

Applications of Alginate in Geotechnical Engineering and Construction: A Review

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Abstract

Alginate, primarily sodium alginate, is a biopolymer derived from brown algae or bacterial sources that forms hydrogels via ionic crosslinking with certain divalent cations. Its incorporation into soils, earthen materials, cementitious composites, and asphalt mixtures improves mechanical performance and durability. This review collates recent advances in alginate-based treatments for geotechnical and construction applications, highlighting how alginate dosage, substrate type, gelation method, mixing strategy, and curing regime influence mechanical strength, physical properties, and self-healing efficiency. In soil stabilization, alginate treatments increase unconfined compressive strength (UCS) by 0.2–1.5 MPa in sand, with some studies reporting increases of over 2 MPa. Reported UCS improvements in alginate-treated clayey soils generally fall within the range of 50–150% compared to untreated samples, although isolated studies document increases exceeding 200%, depending on material composition and curing conditions. In cementitious systems, alginate-based capsules and hydrogels facilitate self-healing, achieving high closure rates of 70–100% for microcracks <0.4 mm, with some studies achieving complete sealing of macrocracks up to 4 mm while also recovering significant mechanical strength. Depending on dosage and formulation, alginate can also serve as a viscosity-modifying admixture, increasing the plastic viscosity and yield stress of the fresh mix, with this thickening effect becoming pronounced at dosages above approximately 0.1 w/w% by cementitious binder mass. For asphalt pavements, alginate-encapsulated rejuvenators facilitate high healing efficiency under cyclic loading and thermal cycling; rheological tests confirm elevated complex modulus and improved viscoelastic response. This review also synthesizes an explanatory framework for the divergent results found in the literature, advocates for standardized experimental protocols and material characterization, and outlines future research directions to advance alginate as a suitable alternative to conventional stabilizers.

Keywords: alginate; biopolymer; crosslinking; gelation; UCS

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1. Introduction

Since antiquity, humans have relied on earth materials and chemical processes to construct structures and improve the geotechnical properties of land. As early as 3000 B.C., civilizations such as the Mesopotamians treated weak soils with additives (e.g., limestones and organic matters) to enhance road durability and traffic flow [1]. While lime remained a staple in construction, cement now dominates modern soil improvement.

Cement production is responsible for roughly 8% of global CO₂ emissions annually [2,3]. Cement increases the embodied energy of stabilized soils and reduces recyclability by transforming earthen materials into synthetic stone-like structures [4]. This issue has prompted a shift in research toward environmentally sustainable stabilizers, particularly biopolymers. Once confined to food and medical applications, biopolymers are now emerging in construction. Their capacity to enhance interparticle bonding in soils and improve microstructure hydration in cements comes with non-toxicity, renewability, and safe degradability [1,5,6].

Among the various biopolymers investigated, alginate, an anionic polysaccharide from brown algae or bacteria, stands out for its ionic crosslinking, high water affinity, and viscoelastic hydrogel formation via metal-ion gelation [7,8]. Alginate can more than double the unconfined compressive strength (UCS) of kaolinite soils compared to xanthan gum, as well as retain moisture up to 1.5 times its weight [9,10]. In cementitious systems, along with healing agent encapsulation, alginate can function as a Viscosity-Modifying Agent by increasing the plastic viscosity and yield stress of the fresh mixture to control stability and mitigate segregation [11]. Research on algae-derived biopolymers, including alginate, in earth suspensions confirms this thickening action, showing they alter hydration kinetics and improve suspension stability [12]. Consequently, the dominant role of alginate in fresh cement is that of a thickener, a critical consideration for accurate mix design.

However, synthesis of literature reveals a landscape marked by significant contradictions. In geotechnical systems, for example, findings on fundamental properties diverge sharply; in soils, clear optimal dosages of alginate for compressive strength are established in some studies yet entirely absent in others for similar soil types [13–18]. These pervasive discrepancies create a barrier to the reliable design and field-scale implementation of alginate-based technologies. The central knowledge gap addressed by this review is the lack of a unified framework to explain and reconcile these contradictory outcomes. It remains unclear how the intrinsic properties of alginate (molecular weight, M/G ratio), the specifics of its processing and application, and the complex ionic environment of host materials interact to produce such divergent results. Consequently, there is no established guidance for selecting or engineering alginate to achieve predictable performance across different construction applications.

To bridge this gap, this review is structured to (1) establish the fundamental material science of alginate and define the key variable properties; (2) systematically catalog and contrast the reported performance outcomes across all major application domains (soils, earth construction, cement, asphalt, insulation); and (3) synthesize these findings to develop an explanatory framework. This framework aims to explicitly link the observed variability to its root causes where possible, thereby transforming apparent contradictions into understandable consequences of material-process interactions. The review concludes by outlining the standardized reporting and targeted research required to advance alginate from a promising material to a reliable solution for sustainable engineering.

2. Methodology

The following systematic review was conducted to evaluate the efficacy of alginate in construction and geotechnical engineering applications, focusing on its role in enhancing the mechanical performance and durability of soils, earth-based materials, cementitious composites, and asphalt mixtures. The methodology followed a structured approach to ensure reproducibility, transparency, and comprehensiveness, as outlined in detail below.

2.1. Search Strategy

A comprehensive literature search was conducted using the following electronic databases: ASCE Library, ICE Virtual Library, Scopus, MDPI, Web of Science, Elsevier ScienceDirect, SpringerLink, Wiley Online Library, Google Scholar, and ResearchGate. The search encompassed peer-reviewed journal articles, conference proceedings, and technical reports published between 2014 and 2025, covering the last decade to ensure relevance to current research and applications. The following keywords and Boolean operators were used in varying combinations: (“Alginate” or “Sodium Alginate” or “Calcium Alginate”) and (“Biopolymer” or “Hydrogel”) and (“Soil Stabilization” or “Ground Improvement” or “Expansive Soil” or “Collapsible Soil” or “Clay” or “Sand”) and (“Cementitious Composites” or “Concrete” or “Mortar” or “Self-healing” or “Self-Sealing”) and (“Mechanical Properties” or “Durability”). To enhance coverage, the reference lists of all eligible articles were manually screened (backward snowballing) to identify additional relevant studies that may not have been captured by the electronic search strategy.

Studies were screened and included according to the following criteria:

- Published between 2014 and 2025.
- Focused on experimental or field applications of alginate in geotechnical or construction materials.
- Reported quantitative data on at least two parameters related to mechanical performance (e.g., compressive strength, tensile strength, elastic modulus) and/or durability (e.g., water and freeze–thaw resistance, self-healing efficiency).
- Utilized standardized testing methods (e.g., ASTM, AASHTO, EN, ISO).
- Included comparisons with untreated or traditionally stabilized materials (e.g., cement, lime).

Studies were screened and excluded according to the following criteria:

- Studies not written in English.
- Purely theoretical, computational, or review articles without original experimental data.
- Studies focusing solely on biomedical, food, or non-construction applications.
- Research with incomplete methodological descriptions or insufficient data for comparative analysis.

The search results were compiled and duplicates removed manually. Titles and abstracts were screened for relevance, followed by full-text assessment against the inclusion criteria. Data from eligible studies were extracted into a standardized spreadsheet, capturing the following:

- Authors, publication year, and source.
- Alginate type, alginate concentration, calcium source, and gelation method.
- Material type (e.g., soil or cementitious material).
- Test methods and measured parameters.
- Key findings and comparative outcomes.

