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Enhancing the strength and durability of lime mortar with Acacia Seyal Gum: A sustainable solution for diverse climatic conditions

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ABSTRACT

This study investigates the enhancement of lime mortar using Acacia Seyal Gum (ASG), a natural biopolymer, to improve its strength and durability under various environmental conditions. Mortar samples were prepared by adding ASG at 1%, 3%, and 5% by weight to its volume. The mechanical properties of the modified mortar were assessed under varying climatic conditions, specifically at temperatures of 25 °C and 35 °C and relative humidity levels of 20%, 50%, and 72%. The 3% gum-modified mortar showed the most significant improvement, exhibiting superior strength and durability compared to the reference mortar across all tested environments. Adding Acacia Seyal Gum improved the bond between lime and sand particles, decreased porosity, and increased moisture retention, which helped prevent early shrinkage and cracking. This study highlights the potential of Acacia Seyal Gum as a sustainable and effective additive for lime mortar, contributing to modern eco-friendly construction and the restoration of historic structures. The findings suggest that the gum-modified mortar could provide a reliable, durable, and environmentally responsible alternative to traditional lime mortars in regions with challenging environmental conditions.

Keywords: mechanical strength, durability, sustainable construction, heritage restoration, climatic conditions.

INTRODUCTION

Lime mortar played a vital role in construction for thousands of years, particularly in historic buildings, due to its compatibility with masonry, breathability, and sustainability [1]. Traditional lime mortars, made from hydraulic lime and sand, have been valued for their flexibility and self-healing properties, which allow for movement in the structure without significant cracking [2]. However, these mortars often lack the mechanical strength and durability required for modern construction, especially when exposed to harsh environmental conditions. In regions like India, where temperatures and humidity levels can vary dramatically, the performance of lime mortar can degrade over time, making it unsuitable for certain applications [3]. These challenges have led to the search for natural additives that can improve the mechanical properties of lime mortar without compromising its traditional advantages [4–6].

Natural organic additives have a long history in construction, with ancient civilizations using various biopolymers to enhance the strength and durability of building materials [7]. For example, the Egyptians added animal blood, egg whites, and plant extracts to their mortars, and similar practices can be found in ancient Chinese, Greek, and Roman architecture [7]. Modern research has revived this interest in natural admixtures, as these materials offer a sustainable alternative to chemical additives [8]. Among the various natural polymers, Acacia Seyal Gum (ASG) stands out for its potential to enhance the performance of lime mortar while remaining eco-friendly. Acacia Seyal Gum is a biopolymer derived from the sap of the Acacia tree, widely available in arid regions and traditionally used in various industries due to its binding and emulsifying properties.

In this study, ASG was introduced into lime mortar at different concentrations 1%, 3%, and 5% by weight to evaluate its effects on the mortar's strength and durability. The objective was to determine whether the addition of this natural gum could address the limitations of traditional lime mortar, especially under varying environmental conditions. Initial results indicated that the 3% concentration offered the most significant improvement in both strength and durability, outperforming both the reference (unmodified) mortar and the samples with higher or lower concentrations of gum. This finding aligns with previous research that suggests natural polymers can significantly enhance the performance of lime mortars by improving cohesion between particles, reducing porosity, and increasing the mechanical strength [9].

A major focus of this research is the performance of the modified lime mortar under diverse environmental conditions, particularly the climatic variations typical of India. The Indian climate ranges from dry, arid regions to humid, tropical areas, and construction materials must withstand these extremes to ensure long-term durability [11]. To simulate real-world conditions, the mortar samples were tested at two temperatures 25 °C and 35 °C with relative humidity levels of 20%, 50%, and 72%. These conditions were chosen to represent dry, moderate, and humid environments, reflecting the challenges faced by construction projects across the country.

The results of these tests were promising. The mortar sample containing 3% ASG showed superior strength and durability across all tested conditions, maintaining performance levels comparable to those observed under controlled laboratory conditions. This suggests that the gum-modified mortar has the potential to perform reliably in a wide range of environmental settings, making it an ideal material for use in regions with fluctuating climates [2]. Notably, the gum also helped retain moisture within the mortar, preventing rapid drying, which is a common cause of cracking in traditional lime mortars. This moisture retention allowed the mortar to set more slowly and consistently, reducing the risk of early shrinkage and improving the overall

Durability of the material.

The incorporation of natural organic additives like Acacia Seyal Gum also offers environmental benefits. Unlike chemical additives, which can be harmful to both workers and the environment, ASG is biodegradable and non-toxic. Its use aligns with the global trend toward more sustainable construction practices, which seek to reduce the carbon footprint of building materials while improving their performance [12]. By enhancing the properties of lime mortar with a natural, renewable additive, this research contributes to the growing body of knowledge on eco-friendly construction materials [13]. It also supports the conservation of historic buildings, where lime mortars are often preferred due to their compatibility with traditional masonry techniques.

Furthermore, the use of ASG as an admixture presents a valuable opportunity for developing countries like India, where access to sustainable and locally sourced building materials is crucial. Acacia trees are abundant in many arid regions, and the gum is already harvested for various industrial purposes. By repurposing this natural resource for construction, the industry can reduce its reliance on imported or synthetic materials, further promoting sustainability and supporting local economies.

Previous studies have shown that natural polymers, such as proteins and polysaccharides, can improve lime mortars' mechanical and durability properties by reducing porosity, enhancing carbonation, and preventing water ingress [14]. Acacia Seyal Gum shares many of these properties, forming strong bonds between the lime and sand particles, improving workability, and reducing water permeability. This study aims to build on that knowledge by exploring how the gum-modified lime mortar performs under practical conditions, offering insights into its potential applications in both modern and heritage construction.

This paper details the methodology used to prepare and test the lime mortars modified with ASG, as well as an analysis of the results. It will also explore the broader implications of using natural additives in construction, particularly in terms of sustainability and environmental impact. Ultimately, this research seeks to demonstrate that Acacia Seyal Gum can enhance the performance of lime mortars, making them a viable option for sustainable construction in regions with diverse and challenging climates.

MATERIALS AND TECHNIQUES

Raw materials

The hydraulic lime for the mortar samples was sourced from Ms. Murugan Enterprises in Sunambukulam, Gummidipoondi, and its chemical composition was identified using IS: 6932 (Part I) – 1973 [15] (Table 1). The investigation used fine aggregate (river sand) with a specific gravity 2.61. To ensure the purity of the sand, it was initially sieved using a 2.36 mm sieve and subsequently washed, then dried under the sun. The distribution of particle sizes was determined by IS: 2386 (Part-I)-1963 [16] Figure 1. The sand was found to contain silica from quartz, feldspar, and zircon. The method described in IS: 6932 (Part 11) - 1983 [17] was used to establish lime's beginning and ultimate setting times, demonstrating the precision and reliability of our results. The water retention test was performed following the steps outlined in DIN 18555 (Part 7) - 2000, [18] and the consistency and workability of lime were assessed following IS: 6932 (Part VIII) – 1973 [19].

