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Original Article

Mineralogical, Microstructural, Fresh-State and Mechanical Performance Evaluation of Cement Mortar Incorporating Processed Overburden Sand as a Sustainable Fine Aggregate Replacement

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Abstract - *The present study explores the potential of replacing natural river sand with processed Overburden Sand (OBS) from lignite mines for sustainable production of cement mortar by means of mineralogical, microstructural, fresh properties, and mechanical investigation. SEM, and EDS analysis revealed that both river sand and OBS consisted mainly of silica, with OBS having some alumina, iron, and alkali constituents, thus affecting the surface characteristics and chemical activity of OBS. Tests using flow table, marsh cone test, and fresh density method were carried out on diverse water-cement (w/c) proportions between 0.4 and 0.8 to examine workability property. Flow characteristics improved for RS from w/c proportion of 0.5, while OBS had lower spread diameters till w/c of 0.6. The maximum compression strength obtained for river sand mortar was 31.8 MPa at 0.5 w/c ratio, and 27.1 MPa for OBS mortar at 0.6 w/c proportion. From substitution study carried out at a proportion of 0.6 w/c, a gradual decrease in strength was observed with increasing OBS amount. This study shows the feasibility of utilizing processed overburden sand as an alternative fine aggregate in mortar while maintaining satisfactory mechanical performance.*

Keywords *- Cement mortar, Compressive strength, Fine aggregate replacement, Processed Overburden Sand, Fresh-state properties, SEM-EDS.*

1. Introduction

Currently, there are many pressures for the construction sector to minimize their dependency on the natural sand found in rivers due to environmental hazards caused by over-extraction, including degradation of the riverbed, environmental imbalance, depletion of groundwater, and increase in materials' cost, especially in developing countries. Fine aggregates are known to make up a significant proportion of the volume fraction of cement mortars, making it essential to find suitable and environmentally friendly substitutes. Overburden sand from coal mining activities stands out as one of the most suitable sources of secondary aggregates due to its abundant supply and silicon content and its practical application in cement mortars should be evaluated.

1.1. Background and Need for Sustainable Fine Aggregate Alternative

The use of river sand is still the typical selection of fine aggregate in the production of paste due to the gradation, smooth texture, and compatibility with cement hydration process. Nevertheless, there is an escalating increase in demand for natural aggregates owing to fast-paced development of infrastructures which leads to exhaustion of natural resources and adverse effects to the environment. Consequently, the current researches have been concentrated on alternative fine aggregates obtained from waste materials such as recycled sand, sandstone waste, fly ash, pond ash, recycled concrete powder, and mine wastes [1, 2, 3, 4, 5]. Urban infrastructural development along with the rising number of people living in cities has increased the need for the use of natural river sand as a dominant source of fine aggregate in the preparation of cement-based building component. The extraction of large quantities of river sand has caused numerous adverse environmental effects such as river bank erosion, the deterioration of the ecological balance of water bodies, groundwater depletion, and disturbance of natural sediment flow processes. Tighter regulations governing the extraction of river sand have led to the necessity to observe for environmentally friendly alternatives to river sand that will preserve the characterizes of cement mortar.

Among mine wastes, the overburden materials from the mining process have been shown to be abundant and discarded without proper use, leading to land occupation and environmental challenges [6, 7]. The chemical compositions of overburden materials have been reported to include silicon, aluminum-silicon oxides, various feldspars, and traces of iron compounds, suggesting their possible cementing properties provided particle size and water requirements are appropriately managed [8]. Some recent studies have revealed that mine overburden sand can perform well as sustainable aggregates for mortars, when used in proper proportions [9, 10]. Sand overburden produced from lignite mining is one of those materials which can be effectively put into use for construction purposes. Sand overburden is mined in huge amounts during mining activities and is normally deposited on dumping sites where it covers huge lands and is difficult to manage environmentally. Conversion of the mine waste into construction material will help to reduce environmental burden along with conservation of natural river sand.

1.2. Significance of Fresh State Characteristics on Mortar Quality

Workability is an important factor in mortar composition, as it impacts compactness, homogeneity, porosity formation, and eventually leads to the development of hardened strength. The flow table, Marsh cone discharge time, and fresh density test are commonly recognized parameters used in mortar rheological assessment [11, 12]. Surface roughness is an important feature influencing water requirement in cases where angular waste materials are employed. A greater amount of roughness typically causes increased friction and decreased spread area at a smaller water-cement ratio. Waste aggregates and mining products were reported to exhibit lesser flowability than river sand owing to their irregular shape and higher surface absorption rate [13, 14, 15]. Thus, the importance of finding the optimal water-cement ratio cannot be ignored prior to undertaking replacement studies. It is therefore imperative that the ASTM-based assessment of fresh properties of mortar remains crucial when assessing the suitability of waste fine aggregates [11, 12].

1.3. Overburden Sand as an Alternative Source of Aggregate

Coal overburden sand has become an area of interest owing to its abundance and its engineering applications. According to past researches, overburden wastes after processing can be incorporated as a material in low-strength concrete mixes, masonry mortar mixes, and cement mortar mixes, all of which showed satisfactory results [6, 8, 9]. Overburden sand used as fine aggregates can produce high strengths provided that grading and water requirements are optimized [8]. Processed overburden sand was found to produce satisfactory results as an ingredient in fly ash masonry mortars [9]. The past research is more concerned about their hardened characteristics than their optimization in fresh state conditions.

1.4. Importance of Microstructure Investigation

Material investigation using X-ray diffraction (XRD), scanning electron microscope (SEM), and energy-dispersive spectroscopy (EDS) has a major influence in the investigation of mineralogical compatibility of new aggregates in cement materials. XRD facilitates identification of major crystal structures such as quartz, feldspar, calcite, and aluminosilicates. On the other hand, SEM is helpful in determining particle structure and surface characteristics [13, 16]. EDS is useful in establishing the existence of silica, alumina, calcium, iron, and alkali elements that impact interfacial bonding and water interaction. For example, sandstone waste, reclaimed road aggregates, and waste materials powder used in experimental research confirm that microstructure characteristics control mortar performance [5], [13, 15]. Consequently, incorporating mineralogy and microstructural investigations with engineering testing leads to scientific evidence-based aggregate substitution. From the previous researches have indicated the possibility of the use of recycled aggregates, quarry dust, industrial waste products, and mining waste materials in place of natural river sand, there still exist some critical gaps in the research that need to be explored. In most previous researches, the focus has been on the compressive strength or workability of the material but relatively little has been known about comprehensive analysis concerning the mineralogical study, fresh state properties, microstructure, and mechanical behavior of the processed overburden sand produced from lignite mining. The impact of aggregate mineralogy and form on the engineering behavior of cement paste has received insufficient attention.

1.5. Objectives and Novelty of this Research

This research aimed at achieving a thorough technical assessment of the overburden sand, as an eco-friendly fine aggregate replacement material for the commonly used river sand in the cement mortar, through an integration of mineralogical evaluation, evaluation of fresh mortar performance, and mechanical testing under one experimental scheme. While previous literature had proven that waste materials extracted from mines could be used in mortar and concrete mixes, most experiments were based on hardening mechanical properties and not on fresh properties, as well as partial replacement ratios. Considering that fresh mortar properties affect the process of compaction, particle distribution, porosity formation, and subsequent mechanical properties, an evaluation of their workability is crucial before using the aggregates on a larger scale. The mineralogy composition was determined using techniques like X-ray diffraction, scanning electron microscopy, and energy-dispersive spectroscopy, grain morphologies, and elemental content of both river and overburden sand samples. These tests are essential since the surface structure of aggregates and the crystalline phases with high silica content have a significant effect on the water requirement and interfacial bonds formation of cementitious matrix [5, 13, 15]. The fresh qualities of the samples were examined by analyzing the spread diameter on flow tables, Marsh cone discharge duration, and fresh density at varied water-to-cement ratios ranging from 0.4 to 0.8, according to ASTM mortar test standards [11, 12]. Thus, the most suitable water-to-cement proportion for the river sand mortar and the overburden sand mortar was determined before the replacement experiments. A key contribution of this research is the choice of the ideal water-cement ratio for assessing compatibility in the fresh state before examining different replacement percentages from 0 to 100 percent with overburden sand. Previous research studies usually considered constant water content in their replacement experiments, which generally does not reflect the actual effects of the rheological properties of waste-derived fine aggregate materials [8, 10]. In the current experimental study, compression strength tests were conducted on the third, seventh, and 28th days in the optimum fresh state using mortar compression strength testing criteria [17]. Yet another valuable outcome of the research relates to the correlation observed between mineralogical findings and engineering properties. The XRD, SEM, and EDS tests conducted for the replacement blends allow understanding the reasons for the modest decrease in strength at higher content levels of overburden sand despite satisfactory mechanical properties in fresh state. Such connections between microstructure and strength characteristics have been reported recently in the context of sustainable mortars based on recycled and waste products [4, 5]. Consequently, the current research contributes to proving the feasibility of using overburden sand as an alternative fine aggregate for sustainable cement paste.

The objectives of the present investigation are

1. Characterization of processed overburden sand through mineralogical and physical characterization.
2. Fresh state characterization of cement mortar using processed overburden sand.
3. Compressive strength evaluation of mortar containing various percentages of processed overburden sand.
4. Microstructural analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS).

Processed overburden sand is a feasible and sustainable alternative to natural river sand.

1.6. Scope of the Current Study

The current work covers the whole experimental examination into the usage of overburden sand as a sustainable alternative to river sand in cement mortar using a systematic procedure that includes material characterization, fresh state properties, and hardened strength determination. The study involves identification of minerals and characterization of the physical structure of both sands by techniques such as XRD, SEM-EDS to provide information about crystalline phases, surface features, and elemental composition. This is important because aggregate mineralogy and texture play an important role in influencing water requirement, workability, and interaction of aggregates with cement paste [5, 13, 15]. The experimentally carried out program also entails testing of fresh-state properties including the spread diameter on the flow table, the Marsh cone discharge time, and fresh density at alternative water-cement proportions of 0.4 to 0.8. This is because fresh state properties affect the properties of the mortar in terms of its placement ease and internal density especially when fine aggregate of a different morphology from river sand is used [11, 12]. The experiments of the mortar of river sand and mortar of overburden sand were separately optimized to ensure that the most appropriate water-cement ratio was identified before carrying out the replacement experiments.

Considering the optimum performance of fresh cement mortar, various compositions of cement mortar incorporating incremental substitution of river sand by overburden sand between 0% and 100% were designed, fabricated, and their compression strength value was observed at ages of 3^{rd} , 7^{th} , and 28^{th} days in accordance with mortar strength test methods [17]. It facilitates the assessment of the early age hydration behavior as well as strength gain at different levels of substitutions. The study also includes researching the impact of microstructure characteristics on mechanical properties, thus linking observations at a microscopic scale to engineering behavior. The current research focuses on cement mortar uses only and does not include durability, shrinkage, and outdoor exposures relevant to concrete-scale application that can be addressed in future work [8, 10]. In the light of the above-mentioned research challenges and gaps in current knowledge, the literature review presented here evaluates earlier studies concerning sustainable fine aggregates, mining waste, fresh properties, mineralogical analysis, and mechanical properties of cement mortar. This literature review provides the scientific foundation for the current study and the necessity of comprehensive study of processed overburden sand.

2. Literature Review

Utilization of industrial by-products and mine wastes in a sustainable manner has attracted much interest over the last few years due to the growing concern about natural resource exhaustion and sustainability issues. Many studies have focused on assessing different alternative fine aggregates such as recycled concrete powder, quarry dust, artificial sand, and industrial by-products/mine wastes in order to minimize the reliance on the use of natural river sand. However, the engineering fitness of the aforementioned material types is not limited to the mechanical properties but rather is highly dependent on mineralogical makeup, particle shape, fresh properties, and compatibility over time with the cementitious binder. The quest for sustainable substitutes to natural river sand has emerged as an important trend in the study of cement mortar, as construction expansion is still growing at a fast pace and the mining of sand leads to the destruction of the ecosystem, instabilities in the riverbeds and changes in groundwater composition. It is henceforth that the investigation of fine aggregate substitution has turned to waste from various industries, recyclable material, mining waste, and mineral processing residues which can help maintain mortar performance with minimal impact on the environment. However, the assessment of the sustainability of the fine aggregates to be used in mortars requires more than just compressive strength test, but also includes an analysis of the properties of fresh concrete and even microstructural stability among others [11, 12, 17].

2.1. Other Materials for Fine Aggregates in Cement Mortar

The various waste products have been explored as possible substitutes for river sand in cement pastes. The recycled sand from sandstone waste was found to be an excellent alternative owing to the well-defined particle size distribution and high silica content in the minerals, leading to consistent mortar strength with optimal mixes [1]. Sandstone waste employed in biomineralized mortar systems was also noted to have good packing and satisfactory mechanical behavior under normal curing conditions [5]. In addition, sandstone sand derived from excavated waste was found to yield mortar with good workability and consistency provided that water consumption is adequately regulated [15]. Kaolin tailing sand has also been identified as an eco-friendly replacement due to mineral compatibility and reduced environmental impact, providing satisfactory engineering properties similar to sand-based mortars [18]. despite the satisfactory performance of engineering behavior exhibited by some of these recycled fine aggregates, it is important to note that the materials examined in these studies are quite different from overburden sand in terms of their mineralogy, particle shape, water absorption, and surface properties. Therefore, the results of these studies cannot be applied directly to overburden sand produced from lignite mining operations.

2.2. Industrial and Secondary Waste in Mortar Mixes

The usage of industrial waste products has also proven to be highly effective in mortar manufacture. The incorporation of pond ash in cement mortar mixes showed favorable results with proper replacement ratios providing acceptable properties without compromising the material cost and minimizing waste disposal [2]. Fly ash along with waste concrete powder combination has also been proven useful in producing cleaner masonry mortars with stable hardened performance [3]. The combination of recycled concrete powder with metakaolin enhanced the performance due to better internal porosity [4].

Fly ash made from pulverized coal along with the circulating fluidized bed fly ash combination in ternary eco-binder mortar mixes improved cementation properties and performance, particularly when using optimized binder ratios [7]. The importance of material characterization and mixture proportioning to achieve effective use of industrial byproducts has also been highlighted by recent research work. However, most of the studies were concerned with the evaluation of hardened properties only, and few studies attempted to evaluate the properties incorporating fresh state behavior and microstructure.

