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Research Article

Using sewage sludge ash as a replacement for cement in mortar applications

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Abstract

In the quest for sustainable construction practices, integrating waste materials into the construction sector has gained significant attention. Sewage sludge ash (SSA) is a very attractive resource since it is readily available in large quantities and has the potential to provide significant environmental advantages. The present study, this study investigates the feasibility of utilizing supplementary cementitious materials (such as SSA) as a portion alternative to cement in mortar, aiming to reduce the environmental burden of sewage waste and enhance mortar properties. Experiments incorporated integrated SSA at 0% (control), 15%, 25%, 50%, and 75% of cement's weight. Characteristics of mortar were evaluated at 7, 28, 60, and 90 days, evaluating mechanical characteristics such as flexural and compressive strengths, as well as physical attributes including water absorption, dry bulk density, and apparent porosity. The findings revealed that SSA inclusion significantly influenced the physical and mechanical characteristics of the mortar. 28-day compressive strength of the mortar sample reached 31 MPa when 25% of the cement was substituted with SSA. In comparison, the control sample exhibited a compressive strength of 42.25 MPa, indicating that up to 25% substitution is feasible and meets standard norms. SSA inclusion decreased dry bulk densities, increased water absorption, and improved porosity. Thus, this study demonstrates the performance of using SSA as an environmentally friendly substance and economical cement alternative in sustainable construction materials.

1. Introduction

Sewage sludge is a byproduct that is initiated as a result of the techniques used in treating and cleansing wastewater which presents considerable difficulties when it comes to disposal within areas with high population. The accumulation of substantial quantities of sewage sludge at treatment facilities and the constrained disposal options heightens environmental concerns. Traditionally, landfilling has served as the primary method for sewage sludge disposal [1,2]. Nevertheless, the increasing amount of sewage sludge requires the investigation of viable alternative solutions. New strategy includes using sewage sludge ash (SSA) in concrete where it functions as a partial replacement for cement or filler by relying on its physicochemical properties [3,4]. This strategy doesn't only mitigate the dilemma of disposal but also reduces the environmental footprint associated with conventional landfilling and agricultural applications which are prone to contaminating soil and water bodies. By embedding SSA within building materials, the management of its burgeoning production can be optimized, presenting a forward-thinking solution to the sewage sludge disposal quandary.

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Regarding decreasing of volume, burning sewage sludge is a very efficient approach. This process can reduce the volume of sludge to 95% or even more with significantly mitigating the levels of heavy metals and organic pollutants contained within the sludge [5-8]. The resulted product, known as sewage sludge ash (SSA), harbors diverse applications which are primarily used as an additive in the manufacturing of mortar and concrete, thereby, it replaces a portion of the cement. This application of SSA has attracted considerable global interest through spotlighting its potential as a sustainable solution in the construction sector.Cement is crucial in the manufacturing of concrete since it directly affects its mechanical and thermal properties [9,10]. Producing one ton of cement releases a considerable amount of CO_2 that contributes to 7% of the total global CO_2 emissions [11-13]. Over the last several decades, many experiments have been carried out to create sustainable concrete by substituting a portion of Ordinary Portland Cement (OPC) with other materials [14,15]. Collectively, these facts clearly highlight the potential benefits of substituting cement with SSA, both in terms of addressing sewage sludge disposal and reducing cement production which in turn would lead to a decrease of CO_2 emissions [16].

Furthermore, the variances in SSA's mineral composition, attributable to geographic differences, significantly affect the fundamental characteristics of mortar, for instance, compressive and flexural strength, workability, and durability. These disparities underscore the necessity for meticulous evaluation of SSA's applicability as a construction material to ensure that its integration preserves or enhances the desired characteristics of the final product. Hence, localized research and development endeavors are imperative to refine the usage of SSA in concrete formulations, accounting for the unique attributes of SSA derived from various locations.

The density of concrete that incorporates SSA likely varies based on the incineration temperature, leading to fluctuations in its density [17,18]. A significant amount of sewage sludge is produced in Algeria, a quantity that continues to increase, with projections reaching four hundred thousand tons per year by 2025 [19]. Given its composition of organic substances and harmful heavy metals, it presents a worldwide concern [20]. Yet, with advancements in industrial techniques related to pozzolanic activities, integrating SSA and its constituents – including SiO_2, AL_2O_3, Fe_2O_3, CaO, MgO, P_2O_5 – which result from the burning of sewage sludge, has emerged as a strategy to curb CO_2 emissions (Roughly 900 kilograms per metric tons of cement.) and minimize their ecological footprint [21,22].

In 1999, Monzó et al [23] conducted a study. The investigation revealed that substituting cement with either 15% or 30% SSA had little impact on the compressive strength of cement mortar when exposed to a temperature of 40°.Include a grace period that spans from 3 to 28 days. In 2003, Pan et al [24] made a discovery that changing the size of particles in mortar mixes containing SSA could improve their effectiveness. Their investigation concluded that the length of time spent grinding the SSA particles did not have a notable impact on the compressive strength of the mortar. In a 2007 investigation, In a study conducted by Cyr et al [4], it was discovered that replacing cement with 25% and 50% SSA led to a primary decline in the compressive strength of the cement mortars. However, after a long period of time, this change greatly enhanced the compressive strength. Garcés et al [25] Performed a study to assess the appropriateness of utilizing SSA with different types of cement. The study determined that CEM II/B-M (V-LL) 42.5R cement is the most suitable option for using SSA. Moreover, it has been demonstrated that a substitution rate of 10% yields the most substantial improvement in compressive strength. Moreover, the employment of superplasticizers was acknowledged as a technique to mitigate the adverse consequences of SSA on the workability. The research conducted by Chang et al [26].Examined the chemistry makeup of SSA and its use in concrete blends. the findings Indicated that the inclusion of SSA led to a decrease in both the workability and compressive strength of the mortar. Lynn et al concluded that SSA can be successfully incorporated into concrete as either fine aggregates or fillers, mostly due to its particle morphology. The particles, distinguished by their irregular morphology, were found to have a size range that falls between fine sand and silt, as determined by their percent [27].

