REVISTAMATÉRIA V.29 N.3
ISSN 1517-7076 articles e20240251, 2024

# Sustainable enhancement of concrete performance through waste foundry sand: a comprehensive analysis of mechanical and microstructural properties

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## ABSTRACT

This study investigates the use of WFS as a sustainable substitute for fine aggregate in concrete, aiming to enhance environmental sustainability and reduce waste material impact.The research explores the mechanical and microstructural properties of concrete incorporating WFS through various experimental techniques, including Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Fourier Transform Infrared (FTIR) spectroscopy. Concrete mixes were prepared with incremental WFS substitutions ranging from 10% to 100%. Key findings reveal that a 45% replacement level of WFS is optimal, significantly enhancing concrete performance. Specifically, this substitution increased compressive strength by 58%, split tensile strength by 48%, and flexural strength by 43% compared to the control mix. SEM analysis showed improved particle cohesion and bonding at this level, contributing to greater strength and durability. These results underscore the potential of WFS as a viable replacement for natural sand in concrete production, offering significant environmental and economic benefits. The adoption of WFS can reduce the reliance on natural resources and improve waste management practices, thereby promoting a circular economy and minimizing the environmental footprint of construction materials. This research contributes valuable insights into the material properties of WFS and demonstrates its practical and sustainable application in concrete production.

**Keywords:** Waste Foundry Sand (WFS); Concrete Sustainability; Pozzolanic Reaction; Microstructural Analysis; Mechanical Properties of Concrete.

## 1. INTRODUCTION

Concrete is a fundamental building material used extensively across the globe. Investigating the potential for incorporating Waste Foundry Sand (WFS) into concrete presents an opportunity to develop more sustainable building practices by minimizing the environmental footprint associated with traditional concrete production. As the demand for environmentally sustainable building materials grows, researchers are increasingly exploring alternative substances that can be used in concrete production. WFS, a residual material from metal casting industry, is produced in large quantities when sand molds are no longer usable after metal casting. This waste accumulates significantly worldwide, with an estimated 15–20 million tons generated annually [1, 2]. Particularly in India, the foundry industry contributes nearly 6–7 million tons of this waste each year, underscoring its profound environmental implications [3, 4]. The examination of concrete's mechanical and microstructural properties is essential to grasp its functional longevity and performance. This present study also intends to improve the integration of recyclable materials, tackling the issues of resource conservation and waste management [5, 6]. The rationale behind using (WFS) as a replacement for fine aggregate in concrete is threefold. First, it serves as an environmentally friendly alternative to natural sand, which is facing rapid depletion. Second, employing WFS in concrete improves waste management strategies by reducing the reliance on landfill disposal and mitigating associated environmental risks. Third, this approach investigates potential enhancements in concrete's strength as well as durability from WFS inclusion. Extensive research has assessed the viability of WFS as a partial replacement in concrete mixes. Various studies [7] have noted its promising ability to substitute for fine aggregate. Investigations into WFS's impact on concrete's compressive strength have been positive, with findings indicating that inclusion levels up to 50% can yield beneficial outcomes. Comparative analyses reveal that mixtures containing WFS generally possess higher compressive strength than those without. The split tensile

Corresponding Author: Sharmiladevi Kandasamy Received on 13/05/2024 Accepted on 15/07/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0251

strength of concrete, a critical mechanical parameter, has also been improved by incorporating WFS. Studies suggest that replacing capped at 30% of fine aggregate with WFS can enhance split tensile strength, particularly noticeable at a 30% replacement rate. Furthermore, research has shown that a 25% inclusion of WFS can favorably affect concrete's flexural strength, which is vital for structural applications. The workability of concrete, which influences its handling and compaction, remains an important consideration. Experiments indicate that concrete with WFS maintains robust flexural strength and workability, making it suitable for practical use [8, 9]. Another study confirmed that concrete's rheological possessions are not compromised by the inclusion of WFS, supporting its application in construction. Despite these positive findings, there is a significant research gap concerning the long-term durability, environmental impacts, and optimal mixing ratios of concrete with WFS. While initial studies focus on compressive strength to determine the appropriate WFS replacement percentage, more extensive evaluations are necessary to fully understand its field performance, economic viability, and microstructural characteristics. Addressing these research gaps can enhance the understanding of the material's behavior, promote sustainable practices, and facilitate its practical implementation in the construction industry. The various studies which includes the study on the mechanical properties of concrete containing silica fume (7%) and fly ash (15%). Results showed that using limestone as a cement replacement (LCE) is more effective up to 28 days, while limestone as a fine aggregate replacement (LF) performs better between 28 and 90 days. Optimal limestone replacement levels were found to be around 10% for best performance and 40% for worst [10]. This study [11] investigated the compressive strength of concrete made with nonpotable pipeline water in Larestan. By replacing 50% of normal aggregates with granite aggregates, the compressive strength met standards despite the use of nonpotable water, suggesting granite can mitigate the adverse effects of poor-quality water. The findings recommend using granite aggregates or potable water to ensure the concrete meets strength requirements. The study [12] investigates the post-buckling behavior of geometrically imperfect concrete plates reinforced with graphene oxide powder (GOP) using a higher-order plate model. Uniform and linear GOP distributions are considered, with the model accounting for transverse shear effects without needing a correction factor. In another study [13] Analytical solutions reveal the impact of GOP distribution, geometric imperfections, foundation factors, material compositions, and geometric factors on the post-buckling properties of the reinforced concrete plates.Artificial Neural Networks (ANN) and Particle Swarm Optimization (PSO) were used [14] to model and predict the buckling behavior of self-compacting concrete columns incorporating Rice Husk Ash. This experimental study investigates the flexural performance of functionally graded concrete beams incorporating fly ash and red mud [15]. The findings demonstrate the potential of these industrial by-products [16] to enhance the structural performance and sustainability of concrete beams. While initial studies highlight the potential benefits of incorporating WFS in concrete [17], there is still a need for comprehensive research on its long-term durability, environmental impact, and optimal mix ratios. This study aims to bridge these gaps by exploring these critical aspects, thereby enhancing our understanding of WFS's viability as a sustainable building material and promoting its practical use in the construction industry. This study introduces a novel perspective by examining not only the mechanical properties and strength enhancements but also the potential for using WFS as a primary material in sustainable concrete production. By focusing on the optimal mixing ratios and the comparative analysis of mechanical parameters, this research aims to validate WFS as a credible alternative to traditional fine aggregates. This approach uniquely combines sustainability with practical performance improvements, setting a new benchmark for future research in sustainable construction materials.

## 2. EXPERIMENTAL INVESTIGATION

### 2.1. Materials

Grade 53 OPC cement is utilized in accordance with IS 12269-1987 standards [18]. The fine aggregate used was M-sand, which passed through a 4.75 mm sieve, and had a specific gravity of 2.65 and a fineness modulus of 2.7. In substitution for fine aggregate, WFS with a fineness modulus of 2.32 was utilised.The chemical compostion of waste foundry sand is depicted in Figure 1. Natural aggregate with a 20 mm size, a specific gravity of 2.74, and a fineness modulus of 6.15 was used as the coarse aggregate [19]. To ensure the required workability, a polycarboxylic-ether based superplasticizer was added at 0.2% by weight of the cement, adhering to IS 9103:1999 standards [20].

### 2.2. Mix proportions

A Conventional Concrete (CC) of grade M25 was produced, achieving strength of 26.11 $N/mm^2$. The mix ratio used was 1:1:2. To determine the optimal amount of WFS to use, the mix proportions were adjusted by partially replacing the fine aggregate with WFS in increments of 10%, extending up to a full 100% replacement as revealed in Table 1. A consistent water-to-cement ratio of 0.4 was maintained across the entire mixes [21].