2.3. Mortar Strength Affected by Binder and Other Additives

The various investigations on the development of mortar strength under different binder systems were conducted to assess the effects of hydration compatibility and matrix densification. PCM cement mortar exhibits increased compressive strength due to phase dispersion and curing performance. Silica fume mortar has enhanced strength properties along with low water absorption caused by pozzolanic reactions. The age-related strength behavior was observed for alkali activated geopolymer mortar due to significant hydration and polymerization effects. Fly ash and powdered granulated blast furnace slag geopolymer paste demonstrated binder composition as a significant factor influencing compressive strength formation under different curing processes. Graphene oxide nanosheets mixed with blast furnace slag also revealed the effect on mortar durability properties through microstructural improvement. These investigations, while mostly involving binder alteration, show that mortar strength is very dependent on interactions between particles within mortar, which can be as important for the substitution of fine aggregate materials as well. Though there is much improvement of binder systems in terms of mechanical properties, aggregate properties are still dominant in terms of particle packing, water requirements, and formation of interface transition zones. For this reason, it is equally essential to know about the mineralogy of aggregates.

2.4. Utilization of Mine Wastes and Overburden Sand

Mine wastes have recently shown great potential as an environmentally friendly source of fine aggregate due to their high waste generation rate and relatively limited uses. The first research related to this type of mine waste involves employing Coal mine overburden soft shale as a regulated low-strength material, indicating that mining waste material can be used in cement applications [6]. Further research explored this approach from a different perspective, applying mine waste to concrete and mortar preparation. The use of coal mine overburden waste rock as fine and coarse aggregate shows appropriate corrosion resistance and matrix behavior in cement-based products [7]. Furthermore, the direct application of coal mine overburden as a sustainable fine aggregate for use in cement mortar proved the ability of achieving compressive strength comparable to conventional mortar through suitable treatment [8]. The application of mine overburden sand in fly ash masonry mortar proved that such an application is feasible in terms of mechanical behavior and consistency [9]. In addition, recent research conducted on using overburden sand along with coal bottom ash showed promising results, particularly concerning mechanical characterizes, improved durability, and life cycle evaluation [10]. In spite of the encouraging engineering characteristics associated with aggregates obtained from mines, little research has been done to optimize their performance before determining replacement ratios. In addition, very few researchers have worked on overburden sand extracted from lignite mines

2.5. Fresh State Characteristics of Alternate Aggregate Mortars

Workability still plays an important role in evaluating alternate aggregate materials because compaction, pore distribution, and effectiveness of chemical reactions all depend on this parameter. The most common test method involves flow table assessment of the spread of the mortar at a certain water content in accordance with the relevant standards [11]. Mortar made of waste materials characterized by angular shapes demonstrated poorer spreading results due to higher internal friction and greater water requirement. Recycled aggregate mortars based on waste road materials had poor workability when compared to traditional mortars owing to poor flowability caused by irregular particles [13]. Recycled concrete powder mortars behaved similarly with particle fineness significantly affecting mortar properties both in a fresh and hardened state [4, 14]. Higher water requirement was also observed in lignite bottom ash mortars due to water absorption by porous surfaces of fine aggregates. The fresh density test is equally significant since it shows the packing characteristics and trapped air inside the fresh mortars [12]. The standard density and water absorption tests will be highly crucial in assessing the impacts of aggregate substitution in mortars [12]. All the research works done in the past on workability have been based on one type of test procedure only. Only a few researchers have taken into consideration flow table spread, Marsh cone discharge time, and fresh density to determine the optimum water-cement ratio prior to replacement tests.

2.6. Microstructural Analysis of Mortar Materials

Microstructural analysis is now considered a critical tool in sustainable mortar investigation due to the impact of aggregate mineralogy on mortar properties. X-ray diffraction is usually employed for the identification of crystalline phases including quartz, feldspar, calcite, and aluminosilicate minerals in substitute aggregates. In general, aggregates composed mainly of quartz exhibit good inertness and compatibility in cement mortars [5, 15]. The scanning electron microscope provides information about the morphology of particles including their geometry, angularity, surface roughness, and texture. In an investigation conducted using mortar containing recycled aggregate from scrap roads, a higher surface roughness was found to enhance interlocking but increase water requirement [13]. Another SEM study was carried out on the microstructure of mortar reinforced with wood fiber waste under various curing conditions [16]. Energy dispersive spectroscopy serves as a supplement to scanning electron microscopy in providing details on elemental composition, which includes silica, alumina, calcium, iron, and alkalis. Despite the widespread use of SEM-EDS analysis in the examination of alternative aggregates, the correlations among the composition of elements, particle shapes, behavior, and engineering properties of beneficiated overburden sands are not sufficiently investigated yet. Further studies are thus needed in order to explore these correlations fully.

2.7. Mechanical Properties and Standardized Mortar Assessment

Compression resistance continues to be the key criterion in mortar investigations, and its assessment is carried out following standard procedures for hydraulic cement mortars [1]. The standard mechanical assessment method provides an accurate basis for comparing traditional and non-traditional aggregate mixes. Investigations confirm that mortar compressive strength significantly relies on fresh mortar workability and particle packing, regardless of the aggregate source [4, 8].

2.8. Gap in Literature

Despite many fine aggregates made from waste having been analyzed, several research gaps are still left uncovered. Many studies consider either just the compressive strength or replacement ratios that have not achieved optimization for fresh state properties at various water-cement proportions [8-10]. In some cases, mineralogical analysis is missing; hence it becomes hard to understand any observed trends in terms of compressive strength. Very few studies consider the combined use of XRD, SEM, EDS, behavior using a flow table, Marsh cone discharge time, fresh state density, and compressive strength all in a single experiment setup for overburden sand. Therefore, there is a need for further research in the areas of mineralogy of the aggregate and how it affects the fresh state properties.

The innovation of the current research work is associated with the holistic study of processed overburden sand by employing a holistic experimental approach that includes mineralogy-based analysis, microstructure analysis, fresh-state properties analysis, and mechanical properties analysis. In contrast to the previous research works that focused more on engineering properties individually, the current research work presents the link between mineralogy-based analysis, SEM-EDS analysis, fresh-state properties, and compressive strength development. The study also demonstrates the viability of employing processed lignite mine overburden sand as an eco-friendly substitute to natural river sand in cement mortar.

The significant strides have been made in the development of sustainable substitutes for river sand; there are still notable gaps in research that exist. Most of the earlier studies have been confined to the study of compressive strength or limited replacement of sand without optimizing the fresh state properties at varying water-cement ratios. Besides, very little has been done in terms of studying material characterization, SEM-EDS analysis, fresh state properties, and mechanical performance together in one experiment with respect to processed overburden sand obtained from lignite mining. It can thus be stated that the impact of aggregate mineralogy and aggregate shape on engineering behavior has not been studied comprehensively. Thus, an all-inclusive study on these aspects is needed to determine its engineering feasibility.

3. Materials and Methods

The experimental programme was devised for the purpose of assessing the engineering suitability of processed overburden sand as sustainable fine aggregate via a comprehensive two-stage experiment. Stage 1 involved the determination of the optimum water-cement proportion via the study of fresh state behaviour of control and full-replacement mortars. Stage 2 entailed the consequence of adding processed overburden sand on the compression strength and microstructural behavior of mortar specimens using the optimum water-cement ratio obtained from stage 1. The experimental approach adopted enhanced consistency in the evaluation of mechanical behavior under similar fresh state conditions. A series of experiments were carried out to determine the viability of Overburden Sand (OBS) as a sustainable alternative to River Sand (RS) as a fine aggregate in cement mortar. The tests comprised material characterization, fresh state characteristics testing, and compression testing. This was completed in two phases. In the first step, standard river sand cement mortar and full overburden sand cement mortar were treated with water-cement ratios ranging from 0.4 to 0.8 to establish the optimum performance in terms of fresh state properties. Stage two entailed replacing RS with OBS cement mortar at various percentage levels starting from 0 percent all the way to 100 percent at the optimum water-cement ratio established in stage one.

3.1. Materials Used

The major binder material utilized in the study was Ordinary Portland Cement of 43 grade, which met the specifications of Indian Standard (IS) 269: 2015 - Ordinary Portland Cement—Specification [19]. The physical parameters of the cement are shown in Table 1. The fine aggregate utilized in this experimentation was processed from overburden materials sourced from lignite mines in Neyveli region of Tamil Nadu. The processing included crushing, washing, sieving, drying and grading operations to separate the sand fraction and achieve a gradation comparable to natural fine aggregates. This fine aggregate thus obtained will be henceforth called Processed Overburden Sand (OBS). Natural fine aggregate was made from River Sand (RS), which was readily available locally. Figure 1 depicts the tiny aggregates employed in the investigation. The physical properties of the fine aggregates used in the experiment were determined in accordance with appropriate Indian standards. The particle size distribution and percentage of material finer than 0.075 mm for Processed Overburden Sand (OBS) and River Sand (RS) were determined using IS 2386 (Part 1) [20]. The fineness modulus was computed by combining the cumulative retained mass results from sieve analysis using IS sieves ranging in size from 10 mm to 0.150 mm. The specific gravity, water absorption, and bulk density of the fine aggregates were determined using the techniques described in IS 2386 (Part 3) [21]. These tests are very important to understand their effect on performance of OBS as fine aggregate at various replacement levels on mortar properties. From previous literature, it has been observed that controlled grading of overburden materials mined from the earth is necessary for ensuring proper packing, minimizing generation of fines, and suitability with the cementitious medium. It has been seen that proper processing of overburden materials increases their suitability as a substitute of fine aggregates through obtaining better grading. In the current research work, processing was performed with an objective to achieve a fine aggregate fraction that can be used in mortar mix design and hence evaluate the suitability of OBS as another source of natural river sand in mortar mixes at various substitution levels. RS was used as a reference fine aggregate for mortar mixes in this experimentation. The use of processed overburden sand from lignite mines as an alternative fine aggregate in mortar and concrete overcomes the paucity of river sand while also promoting sustainable mining practices. Tables 2 and 3 display the particle size distribution and other physical parameters of OBS. Tables 4 and 5 show the gradation and physical properties of RS consistently. Before the specimen preparation process, all the fine aggregates used were subjected to grading and moisture uniformity for reduced variation. Characterization of the material was done before the mixture preparation because it was important that their properties be considered in understanding the fresh state and mechanical behavior.

Figure 2 shows the visual comparison of OBS-RS blends at different replacement levels of RS by OBS. The replacement levels are 20%, 40%, 60% and 80 %. The figure depicts the variation in particle texture and color with changing proportions. The gradation curves of OBS and RS along with blends at various replacement levels are shown in Figure 3 which satisfy the Zone II grading requirements of IS 383:2016 [22], confirming their suitability as fine aggregates for mortar and concrete applications.

Table 1. Physical properties of Ordinary Portland Cement (OPC 43 Grade)

S.No	Characteristics	Value
1	Consistency (in %)	28.5
2	Setting time (in minutes)	
3	Initial	125
	Final	205
4	Specific gravity	3.12

5	Compressive strength (in MPa) with Tamil Nadu Minerals Limited (TAMIN) Sand	
	3 days	26.5
	7 days	38.5
	28 days	50.5
6	Fineness in Air Permeability (m^2/kg)	324.7

Table 2. Particle size distribution of Processed Overburden Sand (OBS) and compliance with IS 383:2016 Zone II grading requirements

Sieve Size (mm)	Passed %	Zone-II standards as per IS 383: 2016 [22]
10	100	100
4.75	99	90-100
2.36	92	75-100
1.18	81	55-90
0.6	53	35-59
0.3	24	8 to 30
0.15	2	0-20

Table 3. Physical properties of Processed Overburden Sand (OBS) fine aggregate

Characteristics		Value
Specific gravity		2.48
Fineness modulus		2.49
Grading zone		II
Water absorption	%	2.82
Bulk density (loose)	kg/l	1.49
Bulk density (Voids Removed)	kg/l	1.64
Materials finer than 75 microns	%	3.5

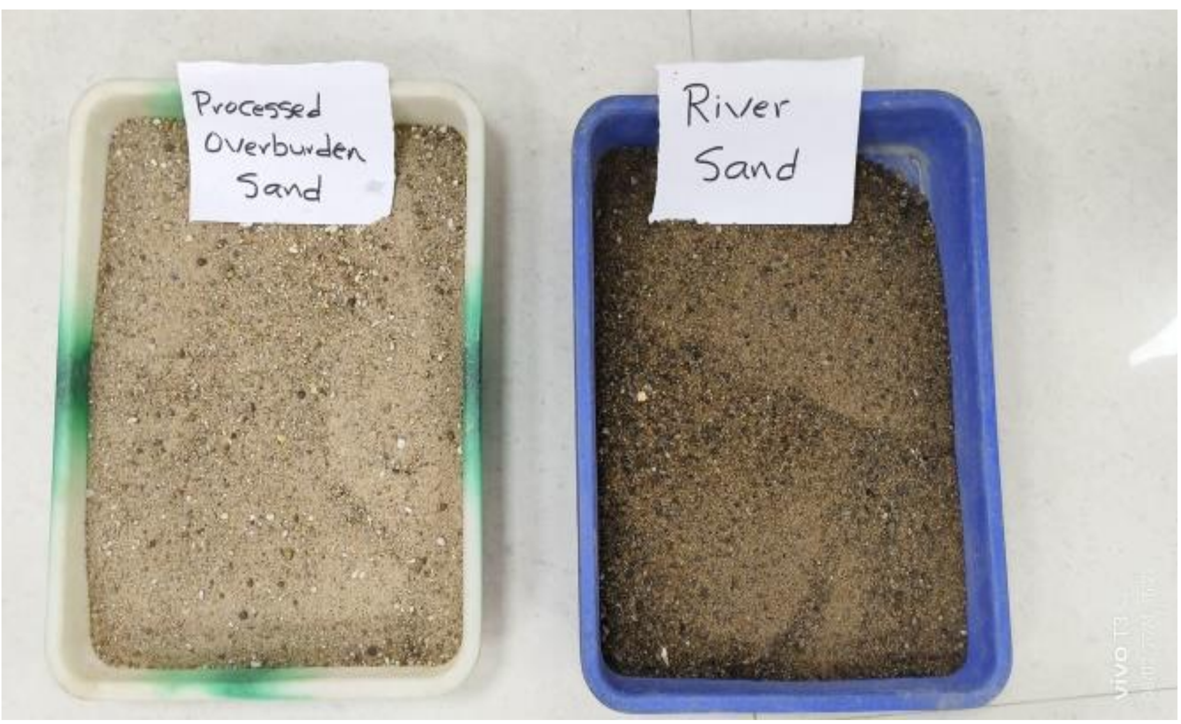

Fig. 1 Processed Overburden Sand (OBS) and Natural River Sand (RS) fine aggregates

Table 4. Natural River Sand (RS) particle size distribution and compliance with IS 383:2016 Zone II grading requirements

Sieve Size (mm)	Passed %	Zone-II standards as per IS 383: 2016 [22]
10	100	100
4.75	98	90-100
2.36	89	75-100
1.18	72	55-90
0.6	38	35-59
0.3	15	8 to 30
0.15	3	0-20

Table 5. Physical properties of Natural River Sand (RS) fine aggregate

Characteristics		Value
Specific gravity		2.66
Fineness modulus		2.85
Grading zone		II
Water absorption	%	0.68
Bulk density (loose)	kg/l	1.66
Bulk density (Voids Removed)	kg/l	1.8
Materials finer than 75 microns	%	1.9

(a) (b) (c) (d) (e) (f)

Fig. 2 Visual comparison of fine aggregate blends with varying proportions of Processed Overburden Sand (OBS) and River Sand (RS): (a) 100% OBS, (b) 80% OBS + 20% RS, (c) 60% OBS + 40% RS, (d) 40% OBS + 60% RS, (e) 20% OBS + 80% RS, and (f) 100% RS.

