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## Research Paper

### Mechanical and microstructural properties of high strength concrete with manufactured sand and recycled coarse aggregates

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#### ABSTRACT

The influence of manufactured sand (M-sand) and Recycled Coarse Aggregates (RCA) on the fresh, mechanical and microstructural properties in the high strength concrete is focused in order to promote sustainable materials in the high strength concrete. Therefore, there are four proposed mixes such as conventional concrete, RCA replaced by 25% coarse aggregate, MS replaced by river sand 100% and combination of MS (100%) and RCA (25%) replaced together are designated as CM, RC, MS and MSRC, respectively. The proposed mixes were evaluated through the mechanical tests such as compression and tension tests as well as the microstructural analysis such as microstructure as well as elements and phase formations through the SEM, XRD and EDX analysis. It was concluded that the inclusion of RCA and M-sand in concrete has reduced the workability because of their higher water absorption capacity. The compressive strength of mix RC and MS was reduced by 12.9 and 8.24%, respectively as compared to CM. Also, the compressive strength of mix MSRC was reduced by 13.3% compared to the control mix. It was observed that the tensile strength of mix RC and MS individually was reduced by 7.7 and 7.17%, whereas the same on mix MSRC was further reduced by 16% as compared to mix CM. The microstructure of the MS was relatively denser as compared to the RC, however the microstructure of mix MSRC was found to be weaker due to untreated silica particles present in the interface of mortar as compared to the control mix CM. The CM mix revealed that the brownmillerite and calcite act as an activator in the early hydration of concrete and as an inert filler. The RC mix mostly showed the presence of quartz and small peaks of hatrurite and the mineral phase on MS mix has strong peaks of quartz and albite, whereas the mineral phases in MSRC show both hatrurite and albite along with quartz are the hydration products of C3S. The presence of higher Sulphur content in a mix of RC, MS and MSRC also indicates lower durability to water penetration and brittle microstructure.

## 1 Introduction

The construction sector contributes about 33% to the global CO<sub>2</sub> emissions and as per IPCC report, about 30% of the emissions resulting from construction and building sector could be reduced making it the sector with highest potential for

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CO<sub>2</sub> emission reduction, IPCC. Summary for policymakers [1]. Fortunately, the global shift towards sustainable practices results in numerous projects in concrete industry to curtail the carbon emissions during production stage. The current construction practices using natural resources are highly energy intensive. Therefore, there is a need for an alternative material to replace the existing natural resources in the current construction industry [2-3]. The recycled aggregate is obtained from processing construction and demolition (C & D) waste which comprises of any waste emerging from demolition of building materials, debris and rubble rising from construction. River sand has been extensively utilized as building material for past several decades because of its ease of availability. The lowest estimate points to global sand extraction reached 40 Gigatonnes in 2014 which is twice the total sediment discharge from river of 20 Gigatonnes, Milliman and Syvitski [4], expressing the lack of sustainability in the present patterns of resource extraction. According to the United Nations Environment Programme (UNEP) [5-6] state that the extraction of sand and other sediment in the marine/coastal environment is estimated at ~6 billion tonnes/year, with a range of 4–8 billion tonnes/year for marine & coastal dredging. As alternatives to river sand, the desert sand, M-sand (manufactured sand), glass sand and garnet sand are available. Manufactured sand (M-sand) or crushed sand is a very popular and affordable alternative to river sand, Mundra et al. [7]; Sharma and Senthil [8]. Although certain aggregate sizes may not fully meet the prescribed grading requirements, however, the economic and sustainability objectives of the project can be achieved more effectively by utilizing locally available materials that are affordable and have lower energy consumption and CO<sub>2</sub> emissions associated with their production and transportation. Therefore, the M-sand found a new era for pushing the environmental agenda and many leading builders across the globe are adopting M-sand for construction projects [9-11].

The utilization of recycled concrete aggregate (RCA) is vastly studied to develop normal strength concrete, Etxeberria et al. [12]. The strength of concrete using recycled aggregate depends mostly on the strength of original aggregate. Original aggregate referring to the aggregate used in the original concrete. For replacement up to 30% RCA, the compressive strength of RAC same as to control concrete, Xiao et al. [13]. Kou and Poon [14] studied the effect of parent aggregate on strength and durability measures of normal and high-performance RAC. For making high-performance RAC, waste concrete samples with strength extending from 30-100 MPa were utilized. It was suggested that to achieve high performance concrete, aggregates derived from parent concrete of 80-100 MPa strength was required. The properties of recycled aggregates are enhanced by different mixing approaches or by treatment process of aggregates. Various methods are commonly employed to RCA to treat the damaged interfacial transition zone (ITZ) and to strip off weakened mortar from aggregate exterior. These methods include mechanical treatment, modified concrete mix approach, the utilization of supplementary cementitious materials (SCMs), carbonation treatment, acidic treatment and the incorporation of fibers [15-17]. Pin et al. [15] presents a comprehensive review of the mixing techniques to enhance the mechanical properties of RCA. It was concluded that quality of concrete using RCA may be enhanced by surface modifying techniques such as saturated RCA, incorporating SCMs like silica fume (SiF), ground granulated blast slag (GGBS) and fly ash (FA) within the mix. The primary defect for RCA in concrete was the adhered mortar attached to the aggregate. It was suggested that pre-soaking recycled aggregates in water or in polymer emulsions enhance the quality of old mortar. Yang et al. [16] investigated effect of locally manufactured M-sand on ultra-high-performance concrete (UHPC). It was inferred that adding M-sand particles disrupts the packing structure of developed mix. Furthermore, it was concluded that utilization of M-sand has minimal effect on hydration and distribution of pores. Ma et al. [17] studied strength behaviour of concrete containing M-sand via waste stone dust, FA and SiF using response surface methodology. It was inferred that considering single factor effect, highest effect on compressive strength for M-sand concrete was obtained for stone dust followed by FA and silica fume. It was concluded that the manufactured sand is performed equivalent to the river sand in terms of measuring the impact force, contact time and plateau force. However, the concrete with manufactured sand performed better than river sand in terms of scabbing phenomena. Therefore, it was recommended to use manufactured sand as full replacement with river sand in the application of concrete with high strength, [18-19].

Based on the detailed literature review, it was inferred that the influence of M-sand and RCA in high strength concrete related studies found limited. Moreover, the synergic effect of M-sand and RCA on the microstructural properties of high strength concrete is also found limited. Therefore, present study is motivated to evaluate mechanical and microstructural properties of mix with M-sand and RCA in high strength concrete applications. The primary objective is to investigate how the partial or full replacement of fine and coarse aggregates with M-sand and RCA influences the mechanical and microstructural properties of concrete. Specifically, the study aims to assess the impact of these alternative materials on key mechanical characteristics such as compressive strength and split tensile strength of high-strength concrete. In addition, the research seeks to analyze the microstructural behavior through techniques such as SEM, EDX and XRD to understand the bonding characteristics, pore structure, and interfacial transition zone (ITZ) between the cement paste and aggregates. The

physical and chemical properties of the materials and test methodologies along with mix designs were presented and discussed in Section 2. The fresh properties of the concrete containing M-sand and RCA in terms of density and workability of concrete is discussed in Section 3. The mechanical properties of concrete tested under compression and tension were presented and discussed in Section 4. The microstructure as well as elemental and phase formations of high-strength concrete mixes were examined using SEM, XRD and EDX analysis, see Section 5.

