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Article

Performance Evaluation of Mortar Incorporating Olivine Sand as a Partial Cement Replacement: Mechanical, Microstructural, and Durability Aspects

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Abstract: The construction industry's environmental footprint, driven by Portland cement production's high CO₂ emissions, necessitates sustainable alternatives. This study explores olivine sand, a magnesium-iron silicate mineral, as a partial cement replacement in mortar cubes. Mortar mixtures with 5–30% olivine sand substitution were prepared, maintaining consistent workability. Olivine was characterized using XRF, XRD, SEM, and particle size analysis. Fresh properties (workability, setting time, density) and hardened properties (compressive/flexural strength, density, water absorption) were assessed at various curing ages. Microstructural analysis via SEM-EDS and XRD examined hydration products and interfacial transition zones. Results indicate olivine's potential as a filler, with possible slow pozzolanic activity, influencing strength and durability. Statistical validation confirmed significant effects of replacement levels. Findings suggest optimal olivine incorporation ranges, contributing to sustainable cementitious materials and reduced clinker reliance.

Keywords: olivine sand; cement replacement; supplementary cementitious materials; mortar properties; sustainability; mechanical strength; durability; microstructure

Introduction

Background and Significance of Sustainable Cementitious Materials

The construction industry is a cornerstone of global economic development and societal progress, yet it is concurrently one of the largest consumers of natural resources and a significant contributor to anthropogenic environmental impacts. Central to modern construction is Portland cement, the primary binding agent in concrete and mortar. The production of Portland cement is an energy-intensive process, responsible for approximately 7-8% of global carbon dioxide (CO₂) emissions, primarily arising from the calcination of limestone and the combustion of fossil fuels in kiln operations. As global infrastructure demands continue to escalate, particularly in developing nations, the environmental burden associated with conventional cement manufacturing presents a formidable challenge to sustainable development goals [1]. Consequently, there is an imperative and growing research focus on developing alternative and supplementary cementitious materials (SCMs) that can reduce the clinker factor in blended cements or partially replace cement in concrete and mortar formulations [2]. The utilization of such materials not only aims to mitigate CO₂ emissions but also seeks to conserve non-renewable raw materials, reduce energy consumption in material production, and often, beneficially incorporate industrial by-products or waste streams, thereby contributing to a circular economy [3]. Sustainable cementitious materials are designed to meet or exceed the performance requirements of traditional materials while offering a reduced environmental footprint, enhancing the overall sustainability and resilience of the built environment [4]. The quest for these materials involves exploring a wide array of natural pozzolans, industrial by-products, and even novel synthesized compounds that can exhibit cementitious or pozzolanic properties, contributing to strength development and durability enhancement in cement-based

composites [5]. The long-term performance and durability of structures built with these innovative materials are critical considerations, ensuring that environmental benefits are not achieved at the expense of service life or safety [1].

Rationale for Investigating Olivine Sand as a Cement Replacement

Olivine, a group of magnesium iron silicate minerals ($(\text{Mg,Fe})_2\text{SiO}_4$), is an abundant nesosilicate found extensively in the Earth's upper mantle and in certain mafic and ultramafic igneous rocks. While traditionally utilized in refractory applications, steelmaking (as a slag conditioner), and more recently explored for carbon sequestration due to its reactivity with CO_2 , its potential as a constituent in cementitious systems remains largely under-explored. The rationale for investigating olivine sand as a partial cement replacement stem from several considerations. Firstly, its silicate composition suggests potential, albeit slow, pozzolanic reactivity if processed to achieve sufficient fineness and surface area, or it might act as a reactive filler influencing hydration kinetics and microstructure. The magnesium content in olivine could also interact with cement hydration products, potentially forming phases like magnesium silicate hydrate (M-S-H), which could contribute to the densification of the matrix. Secondly, the widespread geological availability of olivine deposits in various global locations could offer a locally sourced material, reducing transportation costs and associated emissions compared to some other SCMs. If olivine can partially replace cement without significantly compromising, or even enhancing, certain properties of mortar or concrete, it could contribute to reducing the clinker content in cementitious binders. The investigation into olivine is also spurred by the continuous search for novel SCMs, as traditional SCMs like fly ash and ground granulated blast-furnace slag (GGBS) face issues of variable quality, declining availability in some regions due to changes in industrial processes (e.g., closure of coal-fired power plants), and increasing competition for their use [3]. Therefore, exploring naturally abundant minerals like olivine, which are not primary industrial by-products, presents a proactive approach to diversifying the SCM portfolio. Preliminary characterization of olivine, such as particle size distribution and chemical composition, is essential to understand its suitability and potential interactions within a cement matrix [6]. The study of olivine sand as a cement replacement is therefore a pertinent area of research in the pursuit of more sustainable construction materials.

Research Objectives and Scope of the Study

The primary objective of this research is to comprehensively evaluate the feasibility of utilizing olivine sand as a partial replacement for Ordinary Portland Cement (OPC) in mortar mixtures. This investigation seeks to understand the influence of varying olivine sand proportions on the fresh and hardened properties of mortar, as well as its effects on microstructure and durability characteristics. The specific objectives are:

1. To procure and thoroughly characterize olivine sand, including its physical, chemical, and mineralogical properties, using techniques such as particle size analysis, X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and Scanning Electron Microscopy (SEM).
2. To design and prepare mortar mixtures with different percentage replacements of OPC by olivine sand, alongside a control mixture without olivine, ensuring consistent workability where feasible.
3. To assess the fresh properties of the olivine-modified mortars, including workability (flow), setting times, and fresh density.
4. To evaluate the mechanical performance of hardened mortar specimens at various curing ages, focusing on compressive strength, flexural strength, hardened density, and water absorption.
5. To investigate the microstructural development of the olivine-modified mortars using SEM coupled with Energy-Dispersive X-ray Spectroscopy (EDS) and XRD analysis, paying particular attention to the interfacial transition zone (ITZ) and the nature of hydration products.

6. To conduct preliminary durability assessments, including tests related to porosity, water sorptivity, and potentially resistance to common chemical attacks if indicated by microstructural findings.
7. To analyze the collected data, interpret the findings in the context of cement chemistry and material science, and determine an optimal replacement level of olivine sand, if any, that balances performance with sustainability benefits.

The scope of this study is confined to laboratory-scale investigations using mortar cubes. The olivine sand will be sourced from a specific geological deposit and may undergo pre-processing (e.g., grinding, sieving) to achieve a desired particle size range suitable for cement replacement. The replacement levels will be systematically varied. While long-term durability under aggressive field conditions is beyond the immediate scope, the study aims to provide foundational data on key durability indicators. The findings are intended to contribute to the knowledge base on unconventional SCMs and inform future research directions for olivine in cementitious applications.

Literature Review

Conventional Cement Production: Environmental Impact and Sustainability Concerns

Ordinary Portland Cement (OPC) is the most widely used construction material globally, prized for its versatility, cost-effectiveness, and ability to form durable and high-strength composites when mixed with water and aggregates. However, the production of OPC is a resource and energy-intensive process with significant environmental repercussions. The manufacturing process involves quarrying raw materials (primarily limestone and clay), grinding them, and then heating them to approximately 1450°C in a rotary kiln to produce clinker, the principal active component of cement. This clinkering process is responsible for the bulk of the environmental impact [3]. Approximately 50-60% of the CO₂ emissions from cement production arise from the chemical decarbonation of calcium carbonate (CaCO₃) in limestone to form calcium oxide (CaO), a key ingredient in clinker. The remaining 40-50% of CO₂ emissions are attributed to the combustion of fossil fuels required to achieve the high temperatures in the kiln, as well as emissions from electricity consumption for grinding and other plant operations. Beyond CO₂ emissions, cement production also contributes to air pollution through the release of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter. The quarrying of raw materials can lead to habitat destruction, landscape degradation, and changes in local hydrology. The substantial energy demand, typically in the range of 3.2-5.5 GJ per tonne of clinker, places a significant strain on energy resources. With global cement production exceeding 4 billion tonnes annually, the cumulative environmental footprint is immense, making the cement industry a primary target for emissions reduction strategies and sustainability initiatives [1]. These concerns have driven extensive research into alternative binders, supplementary cementitious materials, and process efficiency improvements to mitigate the ecological burden of concrete construction [2]. The long-term sustainability of the construction sector hinges on addressing these environmental challenges associated with conventional cement production [4].

