Experimental analysis of mechanical performance and microstructural behavior of recycled aggregate concrete

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Abstract. The use of recycled aggregates in concrete offers significant opportunities for material reuse and waste reduction in construction. The utilization offers a sustainable solution to the growing problem of excess waste material, provided that the required quality standards are achieved. The practice of using recycled aggregates has been adopted for decades in several developed European and Asian countries, with research confirming their potential for structural applications. This study presents an experimental investigation into the strength and microstructural properties of recycled aggregate concrete, comparing them with those of natural aggregates. The findings reveal that recycled aggregates generally have lower specific gravity, reduced workability, higher crushing and impact values, and greater water absorption than natural aggregates. However, when subjected to proper treatment and combined with optimized mix proportions, recycled aggregates can produce concrete with satisfactory strength and durability. Therefore, their application not only reduces environmental impact and conserves natural resources but also supports sustainable development in the construction industry.

1 Introduction

With the growth of the population and the rise in urban development, the reuse of construction waste materials becomes essential. These recycled materials can be incorporated into concrete [1] as aggregates. Since recycled aggregates [2] are readily available and more cost-effective, they can serve as substitutes for natural aggregates. They offer several advantages, including lower energy requirements, and can be effectively used in various environmental conditions. The use of reused aggregate becomes crucial because there is a lack of a sensible disposal method. The reuse of aggregate production operation is usually straightforward, as it involves removing, evacuating, and crushing the existing cement into a predefined estimated content. Generally, the cost of recycled aggregates [3] is 15–30% lower than that of conventional aggregates. Recently, concrete [1] recycling has emerged as an effective solution to minimize construction waste. In India, the shortage of adequate infrastructure has been a significant concern. The Planning Commission allocated nearly half of the capital expenditure toward infrastructure development during the 10th and 11th Year Plans, which led to increased demand and a consequent rise in the cost of construction materials. Therefore, reusing demolished concrete [3] waste has become essential to conserve both cost and given these conditions, the use of recycled aggregates [2] not only offers a practical solution to material and cost constraints but also makes a significant contribution to supporting sustainable [4] development. By reusing used concrete [1], the construction industry can reduce its dependence on increasingly scarce natural resources while minimizing its environmental impact.

2 Need for the current study

The advancement in the field of construction is tremendous. Currently, it is essential to prioritize sustainability in the construction industry. Across the world, many governments have made it mandatory to assess the environmental impact of any construction activity. Nowadays, it is crucial to ensure that no negative impact on the environment results from any construction. As civil engineers, it has become our responsibility to ensure safety and provide all necessary design criteria, while also minimizing any adverse impact on the environment. Using an alternative material instead of the conventional one is the best approach. This method has two advantages: one is that it reduces the use of natural aggregates, and the second is that it appears to be the most effective way to dispose of demolition waste. The use of recycled aggregate [3] in concrete [1] leads to a decrease in strength [4]. Various parameters contribute to this reduction, including microstructural build-up or behavior. Hence, it is necessary to conduct microstructure [5] tests on the concrete [1] to determine whether this parameter affects the concrete [3] strength [1]. If it is found to be

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affecting, what are the reasons for the cause that need to be studied? Therefore, research on the use of recycled aggregate [2] should not only focus on measuring the mechanical properties of concrete [1] but also examine the microstructural aspects that influence them [6]. The results of such research will provide a more comprehensive understanding of the behavior of concrete [1] with recycled aggregate [3], offering a scientific basis for formulating strategies to enhance material quality [6]. Ultimately, these findings will support the development of more efficient, economical, and environmentally friendly construction technologies.

3 Study objectives

- To evaluate the characteristic properties of recycled aggregates produced from destroyed concrete waste and to compare them with real aggregate characteristics.
- Develop the M60-grade concrete mix according to the Perumal mixing design method.
- To evaluate organic aggregate concrete's mechanical features, such as compressive strength, split tensile strength, flexural strength, fragment power resistance, and recycled concrete overall.
- Determine the optimum proportion of replacement of the recycled aggregate without failing to achieve the required mixing energy.
- Determine the character of natural and recycled aggregate concrete microstructures by testing with SEM.