The natural polymer Acacia Seyal Gum in this research is rich in polysaccharides and notable proteins and fats (Table 2). D. Mudgil and S. Mudgil [20] have discussed the presence of polysaccharides and proteins in the Acacia Seyal Gum and also its molecular weight. Notably, polysaccharides such as arabinose, galactose, and glucuronic acid are present in the optimum molar ratio of 3:3:1, respectively [20]. The molecular weight was in the region of 250,000–600,000 g/mol, which changes with the different concentrations of ethanol [20] – the structure of arabinose, galactose, and glucuronic acid shown in Figure 2a. The gums are crushed and soaked in water for three days with varying concentrations of 1%, 3% and 5% and then filtered. The liquid obtained after filtration is called Acacia Seyal Gum. The content was then tightly sealed in a plastic container for a fermentation period of 3 days. The amount of fats present in the ASG calculated by the crude fat method by IS: 7874 (Part I)-1975 [21]. The Kjeldahl digestion test determines the additives protein content. The polysaccharides were obtained as follows: 100 (percentage of moisture + percentage of proteins + percentage of fat + percentage of total ash).

GCMS for Acacia Seyal Gum

A 10 ml sample is dried at 105 °C for two hours to identify the phytochemical components in the fermented organic materials. After drying the sample, we add it to methanol and sonicate it for 30 minutes. Following the sonication, we centrifuge the solution at 1000 rpm for 5 minutes, collect the supernatant, and then load it into the GCMS. This investigation employs the Toshvin

Table 1. Chemical composition of hydraulic lime

Parameters	Composition (%)
Calcium oxide (CaO)	67
Magnesium oxide (MgO)	1.3
Silica (SiO_2)	21.39
Alumina (Al_2O_3)	3.65
Iron (Fe_2O_3)	2.29
Insoluble residues	12.34

Table 2. Organic content in Acacia Seyal Gum

Constituents	Concentration (%)
Polysaccharides	78.6
Proteins	3.4
Fats	0.5
Moisture content	13.3
Ash	4.2

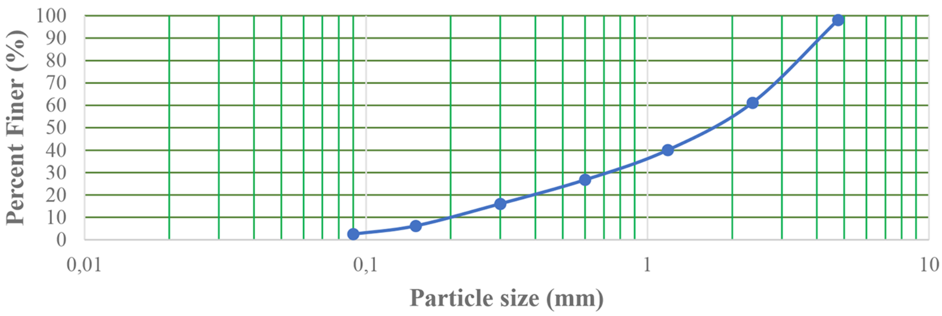


Figure 1. Particle size distribution of sand

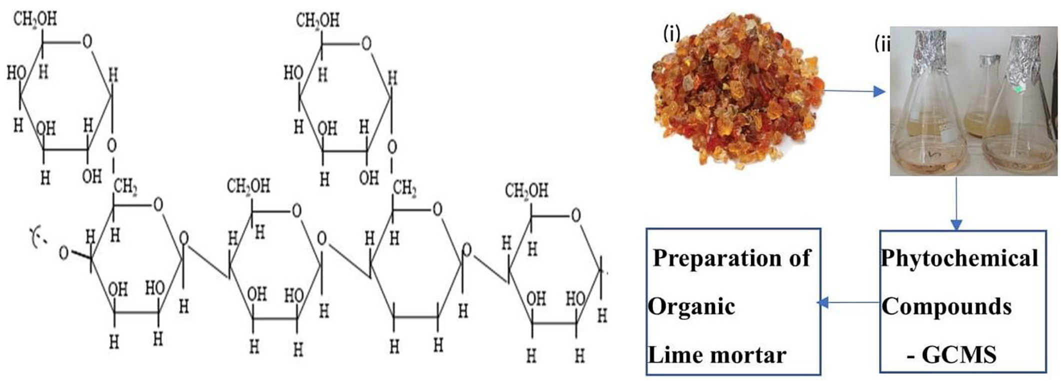


Figure 2. (a) Structure of Acacia Seyal Gum, (b) Preparation of mortar (i) Acacia gum (ii) Fermented gum

TQ8040 NX model instrument to analyze the phytochemical profile.

Fresh and hardened properties of mortar

The binder to aggregate weight ratio of 1:3 was chosen since it is the most often used ratio in architectural conservation projects. According to IS: 6932 Part VII-1973 [19], the lime mortars have been cast. In an initial research, cubes were made using water/lime ratios of 0.6, 0.7, and 0.8 and tested for compressive strength over a period of seven days. 0.7 water/lime ratio was chosen for the subsequent inquiry since it produced better outcomes based on the results that were obtained. IS: 6932 (Part VIII) – 1973 [22] was used to assess the workability of the lime mortar mix prior to the casting of mortar specimens (cubes and prisms).

Water resistance was measured in accordance with DIN 18,555 (Part 7) – 2000 [18]. Using a pressure method and an air content meter in accordance with IS 1199 (2004) [23], the fresh lime mortar was examined for any trapped air. For their workable mix, or for a spread of 130 mm in the lime mortar flow table following flow table dropping, mortar samples were made. Reference mortar (R), mortars modified by the addition of 1%, 3%, and 5% polysaccharides (ASG1, ASG3, and ASG5, respectively), were the four different types of mortar specimens. The process for preparing the mortar is illustrated in Figure 2b.

The prismatic mould measures 40 × 40 × 160 mm, and the cube mould measures 50 × 50 × 50 mm. The cube and prismatic moulds were filled with the freshly made mortar, which was then lightly tamped and gently pushed with the thumb. The moulds were covered with damp fabric after casting and remolded after 72 hours while being kept at a temperature of 27 ±2 °C. After four days, the samples were allowed to cure in water for 21 days and kept in the air at room temperature of 27 ± 2 °C with 90% relative humidity.

