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Wheat Straw Ash as a Sustainable Supplementary Cementitious Material in Concrete: Effects of Replacement Level, Physicochemical Characteristics, and Mechanical Performance

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Abstract

This study aims to critically evaluate the potential of wheat straw ash (WSA) as a sustainable supplementary cementitious material (SCM) for enhancing the mechanical performance of concrete while reducing Portland cement consumption and promoting agricultural waste valorization. The research systematically examines the influence of WSA replacement levels on compressive, splitting tensile, and flexural strengths, with particular emphasis on identifying the optimum replacement level and assessing the feasibility of relatively high WSA incorporation. A comparative synthesis of published literature is integrated with experimental observations to establish the consistency of reported strength trends across different WSA contents and processing conditions. The study further investigates the mechanisms governing strength development, particularly the contribution of silica-rich WSA to pozzolanic reactions and subsequent calcium silicate hydrate (C–S–H) formation. Particular attention is given to the effects of WSA physicochemical characteristics, including silica structure, particle fineness, combustion temperature, combustion duration, and post-processing, on pozzolanic reactivity and mechanical performance. The overall objective is to establish scientifically robust relationships between WSA characteristics, replacement level, and concrete strength development, thereby determining the conditions under which WSA can function effectively as an SCM. The findings are intended to support optimized WSA utilization and advance sustainable, low-carbon concrete production.

1. Introduction

Concrete remains the most extensively utilized construction material worldwide owing to its versatility, durability, and economic viability. However, increasing concerns regarding the environmental footprint of cement production have intensified the search for sustainable supplementary cementitious materials (SCMs) capable of partially replacing cement while enhancing concrete performance. Agricultural residues, including rice husk ash, sugarcane bagasse ash, and wheat straw ash (WSA), have attracted considerable attention because of their abundance and pozzolanic potential. Wheat straw generated during agricultural processing is frequently disposed of through open-field burning (Fig. 1), resulting in substantial environmental pollution [1]. Conversely, controlled combustion of wheat straw can yield silica-rich amorphous ash [2], which constitutes an essential component in cementitious systems. Owing to its high silica content and pronounced pozzolanic reactivity, WSA has been recognized as a promising supplementary cementitious material [3]. As an abundant agricultural by-product, wheat straw is often indiscriminately burned or discarded, exacerbating environmental concerns [4]. When suitably processed, WSA reacts with calcium hydroxide released during cement hydration to form secondary calcium silicate hydrate (C–S–H) gel, thereby promoting strength development and enhancing the durability characteristics of concrete Morsy [5].

Doğruyol and Çetin [6] reported that the silica (SiO_2) content of wheat straw ash (WSA) reached 85.19% of its total chemical composition. Similarly, Babar et al. [7], utilizing wheat straw obtained from a flour mill in Hyderabad, Pakistan, determined a SiO_2 content of 73.95%. Comparable findings were reported by Bheel et al. [8], who identified a silica content of approximately 67.34%, whereas Amin et al. [3] and

Qudoos et al. [9] reported values of 53.69% and 65.70%, respectively. In contrast, Ahmad et al. [10] recorded a comparatively lower silica content of 39.63%, while Aksoğan et al. [11] reported a markedly lower value of 4.99%. Such disparities in silica composition are primarily attributable to variations in geographical conditions, soil characteristics, agronomic practices, and fertilizer application. Numerous studies have examined the feasibility of utilizing WSA as a partial cement replacement, demonstrating varying effects on compressive, tensile, and flexural strengths as a function of particle fineness, replacement ratio, and curing regime [8, 12–15]. The influence of WSA silica content on the mechanical performance of concrete as reported by various researchers summarizes in Table 1.

Despite the growing body of research, a consensus regarding the optimum replacement level and processing conditions of WSA for enhancing concrete performance remains elusive. A comprehensive comparative assessment of the existing literature is therefore essential to elucidate the effectiveness of WSA, identify existing knowledge gaps, and provide direction for future developments in sustainable cementitious materials. In general, the findings presented in Table 1 reveal considerable discrepancies concerning the influence of WSA incorporation on concrete strength. Several investigations, including those of Babar et al. [7], Bheel et al. [8], Katman et al. [14] and Sayed et al. [16] reported enhancements in compressive strength at low to moderate replacement levels, typically ranging from 5% to 20%. Conversely, other studies have documented a decline in strength beyond specific substitution thresholds. For example, Amin et al. [3] and Khan et al. [17] observed a progressive reduction in compressive strength with increasing WSA content, particularly at elevated replacement ratios. Likewise, Memon et al. [15] reported fluctuating results, indicating the absence of a definitive trend in strength development. In contrast, Qudoos et al. [9], Khushnood et al. [18], and Jankovsky et al. [19], Darweesh et al. [20], Hussein et al. [21] and Memon et al. [22] demonstrated substantial strength enhancement relative to ordinary Portland cement (OPC), thereby underscoring the potential of WSA as an effective supplementary cementitious material under optimized conditions.