Studies have shown that adding 8% by weight of SSA to ultra-high strength concrete (UHPC) has a negative impact on its ductility and hampers the initial hydration process of the cement [28]. However, subsequent phases of the curing process exhibited improvements in pozzolanic reactions

[28]. The utilization of SSA led to alterations to the pore structure of UHPC, resulting in an increase in the overall pore volume and a decrease in the volume of bigger pores [28]. Xia et al. conducted economic and environmental assessments which indicated that the inclusion of SSA in UHPC might lead to substantial cost reductions and a reduction in impact on the environment [28]. The addition of SSA into the mixture yielded in a marginal decrease in the flexural strength and workability of UHPC, as evidenced by compressive strength tests conducted at 7 and 28 days. The experiments showed a progressive improvement in compressive strength with a 10% replacement of supplementary cementitious materials (SCMs) [29]. Furthermore, the SSA was found to lead to increase levels of autogenous and drying shrinkage [29]. The additional SSA to mortar improved its ability to withstand compression and decrease its rate of water absorption. The most favorable outcomes were observed when using 10% SSA to boost compressive strength and between 5% and 10% SSA to lower water absorption rates [30]. Higher SSA concentrations in the binder increased the drying shrinkage in the blocks. Overall, the literature suggests that SSA improves mortar performance and extends concrete setting time [31,32]. Therefore, this study seeks to fill the substantial research void thorough examination of the influence of Sewage Sludge Ash (SSA) derived from an Algerian desert location on mortar properties. By focusing on a specific source which is Touggourt City in Algeria, this research Aims to understand the intricate relationship between SSA composition and mortar performance. The study not only contribute to existing knowledge but also offers practical insights for developing robust and region-specific strategies for incorporating SSA into mortar mixes. The collection of sewage sludge was carried out in a sewage treatment facility situated in the same city and subjected to detailed analysis. The dehydrated sludge underwent incineration and pulverization before being used as a substitute for a portion of cement in mortar compositions by employing five different ratios of SSA (0%, 15%, 25%, 50%, and 75%).

Several experiments were performed on these specimens so as to examine their physical and chemical characteristics. The included tasks in this study encompassed the analysis of the elemental and crystalline content of the SSA, as well as the assessment of its pozzolanic activity in mortar. Further evaluations are included which are testing the specimens' workability, durability, flexural strength, and compressive strength.

2. Materials and Experimental Methodology

2.1. Materials

2.1.1 Ash SSA

The dry sewage sludge, obtained as the final output of the purification process, was gathered from a metropolitan wastewater facility located in Touggourt City, as shown in Figure 1. After the drying process, the stones and impurities were removed. Due to the normally elevated levels of organic matter in sludge obtained from urban sewage treatment plants, the dewatered sludge was subjected to incineration at a temperature of 850°C to reduce its organic content and prevent any potential negative effects.

(a) (b)

Fig. 1. Plant for treating wastewater :(a) dry sewage sludge and (b) activated sludge

As a consequence of this process, sewage sludge ash (SSA) was generated, as depicted in Figure 2. In order to utilize SSA as an additive in mortar, additional processing of the ash was required. The furnace-produced ash had larger particle sizes. Therefore, we thoroughly crushed it with a hammer to reduce its particle size and then sieved it through a 0.08 mm sieve to ensure uniformity and readiness for use in mortar formulations.

Fig. 2. Sewage Sludge Ash (SSA)

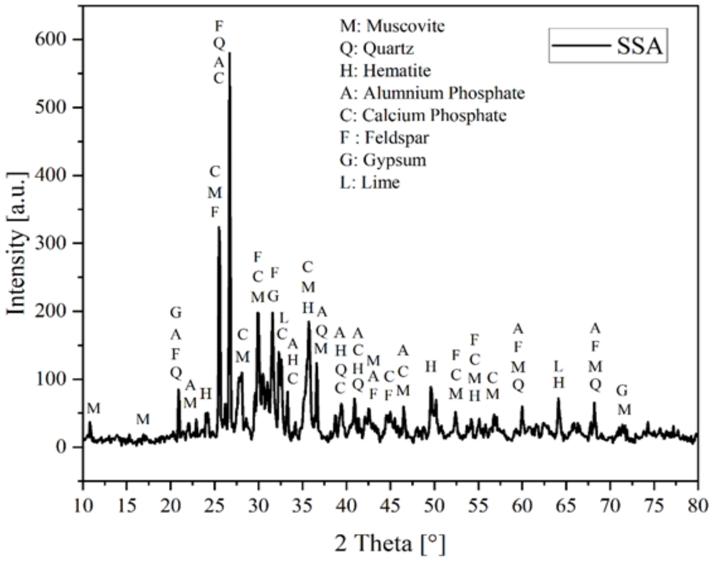

Fig. 3. XRD analysis of Sewage Sludge Ash SSA

The X-ray diffraction (XRD) pattern of the sewage sludge ash (SSA) sample, as depicted in Figure 3, provides a comprehensive overview of its major mineral phases. Notably, the analysis identifies significant peaks corresponding to Quartz, muscovite, Hematite, Aluminum Phosphate, and calcium Phosphate, indicating the prevalence of these crystalline constituents. Additionally, smaller fractions of Feldspar, Gypsum, and Lime are discernible in the pattern, contributing to the overall diversity of the mineral composition.

2.1.2 Sand

The standardized CEN sand (ISO standardized sand) is a natural sand, particularly siliceous in its finest fractions. It is characterized by its clean, isometric, and rounded grains, ensuring uniformity and minimal variability in size and shape. This sand undergoes a meticulous drying, sieving, and preparation process in a modern workshop that adheres to the highest standards of quality and consistency, thus meeting the specific requirements set forth by NF EN 196-1 [33]. The physical properties of this sand, including its grain size distribution, density, and moisture content, are rigorously controlled to ensure optimal performance in its applications. Table 1 and Figure 4 illustrate the physical properties and The distribution of particle sizes curve of the CEN standardized sand. the utilized sand not only guarantees the structural integrity of the materials produced with it but also enhances the reproducibility of test results in cement and mortar research.