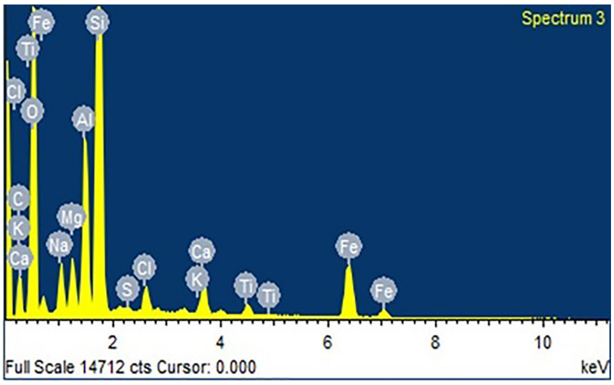


**Figure 1:** Chemical composition of waste foundry sand.

**Table 1:** Concrete mix proportions.

| MIX | % OF REPLACEMENT BY FOUNDRY SAND | CEMENT (kg) | M SAND (kg) | FOUNDRY SAND (kg) | COARSE AGGREGATE (kg) |
|---|---|---|---|---|---|
| CC | 0 | 1.67 | 2.166 | 0 | 3.8 |
| M1 | 10 | 1.67 | 1.9494 | 0.2166 | 3.8 |
| M2 | 20 | 1.67 | 1.7328 | 0.4332 | 3.8 |
| M3 | 30 | 1.67 | 1.5162 | 0.6498 | 3.8 |
| M4 | 40 | 1.67 | 1.2996 | 0.8664 | 3.8 |
| M5 | 45 | 1.67 | 1.1913 | 0.9747 | 3.8 |
| M6 | 50 | 1.67 | 1.083 | 1.083 | 3.8 |
| M7 | 60 | 1.67 | 0.8664 | 1.2996 | 3.8 |
| M8 | 70 | 1.67 | 0.6498 | 1.5162 | 3.8 |
| M9 | 80 | 1.67 | 0.4332 | 1.7328 | 3.8 |
| M10 | 90 | 1.67 | 0.2166 | 1.9494 | 3.8 |
| M11 | 100 | 1.67 | 0 | 2.166 | 3.8 |

### 2.3. Fresh concrete properties

To evaluate the workability and consistency of the freshly mixed concrete, which are crucial for ensuring ease of placement and compaction during the construction process, tests on its fresh properties were conducted [22]. This study prepared various mixtures of M25 grade concrete by replacing different percentages of fine aggregate with foundry sand. The fresh properties of the mixtures complied with the specifications outlined in IS 1199:1959 [23]. The workability of the concrete mixtures was assessed using the slump test, which is a standard method to measure the consistency and ease of flow of the concrete. The slump test involves filling a truncated cone with concrete in three layers, each layer being tamped 25 times with a standard rod. After filling, the cone is lifted vertically, allowing the concrete to slump. The vertical distance between the top of the cone and the highest point of the slumped concrete is measured, which indicates the workability. Higher slump values correspond to higher workability, indicating a more fluid mix, while lower slump values indicate a stiffer mix. The slump test carried out is depictied in Figure 2. In addition to the slump test, other tests were conducted to evaluate the fresh properties of the concrete mixtures. Compaction Factor Test measures the degree of compaction achieved by a standard amount of work. It provides a measure of the workability of the concrete, especially useful for mixes with low workability. The test involves filling a hopper with concrete, allowing it to fall into a cylinder, and then measuring the weight of the compacted concrete. Vee-Bee Consistometer Test measures the time required for a given mass of concrete to change shape under vibration. It is particularly suitable for dry mixes and provides an indication of the concrete's workability. Flow Table Test Used to determine the flow of concrete, this test involves placing the concrete on a flow table, lifting the table, and dropping it a specified number of times. The spread of the concrete is then measured to evaluate its consistency. These tests provided comprehensive insights into the workability and consistency of the concrete mixtures. The results of these tests, including slump values,

**Figure 2:** Slump cone test.

**Table 2:** Results of fresh property test.

| MIX | % OF REPLACEMENT BY FOUNDRY SAND | SLUMP (mm) | COMPACTION FACTOR | VEE-BEE CONSISTOMETRE (s) |
|---|---|---|---|---|
| CC | 0 | 110 | 0.94 | 15 |
| M1 | 10 | 100 | 0.90 | 23 |
| M2 | 20 | 95 | 0.83 | 35 |
| M3 | 30 | 95 | 0.77 | 43 |
| M4 | 40 | 90 | 0.70 | 54 |
| M5 | 45 | 85 | 0.69 | 60 |
| M6 | 50 | 85 | 0.65 | 62 |
| M7 | 60 | 80 | 0.63 | 65 |
| M8 | 70 | 75 | 0.59 | 74 |
| M9 | 80 | 70 | 0.55 | 78 |
| M10 | 90 | 60 | 0.48 | 80 |
| M11 | 100 | 60 | 0.42 | 82 |

compaction factor, Vee-Bee time, and flow spread, are detailed in Table 2. These results provide insights into the effects of replacing fine aggregate with foundry sand on the workability of M25 grade concrete.

As the proportion of WFS in the mix increased, there was a noticeable decrease in the slump value, indicating a reduction in workability. Concrete with higher percentages of foundry sand showed lower slump values, requiring more effort during compaction. Additionally, the compaction factor decreased and the Vee-Bee times increased, indicating a decline in workability [24]. This reduction in workability is attributed to the higher volume of fine particles in the concrete mix, resulting in less available space for water to lubricate the particles.

This reduction in workability with increasing WFS content leads to lower slump values, higher compaction factors, and longer Vee-Bee times due to the increased volume of fine particles [25]. These particles absorb more water and create higher internal friction, reducing the concrete's ease of flow and compaction [26]. This necessitates more effort during compaction to achieve the desired consistency and uniformity in the concrete mixture.

### 2.4. Specimen preparation and casting

Cubes measuring 150 × 150 × 150 mm, as illustrated in Figure 3, were casted to assess the compressive strength. Cylinders with magnitudes of 150 × 300 mm were used to evaluate the split tensile strength, and prisms (beams) sized 100 mm × 100 mm × 500 mm were utilized to measure the flexural strength. The preparation of these

**Figure 3:** Casted cubes.

specimens adhered to the codal requirements specified in IS 1199-1959. All specimens underwent a curing period of 28 days before testing [27].

## 3. RESULTS AND DISCUSSIONS

Hardened concrete is rigorously tested to determine its various characteristics, ensuring it meets the required standards for quality, durability, and fitness for construction applications. Essential tests conducted on hardened concrete encompass the Compressive Strength Test, Flexural Strength Test (also referred to as Modulus of Rupture), and Split Tensile Strength Test, each assessing different aspects of concrete's structural integrity. Further in-depth analysis is carried out using Scanning Electron Microscopy (SEM), which provides detailed insights into the microstructural properties and the interlocking mechanisms between the concrete's aggregate and cement matrix. These comprehensive evaluations help verify that the concrete's properties align with construction requirements and performance expectations.

### 3.1. Compressive strength

The compressive strength results for various mixes are displayed in Figure 4. At 28 days, the results demonstrate an increase in compressive strength for all the mixes when compared to the control concrete. The percentage increases in compressive strength for each mix are as follows: 29.17%, 26.25%, 18.33%, 14.17%, 21.25%, 18.33%, 20.83%, 16.67%, 9.17%, 18.75%, and 12.50% [28]. The percentage changes represent how much the strength of each mix has improved or decreased equated to the CC on 28 days curing period. The optimum strength among all the mixes is 36.89 N/mm$^2$, which is achieved in Mix 5. Beyond this level, a decline in strength is observed in Mixes 6 to 11.

Additional researches as well as testing are required to determine the exact optimal level of foundry sand replacement for various grades and uses of concrete. The observed reduction in compressive strength from Mix 6 to Mix 11, despite higher percentages of foundry sand, can be linked to issues with gradation and particle shape. As the proportion of foundry sand increases, it could result in uneven gradation, impacting the overall particle packing. This can result in reduced interlocking and bonding between aggregates, leading to a weaker concrete matrix [29]. Foundry sand may have higher porosity compared to conventional fine aggregate, which can introduce more voids in the concrete and reduce its strength. Foundry sand may adversely affect the Interfacial Transition Zone (ITZ) amongst cement paste as well as aggregate particles, potentially weakening their bond.The inclusion of foundry sand as a replacement for fine aggregate may have affected the hydration process and early strength development. Foundry sand can introduce variability in the mix, which might influence the early compressive strength. This deterioration can adversely impact the concrete's structural integrity. Furthermore, as the inclusion of WFS rises, the workability of the concrete tends to diminish, which could result in poor compaction and increased porosity.