These inconsistencies may be ascribed to variations in critical parameters, including silica content, which ranges from approximately 39% to more than 85%, combustion conditions, particle size distribution, mixture proportions, and curing protocols. Consequently, the highly variable findings reported in the literature suggest that the performance of WSA-based concrete is intrinsically governed by the physicochemical characteristics and processing conditions of the ashes, thereby precluding the establishment of a universally applicable optimum replacement level in the absence of standardized production and characterization procedures. This study aims to undertake a comprehensive and critical comparative evaluation of the existing body of literature concerning the utilization of wheat straw ash (WSA) as a supplementary cementitious material and its influence on the mechanical performance of concrete. Emphasis is placed on elucidating the effects of WSA incorporation on compressive, tensile, and flexural strengths, while systematically examining the underlying factors governing its performance, including silica content, particle fineness, replacement level, combustion conditions, and curing regime. Furthermore, the study seeks to synthesize prevailing research findings, identify existing inconsistencies and knowledge gaps, and establish correlations between the physicochemical characteristics of WSA and the resulting development of concrete strength. By providing a critical appraisal of previous

investigations and integrating their findings, this work aims to furnish valuable insights into the viability of WSA as a sustainable supplementary cementitious material and to delineate its practical implications for the design and production of environmentally benign, high-performance concrete for contemporary construction applications.

2. Methods (materials and methods)

2.1. Cement

Cement type CEM I 42.5R, conform with Iraqi Standard Specifications (IQS 5:2019) and European standards (EN 197-1:2011 was used in the experimental study. The properties and mineral composition of cement shown in Table 2 were provided by the manufacturer (KAR Company for Cement Industry).

2.2. Wheat Straw Ash

2.2.1. Wheat Straw Ash Samples Preparation

Wheat straw ash (WSA) was first collected from an open field after the uncontrolled burning of locally accessible wheat straw, with an estimated combustion temperature ranging from 350 to 500°C. After cooling to ambient temperature, the collected ash underwent controlled secondary calcination to improve its physicochemical properties. The ash was re-incinerated in a laboratory furnace (Lab rotary kiln furnace) at three different temperatures, namely 550 and 750°C, for one hour to create three separate WSA samples, designated as WSA-1 and WSA-2, respectively. Each sample was then cooled and processed in a ball mill to produce a finer, more uniform powder appropriate for use as a supplemental cementitious material. Figure 2 depicts the color variation of wheat straw ash (WSA) produced at various burning temperatures. The color of the ash gradually changed from dark to white gray as the burning temperature increased. This color change is typically connected with the gradual elimination of unburned carbon and other organic compounds during combustion. However, visual appearance alone was not deemed sufficient to establish the optimal burning temperature. To achieve the intended particle size, wheat straw ash (WSA) was mechanically processed in a laboratory-scale grinder to reduce particle size while improving fineness and specific surface area. The grinding operation was carried out for 2 hours to produce a fine and uniform WSA powder appropriate for usage as a supplemental cementitious material. The physical parameters of the ground WSA were then characterized using particle-size distribution and specific surface area analyzing.

2.2.2 Physical properties

The particle size distribution and specific surface area of the wheat straw ash (WSA) samples were evaluated using laser particle size analysis (X-Ray diffraction). The data obtained are presented in Tables 3. The analysis revealed that the majority of WSA particles were distributed within a size range of approximately 15–41μm. Furthermore, the median particle diameter (D50) of the samples investigated was found 28.53μm. In general, the particle size characteristics of WSA are highly dependent on the

grinding duration and milling conditions employed during processing. Prolonged grinding typically results in finer particles and a larger specific surface area.

2.2.3. Chemical properties

The chemical oxide compositions in weight percent of the WSA samples, determined used X-Ray Fluorescence are presented in Table 4. The obtained chemical composition results were compared with the requirements of relevant standards for pozzolanic materials to assess the feasibility of utilizing WSA as a partial replacement for ordinary Portland cement in concrete mixtures.

2.2.3. X-Ray diffraction analysis of WSA Samples

Figures 3 and 4 show the microstructure of WSA-1, WAS-2 based on X-ray diffraction (XRD) scan. The XRD pattern of the sample burned at 550°C reveals the presence of quartz, cristobalite, and kyanite phases. The diffraction pattern is dominated by a strong cristobalite reflection at approximately 27–28° 2θ, reaching an intensity of about 427 counts, while a prominent quartz reflection occurs at approximately 22–23° 2θ with an intensity of about 288 counts. Additional cristobalite reflections are observed near 31° and 44°, whereas quartz exhibits another reflection near 52°. A weak kyanite reflection is detected at approximately 70°. The presence of distinct diffraction peaks together with the broad background indicates a partially crystalline structure with an appreciable amorphous fraction. Overall, cristobalite represents the dominant crystalline SiO_2 phase in the sample treated at 550°C.

The XRD pattern of the sample burned at 750°C demonstrates the presence of cristobalite, quartz, and kyanite. The most intense diffraction peak is attributed to cristobalite at approximately 24° 2θ, with an intensity of about 590 counts. Strong quartz reflections are observed at approximately 20° and 27° 2θ, with intensities of approximately 370 and 465 counts, respectively. Additional cristobalite reflections occur near 31° and 43°, while quartz is also detected near 53°. A weak reflection corresponding to kyanite is observed at approximately 68–69° 2θ. Compared with the sample burned at 550°C, the increased peak intensities and sharper reflections at 750°C indicate enhanced crystallinity and development of the crystalline silica phases. Cristobalite appears to be the dominant crystalline phase at this temperature, although quartz remains clearly present.

