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Orginal Article

Influence of relative humidity and temperature on shell lime mortar with the addition of acacia gum and rice soup

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Abstract: The purpose of this study was to evaluate the effectiveness of organic lime mortar containing rice soup and acacia gum in three different climatic regions with varying temperatures and humidity levels: warm and humid (35°C, 72%), dry (25°C, 20%), and cold (25°C, 50%). The rice soup and acacia gum were fermented for one day and then analysed for photochemical composition using gas chromatography-mass spectrometry (GC-MS). The hydrated phases of organic lime mortars were examined using X-ray diffraction (XRD) to understand the interaction between lime and the organic components. The photochemical composition of rice soup included 62.35% alkanes and 10.14% saturated long-chain fatty acids, while acacia gum contained 56.25% polysaccharides and 32.76% carboxylic acids. The alkanes in rice soup contributed to an increase in compressive strength in the S2 sample (2.63 N/mm²), which was higher than in all other samples. The mineral components in rice soup included calcite, portlandite, albite, anorthite, aragonite, quartz, $C_3S_2H_3$ (afwillite), and tobermorite. The fatty acids reacted with lime mortar to generate complex compounds; polymerisation occurred, leading to the formation of CSH (calcium silicate hydrate). Similarly, acacia gum contained calcite, albite, anorthite, quartz, portlandite, and vaterite. The polysaccharides in acacia gum contributed to improved carbonation. During fermentation, carboxylic acids reduced CO_2, enhancing carbonation and leading to the formation of calcite, aragonite, and vaterite. Rice soup exhibited superior performance in warm and humid climates due to enhanced CSH mineral formation; however, it was unsuitable for dry and cold climatic conditions. Acacia gum mortar performed best in dry climates due to its enhanced mineralogical properties; however, it was unsuitable for warm, humid, or cold climatic conditions.

Keywords: humidity level, climatic region, acacia gum, rice soup

1. Introduction

The primary objective of environmentally conscious buildings is to reduce carbon dioxide emissions [1]. Adverse environmental conditions, such as extreme temperatures, high humidity, pollution, and exposure to salty atmospheres, can damage heritage structures [2]. Lime mortar has been used in historic buildings for over ten thousand years due to its exceptional durability against varying weather conditions and its impressively low carbon footprint [3,4]. Europeans introduced the technology of calcining limestone in 2450 BC [5]. Furthermore, the Romans enhanced lime mortars by incorporating sand, gypsum, volcanic ash, and pottery [6]. Western Asian and European cultures widely utilised lime mortar until the 19th century when cement became popular [7]. Archaeological findings suggest that lime was used during prehistoric times in Iran and China [8]; notably, in India, emperors and the Mughals constructed many architectural marvels. For instance, Qutab Shah built the Charminar, an early impressive architectural structure, using granite stones and lime mortar [9].

Lime mortar production typically involves combining lime, water, aggregate, and organic additives. These additives modify specific mortar characteristics, such as workability, permeability, strength, and durability [10]. Incorporating organic materials such as egg, casein, animal glue, blood, vegetable juices, sticky rice, jaggery, kadukkai, and gums significantly enhances the strength and longevity of lime mortar [11]. These organic elements, comprising a variety of polysaccharides, fats, proteins, acids, esters, and other substances, offer tangible benefits in bolstering the stability and durability of the mortar [12]. In traditional construction, the selection of organic materials is guided by factors such as specific requirements, material availability, cost, properties, and regional climate conditions [13]. The findings of this study, which could influence the selection of organic materials in future construction projects, offer a promising path towards more durable and sustainable structures, instilling hope for the future of construction.