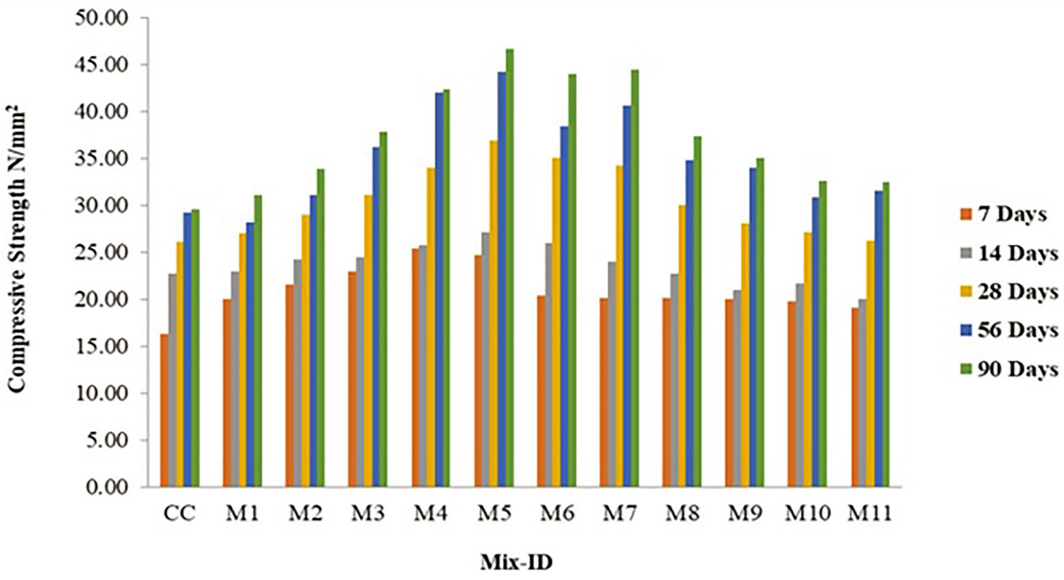


**Figure 4:** Compressive strength of foundry sand replaced concrete.

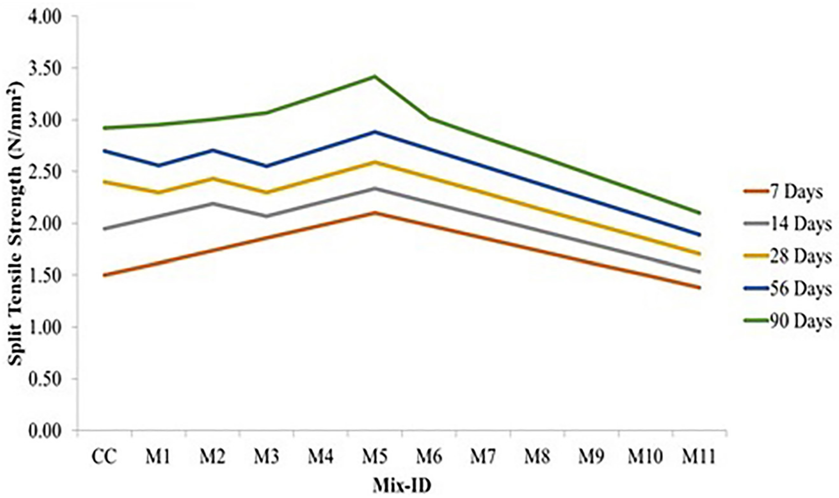


**Figure 5:** Split tensile strength of foundry sand replaced concrete.

### 3.2. Split tensile strength

Integrating WFS for fine aggregate in concrete can variably affect its split tensile strength. Mix 5, which featured a 45% replacement, exhibited the highest split tensile strength, showing an optimum replacement level. However, some mixes (1, 2, 4, 9, 10, and 11) showed a decline in split tensile strength, indicating that certain percentages of foundry sand may negatively affect tensile performance. Mixes 3, 6, and 7 displayed consistent but lower strengths compared to the optimum value as evidenced in Figure 5.

To attain required split tensile strength, it is crucial to meticulously adjust the amount of foundry sand used and tailor the mix proportions for each particular use. Foundry sand, while useful, may possess inherent constraints in strength and properties when compared to traditional fine aggregate. High concentrations of foundry sand could cause a weaker overall concrete mix. Therefore, it is essential to carefully optimize the replacement level of WFS to maintain the desired mechanical properties of concrete.

### 3.3. Flexural strength

Flexural strength tests show that using WFS as a partial replacement for fine aggregate significantly impacts the flexural performance of the concrete. Specifically, Mix 5, which uses a 45% replacement rate, consistently demonstrates the highest flexural strength at 28 days, suggesting this is the optimal level of replacement. This

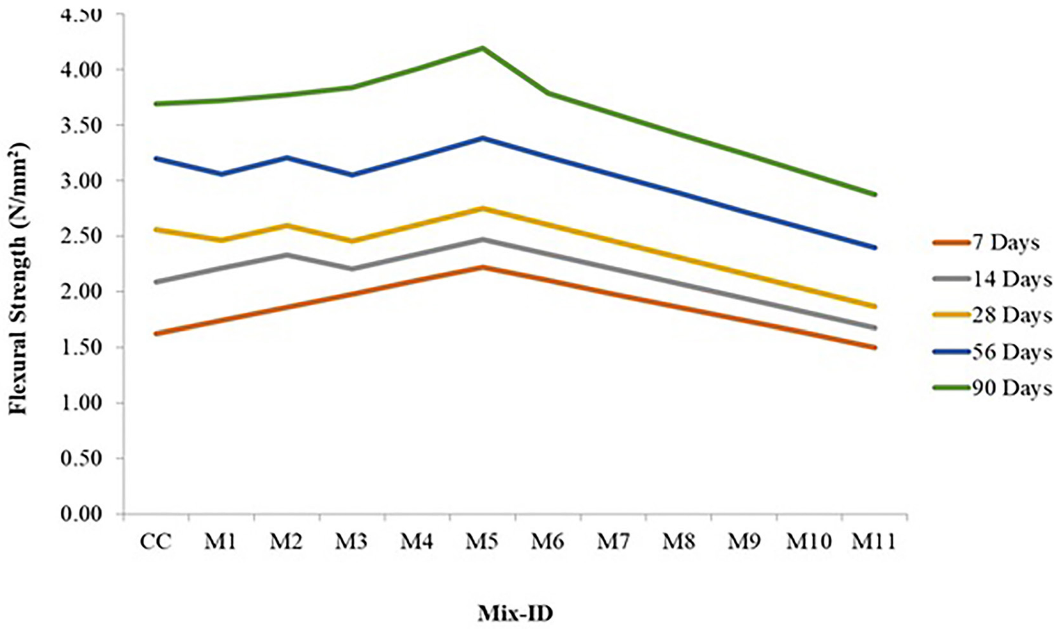


**Figure 6:** Flexural strength of foundry sand replaced concrete.

mix demonstrates an effective balance between improved strength and the sustainable use of foundry sand. The graphical representation of the test results is exhibited in Figure 6.

While Mixes 1 to 4 also display good flexural strengths, indicating some improvement with partial replacements, Mixes 6 to 11 show a decline in flexural strength as the percentage of foundry sand escalates beyond the optimal level. It is essential to carefully optimize the replacement percentage to achieve the desired flexural performance and ensure the concrete's long-term durability. Careful mix design and consideration of specific application requirements are necessary to harness the benefits of foundry sand while maintaining adequate structural integrity.

### 3.4. Microstructural analysis of concrete incorporating waste foundry sand

Scanning Electron Microscopy (SEM) is a powerful technique that offers both topographic and compositional analysis of materials. It helps determine the microstructure of a solid by analyzing the distribution of phases present. This technique is particularly useful in the study of cement and concrete, enabling detailed observation of materials down to a segment of 1 micron. Furthermore, the relationships between microstructure properties in concrete are not entirely understood. Observations of the unique microstructure as well as morphology of the hydrate blends were made on splintered surfaces. Tiny, broken samples were coated in carbon and scrutinized using a SEM in the backscattered electron mode at an accelerating voltage of 20 KeV, ensuring uniform backscattered intensity across all samples. The SEM analyses of conventional concrete (CC), Waste Foundry Sand, and the optimum mix M5 are depicted in Figures 7 and 8, respectively. The SEM image will show the distribution and morphology of pores and voids within the concrete. The pores observed in concrete are primarily influenced by the water-cement ratio, which is a key factor in determining the material's porosity, permeability, and overall durability. Interfacial Transition Zone (ITZ), evident in SEM images, is the space where the cement paste interfaces with aggregate particles.This zone is crucial for establishing bond strength amongst the aggregates as well as cement matrix. SEM imaging can also reveal the presence of C-S-H liniment, the primary result of cement hydration, which is crucial for imparting strength and structural stability to concrete [30]. Unreacted cement particles may also be evident in the SEM image, especially in areas with insufficient hydration.