Measurements were taken along the cube's three sides during the drying shrinkage test. 5 days, 10 days, 15 days, 20 days, 30 days, 40 days, 50 days, 60 days, 70 days, 80 days, and 90 days of testing in accordance with ASTM C596-01 [24] were carried out on the specimen. The lime mortar is made harder through the process of carbonation. In a mortar with a high calcium content, carbonation is the primary cause of all material changes. Understanding these changes requires a basic understanding of carbonation depth Lawrence et al. 2007 [25]. By turning calcium hydroxide into calcium carbonate, a process known as carbonation results in an increase in mass [26, 27]. After 90 days of casting according to BS EN 13295:2004 [28]. Lime mortar sets and hardens through carbonation, where calcium hydroxide (lime) reacts with atmospheric carbon dioxide to form calcium carbonate. High humidity supports this process because moisture helps dissolve CO_2, aiding its absorption into the mortar. Optimal humidity levels promote consistent carbonation, leading to stronger and more durable mortar. Flexural strength tests were performed in accordance with BS EN 1015-11:1999 [29].

Physical properties of mortar

According to RILEM (1980) [31], the physical characteristics such porosity, bulk density, and water absorption were investigated. The constant head approach was used to study the permeability in accordance with IS: 3085 (1965) [32]. Humidified 50 mm cube specimens were subjected to it at a 120-day age.

Climate model studies

To test the suitability of the samples in different regions with varying temperature and relative humidity, sixteen sets of samples were casted and cured in humidity chamber for 28 days. They were then kept in a humidity chamber at 35 °C with 72% relative humidity, and at 25 °C with 20% and 50% relative humidity. According to IS 6932-Part I (1973) [15], the 120 days compressive strength was absorbed for zone 1 (35 °C with relative humidity 72%), Zone 2 and Zone 3 (25 °C with relative humidity 20% and 50% respectively). Extended ageing leads to increased carbonation, changes in microstructure, enhanced bonding, and decreased porosity, all of which affect characteristics such as strength and resistance to environmental stresses. The specimens used in these investigations are listed in Table 3.

Powder X-ray diffraction (XRD) analysis, utilizing a Bruker Desktop-Diffractometer and operating with Cu Ka radiation, was used to qualitatively assess the mineralogical analyses of the manufactured mortars (identification of calcite, portlandite, aragonite, vaterite, etc.). For the purpose of determining the chemical alterations in the hardened mortar, Perkin-Elmer was used for fourier transform infrared spectroscopy (FT-IR) analysis. For XRD and FT-IR analysis, samples from the core of the cracked mortar samples that were put through a 120-day compression test were obtained. Using scanning electron microscopy (SEM), the morphology of the modified and reference lime mortars was observed, while energy dispersive X-ray (EDX) spectroscopy was used to determine the elemental composition, including calcium, oxygen, carbon, and magnesium.

The FEI Quanta FEG 200 – high resolution scanning electron microscope was used for SEM/EDS. The inside of a fractured mortar cube with sides measuring roughly 1 cm was cut to create the sample for the SEM investigation (zone 1–3 samples). The samples are partially gold coated and were highly polished.

Thermogravimetry differential thermal analysis, or TG-DTA, was used to further examine the changes in physical and chemical properties. According to Morpoulou et al. 1995, [30] the weight loss in the TG curve occurs from 0 to 120 °C due to hygroscopic water (i.e., physically adsorbed water), 120 to 400 °C due to dehydration of CSH and CAH, 400 to 520 °C due to dehydration of calcium hydroxide, and 600 to 800 °C due to decarbonation of calcium carbonate.

RESULTS AND DISCUSSION

Raw materials characterization

The chemical composition of natural hydraulic lime is presented in Table 1, and the hydraulic index (HI) was 0.44, classifying it as hydraulic lime according to IS 712 (1984). Based on the HI value, this lime would fall under the category of Class A. River sand used as fine aggregate in mortar production has a coefficient of curvature (Cc) of one, indicating good grade: earth handbook, 1960 US Bureau of Reclamation [33]. In Table 4, Acacia Seyal Gum extract increased the lime mortar's initial and final setting times by 55 and 60 minutes for ASG5 and 50 and 40 minutes for ASG3. Additives are widely recognized for their ability to delay the setting time of lime

Table 3. Description of samples used for climatic studies

Zone	Specimen code	Climatic regions in India
Zone 1. Temperature 35 °C & relative humidity 72%	R1	Bangalore, Goa, Parts of Deccan, Kerala, Tamil Nādu, Coastal parts of Andhra Pradesh
	A1	
	A2	
	A3	
Zone 2. Temperature 25 °C & relative humidity -20%	R1H	Rajasthan, Gujarat
	A1H	
	A2H	
	A3H	
Zone 3.Temperature 25 °C & relative humidity 50%	R1H1	Sikkim, Uttaranchal, Arunachal Pradesh
	A1H1	
	A2H1	
	A3H1	

Table 4. Setting time of mortar sample

Sample	Initial setting time	Final setting time
R	2:40	13
ASG1	2:55	14:20
ASG 3	3:45	14:45
ASG 5	4:10	15

mortar. This effect is attributed to the admixtures' adsorption on the surfaces of the hydrated phases (Earth manual, US Bureau of Reclamation, 1960 [33, 34]), where it complexes with the alkaline degradation products of the carbohydrates [31] to form a semipermeable coating that delays the formation of hydration products [35].

In low humidity, lime mortar may dry out too soon, restricting carbonation and making it weaker and brittle. High humidity prevents premature drying and permits steady carbonation for maximum strength. The study found AGS3's maximum setup time. The observed delay in the lime's setting time when mixed with AGS could be attributed to the admixture's moisture-retaining capacity, which delayed the drying of the water from the hydraulic lime [36]. Due to its viscosity, Acacia Seyal Gum mixed well with lime molecules and created a gel-like paste that held water and delayed settling [12]. When proteins in the blend are mixed with lime, they make a thin layer that doesn't like water. It kept lime particles hydrated, preventing mortar drying [37]. The quantitative organic analysis data for Acacia Seyal Gum is shown in Table 2. ASG had 78.6% polysaccharides, 3.4% protein, and 0.5% fat. Figure 2 shows arabinose, galactose, and glucuronic acid. Long polysaccharides molecules in ASG chains produce a coil-like or "ramified" shape with branches, forming gels and increasing water viscosity. Since it can interact with hydrophilic and hydrophobic molecules, its branching helps it emulsify and stabilize.