Supplementary Cementitious Materials (SCMs): An Overview

Supplementary Cementitious Materials (SCMs) are finely divided materials that are added to concrete or mortar, either as a partial replacement for Portland cement or as an addition to the cement, to enhance specific properties of the fresh or hardened composite, or to reduce its environmental impact [5]. SCMs can be broadly classified based on their chemical nature and reactivity: pozzolanic materials, which react with calcium hydroxide (CH), a by-product of cement hydration, to form additional calcium silicate hydrate (C-S-H) gel – the primary binding phase in hydrated cement paste; and hydraulic materials, which react directly with water to form cementitious compounds, similar to Portland cement itself. The incorporation of SCMs offers several potential benefits, including improved workability, reduced heat of hydration (beneficial for mass concrete), enhanced long-term

strength, increased durability through refinement of the pore structure and reduced permeability, and improved resistance to chemical attacks such as sulfate attack and alkali-silica reaction (ASR) [7]. From a sustainability perspective, the use of SCMs, particularly industrial by-products like fly ash, slag, and silica fume, reduces the demand for Portland cement, thereby lowering CO₂ emissions, conserving natural resources, and diverting waste materials from landfills [3]. The effectiveness of an SCM depends on its physical characteristics (e.g., fineness, particle shape, specific surface area) and chemical composition (e.g., content of reactive silica, alumina, and lime) [8]. The appropriate selection and proportioning of SCMs are critical for achieving desired performance outcomes in concrete and mortar [5]. The drive towards more eco-efficient cement-based materials has intensified research into a wider variety of SCMs, including calcined clays and other natural pozzolans [9].

Commonly Utilized SCMs and Their Influence on Mortar Properties

Several SCMs have gained widespread acceptance and are commonly used in the construction industry. Fly ash (FA), a by-product of coal combustion in thermal power plants, is one of the most extensively used SCMs [3]. Class F fly ash, typically low in calcium, exhibits pozzolanic activity, reacting with CH to form additional C-S-H, leading to improved long-term strength and durability. Its spherical particle shape can enhance workability and reduce water demand [8]. However, fly ash generally retards early strength development. Ground Granulated Blast-Furnace Slag (GGBS), a by-product of iron production, is a latent hydraulic material. When activated by the alkalis and CH from Portland cement hydration, GGBS contributes to strength gain and significantly improves durability, particularly resistance to chloride ingress and sulfate attack [10]. Silica Fume (SF), a by-product of silicon and ferrosilicon alloy production, is a highly reactive pozzolan due to its high amorphous silica content and extreme fineness. SF dramatically enhances strength and durability by consuming CH, producing dense C-S-H, and refining the pore structure and the interfacial transition zone (ITZ) between aggregate and paste [5]. However, its use increases water demand and can reduce workability if not accompanied by a high-range water reducer. Metakaolin (MK), produced by calcining kaolinitic clay, is another highly reactive pozzolan that improves mechanical properties and durability, including mitigation of ASR and enhanced resistance to chemical attack [7]. Limestone powder (LP), when interground with clinker or added to concrete, can act as a filler, accelerating early hydration through nucleation effects and participating in reactions with aluminate phases to form carboaluminates, potentially improving particle packing and workability at low replacement levels [11]. The influence of these SCMs on mortar properties is complex and depends on the replacement level, fineness, chemical composition of the SCM, and the properties of the Portland cement with which they are blended [12].

Emerging and Unconventional SCMs: A Review

Beyond the well-established SCMs, research into emerging and unconventional materials is continuously expanding the palette available for sustainable construction. Calcined clays, particularly those rich in kaolinite, are gaining prominence as a globally available resource for producing reactive pozzolans like metakaolin, especially in regions lacking traditional SCMs [9]. The controlled calcination of lower-grade clays is also being explored to produce materials with suitable pozzolanicity. Agricultural ashes, such as rice husk ash (RHA) and sugarcane bagasse ash (SBA), when properly incinerated and ground, can yield high silica content and exhibit significant pozzolanic activity [2]. These materials offer a sustainable route for valorizing agricultural waste. Waste glass powder (WGP), derived from grinding post-consumer glass, has shown pozzolanic potential, contributing to strength and potentially mitigating alkali-silica reaction if finely ground [13]. Foundry sand wastes (FSW), if properly processed to remove contaminants and achieve adequate fineness, might also offer pozzolanic or filler effects in mortars [14]. Nanomaterials, such as nano-silica, nano-CaCO₃, carbon nanotubes (CNTs), and graphene oxide (GO), are being investigated for their ability to significantly enhance cementitious composite properties at very low dosages

[15][16][17]. These materials can act as nucleation sites for hydration products, refine pore structure, and bridge microcracks, leading to improvements in mechanical strength and durability [18]. Steel slag, a by-product of steel manufacturing, can have cementitious properties depending on its composition and processing, though its volumetric stability can be a concern [19]. The exploration of such unconventional SCMs is crucial for developing locally adaptable and environmentally sound concrete technologies, reducing reliance on conventional cement and traditional SCMs whose availability may be geographically or economically constrained. The challenge with many emerging SCMs lies in consistent quality control, understanding their long-term performance, and scaling up production for widespread adoption.

Olivine: Geological Origin, Physicochemical Properties, and Potential Applications in Cementitious Composites

Olivine is a common rock-forming mineral series with the general formula $(\text{Mg,Fe})_2\text{SiO}_4$, where forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4) are the magnesium-rich and iron-rich endmembers, respectively. It crystallizes in the orthorhombic system and is characterized by its nesosilicate structure, consisting of isolated $[\text{SiO}_4]^{4-}$ tetrahedra linked by divalent cations (Mg^{2+} , Fe^{2+}) in octahedral coordination. Olivine is a primary constituent of Earth's upper mantle and is commonly found in mafic and ultramafic igneous rocks such as peridotite, dunite, gabbro, and basalt [20]. Its color typically ranges from olive green to yellowish-green, and it has a Mohs hardness of 6.5-7. Physicochemically, olivine exhibits high melting points (forsterite $\sim 1890^\circ\text{C}$, fayalite $\sim 1205^\circ\text{C}$) and is relatively dense (specific gravity $\sim 3.2\text{-}4.4 \text{ g/cm}^3$). Its chemical stability at ambient temperatures is moderate; it is susceptible to weathering and alteration, particularly hydrothermal alteration, which can transform it into serpentine, talc, or magnesite. The potential applications of olivine in cementitious composites are not well-established but are hypothesized based on its silicate nature. If finely ground, the silica component might exhibit slow pozzolanic reactivity, particularly under conditions that favor dissolution, such as elevated temperatures or alkaline environments. The presence of magnesium could lead to the formation of magnesium-based hydration products, such as brucite ($\text{Mg}(\text{OH})_2$) or M-S-H phases, which could influence the microstructure and properties of the hardened paste. The use of olivine as a fine aggregate is also plausible, though this study focuses on its potential as a cement replacement. Its relatively high hardness and density could be beneficial in certain aggregate applications. Hydrothermal synthesis routes have been explored to control the microstructure of olivine materials for other applications, suggesting that processing can significantly alter its particle characteristics [6]. The reactivity of olivine with CO_2 to form stable carbonates has led to its investigation for mineral carbonation, a CO_2 sequestration technology. This reactivity, however, may also imply potential interactions within the CO_2 -rich pore solution of carbonating concrete, which warrants investigation.

Prior Research on Olivine and Related Silicate Minerals in Construction Materials

While extensive research exists on common silicate minerals like quartz (as aggregate) and pozzolanic materials rich in amorphous silica (e.g., fly ash, silica fume), dedicated studies on olivine as a cement replacement or active ingredient in cementitious composites are scarce. Most research involving olivine in a construction context has focused on its use as a refractory material or as an aggregate in specialized applications where its thermal properties are advantageous. Some related magnesium silicate minerals, such as serpentine, have been incidentally studied when present as contaminants in aggregates, often due to concerns about their fibrous nature or potential for deleterious reactions. The broader field of magnesium-based cements, such as magnesium oxychloride or magnesium phosphate cements, utilizes magnesium compounds but typically not olivine directly as a reactive silicate precursor. However, research into the carbonation of olivine for CO_2 sequestration has provided insights into its dissolution kinetics and reactivity, which could be indirectly relevant to its behavior in the alkaline environment of cement paste. Studies on alkali-

activated materials (geopolymers) have explored a wide range of aluminosilicate precursors, but olivine, being a nesosilicate with limited aluminum, has not been a primary focus, although some research considers the use of magnesium-rich industrial wastes which may contain olivine-like phases [21]. The behavior of other silicate minerals, such as wollastonite (CaSiO_3), has been investigated in cement systems, showing some reactivity and influence on hydration. The general understanding from SCM research is that fineness, amorphous content, and specific chemical composition are key to pozzolanic or hydraulic activity [22]. For olivine, its crystalline nature and nesosilicate structure suggest that any reactivity as a pozzolan would likely be slow unless it undergoes significant processing, such as ultra-fine grinding or thermal activation, to enhance its surface area and disorder its structure. The study of olivine materials for battery applications, involving synthesis and characterization, provides some background on controlling its particle size and morphology, which could be adapted for cementitious applications [6]. The use of dune sand, which can contain various silicate minerals, in cementitious materials has shown that particle characteristics and interactions with other binder components are important [10].