Table 1. Comprehensive material properties of construction-grade sand [34]

Real Density	2.64 t/m3	Alumina Content (Al_2O_3)	0.25 %
Apparent Density	1.62 t/m3	Iron Content (Fe_2O_3)	0.06 %
Fineness Modulus	26<> 2.7	Phosphorus Pentoxide Content (P_2O_5)	0.00 %
Loss on Ignition at 950°C	0.16 %	Titanium Dioxide Content (TiO_2)	0.02 %
Water Absorption	0.20 %	Silica Content (SiO_2)	98.69 %
Water Content	<0.2	Chloride Ion Content (Cl^-)	<50ppm

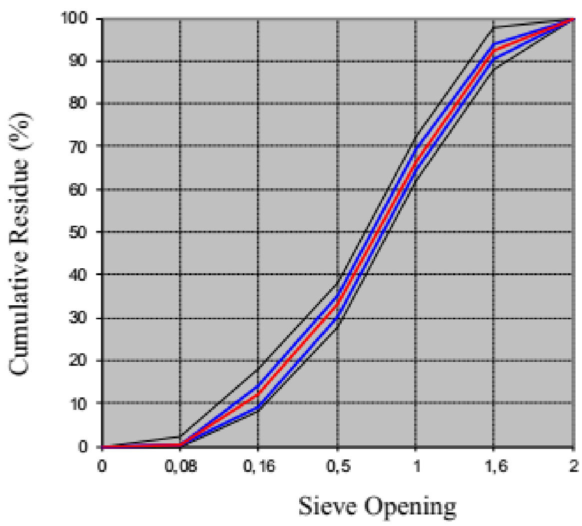

Fig. 4. Particle Size Distribution Curve for Sand Analysis [34]

2.1.3 Cement

All the specimens in this research were crafted using Type I Ordinary Portland Cement (OPC). This complies with EN 197-1 [35] and NA 442 [36]; Tables 2 and 3 provide the chemical and mineral analysis as well as the physical qualities of the cement used.

Table 2. Analysis of the chemical and mineral characteristics of Portland cement [37]

Loss on ignition (%)(NA5042)	0. 5 to 3%
Sulfate (SO_3) (%)	1. 8 to 3
Magnesium oxide MgO (%)	1. 2 to 3
Chloride (Cl^-) (NA5042) (%)	0. 01 to 0.05
C_3A rate	<3. 0 %

Table 3. The findings of the analysis on the physical characteristics [37]

Normal consistency (%)	25 to 28
Blaine technique measures the fineness (cm^2/g)(NA231)	3200 to 3800
28-day shrinkage (μm/m)	< 1000
Enlargement (mm)	≤ 2
Hydration heat	<270 j/g
Start of setting at 20 (min)	>60
End of setting at 20 (min)	240 to 400

2.2 Experimental Methodology

2.2.1 Proportional Blending Of Components and Preparation of Samples

In order to assess the sustainability and efficacy of sludge ash powder as an alternative to traditional cement, our experiment began with the precise blending of sand and sludge ash powder for two minutes to ensure a homogeneous dry mixture. This step was significant for achieving a consistent base before introducing any liquid components. Subsequently, water and 'Sika' - a super plasticizer - was added to the dry mix within a mechanical mixer. This process was carefully monitored to ensure a gradual and uniform combination of the materials, continuing until a consistent and homogenous mixture was achieved. This methodological approach aimed at not only for examining the structural benefits of substituting cement with sludge ash powder but also to explore the environmental advantages with particular emphasis on achieving a vital uniform mixture for ensuring the structural integrity and sustainability of the concoction.

Before employing SSA as a fragmentary replacement for cement, its pozzolanic activity needs to be assessed. To achieve this, samples with varied SSA contents were compared to a control sample (A0) without sludge. Consequently, five mixture configurations were examined to determine the mechanical strength of prismatic 4x4x16 cm mortar samples in accordance with NF EN 196-1 standards [33]. Each configuration consisted of six samples to ensure statistical relevance and accuracy. The specifics of these mixtures are outlined in Table 4.

Table 4. A mortar test piece recipe containing the SSA-specified substitution ratio (in%)

Mixtures	Cement (g)	SSA (g)	Sand (g)	Substitution ratio (%)
A0	450	0	1350	0%
A15	382.5	67.5	1350	15%
A25	337.5	112.5	1350	25%
A50	225	225	1350	50%
A75	112.5	337.5	1350	75%

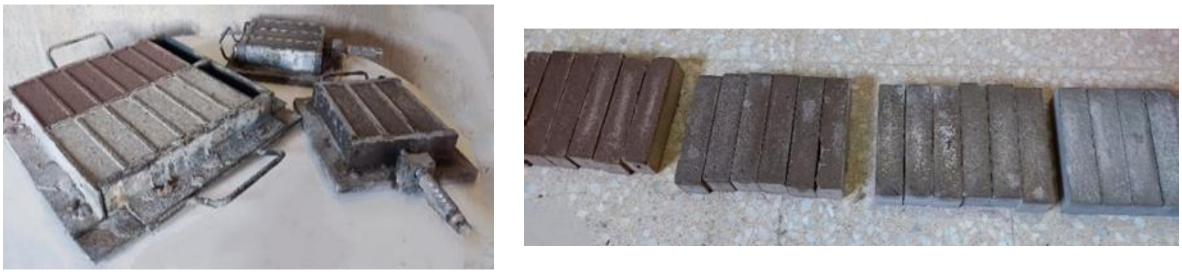

Fig. 5. Prepared mortar samples with different SSA substitution ratios

2.3 Procedure for the Experiment

2.3.1 Flexural Strength

Flexural strength is generally assessed by flexural tensile tests. They are produced on prismatic specimens 4x4x16 cm, resting on two supports and subjected to a single concentrated load applied to the middle. This configuration develops a bending stress in the specimen, allowing its flexural strength to be measured indirectly. Our investigation centered on prismatic mortar specimens measuring 4x4x16 cm, with each batch designed to incorporate SSA at varying replacement ratios: A0 as a control and A15, A25, A50, and A75 representing different percentages of the cement's weight. In order to ensure the dependability and consistency of the outcomes, four distinct studies were created for every level of substitution. The experiment was conducted at different curing periods of 7, 28, 60, and 90 days. This setup is not only allowed for a direct assessment of the specimen's response under bending stress but also provided valuable insights into its flexibility and breakpoint, and offering a comprehensive view of its mechanical behaviors by including resistance to bending and flexural forces. These measurements are pivotal for determining the durability and structural integrity of enhanced concrete with SSA for echoing our objective to confirm SSA's viability as a sustainable and efficacious alternative to conventional cement in mortar.

