Evaluating the Compressive Strength of Sulfur Mortar in Comparison with Conventional Cement Mortar

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ABSTRACT

The quantity of sulfur produced as a byproduct of the industrial refining process is large because of the fast-growing usage of fossil fuels. The future sulfur levels are predicted to rise steadily, therefore without a counterplan, the high expense of waste management will be necessary. Therefore, in this study, sulfur was utilized as a building ingredient for concrete and asphalt. The purpose of the current work was to evaluate the compressive strength of unmodified sulfur mortar (made with unmodified sulfur binder instead of Portland cement) and compare it to the strength of the cement mortar. Specimens of cement mortar and sulfur mortar with three different percentages of sulfur (30, 35, and 40%) were tested and the results showed that the mortar with 40% of sulfur presented the optimum strength. These four types of mortar were further tested to inspect their properties in severe environments, namely their chemical resistance. In the resistance test, in 30% HCl solution, the cement mortar case demonstrated the most significant mass reduction (19.4%) and compressive strength reduction (83%), whereas the 40% of the sulfur mortar case exhibited the lowest reduction percentages for both the mass (3.3%) and compressive strength (36%). These findings demonstrate that the unmodified sulfur mortar, when optimally proportioned, offers superior performance in aggressive environments, a rapid strength gain, and a viable use for excess industrial sulfur. The study contributes to the sustainable construction material research by providing a low-cost, high-durability alternative to cement mortar, with particular applicability in infrastructure exposed to acids, such as sewage systems, industrial floors, and chemical containment structures.

Keywords-cement mortar; compressive strength; HCl acid; sulfur mortar

I. INTRODUCTION

The cost and environmental challenges related to traditional building materials, such as cement and river sand, are becoming increasingly significant [1]. Incorporating nano-sized particles of Banded Iron Formation (BIF) in cement mortar may impart specific properties that can improve the mechanical strength and durability, and even contribute to sustainability [2]. Meanwhile, the quantity of the sulfur produced as a byproduct of the industrial refining process and the usage of fossil fuels is rising quickly [3]. Around 1,000 million tons of sulfur were produced worldwide in 2007. In Korea 120 million tons of sulfur were produced by 2009, 90% of which come from the desulfurization of the oil refining process [4]. Most of the sulfur is exported at a low cost due to limited domestic demand, despite its potential as an industrial chemical [3]. As sulfur emissions continue to rise, researchers are investigating alternative applications for this often undesired byproduct, including its incorporation into construction materials, such as concrete and asphalt [3]. Since almost 7% of the global CO_2 emissions come from the cement manufacturing process alone [5], using sulfur as a substitute for cement in concrete potentially offers additional ecological benefits.

Despite having a similar final look to Portland cement concrete, sulfur concrete is a new material that differs in its production, handling, application, and testing. Sulfur and mineral aggregates are heated to create sulfur concrete, a thermoplastic substance [6]. When sulfur concrete cools, it quickly solidifies and becomes stronger. Sulfur concrete is a general name for a variety of products that differ in terms of the aggregates, sulfur-based binders, and proportions used, in the same way that other concrete materials, like Portland cement concrete and asphaltic concrete, exhibit variation [6]. High-strength, corrosion-resistant sulfur concrete may be used in certain situations where conventional building materials degrade quickly, using sulfur binders and aggregates that are resistant to several mineral acid and salt solutions. While sulfur concrete performs exceptionally well in a variety of acidic and salty conditions, it is often not resistant to oxidizers or alkalis [7]. Sulfur concrete has numerous industrial applications, such as prefabricated construction elements (e.g., roadblocks and sidewalks), sewage and drainage structures, base foundation covers, acid tank linings, and concrete platforms for industrial environments [8].

Durability issues hampered primary sulfur concrete products made with unaltered sulfur as a binder. Even when materials with exceptional mechanical strength were created, they degraded and failed very quickly in real-world applications [9]. However, the creation of modified sulfur cements improved the performance of sulfur concrete and greatly boosted the viability of using it as a building material, due to several special qualities [10], such as:

a) High strength and fatigue resistance.

b) Outstanding resistance to corrosion in most acids and salts.

c) Rapid set and strength gain.