GCMS analysis

The gas chromatography-mass spectrometry (GC-MS) analysis reveals that the fermented acacia gum contains 56.24% polysaccharides, 32.76% carboxylic acid, and 4.31% esters listed in Table 5. The acacia gum samples contain significantly higher polysaccharides (56.24%) The experimental findings suggest that combining acacia gum with lime mortar often leads to carbonation. The materials under investigation include both fats and polysaccharides. The presence of fat increases solubility in alcohol, thereby enhancing carbonation in the lime mortar. On the other hand, polysaccharides accelerate carbonation because they are water-soluble. Therefore, these factors contribute to the overall strengthening process [50]. We observed that acacia gum contains a significant amount of carboxylic acid (32.76%), which reduces open porous volume and increases density as the acid content increases. Low levels of calcium oxalates can help lime mortar self-healing and contribute to crystalline development and carbonation [51]. Carboxylic acids play a role in the formation of calcite and vaterite. During fermentation, carboxylic acids reduce CO_2, which

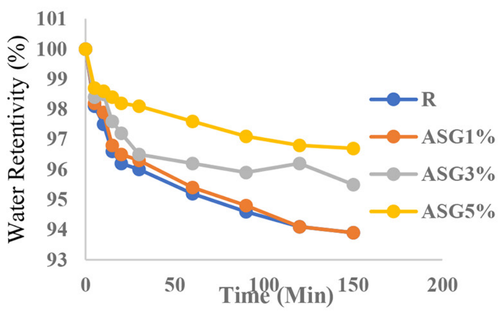
Table 5. Phytochemical compounds present in Acacia Gum Seyal

Peak	R. time	%	Name of the compound	Remarks
1	2.615	0.53	Acridin-1(2H)-one, 3,4-dihydro-3,3-dimethyl-9-propyl amino	$C_{18}H_{22}N_2O$ - Cyclic ketone
2	2.787	2.71	Pyrazole, 1,4-dimethyl-	$C_5H_8N_2$- Heterocyclic compound
3	3.783	1.85	Cyclohexan-1,4,5-triol-3-one-1-carboxylic acid	$C_7H_{10}O_6$ - Carboxylic acid
4	5.486	3.30	Butoxy acetic acid	$C_6H_{12}O_3$-n- Carboxylic acid
5	11.367	56.24	3-O-Methyl-d-glucose	$C_7H_{14}O_6$- Polysaccharides
6	13.152	0.76	n-Hexadecanoic acid	$C_{16}H_{32}O_2$-Long chain saturated fatty acid
7	15.031	0.57	Octadecanoic acid	$C_{18}H_{34}O_2$- Fatty acid
8	22.060	20.35	2,5-Dihydroxybenzoic acid, 3TMS derivative	$C_{16}H_{30}O_4$- Carboxylic acid
9	22.743	6.54	Alpha- Tocopheryl acetate	$C_{31}H_{52}O_3$- Carboxylic acid
10	30.204	2.16	Oleic acid, 3-hydroxypropyl ester	$C_{21}H_{40}O_3$- Esters

enhances carbonation and leads to the formation of calcite, aragonite, and vaterite [51, 52]. Polysaccharides enhance water retention and bonding, while carboxylic acids, like butoxy acetic acid, may help improve adhesion by interacting with the calcium in lime. Esters and fats function as surfactants, enhancing mortar's workability and water resistance. These compounds work together to strengthen carbonation and adhesion, but excessive fats or esters could hinder the lime's ability to bond if their concentration disrupts the matrix balance properly.

Fresh state properties of Acacia Seyal Gum modified mortar

As Per DIN 18,555 (Part 7) – 2000 [18], the results of the water retentivity test are displayed in Figure 3a. Water retentivity rises with mixing. ASG3 samples retain 3% more with admixture. The enhanced water retentivity of the admixture-modified mortar may increase the binding strength of the ASG lime mortar [38]. The average mix spread for one bump showed mix uniformity. Table 2 shows that polysaccharides in the admixture retained water, making the lime more flexible and consistent. High humidity is good, but excess water or inadequate drying conditions can delay curing and cause lime leaching, where unreacted lime dissolves and migrates to the surface. Balanced carbonation and strength gain require humidity control. Compared to the reference mix in Table (91 mm), the modified mixes ASG1, ASG3, and ASG5 had 101, 108, and 114 mm spreads, respectively. To obtain a 190 mm spread, the altered mix needs 11 jolts for ASG1, 9 for ASG3, and 5 for ASG5 instead of 14 for the reference mix (Table 6). Acacia Seyal Gum forms a network of intermolecular linkages between non-polar lengths of starch, increasing mortar viscosity and consistency [39]. Water retention in admixture-modified mortar shows the extract's moisture retention [55] – carbohydrates smooth lime mortar mix components, improving flow. The ASG modified fresh mortar mix had higher trapped air (4%) than the reference samples R (2.5%), according to the results of the air content test Figure 3b. The starch in the admixture enhanced the flexibility, which in turn increased the amount of air in the ASG modified mortars. The flexibility of the ASG mix increases the smoothness of the new lime mortar mix, which acts as a water-reduction agent by lowering particle friction. At intervals of 5, 10, 15, 20, 30, 60, 90, and 120, the mixture's weight loss was observed. It was continued until the weight loss in the mixture remained constant for two consecutive readings [40]. The water retention findings favored the consistency finding. The percentage of water retention by the admixture modified mortars showed a noticeable change. According to the graphic representation shown in Figure 3a, the water retention was at its highest in ASG3. In contrast to reference samples has



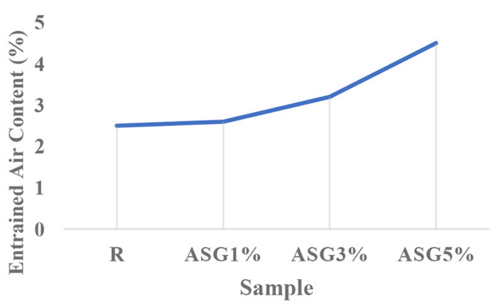


Figure 3. (a) Water retention of mortar samples, (b) air content of mortar samples

Table 6. Fresh state properties of mortar samples

Sample	Average spread of paste in one jolting (mm)	Number of bumps for a spread of 190 mm
R	91	14
ASG1	101	11
ASG 3	108	9
ASG 5	114	5

94% water retention, ASG3 samples had a water retention of 95.5%. Compared to the reference mortar mix, the ASG3 mix successfully holds onto water by 2% more. This trend towards water retention in admixture-modified mortar may be caused by polysaccharides content in the ASG extract.