Fig. 6. Assessment of mechanical properties: a focus on flexural strength testing

2.3.2 Compressive Strength

The compressive strength was calculated by testing specimens which are taken from the original pavers after conducting the tensile strength tests which resulted in each specimen being split into two halves. For each replacement ratio (A0, A15, A25, A50, and A75), four halves were selected to undergo compressive strength testing. These tests were conducted at specific period of 7, 28, 60, and 90 days to monitor the development of strength over time.

During the compressive strength test, the force was applied to the samples via square steel plates with a width of 40 mm. The compressive strength was concluded through dividing the force at the moment of failure by the surface area over which the load was applied. The result for each replacement ratio at each curing period was taken as the average of four measurements. This method ensured the reliability and reproducibility of the results that provide comprehensive insights into the performance and structural integrity of mortar samples incorporating SSA.

Fig. 7. Evaluating mechanical properties: focus on compressive strength testing

3. Results and Discussion

3.1 SSA Test Results

3.1.1 XRD

The X-ray diffraction (XRD) analysis results for the mortar sample A0 (without SSA) are visually represented in Figure 8 that offering crucial insights into the material's mineral composition. Peaks in the spectrum reveal the prevalence of quartz and calcium-bearing minerals, which is serving as key indicators of the primary mineral phases within the mortar. Specifically, the identified peaks point towards the presence of quartz, dicalcite silicate, tricalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite are dominant constituents in the mortat structure. Notably, the distinctive peaks corresponding to calcium-bearing minerals are attributed to the cementitious components, whereas the manifestation of quartz peaks is ascribed to the sand fraction of the mortar mixture.

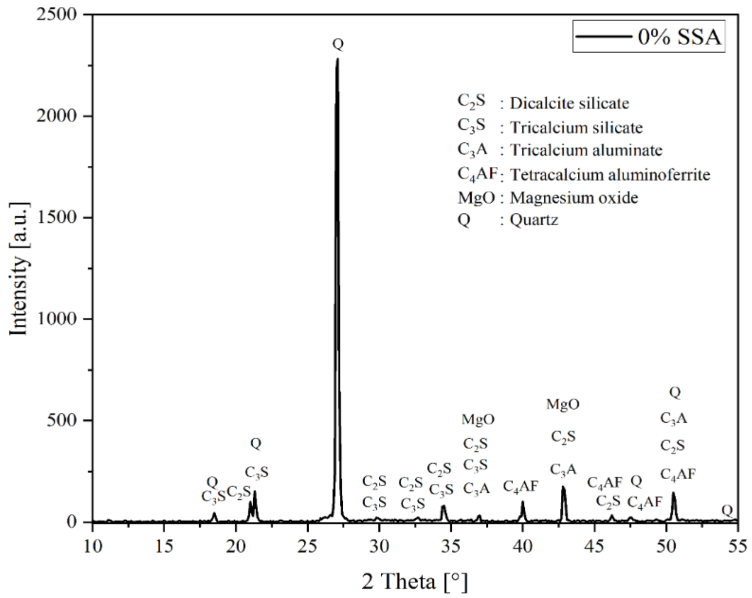

Fig. 8. XRD analysis of mortar powder without SSA (A 0)

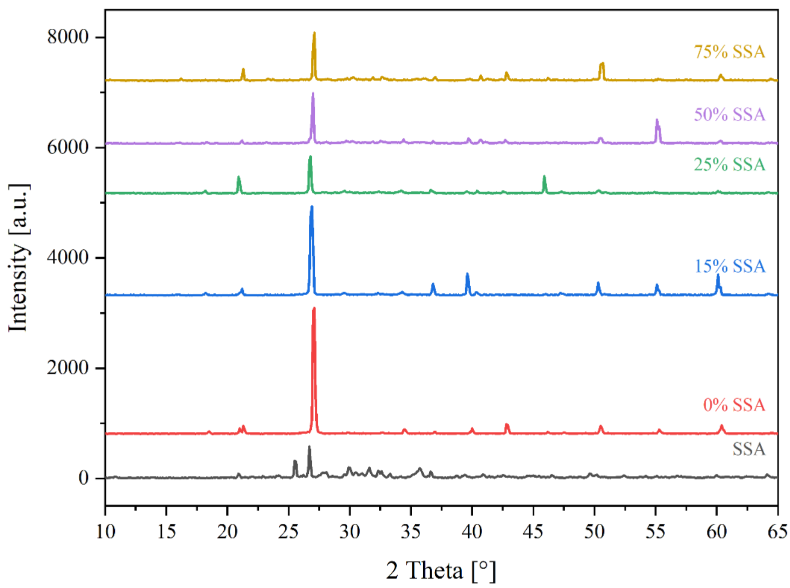

Fig. 9. XRD Analysis of mortar samples with varying SSA content

In Figure 9, the XRD analysis of mortar samples, incorporating different proportions of Sewage Sludge Ash (SSA) as a substitute for cement, is presented. the stacked XRD patterns provide a visual representation facilitating a direct comparison of the mineral phases. Notably, a discernible trend emerges as the proportion of (SSA) rises, revealing a consistent decrease in peak intensity. This diminishing intensity aligns with the inherently lower intensity of SSA peaks compared to the more pronounced peaks observed in samples without SSA. Moreover, the comparative analysis unveils the emergence of specific peaks corresponding to SSA phases within the mortar samples. This observation strongly suggests the successful incorporation of SSA into the mortar matrix.

