or thermal processing. This is a deliberate choice and is a practical, field-based decision to make recycled aggregates use as viable as possible in a real-world construction. Although advanced treatments can enhance the quality of RCA, they are usually more expensive and complex and therefore can be applied in large scale.



Fig. 8 RCA waste



Fig. 9 RCA

- **Mix Proportions:**

Mix Proportions A reference M25 mix is developed through IS 10262:2019. With a w/c ratio of about 0.48, fine/coarse ratio of about 0.57[3] and cement content of about 312.5 kg/m³, trial batches produce a target mix. The last mixes per m³ are as follows

(sample values): Cement 312.5 kg, water 150 kg, sand 724.6 kg, NCA 1239 kg (in case of 0% RCA). In the case of RCA mixes, mass substitutes NCA at a given volume fraction: e.g. at 100 percent RCA, NCA = 0 kg/m³ fiber, RCA = 1239 kg/m³ fiber. Steel fibers (density = -7850 kg/m³) are incorporated at the desired volume fraction: e.g. 1 percent The general mix matrix is provided in Table 1. Trial-mixing is performed on each mix to ensure slump and adjust dosage of SP, workability is brought to be similar between mixes to allow fair comparison of the final slump (approximately 75 mm).

Table 1: Mix Matrix (RCA % vs Fiber %)	0% Fiber	0.5% Fiber	1.0% Fiber	1.5% Fiber	2.0% Fiber
RCA 0% (NCA only)	M1	-	-	-	-
RCA 100%	M2	M3	M4	M5	M6

Note: Every cell represents one mix identification (Mix ID). Each mix is mixed with proportions of RCA/fiber (kg/m³). Trial mix adjusts unspecified parameters.

Optimized mix proportion for M25 grade concrete.

Composition	M1 (control Mix)	M2 (100% RCA)	M3 (100% RCA + 0.5% SF)	M4 (100% RCA + 1% SF)	M5 (100% RCA + 1.5% SF)	M6 (100% RCA + 2% SF)
Cement (kg/m ³)	312.5	312.5	312.5	312.5	312.5	312.5
Water (lt/m ³)	150	150	150	150	150	150
Natural fine Aggregate (kg/m ³)	724.6	724.6	724.6	724.6	724.6	724.6
Natural coarse Aggregate (kg/m ³)	1239	—	—	—	—	—
Recycled coarse aggregate (kg/m ³)	—	1239	1239	1239	1239	1239
Steel fibre (kg/m ³)	—	—	1.56	3.12	4.68	6.25

Super Plasticizer (kg/m ³)	3.12	3.12	3.12	3.12	3.12	3.12
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1.

In this experiment, concrete batching would be done through weight-based proportioning system, which guarantees a high level of accuracy and reproducibility. The measurements of all constituent materials, such as cement, fine aggregate, coarse aggregates (both natural and recycled), water, as well as admixture are taken on a calibrated digital balance, with an accuracy of ± 0.1 kg. Weight batching, instead of volumetric processes, is necessary to reduce variability especially in mixes that use recycled aggregates and fibers, where minimal variances can have a great impact on performance.

All dry materials are taken to the laboratory temperature and moisture conditions are measured before mixing. Calibration is done to incorporate the effects of the water absorption of the aggregates and in particular of RCA, which is kept in a saturated surface-dry (SSD) state in order to make the effective water-cement ratio consistent.

The mixing is carried out in a pan mixer which has been chosen because it gives a homogeneous and uniform mix especially where fibers are to be mixed. The mixing process is a well-managed process aimed at achieving adequate dispersion of the materials and to avoid segregation or clustering of fibers.

At the beginning, a dry mixture is prepared of cement, fine aggregate and coarse aggregates (NCA and/or RCA accordingly according to the mix) and mixed during about 1 minute. This phase enables even allocation of particles and in disrupting any agglomerations, particularly in the recycled aggregates that may have adhesive mortar. It is essential at this point to get a consistent dry blend because it determines the consistency of the final mix.

After dry mixing, around 70 percent of the total mixing water that is pre-blended with the actual dosage of the superplasticizer is slowly added to the mixer. Wet-mixing of the mixture then follows, lasting 2 minutes, and after this, the cement paste starts coating the surfaces of the aggregates. This gradual addition of water would guarantee a greater control over workability and avoid localized concentration of water, which otherwise would result in segregation.

When a unified base mix is obtained, steel fibers are added slowly and evenly into the rotating mixer. The step is done in a duration of 1-2 minutes to ensure that the fibers are distributed uniformly within the matrix. The incremental addition is more crucial to prevent the occurrence of the fiber balling phenomenon, where the fibers are aggregated and form a weak area in the concrete. Sufficient time of mixing and feeding of fibers is necessary to ensure that every fiber is properly incorporated into the cementitious matrix.

Following fiber addition, the rest 30 percent of mixing water as well as any other superplasticizer is introduced. It is then allowed to mix the concrete further 1 to 2 minutes to get a homogenous and workable blend. The overall mixing time is regulated in such a way that the time spent in mixing is balanced with the chances of overmixing that may cause entrained air to be lost or even segregated.

The fresh concrete slump test is performed on the immediately produced concrete to determine its workability in line with the IS 1199:1959. The target slump has been kept at 75 ± 25 mm which can be deemed to be appropriate in terms of proper placement and compaction of fiber-reinforced concrete without excessive segregation. Since both RCA and steel fibers are likely to decrease the workability of the material, the former through increased water absorption and coarse surface texture, and the fibers through greater internal friction, special consideration is paid to the issue of slump.

In case the measured slump is less than 50 mm, then corrective actions are taken. First, the amount of superplasticizer is added in small steps until the maximum level of 0.5 percent by weight of cement is reached in order to enhance flowability without changing the water cement ratio. Marginal increase in water content is only allowed where sufficient workability has not been obtained by adjusting the admixture and such modifications are well documented to ensure consistency among mixes. With this method, the workability is enhanced and the effect on the strength and durability is reduced.