Climatic conditions play a crucial role in influencing the natural performance, durability, and long-term stability of construction materials found in ancient structures [14]. The National Building Code of India (2016) classifies the country into five distinct climatic zones: Hot and Dry, Warm and Humid, Composite, Temperate, and Cold [15]. In warm and humid regions, many areas in India experience temperatures of 35°C with a relative humidity of 72%, leading to the selection of zone 1. Across the five climatic zones, low temperatures of 25°C are prevalent in many areas, while relative humidity fluctuates between 20% and 95%. In arid regions, the temperature is recorded at 25°C with a relative humidity of 20%, leading to the selection of zone 2. In cold regions, the temperature is also 25°C with a relative humidity of 50%, so zone 3 was selected.

In India, no previous research has been conducted on the behaviour of organic lime mortar in various climatic conditions. The objectives of this study are to: i) Produce lime mortar with organic additives, specifically acacia gum (Acacia seyal) and rice soup (Oryza sativa), and use gas chromatography-mass spectrometry (GC-MS) to ascertain the phytochemical compounds present in these additives; ii) Investigate the climate response of organic lime mortar in three different climatic zones; iii) Analyse alterations in the hydrated phases using X-ray diffraction (XRD).

2. Materials and methods

The shell lime sourced from Sunambukulam in Tamil Nadu contains 67% CaO and meets the criteria for Class A Lime as per the IS 712-1984 standards. The river sand particles were sieved using a 2.36 mm sieve to ensure uniformity in particle size. Uncooked rice and potable water were combined in a 1:4 ratio and boiled over medium heat for 30 minutes. Subsequently, the rice soup was extracted, cooled, and subjected to aerobic fermentation for one day. Shell lime, passed through an 850-micron sieve, was mixed with rice soup at concentrations of 1%, 2%, and 3%. The mixture was then combined with three parts of sand and mixed for 30 minutes, resulting in SR1, SR2, and SR3.

Ten grams of acacia gum were immersed in 1000 ml of water for 24 hours under aerobic conditions. This fermented water was then added to shell lime and sieved through an 850-micron sieve. The resulting mixture was blended with two parts sand for 30 minutes, forming AG1. Similarly, 30 grams and 50 grams of acacia gum were immersed in 1000 ml of water, leading to the formation of AG2 and AG3, respectively.

3. Experimental investigations

3.1. Organic analysis

Organic analysis measures the concentrations of carbohydrates, proteins, and fats. The crude fat test, performed according to IS 7874 (Part 1)-1975, verified the presence of fat. The Kjeldahl digestion test was used to determine the protein content of the additive [16,17]. The mass percentages of fat and protein were used to evaluate the carbohydrate content, calculated using the following equation:

$$\text{\% of carbohydrate} = [100 - (\text{\% of moisture} + \text{\% of fat} + \text{\% of proteins} + \text{\% of ash})] \quad (1)$$

Phytochemical compounds in the fermented organic sample were identified [18,19] by mixing the sample with 1 mL of high-purity ethyl acetate, suitable for gas chromatography. The mixture was then vortexed and filtered through a 0.45 μm filter cartridge before being introduced into the GC-MS instrument (Agilent Technologies; Model Nos. 7890B GC and 5977B MSD). The GC-MS operated at a constant oven temperature of 300°C for 45 minutes.

3.2. Properties of organic mortar

The physical parameters of the specimens, including water absorption, porosity, and bulk density, were assessed 90 days after casting in accordance with the RILEM TC-25 1980 standard. The samples used in this research were cubes measuring 50 mm × 50 mm × 50 mm. The porosity of the mortar was evaluated using Mercury Intrusion Porosimetry (MIP) with an AutoPore IV 9500 V1.04.

Mortar carbonation studies were conducted over 90 days, following BS EN 13295 (2004). Based on the literature [17], a 5% CO_2 concentration was adopted for this investigation. Every 48 hours, the chamber was opened to measure the weight of the samples. The surface of the samples was dried and sprayed with 1% phenolphthalein. The maximum and minimum carbonation depths were measured, and their numerical average was taken as the carbonation depth.

3.3. Climatic model studies

After 90 days of ageing, the samples were placed under three artificially created climatic conditions in the laboratory by adjusting humidity and temperature levels to conduct the climatic model studies. The samples were kept in the climate chamber for twenty-eight days. The specimens used in this investigation are detailed in Table 4.