4 Characterization of materials

4.1 Characterization of cement

For all the mixes in this project, 43-grade ordinary Portland Cement was used. This cement was tested in accordance with the codal provisions as per IS 12269:1987. The results obtained are in accordance with the limits and were therefore approved for use in this project. Results are tabulated in Table 1.

Table 1. Results of cement characterization test

Properties	Result
% Fineness	5%
Specific gravity	3.05
Standard consistency	33%
Initial Setting time	40 min
Final Setting time	345 min

4.2 Mineral admixtures – silica fume

The silica fume used in this study was characterized, and its appearance is shown in Fig. 1.

Fig. 1. Silica fume

4.3 Characterization of fine aggregate

The manufactured sand used in this work is free of silt and organic matter, and it is classified as a fine aggregate by passing through a 4.75 mm sieve, confirming it meets the requirements of area 2 as per IS 383. The characterization results (Table 2) and particle size distribution (Fig. 2) support this classification.

Table 2. Results of fine aggregate characterization test

Properties	Result
Moisture Content	0.6%
Specific gravity	2.48
Standard consistency	3.93

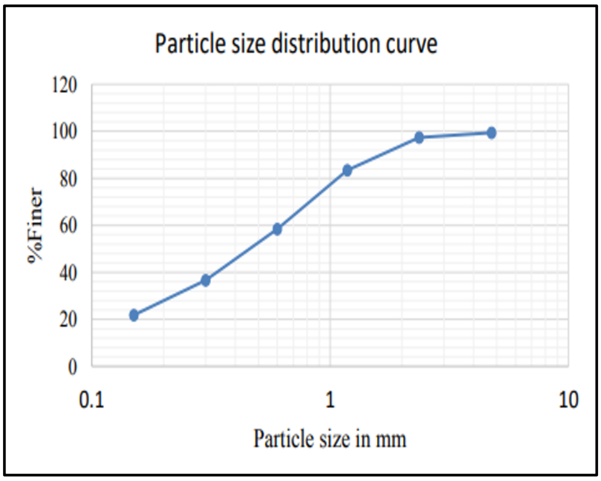

Fig. 2. Particle size distribution curve of fine aggregate

4.4 Characterization of natural coarse aggregate

The Aggregates used in this project were 12.5mm downsize, and their properties are shown in Table 3.

Table 3. Results of coarse aggregate characterization test

Properties	Result
Fineness	8.16
Impact Value	24.5%
Crushing Value	27.5%
Water Absorption	1.3%
Specific Gravity	2.56

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4.5 Characterization of recycled aggregates

The recycled aggregates were obtained from the Rock Crystal Crushing unit used in this project (shown in Fig. 3). Tests on recycled aggregate are confirmed to be in accordance with IS: 8112-1989, IS: 2386-Part 3:1963, and IS: 2386-Part 4:1963. The results of the characterization test are presented in Table 4.

Fig. 3. Sample of recycled aggregate used for investigation

Table 4. Results of the recycled aggregate characterization test

Properties	Result
Fineness Modulus	6.15
Impact Value	29.86%
Crushing Value	35.68%
Water Absorption	3.2%
Specific Gravity	2.3

4.6 Chemical admixtures – superplasticizer

The chemical admixture used in this study was a superplasticizer of type SP 430 Conplast, as shown in Fig. 4.

Fig. 4. SP 430 CONPLAST

4.7 Mix design proportions

The table provides the calculated weight (or volume) of each constituent material per cubic meter of concrete [3]. Cement acts as the binding material, while fine aggregates (such as sand) fill the voids and improve workability, and coarse aggregates provide strength [4] and bulk to the concrete [1] matrix. Water is required for hydration of cement and to ensure adequate workability, whereas admixtures (if used) modify specific properties such as setting time, workability, or durability.