2.3. Aggregate

2.3.1 fine aggregate

The fine aggregate employed in this investigation was natural river sand, which is widely found in Iraq's northern regions. Prior to usage, the sand was sieved through a 4.75 mm (No. 4) sieve to eliminate large particles and ensure uniform particle size distribution. The granulometric properties of the fine aggregate were measured using an oven-dried sample in accordance with Iraqi Specification IQS No. 45/1984 Natural Aggregates Used in Concrete. Table 5 shows the resulting particle size distribution and computed fineness modules for the fraction that passed through the No. 4 sieve. The fine aggregate's physical parameters, including specific gravity and water absorption, were measured in accordance with

Iraqi Specification No. 45/1984 Natural Aggregates Used in Concrete, and to EN 1097-6 standard. The sand had a fineness modulus of 2.63, a specific gravity of 2.67, and a water absorption of 1.13 percent. These qualities suggest that fine aggregate is suitable for use in typical concrete compositions.

2.3.2 Coarse aggregate

Coarse aggregate refers to granular material retained on the No. 4 sieve and represents a fundamental constituent in concrete production. The appropriate aggregate size is generally selected according to the required concrete performance and the specific structural application. In the present investigation, angular and non-crushed coarse aggregates with a maximum nominal size of 20 mm were sourced from the laboratory of the *Building and Construction Technology Engineering Department Al Omniyat University*. Before incorporation into the concrete mixtures, the aggregates were carefully cleaned using potable water to eliminate surface impurities, fine dust, and any harmful substances that could adversely affect the bonding characteristics of the concrete. The characterization of the coarse aggregates was conducted in accordance with the procedures outlined with Iraqi Specification No. 45/1984 Natural Aggregates Used in Concrete, and to EN 1097-6 standard. Laboratory testing included the determination of fineness modulus, specific gravity, and water absorption. The results obtained indicated that the coarse aggregates possessed a fineness modulus of 6.8, a specific gravity of 2.74, and a water absorption value of 0.96%, demonstrating their suitability for concrete production.

2.4 Concrete Mixture

The concrete mixtures were proportioned following the principles of ACI 211.1, Standard Practice for Selecting *Proportions for Normal, Heavyweight, and Mass Concrete*. The reference concrete was designed with a water-to-binder ratio of 0.50, corresponding to 460 kg/m³ of total binder and 230 kg/m³ of mixing water (table – 5). The constituent materials and aggregate properties were characterized in accordance with the relevant Iraqi Standards, including IQS No. 45/1984 for aggregates. The final mixture proportions were adjusted based on the measured physical properties of the constituent materials and verified through trial mixtures to achieve the targeted workability and mechanical performance. The mix design process was carried out to achieve the targeted workability, strength, and durability requirements while maintaining appropriate proportions of cementitious materials, fine aggregate, coarse aggregate, and water. In this study, WSA was utilized as a supplementary cementitious material and incorporated as a partial replacement of ordinary Portland cement at replacement levels of 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50% by weight of cement. A control mixture without WSA was also prepared for comparison purposes. All concrete mixtures were produced using the same mixing, casting, and curing procedures to ensure consistency throughout the experimental program. The detailed proportions of the control and WSA-modified concrete mixtures are presented in Table 5. The total binder content is 460 kg/m^3, fine aggregate of 785kg/m^3, and coarse aggregate of 800kg/m^3, as presented in Table 6. The water-to-binder ratio (w/b) was kept constant at 0.50. Superplasticizer was used to keep the mixtures' workability within the permitted limit for all mixtures.

3. Results and Discussion (Compressive strength)

Figures 5 and 6 illustrate the evolution of compressive strength. The compressive-strength results demonstrate that the incorporation of waste silica ash (WSA) exerted a pronounced influence on the mechanical performance and strength-development characteristics of the cementitious mixtures, with the magnitude of this response being strongly governed by both the WSA type and replacement ratio. In general, the investigated mixtures exhibited a characteristic increase in compressive strength with increasing WSA content up to an optimum replacement level, followed by a progressive deterioration in strength at higher replacement ratios. This behavior indicates that the incorporation of WSA involves a balance between its beneficial pozzolanic contribution, micro-filler effect, particle packing enhancement, and pore-structure refinement on one hand, and the adverse cement dilution effect and reduction in clinker availability on the other. For both WSA-1 and WSA-2, the optimum replacement level was consistently identified as 20%, irrespective of the curing age. This finding is particularly significant because it indicates that the incorporation of WSA does not simply produce a linear response with increasing replacement level; rather, an optimum proportion exists at which the combined physical and chemical contributions of the ash are maximized. At moderate replacement levels, the fine WSA particles can contribute to improved particle packing within the cementitious matrix, potentially reducing interparticle voids and promoting a denser transition zone. In addition, the reactive silica fraction of WSA can participate in secondary pozzolanic reactions with calcium hydroxide generated during Portland cement hydration, resulting in additional calcium–silicate–hydrate (C–S–H) gel. Such secondary hydration products can contribute to matrix densification, reduction of capillary porosity, and enhancement of the load-bearing capacity of the hardened cement paste.