The compressive strength values of the samples across various combinations of climatic zones were calculated following the guidelines stipulated in IS 6932, Part VII-2009. For each combination, six mortar samples were analysed using a 50 kN (HEIKO) low-capacity universal testing machine for evaluation.

For XRD analysis, the crushed mortar fragments collected from the compressive strength analysis were sieved through a 75-micron sieve. The mineralogical studies of the mortars were conducted using a Bruker AXS D8 Advance X-ray diffractometer operating at 40 kV and 40 mA with CuKα radiation, and the results were interpreted using Profex software.

4. Results and discussion

4.1. Organic analysis of rice soup and acacia gum

The quantitative analysis provided a detailed breakdown of the organic composition of rice soup and acacia gum. Specifically, it focused on determining the levels of protein, polysaccharides, and fat content, as outlined in Tab 1.

Table 1. Organic composition of rice soup and acacia gum

Constituents	Rice Soup Concentration (%)	Acacia Gum Concentration (%)
Polysaccharides	56.8	78.6
Proteins	2.9	3.4
Fats	0.5	0.5
Moisture content	39.1	13.3
Ash	0.7	4.2

Figures 1 and 2 show the gas chromatography-mass spectrometry (GC-MS) graphs for the fermented rice soup and acacia gum solutions. The GC-MS analysis reveals that the fermented rice soup consists of 62.35% alkanes, 10.14% saturated fatty acids, 7.1% aromatic hydrocarbons, and 4.45% aldehydes. In contrast, acacia gum contains 56.24% polysaccharides, 32.76% carboxylic acids, and 4.31% esters. Table 2 presents the proportions of compounds in acacia gum and rice soup.