The M-5 mix, as shown in Figure 8, displayed a significant development of C-S-H gel, prominent to the improvement of a solid microstructure. The micrographs of M-5 reveal needle-like structures surrounding waste foundry sand particles in various areas, indicating interactions at the microstructural level. (Siddique) The SEM image will show the cementitious matrix surrounding the (FS) foundry sand particles. The microstructure of the cement paste can provide insights into its hydration and strength development. The integration of FS made the mix with very less pores distribution and connectivity, and it is an evidence to enhance the strength.

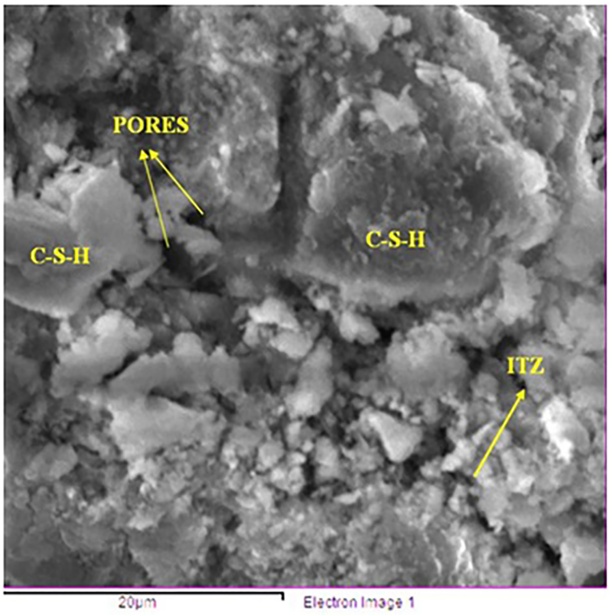


**Figure 7:** Scanning electron microscope image of conventional concrete (CC).

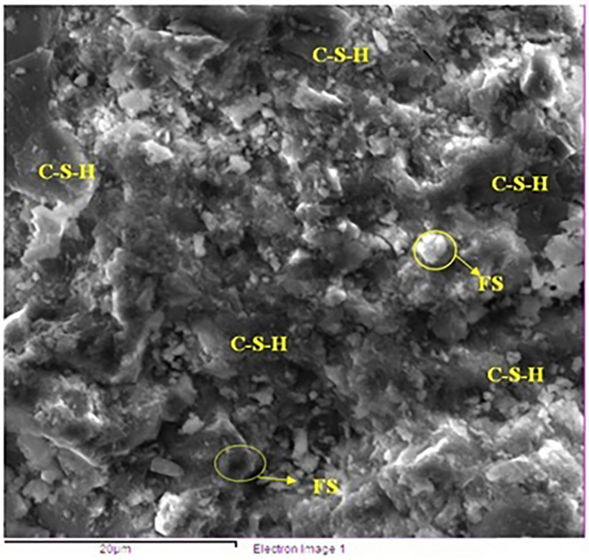


**Figure 8:** Scanning electron microscope image of concrete with WFS(Mix-5).

### 3.5. X-RAY diffraction (XRD)

X-ray Diffraction (XRD) is a method utilized to analyse material composition, such as concrete. XRD reveals the arrangement of atoms and identifies mineral phases, including calcium silicate hydrates, calcium hydroxide, portlandite, and ettringite.

In concrete with waste foundry sand substitution, XRD identifies cementitious phases and foundry sand composition. Potential peaks observed in the XRD patterns of conventional concrete evidenced in Figure 9 may include the existence of (C-S-H) liniment which is evidenced at Peaks around 26°, 28°, 44.5°, and 58.81°. The Calcium Hydroxide (CH) around 18° and 35°, Portlandite (CH): Peak around 18.13° and Ettringite: Peaks around 29.499° and 58.18°.

The XRD patterns indicated a reduction in calcium hydroxide peaks, suggesting that pozzolanic reactions were taking place between the cement hydrates and the silica present in the WFS. The analysis revealed the formation of additional phases such as more stable and less soluble calcium-silicate-hydrate (C-S-H) compounds, which contribute to the enhanced strength and durability of the concrete. If the foundry sand contains amorphous

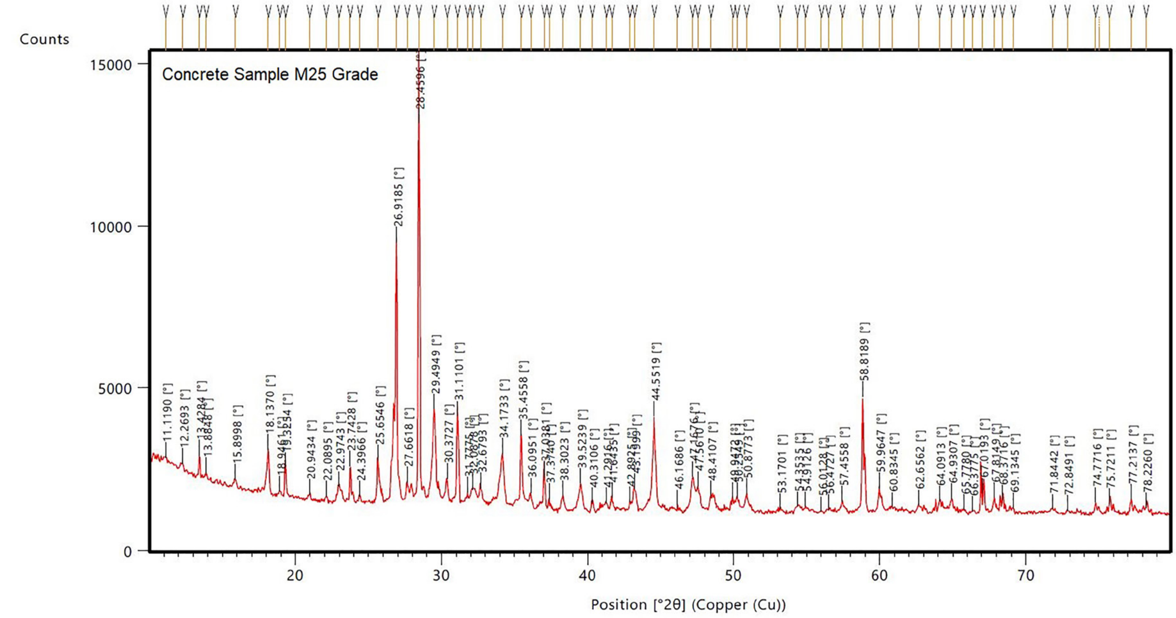


**Figure 9:** XRD of conventional concrete.

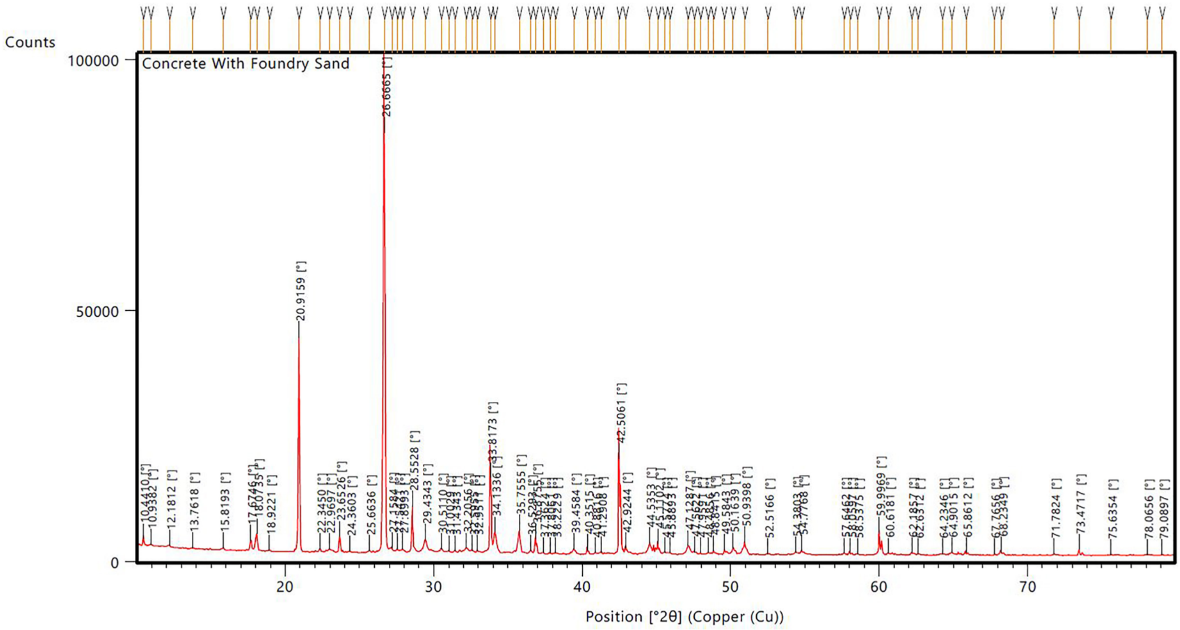


**Figure 10:** XRD of concrete with waste foundry sand.

silica, a broad hump usually appears in the XRD pattern, often around 20-30° 2θ, which is characteristic of the amorphous material. For concrete with waste foundry sand, represented in Figure 10 additional peaks equivalent to minerals present in the foundry sand may be observed [31]. The specific peak positions will depend on the elemental composition of the FS.