2.2. Quantitative Data Synthesis and Limitations

When a single study reported multiple data points (e.g., varying alginate concentrations, curing times, or soil types), each relevant dataset was treated independently in the quantitative analysis. However, the study was cited as a single source to avoid over-representation in trend analyses. Where appropriate, data were normalized (e.g., percentage change relative to control) to facilitate cross-study comparison. To minimize selection and reporting bias, the screening and data extraction were performed independently by the authors.

Discrepancies were resolved through discussion and consensus. Studies that did not clearly report experimental conditions, material properties, or statistical measures were flagged, and their results were interpreted with caution in the synthesis. The extracted data were grouped by application domain (sandy soils, clayey soils, cement mixtures, asphalt, insulation aerogel). Quantitative trends were analyzed using descriptive statistics and correlation measures (e.g., Spearman's rank correlation). Qualitative synthesis focused on identifying consistent patterns, methodological variability, and research gaps.

To visualize trends across the compiled literature, quantitative data points were extracted from eligible studies for the specific relationships analyzed. Each data point represents a unique combination of an independent variable (e.g., concentration, curing time) and its corresponding reported result within a given study. When studies reported results for multiple conditions (including different concentrations, soil types, or curing durations), each relevant outcome was recorded as a separate data point to capture the full range of experimental observations. It is important to note that data points originating from the same study are not statistically independent, as they share common experimental protocols, material sources, and measurement techniques. Consequently, regression analyses and correlation coefficients presented in this review are not intended as predictive models. Instead, they serve as descriptive tools to illustrate general tendencies and qualitative trends across a heterogeneous body of research. Key experimental variables (such as curing temperature, curing duration, soil classification, alginate molecular weight, M/G ratio, and gelation method) were not normalized across the compiled studies. This methodological diversity is a fundamental source of scatter in the data and limits direct quantitative comparability. The figures and trend lines should therefore be interpreted as evidence of broad patterns rather than precise quantitative relationships. The accompanying discussion explicitly addresses the impact of these confounding variables on the observed outcomes.

3. Alginate

The most significant property of alginate is its ability to form close-knit microstructural networks through controlled gelation, enhancing the stability, structural integrity, and resilience of various materials and soils [19]. Moreover, alginate's hydrophilicity allows it to dissolve easily and form gels or thick solutions through cation-induced cross-linking. These qualities have long established alginate's use as a sustainable additive in the food and medical industries. For instance, calcium alginate (Ca-alginate) fibres are used in wound dressings, where they soften and conform when exposed to moisture [20]. Alginate has also been leveraged for controlled chemical release, wherein porous alginate beads can encapsulate healing agents and release them gradually [21]. To better understand the intricacies of alginate hydrogels, the following section aims to detail the sources, extraction processes, and molecular compositions of alginate, as well as the effects of calcium ions on hydrogel formation.

3.1. Sources and Extraction Processes of Alginate

All commercially available alginate is sourced from brown algal seaweeds. Alginate is a structural component of marine brown algae known as Phaeophyceae, where it constitutes up to 40% of the dry matter and occurs in the intercellular mucilage and algal cell wall as an insoluble mixture of calcium, magnesium, potassium, and sodium salts [22,23]. As displayed in Table 1, the Phaeophyceae group—responsible for the major portion of alginate production—includes *Ascophyllum nodosum*, *Laminaria hyperborea*, *Macrocystis pyrifera*, *Ecklonia maxima*, and *Laminaria digitata*. Other species of brown seaweed sometimes used in the production of alginate are not considered for commercial purposes either due to their highly localized cultivation or inferior molecular composition [24].

Table 1. Common alginate types, molar mass, and producer countries from algal and bacterial resources, where G represents Guluronic Acid content. Based on Peteiro [24].

Major Alginate Producing Seaweed and Bacteria	Alginate Type	Major Producer Countries	Molar Mass (kDa)	Reference
Laminaria digitata and Laminaria hyperborea	Medium G and high G	France, Ireland, the United Kingdom, Norway	75–297 and 220–500	[25–27]
Ecklonia maxima	Medium G	South Africa	58–1506	[28]
Saccharina japonica	Medium G	China, Japan	1800	[29]
Azotobacter vinelandii	High G	/	4000	[30,31]

Although some of alginate's algal resources are large, their commercial value cannot always be realized due to the remoteness of wild seaweeds and the difficulties involved with attending harvesting and shipment [32]. In recent years, there has been a significant shift towards farmed seaweeds, which contributed to at least 94% of the world's annual seaweed supplies by the end of the 20th century, compared to around 50% in the mid-1990s [33]. Nevertheless, its cultivation must be managed carefully to preserve ecological functions; for example, certain algal species like *Sargassum muticum* are considered highly invasive, threatening marine biodiversity globally [34].

Alginate may also be extracted from two bacterial sources: *Azotobacter vinelandii* and *Pseudomonas spp.* Bacterial alginate biosynthesis offers distinct advantages over algal-derived polymers, including precise control over molecular weight (MW), acetylation patterns, and molecular structure due to genetic and fermentation optimizations [35,36]. For instance, *Azotobacter vinelandii* has been engineered to produce alginates with an MW of around 4000 kDa, far surpassing that of algal variants [37]. Furthermore, bacterial alginate production is independent of environmental factors and seasonal variations typically involved with the cultivation of algal resources, affecting both yield and quality [31]. While bacterial alginates offer distinct advantages, several hindrances to their commercial adoption remain, mainly due to the pathogenic nature of certain species, the considerably lower concentrations of guluronic acid residues, and the high cost of production associated with bacterial fermentation processes [20,38]. Hence, algae are found to be superior for the use of alginate in civil engineering research and industry.

The process of extracting alginates from algal seaweeds may be fine-tuned to obtain sodium alginate with a range of molecular weights and compositions depending on the requirements [39]. The process, demonstrated in Figure 1, begins with the transformation of water-insoluble mixed salts of alginic acid from the algal cell wall matrix into water-soluble salts in an alkaline medium. Immediately afterwards, the alginate is subjected to precipitation and purification processes. This may be summarized into three main stages:

1. **Pre-Extraction:** Harvested seaweeds are first dried and crushed into a powder, then treated with a mineral acid (typically HCl), leading to insoluble alginic acids which are easily separated from contaminants, such as other polysaccharides (e.g., laminarins, fucoidan), low molecular weight compounds, and polyphenols, either by filtration or centrifugation [40].
2. **Neutralization:** The insoluble residue is then treated by an alkaline solution (using sodium carbonate, sodium hydroxide, or aluminum hydroxide, above pH = 6.0) to convert insoluble alginic acid into soluble sodium alginate [40].
3. **Purification:** After another separation step, soluble sodium alginate is precipitated and then purified using techniques such as acidification, the addition of calcium chloride, or the addition of ethanol [39]. Following this, the purified sodium alginate is dried, milled, and packaged for commercial use.