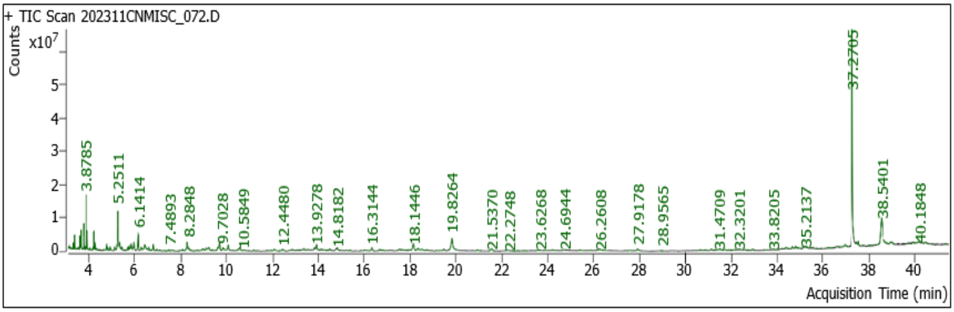

Fig. 1. Chromatogram of fermented rice soup

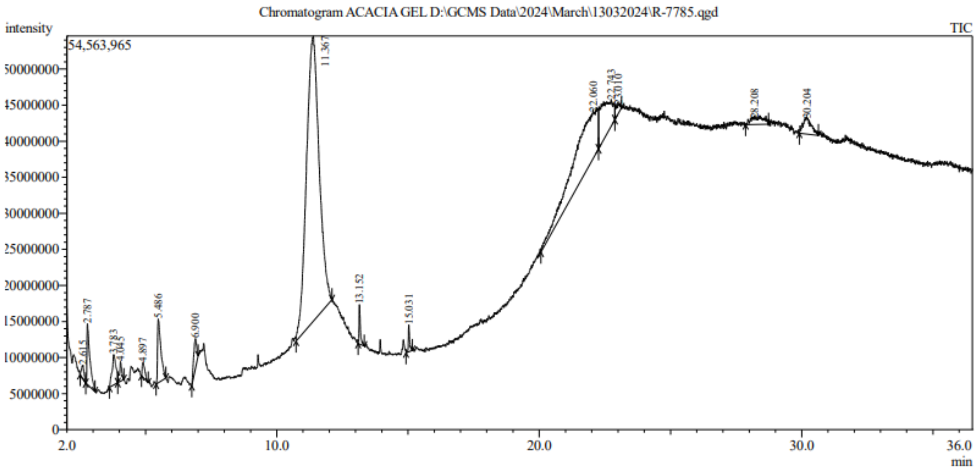

Fig. 2. Chromatogram of fermented acacia gum

Table 2. Compounds present in rice soup and acacia gum

Rice soup		Acacia gum	
Type of compound	Total Weight (%)	Type of compound	Total Weight (%)
Alkane	62.35	Polysaccharides	56.24
Saturated fatty acid	10.14	Carboxylic Acid	32.76
Aromatic Hydrocarbon	7.1	Esters	4.31
Aldehyde	4.45	Heterocyclic compound	2.71
Phenols	2.19	Saturated fatty acid	1.33
Polysaccharides	2.25	Ketones	0.53
Terpenes	2.72	Anhydride	0.61
Ketones	2.2	Amino acids	1.5
Alcohols	0.73		
Esters	0.97		
Carboxylic Acid	1.1		
Heterocyclic compound	3.14		

The organic analysis indicates that both organic additives used in this study are rich in polysaccharides. However, the GC-MS test revealed that these organic components undergo changes during fermentation. Rice soup contains a higher proportion of saturated fatty acids (10.14%) compared to acacia gum (1.33%), making it more hydrophobic and improving bonding and cohesion within the lime mortar. This interaction is believed to enhance mechanical strength [18], as evidenced by the compressive strength of the S2 sample. The presence of n-hexadecenoic acid, a saturated fatty acid, in the fermented rice soup leads to the formation of calcium oxalate peaks, which eventually transform into calcite [19]. Acacia gum samples contain significantly higher polysaccharide content (56.24%) than rice soup. The experimental findings suggest that combining acacia gum with lime mortar often enhances carbonation. Both fats and polysaccharides are present in the materials under investigation. The presence of fat increases solubility in alcohol, thereby enhancing carbonation in lime mortar. On the other hand, polysaccharides accelerate carbonation due to their water solubility. Consequently, these factors contribute to the overall strengthening process [19].

Rice soup contains 2.19% antimicrobial phenols, indicating improved water absorption properties and resistance to carbonation [18]. Additionally, acacia gum has a significant amount of carboxylic acid (32.76%), which reduces open pore volume and increases density as the acid content rises. Low levels of calcium oxalates can aid in the self-healing of lime mortar and contribute to crystalline development and carbonation [15]. Carboxylic acids play a crucial role in the formation of calcite and vaterite. Moreover, rice soup contains 62.35% alkanes, which contribute to a denser microstructural matrix. This, in turn, improves the overall performance of lime mortar by reducing drying shrinkage [20]. This effect is further supported by compressive strength measurements, which indicate higher strength in rice soup-based mortar compared to acacia gum-based mortar.

4.2. Determination of properties of organics-added mortar

The characteristics of lime mortar, including water absorption, bulk density, porosity, and carbonation, are detailed in Tab. 3. The bulk density of the samples increases with the introduction of organic materials, while the porosity of the mortar decreases upon their incorporation. Due to the presence of carboxylic acid, acacia gum exhibits lower porosity, which simultaneously leads to an increase in bulk density [15]. Regarding water absorption properties, it was observed that mortar absorption increases in the presence of rice soup, attributed to the presence of phenols within the mortar [15]. The carbonation depth was higher in organically modified mortar than in reference mortar. The polysaccharide content in acacia gum further enhances carbonation depth. When comparing rice soup mortar with organic acacia gum mortar, the latter exhibits higher carbonation values due to its greater polysaccharide content [16]. This led to a significant reduction in mortar cracking – an encouraging outcome – and a noticeable increase in calcite precipitation, as confirmed by XRD analysis.