3.1.2 The Fourier Transform Infrared (FTIR) Spectra

The Fourier Transform Infrared (FTIR) analysis was conducted on Sewage Sludge Ash (SSA) samples subjected to thermal treatment at 850°C to assess the chemical modifications induced by the combustion process. The analysis included both the initial SSA sample, labeled "Before" to denote its state prior to burning, and subsequent mortar samples that incorporated the thermally treated SSA in varying proportions as a cement substitute. The FTIR spectrum of the "Before" sample exhibited characteristic absorption peaks at wavenumbers 3309, 2922.23, 2847.68, 1655, 1514, 1417.78, 1012.31, and 454 cm^{-1}. These peaks correspond to specific functional groups, revealing the existence of hydroxyl (O-H) and aliphatic (C-H) stretching, carbonyl (C=O) stretching, (N-H) and (C-H) bending, as well as mineral oxides like Si-O-Si stretching vibrations. This spectral analysis not only underscores the chemical complexity of the SSA before thermal treatment but also sets a baseline for comparing the alterations in functional groups and bonding configurations post-combustion when SSA is integrated into the mortar samples.

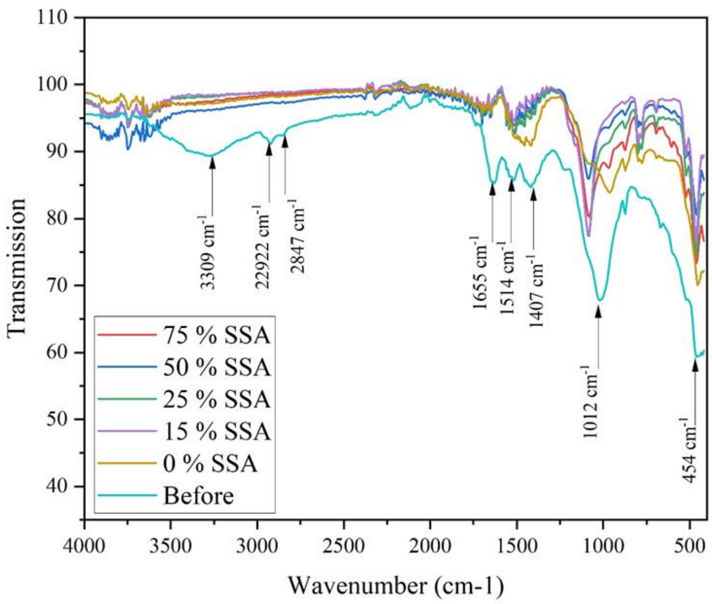

Fig. 10. The Fourier Transform Infrared (FTIR) analysis was conducted on Sewage Sludge Ash and Various Mortar Samples Incorporating Different Proportions of SSA

Following thermal treatment, several peaks, including those at 3309, 2922, 2847.68, 1655, and 1012.31 cm^{-1}, disappeared in the spectra of mortar samples with varying SSA content. This disappearance suggests the effective removal or alteration of specific organic functional groups due to the thermal treatment, aligning with its purpose of eliminating organic matter from the mortar samples. The remaining peaks in the post-treatment spectra indicate the modified composition of SSA in the mortar matrix. The FTIR analysis, therefore, not only delineates the functional groups in the initial SSA sample but also reveals the impact of thermal treatment on the functional group composition in mortar samples incorporating SSA as a cement substitute.

3.2 Mortar Test Results

3.2.1 Workability Test

Before mortar hardens, it is placed in molds. The process of placing should be efficient to save time and avoid deformations resulting from pouring, which are difficult to rectify later. Mortar is considered more workable if the process of pouring it into molds is easier. Therefore, this experiment aimed to measure the flow of mortar using a flow table test, infer from this test about the quality of the mortar, assess its workability, and determine the appropriate water ratio for acceptable workability.

Fig. 11. Flow table apparatus and mortar spread

To attain satisfactory workability, additional water becomes essential when SSA is used to replace cement at proportions of 25%, 50%, and 75%. When comparing mix design A0 with mix design A75, it is evident that the workability of mix design A75 diminishes even with a 20% increase in water content. To maintain workability at this high level of SSA substitution, we incorporated a plasticizer, specifically Sika, which significantly improved the mortar's workability. The flow table test results are summarized in Table 5.

Previous studies support the conclusion that increasing the SSA replacement ratio significantly impacts mortar workability, as the increased SSA content decreases fluidity due to its porous nature and irregular particle morphology [26,39–41].

Table 5. Mix design and flow table results

Mix Design	Plasticizer (Sika)	E/C	Water (gr)	Average Spread Diameter (mm)
A0	No	0.5	225	167
A15	No	0.55	247.5	175
A25	No	0.55	247.5	157
A50	No	0.6	270	165
A75	No	0.6	270	132
A75	Yes	0.6	270	155

The flow table test results demonstrated that for mix design A0, the average spread diameter was 167 mm. For mix design A75, without the plasticizer, the average spread diameter decreased to 132 mm despite the additional water. However, with the inclusion of Sika, the spread diameter for mix design A75 improved to 155 mm, indicating a significant enhancement in workability.

Research by Guo et al. [39] and Chang et al. [26] reinforces this observation, noting that the integration of SSA in concrete tends to lead to a decrease in workability.

3.2.2 Alteration of Physical Appearance

The first alteration seen after the implementation of SSA was evident in the physical characteristics of the specimens. Figure 12 displays five mortar specimens with varying sludge ash levels. It is obvious that samples containing a greater proportion of SSA present a beige color.

Fig. 12. Specimen appearance changes following SSA addition

3.2.3 Bulk Density

Figure 13 illustrates that incorporating sewage sludge ash (SSA) as a substitute for a portion of cement results in a decrease in the overall density of mortar. The decrease in size can be ascribed to the low mass of SSA particles. The employed cement in this experiment has a determined bulk density of 1429.88 kg/m^3, but the bulk density of SSA was found to be 824.65 kg/m^3.