The superiority of WSA-2 over WSA-1 was evident throughout the investigated curing period. At the optimum replacement level of 20%, WSA-2 achieved compressive strengths of 42.0, 61.0, and 71.2 MPa at 7, 28, and 90 days, respectively, whereas the corresponding WSA-1 mixture attained 35.9, 53.9, and 64.9 MPa. Relative to the OPC reference mixture, which exhibited strengths of 34.0, 47.0, and 53.8 MPa at 7, 28, and 90 days, respectively, the 20% WSA-2 mixture produced strength enhancements of approximately 23.5%, 29.8%, and 32.3%, respectively. These results confirm that WSA-2 was more effective than WSA-1 in enhancing the mechanical performance of the cementitious system, particularly at medium and long curing ages. The pronounced improvement observed at 28, and 90 days is indicative of the continuing contribution of secondary cementitious reactions to strength development. Unlike the primary hydration of Portland cement, which contributes substantially to early-age strength, the pozzolanic reaction of reactive silica generally develops progressively with curing. The reaction between reactive SiO_2 and calcium hydroxide can generate additional C–S–H phases, which occupy available pore spaces and progressively refine the internal pore network. Consequently, the higher 90-day strength of the WSA-containing mixtures suggests that the beneficial contribution of WSA extends beyond its initial filler effect and is associated, at least in part, with continued microstructural development during prolonged hydration. Nevertheless, the exact contribution of pozzolanic activity should be correlated with complementary characterization techniques such as XRD, TGA/DTG, SEM–EDS, FTIR, and pore-size distribution analysis.

The difference between the two WSA types is particularly evident at early age. At 7 days, WSA-2 at 20% replacement reached 42.0 MPa, compared with 35.9 MPa for WSA-1, representing an improvement of approximately 17.0% relative to the corresponding WSA-1 mixture. At 28 days, the difference decreased to approximately 13.2%, while at 90 days it further decreased to approximately 9.7%. This progressive reduction in the performance gap suggests that WSA-1 may undergo a relatively slower contribution to strength development, allowing its later-age performance to approach that of WSA-2. Conversely, WSA-2 appears to provide a more effective combination of early-age physical packing and chemical reactivity, resulting in a greater initial enhancement while maintaining superior long-term strength. The strength reduction observed beyond the optimum 20% replacement level is an important feature of the experimental results. For WSA-1, the 90-day compressive strength decreased from 64.9 MPa at 20% replacement to 53.3 MPa at 25%, 42.0 MPa at 30%, and 27.4 MPa at 50% replacement. A comparable trend was observed for WSA-2, for which the 90-day strength decreased from 71.2 MPa at 20% replacement to 59.0 MPa at 25%, 48.9 MPa at 30%, and 31.8 MPa at 50% replacement. This pronounced reduction indicates that, beyond the optimum dosage, the beneficial effects associated with WSA incorporation are progressively outweighed by the reduction in Portland cement content. Excessive substitution reduces the quantity of clinker phases available for primary hydration and consequently limits the formation of the primary C–S–H network. Although the additional silica supplied by WSA may remain available for pozzolanic reaction, the quantity and rate of reaction may not be sufficient to compensate for the loss of cementitious binder.

From a cementitious-materials and concrete-technology perspective, the observed optimum at 20% can therefore be interpreted as the point at which the competing mechanisms of cement dilution and WSA reactivity achieve the most favorable balance. At lower replacement levels, the amount of reactive WSA may be insufficient to fully exploit its potential contribution to matrix refinement, whereas at higher replacement levels, the reduction in cement clinker becomes increasingly dominant. The resulting behavior produces a characteristic bell-shaped strength–replacement relationship, with the maximum compressive strength occurring at approximately 20% WSA incorporation. The findings also have important implications for the structural and durability performance of WSA-based concrete. Higher compressive strength generally reflects a more compact and mechanically efficient cementitious matrix; however, compressive strength alone cannot fully establish the durability implications of WSA incorporation. If the enhanced strength at the optimum replacement level is associated with reduced capillary porosity and a refined pore structure, the material may also exhibit improved resistance to the ingress of aggressive agents. This potential relationship is particularly relevant when assessing WSA as a sustainable supplementary cementitious material for structural concrete applications. Nevertheless, such conclusions should be substantiated through independent durability indicators, including water absorption, sorptivity, chloride penetration, carbonation resistance, sulfate resistance, and pore-structure characterization.