The general aim of this work is to develop a special type of mortar, called sulfur mortar, with specific formulation, using unmodified sulfur, and to perform a comparison between the compressive strength of cement and sulfur mortars before and after immersion in an HCl solution. Different percentages of sulfur were tested to determine the best ratio. The increasing surplus of sulfur, particularly in oil-producing countries, like Iraq, combined with the environmental impact and limited chemical durability of Portland cement, highlights the urgent need for sustainable alternatives in construction. While modified sulfur concretes have shown promise, they often require complex additives and processing. This study addresses this gap by investigating the unmodified sulfur mortar as a simpler, locally viable solution, focusing on its compressive strength and resistance to acid attack compared to the conventional cement mortar.

II. ADVANTAGES AND DISADVANTAGES OF SULFUR CONCRETE

Natural gas processing plants and petroleum refineries generate substantial amounts of sulfur as a byproduct. The global sulfur production exceeds the actual demand, leading to a surplus that necessitates sustainable applications [3, 11]. Many industries use large amounts of sulfur, although not as big as those they create [3]. In certain situations, the sulfur building material can provide advantages over more conventional materials, despite its present lack of widespread use. Sulfur-extended asphalt pavements and sulfur concrete are examples of sulfur-based building materials. When unaltered sulfur and aggregate were combined at a high temperature to create sulfur concrete, the sulfur binder crystallized from the liquid state as monoclinic sulfur (Sβ) 119˚C. When Sβ cools to less than 114 ˚C, it begins to change into orthorhombic sulfur (Sα), a stable form of sulfur at room temperature [12]. Stable sulfur was created by reacting sulfur with dicyclopentadiene (DCPD), an unsaturated hydrocarbon, to generate long-chain polymeric polysulfides.

In regions where sulfur prices are high, it is possible for the cost of the ingredients used to make sulfur concrete to be higher than that of Portland cement concrete. But even with a slight price difference, sulfur concrete is worth considering since its unique qualities offer advantages over Portland cement concrete [13]. Sulfur concrete's primary benefit is that it can be used as a very long-lasting substitute for building materials, particularly Portland cement concrete, in industrial facilities and other places where the acidic and salty conditions cause the latter to deteriorate and fail too soon [10]. Although its ultimate life or durability have not been fully determined in many end-use applications, enough data have been gathered to demonstrate that it is resistant to corrosion and durable enough to last several times the lifespan of other building materials used in corrosive environments [11]. Apart from its exceptional resistance to the chemical attack from acids and salts, the sulfur concrete, typically also exhibits the following beneficial properties [8, 11, 14]:

1. Enhanced fatigue life and improved tensile, compressive, and flexural strength compared to Portland cement concrete.
2. Rapid strength development: it achieves 70–80% of its full compressive strength within 24 h.
3. Year-round applicability in sub-freezing conditions.
4. Low water permeability and suitability for safe mixing and handling when the proper procedures are followed.

To reduce emissions, sulfur concrete should be made between the approved mixing temperature range of 260 and 300 F (127 and 141 C). It will become weaker if it is subjected to temperatures higher than its melting point. Additionally, the sulfur concrete utilization must align with its thermoplastic and strength characteristics [8].

III. MECHANICAL PROPERTIES

To save time and money, authors in [15] tried several methods while manufacturing sulfur mortars and concrete with basic equipment. Dosification, was also improved based on mechanical and workability factors. The best percentages for manufacturing and performance were found to be about 30% binder for sulfur mortars (maximum aggregate size of 2.5 mm) and 15% binder for sulfur concretes (maximum aggregate size of 10 mm). The presence of mineral filler had to be between 5% (mortars) and 10% (concretes) in relation to the mass of sulfur [15]. To make sure that the generated materials matched the qualities reported in the literature, basic mechanical parameters were assessed for the samples. Some of the data collected are displayed in Table I [8, 16, 17]. It is important to note that these strengths were attained in a matter of hours; for instance, 80% of the maximum strength was attained just 3 h after casting for pieces measuring 10 x 10 x 10 cm.

TABLE I. SULFUR MORTAR AND CONCRETE MECHANICAL CHARACTERISTICS

Property	Results for sulfur mortar	Results for sulfur concrete
Compressive strength (MPa)	70.0—75.0	50.0-60.0
Flexural strength (MPa)	12.0 – 13.0	8.0 – 10.0
Indirect tensile strength (MPa)	5.0 – 6.0	5.0
Shrinkage (mm/m)	0.6 -- 0.7	1.4

IV. MATERIALS

- Sulfur

In this study, agricultural sulfur was used (from stores selling agricultural equipment). The color of the sulfur powder is yellow (Figure 1).

