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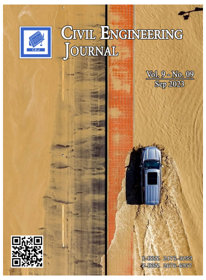
Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 09, September, 2023



Evolution of Durability and Mechanical Behaviour of Mud Mortar Stabilized with Oil Shale Ash, Lime, and Cement

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Received 15 May 2023; Revised 12 July 2023; Accepted 06 August 2023; Published 01 September 2023

Abstract

The investigation into earthen construction technologies and materials is now acknowledged as a crucial area requiring further research. Earthen mortars are prevalent in both modern and traditional construction due to the abundance of earth material, their favorable thermal properties, and their low embodied energy. The objective of this study is to support the use of natural materials collected from north Jordan to enhance the mechanical properties and durability of mud mortar. The local soil was stabilized using Oil Shale Ash (OSA), Ordinary Portland Cement (OPC), and lime for producing mud mortar. Particle size analysis, plastic limit, liquid limit, XRD, and XRF were applied to assess the geotechnical characterization and mineral composition of the earthen stabilizers and local soil. In order to examine the mechanical properties (specifically compressive strength) and durability characteristics (such as water absorption and shrinkage) of mud mortar, a total of 8 mixtures were prepared. One of these mixtures served as a control, while the others were created by substituting soil with varying proportions of OSA, cement, and lime. The results show that the mud mortar contained 10% OSA and 10% cement, which exhibited the highest compressive strength. Moreover, an increase in the proportion of OSA in the soil led to a decrease in absorption and linear shrinkage, indicating that OSA is an effective stabilizing agent for mud mortar.

Keywords: Earth Building; Mud Mortar; Natural Pozzolans; Oil Sale Ash; Lime; Cement.

1. Introduction

Since the dawn of humanity, mud has been a reliable and beneficial building material. Earthen mortar, also known as mud mortar or clay mortar, is defined as an earthen mixture applied while wet in a malleable state to stack stones or bricks [1]. Sand (2–0.075 mm size), silt (0.075–0.002 mm size), clay (less than 0.002 mm size), and water are the main components that make up mud mortar [2]. Mud mortar has the ability to regulate humidity and temperature within buildings [3]. It is also an eco-friendly and sustainable building material, as the ingredients are naturally occurring and do not require high levels of energy to produce [4, 5].

There are various techniques for preparing and applying mud mortar, and it is typically used in conjunction with other traditional building materials such as adobe, cob, rammed earth, and compressed earth block (CEB). Its use is more common in developing countries, where it can provide a low-cost and reliable alternative to more expensive

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http://dx.doi.org/10.28991/CEJ-2023-09-09-06

building materials. However, earthen mortar also has some limitations. It can be susceptible to cracking and erosion if not properly prepared and maintained. In recent years, there has been renewed interest in earthen mortar as a sustainable and low-cost building material. Various organizations and researchers around the world are exploring new techniques and technologies to improve the durability and performance of earthen mortar and promote its use in modern construction projects.

There are several ways to improve the durability of earthen mortar and make it more resistant to cracking, erosion, and water damage. One of the possible strategies is to add stabilizers to improve the strength and stability of earthen mortar [6, 7]. There are several common stabilizing materials that can be added to mud mortar to improve its strength, durability, and resistance to water damage. This can include materials such as lime, cement, or even animal blood, which can help to bind the soil particles together and make the mortar more resistant to erosion and cracking.

Lime is a traditional and widely used stabilizing material for mud mortar. It can be added to the mix in various forms, such as hydrated lime, quicklime, or lime putty [8, 9]. Lime helps to bind the particles of clay and sand together, making the mortar stronger and more durable. It also helps to regulate the pH of the mortar, which can prevent the growth of mold and other organisms. [8] used natural hydraulic lime with 20 and 25% replacement of soil. The effectiveness of lime in reducing clay swelling is notable. Adding lime for the stabilization of earthen materials proves advantageous for enhancing the mechanical properties of earthen mortars. Increasing the content of stabilizing agents from 20% to 25% exhibits a highly positive impact on mechanical performance. Furthermore, the inclusion of lime as a stabilizing agent leads to a decrease in volumetric shrinkage [8]. Studies have been conducted on the stabilization of soil-based materials, typically employing lime as a stabilizer [9–16].

Cement is another common stabilizing material for mud mortar. It is typically used in small amounts, as adding too much cement can make the mortar brittle and prone to cracking. However, when used in the right proportions, cement can significantly improve the strength and durability of mud mortar. The aim of this study [17] was to create a mortar composed of earth that was stabilized using mineral binders, with a binder-to-aggregate mass proportion of 1:3. The binder chosen for this experiment was cement, hydrated lime, fly ash, and metakaolinite. Various combinations of cement (5%, 7.5%, and 10%) and fly ash (11%, 13.5%, and 16%) were used in the mix design. The findings indicated that as the fly ash content increased and the cement content decreased, the workability of the mortars improved, but there was a decrease in their mechanical properties [17]. Sobczyńska et al. [10] presented a study conducted on earth-based mortars with the aim of finding the most effective method to enhance their strength. This involved utilizing cement as a stabilizing agent to create an earth-based mortar with an optimal recipe. Earth-based mortar stabilized with cement fulfilled the mechanical, conservation, durability, and technological requirements [10–12, 14–19]. Investigations have been undertaken to investigate the stabilization of soil-based materials with cement commonly employed as a stabilizer.

Pozzolans are natural or artificial materials that react with lime or cement to form a hard, durable substance. Common pozzolans used in mud mortar include volcanic ash, fly ash, and rice husk ash. These materials can help increase the strength and durability of the mortar, as well as improve its resistance to water damage and erosion. Volcanic tuff is a natural pozzolan that can be used in mud mortar. It is rich in silica and alumina, which react with lime to form a hard, durable substance. Volcanic tuff can also help to improve the workability and plasticity of the mortar, making it easier to apply and shape. The reactions between lime and volcanic tuff occur at a slow and gradual rate, leading to initially weaker early strength. However, the influence of volcanic tuff becomes more pronounced over time. Furthermore, the soil stabilized with a combination of lime and volcanic tuff has undergone successful absorption testing [13].

Oil shale, nanoclay, nanosilica, nanoalumina, and brick dust are other natural pozzolans that are used in mud mortar. These materials are rich in silica and other minerals, which can help improve the strength and durability of the mortar [15, 18, 20]. Fly ash is a byproduct of coal-fired power plants and is often used as a pozzolan in concrete and other building materials. When added to mud mortar, fly ash can help to improve its strength, durability, and resistance to water damage and erosion. It is also a sustainable material, as it is produced from waste materials that would otherwise be discarded [14, 17]. We investigated the use of cow dung, cement, and lime as stabilizers for pure mud and fibers to improve the longevity of reinforced mud mortar, comparing it to conventional mortars for viability.

Incorporating glass fiber and micropolypropylene fibers into earth mixtures enhances both compressive strength and significantly improves flexural strength and linear shrinkage [13, 21]. Table 1 provides a summary of recent research that explores the utilization of various stabilizers as alternatives to the soil in different techniques of earth-building materials.