Abbreviations: Manufactured sand - M-sand or MS, Recycled Coarse Aggregates – RCA, Conventional concrete - CM, RCA replaced by 25% coarse aggregate - RC, MS replaced by river sand 100% - MS, Combination of MS (100%) and RCA (25%) – MSRC, scanning electron microscope - SEM, X-ray diffraction - XRD, Energy Dispersive X-ray - EDX, Ultra-high-performance concrete – UHPC, silica fume - SF, Flyash – FA, Ground granulated blast slag - GGBS, supplementary cementitious materials – SCM, interfacial transition zone – ITZ, construction and demolition waste -C&DW, universal testing machine – UTM, Ordinary Portland Cement -OPC, high strength concrete – HSC and split tensile strength – STS.

## 2 Materials and methodology

This section covers the discussion on the materials considered in the present study. Further, the mix design procedures and proposed mix design are presented. Also, the testing methodology including mechanical tests and microstructural analysis related tests are presented.

### 2.1 Materials

The cement used in this study was 53 grade Ordinary Portland Cement (OPC) conforming to IS 269:2015 [20]. The physical and chemical properties of OPC 53 is shown in Table 1. Silica fume pale white in colour was used as a pozzolan in the treating RCA aggregates. The physical and chemical properties of micro silica fume powder were measured as per following guidelines IS 15388:2003 [21]. The physical and chemical properties of silica fume is shown in Table 2. Alccofine-1203 as a material with low calcium silicate content utilized as SCM to substitute silica fume in the production of high strength concrete (HSC), conforms to IS 16715:2018 [22]. Alccofine-1203 used in different applications in high strength concrete such as high rise building of Nathani Heights, Mumbai and for micro tunnelling project at Vadodara. The microstructural properties of silica fume and Alccofine 1203 powder was studied under X-ray diffraction (XRD) analysis and illustrated in Fig. 1. In order to heal the ruptured interfacial transition zone (ITZ) of RCA, mechanical grinding was performed prior to microsilica treatment, followed by the implementation of a modified two-stage mixing approach.

**Table 1- Physical and chemical properties of OPC 53**

| Physical properties     |                |                            |      |      |          |                   |      |
|-------------------------|----------------|----------------------------|------|------|----------|-------------------|------|
| Property                | Value          | Compressive strength (MPa) |      |      |          | Value             |      |
| Specific gravity        | 3.14           | 3 days                     |      |      |          | 36.0              |      |
| Fineness (m²/kg)        | 329            |                            |      |      |          |                   |      |
| Le-Chatelier expansion  | 1.0            | 7 days                     |      |      |          | 45.0              |      |
| Initial setting time    | 110            |                            |      |      |          |                   |      |
| Final setting time      | 170            | 28 days                    |      |      |          | 58.0              |      |
| Consistency (%)         | 28.3           |                            |      |      |          |                   |      |
| Chemical properties (%) |                |                            |      |      |          |                   |      |
| Test type               | CaO saturation | Al₂O₃/ Fe₂O₃               | SO₃  | MgO  | Chloride | Insoluble residue | LOI  |
| Value                   | 0.82           | 1.36                       | 3.27 | 4.36 | 0.003    | 2.65              | 2.60 |

Locally procured river sand was used in the base mix and conforming to Zone II as per IS: 383:2016 [23]. The physical properties of river sand are illustrated in Table 3 and the particle size distribution was also shown in Fig. 2. The M-sand is characterized as fine aggregates from crushed hard granite or basalt rocks and processed to acceptable grading as per the code. The properties of M-sand primarily rely on the specifications of the crushing and processing plant and may vary from

unprocessed quarry dust to finely processed fine aggregate that is specifically engineered for concrete applications. Due to the presence of higher fines which act as inert fillers as illustrated in Fig. 2 and the percentage fines of M-sand for particle size less than 75  $\mu\text{m}$  is kept at 15%, IS: 383:2016 [23]. The typical appearance of M-sand was shown in Fig. 3(a) and microstructure of M-Sand studied under FE-SEM, energy-dispersive X-ray spectroscopy (EDX) and XRD analyser are also shown in Fig. 3(b-d). As per SEM analysis, the angular and prismatic nature of M-sand help in better bond with the cement paste ensuing higher tensile strength and similar results were reported by O'Flynn [24].

**Table 2- Physical and chemical properties of silica fume**

| Physical properties  |             | Chemical properties            |                   |
|----------------------|-------------|--------------------------------|-------------------|
| Component            | Silica fume | Component                      | Silica fume Value |
| Pack density (gm/cc) | 0.77        | CaO                            | –                 |
|                      |             | SiO <sub>2</sub>               | 99.92             |
|                      |             | Al <sub>2</sub> O <sub>3</sub> | 0.031             |
| Specific gravity     | 2.64        | Fe <sub>2</sub> O <sub>3</sub> | 0.012             |
|                      |             | K <sub>2</sub> O               | 0.002             |
|                      |             | Na <sub>2</sub> O              | 0.004             |
| Surface              | 28000       | LOI                            | 0.001             |

**Table 3- Physical properties of fine and coarse aggregates**

| Property               | R-sand   | M-Sand    | NA       | RCA       |
|------------------------|----------|-----------|----------|-----------|
| Specific gravity (Dry) | 2.62     | 2.49      | 2.64     | 2.56      |
| Apparent density       | 2726     | 2759      | 2751 (–) | 2795      |
| Specific gravity (SSD) | 2.69     | 2.53      | 2.68     | 2.62      |
| Water absorption (%)   | 1.34 (5) | 3.89 (5)  | 0.91 (5) | 3.46 (10) |
| Fineness modulus       | 3.65 (–) | 3.25 (–)  | 5.82 (–) | 5.61 (–)  |
| Percent finer than 75  | 2.6 (3)  | 13.3 (15) | –        | –         |