Table 3. Bulk density, porosity, water absorption and carbonation depth of mortar

Sample	Bulk density (kg/m^3)	Porosity (%)	Water absorption (%)	Depth of carbonation (mm)
R	1704	19.81	17.34	1.01
SR1	1730	18.21	16.82	2.13
SR2	1765	15.63	14.64	3.43
SR3	1744	16.23	15.50	2.98
AG1	1736.21	17.69	15.19	2.35
AG2	1768.32	15.12	14.60	3.53
AG3	1752.66	15.21	15.35	2.78

4.3. Climatic model studies

4.3.1. Compressive strength

Table 4 presents the compressive strength values of the samples, along with their respective average, median, and standard deviation values at 120 days of age. The compressive strength values of rice soup-modified mortar were higher across all climatic zones compared to the reference mortar. The addition of rice soup to lime mortar led to a reduction in porosity (Table 3) and an improvement in compressive strength [21]. Among the tested zones, Zone 1 exhibited the highest performance with rice soup, achieving a compressive strength range of 1.73–2.63 N/mm². The enhanced pozzolanic reactions observed in high-humidity environments contributed to the maximum compressive strength recorded at a 2% rice soup concentration [22]. Zone 2 attained a maximum compressive strength of 1 N/mm², whereas Zone 3 demonstrated a slightly higher maximum compressive strength of 1.09 N/mm², indicating that the performance in Zones 2 and 3 was nearly identical. A thorough analysis of all samples from each zone concluded that a 2% rice soup concentration provided the best overall performance. Furthermore, a comparative analysis of samples from Zones 2 and 3 revealed that Zone 3 performed slightly better. Maintaining high relative humidity (RH) and temperature levels proved essential for achieving higher strength.

In contrast, Acacia gum lime mortar in Zone 1 exhibited a significant reduction in strength compared to the reference mortar. However, Zones 2 and 3 demonstrated clear improvements in strength properties. Zone 2 outperformed the other zones, achieving a maximum compressive strength of 1.968 N/mm². The lower temperature and lower humidity in Zone 2 contributed significantly to strength development. The compressive strength in Zone 3 increased by over 22% compared to Zone 1, with the A3H1 sample achieving a maximum strength value of 1.490 N/mm². Based on these findings, it can be inferred that lower relative humidity and temperatures are optimal for Acacia gum to attain its desired strength.

Table 4. Compressive strength values at 120 days

Zone	Rice Soup		Acacia Gum	
	Specimen code	Average strength value (N/mm^2)	Specimen code	Average strength value (N/mm^2)
Zone 1	R1	1.73±0.039	R1	1.73±0.039
	S1	1.89±0.036	A1	0.83±0.045
	S2	2.63±0.037	A2	0.85±0.056
	S3	2.23±0.052	A3	1.21±0.039
Zone 2	R1H	0.57±0.027	R1H	0.57±0.027
	S1H	0.78±0.024	A1H	1.344±0.051
	S2H	0.98±0.010	A2H	1.358 ±0.045
	S3H	0.84±0.023	A3H	1.968±0.042
Zone 3	R1H1	0.58±0.044	R1H1	0.58±0.044
	S1H1	0.90±0.020	A1HI	1.433±0.053
	S2H1	1.09±0.027	A2H1	1.453±0.048
	S3H1	0.80±0.041	A3H1	1.490±0.037

4.3.2. XRD analysis

Figure 3 presents the XRD analysis results, illustrating the mineral composition of the reference mortar and admixture-modified samples across different climatic zones. The mineral composition of rice soup includes calcite, portlandite, albite, aragonite, quartz, $C_3S_2H_3$ (afwillite), tobermorite, and anorthite. Conversely, acacia gum consists of albite, aragonite, calcite, anorthite, quartz, and tobermorite. Notably, calcite was the predominant phase in all zones, while quartz was present in all samples, acting as a joint filler.