Identification of Knowledge Gaps and Justification for Current Investigation

The existing body of literature reveals a significant knowledge gap concerning the specific role and performance of olivine sand when used as a partial replacement for cement in mortars or concrete. While the general principles of SCMs are well-understood for common materials [5][3], the unique nesosilicate structure and magnesium-iron composition of olivine differentiate it from traditional pozzolans (aluminosilicates) and hydraulic SCMs. Key unanswered questions include:

1. The extent, if any, of pozzolanic or chemical reactivity of unprocessed or moderately processed olivine sand in a Portland cement environment at ambient and slightly elevated curing temperatures.
2. The nature of any new phases formed due to the interaction of olivine with cement hydration products, particularly the potential formation and impact of magnesium-containing hydrates like M-S-H or brucite.
3. The influence of varying olivine replacement levels on the rheological properties of fresh mortar, such as workability and setting time, which are critical for practical applications.
4. The effect of olivine incorporation on the mechanical strength development (compressive and flexural) of mortars at different curing ages.
5. The impact of olivine on the microstructure of the hardened cement paste, including pore structure refinement, changes in the ITZ, and overall densification.
6. The durability implications of using olivine, such as its effect on water absorption, permeability, and resistance to common deterioration mechanisms like sulfate attack or ASR, particularly given its magnesium content and potential for expansion reactions if not stable.

The current investigation is justified by the pressing need for sustainable construction materials and the potential of olivine as an abundant, naturally occurring mineral. If olivine can effectively replace a portion of cement while maintaining or even enhancing certain mortar properties, it could offer a valuable addition to the range of SCMs, contributing to reduced CO_2 emissions and resource conservation. This study aims to address the identified knowledge gaps by systematically evaluating olivine sand from a specific source, focusing on its physicochemical characteristics and its performance as a cement replacement in mortar. The findings will provide foundational data necessary for assessing the viability of olivine in cementitious applications and for guiding future, more detailed research into its activation, optimization, and long-term behavior. The exploration of unconventional materials like olivine aligns with the broader strategy of diversifying sustainable building material options [4].

Materials and Experimental Methodology

Procurement and Physicochemical Characterization of Constituent Materials

The successful execution of this research hinges on the careful selection and comprehensive characterization of all constituent materials used in the mortar mixtures. This includes Ordinary Portland Cement (OPC), standard fine aggregate (sand), and the olivine sand under investigation. Each material was sourced and prepared according to specific protocols to ensure consistency and enable accurate interpretation of experimental results. The physicochemical properties of these raw materials directly influence the behavior of the fresh mortar and the performance characteristics of the hardened specimens. Therefore, a detailed preliminary assessment of each component was undertaken prior to the commencement of mortar mixing and testing. This initial phase involved determining key physical parameters such as particle size distribution, specific gravity, and morphology, as well as chemical and mineralogical compositions. Adherence to relevant ASTM or equivalent international standards was maintained throughout the characterization process to ensure the reliability and comparability of the data obtained. The characterization data serves as a baseline for understanding the interactions between olivine sand and the cementitious system. For instance, the fineness and chemical makeup of the olivine are expected to play a crucial role in its potential reactivity or its function as a filler material within the mortar matrix [6]. The properties of the OPC and standard sand provide the reference against which the effects of olivine addition are compared. This systematic approach to material characterization is fundamental to drawing meaningful conclusions about the suitability of olivine sand as a cement replacement.

Ordinary Portland Cement (OPC): Properties and Standards Compliance

A commercially available Ordinary Portland Cement (OPC), conforming to ASTM C150/C150M Type I standards, was procured from a single batch to minimize variability throughout the experimental program. Prior to its use, the OPC was characterized to confirm its physical and chemical properties. Physical tests included determination of specific gravity using the Le Chatelier flask method (ASTM C188), fineness by air permeability apparatus (Blaine fineness, ASTM C204), normal consistency (ASTM C187), and setting times (initial and final) using the Vicat apparatus (ASTM C191). The chemical composition of the OPC, including the oxide content (e.g., CaO, SiO₂, Al₂O₃, Fe₂O₃, MgO, SO₃) and loss on ignition (LOI), was determined by X-ray fluorescence (XRF) spectrometry, following procedures outlined in ASTM C114. The potential phase composition (Bogue compounds: C₃S, C₂S, C₃A, C₄AF) was calculated from the oxide analysis. This detailed characterization of the OPC ensures that its properties are well-documented and meet standard requirements, providing a reliable baseline for the control mortar mixtures. Understanding the C₃A content and SO₃ levels in the cement is particularly important as these can influence compatibility with SCMs and early age hydration behavior [12]. The OPC was stored in airtight containers to prevent premature hydration or carbonation due to atmospheric moisture and CO₂ exposure. All tests on the OPC were conducted in a controlled laboratory environment to ensure accuracy and reproducibility of the results. The properties determined were compared against the manufacturer's specifications and the limits prescribed by relevant standards, confirming its suitability for the research.

Fine Aggregate: Standard Sand Characteristics

Natural river sand, complying with the requirements of ASTM C778 for standard sand (graded sand for mortar testing), was used as the fine aggregate in all mortar mixtures. The sand was procured from a reputable local supplier and was thoroughly washed to remove any clay, silt, organic impurities, or deleterious substances that could adversely affect mortar properties. After washing, the sand was oven-dried to a constant mass at 105 ± 5°C and then cooled to room temperature in a desiccator before use to ensure a saturated surface-dry (SSD) condition or a known moisture content for accurate water adjustment in the mixes. The physical properties of the sand were characterized according to relevant ASTM standards. Particle size distribution was determined by sieve analysis (ASTM C136/C136M) to ensure it met the grading requirements for standard mortar sand. Other

properties evaluated included specific gravity and water absorption (ASTM C128), and fineness modulus calculated from the sieve analysis data. The absence of organic impurities was confirmed using the colorimetric test (ASTM C40/C40M). The use of a standardized, well-characterized fine aggregate helps to isolate the effects of the olivine sand replacement on the mortar properties, minimizing variability that could arise from inconsistencies in the aggregate. The characteristics of the sand, such as its grading and particle shape, influence the workability, water demand, and packing density of the mortar mixture, thereby affecting its strength and durability [23]. The consistency of the fine aggregate across all batches is critical for the comparative nature of this study. The sand was stored in covered containers to prevent contamination and maintain its dryness until required for mixing.

Olivine Sand: Source, Pre-Processing, and Preliminary Assessment

The olivine sand used in this investigation was obtained from a specific geological deposit, the details of which (location, geological formation) were recorded. The as-received olivine material was initially in a coarser granular form. To prepare it for potential use as a cement replacement, a pre-processing stage was undertaken. This involved crushing the raw olivine using a jaw crusher, followed by grinding in a laboratory ball mill to achieve a fineness comparable to or finer than that of Portland cement. The grinding time and media were optimized to achieve a target particle size distribution suitable for enhancing potential reactivity or acting as an effective microfiller. After grinding, the olivine powder was sieved through a specific mesh (e.g., 75 μm or 45 μm) to remove any overly coarse particles and to ensure a relatively uniform product. A preliminary assessment of the processed olivine sand was conducted. This included determination of its specific gravity (ASTM D854 or equivalent for fine powders), particle size distribution using a laser diffraction particle size analyzer, and morphological examination using Scanning Electron Microscopy (SEM) to observe particle shape and surface texture [6]. The chemical composition was analyzed using XRF to determine the major oxide constituents (SiO_2 , MgO , FeO , etc.), and the mineralogical phases present were identified using X-Ray Diffraction (XRD) [20]. Loss on ignition (LOI) was also determined to quantify volatile components. This comprehensive initial characterization of the olivine sand is essential for understanding its potential behavior within the cementitious matrix, including its pozzolanic activity (if any), its role as a filler, and its interaction with cement hydration products. The processed olivine sand was stored in airtight containers to prevent any alteration before its incorporation into mortar mixtures.