Table 1. an overview of recent research investigating the use of different stabilizers as substitutes for soil in various Techniques of earth-building materials

Authors	Location	Stabilizer	Replacement Percentages (%)	Earth-Building Techniques
Current study	Jordan	Oil shale ash, cement, lime	Oil shale ash: 5, 10 Cement: 5, 10	Mortar
Al-Fhaid et al. (2023) [18]	Jordan	cement and oil shale	Oil shale: 10, 20 Cement: 5, 10	Compressed Earth Block (CEB)
Paiva et al. (2022) [17]	Brazil	Cement and fly ash	Cement: 5, 7.5, 10 Fly ash: 11, 13.5, 16	Mortar
Sobczyńska et al. (2021) [10]	Russia	Cement, lime	Cement: 12.5 Lime: 4	Mortar
Stathopoulos et al. (2021) [8]	Greece	Natural, hydraulic lime (NHL3.5) and ladle furnace steelmaking slag (LFS)	(NHL3.5): 20, 25 (LFS): 20, 25	Mortar
Benidir et al. (2021) [11]	Algeria	Cement and lime	Cement: 0, 2, 4, 6, 8 Lime: 0, 5, 8 Cement and lime respectively: (5, 3/5, 5/5, 8)	Blocks & Mortar
Edris et al. (2021) [12]	Jordan	Cement, Lime, and Sodium Silicate	Cement: 8 Lime: 8 Sodium Silicate: 2	Compressed Earth Block (CEB)
Edris et al. (2020) [13]	Jordan	volcanic tuff & lime	10%	Compressed Earth Block (CEB)
Araya-Letelier et al. (2019) [21]	Chile	Micro polypropylene fibers	0, 0.25, 0.5, 1	Earthen mixes (Cube, Beam, RILEM beam, Flat, Slab)
Karozou et al. (2019) [20]	Greece	Nano clay, nano silica and nano alumina	Nano clay: 5 Nano silica and Nano alumina respectively: 1.5, 1	Mortar
Sajanthan et al. (2019) [22]	Sri Lanka	Cement	For blocks: 10, 11, 17, 20 For mortar: 10, 12.5, 17	Blocks & Mortar
Gomes et al. (2018) [9]	Portugal	Powder hydrated air lime, hydraulic lime, natural cement and Portland cement)	5, 10, and 15 for each stabilizer	Mortar
Lekshmi et al. (2016) [14]	India	Cement, lime, cow dung	Cement: 5, 17 Lime: 4, 33 Cow dung: 10, 20	Mortar
Vimala et al. (2014) [19]	India	Cement	Cement: 8, 9, 11, 14, 20	Mortar
Rashmi et al. (2014) [15]	-	Cement, lime and Brick dust	Cement: 5, 10, 12 Lime: 5, 10 Brick dust: 25%	Mortar
Walker (2004) [16]	Australia & Zimbabwe	Cement and lime	For blocks cement: 4, 5, 6, 10 Lime: 19 For mortar cement 2.5, 4, 5, 6, 10 Lime: 19	Blocks and Mortar

Oil shale is a fascinating material that finds applications in the construction industry. It is a fine-grained sedimentary rock primarily composed of carbonates such as chalk, marl, and shale, with the presence of organic matter [23]. One of the notable characteristics of oil shale is its high calcium content, which makes it an economically viable fuel source. However, the treatment of oil shale results in approximately 40–50% solid waste, which is commonly disposed of in landfills, accounting for nearly 98% of the waste generated [24]. Jordan is blessed with abundant oil shale reserves, estimated to be around 65 billion tons, distributed throughout the region [25], as illustrated in Figure 1 [26].

After the El Lajjun deposits were discovered by the German Geological Mission in the 1960s, the exploration of oil shale resources commenced [25]. These deposits primarily consist of calcite and quartz, with secondary components such as kaolinite and apatite and minor components including feldspar, muscovite, illite, goethite, and gypsum [25].

Oil shale ash (OSA) has been found to have a detrimental impact on the surrounding land [27]. This impact is attributed to reactions such as the carbonation of free calcium oxide (CaO) and the hydration of calcium silicates, calcium aluminates, and calcium ferrites, leading to increased hardness and the formation of ash stones in the deposits [28]. Therefore, in this study, OSA will be utilized as a chemical stabilizer in mortar to mitigate the environmental harm caused by oil shale ash resulting from mining activities while simultaneously improving its mechanical and durability properties.

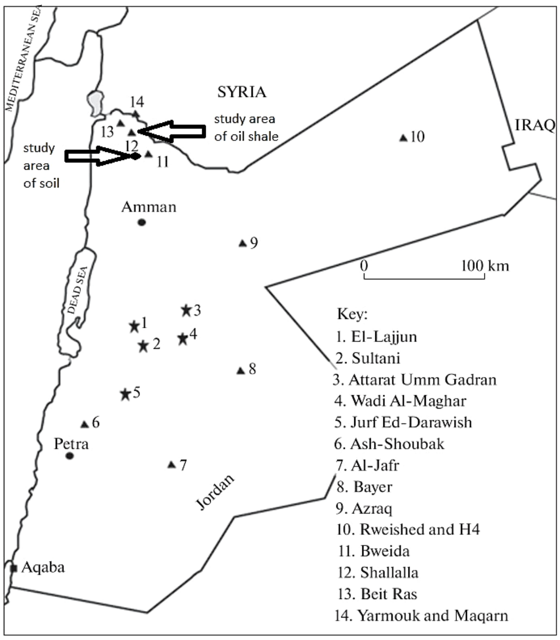

Figure 1. Location map of the oil shale deposits in Jordan

1.1. Research Significance

Mud mortar is an environmentally friendly and sustainable construction material, as its components occur naturally and do not necessitate significant energy consumption during production, along with its capacity to control indoor humidity and temperature. Weak soils present challenges for earth construction, primarily due to their low strength and low resistance to cracking, erosion, and water damage. Extensive research has been conducted to address these issues through soil stabilization, employing various stabilizers. Cement and lime are commonly used stabilizers to enhance mud mortar's mechanical properties and durability. However, an emerging binder known as oil shale ash (OSA) shows promise as a local construction material. The current study focuses on achieving a sustainable and environmentally friendly solution by examining the potential of oil shale ash, lime, and cement as stabilizing agents for earthen mortars. The study aims to investigate their impact on earthen mortars' durability and mechanical properties.

2. Experimental Procedures

2.1. Materials

In this experimental study, various materials, including natural soil, oil shale ash (OSA), cement, and lime, were utilized. Figure 2 shows the flow chart of the research methodology.

The natural soil sample was obtained from Kutum town in Jordan, precisely located at coordinates 32˚ 25' 44.6" N, 35˚ 54' 04.2" E. The soil was air-dried and then passed through a #4 sieve to evaluate its geotechnical properties. Visually, the soil appeared to be dark brown to red in color, consisting mainly of clay-sized particles. Figure 1 illustrates the study area, highlighting the soil and oil shale.