Mechanical properties of Acacia Seyal Gum modified mortar

Even while the carbohydrates in the modified ASG mortar operate as retarders, they eventually reduce the formation of shrinkage cracks after drying. Figure 4 shows mortar drying shrinkage at 3, 7, 28, 60, and 90 days. The drying shrinkage of the ASG1, ASG3, and ASG5 samples was much lower than that of the reference mortars. The shrinking graph shows a steady increase. There was about 1.15 per cent shrinkage in the ASG3 mortar compared to a 1.85 per cent loss in the reference mortar. A relative rise in shrinkage may result in the formation of drying shrinkage fractures, which may serve as a pathway for weathering chemicals into the mortar. Adding admixtures reduces shrinkage [40]. Lime mortar adding admixtures reduces shrinkage [41]. Due to rapid water loss, lime mortar shrinks and expands faster. Higher shrinkage often breaks mortar and weakens the substrate bond. Polysaccharides retain water, limiting shrinkage in the presence of a natural organic admixture [42].

The significant reduction in drying shrinkage of admixture-modified mortar may be due to fewer shrinkage fractures, which make the material less sensitive to the entry of weathering agents. The Acacia Seyal Gum extract contains polysaccharides, which act as retarding agents and impede the drying process in the lime mortar. As a result, the inclusion of carbohydrates causes the hardening of modified mortar to proceed more slowly [35].

Physical properties of Acacia Seyal Gum modified mortar

Compared to the reference mix, the bulk density of ASG1, ASG3, and ASG5 increases by 1.01%, 1.35%, and 1.23%, respectively (Table 7). Under humid curing, adding polysaccharides derived from ASG to lime mortars made the bulk density values more challenging. The carbohydrates in the ASG produce an aqua gel, which becomes embedded in the mortar when consistently added with lime mortar formulations. When the mortar dried, the aqua gel shrank, and voids formed. The lime mortar's polysaccharides stimulate the development of smaller calcium carbonate crystals to fill the spaces. As moisture from aqua gel particles diffused to the mortar's surface and evaporated, its density increased. Compared to reference mortar, the porosity of the ASG-modified mortar decreases. ASG3 has 35.41% less porosity than the reference sample (Table 6). Porosity decreases

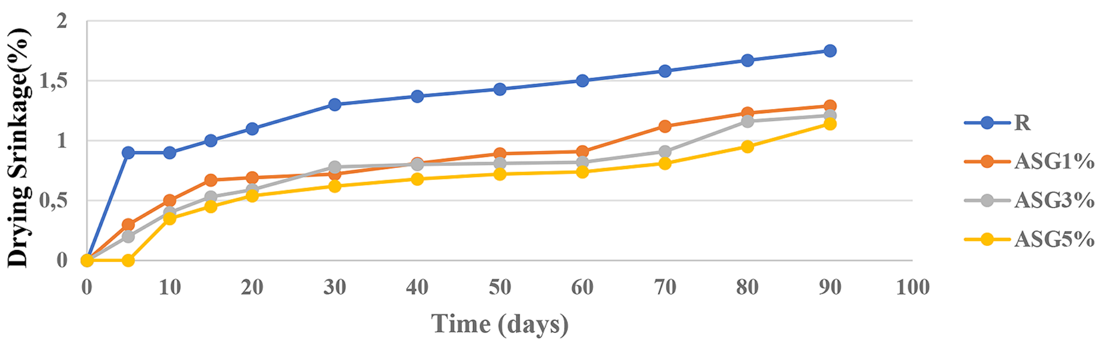


Figure 4. Drying shrinkage of mortar samples

Table 7. Physical properties of mortar samples

Sample	Bulk density (kg/m³)	Porosity (%)	Water absorption (%)
R	1704	19.81	17.34
ASG1	1736.21	17.69	15.19
ASG3	1768.32	15.12	14.60
ASG5	1752.66	15.21	15.35

mainly due to the plasticity of polysaccharide extracts, which causes particles to aggregate. These findings indicate that as porosity decreases, the compressive and flexural strengths of the mortar increase. From Table 6, ASG3 absorbed 23.41% less water than the reference mortar R. The constant production of hydration products in humid environments should diminish pore size, volume, and capillary connections. This will make the mortar denser and more compact by filling the pores with more material. The hydrophobic qualities of the admixture used may be responsible for the decrease in water absorption. Branching polysaccharides increase hydrophobicity [10]. Notably, the IR spectroscopy results suggest that the ASG-modified mortar sample contains protein, as a band at 1034 cm^{-1} is shown in Figure 8.

Role of Acacia Seyal Gum in permeability

The approach indicated in EN 1015-19, a standard method for determining the water absorption of hardened mortar, was used to determine the permeability of the lime mortar. The results are presented in Figure 13. The results show that adding Acacia gum can reduce the permeability of lime mortar to its optimum dosage. Since Acacia gum-lime mortar produces tiny calcium carbonate crystals, this happens. Polysaccharide molecules closed the pores in the ASG-modified specimen. Permeability and bulk density increase oppositely. As a result of its protein component's aerating properties, acacia gum may have contributed to the increased resistance and permeability of lime mortars [48]. Proteins and polysaccharides are impervious to water [49]. Permeability coefficients between reference mortar mix and ASG1 alter progressively.

On the other hand, raising the Acacia gum dosage to 3% by weight resulted in a 34.76% decrease in water permeability values (Figure 13). At optimal dosage, ASG5 sample permeability increases. When polysaccharides are introduced in excess, permeability increases by 1.21%. Aqua gel particles are produced in higher amounts and evaporate, causing voids that increase ASG5 sample permeability. As a result, the right amount of polysaccharides can significantly improve the effectiveness of the lime mortar.

Analytical studies on climate model

The Figure 5a shows the compressive strength after 120 days shows significant improvement even after keeping it in different temperature and various humidity, from this it is very clear that this modified mortar is suitable for restoration work in various humid conditions. These findings show that adding the optimum dosage of extract to modified lime mortars increases their compressive strength. Calcite is made easier to produce since the additive's contains branched polysaccharide which interacts with calcium hydroxide of lime. In order to increase the formation of calcite and improve CO_2 diffusion into the mortar, polysaccharide, a moisturizer, was added to the lime mortar [42, 43]. It also improved the adhesion between the lime and the sand particles, resulting in a solid microstructure. The mortar with the admixture modification exhibits a solid microstructure. The ASG extract also converts the carbohydrate into CO_2. Carbohydrate reduction triggers the carbonation process, which aids in converting additional $Ca(OH)_2$ into $CaCO_3$. The interaction of the admixture's carbohydrate and calcium carbonate may also be a significant influence. The hydrophilic hydroxyl group of polysaccharides is covalently bonded by calcium cation during the solidification of admixture-modified mortar [44], and the alkyl group may provide additional hydrophobicity that results in low water absorption and could protect the structures from water and soluble salt erosion and increase durability [45]. Once the carbonation process begins, the masonry mortar becomes tougher and more resilient [46].