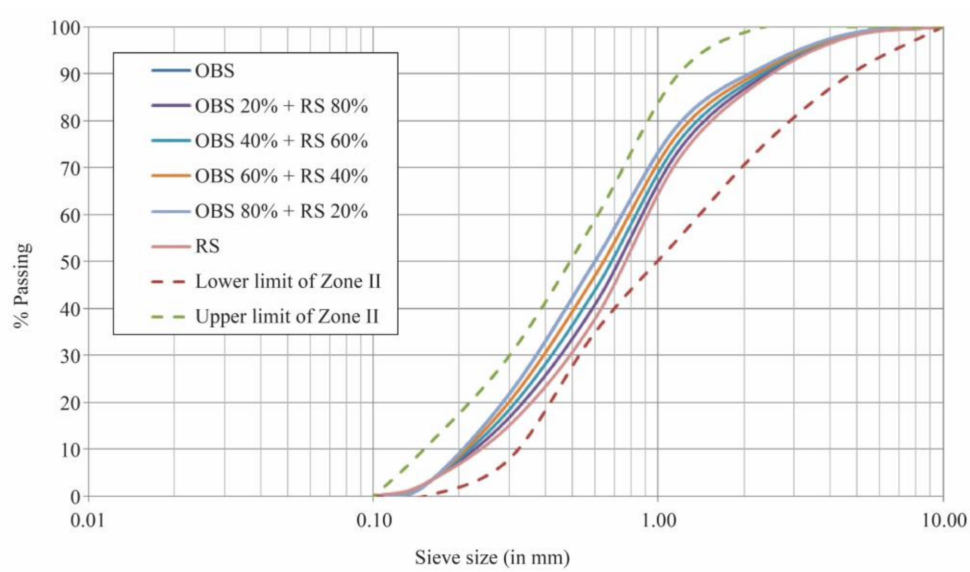

Fig. 3 Gradation curves of Processed Overburden Sand (OBS) and Natural River Sand (RS)

3.2. Mineralogical and Microstructural Characterization of Fine Aggregate

Prior to the fabrication of mortar specimens, both the river sand and overburden sand were analyzed using the mineralogical and microstructural analyses to obtain information about the crystalline phases, morphology, and chemical composition. The first method applied was X-ray Diffraction (XRD). It was observed that river sand had strong crystalline peaks of silica minerals, implying its high content of quartz minerals, while the overburden sand contained silica minerals with some aluminosilicates and iron minerals. The second analysis method was Scanning Electron Microscopy (SEM). In terms of their morphology, river sand particles appeared to have smoother surfaces and rounded shapes, whereas overburden sand particles were angular with irregular textures and rough surfaces. At the same time, Energy-Dispersive Spectroscopy (EDS) was employed to find out the configurations of the examined samples. It was determined that both types of sand included silica minerals; however, the latter type of sand also included aluminum, iron, and alkali elements.

3.3. Mixing Ratio and Sample Identification

The experiment was carried out in two stages. Stage 1 was carried out to establish the optimum water-cement ratio from the testing of the control river sand mortar and overburden sand mortar based on their fresh properties and compression strength. The details of stage 1 with water-cement proportions varying from 0.4 to 0.8 are shown in Table 6. Stage 2 was carried out using the optimum water-cement ratio established from Stage 1 to study the substitution of river sand with overburden sand. The chosen replacement percentages of 0%, 20%, 40%, 60%, 80%, and 100% will assist in systematic analysis of engineering properties across the entire replacement percentage range, and the optimum percentage of replacement can be established easily. The use of uniform replacement percentage intervals will assist in comparative study of engineering properties.

Table 6. Stage 1 Water–cement ratio optimization for control and full replacement mortar

S. No.	Specimen ID	River Sand (%)	Processed Overburden Sand (%)	Water–Cement Ratio
1	CM-RS-0.4	100	0	0.4
2	CM-RS-0.5	100	0	0.5
3	CM-RS-0.6	100	0	0.6
4	CM-RS-0.7	100	0	0.7
5	CM-RS-0.8	100	0	0.8
6	CM-OBS-0.4	0	100	0.4
7	CM-OBS-0.5	0	100	0.5
8	CM-OBS-0.6	0	100	0.6
9	CM-OBS-0.7	0	100	0.7
10	CM-OBS-0.8	0	100	0.8

Table 7. Stage 2 Replacement-level study at optimum water–cement ratio

S. No.	Mix ID	River Sand (%)	Processed Overburden Sand (%)	Water–Cement Ratio
1	CM-R100	100	0	0.6
2	CM-R80-O20	80	20	0.6
3	CM-R60-O40	60	40	0.6
4	CM-R40-O60	40	60	0.6
5	CM-R20-O80	20	80	0.6
6	CM-O100	0	100	0.6

All of the mixes had a set cement-to-fine aggregate proportion of 1:2.75. Because the water-cement proportion was discovered to have a substantial effect on fresh mortar qualities in Stage 1, a water-cement proportion of 0.6 was chosen for replacement analysis in Stage 2 to ensure consistent workability across all fresh mixes. Table 7 contains the details.

3.4. Fresh-State Testing Procedure

The testing of fresh state properties was carried out immediately after mixing with three independent testing procedures which were flow table spread test, Marsh cone discharge test, and measurement of fresh mortar density. In the case of all fresh-state tests, they were carried out right after mixing and under similar laboratory conditions so that time should not affect the workability test results. All tests were done according to standard procedures.

3.4.1. Flow Table Test

The procedure for flow table testing was done as per the mortar spread test procedure [11]. The fresh mortar was filled in a flow mold, which was subjected to lifting and impact in controlled cycles. The spread diameter was taken in millimeters and flow percentage calculated as a fraction of mold diameter. This test procedure was mainly utilized to analyze the variation in workability of river sand mortar and overburden sand mortar at different water-cement ratios.

3.4.2. Marsh Cone Test

Discharge test of Marsh cone following [23] was done to assess the discharge time and relative viscosity of the fresh cement paste. The discharge time was noted in seconds, which took place from start to end of discharge.

3.4.3. Fresh Density test

Test for Fresh density for fresh mortar mixture was conducted following conventional density determination procedure [4, 12]. Fresh mortar was poured into a known volume container and then the mass of the mortar mixture is weighed in order to determine density expressed as kg/m³. Combination of the above-mentioned test results made it possible to choose the most optimal value of the water/cement proportion based on the consistency rather than the arbitrary water content.

3.5. Compressive Strength Test

Compression strength tests were conducted by casting mortar cubes of 50 mm size at three curing ages of 3rd, 7th and 28th day as per recommended procedure of hydraulic cement mortar testing [24]. Mortar samples were molded, compacted, demolded after initial set, and then cured in laboratory for specified period before testing. First stage involved tests for comparison of river sand mortar with overburden sand mortar at different water/cement ratio values. The most optimal water/cement ratio value was chosen based on previous test results. Second stage consisted of tests for mortar samples containing overburden sand at 3rd, 7th and 28th day of curing period. Values were derived as the average of three independently prepared samples. The variation in experiments was analyzed by using statistical measures that have been discussed in the Results section.

3.6. Microstructural Characterization of Stage 2 Mixes

Following the compression strength test, mortar specimens formulated with the optimal water-to-cement ratio of 0.6 from Stage 2 were analyzed using Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS) to determine the impact of replacing overburden sand on the mortar's hardened microstructure. The samples used for microstructural analysis include CM-R100, CM-R80-O20, CM-R60-O40, CM-R40-O60, CM-R20-O80, and CM-O100. SEM analysis investigated the morphological characteristics of the matrix, porosity, and aggregate-paste interface. EDS analysis quantified the elemental composition, especially those of silica, calcium, alumina, and iron. The study of microstructure was done following mechanical testing in order to correlate aggregate morphology, elemental composition, hydration properties, and compressive strength. The results of SEM and EDS elemental analysis were combined to better understand the technical behavior of mortar formed from processed overburden sand.

3.7. Statistical Analysis

The statistical analysis was conducted to determine the consistency and reliability of the experimental data. Statistical metrics such as the arithmetic mean, standard deviation, and coefficient of variation were computed from experimental data on the materials' fresh state and mechanical properties. The statistical parameter values for the various replacement percentages were used in the comparative study.

4. Mineralogical and Elemental Composition of Aggregates via SEM-EDS

Material characterization was carried out to identify the mineralogical composition, surface structure, and elemental constitution of the two fine aggregates tested in the current study. Before producing the samples, river sand and overburden sand were tested to determine the qualities that may affect workability, water demand, particle packing, and cement-aggregate bonding. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were used to determine surface structure and element composition.

4.1. River Sand SEM-EDS

River sand has been chosen for use in mortar mixes as the control fine aggregate due to its popular usage in cement mortar and its known performance under standard mixing techniques. Prior to incorporating river sand into mortar production, various characterizations were conducted on the material to understand its properties. SEM-EDS was used to determine the morphology and proportions of the sample. The qualities of river sand must be studied since they directly affect the workability, water demand, and compressive strength of cement paste. Figure 4 shows a SEM picture of RS at 10,000× magnification. The SEM image of river sand indicates that there are many particles with a smoother surface and irregularly shaped sub-rounded grains. The minimal surface roughness and particle packing imply that internal friction is low, making it easier to handle when mixing cement mortar.

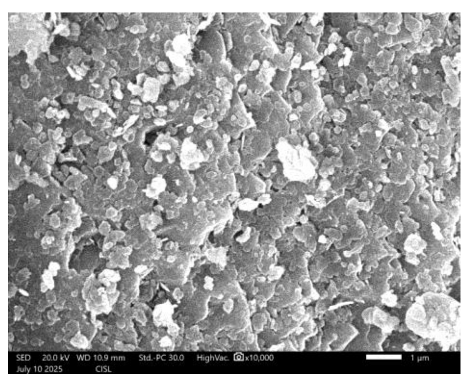

Fig. 4 SEM image of natural river sand showing particle morphology and surface texture at 10,000× magnification

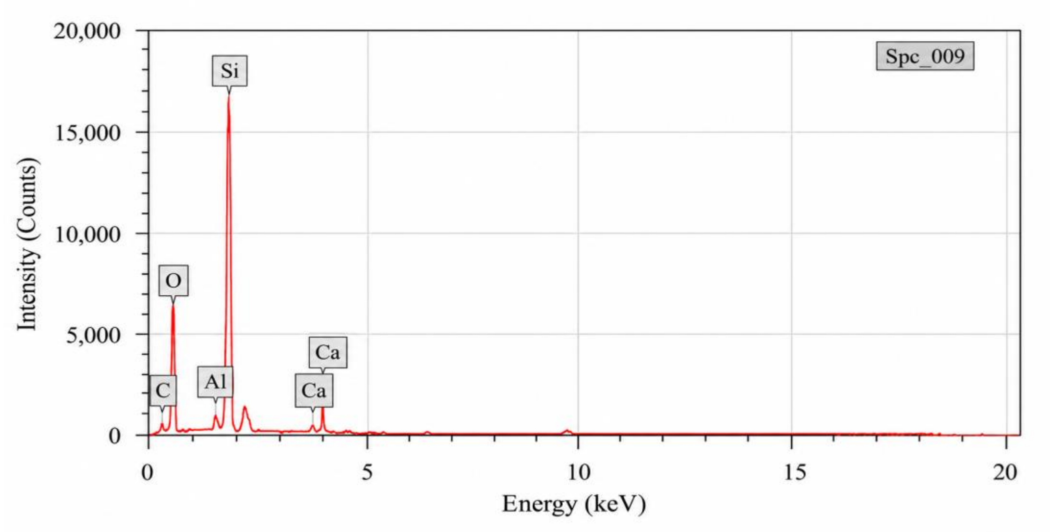

Fig. 5 EDS of natural river sand

Table 8. Elemental composition of natural river sand from EDS analysis

Element	Line	Mass %	Atom %
C	K	10.78 ± 0.17	16.96 ± 0.26
O	K	45.48 ± 0.24	53.71 ± 0.29
Al	K	1.33 ± 0.04	0.93 ± 0.02
Si	K	41.79 ± 0.17	28.11 ± 0.11
Ca	K	0.62 ± 0.03	0.29 ± 0.01

The dominance of oxygen (45.48 wt.%) and silicon (41.79 wt.%) demonstrates that the main mineral component of natural river sand is quartz. The relatively small presence of aluminium and calcium proves that the mineralogical heterogeneity of this type of sand is not significant, which leads to its nonreactivity during cement hydration. High SiO2 composition and smooth shape of particles result in reduced water requirement, good mobility and proper packing of particles in the mixture.

Figure 5 shows the elemental composition of RS from EDS analysis. The quantitative elemental composition of the natural river sand as identified using EDS analysis has been specified in Table 8. It has been understood from the table that oxygen (45.48%) and silicon (41.79%) constitute the major elemental components of the aggregate. The presence of the higher percentage of Si-O compounds indicates that quartz acts as the primary mineral phase. This is further supported by the fact that these minerals are generally considered to be chemically inert and hence are used as fine aggregates in cement mortar. Aluminum (1.33%) and Calcium (0.62%) occur in trace amounts as reported in Table 8.