To analyze the natural soil samples, several laboratory tests were conducted, including sieve analysis, plastic limit, liquid limit, X-ray diffraction (XRD), and X-ray fluorescence (XRF). For XRD and XRF testing, the samples were ground and sieved using a #120 mesh with 0.125mm holes. The samples intended for XRF analysis were additionally dried for 2 hours at 105 ºC prior to testing.

Particle size analysis was performed at the Geotechnical Laboratory of the University of Yarmouk using sieving in combination with wet laser granulometry. The coarsest particles (>75 µm) were sieved, while the Department of Earth Sciences' Size Analyzer Laboratory at Yarmouk University utilized the Fritsch Analysts 22 Micro-Tec Plus Analyzer for laser granulometry of the finest particles (those less than 75 µm). This allowed for the distribution of particles based on their grain size to be determined.

Overall, these laboratory procedures were conducted to assess the geotechnical properties and particle size distribution of the materials utilized in the study. At the Geotechnical Laboratory of the University of Yarmouk [29], the Atterberg Limits were determined following the D4318-10 standards using a Casagrande apparatus. This involved the examination of soil material with a particle size smaller than 425 µm. The Atterberg Limits test allows for the calculation of the plasticity index (PI), which is obtained by subtracting the plastic limit (PL) from the liquid limit (LL). The PI provides an indication of the soil material's formability. The American Association of State Highway and Transportation Officials (AASHTO) classification categorizes the soil sample as A-7-6 [30].

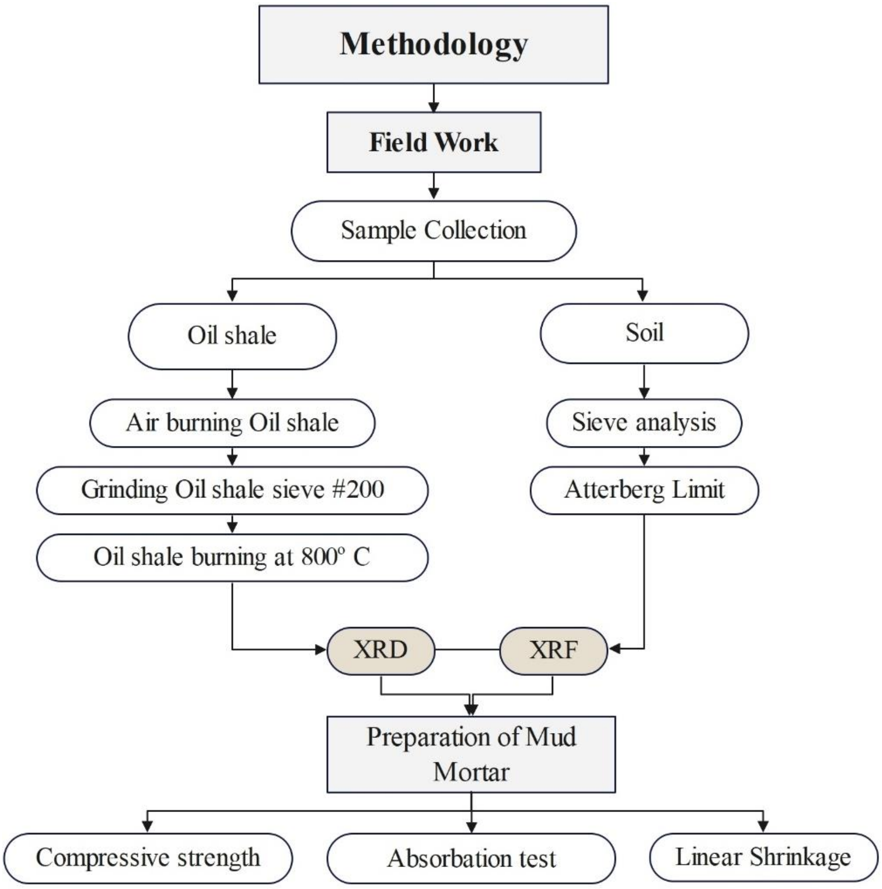

Figure 2. Research methodology flowchart

The clay content in the soil significantly influences its plasticity, and the liquid limit can vary depending on the type and quantity of clay minerals present. As part of the geotechnical characterization, a liquid limit test was performed on a sample of the natural soil. The results provide insights into the soil's behavior and response to moisture content changes. Additionally, the sieve analysis yielded the grain-size distribution, which is graphed on semi-logarithmic graph paper. The logarithmic scale represents grain size, while the natural scale represents the percentage of particles finer than a particular size [31]. Figure 3 presents the grain size distribution for the largest particle size observed in the soil sample. These laboratory procedures and analyses contribute to a comprehensive understanding of the geotechnical properties and particle size characteristics of the materials investigated in this study.

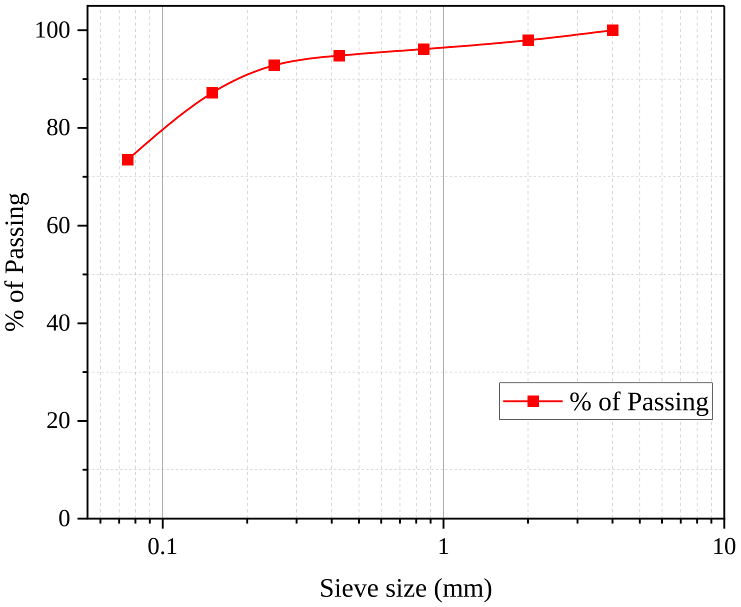

Figure 3. Grain-Size Distribution for the Largest Particle of Soil Sample

The grain size distribution of the fine particles in the soil sample, specifically silt and clay, was determined using wet laser granulometry. The findings of this analysis are depicted in Figure 4. This method provides valuable information about the distribution of particle sizes within the fine fraction of the soil.