During the batching and mixing, quality control is done strictly. Between batches, the mixer is washed down to avoid cross-contamination and the duration of mixing, order of mixing and environmental factors are maintained constant. Other qualitative features like ease of mixing, fiber dispersion, and visual homogeneity are also recorded because these characteristics usually give an insight into the behavior of fiber-reinforced recycled aggregate concrete.

3.4 Casting, Curing and Specimen Schedule

Test specimen preparation is one of the most important stages of the experimental program because it is directly connected to the reliability and reproducibility of the measured mechanical properties. In the current work, casting, curing and specimen handling

are performed strictly in accordance with the Indian Standard procedures and the extra controls are implemented to take into consideration the existence of the recycled aggregates and steel fibers.

Casting Procedure

Fresh concrete is poured into rigid steel moulds based on the specifications of the geometries of the specimen that is needed. All moulds are cleaned before casting, to ensure that there is no residual material and they are lightly sprayed with mineral oil to avoid sticking as well as to be easily demoulded, without leaving edges of the specimen damaged. The mould preparation should be carried out properly to guarantee the dimensional accuracy and surface integrity especially when dealing with flexural specimens where surface defect may have a profound impact.

Concrete is introduced in the moulds in two approximately equal layers as suggested in the IS 516:1959. All the layers are compacted by standard tamping (rodding) or by mechanical vibration according to the workability of the mix. In blends with more fiber content or RCA content - where workability is more likely to be low - controlled vibration is more likely to achieve good compaction without segregation or fiber orientation. Precaution is observed so as to prevent over-vibration that may result in bleeding of aggregates or settlement.



Fig.10 Concrete Mixture

When compaction is done, special care is taken to ensure that there is even distribution of fibers in the mould. Localized clustering is more prone in fiber-reinforced mixes, and thus compaction process is conducted in a systematic way so as to maintain uniformity across the volume of the specimen.

Following compaction, the surface of the top of the individual specifications is struck off and finished with a trowel to a smooth and level surface. This is especially important for compressive strength testing, where uneven surfaces may result in non-uniform load distribution.

Plastic sheets or burlap that has been wettened are immediately placed over the specimens to avoid loss of moisture and environmental changes. The specimens are then stored under a controlled condition with a temperature range of 20-25 °C and relative humidity of more than 95 percent during the first 24 hours to ensure adequate initial hydration and cement setting.

• Demoulding and Curing

The specimens are then demoulded after 24 + 2 hours to eliminate edge damage or microcracking. After demoulding, all the specimens are immediately placed in a curing tank with potable water, and at a temperature of 27 ± 2 °C, as recommended in IS 516:1959 and IS 2386.

The water curing will proceed over the designated periods of 7, 28, 56, and 90 days so that the development of the early-age strengths of the structures and the long-term performance could be obtained. The long curing time is also especially pertinent to recycled aggregate concrete, in which the existence of adhered mortar and greater porosity can affect hydration kinetics and the internal curing impacts.

Curing tank is checked frequently to ensure that the temperature and cleanliness is maintained. The water is changed on a regular basis to avoid contamination which may cause the process of hydration to be impaired.



Fig. 11 Curing Tank

• **Types and Quantities of specimens**

A specimen of standard size is prepared to each mix in order to determine the various mechanical properties. The casts of the three samples ($n = 3$) are made and cast under each test condition and curing age to achieve statistical reliability.

Compressive Strength

Specimen: Cube ($150 \times 150 \times 150$ mm)

Standard: IS 516:1959

Quantity: 3 specimens of each mix of each age.

Cube specimens are used because they are used widely in Indian practice and they are also used to measure compressive strength because of the uniform conditions of loading.



Fig. 12 Cube Mould

Split Tensile Strength

Specimen: Cylinder (150×300 mm)

Standard: IS 5816:1999

Volume: 3 specimens per mix (mostly 28 days; but may be 56 days)

Even though both cubes and cylinders can be used according to the IS 5816, the cylindrical specimens are chosen in the current research due to the uniformity of stress distribution in the diameter and the popularity of cylindrical specimens in experimental studies.

Flexural Strength

Specimen: Prism (100 × 100 × 500 mm)

Standard: IS 516:1959

Quantity: 3 specimens in each mix in each age (28 and 56 days)

Although IS 516 can accommodate 150 x 150 x 700 mm and 100 x 100 x 500 mm beams, the latter is chosen due to its convenience in working with and the ability to use its material efficiently without affecting the precision of results.

• Conditioning of Specimens Before Testing

Prior to testing, specimens are taken out of the curing tank and made ready based on the particular demands of the test. In split tensile strength testing, the specimens are initially dried at the surface to eliminate any extra free water and then placed under a 24-hour soaking time as suggested in the standard IS 5816:1999 to give a uniform moisture environment.

In compressive and flexural strength tests, specimens are tested under wet or saturated surface-dry (SSD) conditions immediately after excavation unless otherwise stated. It is also necessary to maintain the same moisture conditions in all specimens to reduce variability and give the results comparability.

• Test Plan and Schedule of Specimen

Samples will be subjected to various curing periods, i.e. 7, 28, 56 and 90 days to reflect the change in mechanical properties with time. The strength of the 28 days is regarded as the reference strength of M25 concrete, with other points of age giving more information about the long-term performance especially in the mixes that contain RCA and fibers.

A specimen schedule (Table 2) is planned to be structured to have a systematic testing of all combinations of RCA replacement and fiber dosage. Averages, standard deviation and coefficient of variation may be calculated by using statistical replicates (n = 3). The target coefficient of variation is kept below 5-10 percent to ascertain reliability of data and consistency of the experiment.