4.2. SEM-EDS of Processed Overburden Sand

The processed overburden sand was characterized before preparing mortar in order to investigate whether this overburden sand can serve as an alternate fine aggregate for producing sustainable cement mortars. In the case of overburden sand, since it comes from mining waste deposits, the mineralogical makeup and surface structure of this sand vary considerably from normal river sand, which might have an impact on mortar behavior. The particle texture and elemental analysis of this sand were analyzed using the SEM and EDS techniques.

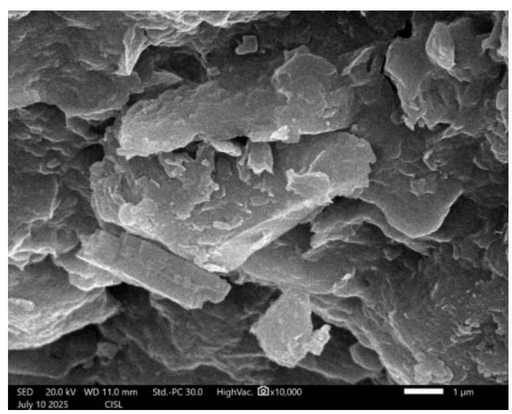

Fig. 6 SEM image of processed Overburden Sand

The morphology of the treated overburden sand is shown in Figure 6 and has a very characteristic angular shape with sharp and cracked edges and also a highly textured surface. This morphology leads to high surface roughness, hence high friction between particles, which explains the excess water required for flowability.

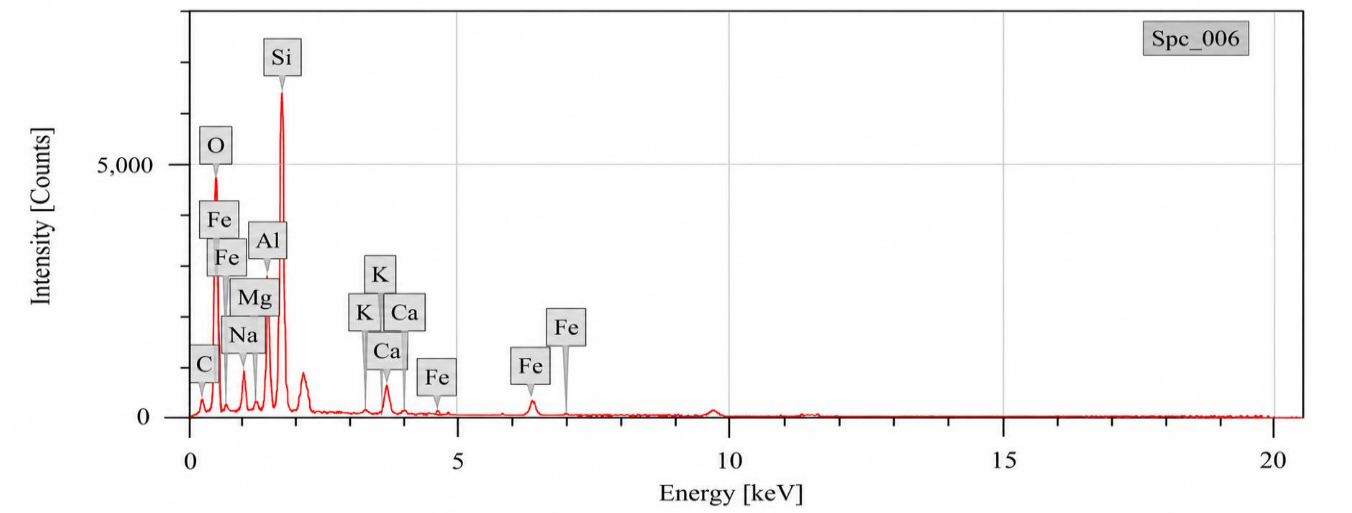

Fig. 7 EDS of Processed Overburden Sand

Table 9. Elemental composition of processed Overburden Sand from EDS analysis

Element	Line	Mass %	Atom %
C	K	11.22 ± 0.16	17.89 ± 0.25
O	K	44.03 ± 0.26	52.72 ± 0.31
Na	K	3.51 ± 0.07	2.93 ± 0.06
Mg	K	0.79 ± 0.03	0.62 ± 0.03
Al	K	9.23 ± 0.09	6.55 ± 0.07
Si	K	23.72 ± 0.15	16.18 ± 0.10
K	K	0.44 ± 0.03	0.22 ± 0.01
Ca	K	3.47 ± 0.07	1.66 ± 0.03
Fe	K	3.60 ± 0.09	1.23 ± 0.03

Figure 7 shows the elemental composition of OBS from EDS analysis. The elemental composition of overburden sand is listed in Table 9, which was analyzed using energy dispersive spectroscopy, and oxygen (44.03%) and silicon (23.72%) are present in higher percentages, demonstrating the dominance of silica-based minerals. It has been observed that higher amounts of aluminum (9.23%), iron (3.60%), sodium (3.51%), and calcium (3.47%) in comparison to river sand imply that overburden contains alumino-silicate and iron minerals.

4.3. Descriptive Statistics of Experimental Data

To evaluate the repeatability and reproducibility of the experimental results, a statistical analysis of the physical and mechanical attributes in fresh and hardened states was conducted. If the experiments had been repeated, the average value, standard deviation, and coefficient of variation were computed. These statistical factors enabled us to evaluate the variability of the experimental data. A comparison of the SEM–EDS observations for river sand and processed overburden sand demonstrates that differences in engineering behavior are primarily governed by particle morphology and elemental composition. River sand exhibited relatively smooth and rounded particles, promoting improved packing density and reduced internal friction during mixing. In contrast, processed overburden sand contained angular particles with rough surface textures, increasing water demand and reducing fresh-state flowability. However, despite these morphological differences, the mineralogical compatibility of processed overburden sand with the cement matrix enabled satisfactory strength development, indicating its suitability as an alternative fine aggregate. From an engineering perspective, the SEM-EDS analysis verifies that the variability in fresh state behavior and compressive strength is justified by the mineralogical and morphological features of the studied aggregates. The joint analysis of SEM morphology and chemical composition explains the obtained results from the point of mechanics of materials instead of purely engineering-based performance evaluation. It increases the reliability of using processed overburden sand for sustainable mortar production.

5. Fresh State Performance Testing

Tests for fresh state performance were conducted to assess the impact that water-cement ratio and aggregates had on the consistency of the mortar before testing for hardness. Given that the surface parameters of the aggregates had a direct impact on the water requirement, flow table spread, Marsh cone discharging times, and density of fresh mortars were determined for the river sand mortar and overburden mortar, where the water-cement proportion ranged from 0.4 to 0.8.

5.1. Flow Table Test outcomes

The findings of the flow table tests as shown in Table 10 and Figure 8 revealed that consistency increases gradually with increasing water-cement proportions in both river sand and overburden sand systems. River sand mortar indicated dry flow at water-cement proportion of 0.4. This implies that free water is low in this mortar and thus not enough for the particles to flow well. The spread diameter increased to 144 mm with a modified flow value of 44% at a water-cement proportion of 0.5 and increased to 200 mm with a modified flow value of 100% at a water-cement proportion of 0.6.

Increase in the water-cement proportion further to 0.7 and 0.8 resulted in wet flow, which means that excess fluidity occurred, thus poor mortar cohesion. On the other hand, overburden sand mortar yielded low spread diameter values at identical water-cement ratios because of its rough surface texture and angular particles. At a water-cement proportion of 0.5, spread diameter is 109 mm; 0.6, spread diameter is 156 mm; and 0.7, spread diameter is 217 mm.

This was considered acceptable based on conditions generally required for mortar placement. Low spread diameters in overburden sand mortar indicated that there are more internal friction and more water absorption due to rough particle surface. Table 10 shows flow characteristics of control mortar prepared with river sand and Overburden Sand (OBS) at different water–cement ratios.

Table 10. Flow characteristics of control mortar prepared with river sand and Overburden Sand (OBS) at different water–cement ratios

S.No.	Specimen ID	River sand (%)	OBS (%)	w/c ratio	Spread Diameter (in mm)	Flow value (%)
1	CM-RS-0.4	100	0	0.4	100	Dry flow
2	CM-RS-0.5	100	0	0.5	144	44
3	CM-RS-0.6	100	0	0.6	200	100
4	CM-RS-0.7	100	0	0.7	Wet flow	Wet flow
5	CM-RS-0.8	100	0	0.8	Wet flow	Wet flow
6	CM-OBS-0.4	0	100	0.4	100	Dry flow
7	CM-OBS-0.5	0	100	0.5	109	9
8	CM-OBS-0.6	0	100	0.6	156	56
9	CM-OBS-0.7	0	100	0.7	217	117
10	CM-OBS-0.8	0	100	0.8	Wet flow	Wet flow

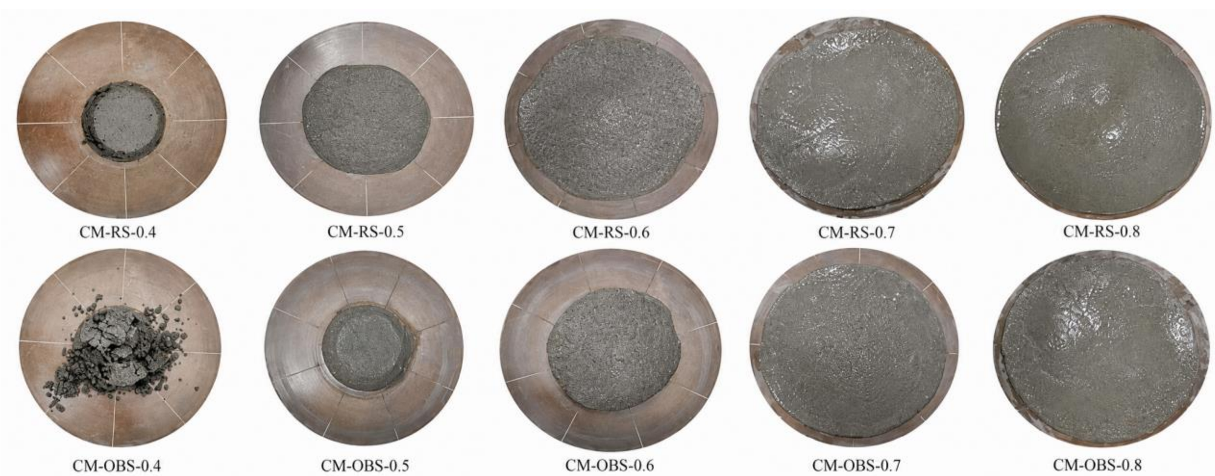

Fig. 8 Mortar spread in the Flow table test

To enhance the reliability and interpretation of the findings from the experiment, descriptive statistical analysis was undertaken on the determined fresh-state properties. The results obtained showed that there were consistent trends relative to the tested water-cement ratio values, suggesting that the test conducted was sufficiently repeatable. The gradual increase in flow diameter with increased water-to-cement ratio supports the hypothesis that availability of water controls particle movement and internal friction in the mortar mix. The relatively low value of flow for processed Overburden Sand (OBS) mortar is due to the angularity and roughness of particles, which lead to an increased demand for water and limited particle movement.

5.2. Results of Marsh Cone Test

Discharge time in Marsh cone test was inversely proportional to the raise in water-cement proportion, showing that viscosity of mortar reduced with the increasing proportion of water in mortar mixture. The river sand mortar showed discharge time of 18.9 s when water–cement ratio was 0.4, decreasing to 12.1 s at 0.5 and 9.1 s at 0.6 w/c ratio. When the amount of water was more, the values were 7.6 s and 6.8 s for 0.7 and 0.8 w/c ratios, respectively. Discharge times of processed overburden sand mortar were obtained to be greater than that of river sand mortar for corresponding ratios, 21.6 s for 0.4, 15.4 s for 0.5 and 12.3 s for 0.6. This clearly shows that overburden sand mortar shows higher resistance to flow due to its angularity. Table 11 and Figure 9 show the results of marsh cone test.

Table 11. Marsh cone test results

S.No	Specimen ID	River sand (%)	OBS (%)	w/c ratio	Marsh cone time (s)
1	CM-RS-0.4	100	0	0.4	18.9
2	CM-RS-0.5	100	0	0.5	12.1
3	CM-RS-0.6	100	0	0.6	9.1
4	CM-RS-0.7	100	0	0.7	7.6
5	CM-RS-0.8	100	0	0.8	6.8
6	CM-OBS-0.4	0	100	0.4	21.6
7	CM-OBS-0.5	0	100	0.5	15.4
8	CM-OBS-0.6	0	100	0.6	12.3
9	CM-OBS-0.7	0	100	0.7	8.8
10	CM-OBS-0.8	0	100	0.8	7.2

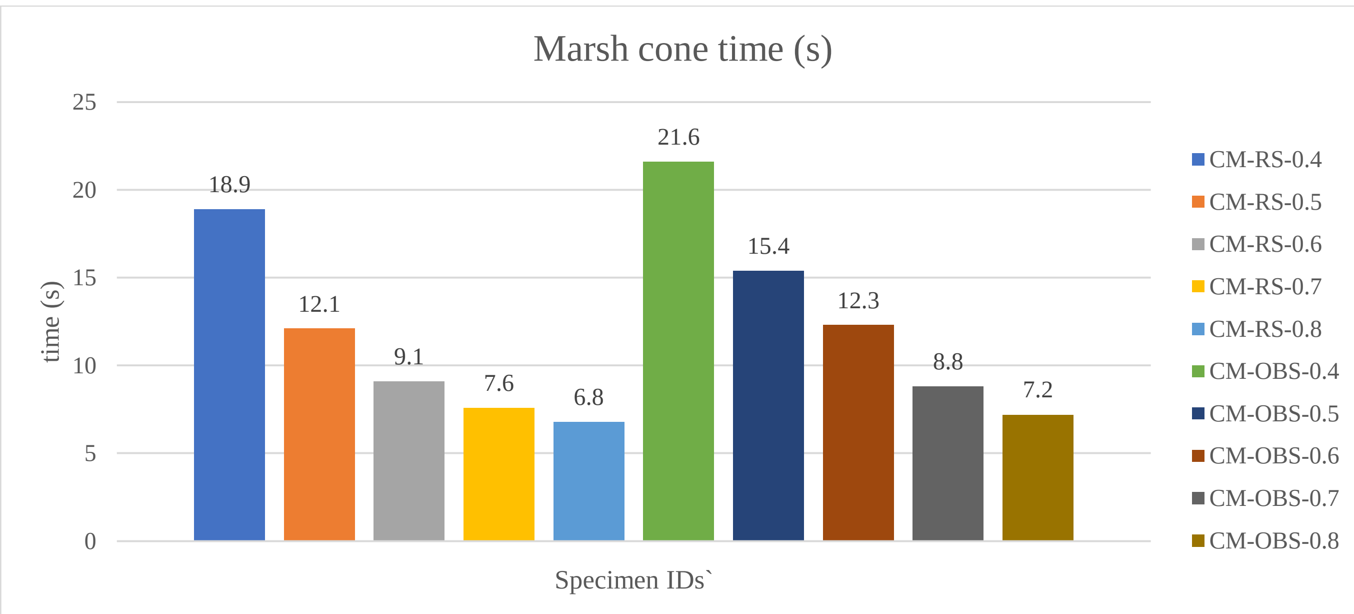

Fig. 9 Variation of Marsh cone time with water–cement ratios

Results of the Marsh cone test served to reaffirm the consistency of the fresh state behavior witnessed during the flow table test. An increase in water-cement proportion leads to a decline in mortar viscosity and flow ability as seen by a gradual decrease in discharge time.