A comparison of the two ashes further demonstrates that WSA-2 possesses a more favorable performance profile than WSA-1 under the investigated conditions. The maximum 90-day strength of 71.2 MPa obtained with 20% WSA-2 represents an increase of approximately 32.3% over the OPC control

and approximately 9.7% over the corresponding 20% WSA-1 mixture. This difference may reflect variations in the physicochemical characteristics of the two ashes, including reactive silica content, amorphous-to-crystalline silica ratio, specific surface area, particle morphology, fineness, loss on ignition, and residual carbon content. These parameters can substantially influence both the kinetics of pozzolanic reaction and the packing characteristics of the fresh and hardened cementitious matrix. Therefore, the superior performance of WSA-2 should be interpreted in conjunction with its physicochemical and microstructural characteristics rather than attributed solely to its silica content. Overall, the experimental results establish that WSA replacement has a non-linear effect on compressive-strength development, and that the optimum replacement level is controlled by the interaction between the physical filler effect, particle packing, pozzolanic reactivity, cement dilution, and curing age. Both WSA-1 and WSA-2 achieved their maximum compressive strength at 20% replacement, confirming this dosage as the most favorable proportion within the investigated range. However, WSA-2 demonstrated consistently superior performance, achieving 42.0, 61.0, and 71.2 MPa at 7, 28, and 90 days, respectively. The corresponding WSA-1 mixture achieved 35.9, 53.9, and 64.9 MPa, while the OPC control reached 34.0, 47.0, and 53.8 MPa. The results therefore indicate that 20% WSA-2 provides the most effective balance between supplementary cementitious-material utilization and mechanical performance, making it the most promising formulation among the investigated mixtures

3.2 SEM microstructure of WSA concrete for 28 days.

The SEM micrographs reveal distinct differences in the hydration morphology of WSA-1 and WSA-2. WSA-1 exhibits a comparatively heterogeneous microstructure characterized by coarse, irregular agglomerates and a relatively limited distribution of well-developed fibrous C–S–H phases. In contrast, WSA-2 presents a more extensively developed hydration network, with abundant needle-like C–S–H products, rough and locally pitted particle surfaces, and discrete C–H deposits. The greater development of secondary C–S–H in WSA-2 suggests enhanced pozzolanic reactivity and more extensive consumption of $Ca(OH)_2$. This behavior may be associated with differences in particle fineness, specific surface area, and, particularly, the proportion of reactive amorphous silica in WSA-2. The formation of additional C–S–H progressively fills interparticle voids and contributes to matrix densification, which can explain the potentially superior mechanical and durability performance of WSA-2.

4. Conclusion

i. WSA has strong potential as a supplementary cementitious material (SCM) for partial replacement of Portland cement, providing both agricultural-waste valorization and potential reductions in cement consumption.

ii. The literature review indicates that the performance of WSA concrete is highly variable, mainly because of differences in silica content, combustion temperature and duration, particle fineness, replacement level, and curing conditions.

iii. The experimental results showed a nonlinear relationship between WSA replacement and compressive strength, with strength increasing up to an optimum level and subsequently decreasing at higher replacement ratios.

iv. 20% WSA replacement was identified as the optimum level for both WSA-1 and WSA-2 under the conditions investigated.

v. WSA-2 showed superior performance compared with WSA-1, achieving compressive strengths of 42.0, 61.0, and 71.2 MPa at 7, 28, and 90 days, respectively.

vi. At 20% replacement, WSA-2 increased compressive strength relative to the OPC control by approximately 23.5% at 7 days, 29.8% at 28 days, and 32.3% at 90 days.

vii. The improved strength is attributed to the combined effects of pozzolanic activity, particle packing, filler action, pore refinement, and additional C–S–H formation.

viii. SEM observations support the higher reactivity of WSA-2, showing a more developed C–S–H network and greater matrix densification than WSA-1.

ix. Increasing WSA replacement beyond 20% caused a progressive reduction in compressive strength, primarily because cement dilution and reduced clinker availability outweighed the beneficial contribution of WSA.

x. Overall, 20% WSA-2 represents the most promising mixture investigated, achieving the best balance between cement replacement and mechanical performance.

xi. The results demonstrate that appropriately processed WSA can contribute to the development of more sustainable and potentially lower-carbon concrete.

Declarations

Ethics, Consent to Participate, and Consent to Publish declarations

not applicable.

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Author Contribution

Author ContributionsBinyamien .I Rasoul.: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, and writing—original draft. O.A.M.: Methodology, investigation, data analysis, and writing—review and editing and Validation, interpretation of results, and writing—review and editing. All authors contributed to the discussion and interpretation of the results, critically reviewed the manuscript, approved the final version, and agreed to be accountable for all aspects of the work.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Tables

Table 1 to 5 are available in the Supplementary Files section.