Figure 5b shows the carbonation profiles [47] of the reference mortar and the ASG modified mortar. However, the development of strength in lime mortar depends on the transformation of calcium hydroxide into calcium carbonate, which in turn depends on variables like temperature, CO_2 concentration, and relative humidity [26, 27]. The branched polysaccharides in the ASG-modified lime mortar aid in the carbonation process by preserving the lime mortar's moisture content. Thus, converting portlandite to calcite or aragonite.

Compared to reference mortar, where portlandite crystals are not properly changed to calcite in the reference sample as seen in XRD examination, the AGS modified mortar exhibits good mechanical strength and durability attributes. In the XRD analysis, portlandite peaks in the lime sample (Figure 6a, b, c) were constant in the reference sample, indicating inadequate carbonation. However, the ASG-modified mortar revealed improved carbonation consistent with the XRD analysis findings in Figure 6 and superior carbonation.

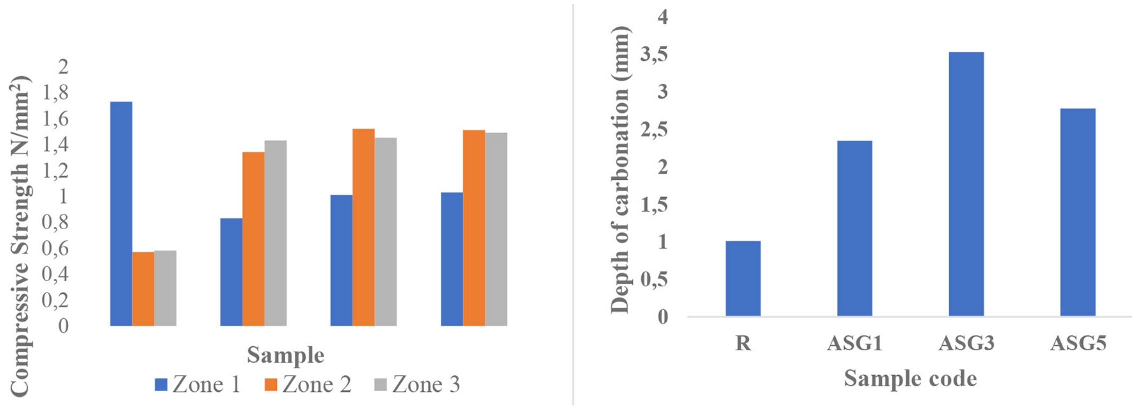


Figure 5. (a) Compressive strength of samples, (b) carbonation depth

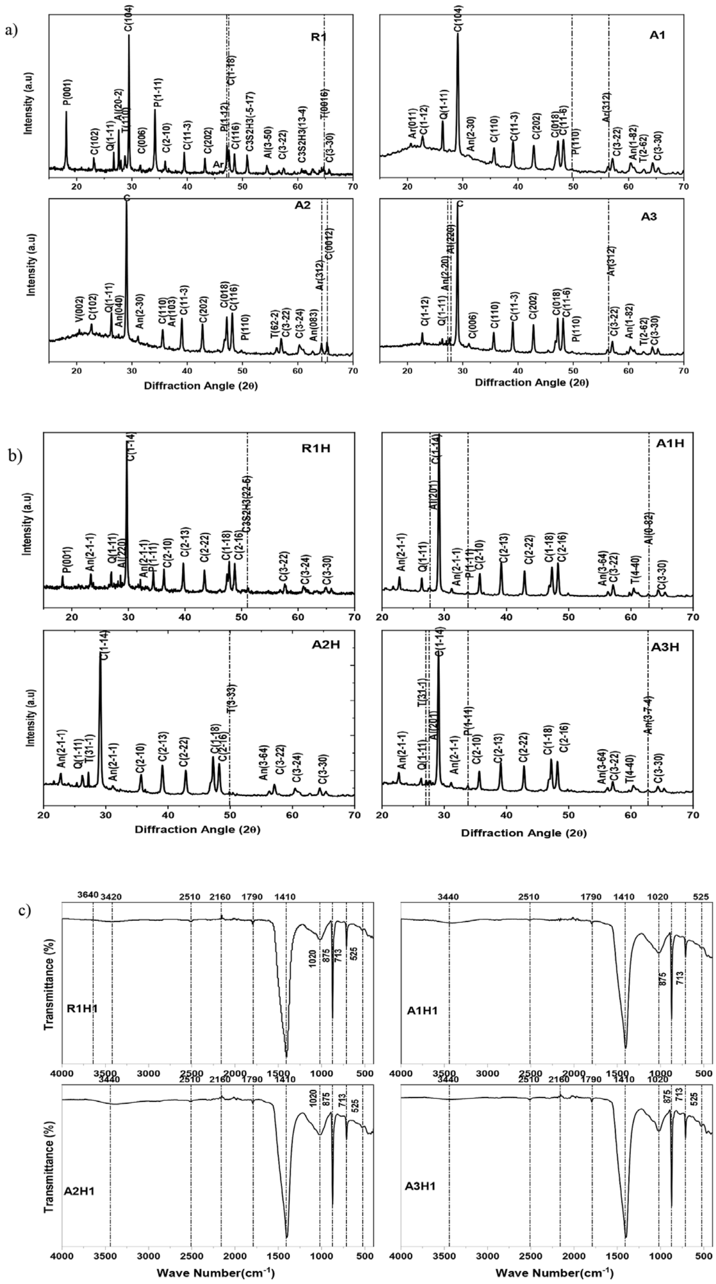


Figure 6. XRD analysis of samples (a) Zone 1 (b) Zone 2 (c) Zone 3

Compared to the reference sample, the modified sample's calcite peak had a relatively high intensity. Some of the calcite peaks in the reference sample are pretty low, indicating the early stages of carbonation. In ASG modification mortar sample, moderate peaks of meta-stable aragonite and unstable vaterite are visible. This observation shows that there is numerous calcite forms in the ASG treated samples. In general, calcium carbonate can be found in a variety of crystalline solid forms, including hydrated polymorphs (ikaite and calcium carbonate monohydrate) as well as anhydrous forms (calcite, aragonite, and vaterite). While aragonite and vaterite are meta-stable in nature, calcium carbonate in the form of calcite is more stable [48]. However, the precipitation of aragonite and vaterite may be favoured in the presence of polysaccharides, a branching polylactide by nature. The presence of polysaccharides would have unquestionably aided in stabilizing meta stable forms of calcium carbonate [49]. The development of aragonite crystals is caused by the high carbon dioxide content and subsequent carbonation. Therefore, the action CO_2 given by the polysaccharides in the mortar mix may have contributed to the development of aragonite in the