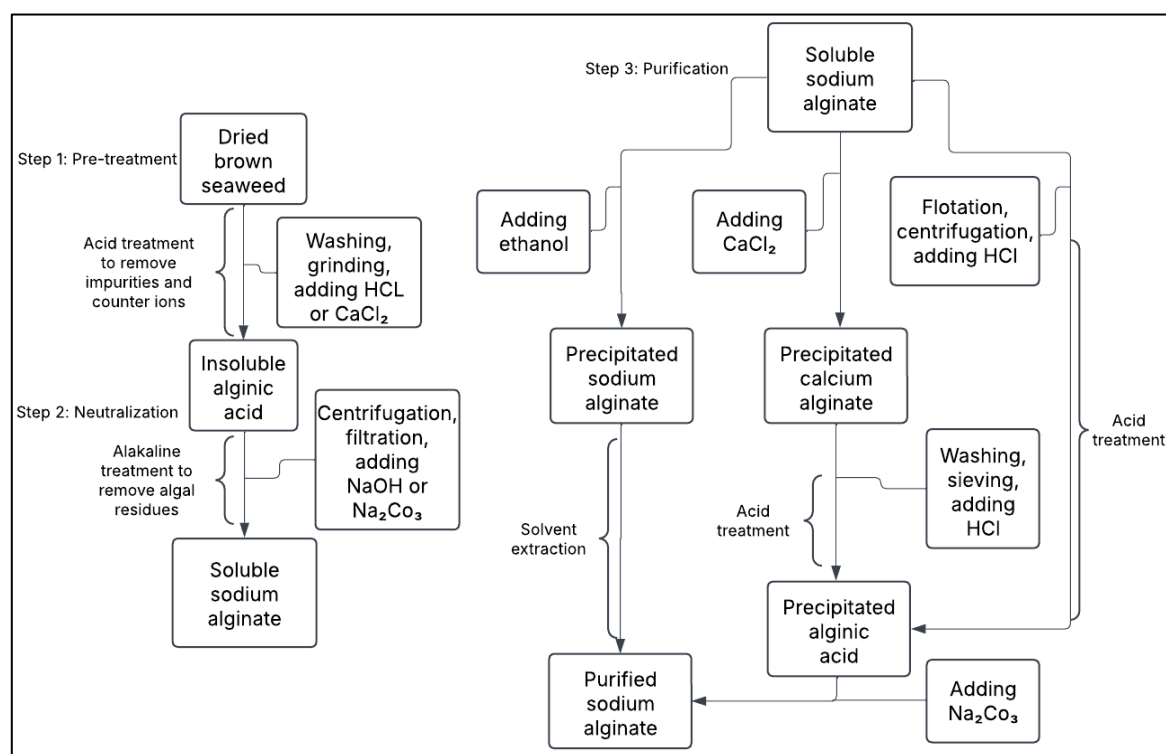


Figure 1. Alginate Production Process from Algal Sources. Adapted from Peteiro [24].

Several studies have shown that factors such as temperature, alkaline concentration, extraction time, pH, precipitation, purification, and drying methods impact the quality of extracted alginate products. Table 2 summarizes the outcomes of the analysis by Bojorges et al. [39] on the factors influencing the quality and yield of alginate extraction processes.

Table 2. Overview of factors influencing alginate extraction processes. Summarized from Bojorges et al. [39].

Factor	Influence on Alginate Extraction	Reference
Temperature	- Higher temperatures (up to a point) increase extraction yield. - Excessive temperatures (>60 °C) can degrade alginate polymers, reducing viscosity and molecular weight. - Optimal temperature varies depending on the algae species.	[41–47]
Alkaline Concentration	- Na₂CO₃ is commonly used to raise the pH to 9–10. - Optimal concentration ranges between 2 and 4% for maximum yield. - Higher concentrations (>4%) can decrease yield due to degradation and formation of carboxylic acids.	[47–51]
pH	- Alkaline pH (above 10) converts alginic acid into soluble sodium alginate. - A pH around 10 is generally optimal for higher yield. - Extreme pH values can cause degradation or affect the quality of the alginate.	[40,47,50–53]
Extraction Time	- Longer extraction times generally increase yield. - Excessive time can lead to depolymerization, reducing viscosity and altering the M/G ratio. - Optimal extraction time varies, typically ranging from 2 to 6 h.	[26,43,46,47,54,55]
Interactions Between Factors	- Temperature, time, and pH interact to influence yield and quality. - High temperature combined with longer extraction time can cause depolymerization. - Optimal extraction conditions depend on the specific algal species and desired alginate properties.	[46,54]

Precipitation Method	- Different methods (ethanol, CaCl_2 , HCl) impact the molecular weight and mechanical properties of alginate.	[24,40,56]
	- The ethanol route is simpler with higher yield and better rheological properties.	
Purification and Drying	- The calcium and HCl routes can lead to reduced mechanical properties.	[57–61]
	- Purification methods vary and aim to remove impurities.	
	- Standard methods are not always efficient at fully removing proteins.	
	- Drying methods influence the final particle size and quality of the alginate.	

The choice of precipitation method has been shown to have the greatest impact on the quality and yield of alginate. Therefore, most research on alginate treatment has employed the ethanol route due to its time efficiency, simplicity, and the more desirable rheological and mechanical properties of the alginate it produces.

3.2. Molecular Composition and Ionic Crosslinking of Alginate Hydrogels

Alginates are natural polymers made up of long chains of sugar molecules, consisting of two types of sugar residues known as guluronic (G) and mannuronic acids (M). The way these sugars are arranged can vary depending on the specific algal organism and the part of the organism from which they are extracted. In the alginate chain, these sugars can appear in different sequences; they might be grouped into blocks of G residues, blocks of M residues, or alternating blocks of M and G residues, as demonstrated in Figure 2A.

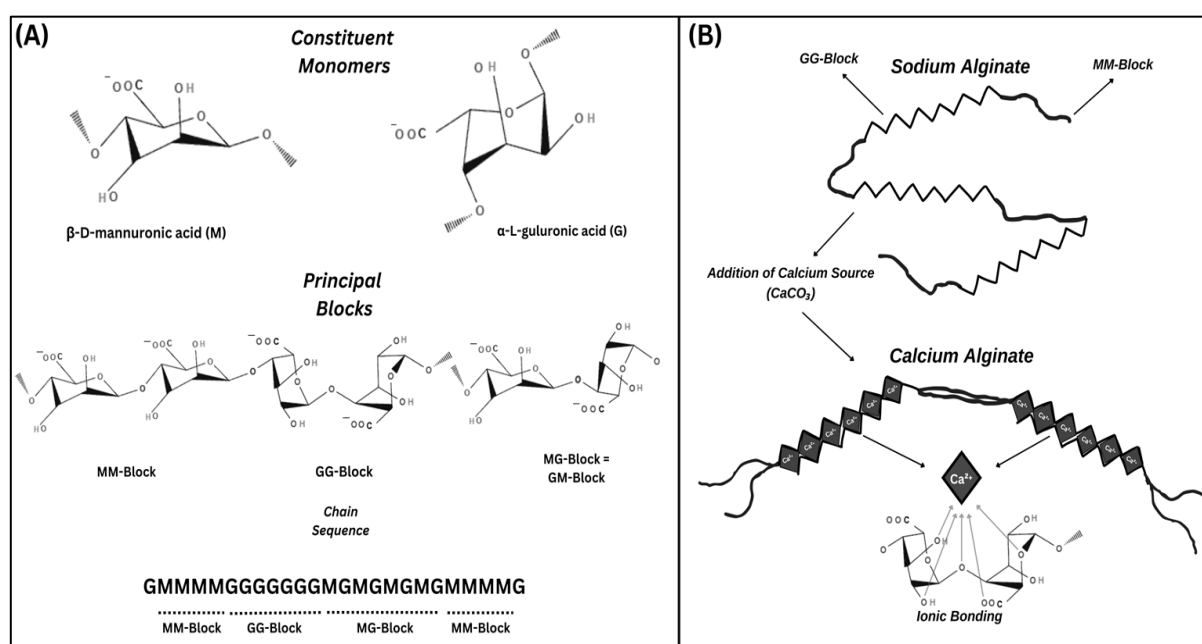


Figure 2. (A) Molecular structure of alginate, adapted from Davis et al. [62]. (B) Formation of the egg-box structure during ionic gelation of sodium alginate with calcium ions, adapted from Peteiro [24] and Bojorges et al. [39].