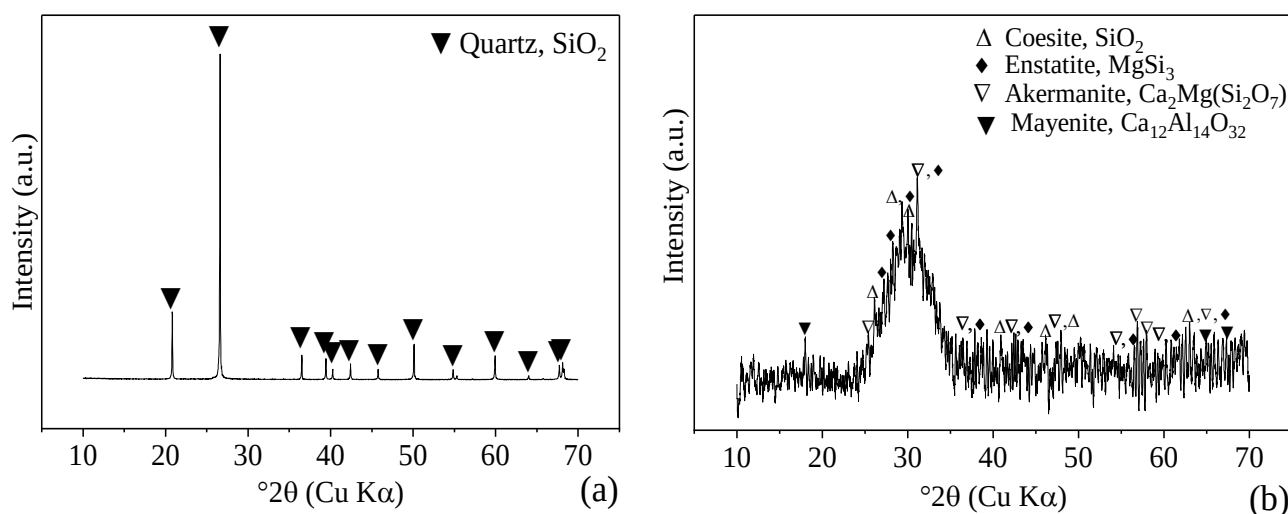


**Fig. 1 – Phase analysis of (a) silica fume and (b) Alccofine-1203 through XRD.**

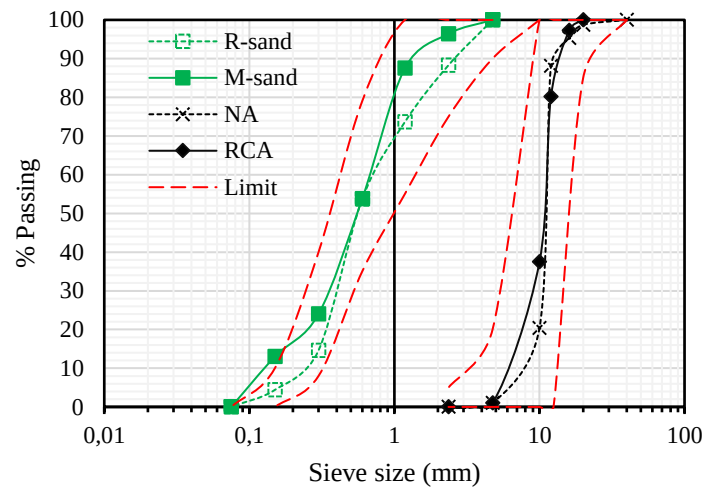


**Fig. 2 – Particle size distribution curve of aggregates.**

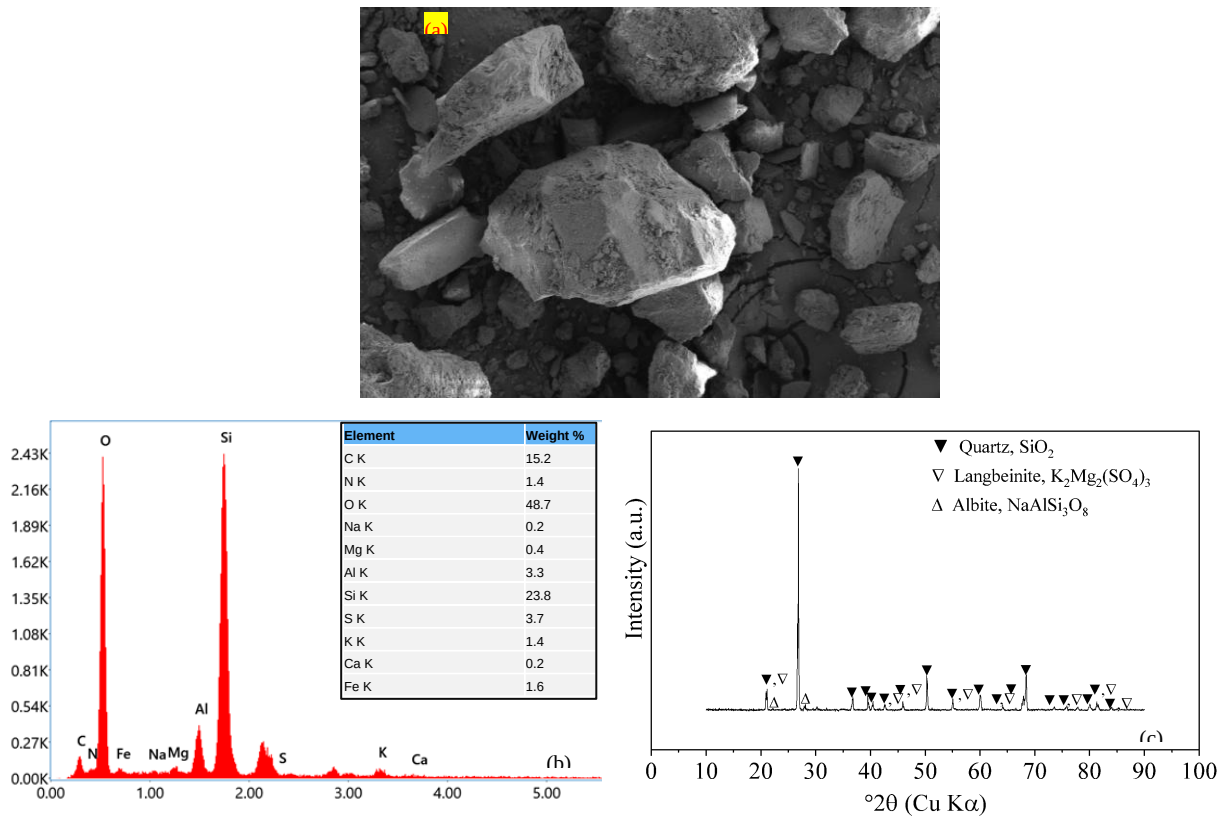


**Fig. 3- (a) SEM performed at 500 X magnification, EHT is 6kV and 9.4mm wide (b) EDX spectra and (c) XRD on M-sand**

The XRD analysis of the manufactured sand revealed the presence of mineral phases such as Quartz, Langbeinite, and Albite, each of which contributes differently to the performance and reactivity of concrete, see Fig. 3(c). Quartz, being a hard and chemically stable mineral, enhances the mechanical strength and abrasion resistance of concrete. Its angular particle shape also improves the interlocking between the paste and aggregate, leading to better mechanical interfacial bonding and reduced bleeding. However, because quartz is largely inert, it does not significantly contribute to any pozzolanic or chemical reactivity within the matrix. In contrast, Langbeinite, a double sulfate of potassium and magnesium, can influence the sulfate balance in the cementitious system. The presence of Langbeinite may contribute to limited internal sulfate availability, which can aid in early hydration reactions of aluminates, potentially improving early strength development. However, an excessive

amount could increase the risk of secondary ettringite formation, which must be controlled through proper mix design and curing conditions. Albite, a sodium-rich feldspar, contributes both physical and chemical benefits. While it primarily acts as a filler due to its crystalline nature, partial dissolution under alkaline conditions can release reactive silica and alumina. This can enhance the secondary formation of calcium silicate hydrate (C–S–H) gels, improving the density and microstructural integrity of the concrete. The presence of Albite, therefore, may slightly enhance the long-term strength and durability through limited pozzolanic reactivity. Overall, the combination of these mineral phases indicates that the M-sand used in this study not only provides mechanical stability through its siliceous content but also contributes to a denser and more durable concrete microstructure with controlled reactivity.

Crushed coarse aggregates passing 12.5 mm sieve were used and retained on 4.75 mm sieve as per specifications of IS:383:2016 [23]. The physical properties of coarse aggregates were tested as per IS 2386- Part III, (1963) [25]. The recycled aggregates were obtained from demolished concrete cubes with strength ranging from 20–40 MPa. As per procedure of Babu et al. [26], the mechanical treatment of recycled aggregates in Los Angeles abrasion machine were performed. The treatment of aggregates led to reduce water absorption of 14% and increase in specific gravity of 11% as compared to untreated aggregates. For ITZ treatment of recycled aggregates, the recycled aggregates were fed with silica fume (7% by weight of cement) to treat the damaged ITZ. Standard tap water was used for casting and curing purposes. In order to achieve the desired workability, high range water reducing superplasticizer named “MasterGalenium SKY 8866” conforming to IS:9103:1999 [27] was used in the present study. The chloride ion content for “MasterGalenium SKY 8866” was less than 0.2% and has a specific gravity of  $1.10 \pm 0.02$ .