5 Results and discussion

Various tests were conducted on hardened concrete to evaluate the performance of the designed mixes. The observations are compared with conventional concrete to highlight the influence of recycled aggregates and other mix parameters.

5.1 Compression strength test

The compressive strength test is one of the most important tests conducted on hardened concrete. It measures the ability of concrete to withstand axial compressive loads and is a key indicator of its quality and performance.

From the consolidated Fig. 5, from the 7-day and 28-day compressive strength results, it can be observed that there is a gradual reduction in strength as the replacement ratio increases from 0% to 45%. The overall decrease in compressive strength is 18.03% for 7 days and 7.37% for 28 days, indicating a relatively uniform reduction in strength over time then, after the strength reduction steepens from 45% to 100% for both 7 days and 28 days, which corresponds to 25.52% and 36.36%, respectively.

Table 5. 7- & 28-days compressive strength

Replacement ratio (%)	7 Days Compressive strength (MPa)	28 Days Compressive strength (MPa)
0	49.99	69.03
10	48.83	68.16
20	46.21	67.87
30	45.19	67.43
40	43.6	64.23
45	40.98	63.94
50	38.94	59.87
60	38.8	55.22
70	34.88	49.55
80	33.86	47.23
90	32.12	42.43
100	30.52	40.69

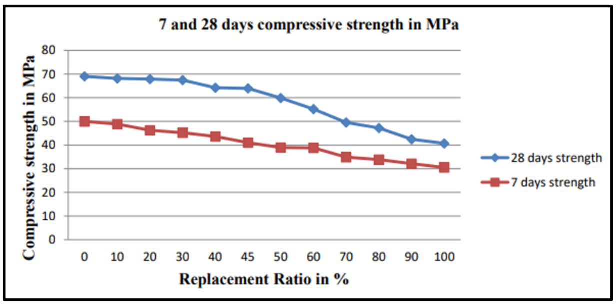

Fig. 5. 7- and 28-days compressive strength

5.2 Split tensile strength test

The split tensile strength test is conducted to determine the tensile strength of concrete, one of the key mechanical properties that influences crack resistance and structural performance. Since concrete is weak in tension, this test provides valuable insight into its ability to resist cracking under load.

Table 6. 7 and 28 days split tensile strength

Replacement ratio (%)	7 Days Split tensile strength (MPa)	28 Days Split tensile strength (MPa)
0	5.1	7.9
10	5.08	7.8
20	4.47	6.97
30	4.37	6.04
40	4.06	5.83
45	3.95	5.62
50	3.64	5.31
60	3.54	5.09
70	3.33	4.99
80	3.22	4.89
90	3.12	4.78
100	3.02	4.68

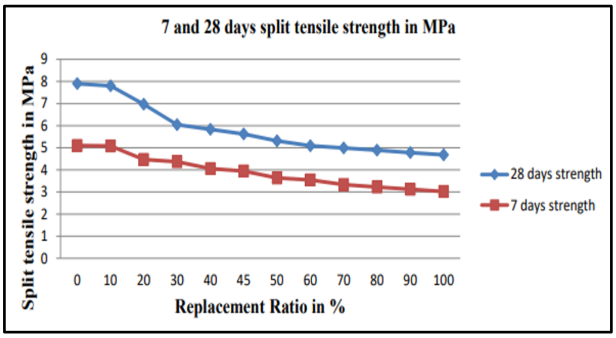

Fig. 6. 7 and 28 days split tensile strength

From the consolidated Fig. 6 and Table 6 depicting the 7-day and 28-day split tensile strengths, it is evident that there is a sharp decline in strength as the replacement ratio increases from 0% to 45%, with reductions of 22.54% and 28.86% for 7 days and 28 days, respectively. Beyond 45%, the reduction trend becomes more gradual and linear, reaching 100% replacement, with decreases of 23.54% and 16.72% for the 7day and 28day strengths, respectively.