The most characteristic property of alginate is its ability to form stable gels in the presence of certain metal cations, particularly calcium, through a cross-linking reaction. This ability is conventionally described in terms of the so-called “egg-box” model [63]. According to this model, divalent cations are embedded into cavities formed naturally by two adjacent polymer chains containing GG blocks in a helical conformation, as illustrated in Figure 2B. Ionic crosslinking with calcium over other crosslinking ions generally results in more desirable hydrogels with balanced elastic moduli, providing sufficient rigidity for stability while maintaining durability against environmental detriments. Choi et al. [64] found that Ca^{2+} crosslinked films had over 27% higher tensile strength values than Fe^{2+}

crosslinked films. However, the tensile strength of FeCl_3 crosslinked films was over 13% of CaCl_2 crosslinked films. This was attributed to the formation of three-dimensional chelating bonds of alginate with trivalent cations such as Fe^{3+} , creating a more complex and tighter structure, reducing excess moisture in the film matrix, and limiting chain mobility. As a result, the moisture content of the FeCl_3 crosslinked films was much lower than that of other crosslinked films, resulting in high tensile strength and low elongation at break values. The CaCl_2 crosslinked films showed about 1.8 times higher elongation at break values than FeCl_3 crosslinked films at 7.43%.

Malektaj et al. [65] determined the equilibrium degree of swelling by measuring the weight of different alginate hydrogel samples at swelling equilibrium; the results are presented in Figure 3. Ca^{2+} crosslinked alginate exhibits a relatively high degree of swelling, which enhances a treated material's capacity to retain water and prevent desiccation, a particularly useful characteristic for use in environments where flexibility and adaptability are key for long-term durability.

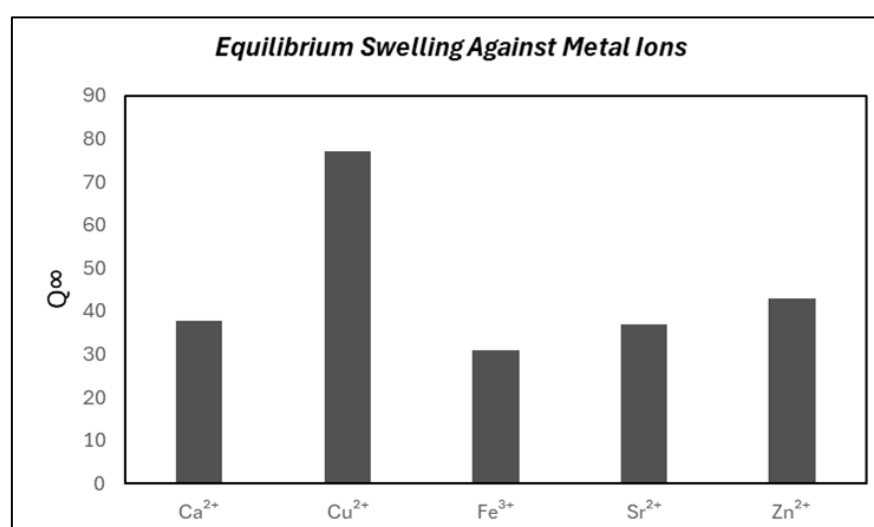


Figure 3. Equilibrium degree of swelling Q_∞ of Alginate hydrogels cross-linked with various cations. [65].

Table 3 summarizes the outcomes of the study of Hasnain et al. [66], which investigated the solubility of alginate. The study found that Ca-alginate is insoluble in most environments, which is crucial for maintaining the structural integrity of treated materials. Additionally, the gelation process using Ca^{2+} can be more easily controlled; by slowly releasing calcium ions, as is the case with the internal gelation method, it is possible to control the rate of gel formation and achieve a more uniform gel structure. This control over gelation is particularly advantageous for producing consistently uniform gels with desirable mechanical properties, a crucial consideration in soil stabilization and material strengthening applications.

Table 3. Solubility of alginates in various conditions [66].

Alginates	Acidic Environment	Alkaline Environment	Presence of Divalent/Trivalent Metal Cations
Alginic acid	Insoluble	Soluble	Insoluble
Sodium alginate	Insoluble	Soluble	Insoluble
Potassium alginate	Insoluble	Soluble	Insoluble
Calcium alginate	Insoluble	Insoluble	Insoluble
Ammonium alginate	Soluble	Soluble	Soluble

3.3. Calcium Sources and Crosslinking Methods of Alginate Hydrogels

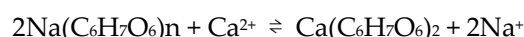
The ability of calcium to form mechanically flexible and ionically stable crosslinked alginate networks that can adapt to dynamic conditions renders Ca-alginate hydrogel the most common form of alginate for a range of soil stabilization and material enhancement applications, as presented in Table 4. Moreover, the source of calcium ions for gelation may pre-exist in the host material of treatment, such as in calcareous soils and certain cement concretes, further enhancing the practicality and cost-effectiveness of alginate's application.

Table 4. Sources of Calcium for Alginate cross-linking and gelation method.

Alginate Application	Source of Calcium	Naturally Found or Additive	Gelation Method	Reference Study
Bio-Composite Adhesive	Calcium Sulphate (CaSO ₄)	Additive	Internal	[67]
Bio-Brick Binder	Calcium Chloride (CaCl ₂)	Additive	External	[68]
Sandy Soil Stabilizer	Calcium Chloride (CaCl ₂)	Additive	External	[15]
Clay Soil Stabilizer	Calcium Chloride (CaCl ₂)	Additive	External	[18]
Self-Healing Asphalt Concrete Emulsifier	Calcium Chloride (CaCl ₂)	Additive	External	[69]
Sandy Soil Stabilizer	Calcium Carbonate (CaCO ₃)	Additive	Internal	[70]
Sandy Soil Stabilizer	Soil	Naturally Found	Internal	[71]
Poured Earth Binder	Calcium Carbonate (CaCO ₃)	Additive	Internal	[72]
Unfired Earth Brick Binder	Soil	Naturally Found	Internal	[73]
Clay Soil Stabilizer	Soil	Naturally Found	Uncontrolled	[74]
Self-Healing Cement Composite	Soil	Naturally Found	Uncontrolled	[75]
Concrete Strengthener	Soil	Naturally Found	Uncontrolled	[76]

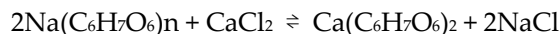
The formation of Ca-alginate may occur through internal, external, or uncontrolled gelation processes. The methods differ in the way crosslinking ions are introduced to alginic polymers, resulting in distinct gelling structures and crosslinking uniformity:

- In internal gelation, the release of calcium ions is induced by the addition of a slow acid-releasing agent into a solution containing soluble calcium salts or directly into soils, typically using GDL (D-glucono-δ-lactone), which lowers the pH of the solution, causing the source of calcium to dissolve and gradually release Ca²⁺ ions, forming a gel according to the reaction:



This controlled reaction allows for the formation of an ionically homogenous, uniform gel as shown in Figure 4A [77].