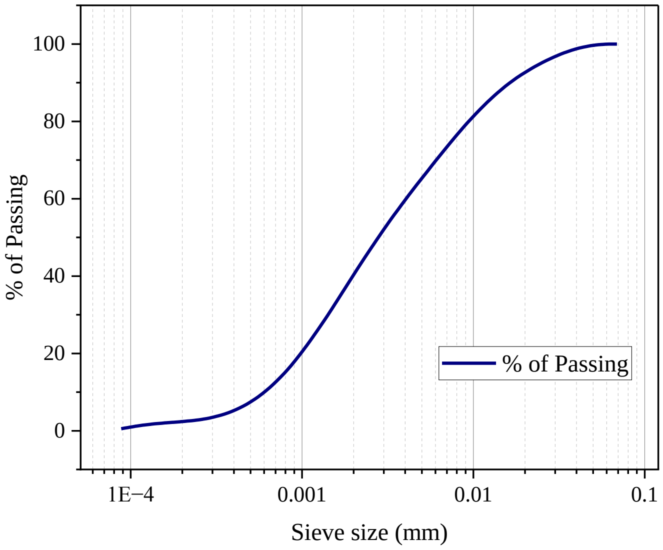

Figure 4. Grain-size distribution for the finest particle of the soil

The soil sample analyzed in this study consists of various particles, with clay accounting for 37.3%, silt for 36%, sand for 24.4%, and gravel for 2.3% of the total composition. It is important to note that the soil in the Irbid area is predominantly clayey, characterized by a high expansion coefficient. Consequently, it may not be suitable for the production of Compressed Earth Blocks (CEBs). A summary of the geotechnical test results can be found in Table 2.

Table 2. Geotechnical characterization of the natural soil

Property	Value (%)
Atterberg	
Liquidity	51.5
Plasticity	27
Plasticity index	24.5
Granulometry	
Clay friction (0-0.002) mm	37.3
Silt friction (0.002-0.075) mm	36
Fine sand (0.075-0.425) mm	21.3
Coarse sand (0.425-2) mm	3.1
Gravel (2-75) mm	2.3
Mineralogy	
Quartz	61
Plagioclase	12
Apatite	12
Orthoclase	3
Clay minerals content	12
Smectite	40
Chlorite	60

The chemical composition of the soil is presented in Table 3. When compared to the red soil utilized by El-Hasan et al. (2019) [32], notable similarities can be observed in the oxide composition, particularly in silicon, aluminum, manganese, iron, and potassium oxide.

Table 3. XRF result of the soil

Item	SiO_2	Al_2O_3	MgO	Fe_2O_3	MnO	TiO_2	CaO	K2O	P_2O_5	Na_2O	LOI
wt. (%)	52.7	15	1.9	8	0.2	1.5	3.3	1.7	0.2	0.2	15.3

The XRD analysis of the soil is depicted in Figure 5. The prominent peak reflections reveal that Quartz is the predominant mineral present. Additionally, other minerals such as Apatite, Plagioclase, Orthoclase, Chlorite, and Smectite (Montmorillonite) are also identified in the soil sample.

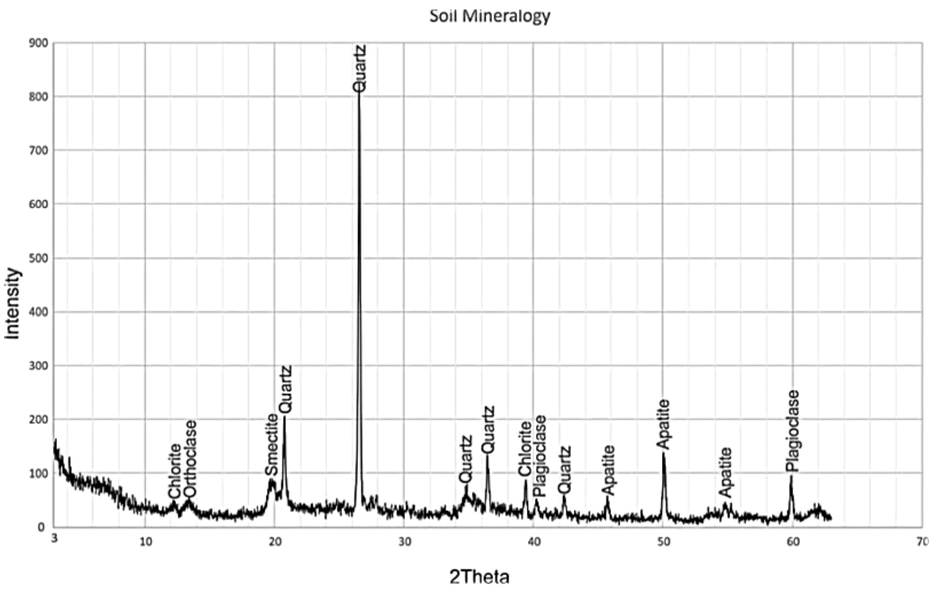

Figure 5. The XRD result of the soil

The fine aggregate (sand) used in the study had a maximum particle size of 1.2 mm, as depicted in Figure 6. The fineness modulus of the sand was determined to be 3.2%, which indicates its particle size distribution. The gradation curve of the sand was obtained in accordance with established standards [33].

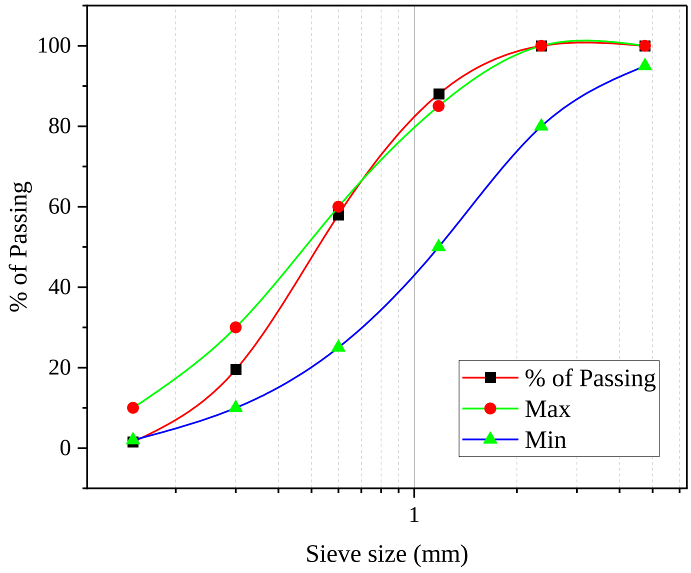

Figure 6. Fineness modulus of fine aggregate

The oil shale used in this study was sourced from Wadi Shallalh, located in the northeastern part of Irbid Governorate. To analyze its chemical composition, X-ray Fluorescence (XRF) analysis was performed. Table 4 provides the chemical composition of the obtained oil shale ash (OSA). The collected oil shale was then crushed in a ball mill until the particles were smaller than a standard 200 µm sieve (0.075mm). Subsequently, the ground oil shale was subjected to a burning process at an optimal temperature of 800 °C for 24 hours. This temperature range, between 700 °C and 900 °C, is known to produce oil shale ash with properties similar to cement [34]. The resulting ash was further pulverized to pass through a 63 µm sieve.

Table 4. The chemical composition of OSA

Oxide	**CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**SO_3**	**SiO_2**	**Fe_2O_3**	**L.O.I**
OSA	62.20%	21.4%	1.1%	1.9%	0.23%	0.14%	0.87%	11.41%

The X-ray Diffraction (XRD) analysis of the oil shale ash (OSA) is presented in Figure 7. The prominent band reflections observed in the XRD pattern indicate that Calcite is the predominant mineral present in the OSA. Additionally, other minerals such as Apatite, Anhydrite, and Orthoclase are also detected in the OSA sample.