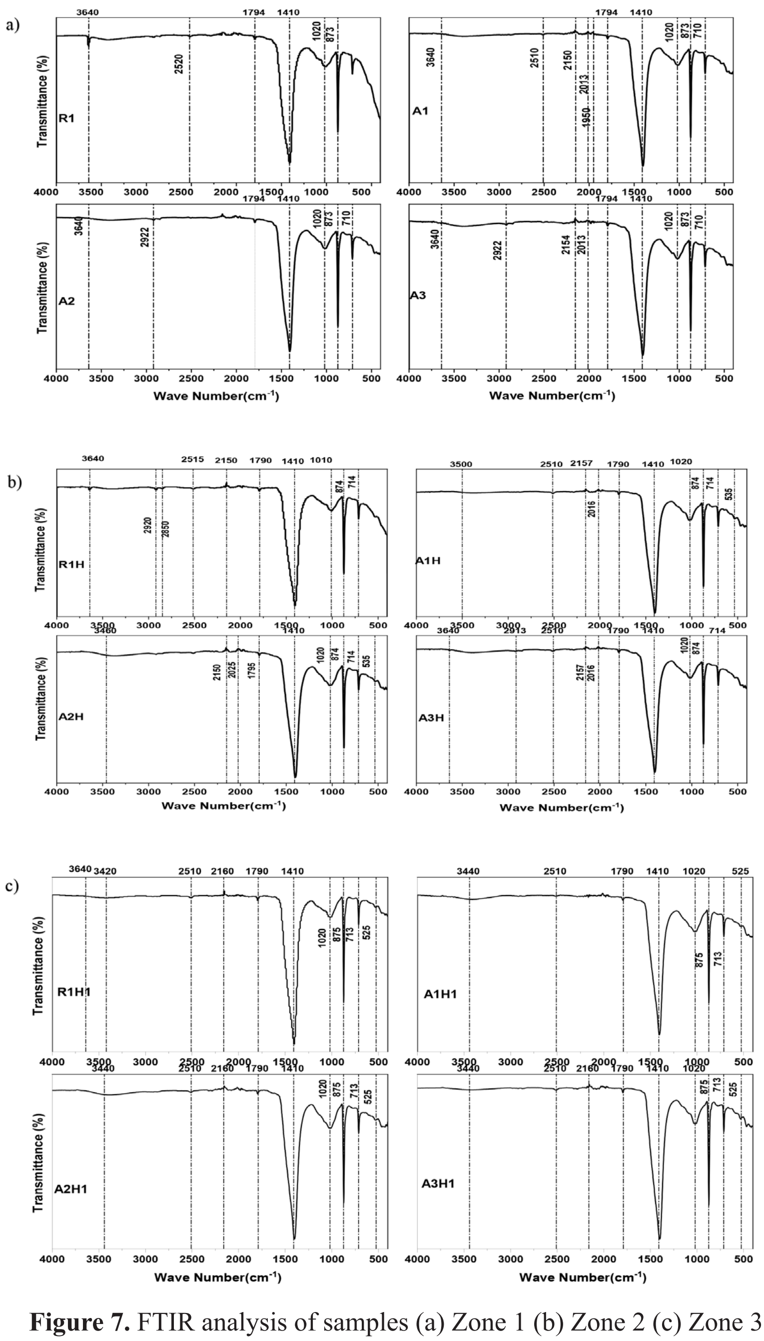


Figure 7. FTIR analysis of samples (a) Zone 1 (b) Zone 2 (c) Zone 3

ASG sample. The FTIR results (Figure 7) confirm the presence of minerals, inorganic phases, and organic compounds identified through the XRD analysis of the lime mortar mixtures. In the ASG-modified sample (ASG 3), there are highly intense and deeper bands corresponding to CO_3 bending variations at 2315 cm^{-1}, 1851 cm^{-1}, 874 cm^{-1}, and 716 cm^{-1}, compared to the low-intensity CO_3 bending peak at 874 cm^{-1} in the reference sample. The bands at 2798 cm^{-1} and 2899 cm^{-1} indicate the presence of polysaccharides and alkane C-H groups, further supported by the broad centered band at 3514 cm^{-1}, which contributes to the enhanced mechanical strength and durability of the modified mortar. The sharp, deep bands at 3674 cm^{-1} and 3705 cm^{-1} reflect the presence of OH stretching, H-bonding hydroxyl, and polymerized amide groups. Additionally, the broad and deep peak at 1482 cm^{-1} in the ASG sample is attributed to aromatic C-C stretching vibrations. The lime silica matrix is seen in the SEM images of the ASG mortars (Figure 8). The siliceous aggregate that can be seen in the sand XRD data is what causes the presence of silica in the lime mortar (Figure 7).

Calcium carbonate is created in lime mortars by the reaction between calcium oxide and carbon dioxide; silica is not a component of the reaction. However, because silica makes it easier for CO_2 to diffuse, its presence in the lime matrix affects the pace of carbonation. Poor carbonation is visible in the reference sample (Figure 5b). However, calcium carbonate was discovered in the admixture changed samples as rhombohedral vaterite crystals and white layers of amorphous calcite near the mortar's edge. On Figure 8, aragonite fiber visibility is also noticeable. Thus, the inclusion of protein in the lime mortar promotes the polymerization process between the lime and organic compounds, which frequently results in the production of calcite that is both crystallized and amorphous in nature. The complete amount of calcium hydroxide