- In external gelation, a source of calcium is directly added to alginate solutions, where cations diffuse from a higher concentration region into the interior region of alginate particles, as demonstrated in Figure 4B. The diffusion method produces an alginate gel that is inhomogeneous with a high cation gradient near the gel surface, which decreases as it approaches the core [78]. At the outermost layer of the hydrogel-cation layer, gelling kinetics are rapid, and gel formation is instantaneous. This method of gelation is represented by the following reaction:



Rapid gel formation is important in applications where a certain size and shape of gel is required, such as alginate beads for encapsulating repair materials in cement and concrete mixtures [75].

- Uncontrolled gelation refers to alginate gelation driven by divalent ions naturally present in the surrounding environment, particularly soils rich in calcium or magnesium, as displayed in Figure 4C. In this case, alginate is introduced directly into the soil without a defined external source of Ca^{2+} . Crosslinking occurs as the alginate absorbs ions from the pore water or from native minerals, resulting in highly variable, spatially inconsistent gels. This mechanism lacks temporal or spatial control, often producing weak or non-uniform gels, and is influenced by the local ionic strength, mineral composition, and moisture content of the soil. Despite its variability, uncontrolled gelation is commonly employed in biopolymer soil treatment studies due to its simplicity and relevance to field-scale application [79–81].

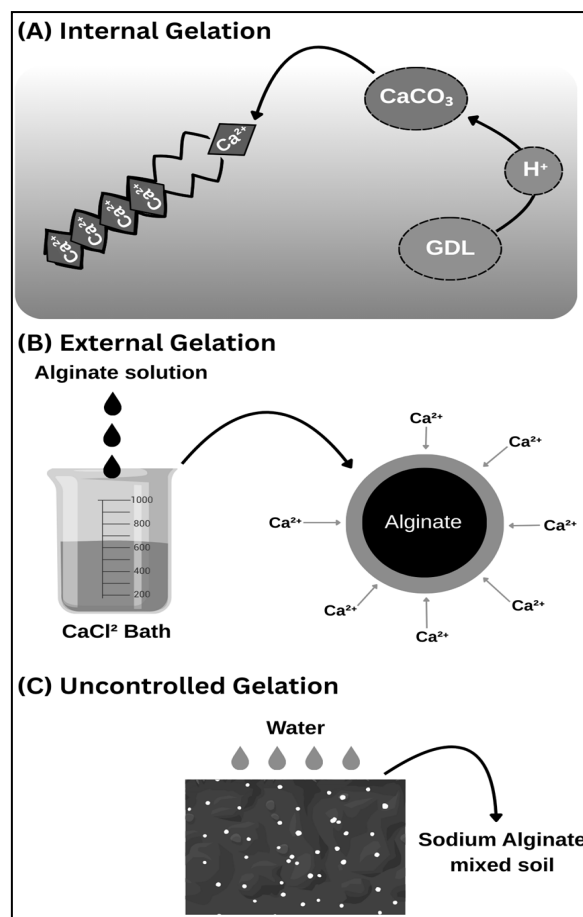


Figure 4. (A) Formation of Ca-alginate gel through internal gelation, (B) Formation of Ca-alginate gel through external gelation, (C) Formation of Ca-alginate gel through uncontrolled gelation. Adapted from [82].

4. Mechanical and Physical Properties of Ca-Alginate Hydrogels

The type of crosslinking cation and its concentration, method of gelation, and molecular composition of alginate influence the physical and mechanical properties of the resulting gels [23]. These factors are fundamental for understanding how alginate-treated materials are produced with varying mechanical and physical properties.

4.1. Effect of M/G Ratio

Alginate molecules exhibit inherent stiffness due to the conformational rigidity of their sugar rings (β -D-mannuronic and α -L-guluronic acids) and the restricted rotation of their glycosidic bonds. Stiffness varies with G/M block sequences: GG-rich chains are the stiffest, followed by MM and then MG/GM blocks [83]. As shown in Table 5, algal alginates differ widely in composition. High G-block alginates form strong, rigid gels via Ca^{2+} ‘egg-box’ crosslinking, whereas M-rich alginates produce more flexible, structurally weaker gels [84]. Lee et al. [85] observed that GG-rich alginate films retained stable tensile properties under stress, as rigid GG blocks limited chain mobility during crosslinking. In contrast, MM/MG-rich chains exhibited greater flexibility, enabling alignment but reducing mechanical strength. Thus, hydrogel performance depends on both crosslinking density and chain mobility, with the latter dominating in systems requiring ductility.

Table 5. Molecular composition and sequence of common algal alginates. Based on Peteiro [24].

Seaweed Species	Composition			Sequence			Reference
	F M	F G	M/G	F MM	F GG	F MG, GM	
Macrocystis pyrifera	0.62	0.38	1.63	0.42	0.18	0.20	[86]
Laminaria digitata	0.59	0.41	1.43	0.43	0.25	0.16	[87]
Laminaria hyperborea	0.45	0.55	0.81	0.28	0.38	0.17	[88]
Saccharina latissima	0.45	0.55	0.82	0.33	0.43	0.12	[24]
Ecklonia maxima	0.55	0.45	1.22	0.32	0.22	0.32	[88]
Ascophyllum nodosum	0.61	0.39	1.56	0.46	0.23	0.16	[24]
Legend	F M = fraction of mannuronic acid units, F G = fraction of guluronic acid units, M/G = ratio of mannuronic to guluronic acid, F MM = fraction of MM blocks, F GG = fraction of GG blocks, F MG, GM = fraction of alternating MG/GM blocks						

4.2. Effect of Molecular Weight

Molar weight manipulation allows independent control of pre-gel viscosity and post-gel stiffness in alginate hydrogels [89]. Lee et al. [85] found that higher-MW alginates yield hydrogels with tensile stresses up to ~1.3 MPa and Young’s moduli of ~15 kPa, but modulus gains plateau beyond 200 kDa due to maximal chain entanglement [90]. An experiment by Kong and Mooney [91] reveals that blending low-MW alginate (~33 kDa) into high-MW alginate (~220 kDa) increased post-gel stiffness by over 50% (from ~10 kPa to ~15 kPa elastic modulus) while maintaining pre-gel solution viscosity below 100 mPa·s, enabling injectability. Tansik and Stowers [92] find that low-MW alginates (35 kDa) produce weaker networks (elastic modulus ~1–3 kPa) with faster stress relaxation (50% relaxation in <100 s) due to increased chain mobility. Hence, the following may be inferred from these findings: (1) alginates with higher MW provide stronger molecular networks with higher post-gelling viscosity at the expense of chain mobility; (2) high-MW alginates may form solutions with excessively high viscosity, which may complicate processes like injection or mixing.

4.3. Effect of Calcium Ion Concentration

Alginate hydrogels exhibit significant swelling in water, a critical property for applications in material strengthening and soil stabilization [93]. This behaviour is directly influenced by the concentration of crosslinking ions. Increasing the concentration of divalent cations (e.g., Ca^{2+}) in alginate solutions reduces hydrogel swelling due to enhanced ionic crosslinking. For example, higher CaCl_2 concentrations (10 mM) produced stiffer gels with reduced swelling, while lower concentrations (2 mM) resulted in softer, more

swollen networks [94]. This inverse relationship arises because elevated ion concentrations promote the formation of additional ionic bridges between guluronic acid (G-block) residues, creating a denser “egg-box” structure that restricts polymer chain mobility and limits water absorption. While higher Ca^{2+} concentrations improve gel strength and surface homogeneity, they concurrently reduce elongation at break and swelling capacity [95]. Rheolution Inc. [96] demonstrated alginate films crosslinked with 50 mM CaCl_2 achieved a shear storage modulus (G') of ~2800 Pa but exhibited significant shrinkage, whereas 10 mM CaCl_2 yielded softer behaviour ($G' \sim 645$ Pa) with sustained swelling over 24 h. These findings align with the broader principle that increased crosslinking density creates a rigid hydrogel matrix resistant to expansion, whereas lower crosslinking allows greater chain flexibility and water uptake. This behaviour is pivotal for designing hydrogels tailored to specific environmental or structural needs, such as soil stabilization with controlled water retention.