The discharge time for mortars made using overburden sand was always higher compared to those using river sand because of particle angularity, surface roughness and inter-particle friction. These results were consistent throughout the testing procedure.

5.3. Fresh Density Findings

The fresh density reduced gradually with increased water-to-cement proportion in both mortar compositions. The mortar sample with river sand gave fresh densities ranging from 2218 kg/m³ at water-to-cement proportion of 0.4 to 2087 kg/m³ at 0.8, while that of overburden sand mortar ranged from 2189 kg/m³ at 0.4 to 2064 kg/m³ at 0.8. Table 12 and Figure 10 illustrate the impact of water cement ratio on fresh density of mortar. The mortar made with river sand showed slightly greater fresh density compared to the overburden sand mortar at all water-to-cement ratios; this is attributed to better packing as the particles have smoother shapes. The reduction in fresh density in mortar samples with overburden sand was due to poor packing and trapped voids in the aggregate. There were uniform variations in the values of the fresh density due to changes in the types of aggregates used and water-cement ratios. Mortars made from overburden sand had slightly lower fresh densities compared to mortars made from river sand due to poor packing of the aggregates caused by the irregular shapes of particles of the overburden sand. However, there were uniform variations in the acceptable engineering range, implying that processed overburden sand could give uniform mixtures provided that the water-cement ratio is optimal.

Table 12. Fresh density test results

S.No	Specimen ID	River sand (%)	OBS (%)	w/c ratio	Fresh density (kg/m³)
1	CM-RS-0.4	100	0	0.4	2218
2	CM-RS-0.5	100	0	0.5	2186
3	CM-RS-0.6	100	0	0.6	2152
4	CM-RS-0.7	100	0	0.7	2119
5	CM-RS-0.8	100	0	0.8	2087
6	CM-OBS-0.4	0	100	0.4	2189
7	CM-OBS-0.5	0	100	0.5	2158
8	CM-OBS-0.6	0	100	0.6	2126
9	CM-OBS-0.7	0	100	0.7	2095
10	CM-OBS-0.8	0	100	0.8	2064

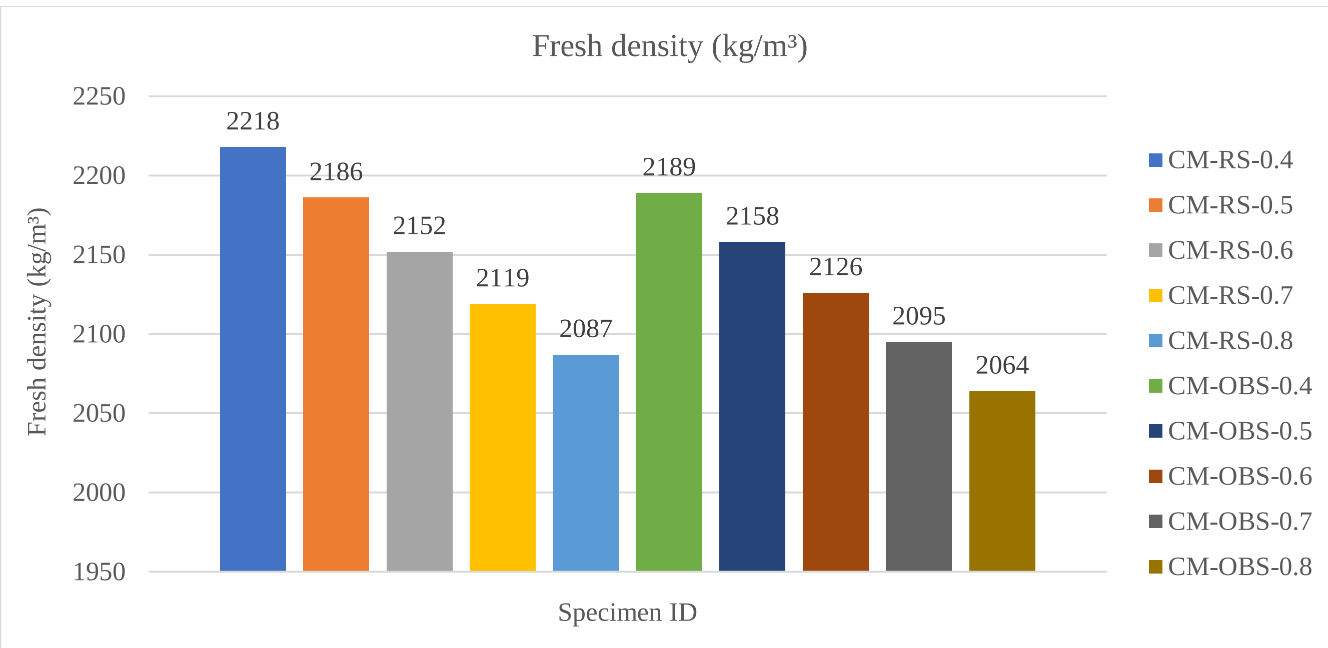

Fig. 10 Fresh density of River Sand and Overburden Sand mortar at different water–cement ratio

6. Mechanical Performance Evaluation

Strength development tests were conducted in order to see how the water-cement proportion and the aggregate substitution affect the strength of the mortar samples. The strength test was conducted after curing for 3, 7, and 28 days.

6.1. Stage-1 Strength with Water-Cement Ratio Changes

The maximum 28th day compression strength of mortar with river sand was recorded at 0.5 water-cement ratio, with 31.8 MPa. Below this, at 0.4 water-cement ratio, strength was less due to insufficient water for effective hydration. Strength started decreasing after 0.5 water-cement proportion. since an increased amount of water increased pore volume.

In mortar cubes incorporating Processed Overburden Sand, the progressive increase in strength was noted up to 0.6 water-cement ratio, with maximum 28-day compressive strength being 27.1 MPa at 0.6 water-cement ratio. Further decrease was noted at 0.7 and 0.8. Strength was less at lower water-cement ratios in overburden sand mortar due to inadequate workability. Table 13 and Figure 11 show the compressive strength results of this stage at varying water cement ratios.

Table 13. Compressive strength of river sand and Overburden Sand mortar at different water–cement ratios

S.No	Specimen ID	w/c ratio	Compression Strength at 3rd day	Compression Strength at 7th day	Compression Strength at 28th day
1	CM-RS-0.4	0.4	6.8	15.3	26.1
2	CM-RS-0.5	0.5	11.5	18.2	31.8
3	CM-RS-0.6	0.6	11.3	17.1	28.8
4	CM-RS-0.7	0.7	7.0	11.6	22.4
5	CM-RS-0.8	0.8	4.9	11.1	21.7
6	CM-OBS-0.4	0.4	5.0	8.3	9.9
7	CM-OBS-0.5	0.5	7.8	12.9	23.6
8	CM-OBS-0.6	0.6	10.3	15.5	27.1
9	CM-OBS-0.7	0.7	6.8	11.1	25.1
10	CM-OBS-0.8	0.8	4.5	6.4	18.1

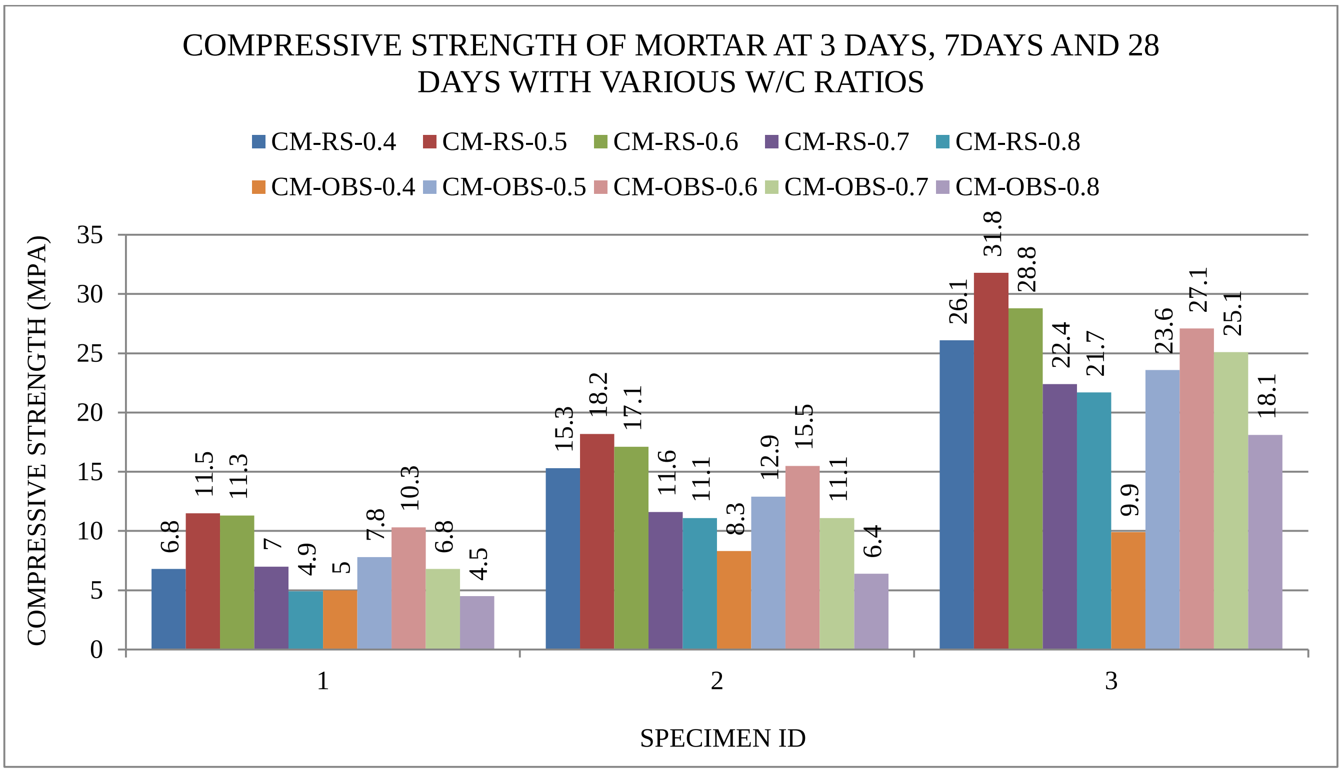

Fig. 11 Compressive strength variation of River Sand and Overburden Sand mortar at different water–cement ratios

Compressive strength test results clearly showed a correlation between the processed overburden sand percentage substitution and the attributes of cement paste. Even though a reduction in compression strength with an increase in substitution ratio occurred, the decrease was moderate and steady throughout the entire experimental procedure.

Optimum water-to-cement ratio found out in the fresh state study helped in the formation of better particle dispersion and aggregate–paste bonding, hence minimizing the compressive strength loss. This implies that processed overburden sand has considerable engineering capacity as a sustainable fine aggregate.

6.2. Strength Development of Mortar with Progressive Overburden Sand Replacement at W/C is 0.6

Stage 2 Compressive Strength Results show a marginal decline in strength with the surge in overburden sand substitution ratio when the water-cement proportion of 0.6 is employed for a balance strength and flow characteristics. CM-R100 had the highest 28-day strength of 28.8 MPa, while CM-O100 had 27.1 MPa, showing that there was a slight decrease in strength. Table 14 and Figure 12 show the compression strength experimentation outcome of this stage at variable substitutions levels of RS by OBS. Comparable observations were made on the third and seventh days, implying consistent hydration throughout all specimens. This implies that the processed overburden sand had sufficient packing efficiency and cement matrix bonding despite having angular grain shape and chemical diversity. These experimental findings from fresh-state and mechanical tests have been explained further using microstructural analysis. SEM and EDS analyses have been conducted to determine the correlation between aggregate structure, elemental composition, and engineering properties. The correlation between the microstructure and the fresh-state behavior and compressive strength will give a better understanding of the behavior of the processed overburden sand mortar.