Mortar Mixture Design and Proportionality

The design of mortar mixtures was systematically planned to evaluate the effect of partially replacing OPC with olivine sand at various predetermined levels. A control mixture, without any olivine sand, was designed as a reference. The experimental mixtures incorporated olivine sand as a direct weight replacement for cement. Key parameters such as the water-to-binder (w/b) ratio and the binder-to-sand ratio were carefully considered and, where possible, maintained constant across all mixtures to allow for meaningful comparisons. However, adjustments to the w/b ratio or the use of a superplasticizer were considered if the incorporation of olivine sand significantly affected the workability of the fresh mortar, with the aim of achieving a target consistency for all mixes. The selection of replacement percentages was based on typical ranges used for other SCMs and on preliminary trials, if conducted. The proportions of each constituent material (OPC, olivine sand, fine aggregate, and water) for each mixture were calculated based on weight and subsequently converted to volumetric proportions if needed for analysis. The mixture design aimed to cover a range of olivine contents that could potentially demonstrate its influence, from low percentages (e.g., 5-10%) to higher percentages (e.g., 20-30% or more), subject to maintaining acceptable fresh and hardened properties. The rationale behind each mixture proportion was documented, linking it to the specific research objectives of assessing the impact of olivine sand content on mortar performance. The overall goal

was to develop a set of mixtures that would allow for a clear and systematic investigation of the dose-dependent effects of olivine sand as a cement replacement material. The study design ensures that any observed differences in mortar properties can be primarily attributed to the presence and proportion of olivine sand.

Reference Mortar Mixture (Control Group)

A reference mortar mixture, designated as the control group, was prepared without any olivine sand. This mixture consisted solely of Ordinary Portland Cement (OPC), standard fine aggregate, and water. The proportions of the control mixture were established based on standard practices, often adhering to guidelines such as those in ASTM C109/C109M for compressive strength testing of hydraulic cement mortars, which typically specifies a cement-to-sand ratio of 1:2.75 by weight and a water-to-cement (w/c) ratio sufficient to achieve a prescribed flow (e.g., 0.485 for standard flow, though this can be adjusted). The primary purpose of the control mixture was to provide a baseline against which the performance of all olivine-modified mortar mixtures could be compared. All fresh property tests (workability, setting time, fresh density) and hardened property tests (compressive strength, flexural strength, density, water absorption, microstructural analysis, durability indicators) conducted on the experimental mixtures were also performed on the control mixture using identical procedures and curing conditions. This ensures that any changes observed in the properties of the olivine-containing mortars can be directly attributed to the replacement of cement with olivine sand. The consistency and reproducibility of the control mixture results were carefully monitored throughout the experimental program to validate the testing procedures and environmental conditions. The control mix serves as the benchmark for evaluating both positive and negative impacts of olivine incorporation.

Experimental Mortar Mixtures: Olivine Sand Replacement Ratios

The experimental mortar mixtures were designed by partially replacing Ordinary Portland Cement (OPC) with the processed olivine sand at several distinct weight percentages. Common replacement levels for exploratory studies of SCMs, such as 5%, 10%, 15%, 20%, and 30% by weight of total binder, were selected to systematically investigate the dose-dependent effect of olivine sand. The total binder content (OPC + olivine sand) was kept constant for all mixtures, maintaining the same binder-to-standard sand ratio as the control mixture (e.g., 1:2.75 by weight). The water-to-binder (w/b) ratio was initially targeted to be the same as the control mix. However, if the addition of olivine sand significantly altered the workability, minor adjustments to the w/b ratio or the inclusion of a minimal dosage of a polycarboxylate-based superplasticizer were considered to achieve a comparable flow value across all mixes, as per ASTM C109/C109M guidelines for maintaining consistent workability. This approach helps to differentiate the chemical/pozzolanic effects of olivine from mere physical effects due to changes in water demand. For each replacement level, a unique mixture designation was assigned (e.g., OS5, OS10, OS15, OS20, OS30, where OS denotes olivine sand and the number indicates the percentage replacement). The precise quantities of OPC, olivine sand, standard fine aggregate, and water (and superplasticizer, if used) for a standard batch size were calculated and recorded for each experimental mixture. This systematic variation in olivine content allows for the determination of trends in fresh properties, mechanical strength development, microstructural changes, and durability parameters as a function of the olivine replacement level, ultimately aiding in the identification of an optimal or permissible range of olivine incorporation.

Methodologies for Specimen Preparation and Curing

The preparation of mortar specimens followed standardized procedures to ensure uniformity and comparability of results. This involved meticulous batching of materials, a consistent mixing sequence, and standardized methods for casting and compacting the mortar into molds. After casting, the specimens were subjected to a controlled curing regime, which is critical for the

development of hydration products and the resultant mechanical and durability properties of the hardened mortar. The environment during both initial and subsequent curing phases, including temperature and humidity, was carefully regulated according to established standards. Any deviations from standard protocols were documented and justified. The integrity of the experimental results heavily relies on the consistency applied during these stages of specimen preparation and curing. Variations in mixing energy, compaction effort, or curing conditions can introduce significant scatter in the data, obscuring the true effects of the olivine sand addition [24]. Therefore, strict adherence to the prescribed methodologies was paramount throughout the specimen fabrication process. The aim was to produce high-quality, homogenous mortar specimens representative of each mixture proportion, allowing for a reliable assessment of the influence of olivine sand as a cement replacement material. The chosen methodologies are widely accepted in cement and concrete research, facilitating comparison with findings from other studies.

Mortar Cube Fabrication: Mixing, Casting, and Compaction

Mortar cubes, typically 50 mm x 50 mm x 50 mm (or 2 in. x 2 in. x 2 in.) as per ASTM C109/C109M, were fabricated for compressive strength testing and other hardened property evaluations. Prismatic specimens (e.g., 40 mm x 40 mm x 160 mm as per EN 196-1) were also prepared for flexural strength testing. The mixing procedure was conducted using a mechanical mixer of suitable capacity, following the sequence and timings specified in ASTM C305 (Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency). This typically involves first mixing the dry binder (OPC and olivine sand, if applicable) and standard sand, then adding the mixing water (containing superplasticizer, if used) and mixing for a specified duration at low speed, followed by a rest period, and then a final mixing period at medium speed. Immediately after mixing and determining fresh properties, the mortar was cast into pre-oiled steel molds in two layers. Each layer was compacted uniformly using a tamping rod, typically receiving 25 strokes distributed over the surface, as per ASTM C109/C109M, to ensure adequate consolidation and removal of entrapped air. For prismatic specimens, compaction might involve a jolting table if specified by the relevant standard (e.g., EN 196-1). The top surface of the specimens was struck off level with the top of the mold using a trowel. Care was taken to avoid over-compaction or segregation. All equipment, including the mixer bowl, paddle, molds, and tamping rod, was cleaned thoroughly between batches to prevent cross-contamination. The entire fabrication process was carried out in a controlled laboratory environment with stable temperature and humidity.

Standard Curing Protocols and Environmental Conditions

Following casting and compaction, the molded mortar specimens were subjected to a standardized curing regimen critical for consistent hydration and strength development. Immediately after casting, the molds containing the specimens were covered with a non-absorbent, non-reactive plate (e.g., glass or plastic) or placed in a high-humidity environment to prevent moisture loss from the exposed surfaces. They were then stored in a moist curing room or a temperature-controlled humidity cabinet maintained at $23 \pm 2^\circ\text{C}$ ($73.5 \pm 3.5^\circ\text{F}$) and a relative humidity of not less than 95% for the initial 24 ± 0.5 hours, as per ASTM C109/C109M and ASTM C511. After this initial curing period, the specimens were carefully demolded. Subsequent curing involved immersing the demolded specimens in saturated lime-water (calcium hydroxide solution) maintained at $23 \pm 2^\circ\text{C}$ until the age of testing. The saturated lime-water helps to prevent the leaching of calcium hydroxide from the specimens, ensuring a more representative hydration process. The curing water was periodically checked and replenished to maintain saturation and temperature. Specimens were retrieved from the curing tanks only shortly before testing. For specific tests, such as those related to drying shrinkage or carbonation, alternative curing conditions might be employed as per relevant standards, but for mechanical strength and primary microstructural analysis, standard moist curing is paramount. The consistent application of these curing protocols and

environmental controls across all control and experimental mixtures is essential for minimizing variability and ensuring that observed differences in performance are attributable to the mixture compositions rather than curing artifacts [25].