4.4. Effect of Gelation Method

The binding mechanism of calcium ions to alginate molecules significantly influences the properties of the resulting hydrogels. Chan et al. [97] investigated the effects of internal and external gelation on the mechanical properties of calcium-alginate hydrogel films. While it was found that surface roughness increased for both gelation techniques, the mechanical properties of alginate matrices were profoundly affected by the gelation method and the amount of CaCO_3 used. External gelation produced films with higher tensile strength and elastic modulus (89–99 MPa and 2532–3142 MPa, respectively), while internal gelation yielded more flexible films with lower stiffness (86–88 MPa and 2210–2974 MPa, respectively). This discrepancy is attributed to differences in crosslinking kinetics: external gelation promotes rapid, localized Ca^{2+} binding, creating a denser and more rigid network, whereas internal gelation allows slower, more uniform crosslinking, resulting in a more homogeneous but less stiff matrix. Hence, gelation method selection is trivial for tailoring hydrogel properties to specific applications, such as rigid structural supports or flexible encapsulation beads.

4.5. Impact of pH and Temperature

In a low pH environment, alginate gel particles shrink due to the protonation of carboxylate groups (COO^-) on the alginate polymer chains. The presence of hydrogen ions (H^+) in acidic conditions neutralizes the negative charges on the alginate molecules, reducing electrostatic repulsion and causing the gel network to contract. This contraction decreases pore size and overall gel volume [98]. In highly acidic conditions ($\text{pH} < 3$), proton-catalyzed hydrolysis can occur, leading to the formation of hydrogen bonds between alginate chains. This process reduces gel strength while increasing viscosity, with peak viscosity typically observed at pH 3–3.5 [89]. These pH-dependent changes in viscosity and gel structure are directly influenced by the distribution of carboxylate groups along the alginate polymer chain, which dictate its behaviour under varying pH conditions [99]. Conversely, prolonged exposure to high pH levels (alkaline conditions) disrupts the ionic crosslinks within the gel, breaking it down into smaller molecules and ultimately leading to gel dissolution [100]. This occurs because hydroxide ions (OH^-) compete with divalent cations (e.g., Ca^{2+}) for binding sites on the alginate chains, destabilizing the gel network.

Alginate gels are generally thermostable within the range of 0–100 °C [101]. However, their thermal stability is influenced by the composition of the alginate. For instance, gels rich in mannuronic acid (M-blocks) are less thermally stable than those with higher guluronic acid (G-block) content, as G-blocks form stronger “egg-box” structures with divalent cations [101]. Above 100–120 °C, alginate gels undergo depolymerization, leading to a loss of structural integrity. Crosslinked alginate gels become less rigid as temperature

increases, with gel strength peaking at 90 °C and dropping sharply at higher temperatures [102]. This depolymerization results in a more open gel structure, increased particle size, and higher porosity, all of which contribute to weakened mechanical properties.

4.6. Stability of Alginate Gels

Alginate gels are composed of viscoelastic networks that deform reversibly in response to external stimuli due to water mobility within the matrix [103]. Their elasticity and recovery properties are governed by composition and cross-linking density [76]. Hashemnejad and Kundu [104] systematically compared the rheological behaviour of ionic (e.g., Ca^{2+} -crosslinked) and covalent alginate hydrogels under mechanical strain using shear and cavitation rheometry. They observed strain-stiffening behaviour (increased rigidity under deformation) in ionic gels, accompanied by negative normal stress, indicating lateral contraction rather than expansion under strain. This contrasts with chemically crosslinked gels, which exhibited homogeneous stress distribution. The adhesive failure observed in ionic gels at large strains was attributed to the egg-box model mechanism: Ca^{2+} ions form brittle, discrete junction zones that resist deformation but detach abruptly under stress [105]. Alginate hydrogels disintegrate either through external chelation of crosslinking ions (e.g., Ca^{2+}) or high pH-induced swelling. In alkaline environments, deprotonation of alginate carboxyl groups generates electrostatic repulsion between chains, expanding the network and increasing pore size [106]. Chelating agents like citrate or EDTA accelerate degradation by sequestering divalent ions, destabilizing the “egg-box” junctions. This process is exacerbated by monovalent ions (e.g., Na^+), which displace Ca^{2+} via ion exchange, leading to gradual “unzipping” of the crosslinked network, as demonstrated in Figure 5 [89].

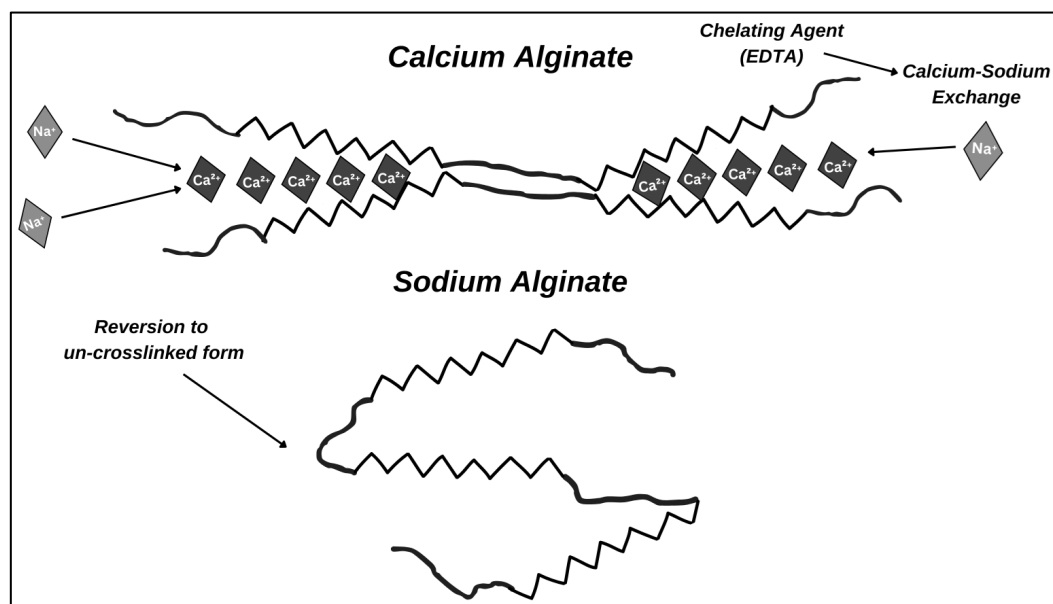


Figure 5. Disintegration of Ca-alginate gel through calcium ion chelation.

Crosslinking homogeneity further modulates stability. Malektaj et al. [65] demonstrated that homogeneous Ca-alginate gels exhibit greater pH-sensitive swelling than inhomogeneous variants. When cycled between low and high pH NaCl solutions, homogeneous gels swelled more due to uniform ion distribution, facilitating rapid Na^+ - Ca^{2+} exchange. Conversely, inhomogeneous gels, with clustered crosslinks, resisted swelling and degradation due to localized stress distribution. This highlights how the crosslinking method directly impacts the structural resilience of alginate gels in dynamic environments.