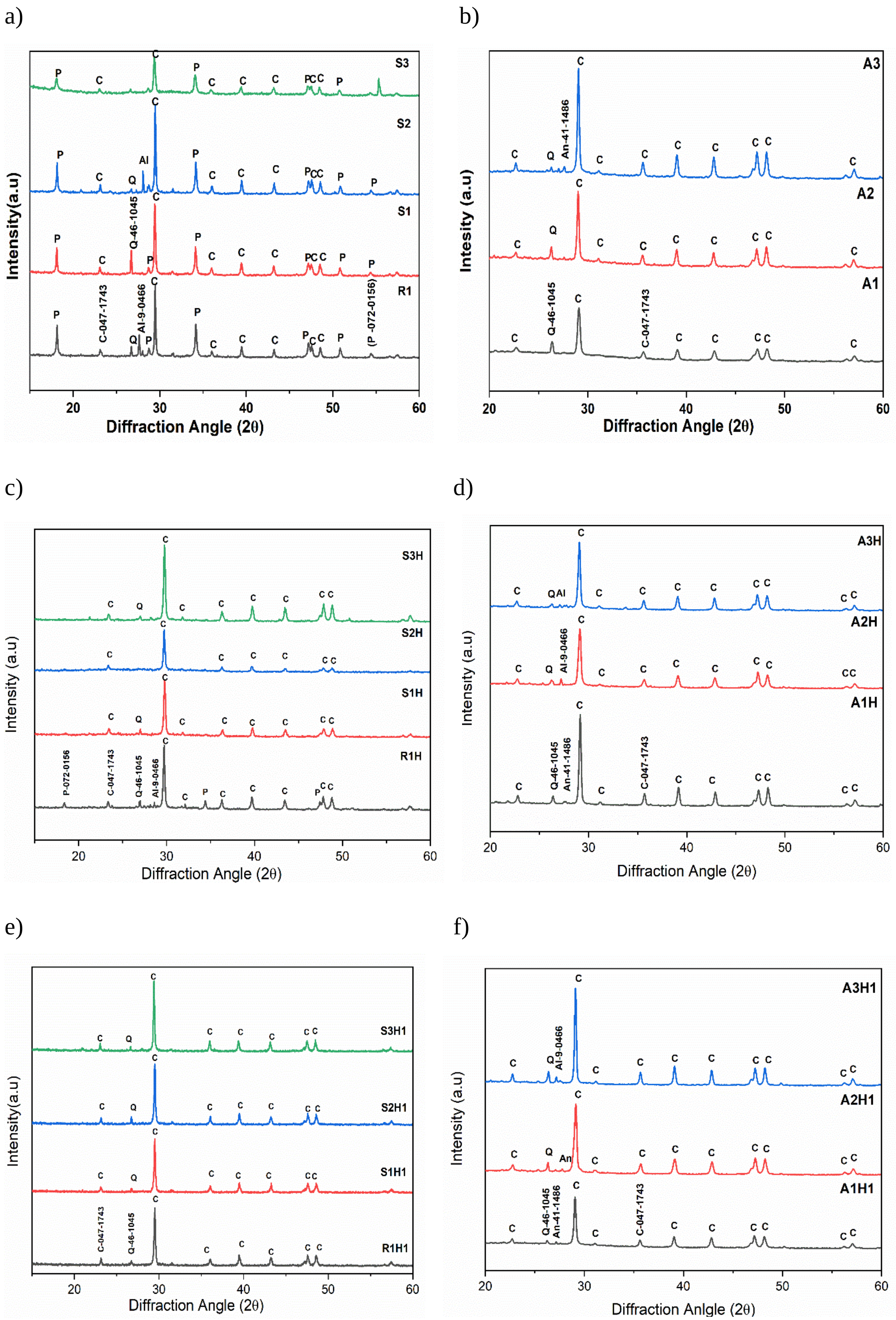

Fig. 3. XRD of samples: (a), (b) zone 1; (c), (d) zone 2; (e), (f) zone 3

In Zone 1, the samples containing organic additives exhibited a higher calcite concentration than the reference mortar, promoting carbonation [23]. The rice soup sample demonstrated a rapid distribution of mineral phases, whereas the acacia gum sample primarily contained calcite in approximately 60% of its phases. This result is supported by GC-MS analysis, which confirmed a higher polysaccharide content. The rice soup sample in Zone 1 was primarily composed of portlandite, while other zones showed very low or negligible amounts, indicating that carbonation was still actively occurring in this zone. The S2 sample in Zone 1 had the highest concentration of tobermorite (10.1%), contributing to excellent hydraulic set characteristics, which enhanced specimen strength and load-bearing capacity [24], as reflected in its significantly higher compressive strength of 2.63 N/mm². Albite ($NaAlSiO_2$) reacts with calcium hydroxide ($Ca(OH)_2$) from lime, producing sodium hydroxide (NaOH) as a by-product, which leads to the formation of calcium silicate hydrate (C-S-H) gel. The presence of C-S-H improves the mechanical properties, pozzolanic strength, and durability of lime mortar [25]. When comparing mortar performance in Zone 1, rice soup demonstrated superior performance. The temperature and relative humidity in this zone played a crucial role in mineral formation, influencing the rate of carbonation and the distribution of mineral phases, ultimately enhancing strength, durability, and the carbonation process [26].