Figures



Figure 1

Open field Burning of Wheat Straw

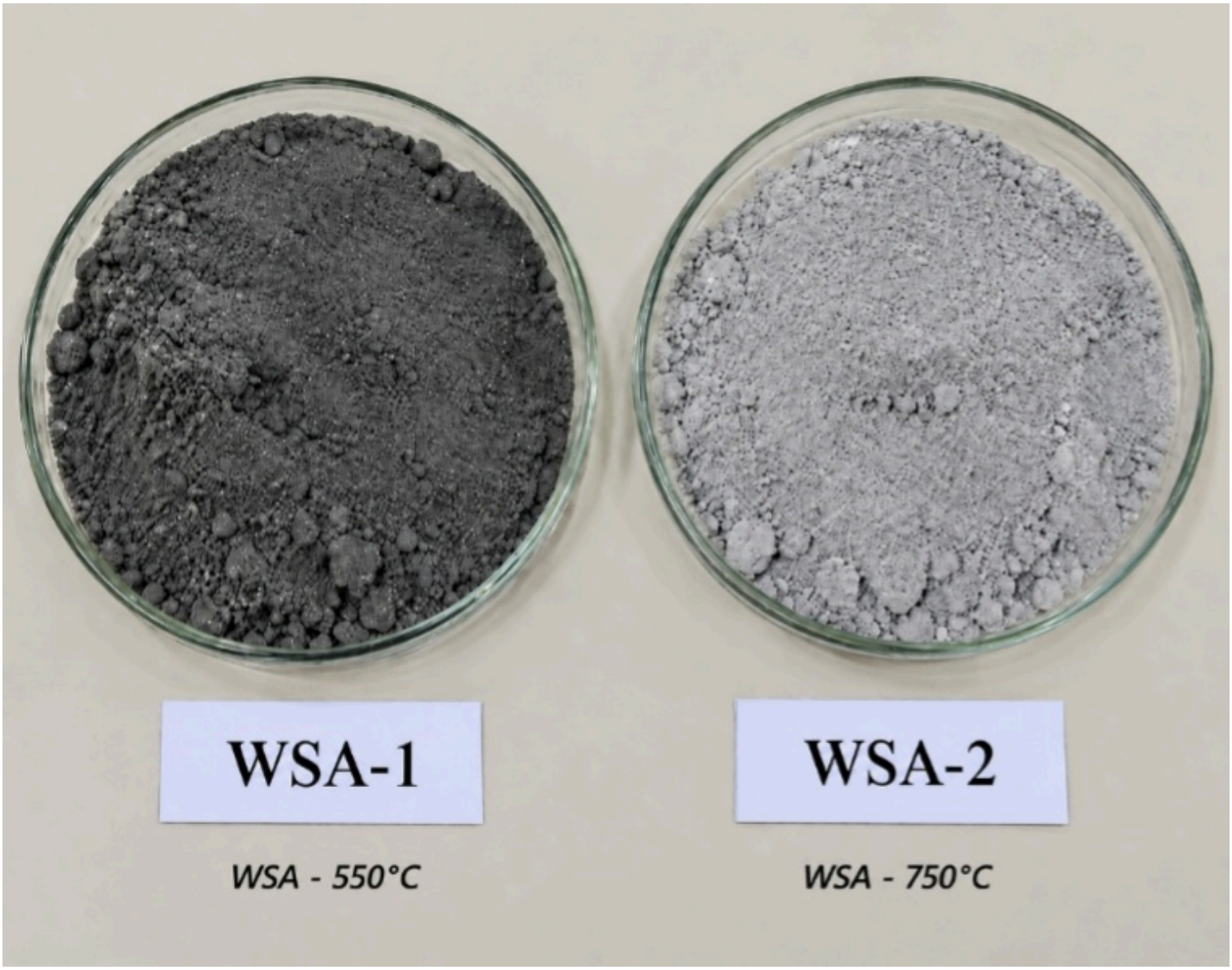


Figure 2

Types of wheat straw ash (WSA) used in the experimental study.

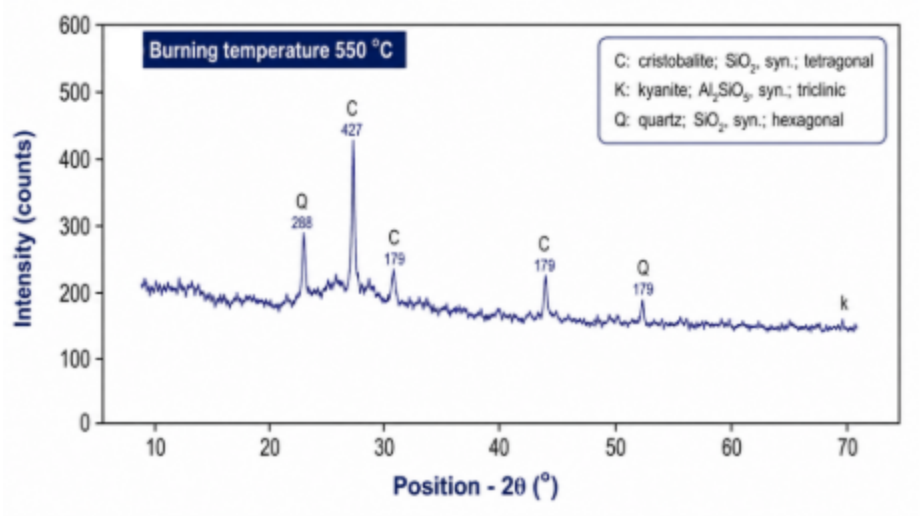


Figure 3

X-ray diffraction (XRD) pattern of WSA after incineration at 550 °C for 2 h.