5.3 Flexure strength test

The flexural strength test evaluates the ability of concrete to resist failure in bending. It is a measure of the tensile strength of concrete in the extreme fiber of a beam subjected to flexure. This property is significant for pavements, slabs, and other structures where tensile stresses due to bending are substantial.

Table 7. 28-day flexure strength

Replacement Ratio (%)	28 Days strength (MPa)
0	6.95
10	6.83
20	6.65
30	6.59
40	6.42
45	6.29
50	5.89
60	5.71
70	5.47
80	5.36
90	5.18
100	4.94

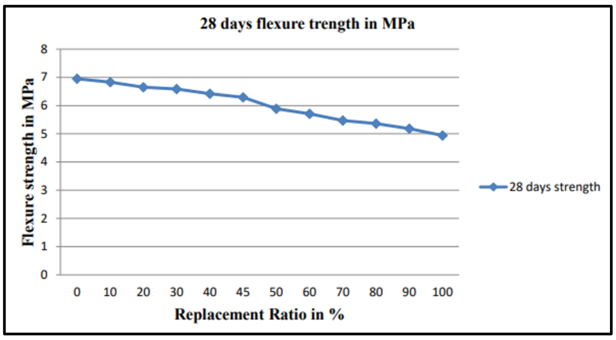

Fig. 7. 28 days flexure strength

From Fig. 7 and Table 7, it can be observed that at 28 days of curing, the maximum flexural strength obtained was 6.95 MPa, which is for natural aggregate concrete. In recycled aggregate concrete, a 10% replacement yields the highest compressive strength of 6.83 MPa, which is only 1.72% lower than that of natural aggregate concrete. In contrast, a 100% replacement results in the lowest compressive strength of 4.94 MPa, representing a 28.92% reduction. For intermediate replacement levels, the compressive strength gradually decreases from 10% to 90% replacement.

5.4 Fracture energy test

The fracture energy test evaluates the energy required to propagate a crack through a concrete [1] specimen. Unlike compressive or tensile strength [4] tests, this test provides a measure of the toughness and ductility of concrete [1], which are critical for assessing its post-cracking behavior. Fracture energy is crucial for pavements, structural elements subjected to dynamic loading, and recycled aggregate [2] concrete [3], where cracking resistance plays a vital role in long-term durability.

Table 8. 28-day fracture strength

Replacement Ratio (%)	Fracture energy in N/ mm3/2
0	59.25
10	56.83
20	53.21
30	49.58
40	47.16
45	45.95
50	41.11
60	36.27
70	32.64
80	29.02
90	26.60
100	24.18

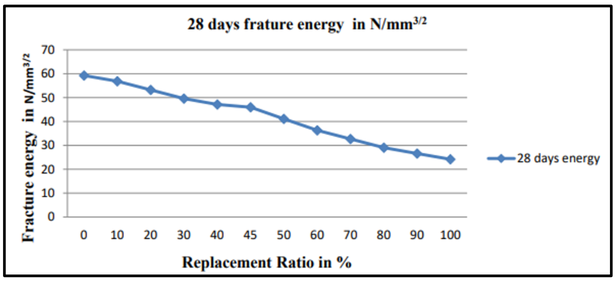

Fig. 8. 28 days fracture energy

From the trend shown in Fig. 8 and Table 8 for 28-day fracture energy, it can be seen that the energy reduction is moderately steep as the replacement ratio increases from 0% to 45%, with a decrease of 22.44%. Beyond 45%, the energy reduction becomes much more pronounced, showing a sharp decline of 47.37% from 45% to 100% replacement at 28 days.

5.5 Microscopic test results

Once the tests on hardened concrete are completed, failed test samples are crushed and collected in a manner that allows for their microstructural behavior to be tested. Rather than testing all twelve replacement proportions from 0% to 100%, only the most significant ratios 0%, 40%, 45%, and 100% were evaluated, and the corresponding results are presented below.

5.6 Scanning electron microscopy

SEM tests were conducted on four mixes (R0, R40, R45, R100) at magnification levels of 1k, 3k, and 10k. This test was conducted using a Vega 3 Tescan; the high-voltage value of the SEM was set to 10 kV, as shown in the images below of different mixes (Fig. 9).