Table 14. Compressive strength development of replacement mixes at 0.6 water–cement ratio

S.No	Specimen ID	Compressive Strength at 3rd day	Compressive Strength at 7th day	Compressive Strength at 28th day
1	CM-R100	11.3	17.1	28.8
2	CM-R80-O20	11.2	16.4	27.8
3	CM-R60-O40	10.9	16.1	27.5
4	CM-R40-O60	10.5	15.7	27.4
5	CM-R20-O80	10.4	15.6	27.2
6	CM-O100	10.3	15.5	27.1

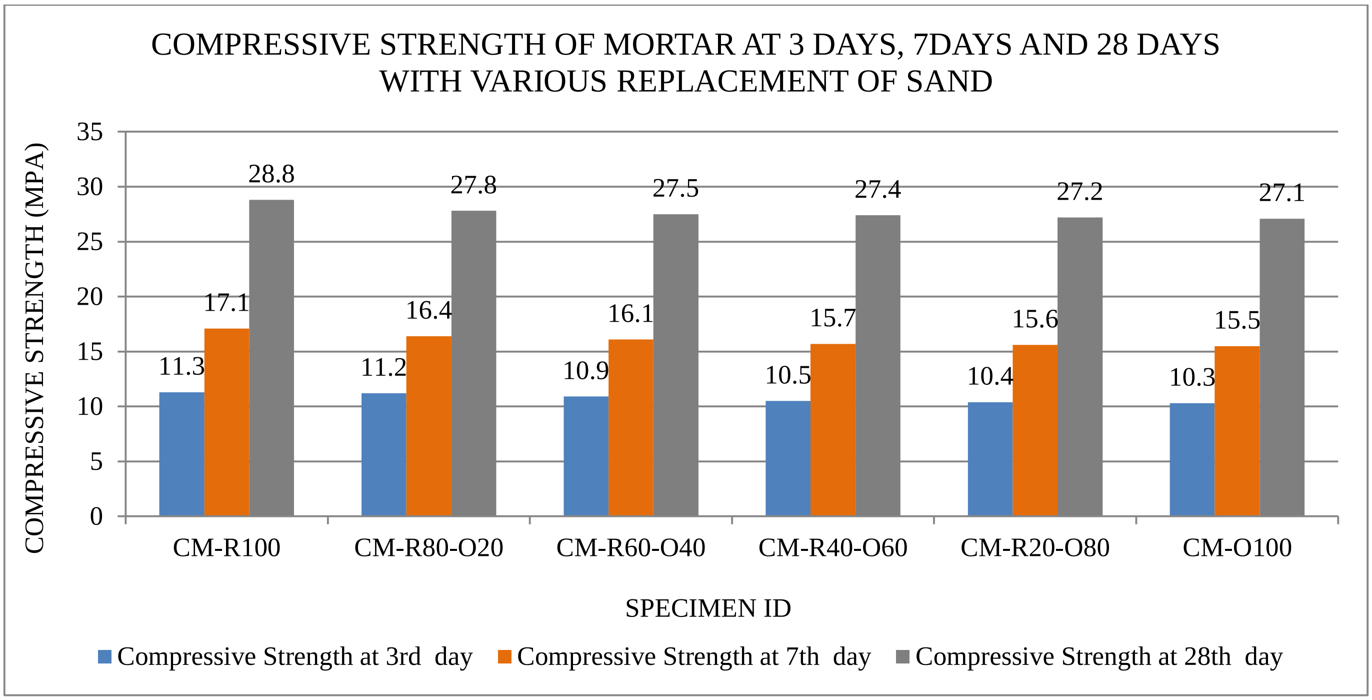

Fig. 12 Compressive strength of replacement mixes at optimum water–cement ratio 0.6

7. Microstructure Analysis of Replacement Mixes through SEM and EDS Techniques

In order to study the impact of increasing overburden sand replacement in the Stage 2 mortar mixes on microstructure formation and elemental analysis, the mixes have been studied using the SEM–EDS technique at an optimal water-cement proportion of 0.6. As there was only a marginal reduction in compressive strengths in the case of different replacement mixes, SEM and EDS studies were conducted on each mix for studying their microstructures and elements.

7.1. SEM-EDS Analysis of CM-R100

Microstructure investigation results of CM-R100 prove the formation of a relatively dense and chemically stable cementitious matrix at an optimal water to cement proportion equal to 0.6. The SEM micrograph of CM-R100 is shown in Figure 13. The respective analysis of EDS results are presented in Figure 14 along with quantitative chemical composition analysis in Table 15. The results show that oxygen and calcium, composing 51.49% and 22.30% of mass, respectively, are prevalent elements, which demonstrates that calcium-containing hydrates form the main components of mortar matrix structure. In addition, considerable silicon content of 9.60% indicates that silicate hydrates form a significant portion of mortar matrix.

From the SEM micrograph of CM-R100, it can be seen that there is an indication of a microstructure that has a denser surface formation, meaning there is good internal particle binding due to effective hydration. The dense morphology of the matrix texture, which is somewhat rough yet continuous, implies successful formation of cementitious gels around the surfaces of the aggregates. At the observed magnification as there are no major visible cracks in the microstructure, which explains relatively higher 28 days compressive strength of CM-R100.

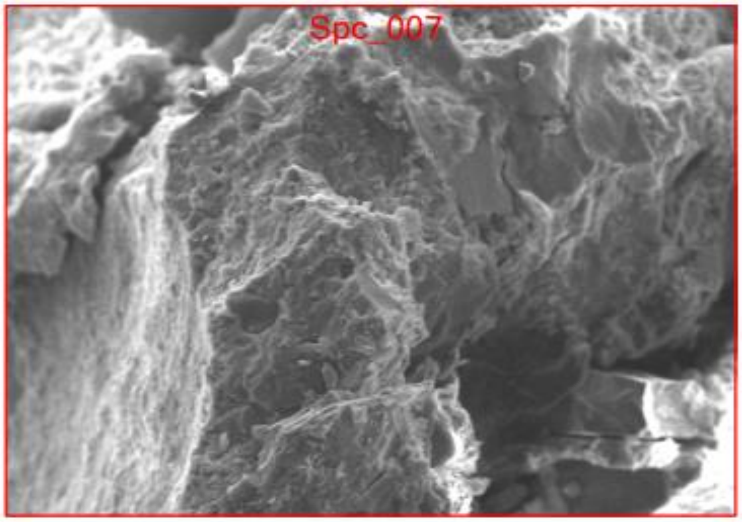

Fig. 13 SEM image of CM-R100 mortar

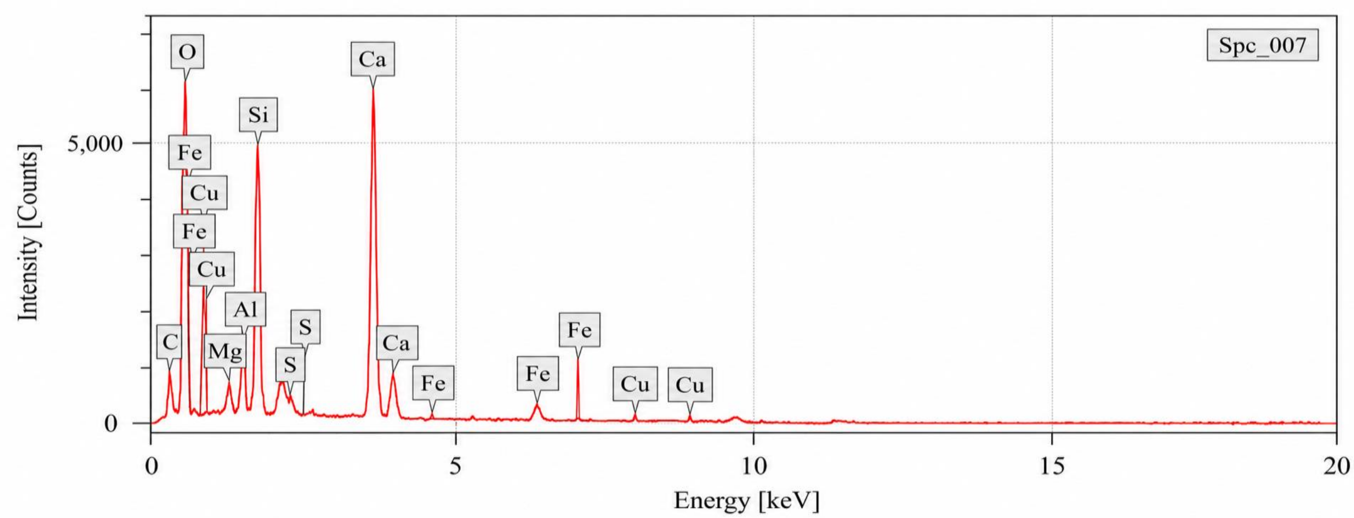

Fig. 14 EDS spectrum of CM-R100 mortar

Table 15. Elemental composition of CM-R100 mortar from EDS analysis

Element	Line	Mass %	Atom %
C	K	9.33 ± 0.08	15.19 ± 0.13
O	K	51.49 ± 0.27	62.94 ± 0.33
Mg	K	1.16 ± 0.03	0.93 ± 0.03
Al	K	3.09 ± 0.05	2.24 ± 0.03
Si	K	9.60 ± 0.07	6.69 ± 0.05
S	K	0.35 ± 0.02	0.21 ± 0.01
Ca	K	22.30 ± 0.12	10.88 ± 0.06
Fe	K	2.25 ± 0.05	0.79 ± 0.02
Cu	K	0.44 ± 0.04	0.13 ± 0.01

7.2. SEM-EDS Analysis of CM-R80-O20

The SEM image of CM-R80-O20 mortar as shown in Figure 15 reveals a tightly-bound hydration matrix with irregular compact structures, demonstrating that although the percentage of overburden sand is higher, the bonding between the constituent particles is very efficient. It indicates that the microstructure of the CM-R80-O20 mortar possesses stability in the growth of the cement gel phase and proper interactions between aggregates and paste. The EDS pattern in Figure 16 and Table 16 reveal that oxygen (55.87%), calcium (24.15%), and silicon (14.09%) are the major components in the composition, signifying ongoing hydration of the calcium silicates in the mortar matrix.

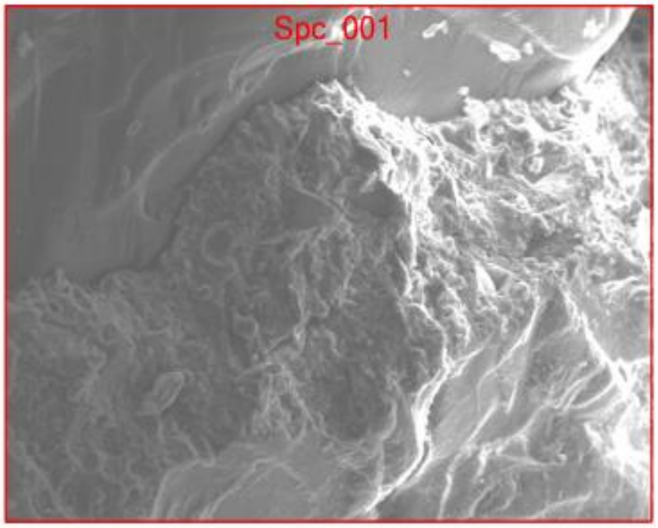

Fig. 15 SEM image of CM-R80-O20 mortar

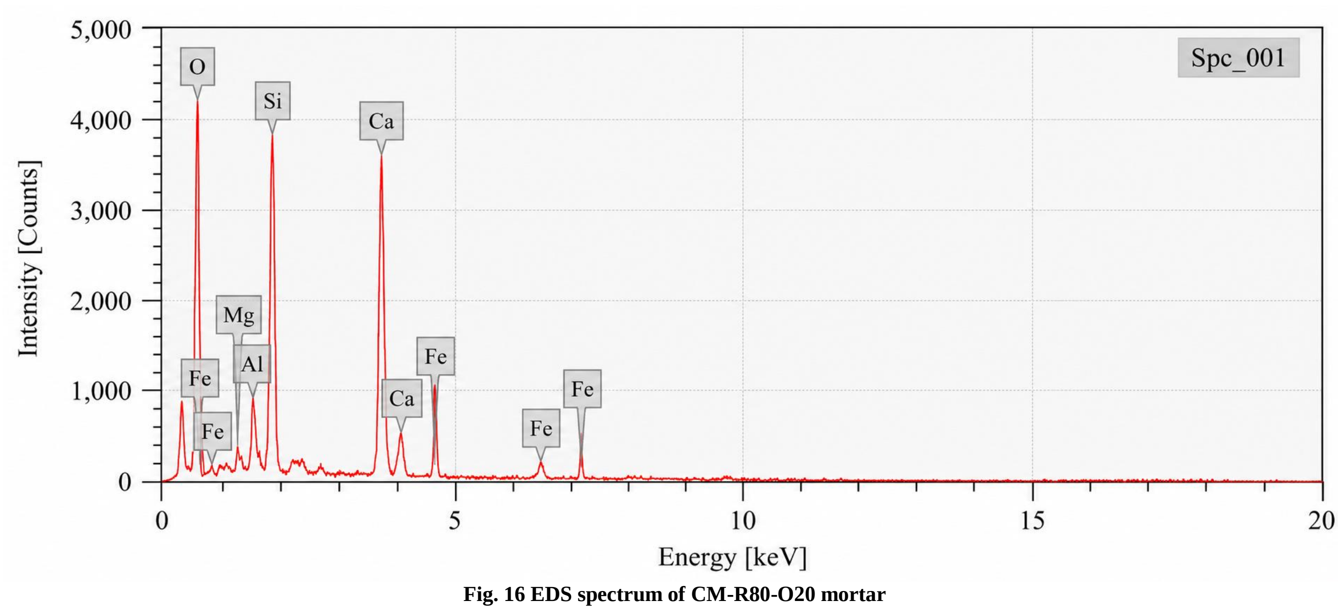

Fig. 16 EDS spectrum of CM-R80-O20 mortar

Table 16. Elemental composition of CM-R80-O20 mortar from EDS analysis

Element	Line	Mass %	Atom %
O	K	55.87 ± 0.36	72.91 ± 0.47
Mg	K	1.44 ± 0.04	1.24 ± 0.04
Al	K	2.82 ± 0.06	2.18 ± 0.04
Si	K	14.09 ± 0.12	10.47 ± 0.09
Ca	K	24.15 ± 0.16	12.58 ± 0.08
Fe	K	1.63 ± 0.06	0.61 ± 0.02

7.3. SEM-EDS Analysis of CM-R60-O40

According to the Figure 17 SEM image of CM-R60-O40 mortar, the hydrated matrix is heterogeneous yet continuously formed with some areas that appear slightly rough and have partially compacted surfaces, which means that there has been efficient formation of cement paste even after adding more overburden sand. In addition, it has limited pores connectivity; hence, the densification inside the mortar is acceptable. From the EDS analysis spectrum as shown in Figure 18 as well as Table 17, oxygen (49.34%), calcium (19.22%), and silicon (15.70%) are the main components, meaning that the calcium silicate hydration phases are still present.