Table 2 :

Specimen Schedule (per mix)	Specimen Type & Size	No. per Mix per Age	Test Ages (days)	Standard Method
Slump Flow (workability)	Fresh concrete (slump cone)	1 (per batch)	-	IS 1199:1959 [22]
Compressive Strength	Cube 150×150×150 mm	3 per age	7, 28, 56,	IS 516:1959 [13]
Splitting Tensile Strength	Cylinder Ø150×300 mm	3 per age (see note)	28, 56	IS 5816:1999 [15]
Flexural Strength	Prism 100×100×500 mm	3 per age	28, 56	IS 516:1959 (clause 8) [15]

Note: Splitting tensile can also be done on 150 mm cubes per IS 5816, but cylinders are preferred. Acceptable testing ages are ≥7 and 28 days 10. Additional ages (56, 90) are for long-term trends.

3.5 Testing Procedures

• Compressive Strength Test (IS 516:1959)

Apparatus and Setup

According to the provisions of IS, the compressive strength of concrete is measured with a calibrated compression testing machine (CTM) with a minimum capacity of 2000 kN and an error of 1 percent. Before testing, the machine is verified as being correctly platen aligned so that the load is applied evenly on the surface of the specimen. The surfaces of the platens are wiped and a small amount of lubricant applied to the bearing surfaces to reduce frictional restraint and evenly distribute the load.

The CTM is also calibrated on a regular basis (ideally every month) with certified reference standards, and thus, the test results will be consistent and reliable across the entire program of the experiment.

Specimen Preparation

The test is done in standard cube specimens of 150 x 150 x 150 mm. All specimens are also checked thoroughly with respect to visible defects before testing, including cracks, honeycombing or edge damage. The surfaces are wiped down to clean up the excess moisture and no free water is left on the specimen which would otherwise affect the distribution of loads.

The size of the cube is measured to the closest 0.5 mm and any variation in size is recorded. Gypsum capping or neoprene pads are used to level the bearing surfaces where required, so as to have a uniform contact with the machine platens. Surface preparation is important because the uneven bearing may cause stress concentration and earlier failure.

Loading Procedure

The specimen is centred over the lower platen of the CTM with one of its cast faces touching the platen, and the load being applied perpendicular to the direction of the casting. The load is sustained continuously without shock till it fails.

Though there is no specific loading rate that is prescribed in IS 516:1959, it is agreed that the load must be applied in such a way that failure must take place between 300 and 500 seconds. Practically, a loading rate of about 0.7 MPa/s (which is equal to 140 kgf/cm²/min) is used on 150 mm cubes in order to ensure consistency in tests.

This process of loading is repeated until a certain reduction in load or observable pattern of cracking is observed, which is a failure of the specimen.

Recording and Calculation of Data

The highest load (P) that the specimen can take before failure is measured in kilonewtons (kN). Compressive strength is determined by:

$$f_{cu} = \frac{P}{A}$$

Where:

f_{cu} = Compressive strength (MPa or N/mm^2)

P = Maximum load at failure (N)

A = Loaded area of the specimen (mm^2)

The reporting of the results is to the nearest 0.5 Mpa.

Acceptance and Quality Control.

At least three specimens of a mix at each curing age are also tested and the average is reported. Repeatability is acceptable with the coefficient of variation (COV) being less than 15. Whenever any single result is more than 15 percent below or above the average, it will be investigated very carefully and retesting could be conducted where appropriate.



Fig. 13 Ultimate Testing Machine

• Split Tensile Strength Test (IS 5816:1999)

Apparatus and Setup

A compression testing machine that has bearing strips is used to determine the split tensile strength. There are two steel strips, usually 20mm wide, 3mm thick and 150mm long, placed on the top and bottom of the specimen. Such strips are stuffed with plywood or neoprene so that the load distribution is even and that the stress is not concentrated at the point of contact.

Specimen Preparation

The standard cylindrical specimen is used (150 mm diameter and 300 mm height). The cylinders are mounted horizontally in between the bearing strips with the line of loading being parallel to the vertical diameter of the specimen.

It is properly aligned in order to have uniform application of the load throughout the length of the cylinder. The misalignment may cause eccentric loading and wrong value of tensile strength.

Loading Procedure

The load is sustained continuously and shock free till failure. The loading rate is not given in IS 5816, but this is important because the rate must be gradual enough to prevent dynamic effects. Usually loading is manipulated to ensure that failure happens in a smooth manner, and crack development can be effectively observed.

Failure is defined as the development of a vertical crack on the diameter, which implies tensile dismemberment of the specimen. Recording and Calculation of Data.

The highest load (P) at failure is noted and split tensile strength is computed using:

$$f_{sp} = \frac{2P}{\pi DL}$$

Where:

f_{sp} = Split tensile strength (MPa)

P = Failure load (N)

D = Diameter of cylinder (mm)

L = Length of cylinder (mm)

The report is in MPa and the round-off of the results is to 0.1 MPa according to IS 2:1960.

Conditioning and Age of testing.

Testings are mostly done at 28 days, and there are other testings at 56 days where necessary. Before testing, specimens are moistened in water 24 hours as suggested by IS 5816, and wiped off prior to testing to have a uniform level of moisture content.

Acceptance Criteria

At least three specimens of each mix are tested and the mean value is reported. Control mixes are used to compare the results against to determine the effect of RCA and fiber content.

• Flexural Strength Test (Modulus of rupture) (IS 516:1959)

Apparatus and Setup

Flexural strength is measured with the help of flexural testing machine with either center point loading or two-point (third point) loading. The specimen is held in place by the use of two rollers and the length of the span is 400 mm in case of 100 x 100 x 500mm prisms as per IS 516.

In the case of third-point loading, the loading is done at two points which are at a distance of one-third span, so that the bending moment is constant in the central part. Mid-span dial gauge or LVDT is applied to measure the deflection, which is used to provide knowledge about the ductility and post-cracking behavior.

Specimen Preparation

Prismatic specimens of size 100 × 100 × 500 mm are used. Defects on the specimen surfaces are checked and edges marked to locate the mid-span position where the cracking is likely to start.