Fig. 9. Samples collected for SEM testing

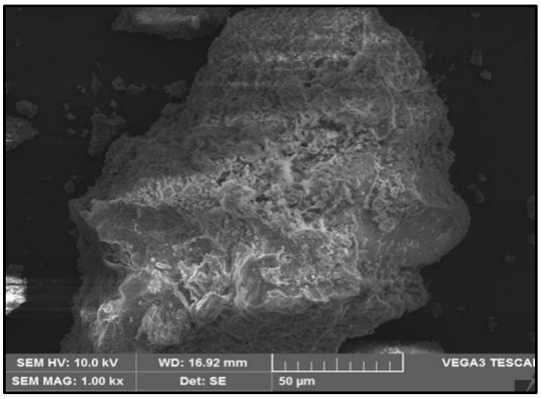

Fig. 10. SEM mix R0 in 1kx magnification

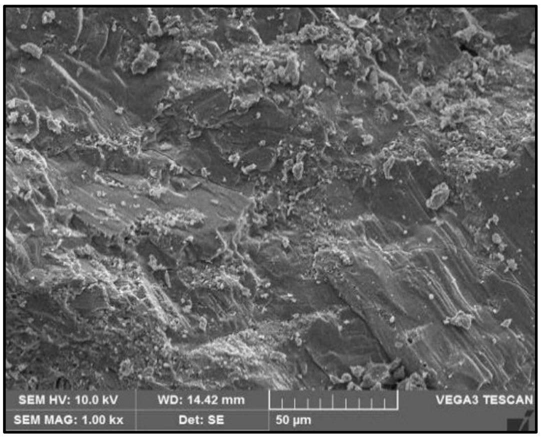

Fig. 11. SEM mix R40 in 1kx magnification

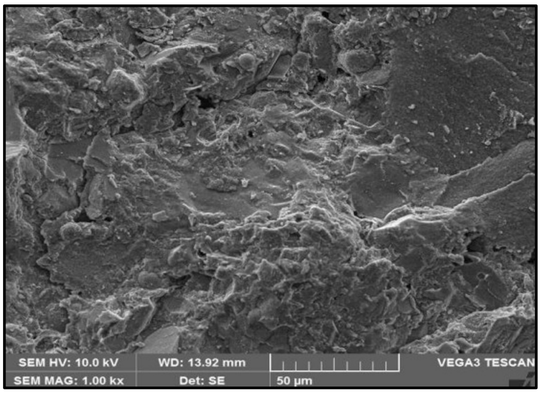

Fig. 12. SEM mix R45 in 1kx magnification

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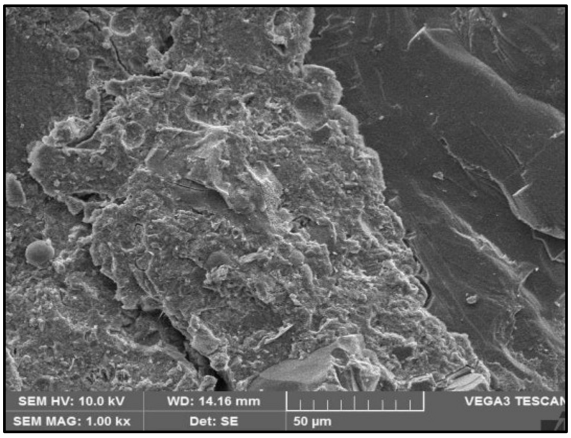

Fig. 13. SEM mix R100 in 1kx magnification.

Four figures above, Figs. 10, 11, 12, and 13 represent the mixes Ro, R40, R45, and R100, respectively, at a magnification level of 1k.In this magnification we are observing how the cracks are happened and nature of cracks, in regular aggregate concrete (R 0) Cracks are fragile, linear and are very rare, and in proportions of R - 40 and R 45 of recycled aggregate concrete number cracks are considerably increased, width and length of cracks are also improved and in proportion of R 100, cracks became thick with nonlinear run and are very common, also width and lengths drastically increased in this case.