Common minerals found in WFS comprise silica ($SiO_2$), alumina ($Al_2O_3$), iron oxides (Fe2O3), and others. Some common minerals found in waste foundry sand include Quartz ($SiO_2$) which is at the Peaks around 26.66°, 42.50, Alumina ($Al_2O_3$): Peaks around 38.229°, 45.53°, and 60.6°, Silicates: Peaks around 12°, 31°, and 34.136°, Iron Oxides (Fe2O3): Peaks around 23.632°, 33.81°, and 41.209°, Calcium Carbonate (CaCO3): Peak around 20.9° and finally Magnesium Oxide (MgO): Peak around 42.506°.

Additionally, complementary techniques like SEM (Scanning Electron Microscopy) confirmed the presence of specific minerals and provide further insights into the microstructure of the WFS. In conclusion, the XRD analysis provided valued discernments into the mineralogical composition of concrete mixes, highlighting the special effects of integrating WFS on the microstructure. A reduction in the intensity of the $Ca(OH)_2$ peaks in the XRD pattern for the FS concrete, compared to conventional concrete (CC), indicates that the $Ca(OH)_2$ is being functioned in pozzolanic reactions to articulate additional calcium-silicate-hydrate (C-S-H), enhancing the concrete's structural properties. The presence of a broad hump in XRD pattern for FS concrete would indicate the amorphous content of the foundry sand is reacting with the available lime [32]. This is consistent with the SEM observations of a denser and more homogenous C-S-H matrix. If new peaks appear in the XRD pattern of FS concrete that are not present in the CC pattern, it might indicate the development of new crystalline hydration products in line for to the foundry sand's contribution to the reaction.

### 3.6. FTIR

The FTIR (Fourier Transform Infrared) spectra were collected to analyze the chemical composition and identify the presence of functional groups in the concrete matrices. This analysis helps to understand the molecular interactions as well as changes within the concrete. The Fourier Transform Infrared (FTIR) spectrum of the conventional concrete mix (CC) revealed characteristic bands associated with different cementitious constituents, including C-S-H, ettringite besides ($Ca(OH)_2$). The observed bands in the spectra provided evidence for the existence of significant cement hydration products, which were found to be in accordance with the typical composition of concrete. The FTIR of conventional concrete mixture is as shown in the Figure 11.

For conventional concrete, the spectrum often displays a broad band around 3400 $cm^{-1}$, a hallmark of O-H stretching vibrations attributable to water molecules and hydroxyl groups present in both calcium hydroxide and the silanol groups that are part of the calcium-silicate-hydrate structures. This is a critical indicator of the hydration status and the ongoing chemical evolution within the concrete matrix. Another distinctive feature is the sharp peak in the vicinity of 1640 $cm^{-1}$, suggesting the bending vibrations of water, indicative of physically absorbed water that resides in the capillary pores, a common feature in concrete's microstructure. Furthermore, the peak near 1420 $cm^{-1}$ potentially points to the C-O stretching vibration in carbonates, such as calcite, which could emerge from the carbonation of calcium hydroxide or be a constituent of the aggregates or other filler materials within the concrete [25]. The region between 900-1200 $cm^{-1}$, which generally corresponds to Si-O stretching vibrations, is particularly insightful as it relates to the silicate chains in the calcium-silicate-hydrate phase, the fundamental building block that imparts strength to the concrete structure. In contrast, the Fourier