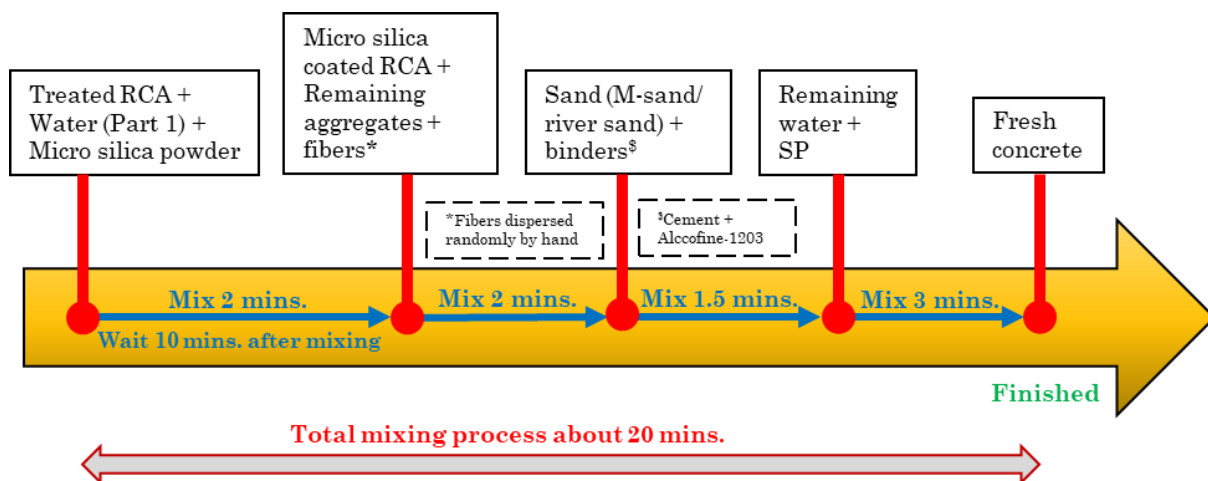


Fig. 4 – Flow chart for preparation of mixes containing RCA.

## 2.2 Mix design and proportions

The mix proportions was developed as per IS: 10262:2019 [28] to achieve a design compressive strength of 80 MPa and the details of the various mixes is shown in Table 4. A total of four mixes were prepared to study the effect of M-sand and RCA through the mechanical strength and microstructure of concrete. The replacement proportions were kept constant for M-sand and RCA at 100 and 25% by weight of sand and crushed coarse aggregate, respectively. The “CM” refers to the concrete control mix, “RC” refers to recycled aggregate concrete, “MS” refers to Manufactured sand (M-sand) concrete, “MSRC” refers to High strength concrete with M-sand and recycled aggregate. The mixes were designed for a consistency in terms of slump of more than 150 mm. The micro silica powder added by 7% weight of cement in the mixes containing RCA (25% replacement), as per the procedure “within mix approach” to enhance the quality of old interfacial zone of recycled aggregates, (Tam and Tam 2008 [29]; Wang et al. 2020 [30]), see Fig. 4. For mixes containing RCA (25%), the micro silica treatment was performed to enhance the ITZ and micro filling of voids in adhered mortar of RCA. In case of other mixes such as the aggregates were used in dry condition and the mixes were prepared as per IS 456:2000 [31]. In the beginning, a mixture of micro silica powder and water (part1), accounting for 20% of the total required water, was blended in the mixer for a duration of 2 minutes. The drum mixer was then stopped for 15 minutes and then remaining constituents (aggregate + cement + water and superplasticizer) added in the mixer and rotated for 3 minutes.

**Table 4- Mix proportions of concrete mixes (per m<sup>3</sup>)**

| Mix  | Cement<br>(kg) | Fine aggregate<br>(kg) |        | Crushed coarse<br>aggregate (kg) |     | Water<br>(kg) | SP<br>(kg) | Micro silica<br>powder (kg) | Alccofine<br>1203 (kg) |
|------|----------------|------------------------|--------|----------------------------------|-----|---------------|------------|-----------------------------|------------------------|
|      |                | R-sand                 | M-sand | NA                               | RCA |               |            |                             |                        |
| CM   | 520            | 678                    | –      | 810                              | –   | 153           | 6.12       | –                           | 92                     |
| RC   | 520            | 678                    | –      | 607                              | 203 | 153           | 6.73       | 31.85                       | 92                     |
| MS   | 520            | –                      | 678    | 810                              | –   | 153           | 7.34       | –                           | 92                     |
| MSRC | 520            |                        | 678    | 607                              | 203 | 153           | 7.96       | 31.85                       | 92                     |

### 2.3 Testing methodology

The dry density of various mixes was measured using a weighing balance for three-cylinder specimens of size  $\varnothing 100 \times 200$  mm as per, see Fig. 5(a). The workability of fresh concrete was studied using an inverted slump cone test as per IS 1199:1959 [32]. The compressive strength test was conducted on concrete cylinders with dimensions ( $\varnothing 100 \times 200$  mm) in accordance with the guidelines outlined in IS:516 Part-1/Sec-1, 2021 [33]. The cylinder specimens were dried for 24 hours after being water cured for 28 days, see Fig. 5(b) and tested under 2000 kN capacity universal testing machine (UTM). The test is carried out using load-controlled, with loading rate of 5 kN/s. The splitting tensile test was conducted on similar cylinders of dimension ( $\varnothing 100 \times 200$  mm) as per IS:516 Part-1/Sec-1, (2021) [33] at 1 kN/s pace loading. The microstructural properties of concrete mixes were studied using SEM (Sigma 500 VP). The samples were cut to a size of 10 mm width for microstructural imaging and phase testing. The fracture surface of the concrete was analyzed using X-ray energy dispersion spectroscopy (EDX) integrated with FE to obtain the elemental mapping. Further, the X-ray powder diffraction (XRD) technique was used to determine the mineral phases of M-Sand and RCA mixes. The samples considered for XRD testing were powdered using a hammer and further using a planetary ball and the scanning angles of the sample ranged from 10 to 70°.

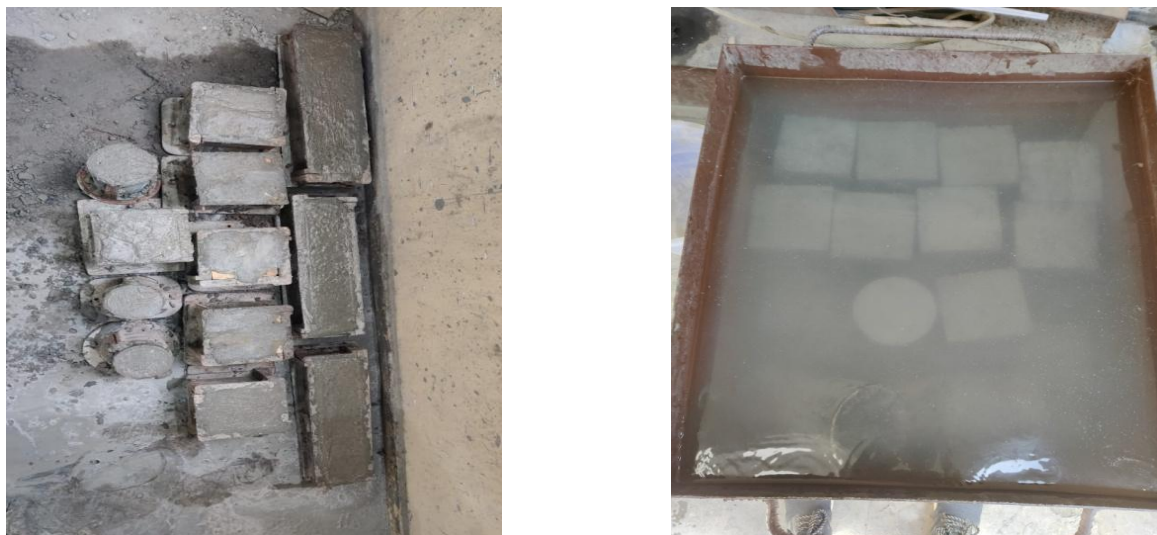


**Fig. 5 - Preparation of (a) specimens and (b) curing.**

## 3 Basic properties of proposed mixes

The basic properties of the proposed mixes are measured through the dry density and slump value. The dry density and slump value of the various concrete mixes are presented and discussed in this section.