The specimens are run in a surface dry state, right after taking them out of curing and without any further soaking.

Loading Procedure

The load is introduced at a slow rate that the extreme fiber stress rises at a constant rate, which in this case is approximately 1.8 MPa/min (1/2 3.6 kg/cm² /min) at the specimen size of the selected specimen. This is a controlled loading whereby the development of the crack and the accurate measurement of peak load is guaranteed.

The test is carried on till fracture is achieved and this is normally realized by a visible crack on the tension face and an abrupt drop in load.

Recording and Calculation of Data

The highest value of load (P) at failure is measured. The flexural strength (modulus of rupture) is determined by:

$$f_r = \frac{3PL}{2bd^2}$$

Where:

f_r = Flexural strength (MPa)

P = Maximum applied load (N)

L = Span length (mm)

b = Width of specimen (mm)

d = Depth of specimen (mm)

To be complete, when larger prisms (150 × 150 mm) are to be used, the alternative formula is used according to the provisions of the IS.

The reports on results are presented to the nearest 0.05 MPa.

Acceptance and Quality Control

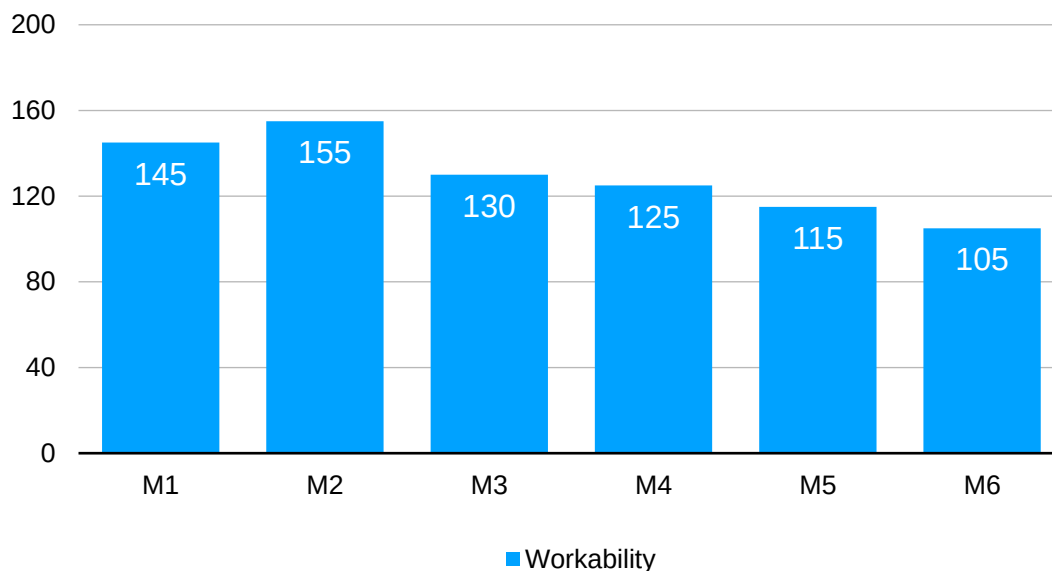
Three or more specimens of each mix of each age are tested, and the mean value is given. The periodical check of machine calibration is performed with the help of standard reference beams or calibration blocks.

CHAPTER 4 : RESULT AND DISCUSSION

4.1 Workability properties of recycled aggregate concrete

The differences in slump values for various recycled aggregate concrete mixes illustrate the need to assess workability characteristics when using recycled concrete aggregates. The variable nature of this indicator underlines the necessity to strike a balance between sustainable goals and the concrete production process's requirements.

When the natural and recycled coarse aggregates constitute 100% of the concrete mix (C1), slump value decreases by 10.71%