Fig. 1. Sample of sulfur powder used in the current study.

- Cement

Sulfate-resisting Portland cement (Type V), also called bridge cement, manufactured by Karbala cement factory was utilized throughout this project corresponding to Iraqi specifications [18]. To avoid any variations between different batches, the whole quantity of cement was brought to the laboratory and stored in a dry place. The physical and chemical properties of this cement are given in Tables II and III.

TABLE II. CHEMICAL COMPOSITION OF CEMENT

Oxide	(%)	Limit of [18]
CaO	60.92	…………
SiO_2	19.88	…………
Al_2O_3	3.34	…………
Fe_2O_3	4.76	…………
MgO	2.11	≤ 5.0
SO_3	2.21	≤ 2.8
LSF	0.946	0.66 - 1.02
L.O.I.	3.26	≤ 4.0
I.R.	0.81	≤ 1.5

TABLE III. PHYSICAL PROPERTIES OF CEMENT

Physical properties		Test results	Limit of [18]
Fineness (Blain method) cm^2/gm		2990	≥2300
Setting time(Vicat method) hours:min	Initial	1:10	≥0:45
	Final	3:50	≤10:00
Compressive strength MPa	3 days	17.28	≥15
	7 days	26.85	≥23

- Fine Aggregate (Sand)

The graded standard sand (Table IV) utilized in this study was brought from Al-Nawafith Co.LTD for the sand and gravel filters in Najaf.

TABLE IV. GRADING OF STANDARD SAND

Sieve size	Percent retained	ASTM C778-2021 limits [19]
No.16 (1.18mm)	None	None
No.30 (600Mm)	2.0	2.0 ± 2.0
No.40 (425Mm)	27.0	30.0 ± 5.0
No.50 (300Mm)	75.0	75.0 ± 5.0
No.100 (150Mm)	97.0	98.0 ± 2.0

- Mixing water

The water used throughout the experimental program was drinking water supplied from ordinary tap in the laboratory.

V. OUTLINE OF THE EXPERIMENTAL PROGRAM

The laboratory work can be divided into four stages:

1. Preparation of the cement mortar specimens (Group 1).
2. Preparation of the sulfur mortar specimens (Group 2).
3. Compressive strength test for Groups 1 and 2.
4. Chemical resistance test for Groups 1 and 2, by immersing them in the HCl solution.

A. Preparation of Cement Mortar Specimens (Group 1)

- Mixing

The dry components of mortar were manually mixed until homogeneity was achieved, and then mixing water was added.

- Casting and compaction

Steel molds (Figure 2) were utilized to cast the mortar specimens and were compacted by a vibration (Figure 3).

- Curing

Following the casting, the specimens were wrapped in plastic sheets and left in a room at 20 ± 2 ℃ for a whole day until they were demolded. They were then placed in water tanks to cure for a duration ranging from 7 to 28 days before testing (Figure 4). To maintain optimal curing conditions, the water in the tanks was replaced every 7-10 days, i.e., 2-3 times throughout the 28-day period.

Fig. 2. Steel molds.

B. Preparation of Sulfur Mortar Specimens (Group 2)

Sulfur was used as a replacement material for Portland cement to prepare the sulfur mortar. Three percentages of sulfur were used: 30, 35, and 40% of the weight of the mixture. The sulfur mortar specimens were fabricated using the method proposed by ACI 548.2R-93 [8]. At first, fine aggregate preheated in an oven at 180 ˚C for 3 h was added to the container that was preheated up to 130˚C by a gas cooker.

Unmodified sulfur binder was also poured into the container. After the sulfur binder liquefied, the mixing process continued for 5 more min. The sulfur mortar was then compacted and cast. After a day, the sulfur mortar specimens were demolded (Figure 5) and stored at ambient temperature (20–25 ˚C) with a constant humidity level.

Fig. 3. Cement mortar sample during casting.

Fig. 4. Samples during curing

Fig. 5. Sulfur mortar specimens.

C. Testing of Compressive Strength

The compressive strength test was performed on 50 × 50 × 50 mm cubes [20], by uni-axial compression load after 7 and 28 days from casting for the cement mortar samples, and after 1 and 28 days for the unmodified sulfur mortar specimens (Figure 6). The average value of three specimens in each age was recorded. The compressive strength was determined using:

$$\sigma = \frac{P}{A} \quad (1)$$

where:

σ: The compressive strength of the cubic specimen in MPa.