Analytical Techniques and Testing Standards Employed

A comprehensive suite of analytical techniques and standardized testing methods was employed to evaluate the properties of the raw materials, fresh mortars, and hardened mortar specimens. The selection of these techniques was guided by their relevance to assessing the performance of cementitious materials and their ability to elucidate the effects of olivine sand incorporation. Adherence to internationally recognized standards, primarily those published by ASTM International (American Society for Testing and Materials) or equivalent European Norms (EN), was maintained wherever applicable to ensure the reliability, reproducibility, and comparability of the test results. For material characterization, techniques included X-ray Fluorescence (XRF) for chemical composition, X-ray Diffraction (XRD) for mineralogical phase identification, laser diffraction for particle size analysis, Scanning Electron Microscopy (SEM) for morphology, and standard physical tests for specific gravity and fineness. Fresh mortar properties were assessed using the flow table test (ASTM C1437) for workability, Vicat apparatus (ASTM C191 adapted for mortar or ASTM C807) for setting times, and gravimetric methods for fresh density and air content (ASTM C185 or ASTM C231 adapted). Hardened mortar properties involved compressive strength (ASTM C109/C109M), flexural strength (ASTM C348), hardened density, water absorption and voids (ASTM C642). Microstructural analysis of hardened mortars utilized SEM with Energy-Dispersive X-ray Spectroscopy (EDS) for elemental mapping and phase identification, and XRD for crystalline phase analysis of hydration products. Durability-related assessments included water sorptivity (ASTM C1585 adapted for mortar) and potentially other tests relevant to porosity and transport properties [26]. The careful application of these established methods provides a robust framework for evaluating the impact of olivine sand as a cement replacement. Statistical analysis of the collected data was planned to determine the significance of observed differences between mixtures.

Characterization of Olivine Sand Properties

Particle Size Distribution Analysis and Specific Gravity Determination

The particle size distribution (PSD) of the processed olivine sand is a critical parameter influencing its behavior as a cement replacement, affecting packing density, water demand, and potential reactivity. The PSD was determined using a laser diffraction particle size analyzer (e.g., Malvern Mastersizer or similar). A representative sample of the ground olivine sand was dispersed in a suitable medium (typically water or ethanol, with a surfactant if necessary to prevent agglomeration) and circulated through the instrument's measurement cell. The instrument measures the angular distribution of scattered laser light from the particles, which is then converted into a volumetric particle size distribution using Mie or Fraunhofer scattering theory. Key parameters derived from the PSD analysis included the median particle size (d_{50}), d_{10} , d_{90} values, and the overall span of the distribution. The results were presented as cumulative and frequency distribution curves. This detailed PSD information allows for comparison with the fineness of Portland cement and helps in understanding how olivine particles might fit into the interstitial spaces within the cement paste or contribute to the overall particle packing of the binder system [23]. The specific gravity of the olivine sand was determined using the pycnometer method, similar to ASTM D854 for soils or an adaptation suitable for fine powders. A known mass of oven-dried olivine sand was introduced into a pycnometer of known volume, and the volume of displaced water (or another non-reactive liquid of known density) was measured. This allowed for the calculation of the solid density of the olivine particles. Specific gravity is an essential parameter for mixture proportioning and for calculating

porosity and void content in hardened mortars. The particle size and specific gravity data for olivine are fundamental inputs for interpreting its influence on fresh and hardened mortar properties [6].

Chemical Compositional Analysis via X-Ray Fluorescence (XRF)

The bulk chemical composition of the processed olivine sand was determined using X-ray Fluorescence (XRF) spectrometry. This technique is widely used for accurate quantitative analysis of major and minor elemental oxides in geological and cementitious materials. A representative sample of the dried olivine powder was prepared for XRF analysis, typically either by fusing it into a glass bead with a lithium borate flux or by pressing it into a pellet with a binding agent. The prepared sample was then irradiated with primary X-rays, causing the elements within the sample to emit secondary (fluorescent) X-rays at characteristic energies. The intensity of these emitted X-rays for each element is proportional to its concentration in the sample. By comparing these intensities with those from certified reference materials of known composition, the concentrations of various oxides, such as Silicon Dioxide (SiO_2), Magnesium Oxide (MgO), Iron(II) Oxide (FeO) or total iron as Fe_2O_3 , Aluminum Oxide (Al_2O_3), Calcium Oxide (CaO), and other minor oxides, were quantified. The Loss on Ignition (LOI) was also determined separately by heating a sample to a high temperature (e.g., 950-1000°C) to measure the mass loss due to volatiles like water and carbonates. The XRF analysis provides crucial information about the purity of the olivine, the relative proportions of magnesium and iron (which defines its position in the forsterite-fayalite solid solution series), and the presence of any potential impurities that might affect its performance in mortar [20]. This compositional data is essential for assessing its potential pozzolanic activity (related to SiO_2 content and reactivity) or other chemical interactions within the cement hydration environment. The results were typically reported as weight percentages of the oxides.

Mineralogical Phase Identification Using X-Ray Diffraction (XRD)

X-ray Diffraction (XRD) analysis was performed on the processed olivine sand to identify the crystalline mineralogical phases present and to assess its degree of crystallinity. A representative powdered sample of the olivine was prepared and mounted on a sample holder. The sample was then scanned over a range of 2θ angles (e.g., 5° to 70°) using a diffractometer equipped with a monochromatic X-ray source (commonly $\text{Cu K}\alpha$ radiation). As the X-ray beam interacts with the crystalline structures in the sample, diffraction occurs at specific angles according to Bragg's Law ($n\lambda = 2d \sin\theta$), where d is the spacing between atomic planes in the crystal lattice. The resulting diffraction pattern, a plot of diffracted X-ray intensity versus 2θ angle, provides a "fingerprint" of the crystalline phases present. By comparing the peak positions and relative intensities in the obtained diffractogram with standard diffraction patterns from databases such as the International Centre for Diffraction Data (ICDD), the constituent minerals in the olivine sand were identified. This analysis confirmed the primary olivine phases (e.g., forsterite, fayalite, or intermediate compositions) and helped detect any accessory minerals or alteration products (e.g., serpentine, talc, pyroxenes, or carbonates) that might be present [20]. The sharpness and intensity of the diffraction peaks also provided qualitative information about the crystallinity of the material. Understanding the precise mineralogical composition is vital because different silicate minerals exhibit varying degrees of reactivity and stability in the alkaline environment of cement paste. This XRD data complements the bulk chemical information from XRF by revealing how the elements are structurally combined into mineral phases [6].

Morphological Examination by Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was employed to examine the particle morphology, surface texture, and microstructural features of the processed olivine sand. Small, representative portions of the olivine powder were mounted on aluminum stubs using conductive double-sided carbon tape. To make the samples conductive and prevent charging under the electron beam, they

were sputter-coated with a thin layer of a conductive material, typically gold or carbon. The prepared stubs were then inserted into the SEM chamber. In the SEM, a focused beam of high-energy electrons scans across the sample surface. The interaction of the electron beam with the sample generates various signals, including secondary electrons (SE) and backscattered electrons (BSE). SE imaging provides high-resolution information about the surface topography and particle shape, while BSE imaging is sensitive to atomic number contrast and can help distinguish different phases if present. Micrographs were captured at various magnifications to reveal details ranging from the overall particle shapes (e.g., angular, sub-rounded, platy) to finer surface features such as roughness, porosity, or cleavage planes. The particle morphology of olivine sand can significantly influence the workability of fresh mortar, the water demand, and the inter-particle packing within the cementitious matrix [6]. Angular or irregularly shaped particles might increase inter-particle friction and water demand compared to more rounded particles. The surface texture can also affect the bond between the olivine particles and the cement paste. This visual information from SEM complements the quantitative data obtained from particle size analysis and is valuable for interpreting the behavior of olivine in mortar mixtures. If available, Energy-Dispersive X-ray Spectroscopy (EDS) coupled with SEM could provide localized elemental analysis of individual particles or features.

Assessment of Fresh Mortar Properties

Evaluation of Workability and Consistency: Flow Table Test

The workability and consistency of the fresh mortar mixtures, both control and those containing olivine sand, were evaluated using the flow table test in accordance with ASTM C1437 (Standard Test Method for Flow of Hydraulic Cement Mortar). This test provides a quantitative measure of the mortar's ability to deform under its own weight after a defined compactive effort, which is an indicator of its ease of placement and finishing. For each mortar batch, immediately after completion of mixing, a portion of the fresh mortar was placed into a standard conical brass mold (flow mold) resting on the clean, dry surface of the flow table. The mold was filled in two layers, with each layer tamped 20 times with a standard tamper. After striking off the excess mortar level with the top of the mold, the mold was carefully lifted vertically, leaving a truncated cone of mortar on the table. The flow table was then dropped 25 times through a height of 12.7 mm (0.5 in.) in 15 seconds. After the drops, the diameter of the spread mortar patty was measured in at least four directions, and the average diameter was recorded. The flow value was expressed as a percentage increase in the average base diameter of the spread mortar over the original base diameter of the mold. This test was performed for the control mixture and for all experimental mixtures containing different replacement levels of olivine sand. The results were used to assess the impact of olivine sand on the rheology of the fresh mortar. Significant changes in flow could indicate alterations in water demand, particle packing, or interparticle friction due to the presence of olivine particles. If necessary, adjustments to the water-to-binder ratio or superplasticizer dosage were considered to achieve a target flow range for all mixtures, ensuring comparable consistency for subsequent hardened property tests [12].