### 3.1 Dry density

The dry density of various mixes was measured on three-cylinder specimens of size  $\varnothing 100 \times 200$  mm using a weighing balance, see Fig. 6. The density of the normal aggregate concrete was observed as 2499.37 kg/m<sup>3</sup>. It was observed that the concrete using RCA (RC) has lower density as compared to CM. However, the use of M-sand in normal aggregate concrete (MS) as well as (MSRC) has resulted in higher density by 0.88 and 1.8%, respectively as compared to CM. The higher dry densities in mixes containing M-sand are due to the particle size packing of the mix as the particle size for M-sand is more regular as compared to river sand.

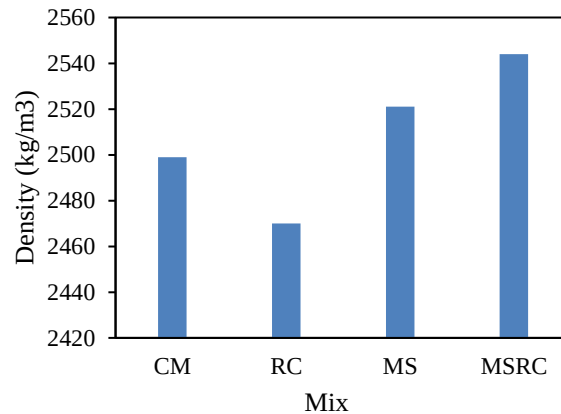
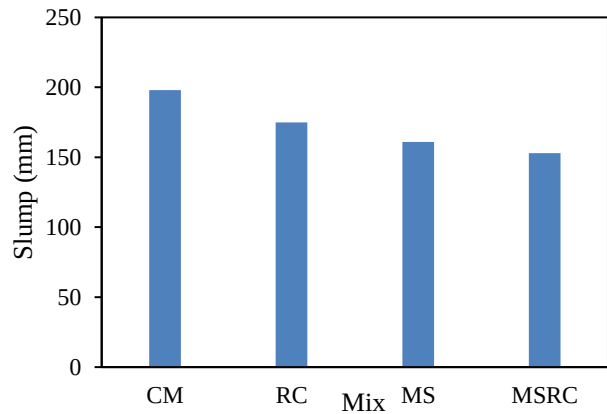


**Fig. 6- Dry densities of concrete mixes.**



**(a)**



**(b)**

**Fig. 7 – Workability of concrete in terms of (a) slump and (b) function of different mixes.**

### 3.2 Slump

The influence of M-Sand and recycled aggregates on the consistency of concrete was measured using inverted slump cone test, see Fig. 7. The slump value of CM, RC, MS and MSRC are 198, 175, 161 and 153 mm, respectively. The use of M-sand and RCA reduced the workability of concrete mix by 12 and 19%, respectively. The utilization of both M-Sand and recycled coarse aggregates concurrently resulted in a further reduction in the concrete mix's workability, primarily due to the water retention capacity and the rough surfaces of both fine and coarse particles. It was concluded that the inclusion of RCA and M-sand in concrete has reduced the workability because of their higher water absorption capacity.

The mixes were designed for a consistency in terms of inverted slump of more than 150 mm. In case of mixes void of RCA, aggregates were used in dry condition, and the mixes were prepared as per IS: 10262 – 2019 [28]. In the beginning, a

mixture of micro silica powder and water (Part 1), accounting for 20% of the total required water, was blended in the mixer for a duration of 2 minutes. The drum mixer was then stopped for 10 minutes and then remaining constituents (aggregate + cement + water and superplasticizer) added in the mixer and rotated for 3 minutes. The waiting period was allowed to provide the pozzolanic material to adhere and repair the damage interface of recycled coarse aggregate, (Shaban et al. 2019) [34]. A superplasticizer was used to enhance fluidity by dispersing cement particles through steric hindrance and electrostatic repulsion. This dispersion effect significantly reduces interparticle friction and yield stress, allowing the concrete to flow more easily despite the limited water available. As a result, a high slump value ( $>150$  mm) maintained even at low w/c ratios. Achieving a slump value exceeding 150 mm at a low water–cement ratio of 0.29, even with the inclusion of M-sand and RCA, can be attributed to careful optimization of the mix rheology through the use of high-range water-reducing admixtures. At such a low w/c ratio, the concrete's workability depends primarily on the dispersion efficiency of cement particles and the lubrication of the solid skeleton rather than the free water content.

## 4 Mechanical properties

The compressive and tensile strength characteristics of various concrete mixes were systematically evaluated to understand the influence of recycled coarse aggregate and manufactured sand on the mechanical performance of high-strength concrete are presented and discussed in this section.

### 4.1 Compressive strength

The typical failure pattern of the cylinder under compression test is shown in Fig. 8(a). The average compressive strength of various concrete mixes tested on three cylindrical specimens was shown in Fig. 8(b).

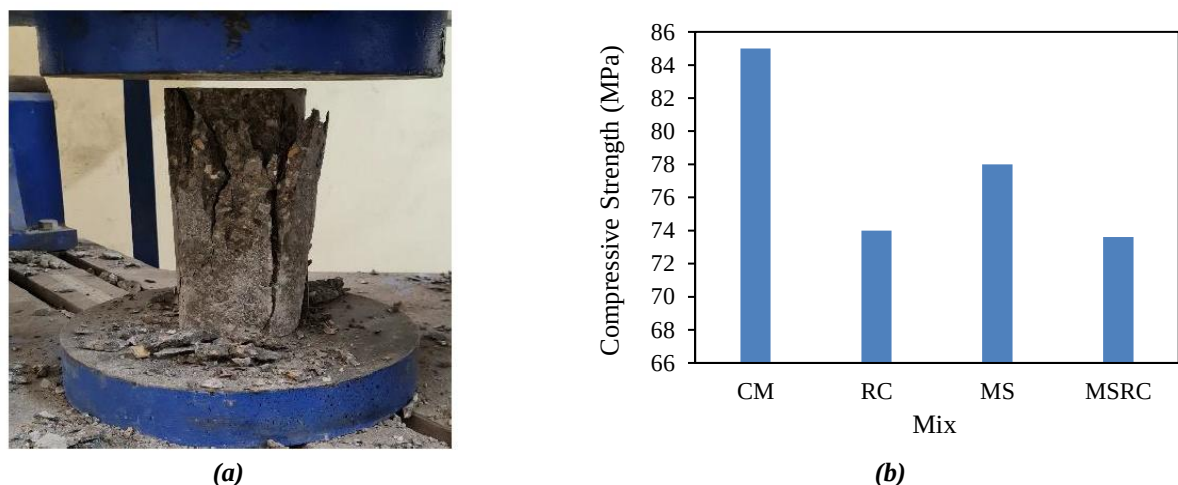


**Fig. 8 – Compressive strength of (a) concrete specimen and (b) function of different mixes.**

It was inferred that strength was found reduced on the mix with M-sand (MS) and RCA (RC) as compared to control mix. The compressive strength of mix RC and MS was reduced by 12.9 and 8.24%, respectively as compared to CM. On mix with MSRC, the strength was reduced by 13.3% compared to the control mix. The reduction in compressive strength was attributed to the lower strength of the original aggregate of RCA (20–40 MPa). Original aggregate referring to the aggregate used in the original concrete. Further, the weaker interface between the aggregate and mortar paste has resulted in lower strengths of these mixes, Andreu and Miren [35]. In the case of RC, the strength reduction primarily arises from the presence of old adhered mortar on the surface of recycled aggregates. This adhered mortar increases the porosity and water absorption capacity of the aggregate, leading to a weaker interfacial transition zone (ITZ) between the cement paste and aggregate particles. The weaker ITZ reduces the overall load-bearing efficiency and contributes to microcrack development under stress, thereby decreasing the compressive strength. For the M-sand mix (MS), the slight reduction in strength compared to the control can be linked to the angular and rough surface texture of M-sand particles. Although such texture improves mechanical interlocking, it also increases the specific surface area, demanding more paste for proper coating and compaction. When the paste content or workability is not proportionally adjusted, localized voids and incomplete particle packing can occur, marginally reducing the compressive strength. The combined mix (MSRC) exhibited the highest reduction (13.3%)