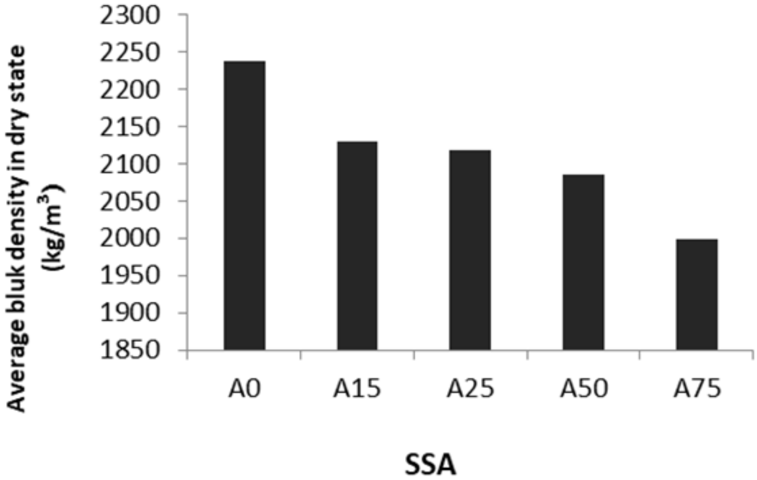

Fig. 13. Bulk density of the combinations that were tested

In specimens A15 and A75, the bulk density is reduced by 4.83% and 10.68%, respectively, compared to specimen A0. The results suggest that when the proportion of SSA rises, the bulk density of the mortar falls. This is because SSA has a lesser density than cement that is resulting in a lighter mixture overall. This discovery highlights the potential of using SSA as a sustainable and lightweight alternative in mortar formulations which can help reduce the overall weight of construction materials while maintaining adequate structural properties.

These results are influential as they show that incorporating SSA can lead to the production of lighter construction materials without compromising structural integrity. This diminution in weight can be particularly advantageous in various construction applications where minimizing weight is critical.

3.2.4 Water Absorption

Figure 14 summarizes the water absorption rates of the various mortar specimens. The data clearly indicates an upward trend with water absorption rates increasing as the percentage of SSA substitution rises. Precisely, the absorption rate starts at approximately 0.45% for the A0 specimens and reaches approximately 1.43% for the A75 specimens. The rise in water absorption may be ascribed to the intrinsic characteristics of SSA which tend to enhance the porosity of the mortar matrix. As more SSA is incorporated into the mix, the overall density of the mixture decreases that resulting in higher water absorption rates. This observation aligns with the previously discussed trends in bulk density, and further emphasizing the impact of SSA on the physical properties of the mortar.

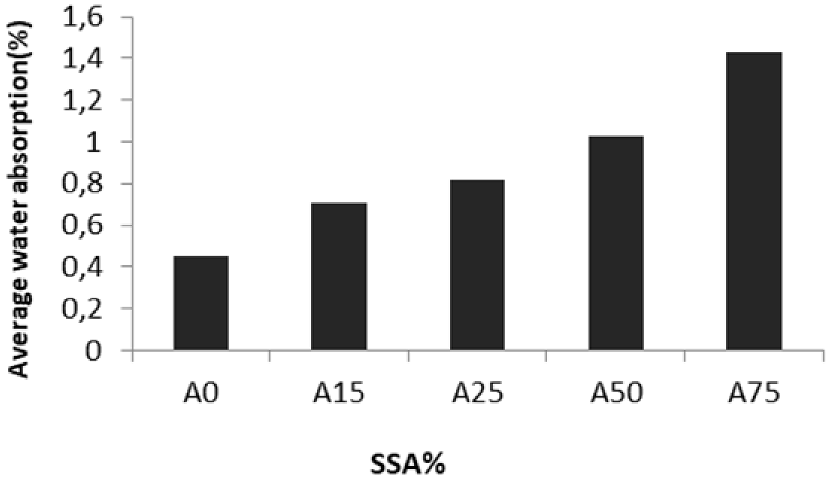

Fig. 14. Absorption of Water by the Tested Combinations

Prior studies have demonstrated that mixing SSA into mortar increases water absorption and demand. This arises from SSA's porous microstructure and irregular morphology, which leads to water adsorption upon the exterior of SSA particles. Consequently, There is less free water in the mortar [43]. Additionally, the rough surface of SSA increases the resistance between particles, impacting fluidity and increasing the need for water [44]. These factors, combined with the lower density of SSA compared to cement, explain the increase in water absorption as the SSA content increases. These results are significant as they underscore the importance of carefully evaluating water absorption rates when designing mortar mixtures containing SSA. Thus, increased water absorption can affect the durability and longevity of the mortar by making it crucial to balance the benefits of using SSA with its impact on water absorption.

3.2.5 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) test is a nondestructive technique employed to assess the soundness and excellence of mortar materials. This method entails the measurement of the duration. It takes an ultrasonic pulse to travel through the material, and gives valuable insights into the material's density, porosity, and microstructure. Mainly in this study, the UPV test was managed to enrich the data on density, porosity, and microstructure that is obtained from other tests. The results, as illustrated in Figure 15, indicate a fall in ultrasonic pulse velocity with the partial substitution of cement by SSA. This decrease in UPV can be attributed to the risen porosity and reduced density of the mortar mixtures containing SSA.

The findings from the UPV test show the impact of SSA on the material integrity of the mortar. As SSA content increases, the ultrasonic pulse velocity decreases that indicates probable changes in the material's internal structure. This insight is crucial for comprehending the impact of SSA on the durability and mechanical characteristics of mortars mixtures.