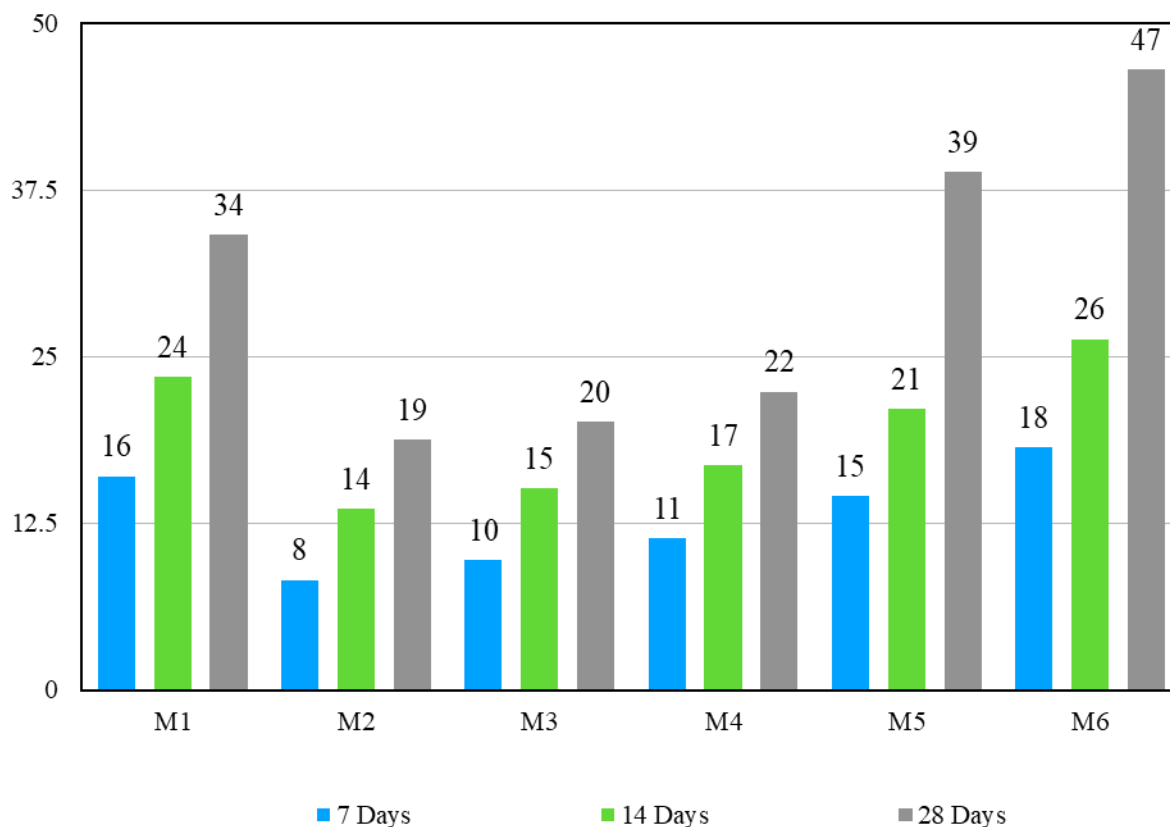


compared to the slump value obtained using the natural aggregate. This increase in slump can be related to the slump of the recycled aggregate which in turn relates to the water demand of the concrete mix. The more porous structure is responsible for the improved water distribution and lubrication properties, which according to Tam et al. (2008) improve the workability. Incorporation of Steel Fibres leads to decrease in the values of slump. Specifically, the addition of 0.5%, 1%, 1.5%, and 2% of hooked end steel fibers leads to slump reductions of 7.14%, 10.71%, 17.85%, and 25%, respectively.

Steel fibers are added to the concrete mix, providing reinforcement, and help to limit the free flow of the mix which helps reduce the concrete slump. Several researchers have studied this phenomenon. Hung et al.[9], Uygunoglu[32] and Mohammed et al.[21] reported that the slump value decreases proportionally with the increasing fibre content. This study shows that when 2% sample is taken as fibre content of recycled aggregate concrete, the slump value of recycled aggregate concrete is reduced by 33.33%. It is noteworthy to mention that slump values of the developed mixes are still under high and very high workability category as mentioned in the IS:1199-2018 and IS:456 – 2000 respectively.

4.2 COMPRESSIVE STRENGTH TEST

The compressive strength results of the control concrete, recycled aggregate-added concrete, and recycled aggregate with steel fibre-added concrete after 7, 14, and 28 days of curing days.



Experimental results show that use of 100% replacement of natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) has a negative impact on the compressive strength of concrete at all ages of curing. However, addition of steel fibres to recycled aggregate concrete (RAC) can greatly increase the compressive strength of the concrete and will partially or fully compensate for any negative characteristics that are found with RAC. This behavior shows synergy effect between rca and steel fibres, showing the possible contribution of fibre reinforcement for guaranteeing a better structural response for the sustainable concrete.

On testing the results, the compressive strength decreased significantly by 48.50%, 43.32%, and 45.03% at 7th, 14th and 28th day respectively when 100% NRCA was replaced by RAC. Reduced amounts were the main cause of the reduction which is largely due to the physical and mechanical properties of recycled aggregates. Recycled aggregates usually contain some old cement mortar residue on their surface that increases their porosity, water absorption, and density of microcracks in the aggregate surface, while decreasing the density and stiffness of the aggregates. Such properties have a negative impact on load-bearing capacity of the concrete matrix and tend to give early cracks under compressive loading.

The Interfacial Transition Zone (ITZ) between the cement paste and the particles of the aggregates is one of the most important factors that affect the reduction in compressive strength. The degree of porosity and the amount of hydration products in the ITZ is the lowest compared to the rest of the hardened concrete making it the weakest part. For recycled aggregate concrete, another ITZ is created between the old mortar which has been attached and the new mortar which is the cement paste. This is known as the "old-new ITZ". This multiple ITZ structure not only creates weak interfaces in the concrete matrix but causes bond strength to become less, thereby promoting the propagation of cracks under applied compressive loads. Therefore, most recycled aggregate concrete has lower compressive strength than natural aggregate concrete, especially when high percentage of recycled aggregates is used.

Even though this result has reduced the strength of the RAC, steel fibres have gradually increased the compressive strength of RAC. As the fibre dosage increased, the improvement became more marked indicating that steel fibres are effective in improving the concrete matrix. The incorporation of 0.5%, 1.0%, 1.5%, and 2.0% steel fibres resulted in compressive strength increases of 18.15%, 37.28%, 75.78%, and 120.46%, respectively, at 7 days. Corresponding improvements at 14 days were 12.33%, 25.34%, 56.53%, and 95.54%, while at 28 days, the increases were 7.24%, 19.16%, 106.92%, and 147.81%, respectively, relative to recycled aggregate concrete without fibre reinforcement.

There are several reinforcing mechanisms that account for the continuous increase in compressive strength as the amount of steel fibre increases. The steel fibres distributed randomly over the whole volume of concrete provide micro-reinforcement throughout the concrete continuum and so serve as a barrier to the propagation of microcracks under loading. This crack-bridging mechanism will relieve the internal stress and decrease stress concentration at the tips of cracks, and also increase the energy absorbing capacity of concrete. Thus the transition between microcracking and macrocracking is slowed down, resulting in higher compressive stresses before failure for the concrete.

Additionally, steel fibres greatly enhance the ductility and toughness of concrete by converting its failure behavior from brittle behavior to relatively ductile behavior. In compression, standard concrete tends to crack in a rapid manner and fail quite abruptly. In fibre-reinforced concrete, however, the fibres will inhibit widening of cracks and ensure structural integrity even when internal cracks have formed. Confinement effect allows the concrete to undertake more of a deformation and to absorb more energy before failure, which gives it a higher apparent compressive strength.