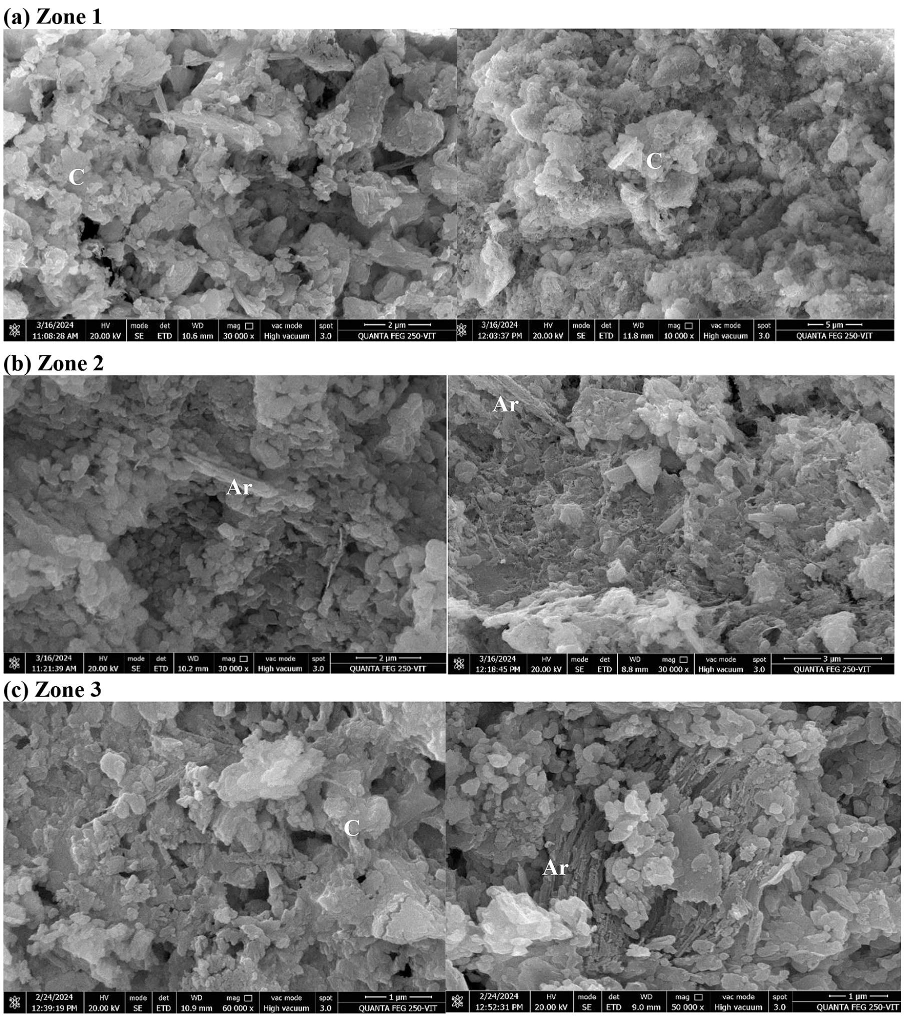


Figure 8. SEM image of (a) Zone 1 (b) Zone 2 (c) Zone 3 samples (C – Calcite Ar – Aragonite)

Table 8. Weight loss of thermogravimetric analysis

Sample	30–120 °C	30–200 °C	200–400 °C	400–600 °C	600–800 °C
R	0.31	0.43	2.45	7.23	3.12
ASG3%	1.45	0.91	2.36	4.89	7.91

in the lime mortar cannot be converted, though. It depends on the carbonation process and the surrounding environment. The aforementioned process is continued as a result of the residual lime particles reacting with the environment.

The texture and microstructure of calcite and vaterite have changed as a result of organic admixtures. When added to lime, the polysaccharides from ASG extract, which is high in carbohydrates compared to proteins and lipids, was transformed into short-chain alcohols in the form of ethanol and iso-propanol. The $Ca(OH)_2$ particles change into calcium alkoxide when short chain alcohols are present. Alkoxides' primary purpose is to transform calcium hydroxide's crystalline structure while simultaneously maintaining its outward hexagonal appearance. Additional calcium alkoxide greatly slows the pace at which carbonation transforms into cementing $CaCO_3$ and promotes the production of meta-stable vaterite. According to 53, environmental alcohol levels have an impact on the stability of meta stable $CaCO_3$ polymorphic phases, resulting in a larger content of meta stable phases such vaterite and aragonite. Additionally, the polysaccharides system carbonates calcium hydroxide nano particles into calcite polymorphic phases more quickly than another environment.

The reference sample has a higher oxygen concentration than the changed sample, which is evidence that more portlandite is not being converted to calcite, according to energy dispersive X-ray spectroscopy results. Notably, the polymer modified sample had higher calcium and carbon concentrations than the reference sample, which had lower calcium and carbon values. It suggests that the reference sample has weak carbonation, which is supported by the results of the carbonation test, XRD, and SEM.

TG-DTA analysis provided additional support for the findings from the XRD, SEM, EDS, and FT-IR experiments. Between 600 °C and 800 °C, there was a significant change in weight that was mostly caused by the de-carbonation of calcite, which was 30.12% in the ASG modified mortar samples compared to 17.64% in the reference sample (Table 6). As a result, the results of the TG analysis are in excellent agreement with those of the SEM and XRD. Between 400 °C and 500 °C, the dehydration of calcium hydroxide was found in the figure of the modified sample (Figure 11b) [30]. The presence of aragonite is indicated by a short peak at 470 °C in the modified sample, but no such peak was seen in the reference sample [54]. Vaterite can be detected by a small exothermic peak in the ASG modified sample that was found at 515 °C [32]. As a result, the results of the XRD analysis are verified by the dehydration of calcium hydroxide and the presence of aragonite and vaterite in XRD. The reference sample's low and short endothermic peak at 680 °C (ranges from 774 °C to 800 °C) represents the escape of CO_2 during structural disintegration and breakdown of calcite (Figure 11) [30] whereas the modified samples' moderate endothermic peak at 680 °C ranges from 648 °C to 800 °C, indicating that more calcite was formed in the modified samples than in the reference samples.

CONCLUSIONS

This study has demonstrated the potential of Acacia Seyal Gum as an effective natural additive for enhancing the mechanical and durability properties of lime mortar. The experimental results show that the incorporation of ASG, particularly at 3% by weight, significantly improves the mortar's strength, durability, and moisture retention. These enhancements are especially valuable for lime mortars exposed to varied environmental conditions, such as those found in India, where temperature and humidity fluctuate widely.

Testing the modified mortar samples under different climatic conditions – 25°C with 20% and 50% relative humidity, and 35 °C with 72% relative humidity – revealed that the 3% gum-modified mortar consistently outperformed the reference mortar. The improved cohesion between lime and sand particles, coupled with reduced porosity, allowed the mortar to maintain its structural integrity and prevent early cracking, even in challenging environments. The moisture retention properties of ASG played a crucial role in slowing the drying process, reducing shrinkage, and enhancing long-term durability.

The results of this study highlight the advantages of using ASG as a sustainable alternative to synthetic additives. Its natural, biodegradable properties align with the growing demand for environmentally responsible construction materials. Moreover, the gum's local availability in regions like India offers economic and ecological benefits by reducing the need for imported or chemically derived products.

In conclusion, the addition of ASG to lime mortar not only enhances its mechanical performance but also offers a viable solution for modern and heritage construction in regions with diverse climates. This research supports the broader application of natural biopolymers in sustainable building practices and paves the way for further studies on eco-efficient materials that balance performance with environmental sustainability.

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