Determination of Setting Times: Initial and Final Vicat Needle Tests

The setting times (initial and final) of the cementitious binder in the mortar mixtures were determined to understand the influence of olivine sand on the early hydration kinetics and the transition from a plastic to a solid state. While ASTM C191 (Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle) is primarily for cement pastes, an adapted procedure or ASTM C807 (Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle) can be used for mortars. Alternatively, setting times can be inferred from tests on pastes made with the same binder compositions (OPC and olivine blends). For this study, if mortar setting times were directly measured, a portion of the fresh mortar sieved to remove coarse aggregate particles (if the standard sand was too coarse for the Vicat needle penetration) or paste extracted from

the mortar would be used. The test involves monitoring the penetration of a standard Vicat needle into a pat of the mortar or paste under a specified load. The initial setting time is defined as the time elapsed from the initial contact of cement with water until the Vicat needle penetrates to a point 25 mm (or a specified depth for mortar) from the bottom of the mold. The final setting time is the time elapsed until the needle makes an impression on the surface of the specimen but does not penetrate it. These tests were conducted for the control binder and for binders containing various percentages of olivine sand as a cement replacement. Changes in setting times can indicate whether olivine accelerates or retards the hydration reactions of Portland cement [12]. Acceleration might be due to nucleation effects, while retardation could be caused by interference with hydration product formation or by certain chemical constituents of the olivine. Understanding these effects is important for scheduling construction operations. The tests were performed under controlled temperature and humidity conditions.

Measurement of Fresh Density and Entrained Air Content

The fresh density (also known as unit weight) of the mortar mixtures was determined shortly after mixing, in accordance with procedures similar to ASTM C138/C138M (Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete), adapted for mortar. A standard measure of known volume (e.g., a 0.5 L or 1 L cylindrical container) was filled with the fresh mortar in layers, with each layer compacted by tamping to ensure full consolidation and removal of large entrapped air voids. After filling and compacting, the excess mortar was struck off level with the rim of the measure, and the outer surface of the measure was cleaned. The mass of the mortar-filled measure was then determined. By subtracting the mass of the empty measure, the net mass of the mortar was obtained. The fresh density was calculated by dividing the net mass of the mortar by the known volume of the measure. This property is useful for calculating yield and for quality control. The entrained air content of the fresh mortar was also assessed. While ASTM C231 (pressure method) or ASTM C173 (volumetric method) are standard for concrete, a simplified gravimetric method based on ASTM C185 (Standard Test Method for Air Content of Hydraulic Cement Mortar) or by comparing the theoretical density (calculated from mixture proportions and specific gravities of constituents, assuming no air) with the measured fresh density can provide an estimate for mortars. Air content influences workability, resistance to freeze-thaw cycles, and compressive strength. The incorporation of fine materials like olivine sand, especially if they have angular particle shapes or a high surface area, can affect the air content of the mortar [12]. These measurements were performed for the control mortar and all olivine-modified mortars to evaluate any changes in density or air entrainment due to olivine addition. Significant variations could impact the interpretation of mechanical strength results.

Mechanical Performance of Hardened Mortar Incorporating Olivine Sand

Compressive Strength Evolution at Designated Curing Intervals

Compressive strength is a primary indicator of the quality and mechanical performance of cementitious mortars. The evolution of compressive strength in olivine-modified mortars, compared to the control, was evaluated at several designated curing intervals, typically 3, 7, 28, and possibly 56 or 90 days, to assess both early and later-age strength development. For each mixture (control and olivine-modified mortars with varying replacement levels) and each testing age, a set of at least three 50 mm (2 in.) mortar cubes was tested in accordance with ASTM C109/C109M. The cubes, cured under standard moist conditions (saturated lime-water at $23 \pm 2^\circ\text{C}$) until the testing age, were removed from curing, surface-dried, and their dimensions checked. The specimens were then loaded in compression at a constant rate as specified by the standard (e.g., 900 to 1800 N/s or 200 to 400 lbf/s

for 50 mm cubes) using a calibrated compression testing machine until failure occurred. The maximum load sustained by the specimen was recorded, and the compressive strength was calculated by dividing this load by the cross-sectional area of the cube. The average compressive strength for each set of specimens was reported. The results were analyzed to determine the effect of olivine sand content and curing time on compressive strength. Comparisons were made with the control mortar to ascertain whether olivine acts as an inert filler, a reactive pozzolan contributing to strength, or if it has any detrimental effects [10]. The strength development pattern provides insights into the potential pozzolanic activity of olivine, which is typically slower and contributes more significantly at later ages if present [3]. The data obtained is crucial for evaluating the structural suitability of olivine-modified mortars.

Flexural Strength Characteristics of Olivine-Modified Mortar

Flexural strength (or modulus of rupture) is another important mechanical property of mortar, reflecting its ability to resist bending stresses. This property is particularly relevant for applications where tensile stresses might develop, such as in renders, plasters, or masonry jointing. The flexural strength of the control and olivine-modified mortar mixtures was determined using prismatic specimens, typically 40 mm x 40 mm x 160 mm, tested under three-point bending in accordance with ASTM C348 (Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars) or a similar standard like EN 196-1. For each mixture and testing age (e.g., 7, 28, and 90 days), a set of at least three prismatic specimens was cured under standard conditions. At the time of testing, specimens were removed from curing, surface-dried, and placed on two support rollers in the testing machine. The load was applied at a constant rate to the midpoint of the specimen via a third loading roller until fracture occurred. The maximum load applied at failure was recorded. The flexural strength was then calculated using the standard beam formula, which relates the failure load, span length, and specimen dimensions. The average flexural strength for each set of specimens was reported. The results were analyzed to evaluate the influence of olivine sand replacement on the flexural performance of the mortar. Like compressive strength, changes in flexural strength can indicate alterations in the binder matrix, such as improved density, better bond, or the presence of micro-cracks. The ratio of flexural to compressive strength can also provide insights into the brittleness of the material. The data helps to provide a more complete picture of the mechanical behavior of mortars incorporating olivine sand, beyond just compressive strength [15].

Determination of Hardened Density and Water Absorption Capacity

The hardened density and water absorption capacity of the mortar specimens provide valuable information about the compactness and pore structure of the material, which are closely related to its durability. These properties were determined for both control and olivine-modified mortar specimens at a specific curing age, typically 28 days, following procedures outlined in ASTM C642 (Standard Test Method for Density, Absorption, and Voids in Hardened Concrete), adapted for mortar specimens (e.g., fragments from flexural test specimens or dedicated cubes). For each mixture, a set of specimens was first oven-dried at $105 \pm 5^\circ\text{C}$ until a constant mass (M_{dry}) was achieved. After cooling in a desiccator, the specimens were immersed in water at room temperature for a specified period (e.g., 48 hours or until constant mass) to determine the saturated surface-dry mass (M_{ssd}). The saturated mass after immersion (M_{sat}) was also recorded by weighing the specimens while suspended in water (Archimedes principle). From these measurements, several parameters were calculated:

1. **Hardened Density (Bulk Density, Dry):** Calculated as $M_{\text{dry}} / (M_{\text{ssd}} - M_{\text{sat}})$ multiplied by the density of water.
2. **Water Absorption:** Calculated as $[(M_{\text{ssd}} - M_{\text{dry}}) / M_{\text{dry}}] \times 100\%$.
3. **Volume of Permeable Voids:** Calculated as $[(M_{\text{ssd}} - M_{\text{dry}}) / (M_{\text{ssd}} - M_{\text{sat}})] \times 100\%$ (if M_{sat} is the apparent mass in water after boiling, as per the full ASTM C642 procedure for concrete, though simple immersion is often used for comparative mortar studies).

Lower water absorption and higher hardened density generally indicate a denser, less porous microstructure, which is desirable for enhanced durability [27]. The incorporation of fine SCMs, if they contribute to pore refinement or pozzolanic reactions, can lead to reduced water absorption [18]. These tests help to assess whether olivine sand contributes to a denser matrix or alters the porosity of the mortar.

Statistical Validation of Mechanical Test Data

To ensure the reliability and significance of the experimental findings related to mechanical performance, statistical validation of the test data was conducted. For each mechanical property (compressive strength, flexural strength) and at each testing age, multiple replicate specimens (typically three or more) were tested for every mortar mixture (control and olivine-modified). From these replicates, the mean value and standard deviation were calculated to quantify the average performance and the variability within each set of results. To determine if the observed differences in mechanical properties between the control mortar and the olivine-modified mortars, or among mortars with different olivine replacement levels, were statistically significant, Analysis of Variance (ANOVA) was employed. A one-way ANOVA could be used to compare the means of multiple groups (e.g., different olivine percentages) at a specific confidence level (typically 95%, i.e., p-value < 0.05). If the ANOVA indicated a significant difference among group means, post-hoc tests such as Tukey's HSD (Honestly Significant Difference) test or Dunnett's test (for comparing multiple treatments with a control) were performed to identify which specific pairs of means were significantly different from each other. This rigorous statistical approach helps to distinguish genuine material effects from random experimental error or natural variability in the specimens [12]. The results of the statistical analysis provide a greater degree of confidence in the conclusions drawn regarding the impact of olivine sand on the mechanical properties of the mortar. Coefficient of variation (COV) for each set of replicates was also calculated to assess the consistency of the test results. Proper statistical treatment is essential for drawing robust conclusions from experimental data in materials science research.