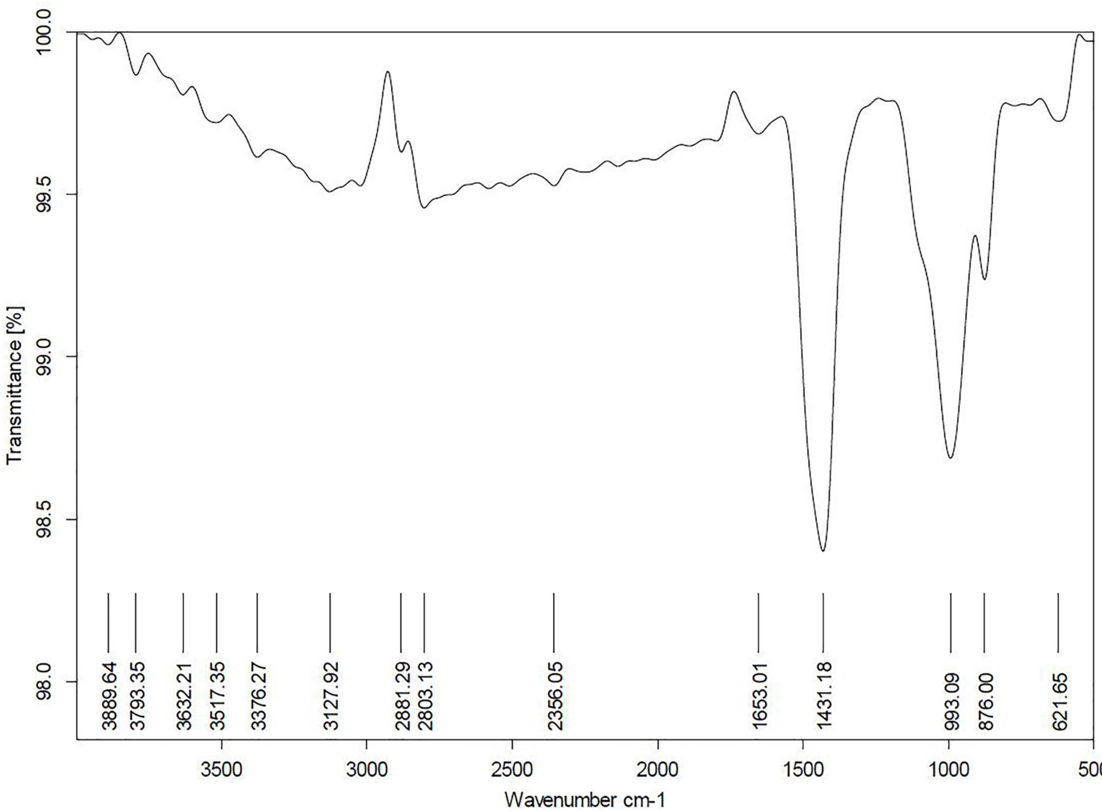


**Figure 11:** FTIR of conventional concrete.

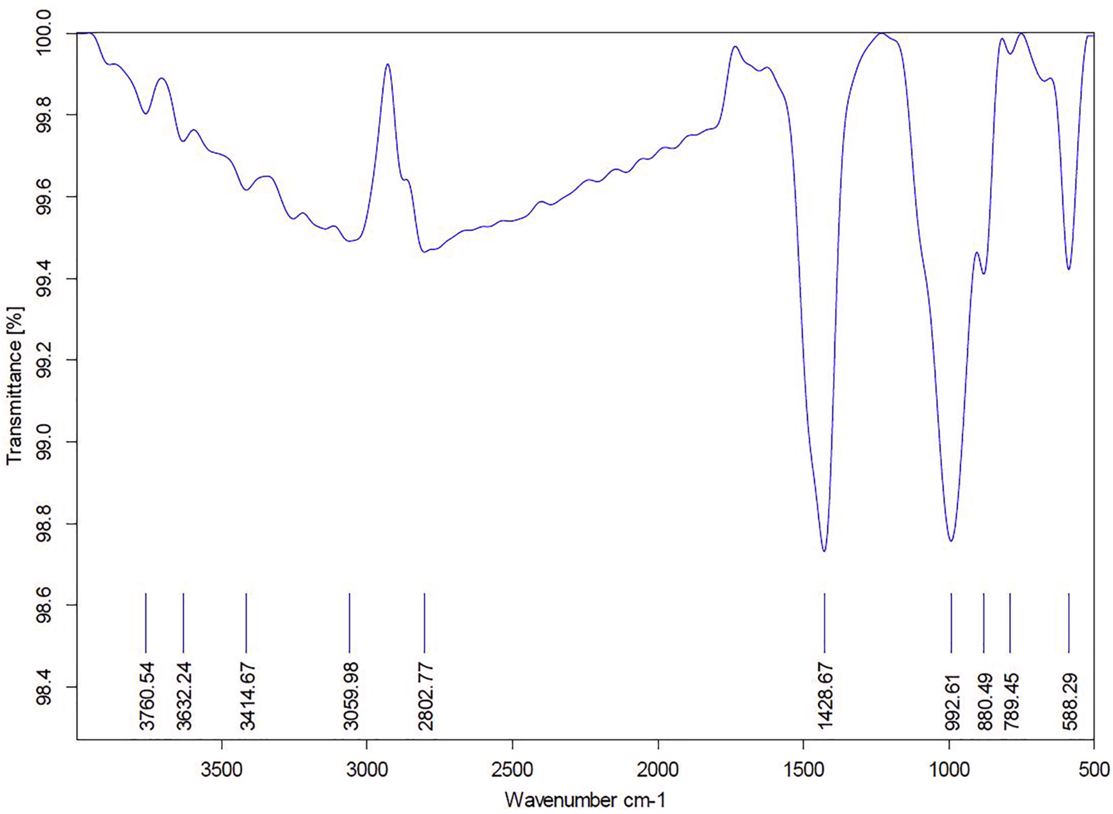


**Figure 12:** FTIR of conventional concrete with WFS.

Transform Infrared (FTIR) spectrum of mix-5 exhibited discernible alterations as a result of the addition of WFS as evidenced in Figure 12.

When examining concrete that includes foundry sand, shifts or changes in the FTIR spectrum can be revelatory of the complex interplay between the foundry sand's constituents and the cement matrix. A notable shift or intensity change at the 3400 $cm^{-1}$ mark can imply alterations in the hydrogen bonding network within the calcium-silicate-hydrate framework, a consequence of the pozzolanic reaction where the foundry sand's amorphous silica reacts with calcium hydroxide. Alterations observed near the 1640 $cm^{-1}$ peak could mirror a modification in the concrete's porosity or a variance in the quantity of gel water, likely attributable to the materialization of supplemental C-S-H precipitated after the pozzolanic process. A variance around the 1420 $cm^{-1}$ band suggests a potential decline in carbonation, perhaps owing to the ingestion of calcium hydroxide in pozzolanic reactions, which sequesters it away from carbon dioxide's reach. Meanwhile, an uptick in the intensity of peaks spanning the 900-1200 $cm^{-1}$ range would fortify the notion that more calcium-silicate-hydrate is being synthesized, a direct result of the silica from the foundry sand undergoing a pozzolanic reaction along with the lime from the cement hydration, culminating in a more robust and cohesive concrete structure.

The progression of supplementary C-S-H owing to the pozzolanic reaction contributes to the strength and durability of the concrete by providing a denser and more cohesive matrix, which can be observed by the increased intensity of the peaks connected with Si-O bonds. A decrease in the characteristic peaks for $Ca(OH)_2$ in the FS sample suggests that the foundry sand is reacting and thus reducing the portlandite in the system, which doesn't contribute to strength directly. This also contributes to strength indirectly by refining the pore structure. If the peak for carbonates is less intense or shifted, it might indicate that the system is less prone to carbonation, which can protect against the associated weakening effects.

### 3.7. Key Reactions and Their Relationship with the SEM Image Observations and XRD Peaks

#### 3.7.1. Pozzolanic reaction

The primary reaction of silica present in the WFS with the CaoH generated during cement hydration is a pozzolanic reaction, forming (C-S-H), which is the key strength-giving segment in concrete.

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO{\cdot}SiO_2{\cdot}H_2O(C\text{-}S\text{-}H)SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO{\cdot}SiO_2{\cdot}H_2O(C\text{-}S\text{-}H) \quad (1)$$

SEM images showing increased density of C-S-H indicates the occurrence of the pozzolanic reaction. The existence of an amorphous mass in the XRD patterns, seen as a broad hump rather than sharp peaks, suggests the reactivity of the silica content. Peaks corresponding to calcium hydroxide (CH) may be lower in intensity in the XRD pattern for the WFS concrete due to its consumption in the pozzolanic reaction, which supports the SEM observations of a denser C-S-H matrix.

## 4. SUSTAINABLE CONCRETE SOLUTIONS

The integration of WFS into concrete presents a promising avenue for addressing environmental problems associated with material cycles and waste management [33]. The points highlighting the environmental benefits of incorporating waste foundry sand into concrete are listed below. The typical picture shows how a waste can be utilized as a resource is depicted in Figure 13.

- Incorporating WFS into concrete effectively diverts significant quantities of this industrial byproduct from landfills, thereby reducing waste and lessening the environmental impact.
- Traditional concrete production depends on natural river sand, a finite resource. By using WFS as a partial replacement for natural sand, we can conserve these essential natural resources and decrease the environmental impact associated with sand extraction.
- The usage of WFS in concrete can contribute to energy savings. The production of concrete typically involves significant energy consumption, and by replacing a portion of the conventional materials with waste foundry sand, there is potential for reduced energy requirements in the concrete manufacturing process [34].
- Incorporating waste foundry sand aligns with the principles of a circular economy, where industrial byproducts are reused or recycled. This approach promotes a more sustainable and resource-efficient system by closing the loop on material use.
- Concrete production is a significant contributor to carbon emissions. Utilizing waste foundry sand in concrete may offer a more environmentally friendly alternative, potentially reducing the carbon footprint associated with traditional concrete manufacturing.
- Beyond environmental advantages, incorporating waste foundry sand into concrete can also have economic benefits. It may lead to cost savings for construction projects, making it an attractive option for both environmental and financial reasons.

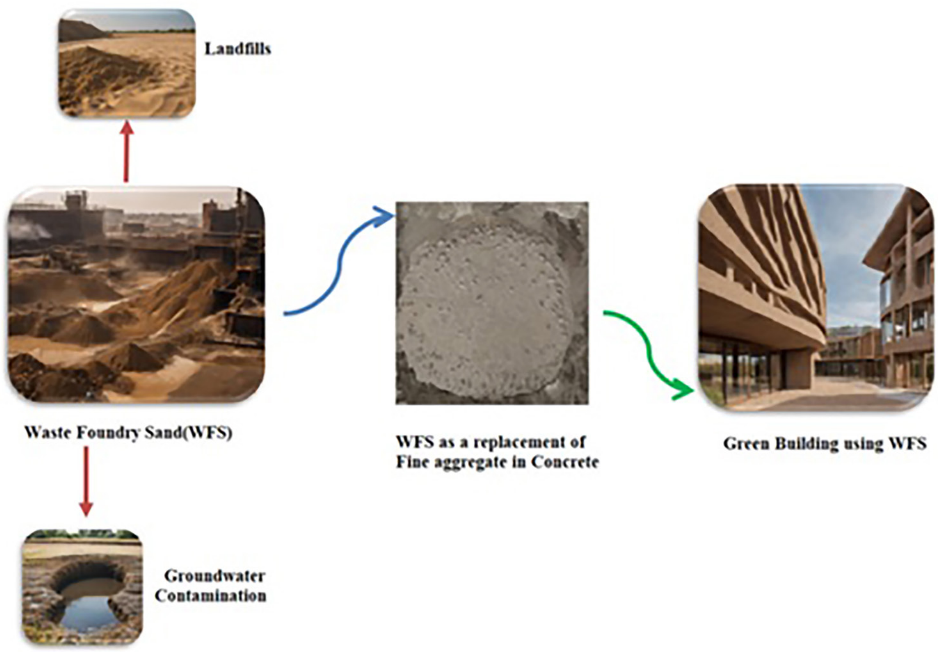


**Figure 13:** Waste to resource – a glimpse.

- The usage of WFS in concrete contributes to overall sustainability of construction practices. It provides an opportunity to create durable and high-performance concrete while simultaneously addressing environmental challenges.