4.7. Implications for Durability in Engineering Environments

The disintegration mechanisms of alginate hydrogels, either through cation chelation or swelling, have direct implications for the long-term durability of treated materials in real-world environments. In the absence of cationic exchange, alginate-treated soils experience mechanical degradation upon cyclic wetting and drying. Alginate-treated clays under non-saline conditions, subject to at least five wetting–drying cycles, demonstrated a ~40% decrease in UCS [13,18]. Moreover, the degradation of sodium alginate’s ionic cross-linked structure is further exacerbated when subject to specific chemical conditions commonly encountered in ground and construction applications, especially under repeated wetting and drying, wherein both ion exchange and swelling occur, creating new pathways for moisture and ion ingress in subsequent cycles [107]. In saline groundwater or marine environments, high concentrations of monovalent cations (such as Na⁺, K⁺) can exchange with Ca²⁺ in the hydrogel network via ion exchange, progressively weakening the crosslinks and leading to softening and eventual loss of cohesion. The reversible conversion of calcium alginate back to sodium alginate, as displayed in Figure 5, is a primary degradation pathway in coastal settings. A durability study by Castro et al. [108] on coastal sands treated with sodium alginate demonstrated that while the calcium alginate membranes maintained chemical stability, specimens subjected to 28 artificial seawater wet–dry cycles exhibited a 26–37% reduction in UCS. The primary failure mechanism was attributed to the physical tearing of alginate membranes from repeated expansion–contraction and crystallization pressure from precipitated salts. Similarly, alkaline environments, such as those surrounding fresh concrete or in soils with high pH, promote deprotonation of alginate carboxyl groups as mentioned in Section 4.6. Hence, the use of alginate for applications in highly saline or chemically exposed environments must account for these potential impacts on the durability of the treated material.

5. Earth Blocks

Several studies have examined the impact of alginate on the mechanical performance, durability, and stability of unfired soil-based composites, demonstrating its suitability as a naturally sourced stabilizer. Table 6 covers alginate’s influence on mechanical performance in clay, silt, or sand admixtures, with some studies extending into shrinkage, freeze–thaw resistance, or thermal conductivity. Alginate concentration is expressed as a weight-to-weight percentage (w/w%) by dry weight of the soil mass/earth material.

Table 6. Systematic survey of Ca-alginate-treated Earth blocks.

Alginate Concentration (w/w by Dry Soil Mass%)	Primary Aim	Calcium Source and Gelation Method	Soil Type	Treatment Method(s)	Variable(s) Studied	Test(s) Performed	Reference
(19.5%)	Mechanical Strength	Soil, Internal	Clay (32%), Sand (22.5%), Silt (45%)	Wet Mixing	Wool Inclusion, Mixture Composition	UCS, 3PB (Three-point bending)	[109]
(0.1%)	Mechanical Strength	Soil, Uncontrolled	Clay (20%), Silt (68%), Sand and Gravel (12%)	Wet Mixing	Alginate Type	UCS, 3PB, Shrinkage	[110]
(0.1%, 0.25%, 0.5%)	Mechanical Strength, Durability	Soil, Uncontrolled	Clay (31%, 27%, 16%), Silt (45%, 44%, 41%), Sand and Gravel (24%, 29%, 23%)	Wet Mixing	Concentration, Alginate Type, Soil Type	UCS, 3PB, Erosion, Water Sensitivity	[111]

(1%, 3%, 5%)	Mechanical Strength	Soil, Uncontrolled	Clay (17%), Sand (83%)	Dry Mixing	Concentration, Dry Density	UCS, 3PB	[19]
(0.5%, 1%, 1.5%)	Mechanical Strength, Durability	CaCl ₂ , External	Sand (100%)	Dry Mixing	Concentration	UCS, 3PB, Water Absorption, Wet-Dry, Freeze-Thaw, Thermal Conductivity	[68]

Galan-Marín et al. [109] combined alginate with wool fibres in clay–silt–sand mixtures, reporting a 20–30% increase in compressive strength alongside enhanced crack resistance and cohesion. Dove [110] explored low alginate dosages (~0.1 w/w% of dry soil mass), achieving a compressive strength of 1.7 MPa while improving plasticity and reducing shrinkage cracks. Rheological testing revealed that even at a low dosage, alginate significantly improved thixotropy and colloidal stability of clay mixtures, with desirable flow and flocculation effects observed. Building on this study, Dove et al. [111] explored the effects of soil and alginate types across a wider dosage range (0.1–0.5 w/w%). The study revealed findings contrary to conventional understanding, whereby earth blocks treated with higher M/G ratio alginates resulted in superior flexural and compressive strength gains (123% and 160%, respectively). It was emphasized that other factors, including viscosity, chain length, and molecular weight, likely affected the results. For instance, the higher viscosity of other alginate types tested may have obstructed homogenous mixing and soil–polymer interactions. Menasria et al. [19] tested 1–5 w/w% alginate, identifying 3% as optimal, resulting in a 50–60% increase in strength, whereas excessive alginate (>5 w/w%) led to local lubrication, reducing strength. Arab et al. [68] introduced enzyme-induced carbonate precipitation (EICP) with alginate, producing bio-bricks with compressive strengths of 1–2.5 MPa, comparable to cement-treated blocks (~20% cement content), while significantly enhancing water resistance. Together, these studies establish alginate as an effective natural stabilizer for earth-based materials, improving mechanical strength and durability and making it a viable alternative to conventional binders like cement and lime; however, further research is needed to optimize formulation and material preparation protocols to fully realize its potential.

6. Poured Earth

The use of alginate-stabilized formulations in poured earth construction represents a transformative approach to sustainable construction, offering a viable alternative to cement-based systems. This technique builds on the inherent advantages of earthen materials in low embodied energy, recyclability, and excellent hygrothermal performance while addressing the challenges of low mechanical strength and workability limitations through innovative biopolymer incorporation. Pinel et al. [72] first focused on achieving a controlled liquid-to-solid transition, enabling the poured earth material to gain sufficient strength to support its own weight within 24 h. Sodium alginate was added to naturally occurring calcium ions to induce internal gelation, which was enhanced by the gradual release of calcium from GDL as an acidifier. This system demonstrated compressive strengths sufficient for formwork removal 24 h after moulding. Furthermore, the addition of a dispersing agent, sodium hexametaphosphate (SHMP), to the alginate–earth mixture enhanced the workability of the concrete due to its calcium-chelating properties. The measured wet resistance was approximately 0.1 MPa, which, according to Pinel et al. [72],

is considered adequate for formwork removal in poured walls approximately 3 m high under controlled conditions.

Following this, Pinel et al. [112] demonstrated the feasibility of poured-earth construction incorporating alginate. A half-scale 1.5 m low concrete wall, which could support its own weight 1 day after pouring without a safety margin, was constructed by utilizing internal gelation of alginate. The study expanded the optimization to poured earth concrete by incorporating sand and gravel aggregates. This required additional adjustments to the water-to-binder ratio and the use of SHMP to ensure high workability while maintaining strength. The chemical composition of the aggregates plays a crucial role in determining the availability of calcium ions for gelation, thereby directly affecting the material's workability. As the source of calcium ions for gelation naturally exists in the clay binder and aggregates, large variability in ion availability was encountered, and as a result, the workability of the wet clay concrete samples was inconsistent. In this regard, the dispersing agent SHMP was found to be a key factor in maintaining a highly fluid mix with a constant setting time of more than 45 min, similar to that of ordinary Portland cement (OPC) concrete with the same properties.