P: The maximum load at failure in N.

A: The area of the top of the cubic specimen of the mortar exposed to compression load acts in mm^2.

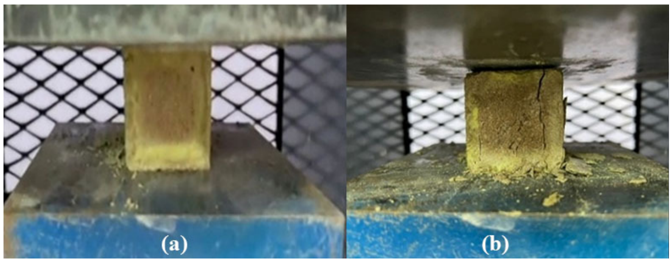

Fig. 6. Unmodified sulfur mortar specimen under compression test (a) and after failure load (b).

D. Chemical Resistance Test

The cubic specimens were submerged in a harsh chemical environment consisting of a 30% HCl solution in order to assess the chemical resistance of the cement and sulfur mortars (Figure 7). By frequently determining the mass on a digital laboratory scale and comparing it to the original mass, the degradation of cement and sulfur mortars over a 30-day period was observed. Additionally, the compressive strength was tested following a 30-day immersion and was compared to the measurements before immersion. The specimens were taken out of the chemical solution, cleaned, and dried in an oven set at 105°C before the mass change and compressive strength were determined.

Fig. 7. Samples immersed in the HCl solution.

VI. RESULTS AND DISCUSSION

The compressive strength results of the cement and unmodified sulfur mortars are presented in Tables V-VII.

A. Sulfate Resisting Cement Mortar (Group 1)

The cement mortar specimens were tested for their compressive strength at 7 and 28 days. It is observed that the compressive strength generally increased when extending the curing period. The magnitude of increment was about 7.2 MPa. The compressive strength increased by 64.75% between day 7 and day 28.

TABLE V. COMPRESSIVE STRENGTH OF CEMENT MORTAR AT 7 AND 28 DAYS

Curing (days)	Compressive strength (MPa)
7	11.120
28	18.320

B. Unmodified Sulfur Mortar (Group 2)

To make sure that the produced materials matched the characteristics listed in the literature, the compressive strength of the sulfur samples was examined. The influence of varying the ratio of the sulfur on the compressive strength of the mortar is shown in Tables VI and VII, for the tests on day 1 and day 28, respectively. A slight increase is observed in the compressive strength at 1 day when using 30 and 35% of sulfur compared to the compressive strength of the cement mortar at 28 days. The optimum compressive strength was observed with 40% of sulfur, achieving 107% increase compared to the cement mortar at 28 days. Regarding the maximum strength, 80% of it was obtained within a few hours after casting. The measurements on day 28 illustrate an even bigger increase in the compressive strength values of the sulfur mortar. The maximum strength value of 40.32 MPa was achieved for 40% of sulfur, leading to an increase of 120% compared to the cement mortar at 28 days.

TABLE VI. COMPRESSIVE STRENGTH OF UNMODIFIED SULFUR MORTAR AT DAY 1

Percentage of sulfur (%)	Compressive strength (MPa)
30	18.76
35	21.00
40	37.96

TABLE VII. COMPRESSIVE STRENGTH OF UNMODIFIED SULFUR MORTAR AT 28 DAYS

Percentage of sulfur (%)	Compressive strength (MPa)
30	20.00
35	23.60
40	40.32

C. Chemical Resistance Test Results

The mass change of the sulfate resisting cement and sulfur mortars (Groups 1 and 2) are displayed in Table VIII. The mass of the sulfate resisting cement mortar decreased up to 19.4%, while the sulfur mortar specimens decreased up to 16%, 4.4%, and 3.3%, respectively, for 30%, 35%, and 40% of sulfur mortar. The mechanism of the reaction with the cement hydrate in the instance of hydrochloric acid is displayed in [21, 22, 23]:

$$Ca(OH)_2 + HCl \rightarrow CaCl_2{\bullet}2H_2O{+}H_2O \quad (2)$$

$$3CaO{\bullet}2SiO_2{\bullet}3H_2O + HCl \rightarrow CaCl_2{\bullet}SiO_2{\bullet}H_2O \quad (3)$$

$$3CaO{\bullet}Al_2O_3{\bullet}CaSO_4{\bullet}32H_2O{+}HCl \rightarrow CaCl_2 + Al_2O_3{\bullet}nH_2O + CaSO_4{\bullet}2H_2O \quad (4)$$

The process causes the cement hydrate to lose its ability to combine. The well-soluble $CaCl_2$ dissolves readily. Additionally, SiO_2 and Al_2O_3 dissolve in a gel condition. Basic and amphoteric oxides react with acids to generate metal chlorides or sulfates, which is the basis for the hydrochloric acid solution's attack on the sulfur mortar [24, 25].