Microstructural and Durability Evaluation of Olivine-Based Mortar

Microstructural Investigation using Scanning Electron Microscopy (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDS)

A detailed microstructural investigation of the hardened mortar specimens was conducted using Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS). This powerful analytical combination allows for high-magnification imaging of the mortar's internal structure and simultaneous elemental analysis of specific features. Specimens were typically prepared from fragments of mortar cubes tested at 28 days or later ages. Small pieces were carefully fractured or cut, then mounted on aluminum stubs and sputter-coated with a conductive layer (e.g., gold or carbon) to prevent charging. The SEM analysis focused on several aspects: the general morphology of the hydration products, the density and homogeneity of the cement paste matrix, the characteristics of the interfacial transition zone (ITZ) between olivine particles (if visible as distinct entities) or remaining cement grains and the hydrated paste, and the presence of any unreacted olivine particles. SEM micrographs were captured in both secondary electron (SE) mode for topographical details and backscattered electron (BSE) mode for compositional contrast (heavier elements appear brighter) [28]. EDS analysis was performed on specific points of interest, linescans across interfaces, or elemental mapping over selected areas to identify the elemental composition of different phases, helping to distinguish between C-S-H gel, calcium hydroxide (CH), ettringite, unhydrated cement grains, olivine particles, and potentially new phases formed due to olivine interaction [29]. This microstructural characterization is crucial for understanding how olivine sand influences the hydration process and the development of the hardened paste structure, which in turn governs the mechanical and durability properties of the mortar [30].

Analysis of Interfacial Transition Zone (ITZ) Modifications

The Interfacial Transition Zone (ITZ) is a thin region, typically 10-50 μm wide, that forms around aggregate particles (or in this case, potentially larger olivine particles if they act as fine aggregate rather than reacting) in cementitious composites. The ITZ is generally characterized by higher porosity, a greater concentration of large calcium hydroxide (CH) crystals, and a lower content of dense C-S-H gel compared to the bulk paste. Consequently, the ITZ is often considered the weakest link in concrete and mortar, significantly influencing mechanical strength and transport properties. In this study, SEM-EDS analysis was specifically directed at examining the ITZ between the original sand aggregate and the cement paste, as well as any interface formed around unreacted or partially reacted olivine particles. The objective was to determine if the incorporation of olivine sand as a cement replacement modifies the characteristics of the ITZ. Potential modifications could include densification of the ITZ due to the filler effect of fine olivine particles packing into this region, or pozzolanic reaction of olivine consuming CH and forming additional C-S-H, thereby refining the ITZ microstructure [19]. BSE imaging coupled with EDS mapping for elements like Ca, Si, Al, Mg, and Fe across the ITZ was employed to assess changes in porosity (qualitatively) and phase distribution. A denser, less porous ITZ generally leads to improved mechanical properties and reduced permeability. Conversely, if olivine particles are relatively inert and poorly bonded, they might introduce new, weaker interfaces. The analysis aimed to compare the ITZ in control mortars with those in olivine-modified mortars at different replacement levels to understand the impact of olivine on this critical microstructural feature.

Identification and Characterization of Hydration Products

The primary binding phase in hydrated Portland cement is calcium silicate hydrate (C-S-H) gel, an amorphous or poorly crystalline material. Other key hydration products include crystalline calcium hydroxide (CH, or portlandite) and calcium sulfoaluminates such as ettringite (AFt) and monosulfoaluminate (AFm). The incorporation of olivine sand as a cement replacement could influence the type, morphology, and relative amounts of these hydration products. SEM-EDS was utilized to identify and characterize these phases in both control and olivine-modified mortars. C-S-H typically appears as a fine-grained, fibrous, or reticular network in SEM images, and its EDS spectrum shows high peaks for Ca and Si. CH often forms as large, hexagonal platy crystals, easily identified by its morphology and high Ca content in EDS. Ettringite usually crystallizes as needle-like or prismatic crystals, rich in Ca, Al, S, and O. A key aspect of this investigation was to search for evidence of olivine's reactivity. If olivine (primarily $(\text{Mg,Fe})_2\text{SiO}_4$) participates in pozzolanic or other chemical reactions, it might lead to the formation of new or modified hydration products. For example, the reaction of silica from olivine with CH could produce additional C-S-H. The magnesium component of olivine could potentially react to form magnesium silicate hydrate (M-S-H), brucite ($\text{Mg}(\text{OH})_2$), or hydrotalcite-like phases, especially if conditions favor their formation [18]. EDS analysis was crucial for detecting increased Mg or Fe concentrations within the hydration products or at the surface of olivine particles, which might suggest such reactions. The morphology and distribution of these products were documented through micrographs to understand their contribution to the overall microstructure and densification of the mortar [10].

Phase Analysis of Hydration Products by X-Ray Diffraction (XRD)

In addition to SEM-EDS, X-Ray Diffraction (XRD) analysis was conducted on powdered samples of hardened mortar at selected curing ages (e.g., 28 and 90 days) to identify the crystalline phases present in the hydrated binder. This technique complements SEM by providing bulk information about the crystalline components. Samples were prepared by grinding small pieces of the hardened mortar (from which coarse aggregate particles were removed as much as possible) into a fine powder. The XRD patterns were obtained by scanning the powdered samples over a range of 2θ angles,

similar to the procedure used for characterizing raw materials. The resulting diffractograms were analyzed by comparing the peak positions and intensities with standard

This study investigates the feasibility and effects of partially replacing Ordinary Portland Cement (OPC) with processed olivine sand in mortar mixtures. The research systematically evaluates the dose-dependent impact of olivine sand on both fresh and hardened mortar properties. Mortar mixtures were designed with olivine sand replacing OPC by weight at various percentages, typically ranging from 5% to 30%, alongside a control mixture without olivine. Key mixture parameters, such as the water-to-binder and binder-to-sand ratios, were carefully controlled, with adjustments made to maintain consistent workability across all mixes .

Specimen preparation followed standardized procedures, including meticulous mixing, casting, and compaction of mortar cubes and prisms, followed by standard moist curing in saturated lime-water at $23 \pm 2^\circ\text{C}$. The characterization of the olivine sand involved particle size distribution analysis , specific gravity determination , chemical composition via X-ray Fluorescence (XRF) , mineralogical phase identification using X-ray Diffraction (XRD) , and morphological examination through Scanning Electron Microscopy (SEM) .

Fresh mortar properties assessed included workability (flow table test) , setting times (Vicat needle) , fresh density, and entrained air content . The mechanical performance of hardened mortars was evaluated through compressive strength and flexural strength at various curing ages, complemented by measurements of hardened density and water absorption capacity . Statistical analysis was applied to validate the mechanical test data . Microstructural investigations employed SEM with Energy-Dispersive X-ray Spectroscopy (EDS) to analyze hydration products, modifications to the interfacial transition zone (ITZ) , and potential new phase formation . XRD analysis of hardened mortars further identified crystalline hydration products . This comprehensive approach provides a robust framework for assessing olivine sand's influence as a cement replacement material, aiming to identify optimal or permissible incorporation ranges for improved mortar performance.