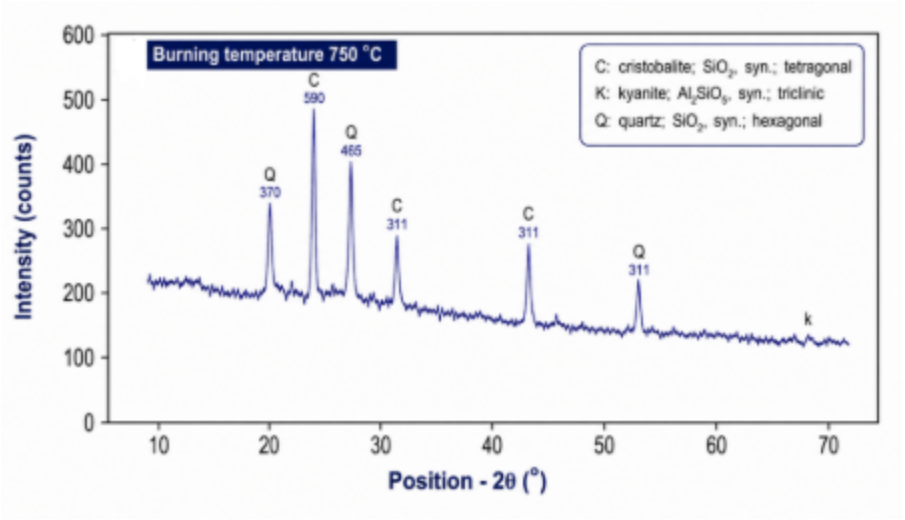


Figure 4

X-ray diffraction (XRD) pattern of WSA after incineration at 750 °C for 2 h.

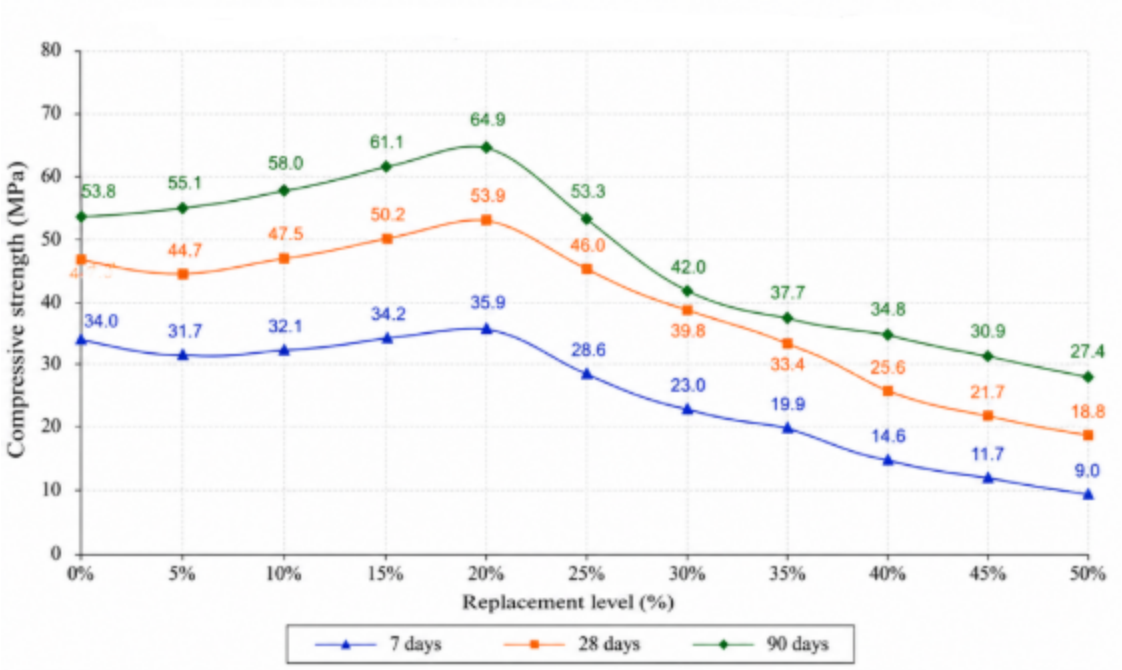


Figure 5

Compressive strength of WSA-1 mixed concrete at three different ages (7, 28, 91-days).