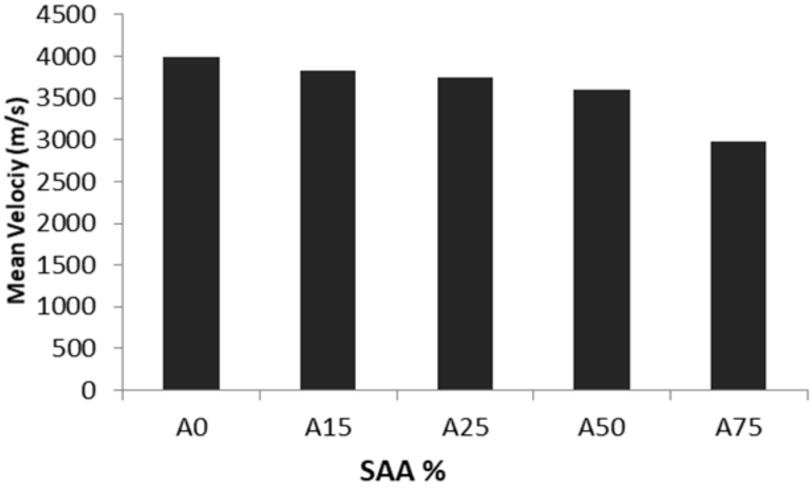

Fig. 15. Measurement of ultrasonic pulse velocity in tested mixes

Fig. 16. Ultrasonic pulse velocity measurement in mortar specime

3.2.6 Flexural Strength

The study aimed at examining the impact of varying quantities of sewage sludge ash (SSA) which affects the flexural strength of mortar samples when employed as a partial alternative to cement. Figure 17 depicts the differences in flexural strength throughout different curing durations. As the curing period advanced, the flexural strength of the mortar enhanced to indicate that the inclusion of SSA did not impede the hardening process within the studied substitution range. However, specimens with A15, A25, A50, and A75 substitution exhibited a reduction in flexural strength compared to the control specimens (A0) without SSA. The flexural strength showed a linear decrease with increasing SSA substitution. There are two possible explanations that may be given to account for this observation:

- Firstly, an excessive amount of water was used to provide the necessary texture for producing a practical mortar mixture. The presence of excessive moisture heightened the flexibility and the susceptibility to collapse of the mortar while diminishing its cohesiveness. Hence, an excessive amount of water and insufficient cement would lead to a less robust and less long-lasting mortar.
- The second theory is that the ash's hydraulic capabilities were inferior to those of cement, perhaps owing to its CaO component. Ash, although being pozzolanic, has a lime content (CaO) of less than 10%. Furthermore, the pozzolanic glassy silica and alumina in the ash require a cementing agent, such as hydrated lime or Portland cement, and water to undergo a reaction and generate cementitious compounds.

The results correspond with prior studies showing that mortar's flexural strength after 28 days with SSA is often less than cement mortar's. Specifically, as shown in several sources, an increased replacement ratio of SSA correlates with decreased flexural strength [4,25,39,41,45–49]. However, it is essential to mention that some researchers have found that at lower replacement ratios, the flexural resistance of SSA mortar may surpass that of cement mortar because of SSA's significant water absorption and filling capabilities. The ideal ratio of water to cement decreases due to SSA's heightened water absorption characteristics, which offsets the cement dilution effect [50]. Nonetheless, significant reductions in flexural strength occur when the SSA replacement rate exceeds 30%, primarily attributable to the minimal reactivity of SSA [45].

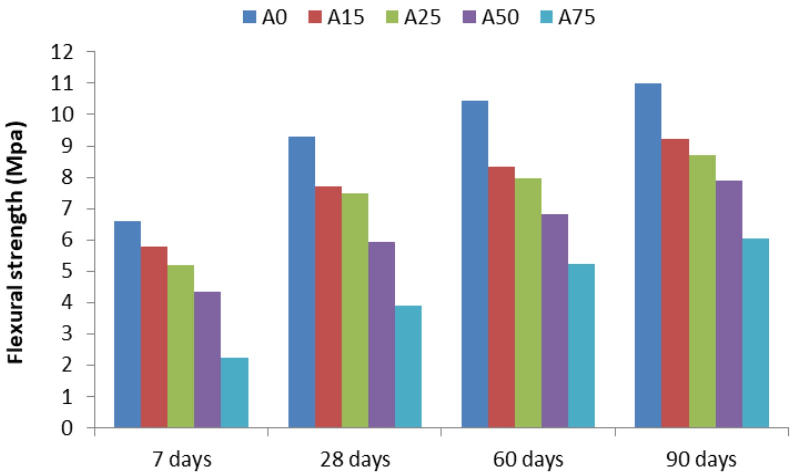

Fig. 17. Flexural strength of mortar specimens with varying levels of changed SSA content was measured over a period of 7to 90 days

3.2.7 Compressive Strength

The study evaluated the compressive strength of mortar samples to analyze the effects of including sewage sludge ash (SSA) as a substitute for cement. Figure 18 presents the compressive strength results over different curing periods. The data indicate a reduction in compressive strength for all specimens with SSA substitution at 7, 28, 60, and 90 days.

Our study aims to explore the impact of pozzolan on the initial compressive strength of mortar during the curing process, notably between 7 to 28 days. Previous research has highlighted this time frame as a period with notable variations in compressive strength. [4,40]. The pozzolanic activity index, which measures the effectiveness of SSA in maintaining compressive strength, is another crucial aspect. This index is the ratio of the compressive strength of SSA-substituted specimens to the reference specimen (A0). Higher values indicate better performance. Table 6 shows the calculated pozzolanic activity index for each curing period.

Furthermore, the chemical interaction between SSA and cement during hydration is essential. SSA which is rich in pozzolanic materials like alumina and silica, undergoes a chemical reaction with calcium hydroxide to generate more calcium silicate hydrate (C-S-H). However, the lower lime content in SSA can slow down the creation of C-S-H, which partly explains the reduced early compressive strength. Moreover, the increased porosity resulting from SSA substitution may weaken the interfacial transition zones (ITZ) between the aggregate and cement matrix, further reducing the overall compressive strength.