TABLE VIII. CHANGE OF MASS AFTER 30 DAYS OF IMMERSION IN HCL SOLUTION

Type of mortar	Mass (g)		Mass change (%)
	Before immersion	After immersion	
Sulfate resisting cement	275	221.67	19.4
30 % sulfur mortar	298	250	16
35 % sulfur mortar	298	285	4.4
40 % sulfur mortar	298.67	288.67	3.3

The results of the compressive strength of sulfate resisting cement and sulfur mortars (Groups 1 and 2) after immersion in acid are shown in Table IX. The average compressive strength of the sulfate resisting the cement mortar decreased by 83% after immersion for 30 days, while the sulfur mortar specimens decreased up to 62.6%, 46%, and 36% respectively for 30%, 35%, and 40% of sulfur mortar. The results also demonstrated that the maximum strength value of 25.640 MPa was achieved for 40% of sulfur, with a 36% reduction ratio compared to the compressive strength before immersion, after 28 days of curing.

Finally, the results of this study were compared with those of previous studies. Table X summarizes key data from the selected studies, evaluating the chemical durability of sulfur-based materials.

TABLE IX. CHANGE OF COMPRESSIVE STRENGTH AFTER 30 DAYS OF IMMERSION IN HCL SOLUTION

Type of mortar	Compressive strength (MPa)		Reduction ratio (%)
	Before immersion	After immersion	
Sulfate resisting cement	18.32	3.08	83
30% sulfur mortar	20.00	7.48	62.6
35% sulfur mortar	23.60	12.76	46
40% sulfur mortar	40.32	25.64	36

TABLE X. COMPARISON OF SULFUR MORTAR ACID RESISTANCE WITH PREVIOUS RESEARCH STUDIES

Ref.	Sulfur type	Acid type and concentration	Duration	Mass loss (%)	Strength loss (%)
This study	Unmodified	30% HCl	30 days	3.3	36
[11]	Modified	10% H_2SO_4 / 5% HNO_3	28 days	<5	20–30
[10]	Modified	15% HCl	30 days	2–4	25–40
[8]	Modified	HCl / H_2SO_4 (varied)	30 days	—	25–35

VII. POTENTIAL APPLICATIONS

This type of unmodified sulfur mortar is particularly suitable for applications in aggressive chemical environments, such as industrial floors, wastewater treatment facilities, acid storage areas, and drainage structures, due to its excellent resistance to acids and salts. It can also be used in precast elements, sidewalks, and non-structural components, where a rapid strength gain and durability are required. However, due to its thermoplastic nature, it is not proposed for use in pavements or structural building elements exposed to high thermal variation or heavy loads [8]. Its low water permeability and fast curing make it ideal for cold-weather construction or rapid repair applications. The mortar's limitations include sensitivity to high temperatures and brittleness at low sulfur contents. Further research is proposed before adopting it for large-scale structural uses.

VIII. CONCLUSIONS

The main points obtained from this study are:

1. For Group 1, the compressive strength of the sulfate resisting cement mortar increased when extending the curing period, and the percentage of increment in strength at 28 days reached 64.75% of the strength at 7 days.

2. For Group 2, the results demonstrated that the compressive strength increases when using sulfur as an alternative to cement in mortar for all tested percentages of sulfur. The optimum strength value of 40.32 MPa was achieved for 40% of sulfur, and is 120% higher than the compressive strength of the cement mortar at 28 days.

3. After immersion in HCl, a decrease in mass was observed for both the sulfate resisting cement and sulfur mortar samples, with a minimum reduction of 3.3% for the case of 40% sulfur mortar.

4. The compressive strength also reduced for both the cement and sulfur mortar specimens after immersion in the HCl acid. The maximum strength value of 25.64 MPa was achieved for 40% sulfur mortar, with a 36% reduction compared to the measurements before immersion.

5. Using various proportions of sulfur as a substitute for Portland cement in concrete mixes is proposed. Further research could also examine the properties of sulfur-modified mortar with fly ash.

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