In Zone 2, acacia gum outperformed the other mortar samples. The presence of calcite phases in this region was more pronounced than other mineral phases. Calcite was the only mineral phase detected at low temperatures and humidity [27]. The presence of tobermorite in gum mortar, which was absent in rice soup mortar, significantly increased compressive strength, enhancing the material's load-bearing capacity. Additionally, acacia gum exhibited a higher albite concentration than rice soup, further promoting the development of calcium silicate hydrate (C-S-H). These findings suggest that the presence of albite and tobermorite in Zone 2 contributed to the overall strength enhancement of gum-based mortar. The afwillite ($C_3S_2H_3$) content in rice soup mortar was 9.3%, 10%, 8%, and 7.7% in the R1H, S1H, S2H, and S3H samples, respectively. The formation of afwillite altered the mortar's microstructure, enhanced mechanical properties, and contributed to crystalline lime mortar formation [28].

In Zone 3, the S3H1 (75.2%) and A1H1 (74.27%) samples exhibited the highest calcite content. The temperature and humidity conditions in this zone were optimal for carbonation, significantly improving the mortar's strength [29]. In rice soup mortar, anorthite formation was observed at 15.4%, 11.8%, 14.2%, and 13% in the R1H1, S1H1, S2H1, and S3H1 samples, respectively. Due to its pozzolanic properties, anorthite-containing limestone aggregates enhanced the mortar's water resistance in this region [30]. Compared to Zone 2, this mineral contributed to improved compressive strength ratings. The identification of tobermorite in acacia gum mortar also resulted in higher strength values, further supporting its effectiveness in this climatic condition.

The tables below (Tables 5 and 6) present the percentage of minerals identified through X-ray diffraction (XRD) analysis. These values indicate the proportion of each mineral present in the samples.