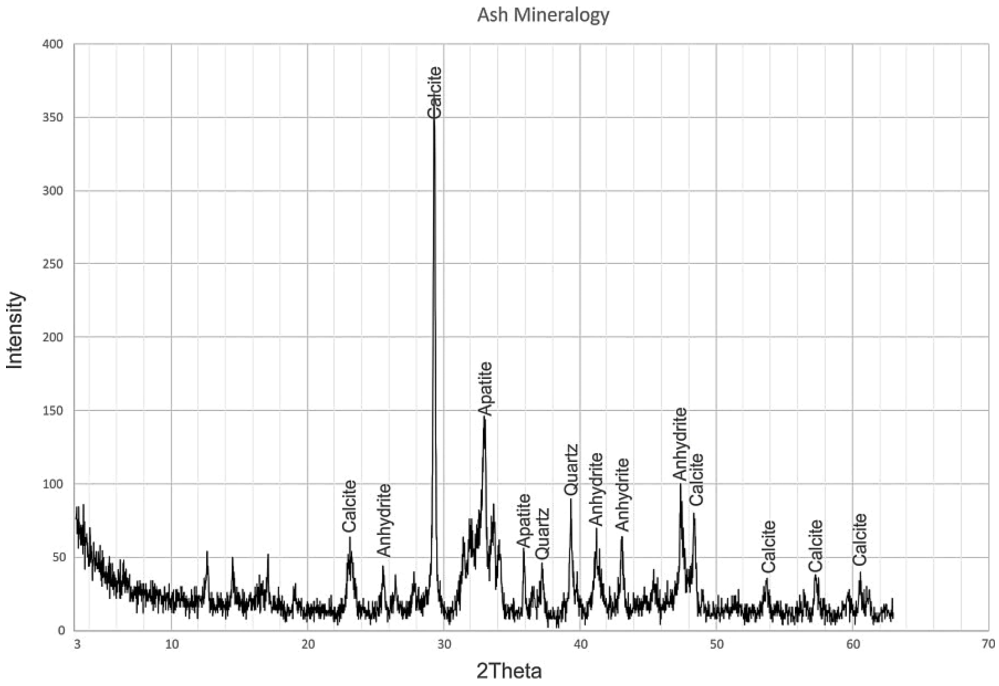

Figure 7. The minerals composition of OSA

2.2. Preparation of Mortar Specimens

The OSA stabilizer was incorporated into the mixture at a 10% weight ratio. A total of eight batches were prepared, each with different ingredient combinations. Seven batches involved replacing the original soil with a mixture containing 30% sand, while one batch consisted solely of the local soil (S mix). For more detailed information on the specific ingredient proportions of each batch, please refer to Table 5.

Table 5. Mortar Batch Schedule

Serial No.	Batch code	Sand content, %	OSA content, %	Cement content, %	Lime content, %
1	S	-	-	-	-
2	SS	30	-	-	-
3	A5	30	5	-	-
4	A10	30	10	-	-
5	A5C10	30	5	10	-
6	A5L10	30	5	-	10
7	A10C10	30	10	10	-
8	A10L10	30	10	-	10

Each batch in the study is assigned a unique code that represents its specific composition. To illustrate, Batch No. 7 will be used as an example. The code for Batch No. 7 is (A10L10), which provides details about the contents of the mixture.

The code breakdown is as follows:

A: Represents the presence of Oil Shale Ash (OSA) in the batch.

O20: Indicates that the OSA constitutes 10% of the total weight of the mixture.

L: Denotes the inclusion of lime in the batch.

L10: Specifies that the lime content in the mixture is 10% of the total weight.

The sand content in all samples, except for the control sample (S mix), is 30% of the total weight.

The soil content in all samples is 45% of the total weight.

It's important to note that the sand content remains consistent at 30% by weight across all samples, while the control sample (S mix) does not contain any added ingredients beyond the local soil.

The materials were manually mixed for 15 minutes to prepare cube samples. The mixture was filled into the cube mold twice. Each layer was compacted using a round steel tool and gently tapped with a soft hammer. The surface was leveled using a spoon to ensure a flat and uniform finish. Subsequently, small cubes measuring 50 millimeters on each side were made from the mixture. Out of these samples, three were set aside for absorption tests, while nine were designated for compression tests. Each sample was appropriately labeled or coded according to the established naming conventions, as depicted in Figure 8.

Figure 8. Cube Samples

The mortar cubes underwent testing at both 7 and 28 days to evaluate their compression strength. Figure 9 displays the machine employed for this purpose. The compression strength of the mortar was determined by subjecting 2-inch (50mm) cubes to the ASTM C109/C109M standard [35].

Figure 9. Machine Compressive Strength

The absorption test was performed in accordance with the IS: 1199-1959 standard [36]. Three specimens of each combination were dried in an oven at 105°C until they reached a consistent mass, and the mass was recorded. Subsequently, the completely dry blocks were immersed in clean water for 24 hours, and the new mass was recorded. The average mass deviation was then calculated as a percentage.

$$Water\ absorption\ (\%) = (W_w - W_d)/W_d \times 100\% \tag{1}$$

where, W_w is wet weight of the sample, and W_d is Oven dry weight of the sample.

For the linear shrinkage experiment, a rectangular box with internal dimensions of 16×4×4 cm was utilized to measure the shrinkage. The interior of the box was lubricated to prevent the soil from adhering to the walls. The soil was carefully packed into the box and levelled with a spatula to ensure it completely filled the mould. Subsequently, the sample was placed in a shaded area for 14 days before measuring its length (as depicted in Figure 10). To calculate the linear shrinkage, the difference in length was expressed as a percentage of the original length. This test was conducted on bar specimens in accordance with the PN-85/B-04500 standard [37].

Figure 10. Linear shrinkage (14 days)

3. Experimental Results and Discussions

3.1. Mechanical Properties of Mortar

The compression strength of the eight samples after 7 and 28 days is illustrated in Figure 11. The addition of 30% sand as an additional component resulted in enhancements in mechanical properties and compression resistance. The inclusion of 5% OSA led to an improvement in pressure resistance compared to the (SS mix) after 28 days of curing, with a recorded compression resistance of 3.3 MPa for the 5A mixture and 3 MPa for the (SS mix). It is noteworthy that 5% and 10% of OSA played a significant role in reducing the pressure resistance of the samples after 7 days.