A remarkable finding in this current study was the strength that was obtained for the 100 per cent recycled coarse aggregate (RCA) mix reinforced with 2 per cent steel fibre (SF) that it surpassed the strength of the conventional natural aggregate concrete (NAC) (control mix). The compressive strength of this mix was about 36.20% higher at 28 days than of the control concrete. The result indicates that a proper proportioning of steel fibre can neutralise the limitations of RACs and even give better overall performance of concrete than that of traditional concrete.

Surface properties of the recycled aggregates are also one of the important factors that can explain the superior performance of the fibre-reinforced recycled aggregate concrete. The aggregate from recyclables have rough and irregular surface, which is caused by residual cement mortar, as opposed to natural aggregate. This roughened, adhered mortar will, in general, enhance the increase of porosity but it can also increase the mechanical interlocking between the newly formed mortar and aggregate. When used with steel fibres, it adds to the mechanical interlocking of the concrete and helps to ensure stress transfer throughout the concrete. The fibres also tie the aggregate-paste interface together, inhibiting the propagation of cracks through the interface and enhancing the composite material's integrity.

The present results were in broad agreement with the results of previously reported investigations, except for differences in the size of the improvement, due to different aggregate quality, fibre characteristics, mix proportions and curing conditions. The results obtained by Adnan et al. (2022)[2] in which they replaced all natural coarse aggregate by recycled coarse aggregate showed 22.3% decrease in compressive strength and correlate with the present observation that only recycled aggregates have a negative effect on the concrete strength. Despite of that, the reduction measured in this research was much more significant, indicating the importance of the quality of the recycled aggregates as well as the properties of the adhered mortar in shaping the mechanical properties of recycled aggregate concrete.

Likewise, Shawais et al., 2023[37], showed that using the right percentage of SF positively reduces the drop in compressive strength that occurred when the 100% of natural coarse aggregate was replaced, in this case 0.44% SF. They succeeded in establishing the positive effect of the steel fibres, but were unable to achieve much strength improvement due to the relatively low concentration of steel fibres. However, in the present study, the steel fibres content used were up to 2% which gives the significant increase of compressive strength. That comparison suggests that the dose of fibre is a pivotal factor that determines the performance of steel fibre for recycled aggregate concrete.

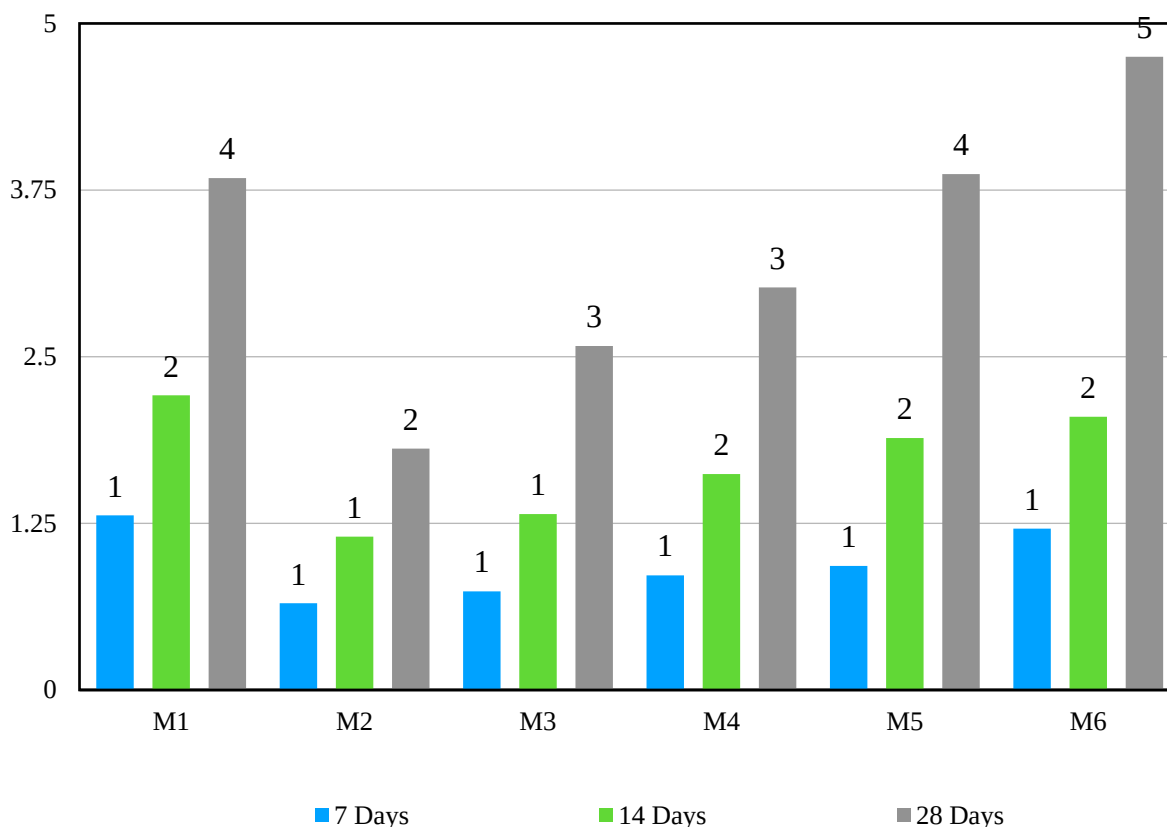
As per the results, it has been compared with the results of Aslani et al. (2018)[4] who reported a compressive strength value of 43.82 MPa with the partial replacement of 40% recycled aggregate. On the other hand, the research work in the present investigation resulted the compressive strength of 46.54 MPa by using 100% recycled coarse aggregate, 10% recycled fine aggregate and 2% steel fibres. The improvements in strength that were achieved in this study indicate that the positive impact of steel fibre can overcome the negative impact of CA replacement when an appropriate mix design and dosage of steel fibre is used.