due to the cumulative effects of both RCA and M-sand. The combined influence of higher water absorption, weaker ITZ from RCA, and increased frictional resistance from M-sand results in reduced paste cohesion and densification. Consequently, the microstructure becomes more heterogeneous, with slightly higher internal porosity and microcrack density, which collectively lower compressive strength. Overall, it is concluded that the compressive strength on both the mix with RC and MSRC was found reduced by 13%, whereas the same on the mix MS reduced by 8.24%, as compared to CM.

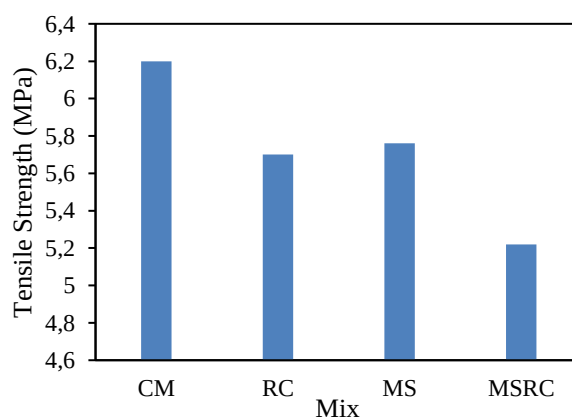
## 4.2 Tensile strength

The typical failure pattern of the cylinder under tension test is shown in Fig. 9(a). The split tensile strength (STS) on cylindrical specimens of dimensions ( $\varnothing 100 \times 200$  mm) at 28 days age of concrete was shown in Fig. 9(b). It was observed that the STS value on mix using recycled coarse aggregates (RC) was reduced by 7.7% as compared to mix CM. Also, the strength was found reduced by 7.17% for concrete containing M-sand (MS) as compared to the control mix (CM). On using both M-sand and RCA in concrete (MSRC), the strength reduction was further weakened to 16% as compared to mix CM. The reduced strength of concrete in RCA and poor synergy between the particles of RCA and M-sand have resulted in strength reduction as compared to the control mix. The finer particles of M-sand may lead to increase the silica content in a concrete mix containing M-sand and RCA which results in alkali-silica reaction and thus strength reduction of the mix.

In the case of RCA-based concrete (RC), the adhered old mortar attached to the recycled aggregate surface acts as a weak porous layer with higher water absorption and microcrack density. This layer not only reduces the bond strength between the new paste and the recycled aggregate but also increases local stress concentrations under tensile loading. For M-sand concrete (MS), the reduction in tensile strength is primarily mechanical in nature. The sharper edges can trap micro air voids and prevent uniform paste coating, weakening the ITZ bond. The finer particles of M-sand also alter the packing density, potentially creating localized zones of weaker matrix continuity, which serve as preferred crack paths under tensile stress. When both RCA and M-sand are used together (MSRC), the combined effect compounds the ITZ weakness. The porous and microcracked old mortar of RCA interacts with the high surface roughness of M-sand, leading to inconsistent paste adhesion and higher local stress gradients. Overall, the tensile strength of RC and MS was reduced by 7.5%, whereas both M-sand and RCA in concrete (MSRC), the strength reduction was further weakened to 16% as compared to mix CM.



(a)



(b)

**Fig. 9 – Tensile strength of (a) concrete specimen and (b) function of different mixes.**

## 5 Microstructural properties

The microstructure as well as elements and phase formations of high-strength concrete mixes were examined using SEM, XRD and EDX analysis. The SEM analysis was performed to understand the microstructure of the concrete mixes. The XRD analysis was conducted to discern the elements within concrete mixes that are integrated by M-sand and RCA. The phase formations of high-strength concrete mixes was examined using SEM, XRD and EDX analysis, respectively.

### 5.1 SEM analysis

The SEM results for high-strength concrete mixes CM, RC, MS and MSRC are shown in Fig. 10(a-d) and the FE-SEM images were taken at 500× magnification. From Fig. 10(a), it was observed that the CM mix has a strong microstructure and dense interface between the aggregate and paste. The number of microcracks observed was higher in mix RC which may be due to the poor initial hydration of CH or  $\text{Ca}(\text{OH})_2$ . A few voids are also visible among these crystalline phases. The microstructure of the MS was relatively denser as compared to the RC, however, a few interfacial cracks were observed, see in Fig. 10(c). It was also observed that the microstructure of mix MSRC was found to be weaker as compared to the control mix CM, see in Fig. 10(d). The weaker microstructure may be due to the untreated silica particles present in the interface of mortar. The “ZEISS” remain kept in the Fig. 7 and mentioning “ZEISS” helps ensure reproducibility and transparency of the experimental setup, which is an important aspect of scientific reporting.