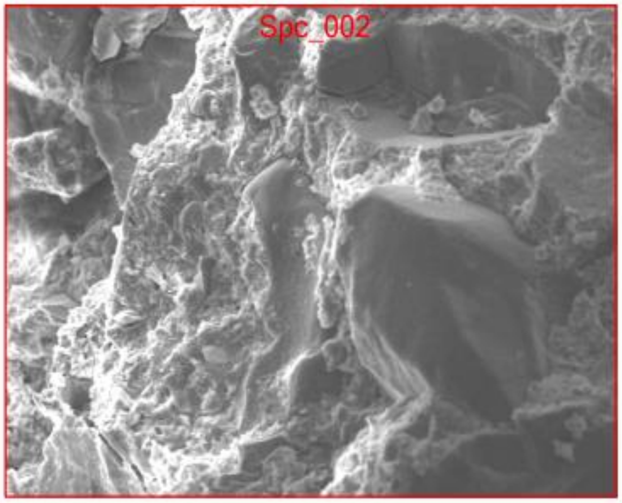

Fig. 17 SEM image of CM-R60-O40 mortar

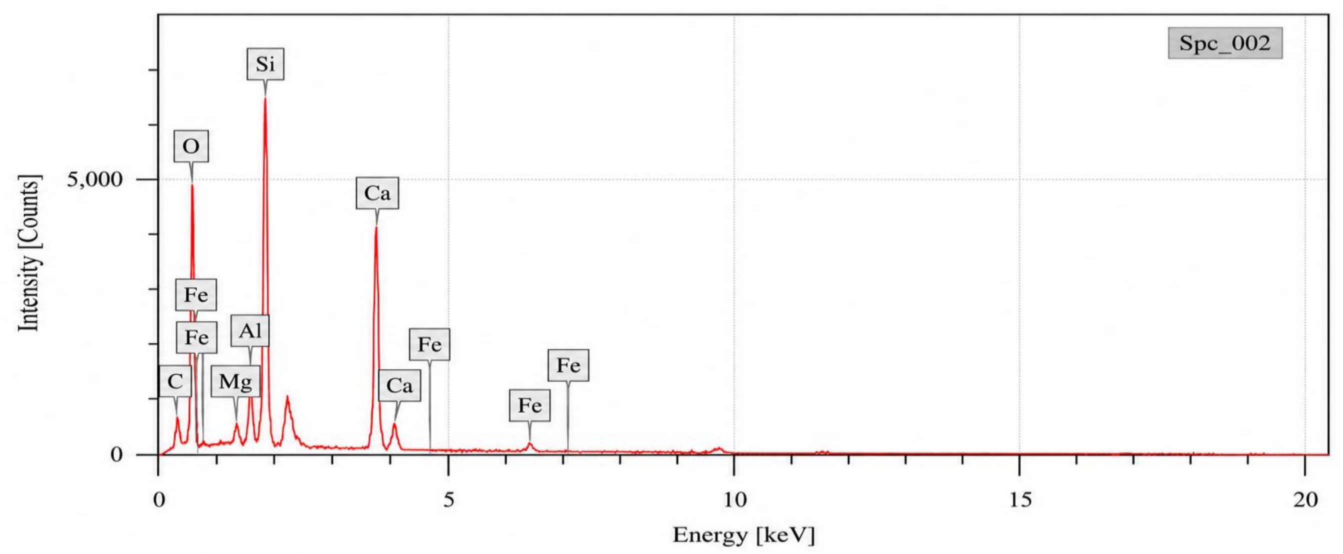

Fig. 18 EDS spectrum of CM-R60-O40 mortar

Table 17. Elemental composition of CM-R60-O40 mortar from EDS analysis

Element	Line	Mass %	Atom %
C	K	9.67 ± 0.10	15.69 ± 0.16
O	K	49.34 ± 0.29	60.12 ± 0.35
Mg	K	1.04 ± 0.03	0.83 ± 0.03
Al	K	3.64 ± 0.05	2.63 ± 0.04
Si	K	15.70 ± 0.10	10.89 ± 0.07
Ca	K	19.22 ± 0.12	9.35 ± 0.06
Fe	K	1.39 ± 0.05	0.49 ± 0.02

7.4. SEM-EDS Analysis of CM-R40-O60

Figure 19 depicts the SEM image of CM-R40-O60 mortar revealing an unevenly distributed hydration network with patches of rough surfaces and void spaces, implying a continuous production of cementitious gels under high levels of overburden sand substitution. From the experimented outcome obtained from the investigation, it can be seen that the interaction between aggregate and paste was not negatively impacted by mineral heterogeneity. According to the EDS spectrum shown in Figure 20 and Table 18, oxygen, silicon, and calcium have been detected as major minerals in terms of percentage at 54.29%, 16.52%, and 16.19%, respectively.

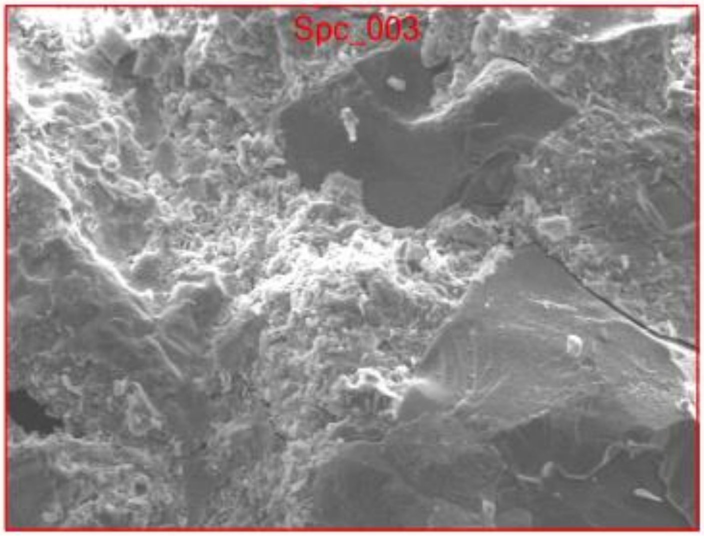

Fig. 19 SEM image of CM-R40-O60 mortar

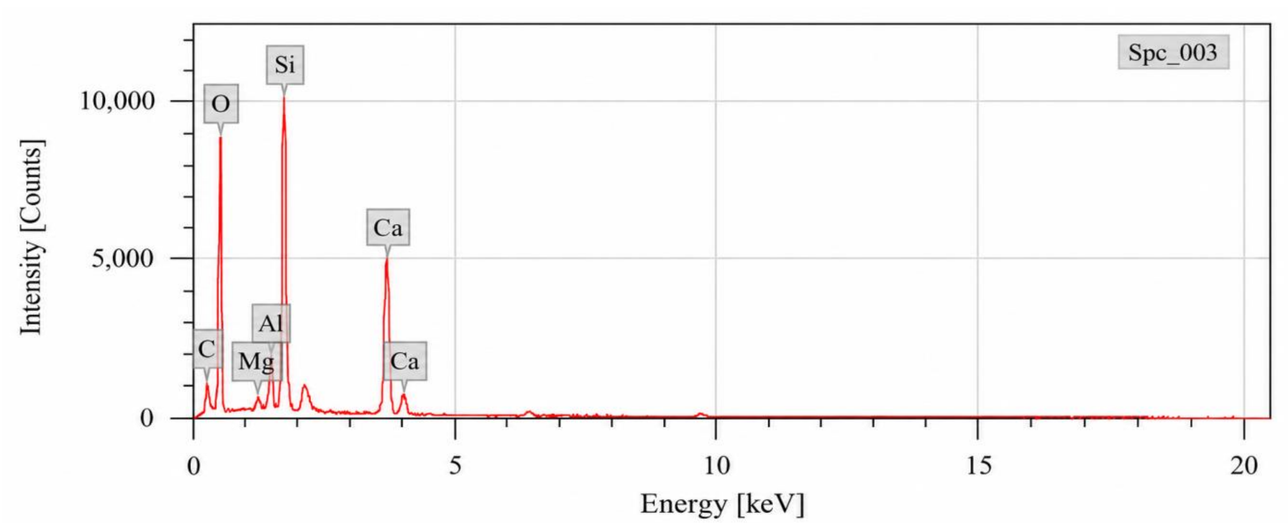

Fig. 20 EDS spectrum of CM-R40-O60 mortar

Table 18. Elemental composition of CM-R40-O60 mortar from EDS analysis

Element	Line	Mass %	Atom %
C	K	9.67 ± 0.08	15.14 ± 0.13
O	K	54.29 ± 0.23	63.83 ± 0.27
Mg	K	0.64 ± 0.02	0.49 ± 0.02
Al	K	2.70 ± 0.04	1.88 ± 0.03
Si	K	16.52 ± 0.08	11.06 ± 0.06
Ca	K	16.19 ± 0.09	7.60 ± 0.04

7.5. SEM-EDS Analysis of CM-R20-O80

The microstructure of CM-R20-O80 Mortar as presented in Figure 21 reveals that the hydrated matrix is quite dense with compact zones and less microvoids, which clearly suggest good internal bonding of cement paste and aggregate particles due to 20% overburden sand substitution. From the observation of surface micrograph structure, it is evident that proper hydration of products with reasonable continuity is achieved. It can be concluded from the EDS Spectroscopy results of Figure 22 and elemental analysis table as shown in Table 19 that the presence of oxygen (45.38%), calcium (24.22%), and silicon (13.73%) are primary elements.

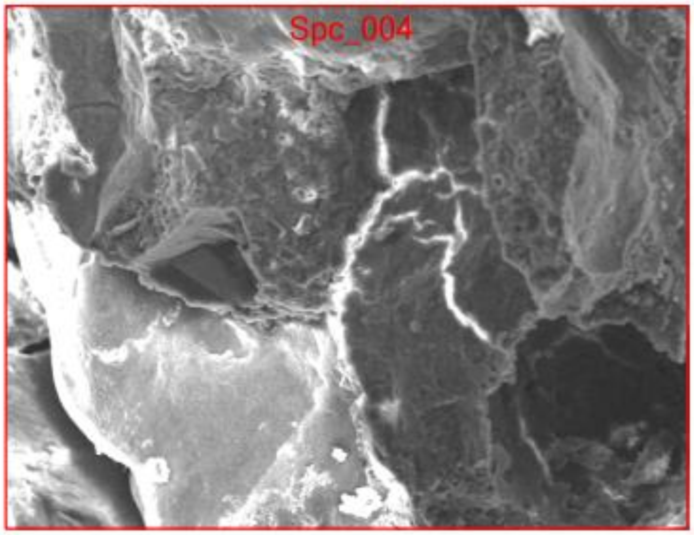

Fig. 21 SEM image of CM-R20-O80 mortar

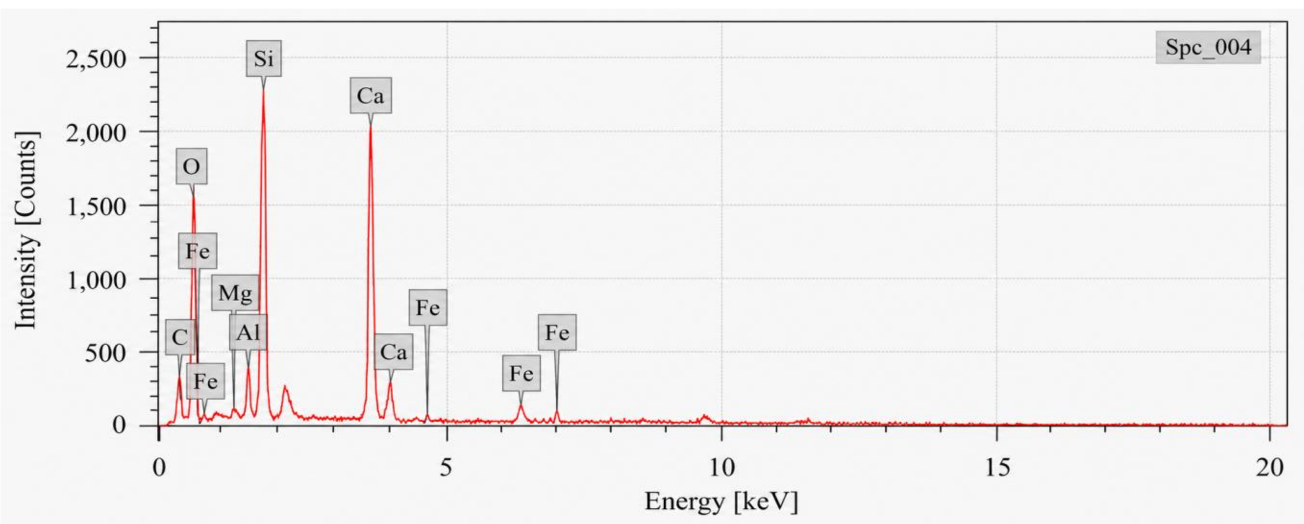

Fig. 22 EDS spectrum of CM-R20-O80 mortar

Table 19. Elemental composition of CM-R20-O80 mortar from EDS analysis

Element	Line	Mass %	Atom %
C	K	12.13 ± 0.16	19.91 ± 0.27
O	K	45.38 ± 0.47	55.92 ± 0.58
Mg	K	0.46 ± 0.04	0.38 ± 0.03
Al	K	2.13 ± 0.06	1.55 ± 0.05
Si	K	13.73 ± 0.15	9.64 ± 0.10
Ca	K	24.22 ± 0.21	11.92 ± 0.11
Fe	K	1.94 ± 0.09	0.69 ± 0.03

7.6. SEM-EDS Analysis of CM-O100

The SEM image of CM-O100 mortar presented in Figure 23 reveals an unbroken hydrated matrix that is rough in nature with some porosity zones, showing that the complete replacement of overburden sand with no adverse effect on cementitious phase formation was possible. While there is a little disturbance in the surface nature, there seems to be sufficient cohesion within the matrix with proper interaction between the aggregate and paste. As indicated by the Figure 24 EDS spectra and Table 20, calcium (25.61%), oxygen (47.11%), and silicon (11.32%) are the main chemical components in the matrix, suggesting sustained production of hydrated products enriched with calcium.