Summarily, the results have confirmed that use of full replacement of natural coarse aggregate with recycled coarse aggregate causes a significant drop in the compressive strength but the problems of lack of quality, strength of recycled coarse aggregate and weaker interfacial transition zones can be over-ridden and a level of performance comparable with that of natural coarse aggregate can be achieved with the use of steel fibre reinforcement. Adding high proportions of steel fibres can improve crack resistance, better load transfer, strength of the aggregate-paste bond and ductility and toughness of RAC. The superior compressive strength compared to and conventional concrete with 2% steel fibre, achieved under the experimental circumstances testing this, confirms the viability of creating high performance eco-responsible structural concrete for use with recycled concrete aggregates. The findings also

complement recent studies suggesting that use of steel fibre reinforcement is one of the promising solutions to address the mechanical limitations of recycled aggregate concrete and to adopt sustainably to construction practices.

4.3 SPLIT TENSILE STRENGTH TEST

The study shows that the use of 100% RCA to replace NCA will result in a significant drop in the split tensile strength of concrete for all ages of curing. The use of steel fibres in recycled aggregate concrete (RAC) can, however, significantly enhance its tensile properties, thereby reducing any detrimental effects of using recycled aggregate. As concrete is a poor material in tension, its improvement due to the strength of fibre reinforcement is especially valuable in terms of crack resistance, strength and long-term durability.



The experimental findings indicated that 100% natural coarse aggregate was completely replaced by recycled coarse aggregate resulting in 50.38%, 47.96%, and 52.86% reduction in the split tensile strength of the fresh concrete at 7, 14 and 28 days respectively in comparison with the control sample (100% natural coarse aggregate). This significant reduction is due mainly to the properties of recycled aggregates which are less optimal than those of natural aggregates. The recycled coarse aggregates usually have adhered old mortar, which makes the internal content of the aggregate more porous, stronger water absorption and higher internal microcracks density than the original coarse aggregates, reduces mechanical strength and stiffness of the aggregate. When using the RCA in concrete mixing, the greater water absorption reduces the amount of water available for the hydration and curing of the cement in the mix without adding extra water or washing the aggregates before combining them with the cement. Due to this, the local reducing of effective water cement ratio can occur which will cause a lack of worthy hydration and lead to higher porosity and less bond strength within the concrete matrix[20].

It is also noteworthy that the quality of Interfacial Transition Zone (ITZ) has a significant effect on the properties of recycled aggregate concrete's tensile strength. The ITZ of recycled aggregates has several interfaces: bond between the old adhered mortar and the recycled aggregates, and the interface between the old mortar and newly hydrated cement paste. Thus all of these multiple transition zones have high levels of porosity in terms of pores and microcracks compared with conventional concrete and provide

preferential routes for the initiation and propagation of cracks at tensile loads. The ITZ gets weakened, leading to a drastic reduction in split tensile strength of recycled aggregate concrete since failure of the ITZ is the major cause of failure for concrete[26].

However, the use of reclaimed aggregate resulted in decrease in split tensile strength but the addition of steel fibres resulted in progressive and significant increase in split tensile strength. The enhancement was always higher with higher dose of fibre, showing the effect of steel fibre to improve the tensile behaviour of recycled aggregate concrete. The incorporation of 0.5%, 1.0%, 1.5%, and 2.0% steel fibres resulted in increases in split tensile strength of 13.84%, 32.30%, 43.07%, and 86.15%, respectively, at 7 days. The improvements in the corresponding physical properties of the recycled aggregate concrete were 78.26%, 66.85%, 113.81% and 162.43% at 14 days and 42.54%, 40.86%, 64.34% and 78.26% at 28 days compared with the recycled aggregate concrete without steel fibres.

This significant increase in tensile strength is thought to be due to the steel fibres acting as a crack-bridging mechanism. When tensile loading occurs, microcracks form in the paste cement and slowly grow towards the aggregates-paste interface. The randomly oriented steel fibre population intercepts these early cracks, bridging the crack faces and preventing the crack opening by pull out of the steel fibres and anchorage. This mechanism slows crack propagation, is a stress redistributive and raises the impetus required for crack propagation. Therefore, the tensile strength, toughness and load carrying capacity of post cracking are increased for the concrete.

Apart from bridging the cracks, the steel fibres also have another effect, namely re-distribution of the stresses around the crack within the concrete matrix so that tensile stresses forming around the crack are carried by the fibres instead of the matrix. The fibres decrease the stress concentration around the pores, microcracks, and weak aggregate interfaces, making the composite more homogeneous of the stresses distribution more uniform among the composite. This behaviour is especially beneficial in recycled aggregate concrete because there are many weak interfacial transition areas in this concrete (with adhered old mortar). The effectiveness of the reinforcing action of steel fibres, however, counteracts these weaknesses and allows that the concrete withstands much higher tensile stresses before breakage.

The increase in tensile strength has also taken into account the increase in ductility provided by steel fibres. The conventional concrete has brittle tensile failure with few deformations before crack propagation, mainly in the form of suddenly appearing cracks. To improve this brittle behaviour to a more ductile failure mode, the gradual widening of cracks is enabled by fibre bridging, thus preserving the integrity of the structure. Thus, under service loads, FRCAC shows high service ability of deformation capacity, fracture toughness and crack propagation resistance.

One of the interesting results of the present research is that 100% recycled coarse aggregate (RCA) concrete with 2% SFC gave higher split tensile strength value than that of conventional natural aggregate concrete (NAC). That is, the tensile strength of the fibre-reinforced recycled aggregate concrete was about 23.70% greater than that of control mix concrete. The results show that the strength loss due to the replacement of recycled aggregates can be fully made up by applying an appropriate dosage of steel fibres and that tensile performance can even be improved beyond that of conventional concrete. These results confirmed that the steel fibre reinforcement has strong effect in solving the main problem of the recycled aggregate concrete; that is the poor tensile properties.