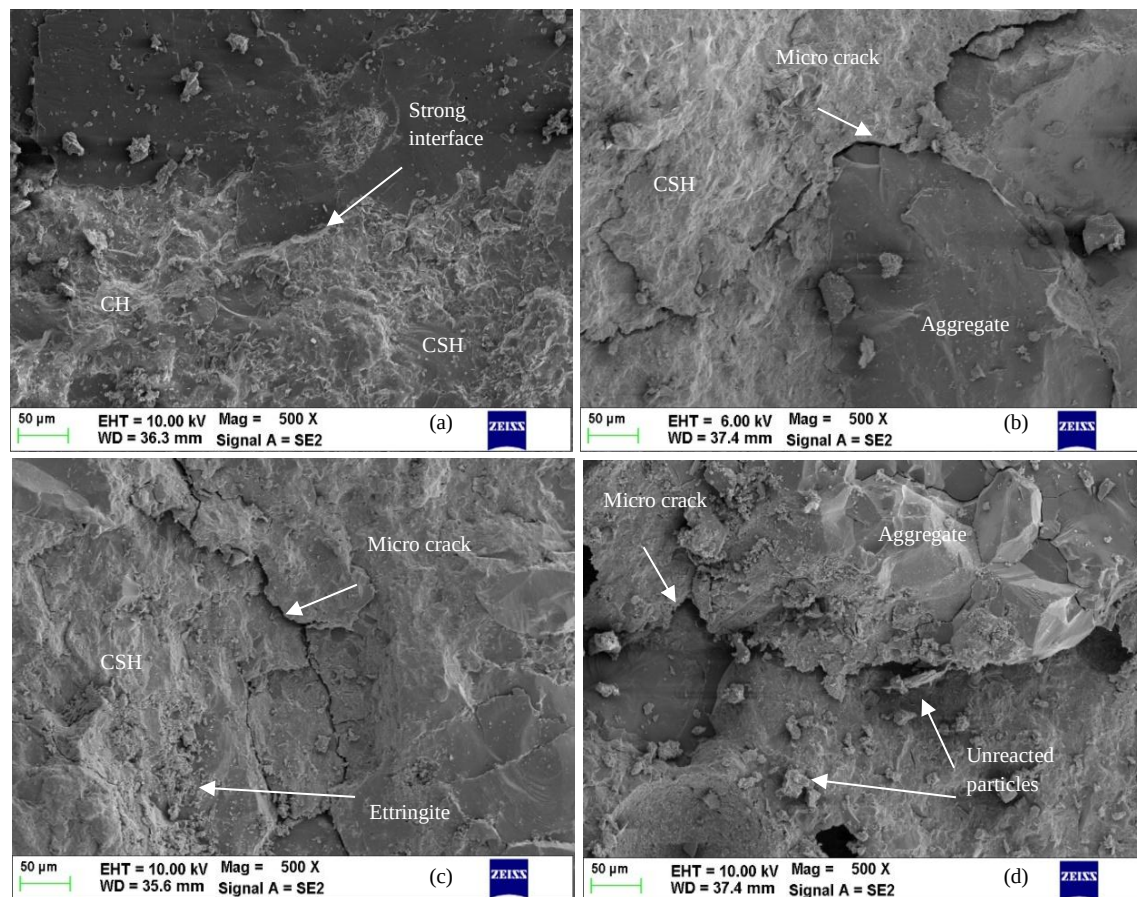


**Fig. 10 – FE-SEM images of concrete mix (a) CM (b) RC (c) MS and (d) MSRC.**

### 5.2 EDX analysis

The EDX analysis of various mixes was shown in Fig. 11 and the EDX spectra reveals the dispersion of Ca, Si, O, C, N and S in the fractured surface. The dispersion of Si was found highest in the control mix CM. The higher percentage of silica from elemental composition forms quartz which confirms the denser microstructure of MS mix, see in Fig. 11(a). The presence of Ca was found highest in mix RC. The elemental composition of mix MS and MSRC were found similar to each other, see in Fig. 11(c) and (d). The elemental composition of MS and MSRC revealed the presence of higher Ca which can lead to unreacted products of Ca in the mix. This elevated calcium content can be attributed to the presence of unhydrated or partially hydrated cementitious phases, as well as calcium-bearing minerals originating from the aggregates or old adhered mortar in the RCA. The excess Ca in the matrix may indicate an incomplete hydration process, leading to the formation of unreacted calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) or other residual calcium compounds. These unreacted products often occupy pore spaces and contribute to local chemical heterogeneity within the concrete microstructure. The presence of higher Sulphur content in a mix of RC, MS and MSRC also indicates lower durability to water penetration and brittle microstructure.

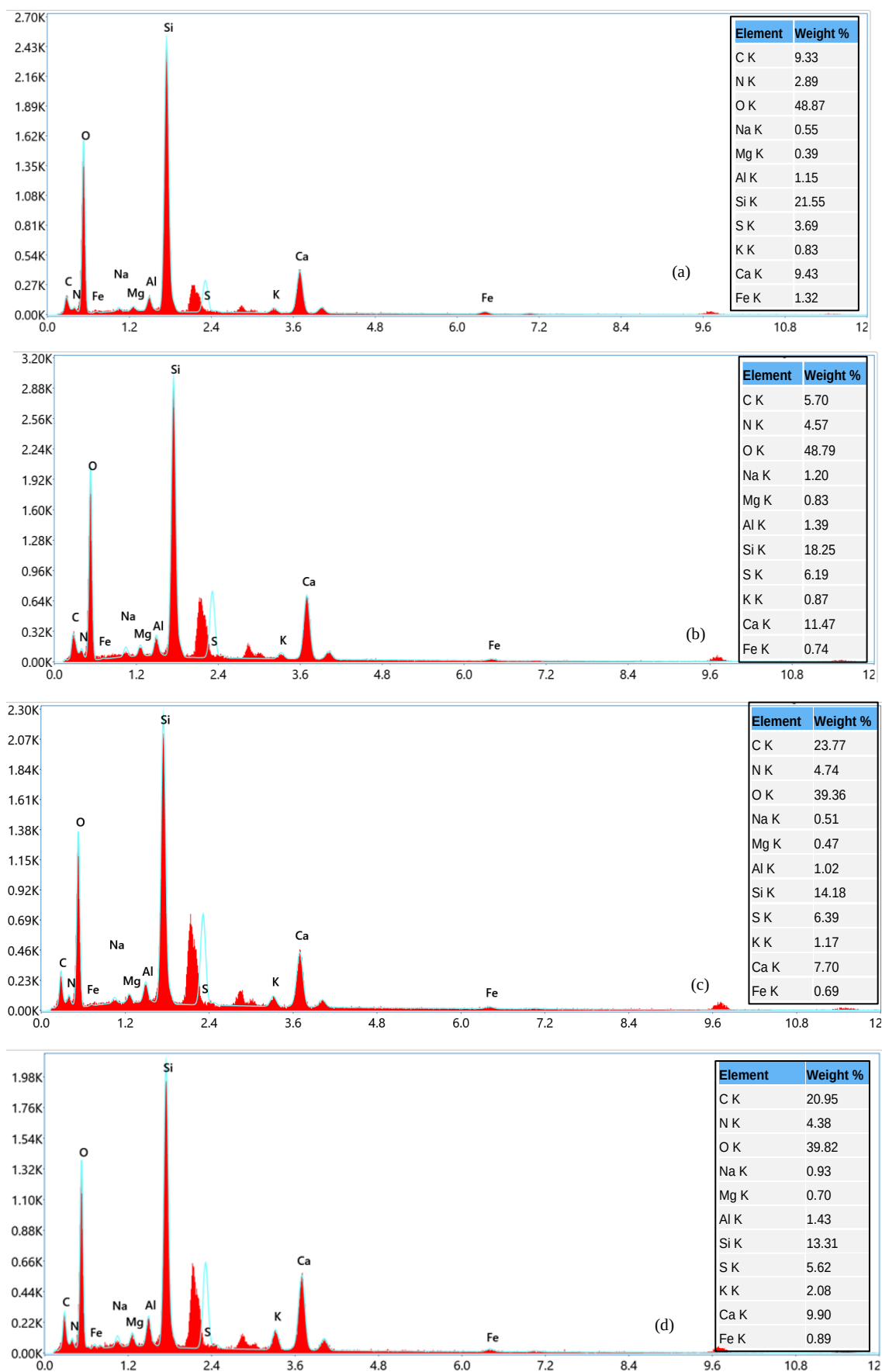


Fig. 11 – EDX analysis of (a) CM (b) RC (c) MS and (d) MSRC mixes.

### 5.3 XRD analysis

The XRD analysis was performed to study the phase elements on different mixes, see Fig. 12. In the control mix CM, the diffractogram of the strong peaks of quartz ( $\text{SiO}_2$ ) was observed and the major peak of quartz ( $26.7^\circ$ ) showed strong bond formation resulting in a dense matrix. It was also observed that the presence of minor peaks of brownmillerite ( $\text{Ca}_2(\text{Al}, \text{Fe})_2\text{O}_5$ ) and calcite ( $\text{CaCO}_3$ ) which acts as an activator in the early hydration of concrete and as an inert filler. The RC mix mostly showed the presence of quartz and small peaks of hatrurite ( $\text{Ca}_3\text{SiO}_5$ ) and these mineral phases are the hydration products of  $\text{C}_3\text{S}$ . The mineral phase on MS mix has strong peaks of quartz and albite ( $\text{NaAlSi}_3\text{O}_8$ ). The primary composition of these minerals is  $\text{SiO}_2$ , which contributes to reinforcing the concrete mixture by serving as a filler substance. The mineral phases on MSRC mix consist of significant peaks of quartz at  $26.72^\circ$ . The quartz contributes to the mineral phases of  $\text{C}_3\text{S}$  and results in a denser and inert concrete matrix.