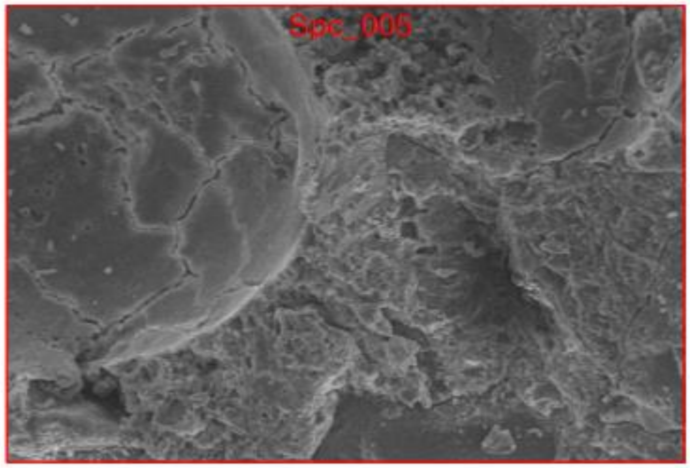

Fig. 23 SEM image of CM-O100 mortar

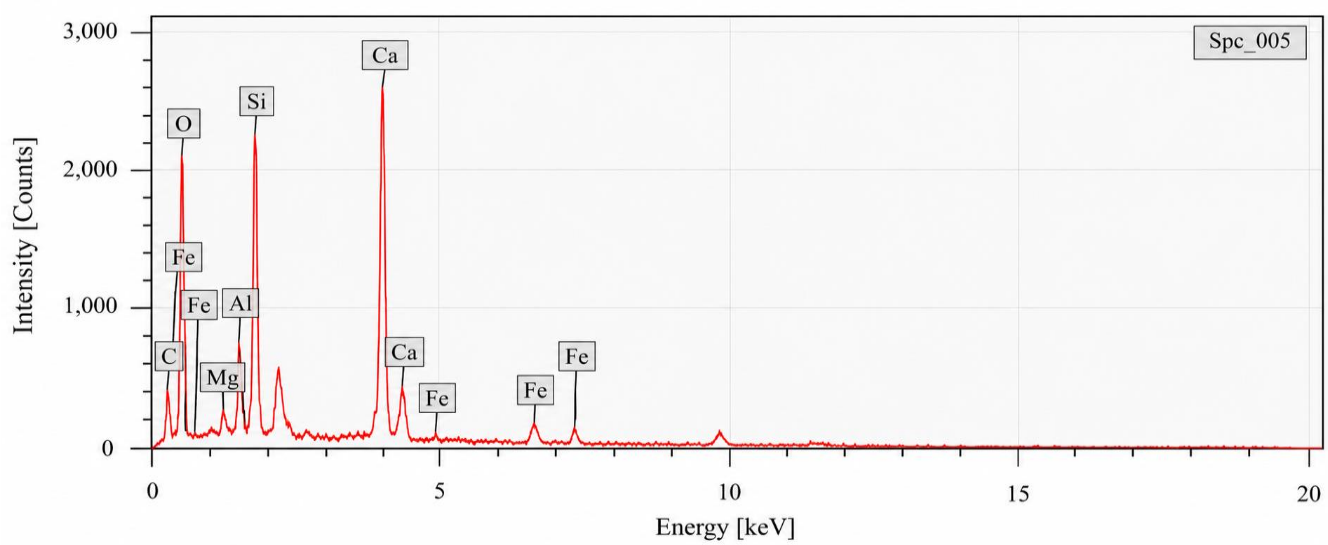

Fig. 24 EDS spectrum of CM-O100 mortar

Table 20. Elemental composition of CM-O100 mortar from EDS analysis

Element	Line	Mass %	Atom %
C	K	9.94 ± 0.13	16.54 ± 0.22
O	K	47.11 ± 0.43	58.85 ± 0.54
Mg	K	0.68 ± 0.04	0.56 ± 0.03
Al	K	3.42 ± 0.07	2.53 ± 0.05
Si	K	11.32 ± 0.12	8.05 ± 0.09
Ca	K	25.61 ± 0.20	12.77 ± 0.10
Fe	K	1.93 ± 0.08	0.69 ± 0.03

7.7. Microstructure-Strength Correlation of Replacement Mixes

The microstructural study conducted via SEM and EDS on all Stage 2 mortar specimens shows convincing proof that the compression strength performance of the compound subjected to progressive overburden sand replacement was dictated by the densification, integrity of the hydration products, and chemical stability in the hardened state of the mortar system. For instance, the control specimen CM-R100 had a dense and compact microstructure characterized by minimal pore interconnectivity and well-formed hydration products evenly dispersed throughout the matrix. This dense structure coincided with the highest compressive strength value of 28.8 MPa at 28 days, demonstrating effective cement hydration and aggregate-paste interaction. The corresponding EDS readings also demonstrated high oxygen and calcium compositions along with constant silicon concentration, implying the significant formation of calcium-containing hydration compounds, especially calcium silicate hydrate (C-S-H), which forms the strength-gaining phase in cement mortars.

SEM images also showed a relatively dense hydration structure with just minor surface anomalies at the overburden sand replacement level of 20% and 40% (CM-R80-O20 and CM-R60-O40). It can be noted that the matrix was still intact, meaning that the partial replacement did not greatly affect the synthesis of the hydration compounds. Based on the EDS test results, calcium was still predominant, but the presence of silicon increased. This suggests that the mineral composition of the overburden sand did not interfere with the process of cement hydration, thus allowing for the creation of the matrix without any detrimental changes to its chemical composition. With respect to replacement ratios of CM-R40-O60 and CM-R20-O80, SEM analyses revealed the existence of surface roughness and formation of microvoids in specific regions, which could be associated with angular nature and rough surface features of overburden sand particles. Nonetheless, it can be seen that the matrix maintained a continuous film coating of cementitious gel over the surface of aggregate grains, demonstrating the presence of efficient interface bonding. Meanwhile, EDS analyses reflected changes in proportions of calcium and silicon, with an increase in aluminum contents due to the presence of alumino-silicate minerals in overburden sand.

In terms of complete replacement (CM-O100), the SEM investigation revealed an irregular yet consistent microstructure with minimal disruptions, while the EDS investigation verified the presence of calcium, oxygen, and silicon as the major elements. Although calcium-containing hydration compounds were found, a slightly lower compressive strength was observed when compared with the control sample. Generally, based on the outcomes of SEM and EDS, it can be concluded that the processed overburden sand was compatible with the cement matrix in terms of microstructure, and the reduced strength values confirm the technical applicability of using it as fine aggregate. The SEM–EDS investigation demonstrates that processed overburden sand possesses satisfactory mineralogical compatibility with cement paste despite its comparatively rough particle morphology. The elevated aluminosilicate content, combined with the angular surface roughness explains the higher water demand and decreased flowability observed during fresh-state tests. Nevertheless, optimization of the water–cement ratio facilitated effective aggregate–paste bonding and satisfactory compressive strength development. These findings demonstrate that processed overburden sand is a technically viable and environmentally friendly replacement to natural river sand in cement mortar applications.

8. Discussion

It can be seen from the current study that the engineering characteristics of the mortar reinforced with processed overburden sand depend on the interaction of various properties, which include the minerals contained in aggregates, their shapes, mortar fresh-state rheological properties, and its hydration-induced microstructure formation. As was established during the XRD and EDS analyses of both types of sands used, both of them belong to the silicon oxides-containing materials, although the processed overburden sand showed more heterogeneous elemental composition due to the presence of alumina, iron, sodium, and calcium oxides-containing minerals. While quartz is the predominant component for both aggregates considered, significant variations have been found in the shape of their particles.

The experimental outcome from the flow table tests showed that mortar using river sand performed better when compared with overburden sand, due to the reduced internal friction because of the smoother particles used. This is because the mortar using overburden sand needed more water for effective spread diameter due to the resistance caused by the angular particles used. The effects of the angularity and roughness of the particles used were also evident during the Marsh cone discharge test, which recorded long times for discharge with the overburden sand despite the use of similar w/c ratio. Density test results showed that the mortar using river sand maintained high density due to particle packing efficiency.

The experimental outcome from the compression strength test show that the determination of optimal water-cement ratio cannot be reliably determined solely based on control mortar. While river sand mortar attained its highest compressive strength after 28 days at 0.5 water-cement ratio, the mortar made using overburden sand attained its optimum strength at 0.6 due to better workability, which led to efficient internal packing and hydration process. The Stage 2 replacement test results showed that replacing river sand with overburden sand resulted in just a modest loss in strength, with total replacement retaining a compressive strength of 27.1 MPa after 28 days, compared to 28.8 MPa for the control sample. This minor fluctuation suggests that, while the existence of imperfections in the texture of overburden sand increases the consumption of fresh water, it has no negative impact on the hardening process of the cementitious matrix.

The continued presence of hydration phases rich in calcium at all replacement levels signifies the chemical stability of the cement hydration process up to 100% overburden sand replacement. Intermediate levels of replacement showed an increase in the amounts of silicon and aluminum, which implies that mineral phases brought about by overburden sand have made the cement microstructure more complex but did not result in any detrimental effects on the stability of the cement matrix. Practically speaking, the findings have shown that the overburden sand, when properly processed, has the capability of serving as an effective substitute fine aggregate with regards to the water-cement ratio that has been adjusted to account for differences in morphology. With the inclusion of good consistency, small loss in compressive strength, and stability of the microstructure, this shows that the overburden sand has high potential for use in sustainable mortar manufacturing, especially areas where there is insufficient natural river sand. Scientifically speaking, the importance of this research comes from having successfully completed an entire experimental series covering the characterization of the aggregates, optimization of their fresh state, mechanical testing, and microstructure interpretation. While many other similar studies focus mainly on strength performance, this research clearly shows the necessity of considering fresh state control and microstructure for proper sustainability assessment.

The experimental results generated in the current study have shown that the processed Overburden Sand (OBS) has similar engineering properties as many of the other sustainable fine aggregates identified in the literature, which include recycled concrete powder, sandstone waste, mine waste products, and industrial waste products. Previous study has demonstrated the feasibility of employing other materials to river sand. However, the majority of past research has focused on certain performance characteristics, such as compression strength and workability. In contrast, the current study used a complete testing procedure that considers mineral composition, fresh-state behavior, mechanical performance, and microstructure analysis. The current study's fresh state behavior is consistent with the inherent features of mine-derived aggregates discovered in previous research. The mortars made with processed overburden sand exhibited very low flowability due to their angular particle morphologies and rough surface roughness, which increased internal friction and water demand. Nevertheless, the current research differs from some previous researches that have tested aggregate replacement without optimizing the water-cement ratio by conducting flow table, Marsh cone, and fresh density tests. Thus, the impact of the water demand was reduced to a minimum level, and the performance of the processed overburden sand could be evaluated in the controlled fresh state environment.

The findings from the compressive strength tests show that the processed overburden sand is an acceptable substitute for the natural river sand with minimal loss in compression strength. The slight discrepancy in the compression strengths of the conventional mortar and OBS mortar is evidence enough to suggest that the processed aggregate has sufficient compatibility with the matrix of the cementing materials. In comparison with the previously published studies on mine aggregate, the current study managed to attain equal or higher strength retention due to the determination of aggregate processing method, gradation, and optimal water-to-cement ratio before carrying out any mechanical testing. The mineralogical characterization along with SEM and EDS analysis serves as further evidence towards the engineering viability of treated overburden sand. High contents of silica along with aluminosilicates prove that treated aggregate is chemically similar to cement hydration products. Although the presence of fairly rough and angular surface of particles caused high water requirement at fresh stage of the material, the analysis of hardened mortar showed good interface between aggregate and paste without any discontinuities.

Unlike previous works, which used only qualitative SEM image interpretation, the current work incorporates elemental composition, mineralogical properties, and mechanical properties into one single concept. The importance of the current research is not limited to the confirmation of engineering characterizes of processed overburden sand but also to the establishment of correlation between properties of aggregates and mortar. In the current research, mineralogical identification, fresh state tests, strength determination, and microstructure studies were carried out together in one experimental series. Such a combined approach allows for more comprehensive understanding of the impact of composition and structure of aggregates on engineering properties compared to approaches which depend only on mechanical testing.

Thus, the current research adds to the scientific basis for using processed overburden sand as a green substitute to natural river sand in cement mortar. Based on an engineering point of view, the current study proves the feasibility of using processed overburden sand in order to diminish the usage of natural river sand and at the same time make use of mining waste produced from the extraction of lignite coal. The results obtained from experiments show that processed overburden sand can give mortar which has good workability, sufficient compressive strength, and microstructure behavior by choosing the right processing of material and optimum mix proportions.

9. Conclusion

The current study conducted a systematic assessment of processed overburden sand as a supernumerary material for fine aggregates in cement mortar based on mineralogical investigation, performance characteristics in fresh state, compressive strength behaviour, and microstructural analysis using a well-organized two-staged experimental program. As per XRD results, quartz was found to be the major component of natural river sand and processed overburden sand. However, experimental outcome of EDS analysis specifies that silicon and oxygen were the major components of river sand, while aluminium, iron, sodium, and calcium were found to be the other mineral components of overburden sand. The fresh state test revealed that river sand mortar obtained maximum spread ability performance with a water-to-cement proportion of 0.5, resulting in a 144 mm spread and a constant Marsh cone discharge behaviour; however, for overburden sand mortar, the water-to-cement ratio had to be set at 0.6 to achieve similar results owing to increased particle friction and higher absorption capacity. The Marsh cone tests further verified this difference in rheology, with overburden sand mortar always discharging more slowly at equal water content.

The consequences of compression strength tests revealed that control mortar had attained its peak 28-day compression strength of 31.8 MPa at 0.5 water-cement proportion, whereas overburden sand mortar had its optimal 28-day compressive strength of 27.1 MPa at 0.6 water-cement proportion. With respect to the optimal water-cement ratio of overburden sand mortar, the gradual increase in replacement content from 20% to 100% of overburden sand had caused marginal reduction in strength; however, the peak compressive strength of 27.1 MPa had been observed even after complete replacement, which was slightly lower than the peak compressive strength of CM-R100 (28.8 MPa). The SEM-EDS characterization of overburden sand replacement mixes indicated constant hydration product formation, calcium-silicon dominance, and adequate internal density for all the replacement contents. The current study is confined to cement mortar in the lab environment, where its properties such as fresh state characteristics, compressive strength, and SEM-EDS analysis were evaluated. In future, there could be scope for studying its durability, drying shrinkage, and permeability, besides its applicability in large concrete structures. Overall, the findings of this study emphasize the suitability of OBS as an eco-friendly fine aggregate for river sand in cement mortar applications.

Conflict of Interest

The authors declare that there are no conflicts of interest in the publication of this study.

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Author Contributions

Kolar Dinesh Singh is responsible for conceptualization, methodology, experimental investigation, data analysis, and writing (original draft preparation).

M. Purushothaman provided experimental support, supervision, guidance, result interpretation, final manuscript review validation, and editing. All authors read and approved the final version of the manuscript.

Ethics Approval

There were no human or animal experiments in this study. Thus, ethical approval was not necessary. The research followed institutional rules for academic research.

Data Availability

The datasets generated and/or analysed during the current investigation are accessible from the corresponding author on reasonable request.

Abbreviations

- OBS: Processed Overburden Sand
- RS: River Sand
- OPC: Ordinary Portland Cement
- F.A: Fine Aggregate
- XRD: X-ray Diffraction
- SEM: Scanning Electron Microscopy
- EDS: Energy Dispersive Spectroscopy

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