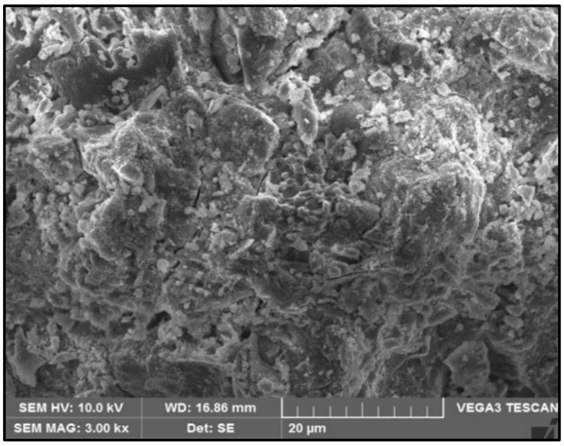

Fig. 14. SEM mix R0 in 3kx magnification

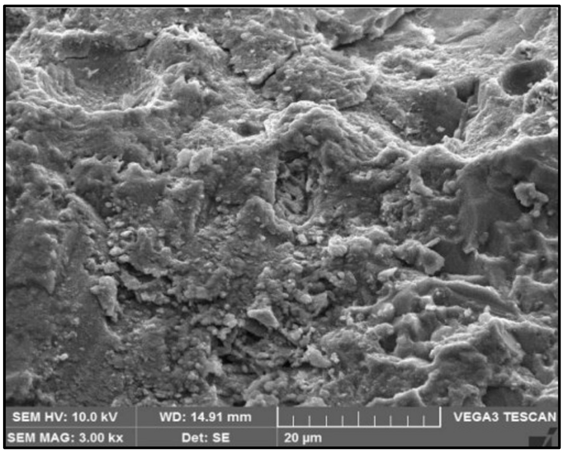

Fig. 15. SEM mix R40 in 3kx magnification

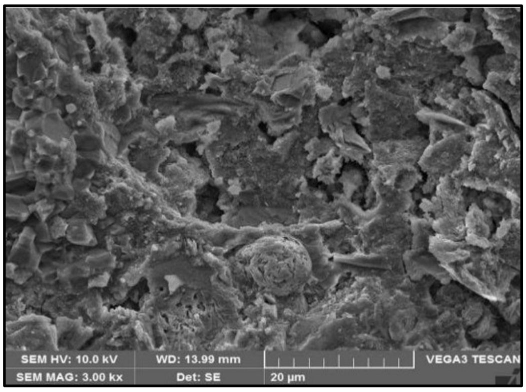

Fig. 16. SEM mix R45 in 3kx magnification.

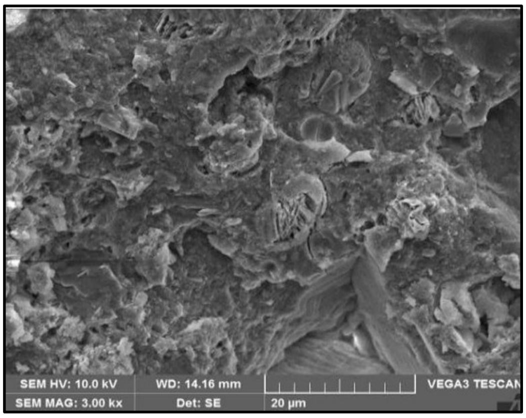

Fig. 17. SEM mix R100 in 3kx magnification.

Four figures above, Figs. 14, 15, 16, and 17 represent the mixes Ro, R40, R45, and R100, respectively, at a magnification level of 3k. In this magnification we are observing how much chemical reaction has happened, in these images white colour portions representing chemically good reacted (hydrated cement) area, black portion representing area where chemical reaction is not completely happened, In regular aggregate concrete (R 0) sample images, we are observing more chemically reacted portions compared recycled aggregate concrete (R 40, R 45, R 100) in which unhydrated portion is more, as the chemical reaction is good makes sample better in bonding and higher density hence the compressive strength increases. This character of recycled aggregate concrete results in a decrease in compressive strength at various ages of concrete.