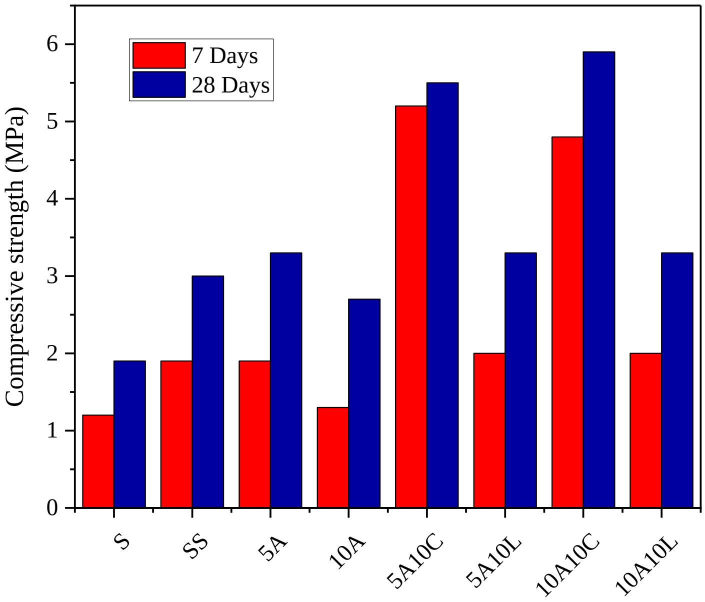

Figure 11. Compressive strength of mortar samples

The addition of 5% ash resulted in improved mechanical properties after 28 days of curing compared to the SS mixture. This improvement can be attributed to the mixing of soil with ash over time, which leads to the formation of ettringite and portlandite phases [32]. These phases contribute to the enhancement of the material's mechanical attributes.

Lime did not show any significant impact on the mechanical properties after 7 or 28 days of curing. However, it is worth noting that the partial substitution of lime with natural pozzolana can be a viable method to enhance compressive strength [38]. The lack of improvement in this study may be attributed to the slow and sluggish reactions that occur in the presence of lime and pozzolana (OSA) [39]. On the other hand, the addition of 5% cement to the soil in the presence of ash resulted in a significant improvement in compression resistance. At 7 and 28 days of curing, the compression resistance increased by approximately 64% and 46%, respectively, compared to the (SS mix). Furthermore, the compressive strength of the 10A10C mixture was higher than that of the (SS mix) by about 61% and 49% at 7 and 28 days of curing, respectively. These results indicate that the combination of ash and cement has a positive effect on the mechanical properties of the soil, leading to increased compression resistance.

Based on the results, the 10A10C mixture demonstrated the highest compressive strength after 28 days of treatment. The use of cement in this mixture resulted in a 5% and 17% increase in compressive strength compared to the results after seven days of curing for the 5A10C and 10A10C mixes, respectively. This can be attributed to the pozzolanic properties of OSA, as it contains a concentration of Al_2O_3 (1.10%) and SiO_2 (21.40%) [27, 40]. The interaction between

OSA and calcium hydroxide in the cement takes longer to develop, which explains the gradual increase in compressive strength over time [41]. These findings indicate that OSA has the potential to contribute to favorable compressive strengths in the future. Therefore, further studies should focus on exploring and optimizing the use of OSA in cement-based mixtures. The research studies mentioned in Table 6 yielded diverse outcomes, occasionally displaying conflicting results. Therefore, the findings of the present study will be presented alongside those obtained in the research studies listed in Table 6 and Figure 12 to facilitate comparisons and highlight any variations. The resulting cubes after undergoing the compressive test can be observed in Figure 13. Due to the significant friction coefficient between the specimen and the steel plates of the testing machine, deformation of the specimen in contact with the platen is prevented. As a result, the fracture process is initiated by stress concentration near the corners of the cube. Micro-cracks form and merge at the corners, leading to the observed crack pattern shown in Figure 13 [42].

Table 6. Numerous research studies have investigated the compressive strength of different stabilizers in earthen materials

Authors	Location	Stabilizer	Replacement Percentages (%)	Max. Compressive Strength (MPa)
Current study	Jordan	Oil shale ash, cement, lime	Oil shale ash: 5, 10 Cement: 5, 10	5.9
Paiva et al. (2022) [17]	Brazil	Cement and fly ash	Cement: 5, 7.5 ,10 Fly ash: 11, 13.5, 16	3,89
Wiehle et al. (2022) [43]	Germany	-	-	4.13
Sobczyńska et al. (2021) [10]	Russia	Cement, lime	Cement: 12.5 Lime: 4	3.55
Stathopoulos et al. (20210 [8]	Greece	Natural, hydraulic lime (NHL3.5) and ladle furnace steelmaking slag (LFS)	(NHL3.5): 20, 25 (LFS): 20, 25	2
Benidir et al. (2021) [11]	Algeria	Cement and lime	Cement: 0, 2, 4, 6, 8 Lime: 0, 5, 8 Cement and lime respectively: (5, 3/5, 5/5, 8)	2
Araya-Letelier et al. (2019) [21]	Chile	Micro polypropylene fibers	0, 0.25, 0.5, 1	2.03
Karozou et al. (2019) [20]	Greece	Nano clay, nano silica and nano alumina	Nano clay: 5 Nano silica and Nano alumina respectively: 1.5, 1	3.022
Sajanthan et al. (2019) [22]	Sri Lanka	Cement	10,12.5, 17	6.90
Gomes et al. (2018) [9]	Portugal	mineral binders (powder hydrated air lime, hydraulic lime, natural cement and Portland cement)	5, 10, and 15 for each stabilizer	0.58
Vimala et al. (2014) [19]	India	Cement	Cement: 8, 9, 11, 14, 20	6.41
Wu et al. (2013) [44]	China	-	-	1.70
Rashmi et al. (2014) [15]	-	Cement, lime and Brick dust	Cement:5, 10, 12 Lime: 5, 10 Brick dust: 25%	4.25
Walker (2004) [16]	Australia & Zimbabwe	Cement and lime	Cement: 2.5, 4, 5, 6, 10 Lime: 19	1.46

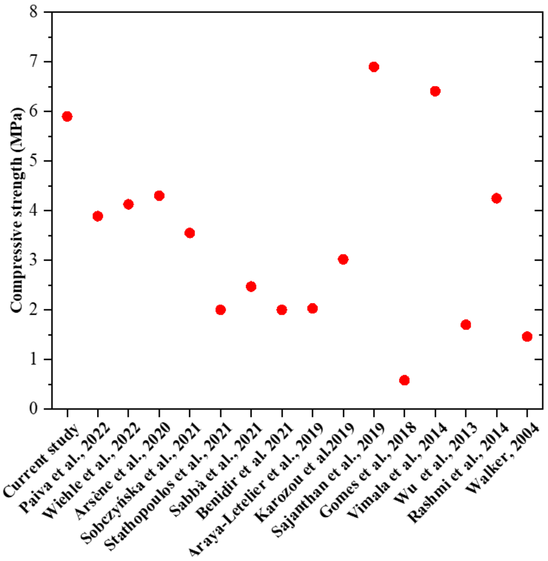

Figure 12. Various studies have examined the compressive strength of different stabilizers in earthen materials

Figure 13. Cube Failure Mode

The maximum compressive strength of earthen materials was investigated in various studies, including the current study conducted in Jordan. In the current study, a mixture of oil shale ash, cement, and lime was used, with oil shale ash and cement being replaced at percentages of 5% and 10% respectively. The maximum compressive strength achieved was 5.9 MPa. Paiva et al. (2022) [17] conducted a study in Brazil using cement and fly ash, with cement replaced at percentages of 5%, 7.5%, and 10%, and fly ash replaced at percentages of 11%, 13.5%, and 16%. The maximum compressive strength recorded was 3.89 MPa. In comparison, the study by Wiehle et al. (2022) [43] in Germany, which did not specify a stabilizer, achieved a maximum compressive strength of 4.13 MPa. Sobczyńska et al. (2021) [10] conducted a study in Russia using cement and lime, with cement replaced at 12.5% and lime at 4%, resulting in a maximum compressive strength of 3.55 MPa. Stathopoulos et al. (2021) [8] conducted a study in Greece using natural hydraulic lime (NHL3.5) and ladle furnace steelmaking slag (LFS), with replacements at percentages of 20% and 25% respectively, achieving a maximum compressive strength of 2 MPa. Benidir et al. (2021) [11] in Algeria used cement and lime, with varying replacement percentages, and achieved a maximum compressive strength of 2 MPa. These results highlight the variations in maximum compressive strength achieved in different studies, indicating the influence of stabilizers and replacement percentages on the mechanical properties of earthen materials.