### 4.1. Environmental advantages

- Using WFS reduces the need for natural sand, thereby conserving natural resources and reducing environmental degradation caused by sand mining.
- Incorporating WFS in concrete helps in recycling industrial waste, reducing landfill usage and the associated environmental impacts.
- By substituting natural sand with WFS, the energy consumption and carbon emissions associated with sand extraction and processing are decreased.

### 4.2. Economic advantages

- WFS is often available at a lower cost compared to natural sand, leading to overall cost savings in concrete production.
- Utilizing WFS in concrete production reduces the costs associated with waste disposal and management for foundries.
- The improved mechanical properties of concrete with WFS, such as increased strength and durability, can lead to longer-lasting structures and reduced maintenance costs over time.

## 5. CONCLUSION

- The incorporation WFS in place of fine aggregate preserved the intrinsic qualities of the fresh concrete. The slump values remained consistent across all mixes, ensuring satisfactory workability.
- Compressive strength enhanced evidently by the inclusion of WFS up to 45% replacement, showing an increase of approximately 58% compared to conventional concrete. The mix with 45% intervening revealed the highest compressive strength of 26.11 $N/mm^2$.
- Up to 45% replacement, the split tensile strength displayed notable enhancement, with an approximate increase of 48% over conventional concrete. The mix with 45% replacement achieved the utmost split tensile strength around 2.75 $N/mm^2$.
- The flexural strength also followed a similar trend, with an increase of about 43% up to 45% replacement compared to conventional concrete. The mix with 45% replacement attained the maximum flexural strength of 3.38 $N/mm^2$.
- Scanning Electron Microscopy (SEM) analysis highlighted the changes in microstructure due to the integration of WFS. The SEM images indicated improved particle packing and interfacial bonding up to 45% replacement, contributing to enhanced strength [30].
- The SEM images highlight a denser matrix in concrete with WFS, indicated by a more homogeneous and compact C-S-H distribution and reduced porosity. This suggests enhanced binding and potentially increased strength compared to the conventional concrete, which exhibits a more heterogeneous structure with visible pores and an evident interfacial transition zone (ITZ).
- XRD patterns reveal a reduction in the intensity of the calcium hydroxide peaks in the concrete with WFS, a sign of the pozzolanic reaction where calcium hydroxide reacts with the silica in the WFS to forms an additional C-S-H. Additionally, the presence of an amorphous hump typically associated with amorphous silica from the WFS indicates the material's reactivity, contributing to the strength as well as durability of the concrete.
- The FTIR analysis confirmed the existence of new efficient clusters introduced by WFS. The appearance of Si-O-Si bending vibrations at around 4500 $cm^{-1}$ substantiated the influence of silica-based foundry sand.
- The FTIR spectra exhibit a shift in the hydroxyl group's absorption band and changes in the water band intensity, which can be correlated with an increased development of C-S-H in the WFS concrete. The reduction in carbonate peak intensity further supports the depletion of CaoH evidenced in pozzolanic reaction,

rather than its participation in carbonation processes, thereby implying a more durable concrete with reduced susceptibility to environmental carbonation.

- The results suggest that incorporating waste foundry sand as a partial replacement for fine aggregate up to 45% can significantly improve the mechanical properties of concrete.
- The use WFS, in concrete production has demonstrated encouraging outcomes and significant potential for enhancing sustainability within the construction industry.
- Incorporating WFS as a partial replacement for fine aggregate in concrete demonstrates a successful waste-to-resource conversion approach. By diverting industrial waste from landfills and repurposing it in concrete production, the construction industry contributes to sustainable waste management practices and reduces environmental burdens.
- Incorporating WFS into concrete significantly cuts down on the use of natural resources such as river sand, a crucial ingredient in concrete production. By reducing sand mining and its associated environmental impacts, the construction sector can contribute to preserving natural ecosystems and maintaining riverine habitats.
- The study results demonstrate that incorporating waste foundry sand up to a 45% replacement level enhances the properties of concrete, highlighting the potential of this industrial byproduct as a valued source in construction. This enhanced material efficiency ensures optimum utilization of available resources, contributing to sustainable construction practices.
- The usage of WFS in concrete can provide economic benefits by reducing raw material costs and waste disposal expenses for industries generating the waste. Additionally, sustainable concrete formulations can create new opportunities for innovative and environmentally conscious construction practices.

## 6. BIBLIOGRAPHY


[1] AHMAD, J., ZHOU, Z., MARTÍNEZ-GARCÍA, R., *et al*., "Waste foundry sand in concrete production instead of natural river sand: a review", *Materials (Basel)*, v. 15, n. 7, pp. 2365, 2022. doi: http://doi.org/10.3390/ma15072365. PubMed PMID: 35407698.

[2] ASLANI, M., AKBARDOOST, J., DELNAVAZ, M., "Investigating the effect of the foundry sand and waste foundry sand on the fracture toughness of concrete", *Arabian Journal of Geosciences*, v. 14, n. 12, pp. 464, 2021. doi: http://doi.org/10.1007/s12517-021-06852-7.

[3] BAHRAQ, A.A., MASLEHUDDIN, M., AL-DULAIJAN, S.U., "Macro- and micro-properties of engineered cementitious composites (eccs) incorporating industrial waste materials: a review", *Arabian Journal for Science and Engineering*, v. 45, n. 10, pp. 7869–7895, 2020. doi: http://doi.org/10.1007/s13369-020-04729-7.

[4] BASAR, H.M., AKSOY, N.D., "The effect of waste foundry sand (WFS) as a partial replacement of sand on the mechanical, leaching, and micro-structural characteristics of ready-mixed concrete", *Construction & Building Materials*, v. 35, pp. 508–515, 2012. doi: http://doi.org/10.1016/j.conbuildmat.2012.04.078.

[5] BHARDWAJ, A., KUMAR, P., SIDDIQUE, S., *et al*., "Comprehensive review on utilization of waste foundry sand in concrete", *European Journal of Environmental and Civil Engineering*, v. 27, n. 3, pp. 1056–1087, 2023. doi: http://doi.org/10.1080/19648189.2022.2070778.

[6] BHARDWAJ, B., KUMAR, P., "Waste foundry sand in concrete: a review", *Construction and Building Materials*, v. 156, pp. 661–674, 2017. doi: http://doi.org/10.1016/j.conbuildmat.2017.09.010.

[7] ÇEVIK, S., MUTUK, T., OKTAY, B.M., *et al*., "Mechanical and microstructural characterization of cement mortars prepared by waste foundry sand (WFS)", *Journal of the Australian Ceramic Society*, v. 53, n. 2, pp. 829–837, 2017. doi: http://doi.org/10.1007/s41779-017-0096-9.

[8] DOMINGUES, L.G.F., SANTOS FERREIRA, G.C., PIRES, M.S.G., "Waste foundry sand used to cover organic waste in landfills", *Journal of Material Cycles and Waste Management*, v. 24, n. 1, pp. 378–385, 2022. http://doi.org/10.1007/s10163-021-01327-z.

[9] FORSAT, M., MIRJAVADI, S.S., HAMOUDA, A.M.S., "Investigation of the effect of Larestan's pipeline water on the mechanical properties of concretes containing granite aggregates", *Advances in Civil Engineering*, v. 2019, n. 1, pp. 4197186, 2019. doi: http://doi.org/10.1155/2019/4197186.

[10] JABAR, A.B., PRADEEP, T., "ANN-PSO modelling for predicting buckling of self-compacting concrete column containing RHA properties", *Matéria (Rio de Janeiro)*, v. 28, n. 2, pp. e20230102, 2021. doi: http://doi.org/10.1590/1517-7076-rmat-2023-0102.

[11] KHAN, M.M., SINGH, M., JADHAV, G.N., *et al*., "Characterization of waste and reclaimed green sand used in foundry processing", *Silicon*, v. 12, n. 3, pp. 677–691, 2020. doi: http://doi.org/10.1007/s12633-019-00146-0.

[12] MANOHARAN, T., LAKSMANAN, D., MYLSAMY, K., *et al*., "Engineering properties of concrete with partial utilization of used foundry sand", *Waste Management (New York, N.Y.)*, v. 71, pp. 454–460, 2018. doi: http://doi.org/10.1016/j.wasman.2017.10.022. PubMed PMID: 29103896.