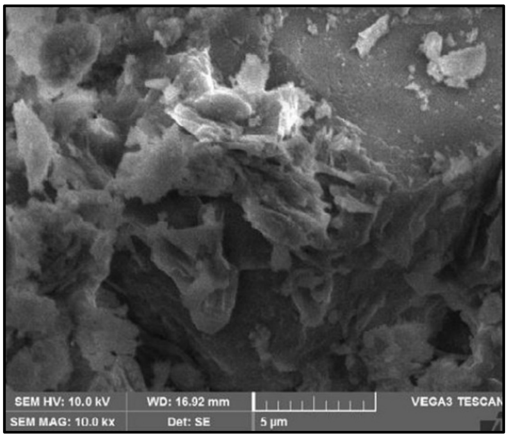

Fig. 18. SEM mix R0 in 10kx magnification.

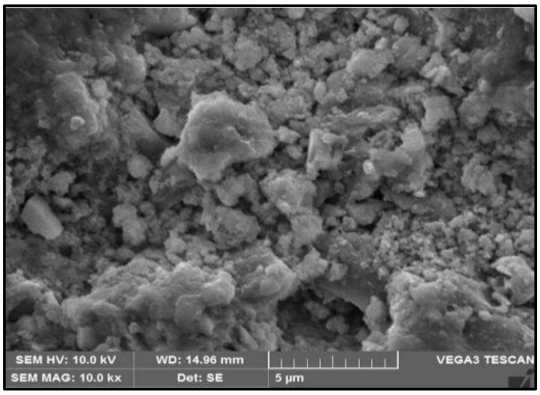

Fig. 19. SEM mix R40 in 10kx magnification`

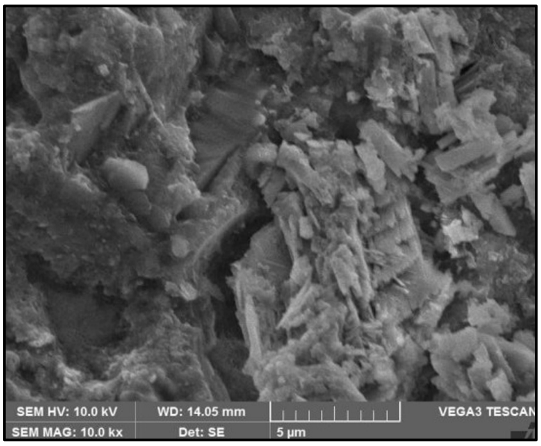

Fig. 20. SEM mix R45 in 10kx magnification.

Three figures above, Figs. 18, 19, and 20 represent the mixes Ro, R40, R45, and R100, respectively, at a magnification level of 10k. In this magnification, we observe the formation of needle-like structures called ettringites, which are products of the dissolution of calcium sulfate and calcium aluminates compounds. The presence of ettringite indicates partial hydration of the cement, as the final product of hydration is monosulfate. As ettringite increases, the concrete becomes more porous in nature, as observed in the figures above.

6 Conclusions

Recycled aggregate concrete exhibits lower specific gravity, higher water absorption, and reduced workability compared to natural aggregate concrete due to adhered mortar and higher porosity. Mechanical properties, including compressive strength, split tensile strength, flexural strength, and fracture energy, decrease with increasing replacement ratios. However, at a 45% replacement level, the concrete achieves a compressive strength of 63.94 MPa, which meets the M60 requirement and is identified as the optimum replacement level. Beyond this, strength values fall below the desired grade. SEM analysis further confirms the porous and less dense microstructure, characterized by ettringite formation, which leads to a reduction in strength. Thus, recycled aggregate can be effectively used as a replacement for up to 45% of the aggregate in structural concrete.

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