The decrease in compressive strength observed in SSA-substituted mortar samples is consistent with findings from previous studies, which report a decrease in strength due to the lower reactivity of SSA and increased porosity caused by its irregular shape and high-water absorption characteristics [26,45,52–55]. Additionally, SSA's lower CaO content can delay hydration and decrease the creation of hydration products such as C-S-H, further affecting early strength [23,56].

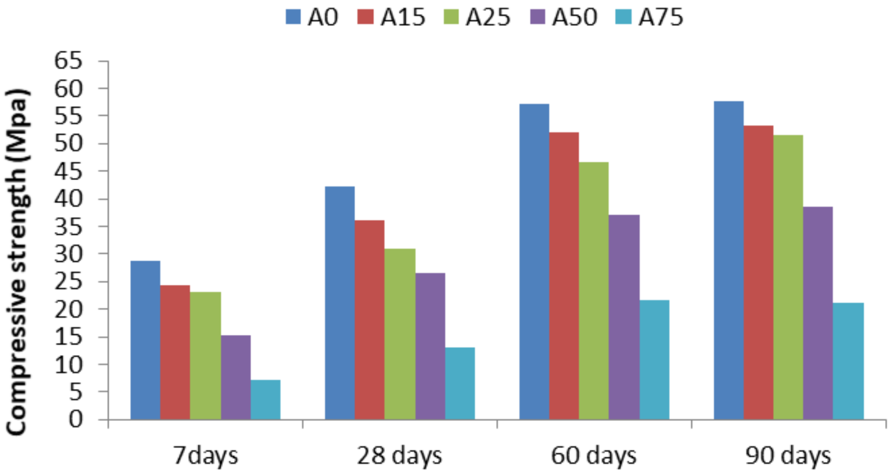

Fig. 18. Compressive strength of mortars specimens with different amounts of changed SSA content measured over a period of 7 to 90 days

Table 6. Pozzolanic activity index of mortars at various ages

	A15	A25	A50	A75
7 days	84.9%	80.8%	52.9%	24.9%
28 days	85.2%	73.4%	62.9%	30.6%
60 days	91%	81.7%	65%	38%
90 days	92.4%	89.6%	66.8%	36.7%

The pozzolanic activity index shows a decreasing trend with higher SSA content aligning with the noticed reduction in compressive strength. These results underscore the need to optimize SSA content in mortar mixtures to balance environmental benefits with mechanical performance. The chemical interactions and increased porosity due to SSA substitution highlight the complex nature of using SSA in cementitious materials and the importance of comprehensive analysis to ensure structural integrity.

3.2.8 Understanding the Pozzolanic Activity of SSA

The pozzolanic activity of SSA was assessed by comparing the compressive strengths at 28 days to those at 7 days for mortar samples with variety of concentrations of SSA. According to the data shown in Table 7, the ratio demonstrates a direct correlation with higher amounts of SSA. The findings suggest that the amorphous structures seen in SSA serve as a pozzolan over extended durations, hence enhancing the strength of the mortar samples.

Table 7. Compressive strength ratios in various SSA contents from 28 days 7 days

Mix Design	Relative Strengths (Compressive, 28-day to 7-day)
A0	1.472125
A15	1.476923
A25	1.336207
A50	1.752883
A75	1.807692

These results highlight the long-term pozzolanic reactivity of SSA contributing to the continued strength development of mortar. Over time, the amorphous silica and alumina in SSA undergo a reaction with calcium hydroxide. This leads to the creation of more calcium silicate hydrate (C-S-H). This technique ultimately improves the compressive strength of the mortar.

4. Conclusion

This research explored the potential use of sewage sludge ash (SSA) as a partial substitute for cement in mortar applications. The study focused on analyzing the physical and mechanical properties of mortar when varying amounts of SSA were introduced. The findings showed that the inclusion of SSA resulted in several key changes in the properties of the mortar.

The addition of SSA led to a decrease in slump measurements, which suggests that the workability of the mortar could be affected, necessitating adjustments in water content or the use of plasticizers to maintain the desired consistency. Furthermore, the increase in SSA content altered the color of the mortar specimens, which may be a consideration for aesthetic purposes in certain construction applications.

From a mechanical standpoint, the introduction of SSA caused a reduction in the mortar's flexural strength, with a 5% increase in SSA content leading to a 4.83% decrease in 28-day flexural strength. This indicates that while SSA can be used as a sustainable alternative to a portion of the cement, it does impact the strength of the mortar, requiring careful balance in mix design to ensure structural integrity.

The study also observed that SSA contributed to an increase in water absorption and a reduction in bulk density and ultrasonic pulse velocity (UPV) of the mortar. These findings suggest that SSA may be beneficial in applications where lighter weight and enhanced thermal properties are desired, though at the cost of some mechanical strength.

While the research provides valuable insights into the use of SSA in mortar, further studies are needed to fully understand its long-term effects on mortar durability and performance under various environmental conditions. Future research should also investigate the optimization of SSA content in mortar mixes to maximize both environmental and structural benefits. Considering the impact of SSA on physical and chemical properties such as compressive strength, density, and porosity, it is crucial to select substitution ratios to ensure satisfactory performance standards carefully. The presence of SSA affects the workability, water absorption, flexural strength, and compressive strength of mortars due to its porous nature and irregular particle morphology. Although these characteristics can decrease mechanical strength, the pozzolanic properties of SSA can enhance durability over time, offering potential advantages in certain circumstances. To balance these benefits and limitations in mechanical performance, it is advisable to use moderate substitution ratios, preferably below 25%, and utilize chemical admixtures to maintain workability and structural integrity.

This research proves that using SSA in mortar production at replacement ratios below 25% can be a sustainable and viable option. This method sheds light on the benefits and obstacles of utilizing SSA, promoting additional studies to comprehend its potential in the construction industry fully. It is essential to fine-tune the mixture compositions to strike a perfect harmony between sustainability and effectiveness. Moreover, upcoming research should explore using ternary blended materials and geopolymers as alternative sustainable choices, which could provide substantial environmental advantages and help overcome some of the difficulties linked with substituting SSA.

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