[13] MARCHIONI, M.L., LYRA, J., PILEGGI, R., *et al*., "Foundry sand for manufacturing paving units", In: *Proceedings of the 10th International Conference on Concrete Block Paving*, pp. 24–26, 2012. https://www.novaerasolucoesambientais.com.br/PDF/019.pdf, accessed in July, 2024.

[14] MAVROULIDOU, M., LAWRENCE, D., "Can waste foundry sand fully replace structural concrete sand?", *Journal of Material Cycles and Waste Management*, v. 21, n. 3, pp. 594–605, 2019. doi: http://doi.org/10.1007/s10163-018-00821-1.

[15] MIRJAVADI, S.S., FORSAT, M., YAHYA, Y.Z., *et al*., "Analysis of post-buckling of higher-order graphene oxide reinforced concrete plates with geometrical imperfection", *Advances in Concrete Construction*, v. 9, n. 4, pp. 397–406, 2020.

[16] NAIK, T.R., PATEL, V.M., PARIKH, D.M., *et al*., "Utilization of used foundry sand in concrete", *Journal of Materials in Civil Engineering*, v. 6, n. 2, pp. 254–263, 1994. doi: http://doi.org/10.1061/(ASCE)0899-1561(1994)6:2(254).

[17] PALANIAPPAN, S.M., GOVINDASAMY, V., JABAR, A.B., "Experimental investigation on flexural performance of functionally graded concrete beams using flyash and red mud", *Matéria (Rio de Janeiro)*, v. 26, n. 1, pp. e12913, 2021. doi: http://doi.org/10.1590/s1517-707620210001.1213.

[18] RAJESH, K.N., RAJU, P.M., MISHRA, K., "Performance of alkali-activated slag-based concrete with partial replacement of fine aggregate by Used Foundry Sand", *Journal of Building Rehabilitation*, v. 6, n. 1, pp. 33, 2021. doi: http://doi.org/10.1007/s41024-021-00127-0.

[19] RAJESH, K.N., RAJU, P.M., "Performance of recycled plastic waste and used foundry sand as a replacement of fine aggregate in concrete", In: Das, B.B., Gomez, C.P., Mohapatra, B.G. (eds), *Recent Developments in Sustainable Infrastructure (ICRDSI-2020)—Structure and Construction Management, Lecture Notes in Civil Engineering*, Singapore, Springer, vol. 221, pp 735–747, 2022. doi: http://doi.org/10.1007/978-981-16-8433-3_61.

[20] RAO, P.T., PRAKASH, J., ALEXANDER, R., *et al*., "Role of graphene oxide infusion in concrete to elevate strength and fire performance in construction concrete", *Diamond and Related Materials*, v. 147, pp. 111269, 2024. doi: http://doi.org/10.1016/j.diamond.2024.111269.

[21] SABOUR, M.R., DERHAMJANI, G., AKBARI, M., *et al*., "Global trends and status in waste foundry sand management research during the years 1971-2020: a systematic analysis", *Environmental Science and Pollution Research International*, v. 28, n. 28, pp. 37312–37321, 2021. doi: http://doi.org/10.1007/s11356-021-13251-8. PubMed PMID: 33713260.

[22] SHAHRABADI, H., NIKOO, H.S., FORSAT, M., "Effect of limestone on the mechanical properties of concrete containing silica fume and fly ash", *Journal of Materials and Environmental Sciences*, v. 8, n. 2, pp. 457–466, 2017. https://jmaterenvironsci.com/Document/vol8/vol8_N2/49-JMES-2248-Shahrabadi.pdf, accessed in July, 2024.

[23] SHARMA, R., "Influence of waste foundry sand, metakaolin and waste glass fiber on stress strain and microstructure of construction waste aggregate concrete", *Innovative Infrastructure Solutions*, v. 7, n. 5, pp. 306, 2022. doi: http://doi.org/10.1007/s41062-022-00902-z.

[24] SIDDIQUE, R., DE SCHUTTER, G., NOUMOWE, A., "Effect of used-foundry sand on the mechanical properties of concrete", *Construction & Building Materials*, v. 23, n. 2, pp. 976–980, 2009. doi: http://doi.org/10.1016/j.conbuildmat.2008.05.005.

[25] SIDDIQUE, R., SINGH, G., BELARBI, R., *et al*., "Comparative investigation on the influence of spent foundry sand as partial replacement of fine aggregates on the properties of two grades of concrete", *Construction & Building Materials*, v. 83, pp. 216–222, 2015. doi: http://doi.org/10.1016/j.conbuildmat.2015.03.011.

[26] SINGH, G., SIDDIQUE, R., "Effect of waste foundry sand (WFS) as partial replacement of sand on the strength, ultrasonic pulse velocity and permeability of concrete", *Construction & Building Materials*, v. 26, n. 1, pp. 416–422, 2012. doi: http://doi.org/10.1016/j.conbuildmat.2011.06.041.

[27] SOUNDAR RAJAN, M., JEGATHEESWARAN, D., "Influence of strength behavior in brick masonry prism and wallette under compression", *Matéria (Rio de Janeiro)*, v. 28, n. 01, pp. e20220260, 2023. doi: http://doi.org/10.1590/1517-7076-rmat-2022-0260.

[28] MUTHUKUMAR, S.R., JEGATHEESWARAN., "Prediction of autoclaved aerated cement block masonry prism strength under compression using machine learning tools", *Matéria (Rio de Janeiro)*, v. 29, n. 1, pp. e20230247, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2023-0247.

[29] YAJNODBHAVI, H.M., RAVI KUMAR, C.M., MARUTHI, T., *et al*. Properties enhancement strategy for fibre reinforced standard concrete using Foundry Sand (FS) and Crushed Concrete Waste (CCW). In NANDAGIRI, L., NARASIMHAN, M.C., MARATHE, S., DINESH, S. (eds), *Sustainability trends and challenges in civil engineering: lecture notes in civil engineering*, Singapore, Springer, v. 162, pp. 927–948, 2022. doi: http://doi.org/10.1007/978-981-16-2826-9_58.

[30] ZALYHINA, V., CHEPRASOVA, V., ROMANOVSKI, V., "Recycling of fine fraction of spent foundry sands into fireclay bricks", *Journal of Material Cycles and Waste Management*, v. 26, n. 1, pp. 322–330, 2024. doi: http://doi.org/10.1007/s10163-023-01825-2.

[31] BUREAU OF INDIAN STANDARDS, *IS 10262:2009: Guidelines for concrete mix proportioning*, New Delhi, Bureau of Indian Standards, 2009.

[32] BUREAU OF INDIAN STANDARDS, *IS 2386:1963 (Part 1): Methods of test for aggregates for concrete: Part 1 particle size and shape*, New Delhi, Bureau of Indian Standards, 1963.

[33] BUREAU OF INDIAN STANDARDS, *IS 2386:1963 (Part 3): Methods of test for aggregates for concrete: Part 3 specific gravity, density, voids, absorption and bulkin*, New Delhi, Bureau of Indian Standards, 1963.

[34] BUREAU OF INDIAN STANDARDS, *IS 2720 (Part 3): Methods of test for aggregates for—specification*, New Delhi, Bureau of Indian Standards, 1980.

[35] BUREAU OF INDIAN STANDARDS, *IS 455:1989 (Reaffirmed 1995): Portland slag cement—specification*, New Delhi, Bureau of Indian Standards, 1989.

[36] BUREAU OF INDIAN STANDARDS, *IS 456: Plain and reinforced concrete code of practice*, New Delhi, Bureau of Indian Standards, 2000.

[37] BUREAU OF INDIAN STANDARDS, *IS 516:1959 (Reaffirmed 2004): Method of tests for strength of concrete*, New Delhi, Bureau of Indian Standards, 1959.

[38] BUREAU OF INDIAN STANDARDS, *IS 12269:1987: 53 grade ordinary Portland cement CED 2: Cement and Concrete*, New Delhi, Bureau of Indian Standards, 1987.

[39] BUREAU OF INDIAN STANDARDS, I*S 9103:1999: Specification for Concrete Admixtures CED 2: Cement and Concrete*, New Delhi, Bureau of Indian Standards, 1999.

[40] BUREAU OF INDIAN STANDARDS, *IS 1199:1959: Methods of sampling and analysis of concrete CED 2: Cement and Concrete*, New Delhi, Bureau of Indian Standards, 1959.