Table 5. XRD Quantification for rice soup mortar

	Zone 1 wt. (%)				Zone 2 wt. (%)				Zone 3 wt. (%)			
	R1	S1	S2	S3	R1H	S1H	S2H	S3H	R1HI	S1H1	S2H1	S3H1
Albite ($NaAlSi_3O_8$)	15.2	2.9	6.5	5.5	2.3	5.4	8.7	5.7	0.9	1.6	0.8	1..3
Aragonite	2.8	5.0	2.0	1.7	4.4	5.4	3.5	3.1	3.5	4.1	3.9	3.2
$C_3S_2H_3$_Afwillite	9.2	4.3	3.9	8.2	9.3	10	8.0	7.7	1.8	3.0	3.0	2.5
Calcite ($CaCO_3$)	40.8	53.8	48.2	46.1	57.6	64.9	67.5	69	70	72	73	75.2
Anorthite ($CaAlSi_3O_8$)	2.0	1.3	7.0	7.2	15.0	6.8	4.5	7.3	15.4	11.8	14.2	11.8
Portlandite	24.8	25.2	20.0	18.9	6.5	1.9	2.4	0.8	0.3	0.3	0.3	0.5
Quartz	3.2	3.8	2.6	3.3.	4.0	4.5	4.1	4.2	4.1	4.2	4.0	4.2
Tobermorite	2.0	3.7	10.1	9.1	1.0	1.1	2. 1	1.7	2 .4	1.8	1.0	1.2

Table 6. XRD Quantification for acacia gum mortar

	Zone 1 wt. (%)				Zone 2 wt. (%)				Zone 3 wt. (%)			
	R1	A1	A2	A3	R1H	A1H	A2H	A3H	R1HI	A1H1	A2H1	A3H1
Albite ($NaAlSi_3O_8$)	15.2	6.00	6.41	5.88	2.3	7.30	3.00	1.80	0.9	3.02	3.68	3.19
Aragonite	2.8	1.60	3.59	3.32	4.4	2.70	1.79	2.05	3.50	2.82	2.34	2.32
$C_3S_2H_3$_Afwillite	9.2				9.3				1.80			
Calcite ($CaCO_3$)	40.8	65.0	69.1	70.8	57.6	70.6	72.5	73.1	70	74.27	69.1	68.6
Anorthite ($CaAlSi_3O_8$)	2.0	8.00	5.30	6.40	15.0	7.30	9.90	10.3	15.4	5.96	10.3	12.2
Portlandite	24.8	4.04	4.10		6.5	4.84	3.74	2.76	0.3	1.20	2.00	2.20
Quartz	3.2	5.80	4.61	5.37	4.0	5.12	5.12	3.12	4.10	4.36	4.75	3.15
Tobermorite	2.0	4.00	4.34	5.10	1.0	1.06	2.41	5.68	2.4	5.40	7.70	6.50
Vaterite		3.80	2.55	3.13		1.13	1.56	1.21		2.97	2.10	2.38

5. Conclusions

The role of organic lime mortar made from rice soup and acacia gum was studied in three different climatic zones: warm & humid (35°C, 72%), dry (25°C, 20%), and cold (25°C, 50%). The key findings are as follows:

- Rice soup mortar exhibited higher compressive strength than acacia gum mortar due to the presence of alkanes and fatty acids. Among the tested samples, 2% rice soup performed best across all climatic zones, particularly in Zone 1 (warm & humid), where the S2 sample achieved a maximum compressive strength of 2.63 N/mm².
- In acacia gum mortar, polysaccharides interacted with lime mortar, leading to the formation of calcium carbonate. Mineralogical studies confirmed that the predominant mineral was calcite, which constituted over 65% of the total composition, as verified by XRD analysis.
- Rice soup lime mortar was particularly effective in warm & humid climatic zones, reaching an optimal strength of 2.63 N/mm². This enhanced performance was attributed to the presence of key minerals, including tobermorite (10.1%), afwillite

(8.2%), and portlandite (25.2%), which were present in significantly lower amounts in other climatic zones.
- Acacia gum mortar is particularly effective in dry climatic zones, achieving optimal performance due to the presence of minerals such as anorthite (10.3%) and tobermorite (5.68%).
- The presence of organic compounds influenced performance differently across climatic zones, making each type of mortar more suitable for specific environmental conditions. However, incorporating both organic additives could potentially improve mortar performance across all climates.
- In general, rice soup lime mortar is well-suited for the states of Tamil Nadu, Kerala, and the coastal regions of Andhra Pradesh. Conversely, acacia gum mortar is more suitable for the dry climatic conditions of Rajasthan.

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