3.2. Durability Test of Mortar

Figure 14 illustrates the water absorption values of all the samples. It can be observed that the raw mud sample, mud mortar with 30% sand, and mud mortar stabilized with 5% OSA completely disintegrated during water exposure, as depicted in Figure 15. This highlights the significance of mud mortar stabilization and emphasizes that the addition of 10% OSA enhances soil properties and increases its resistance to water absorption compared to the S, SS, and 5A mixes. However, in terms of durability, it is evident that 5% OSA is insufficient.

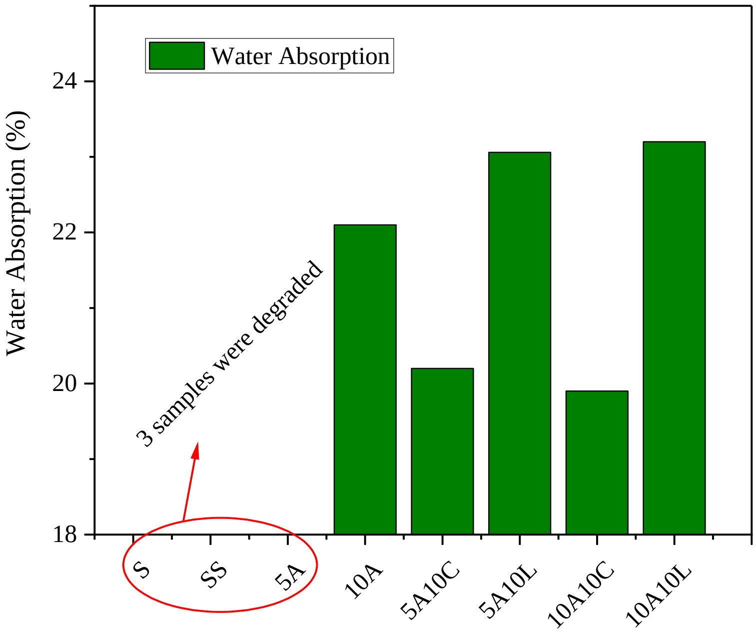

Figure 14. Water Absorption of Mortar Samples

Figure 15. Disintegrated Mortar Samples

The addition of lime results in higher water absorption, making it an unfavourable choice. Furthermore, there was no significant difference in water absorption values between the mixtures that added 5% and 10% lime, with the lowest value observed in the mixture stabilized with 10% cement and 10% ash (10A10C), which recorded a water absorption value of 19.9%. This can be attributed to the higher proportion of C2S in cement and ash, which enhances the resistance and binding of particles in the mixture. As a result, the bond between the soil, water-cement paste, and oil shale ash becomes more stable compared to other stabilizers. This finding aligns with the compressive strength results, where the 10A10C mixture exhibited the highest resistance to pressure after 28 days of curing. It is important to note that OSA, when exposed to rainwater, may release leachates containing toxic elements, leading to severe pollution. However, El-Hasan et al. (2019) [32] concluded that mixing oil shale ash with red soil reduces leaching compared to using OSA without any addition, thereby mitigating the leaching-related concerns.

Several studies have investigated the water absorption properties of different stabilizers in earthen materials as shown in Table 7 and Figure16. In the current study conducted in Jordan, a mixture consisting of oil shale ash, cement, and lime resulted in a minimum water absorption of 19.9%. A study conducted by Paiva et al. (2022) [17] in Brazil, which utilized cement, hydrated lime, metakaolin, and fly ash, reported a water absorption of 17.5 ± 1.00%. Stathopoulos et al. (2021) [8] conducted a study in Greece using NHL3.5 and LFS as stabilizers, and they observed a water absorption of 18.1 ± 0.7%. In comparison, Lekshmi et al. (2016) [14] conducted a study in India with a mixture of cement, lime, and cow dung, resulting in a higher water absorption of 21.93%. Based on these findings, the current study demonstrated a slight increase in water absorption compared to the study in Brazil but a decrease compared to the study in India.

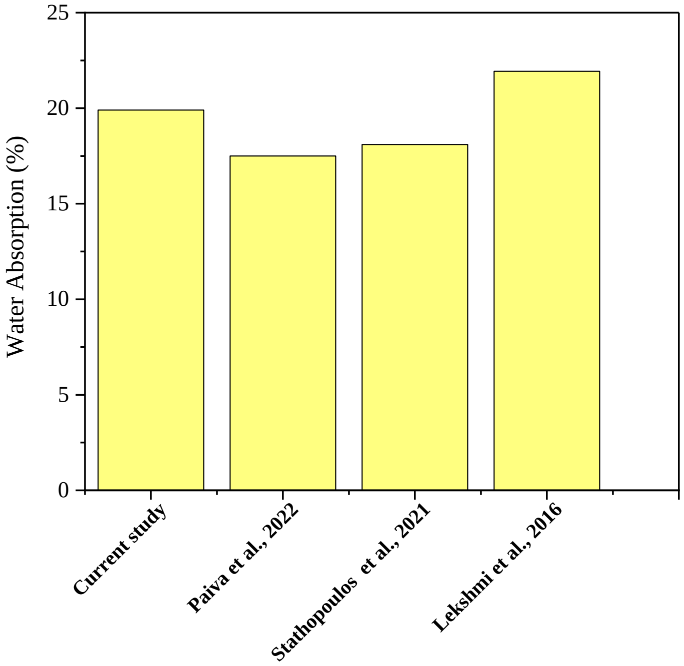

Figure 16. Several studies have investigated the water absorption of different stabilizers in earthen materials

Table 7. Several studies have investigated the water absorption properties of different stabilizers in earthen materials

Authors	Location	Stabilizer	Min. Water Absorption (%)
Current study	Jordan	Oil shale ash, cement, lime	19.9
Paiva et al., 2022 [17]	Brazil	Cement, hydrated lime, metakaolin, and fly ash	17.5 ± 1.00
Stathopoulos et al., 2021 [8]	Greece	*NHL3.5 and LFS	18.1 ± 0.7
Lekshmi et al., 2016 [14]	India	Cement, lime, cow dung	21.93

3.3. Linear Shrinkage

According to the new German standard [45], the maximum allowable linear shrinkage is 2.5%. It was observed that the mud mortar stabilized with 10% cement and 10% OSA exhibited the lowest linear shrinkage, resulting in a 97% reduction compared to the raw mud mortar sample (Figure 17). While OSA alone, without cement, improved the shrinkage properties of the mortar, it did not meet the specified limit. This could be attributed to the absence of clay minerals like smectite in oil shale ash [46, 47], which are typically present in soil and contribute to shrinkage.