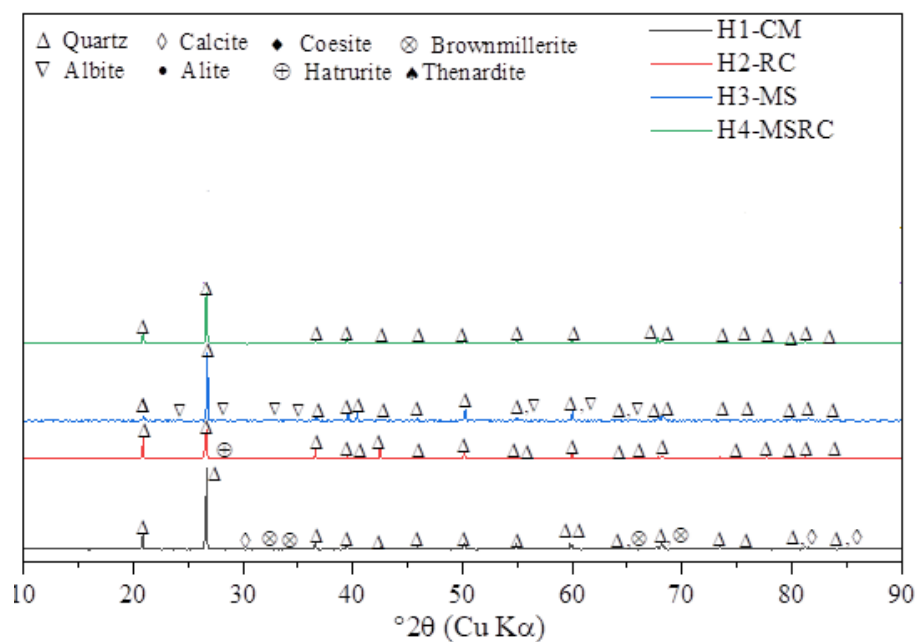


Fig. 12 – XRD analysis different mixes.

## 6 Discussion on mechanical and microstructural properties

The mechanical properties of the concrete mixes are compared with the microstructural properties are discussed in this section. The compressive strength of both mixes containing recycled concrete aggregate (RC) and the combined mix with manufactured sand and RCA (MSRC) was reduced by approximately 13%, whereas the mix incorporating only manufactured sand (MS) showed a relatively smaller reduction of 8.24% compared to the control mix (CM). Similarly, the tensile strength of mixes with RC and MS decreased by about 7.5%, while the mix containing both M-sand and RCA (MSRC) exhibited a more pronounced reduction of 16% relative to CM. Overall, it is concluded that the individual replacement either RCA or MS on the mix RC or MS, found to be best performing at high strength concrete tensile strength.

Based on the SEM analysis, a higher number of microcracks were observed in the RC mix, indicating a more porous and discontinuous microstructure. The microstructure of the MS mix appeared denser, suggesting better particle packing and a more refined interfacial transition zone (ITZ), which contributed to its relatively higher strength retention. In contrast, the MSRC mix exhibited a weaker and more heterogeneous microstructure, characterized by the presence of microvoids and cracks around the RCA particles. This weak ITZ around the recycled aggregates limited the effective stress transfer between the old and new mortar phases, thereby reducing both compressive and tensile strengths.

Based on the XRD analysis, the RC mix showed the presence of quartz and small peaks of hatrurite and these mineral phases are the hydration products of  $\text{C}_3\text{S}$ , whereas the mineral phase on MS mix has strong peaks of quartz and albite. The XRD analysis of the RC mix revealed the presence of quartz along with small peaks of hatrurite ( $\text{C}_3\text{S}$ ), which represents the primary phase responsible for early hydration reactions and strength development in cement paste. However, the limited

intensity of the hatrurite peaks indicates incomplete hydration and the possible presence of unreacted or partially hydrated  $C_3S$ . This incomplete hydration leads to a less cohesive matrix and a weaker interfacial transition zone (ITZ), resulting in reduced tensile strength for the RC mix. In contrast, the MS mix exhibited strong peaks of quartz and albite, indicating the presence of well-crystallized and stable silicate minerals derived from the manufactured sand. These minerals contribute to improved particle packing, enhanced bond formation with the cement matrix, and a denser microstructure. The improved microstructural compactness minimizes microcrack propagation under tensile stress, thereby enhancing the tensile strength of the MS mix compared to the RC mix. It is concluded that the lower tensile strength of the RC mix is primarily attributed to incomplete  $C_3S$  hydration and a weaker ITZ, whereas the higher tensile strength of the MS mix is associated with the dense, well-bonded matrix reinforced by quartz and albite phases that improve overall microstructural integrity.

Based on the EDX analysis, the RC mix exhibited the highest calcium (Ca) content among all the mixes. The elevated Ca concentration is primarily attributed to the residual cement paste adhered to the surface of the recycled concrete aggregate (RCA), which contains significant amounts of calcium-bearing hydration products such as calcium silicate hydrate (C–S–H) and calcium hydroxide (CH). While a higher Ca content generally indicates the presence of hydration products that contribute to strength development, in the case of the RC mix, much of this calcium is associated with old, partially hydrated paste rather than newly formed C–S–H. This leads to a heterogeneous microstructure and a weaker interfacial transition zone (ITZ) between the old, adhered mortar and the new cement matrix. The weak ITZ acts as a preferential path for crack initiation under tensile loading, thereby reducing the overall tensile strength of the RC mix despite its higher Ca content.

## 7 Conclusions

The performance of M-sand along with RCA as an alternate to river sand and coarse aggregates was studied. There are four mixes such as conventional concrete, RCA replaced by 25% coarse aggregate, MS replaced by river sand 100% and combination of MS (100%) and RCA (25%) replaced together are designated as CM, RC, MS and MSRC, respectively, are proposed in the present study. Further, the mechanical properties of high strength concrete were studied under compression and tension tests. The microstructure as well as elements and phase formations of high-strength concrete mixes were examined using SEM, XRD and EDX analysis, respectively. Based on the comprehensive experiment, the following conclusions were postulated:

- It was observed that the concrete MSRC exhibited greater density as compared to the control mix. However, when both M-sand and recycled coarse aggregates were used together, the workability of the concrete mix was further diminished.
- The compressive strength of mix RC and MS was reduced by 12.9 and 8.24%, respectively as compared to CM. Also, the strength on mix MSRC was reduced by 13.3% compared to the control mix. The reduction in compressive strength was attributed to the lower strength of the original aggregate which led to weaker the interface between the aggregate and mortar paste.
- It was observed that the tensile strength of mix RC and MS individually was reduced by 7.7 and 7.17% as compared to the control mix CM. Also, the strength on mix MSRC was further reduced by 16% as compared to mix CM. The reduced strength in RC and MS mix due to the poor synergy between the particles of RCA and M-sand and finer particles of M-sand lead to an increase in the silica content in a concrete mix MSRC which results in alkali-silica reaction.
- The examination of the microstructure in concrete mixes MS and RC indicated the presence of deficient CSH gel and microcracks at the aggregate interface. The weakened microstructure in concrete containing M-sand and RCA may be attributed to untreated silica particles existing within the mortar interface. Analysis of the elemental composition in mixes MS and MSRC unveiled higher levels of calcium and sulfur, potentially leading to the formation of unreacted products and reduced resistance to water penetration, resulting in a brittle microstructure. The fiber mixes led to  $Na_2SO_4$  minerals and presence of sodium sulphate crystallization within the concrete mix, contributes to the deterioration of concrete due to the presence of anhydrous sodium sulphates. These anhydrous phases encourage the formation of micropores within the concrete microstructure.

### Availability of data and material

The authors confirm that the data supporting the findings of this study are available within the article.

### Authors' contributions

Senthil Kasilingam: Conceptualization, Project administration, Investigation, Writing - review & editing and Rachit Sharma: Data curation, Methodology, Investigation.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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