Better tensile properties obtained by increasing the amount of steel fibre could be related to the surface of recycled aggregates. The recycled aggregates have rougher and more angular surface characteristics as a result of mortar to be adhered. This type of adhered mortar is not in most cases significantly reducing porosity of the materials, but instead enhanced interlocking of mechanical function between aggregate and newly hydrated cement paste due to the rough texture. Together for the steel fibres' crack arresting behaviour the resulting enhanced mechanical interlock yields increased tensile resistance and structural integrity.

The present results generally corroborates with previous studies on the positive effects of steel fibres on recycled aggregate concrete, but in varying levels of improvement. For recycled aggregate concrete, Shawais et al. (2023)[37] have claimed that even 0.44% replacement of tensile losses having occurred from full replacement of RAC significantly reduced the tensile strength compared to conventional concrete, estimated to be around 40% loss. This relatively limited improvement in their investigation is probably due to the relatively small amount of fibre they used. This is compared with the present study which included a much higher content (of up to 2%) by volume of steel fibre which gave extreme improvements in tensile strength and finally the value exceeded the values obtained with natural aggregate concrete.

Other differences between the two studies may be attributed to variations in the quality of the recycled aggregates, shape and ratio of the fibres, concrete mix proportions and curing environments. Some previous tests have shown that the reinforcing efficiency of steel fibres not only varies with fibre content but also with fibre orientation, fibre bond properties and distribution in the concrete

matrix. Fibre distribution or fibre balls at high dosages can decrease performance whereas uniform fibre dispersion can provide uniform crack bridging throughout the concrete mass. It is concluded that proper distribution of fibre was obtained in the present study which shows the significant improvement in the investigation and that the fibres were able to effectively reinforce the matrix of recycled aggregate concrete.

Based on all the obtained results, it can be concluded that completely replacing natural coarse aggregate with recycled coarse aggregate contributes to lowering the split tensile strength (STS) due to the increase in porosity, water absorption, poor interface transition zones as well as the existence of pre-existent microcracks in recycled aggregate. However, these shortcomings can be overcome very well if steel fibres are used. When the dosage of steel fibre is raised progressively, crack resistance, the capability of stress redistribution, ductility and the fracture toughness gradually improve, until the tensile performance is significantly improved. The efficacy of recycled aggregate concrete containing 2% steel fibre when compared with the conventional natural aggregate concrete, indicates the huge potential to utilize steel fibre reinforcement in high performance and sustainable concrete for structures. These results showed that the use of a steel fibre- recycled aggregate concrete for the construction waste reduction and natural aggregate resource saving is also environmentally friendly, and it can simultaneously reduce construction waste and conserve natural aggregate resources, while ensuring performance in mechanical properties.

CHAPTER 05: CONCLUSION

In the present Research, an attempt has been made to analyse the implications of replacement of Natural Coarse Aggregate (NCA) by 100% recycled coarse aggregate (RCA) produced in M 25 grade concrete and effect of steel fibre on the fresh and mechanical properties of recycled concrete. Based on the experimental findings, the following conclusions can be drawn:

The slump value increased by 17.85% when 100% natural coarse aggregate was replaced with recycled coarse aggregate. This workability improvement is generally believed to be due to the presence of greater porosity and the presence of higher percentage of adhered mortar remaining on the recycled aggregates affecting the water absorption behaviour and creating availability of free water during mixing. But, the addition of steel fibres decreased slump by 10.34% to 27.58% because the randomly dispersed fibres hampered free flow of the concrete mix and created internal friction which made it less workable.

Using 100% recycled coarse aggregate led to a decrease of 48.50%, 43.32% and 45.03% in their compressive strengths at 7 days, 14 days and 28 days respectively, as compared to that of the control concrete. This reduction is largely attributed to poor quality recycled aggregates, old mortar that has adhered on the surfaces of recycled aggregates, preexisting microcracks in the adhered surface and weaker interfacial transition zones (ITZs) between recycled aggregates and new mortar. These qualities have reduced the bond strength and load transfer in the concrete matrix.

In the same manner, the split tensile strength, after 7, 14 and 28 days, decreased by 50.38%, 47.96% and 52.86%, respectively with 100% replacement of natural coarse aggregate with recycled coarse aggregate. The lower tensile strength is believed to be due to increased porosity and a weaker aggregate–paste bond resulting from recycled aggregate concrete allowing crack initiation and propagation on tensile loading.

The property of concrete was not favorable when using recycled aggregates however the compressive and split tensile strengths were progressively enhanced by progressive addition of steel fibres. The compressive strength of the steel fibre concrete was 36.20% higher than that of control concrete at 28 days with 2% content of steel fibre while the split tensile strength was 23.70% higher. The improvement was mainly because of the crack-bridging effect of steel fibres which slows down the propagation of the cracks, re-distributed stress and increased the ductility and fracture toughness of the concrete.

We observed that the increase in the split tensile strength was greater than increase in compressive strength as the fibres directly resist the opening of tensile crack and effectively act as bridging in the tensile crack. The combination of the fibres when subjected to compressive loading, gave a confinement effect and prevented lateral deformations of the concrete and delayed coalescence of the cracks, thereby lowering the occurrence of brittle failure and improving load carrying capacity of the concrete as a whole.

In general, recycling coarse aggregate with no additions resulted in lower compressive strength due to some of the inferior microstructural properties of recycled coarse aggregate, however the adding of steel fibres adequately supplemented the effect of the lower strength properties. Steel fibre reinforcement gave the recycled aggregate concrete having comparable mechanical characteristics with conventional natural aggregate concrete and for higher amount of steel fibre, the RAC has better mechanical characteristics. Mechanical properties of the steel fibre concrete using recycled aggregate of concrete were compared with natural

aggregate concrete and it was found that the properties are similar or even better for RAC at high level of steel fibre. This results has shown that steel fibre-reinforced recycled aggregate concrete is a promising alternative to natural aggregate concrete in structural applications due to its excellent engineering properties and environmental advantages in conserving the natural aggregate and recycling the construction and demolition waste.

CHAPTER 06 : REFERENCES

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