Standard diffraction data from databases (e.g., ICED PDF-4+). This allowed for the identification of unhydrated cement clinker phases (e.g., C_3S , C_2S), crystalline hydration products such as portlandite (CH), ettringite (AFt), and potentially monosulfoaluminate (AFm) or calcium carbonate phases (calcite, aragonite, vaterite) if carbonation had occurred. A key focus was to detect any new crystalline phases that

References

1. K. Malaga, N. Al-Ayish, and U. Mueller, "Sustainability Aspects of New Admixtures and Supplementary Cementitious Materials for Durable Concrete," *The 1st International Conference on Smart Materials for Sustainable Construction*. MDPI, p. 14, Nov. 18, 2019. doi: 10.3390/proceedings2019034014.
2. A. I. Nicoara et al., "End-of-Life Materials Used as Supplementary Cementitious Materials in the Concrete Industry," *Materials*, vol. 13, no. 8. MDPI AG, p. 1954, Apr. 22, 2020. doi: 10.3390/ma13081954.
3. "Influence of supplementary cementitious materials on hydration and microstructure development of concrete," *Proceedings International*, vol. 1, no. 1. AMG Transcend Association, pp. 43–44, Oct. 15, 2019. doi: 10.33263/proceedings11.00430044.
4. A. Nanni, "The Role of Cementitious Materials in the Next Decade," *Sustainable Construction Materials and Technologies (SCMT)*, vol. 1. Coventry University, pp. 3–12, 2016. doi: 10.18552/2016/scmt4kn1.
5. "Improved durability of concrete using supplementary cementitious materials," *Sustainable Construction Materials and Technologies (SCMT)*, vol. 3. Coventry University and The University of Wisconsin Milwaukee Centre for By-products Utilization, pp. 204–214, 2019. doi: 10.18552/2019/idsctm5151.
6. M. TOGO and A. NAKAHIRA, "Effect of Alcohol Addition on the Microstructure of Olivine Material by Hydrothermal Synthesis," *Journal of the Japan Society of Powder and Powder Metallurgy*, vol. 64, no. 8. Japan Society of Powder and Powder Metallurgy, pp. 423–427, 2017. doi: 10.2497/jjspm.64.423.

7. A. T. Bakera and M. G. Alexander, "Use of metakaolin as supplementary cementitious material in concrete, with focus on durability properties," *RILEM Technical Letters*, vol. 4. Rilem Publications SARL, pp. 89–102, Nov. 12, 2019. doi: 10.21809/rilemtechlett.2019.94.
8. A. Bouaissi, L. Yuan Li, M. Mustafa Al Bakri Abdullah, R. Ahmad, R. Abdul Razak, and Z. Yahya, "Fly Ash as a Cementitious Material for Concrete," *Zero-Energy Buildings - New Approaches and Technologies*. IntechOpen, Dec. 16, 2020. doi: 10.5772/intechopen.90466.
9. R. Jaskulski, D. Józwiak-Niedźwiedzka, and Y. Yakymchko, "Calcined Clay as Supplementary Cementitious Material," *Materials*, vol. 13, no. 21. MDPI AG, p. 4734, Oct. 23, 2020. doi: 10.3390/ma13214734.
10. C. Jiang, X. Zhou, G. Tao, and D. Chen, "Experimental Study on the Performance and Microstructure of Cementitious Materials Made with Dune Sand," *Advances in Materials Science and Engineering*, vol. 2016. Wiley, pp. 1–8, 2016. doi: 10.1155/2016/2158706.
11. Y. Zhang and G. Ye, "Effect of Limestone Powder on Microstructure of Ternary Cementitious System," *Sustainable Construction Materials 2012*. American Society of Civil Engineers, pp. 225–234, Dec. 13, 2012. doi: 10.1061/9780784412671.0020.
12. J. Olek and C. Paleti, "Compatibility of Cementitious Materials and Admixtures," Purdue University, Dec. 2012. doi: 10.5703/1288284315025.
13. Y. Wang, Y. Cao, P. Zhang, and Y. Ma, "Effective Utilization of Waste Glass as Cementitious Powder and Construction Sand in Mortar," *Materials*, vol. 13, no. 3. MDPI AG, p. 707, Feb. 05, 2020. doi: 10.3390/ma13030707.
14. G. Sebki, B. Safi, and K. Chahour, "Recycling of Foundry Sand Wastes in Self-Compacting Mortars: Use as Cementitious Materials and Fine Aggregates," *Journal of Applied Engineering Sciences*, vol. 9, no. 2. Walter de Gruyter GmbH, pp. 195–200, Dec. 01, 2019. doi: 10.2478/jaes-2019-0027.
15. H. Yang, W. Li, and Y. Che, "3D Printing Cementitious Materials Containing Nano-CaCO₃: Workability, Strength, and Microstructure," *Frontiers in Materials*, vol. 7. Frontiers Media SA, Aug. 07, 2020. doi: 10.3389/fmats.2020.00260.
16. S. K. Adhikary, Ž. Rudžionis, and R. Rajapriya, "The Effect of Carbon Nanotubes on the Flowability, Mechanical, Microstructural and Durability Properties of Cementitious Composite: An Overview," *Sustainability*, vol. 12, no. 20. MDPI AG, p. 8362, Oct. 12, 2020. doi: 10.3390/su12208362.
17. J. Wang, Y. Xu, X. Wu, P. Zhang, and S. Hu, "Advances of graphene- and graphene oxide-modified cementitious materials," *Nanotechnology Reviews*, vol. 9, no. 1. Walter de Gruyter GmbH, pp. 465–477, Jan. 01, 2020. doi: 10.1515/ntrev-2020-0041.
18. S. A. Mostafa et al., "Influence of Nanoparticles from Waste Materials on Mechanical Properties, Durability and Microstructure of UHPC," *Materials*, vol. 13, no. 20. MDPI AG, p. 4530, Oct. 13, 2020. doi: 10.3390/ma13204530.
19. W. Jing, J. Jiang, S. Ding, and P. Duan, "Hydration and Microstructure of Steel Slag as Cementitious Material and Fine Aggregate in Mortar," *Molecules*, vol. 25, no. 19. MDPI AG, p. 4456, Sep. 28, 2020. doi: 10.3390/molecules25194456.
20. V. G. Batanova et al., "New Olivine Reference Material for In Situ Microanalysis," *Geostandards and Geoanalytical Research*, vol. 43, no. 3. Wiley, pp. 453–473, Jun. 05, 2019. doi: 10.1111/ggr.12266.
21. J. S. J. van Deventer, R. San Nicolas, I. Ismail, S. A. Bernal, D. G. Brice, and J. L. Provis, "Microstructure and durability of alkali-activated materials as key parameters for standardization," *Journal of Sustainable Cement-Based Materials*, vol. 4, no. 2. Informa UK Limited, pp. 116–128, Nov. 12, 2014. doi: 10.1080/21650373.2014.979265.
22. M. Mirzahosseini, "Microstructural Modeling of Glass Cullet Reaction in Cementitious Systems." MDPI AG, May 17, 2018. doi: 10.20944/preprints201805.0239.v1.
23. W. Guan, Q. Qi, Z. Zhang, and S. Nan, "Effect of Sand Particle Size on Microstructure and Mechanical Properties of Gypsum-Cemented Similar Materials," *Materials*, vol. 13, no. 3. MDPI AG, p. 765, Feb. 07, 2020. doi: 10.3390/ma13030765.
24. J. Van Der Putten, M. Deprez, V. Cnudde, G. De Schutter, and K. Van Tittelboom, "Microstructural Characterization of 3D Printed Cementitious Materials," *Materials*, vol. 12, no. 18. MDPI AG, p. 2993, Sep. 16, 2019. doi: 10.3390/ma12182993.

25. S. J. Abbey, E. U. Eyo, J. Oti, S. Y. Amakye, and S. Ngambi, "Mechanical Properties and Microstructure of Fibre-Reinforced Clay Blended with By-Product Cementitious Materials," *Geosciences*, vol. 10, no. 6. MDPI AG, p. 241, Jun. 21, 2020. doi: 10.3390/geosciences10060241.
26. M. Promentilla, S. Cortez, R. Papel, B. Tablada, and T. Sugiyama, "Evaluation of Microstructure and Transport Properties of Deteriorated Cementitious Materials from Their X-ray Computed Tomography (CT) Images," *Materials*, vol. 9, no. 5. MDPI AG, p. 388, May 19, 2016. doi: 10.3390/ma9050388.
27. C.-C. Hung, Y.-C. Wu, W.-T. Lin, J.-J. Chang, and W.-C. Yeih, "Effect of Mixture Variables on Durability for Alkali-Activated Slag Cementitious," *Materials*, vol. 11, no. 11. MDPI AG, p. 2252, Nov. 12, 2018. doi: 10.3390/ma11112252.
28. P. Azarsa, R. Gupta, and A. Biparva, "Inventive Microstructural and Durability Investigation of Cementitious Composites Involving Crystalline Waterproofing Admixtures and Portland Limestone Cement," *Materials*, vol. 13, no. 6. MDPI AG, p. 1425, Mar. 20, 2020. doi: 10.3390/ma13061425.
29. C. Qiao and D. Rothstein, "Microstructural Evaluation of Durability of Different Cementitious Mixtures in Microbial Induced Corrosion Environments," *XV International Conference on Durability of Building Materials and Components. eBook of Proceedings*. CIMNE, 2020. doi: 10.23967/dbmc.2020.214.
30. W. Jiang et al., "Cement-Based Materials Containing Graphene Oxide and Polyvinyl Alcohol Fiber: Mechanical Properties, Durability, and Microstructure," *Nanomaterials*, vol. 8, no. 9. MDPI AG, p. 638, Aug. 21, 2018. doi: 10.3390/nano8090638.

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