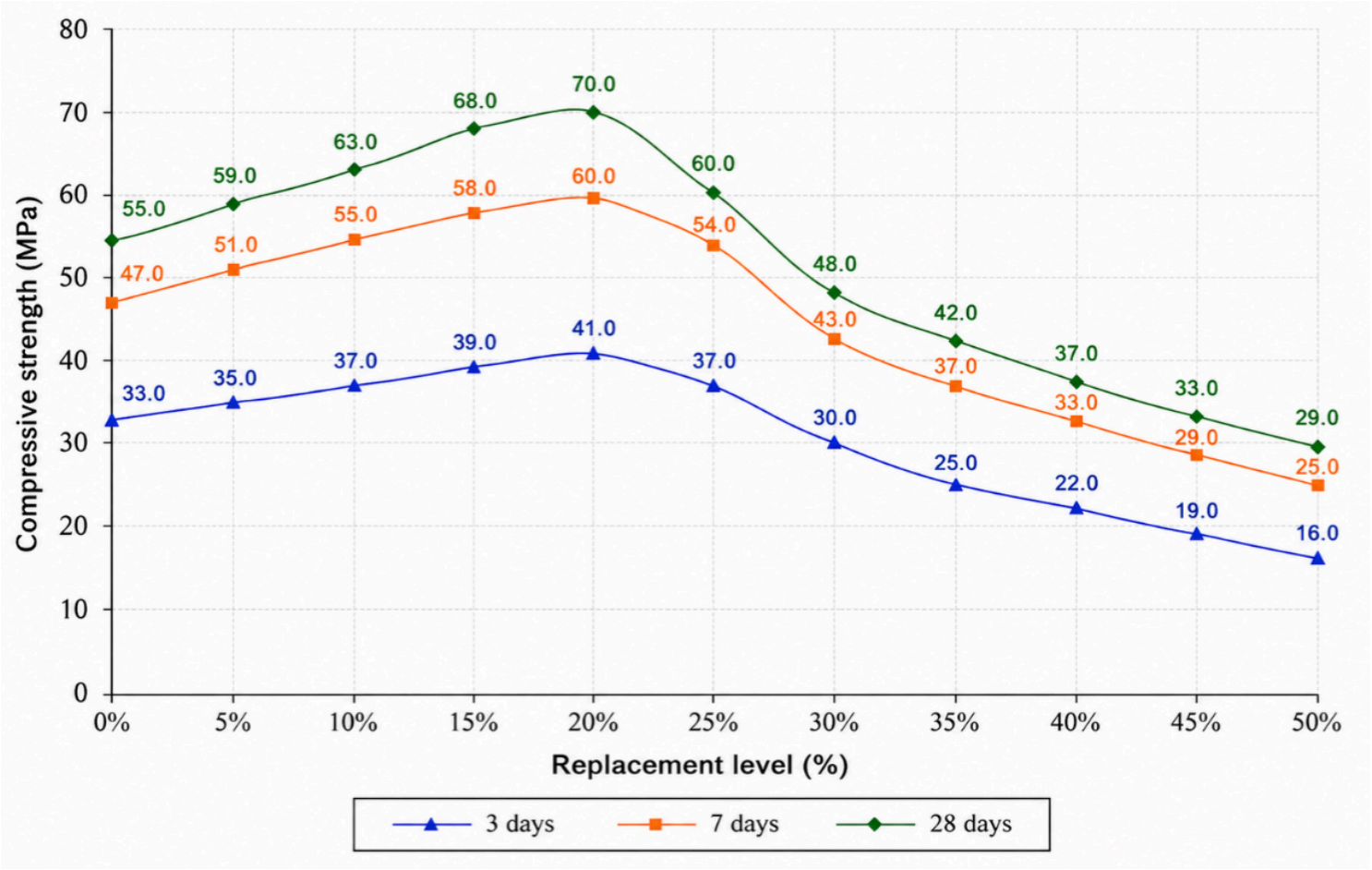


Figure 6

Compressive strength of WSA-2 mixed concrete at three different ages (7, 28, 91-days).

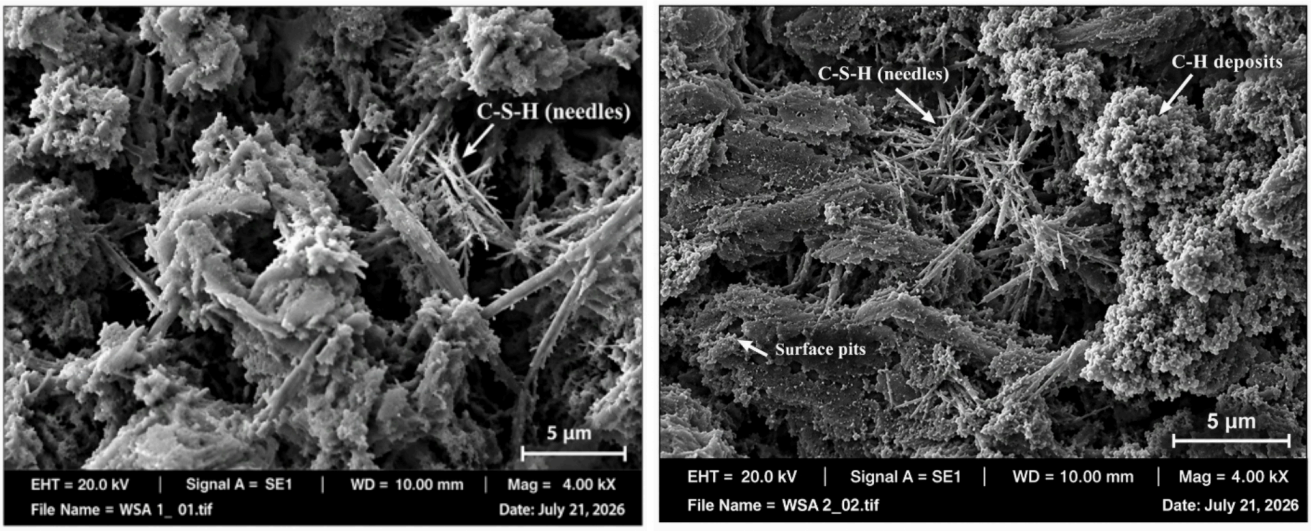


Figure 7

SEM analysis of wheat straw ash samples WSA-1 and WSA-2.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table15.docx