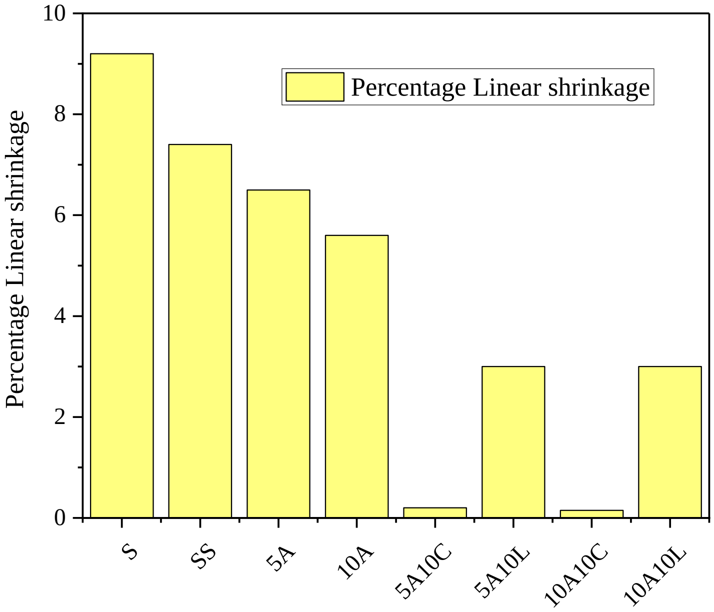

Figure 17. Linear shrinkage of mortar samples

Various studies have examined the linear shrinkage properties of different stabilizers in earthen materials as shown in Table 8 and Figure 18. In the current study conducted in Jordan, a mixture comprising oil shale ash, cement, and lime resulted in a minimum shrinkage of 0.3%. Sobczyńska et al. (2021) [10] conducted a study in Russia using cement, sand, and lime, which resulted in a higher shrinkage of 3%. Similarly, Stathopoulos et al. (2021) [8] conducted a study in Greece utilizing NHL3.5 and LFS as stabilizers and observed a shrinkage of 2%. In comparison, Sabbà et al. (2021) [48] conducted a study in Italy where the shrinkage was also recorded as 0.3%. Gomes et al. (2018) [9] conducted a study in Portugal using either cement or lime, resulting in a comparable shrinkage of 0.33%. Lastly, Lekshmi et al. (2016) [14] conducted a study in India using a combination of cement, lime, and cow dung, which led to a higher shrinkage of 2.43%. Based on these findings, the current study demonstrated comparable shrinkage to the study in Italy and Portugal, but lower shrinkage compared to the studies in Russia and India.

Table 8. Various studies have examined the linear shrinkage properties of different stabilizers in earthen materials

Authors	Location	Stabilizer	Min Shrinkage Test (%)
Current study	Jordan	Oil shale ash, cement, lime	0.3
Sobczyńska et al. (2021) [10]	Russia	Cement, sand, lime,	3
Stathopoulos et al. (2021) [8]	Greece	NHL3.5 and LFS	2
Sabbà et al. (2021) [48]	Italy	-	0.3
Gomes et al. (2018) [9]	Portugal	Cement or Lime	0.33
Lekshmi et al. (2016) [14]	India	Cement, lime, cow dung	2.43

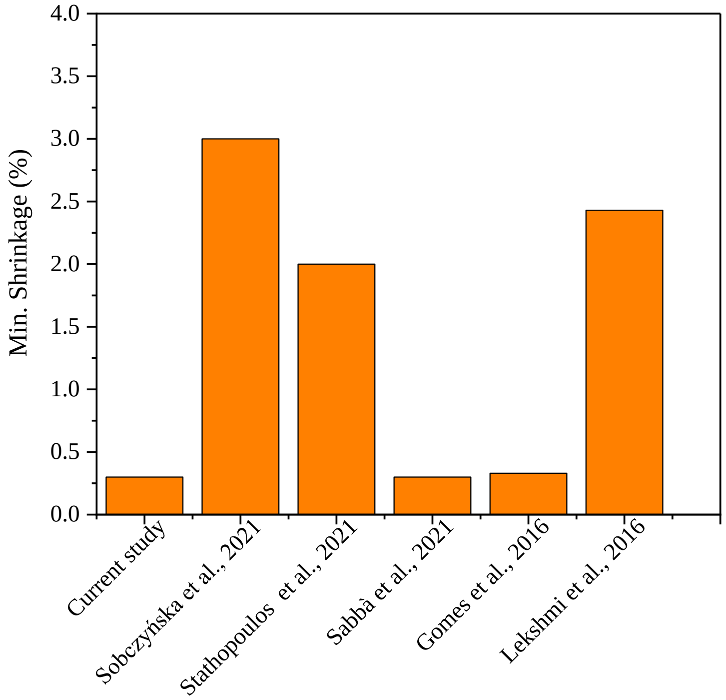

Figure 18. Different investigations have explored the characteristics of linear shrinkage in earthen materials using various stabilizers

4. Conclusion

The objective of this research was to explore the potential of using oil shale ash (OSA) as a stabilizer in earthen mortars to enhance their mechanical and durability properties. Mud mortar was produced by stabilizing the local soil with a combination of Oil Shale Ash (OSA), Ordinary Portland Cement (OPC), and lime. Cement and lime are employed as substitutes, comprising approximately 10% of the soil's weight, while oil shale ash is utilized as a replacement, accounting for 5% and 10% of the soil's weight. Initially, the local soil without any additives exhibited significant shrinkage immediately after the tamping process, rendering it unsuitable for mortar production. However, when the soil was mixed with OSA, the mechanical properties of the mortar improved after 28 days of curing. This improvement was attributed to the formation of resistant minerals during the mixing process. The addition of OSA led to a reduction in shrinkage, with a 10% OSA content resulting in a 1.9% decrease in shrinkage compared to the soil containing 30% sand and without any stabilizer. It was observed that the reaction between cement and OSA occurred gradually, resulting in weaker early strength. However, the effects of OSA became more apparent at later stages. In contrast, lime did not have a significant impact on the mechanical properties after 7 or 28 days of curing. Based on the study's findings, the optimal composition for mortar with superior mechanical properties and durability characteristics involved stabilizing the soil with 10% cement and 10% OSA. Additionally, an increase in the OSA content tended to decrease the absorption of the mortars. Overall, the research demonstrated the potential of OSA as a stabilizer to enhance earthen mortars while addressing environmental concerns, providing valuable insights for the field of construction materials.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A. and W.E.; methodology, H.A. and W.E.; formal analysis, H.A. and W.E.; data curation, H.A., M.A., and W.E.; writing—original draft preparation, H.A. and W.E.; writing—review and editing, M.A. and W.E.; supervision, M.A. and W.E. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

The authors would like to express gratitude to Northern Cement Company (NCCO) for providing the Raw Materials and, to those who will review and support our research.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

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