Maierdan et al. [113] investigated the interaction of alginate with kaolinite clay for 3D-printed earth materials, focusing on how alginate altered particle interactions, suspension stability, and rheological properties. It was found that alginate significantly increased electrostatic repulsion between kaolinite particles, reducing sedimentation and improving the stability of the clay suspension. Initially, increasing alginate concentration decreased the yield stress, acting as a superplasticizer by preventing kaolinite particle flocculation. However, beyond a critical concentration (0.12–0.6 w/w% by dry soil mass), alginate formed a three-dimensional polymer network, leading to higher yield stress and increased flow resistance, which enhanced structural buildup and improved printability. While the study demonstrated that alginate improved the stability and workability of earth-based mixtures, its primary function was to modify rheology for 3D printing rather than act as a traditional binder for mechanical strengthening.

7. Ground Improvement

Studies in the literature were examined based on the primary target application of ground improvement, which could be the increase in mechanical strength, physical properties, or durability of Ca-alginate stabilized soils. The following sections are divided based on soil type (either sandy or clayey), where soils composed of more than 50% of sand were classified as sandy and vice versa. Systemic survey tables are presented for each treated soil type to identify the concentration, soil composition, treatment method, and tests performed in each study. Alginate concentration is expressed as a weight-to-weight percentage (w/w%) by dry weight of the soil mass.

7.1. Sandy Soils

Recent research has demonstrated the effectiveness of sodium alginate in enhancing sand stabilization through various application techniques, including biopolymer-assisted enzyme-induced carbonate precipitation (EICP), biopolymer-assisted microbially induced carbonate precipitation (MICP), and direct hydrogel formation. Table 7 details various studies investigating the use of alginate in sandy soils, focusing on different treatment methods, calcium sources, and testing parameters across a range of soil types. Most studies targeted mechanical improvement, particularly in poorly graded sands, with a few exceptions examining permeability reduction [71,114] and erosion control [115]. Wang et al. [14] utilized alginate as a thickener for a bacterial solution to induce carbonate precipitation rather than as a direct binder of soil particles and obtained enhanced UCS performance.

Table 7. Systematic survey of Ca-alginate-treated sandy soils.

SA Concentration (w/w of Dry Soil Mass%)	Primary Aim	Calcium Source and Gelation Method	Soil Type (USCS) and D50 (mm)	Treatment Method(s)	Variable(s) Studied	Test(s) Performed	Reference
(0.1%, 0.2%, 0.3%, 0.4%)	Mechanical Improvement	CaCl ₂ , External	SP (Poorly graded) Sand, 0.35	Wet Mixing	Concentration, Curing Time, and Temperature	UCS, CU Triaxial, Falling Head Permeability, Wet– Dry, Freeze–Thaw	[15]
(1%, 2%, 3%, 5%)	Mechanical Improvement	Soil, Uncontrolled	SP Sand, 0.18	Dry Mixing	Concentration, Curing Time, and Temperature	UCS	[16]
(0.5%, 1%, 2%)	Erosion Control	CaCl ₂ (EICP), Exter- nal	SP Sand, 0.24	Spraying	Concentration, Curing Time	Surface Strength, Wind Ero- sion Resistance	[115]
(1%, 2%)	Mechanical Improvement	CaCl ₂ , External	SW (Well- graded) Sand with Silt, 0.60	Wet Mixing	Concentration, Curing Time	UCS	[116]
(0.5%)	Physical Improvement	CaCl ₂ (EICP), Exter- nal	SP Sand, 0.62	Dry Mixing	Concentration	Constant Head Permeability	[114]
(0.5%, 1%, 2%, 3%, 5%)	Mechanical Improvement	Soil, Uncontrolled	SP Sand, 0.15	Dry Mixing	Concentration, Curing Time, and Temperature	UCS	[81]
(0.5%, 0.7%, 0.9%, 1.1%, 1.3%)	Mechanical Improvement	CaCl ₂ (MICP), Ex- ternal	SP Sand, N/A	Soaking	Concentration	UCS, Constant Head Per- meability	[14]
(0.25%, 0.5%, 2%)	Mechanical Improvement	Soil, Uncontrolled	SP Sand with Silt, 0.49	Wet Mixing	Concentration, Curing Time, Soil Type	UCS, Curing Time, Wet– Dry	[13]
(0.1%, 0.3%, 0.5%)	Physical Improvement	Soil, Internal	SP Sand, 0.94	Wet Mixing	Concentration, Curing Time	UCS, Falling Head Permea- bility, Water Erosion Re- sistance	[71]
(0.6%, 1.2%)	Mechanical Improvement	CaCl ₂ (EICP), Exter- nal	SP Sand, 0.36	Wet Mixing	Concentration, Curing Time, and Temperature	UCS, Wet–Dry	[117]
(0.3%, 0.4%, 0.5%)	Mechanical Improvement	CaCl ₂ , External	SP Sand, 0.51	Wet Mixing	Concentration, Curing Time, and Temperature	UCS, Consolidated Drained (CD) Triaxial	[118]
(1.4%, 2.3%, 4.6%, 8%, 10%)	Mechanical Improvement	CaCl ₂ , External	SP Sand, 0.21	Dry Mixing, Wet Mixing	Concentration, Alginate Type, Mixing Method	UCS, Wet–Dry	[108]

Figure 6A, compiled from 26 datapoints from five independent studies, illustrates the general relationship between sodium alginate concentration and the corresponding UCS observed in sandy soil samples. A positive trend is observed, with higher alginate dosages resulting in greater increases in UCS. A linear fit ($R^2 = 0.873$) is shown for illustrative purposes; the scatter around the trendline reflects methodological variability across studies (e.g., differences in soil type, alginate sources, curing techniques, and alginate application). This compilation aims to reinforce the conclusion that alginate functions as a binder, forming continuous polymer networks that strengthen soils. However, accurate functional relationships remain bound by contextual factors. In Fatehi et al. [13], UCS initially increases with alginate concentration but then decreases after peaking at 1 w/w% of dry soil mass. While the study reported the highest gains in UCS, this discrepancy is likely due to the inclusion of up to 25% kaolinite clay in their sand samples. Castro et al. [108] uniquely investigated the effects of various sodium alginate powders and mixing methods on the UCS of coastal sand. The study reported negligible impacts of mixing method on the strength of sand samples at concentrations less than 5 w/w%. However, alginate with higher residual calcium resulted in a 44% increase in UCS (0.9 MPa) relative to other types of alginates tested.

The effect of curing time on the compressive strength of alginate-treated sandy soils has been examined in six studies, with the results presented in Figure 6B. Increasing curing time generally enhances UCS up to a certain threshold. The influence of curing duration appears to depend significantly on the mixing technique and gelation mechanism employed. Studies utilizing dry mixing with uncontrolled gelation, such as those by Fatehi et al. [16], Fatehi et al. [13], and Lemboye et al. [81], consistently report strength stabilization around 14 days, with minimal gains thereafter. In contrast, wet mixing and external gelation approaches, including those by Wen et al. [15] and Li et al. [117], display more inconsistent responses with UCS, either increasing progressively with time or reaching an early peak within 7 days. These contrasting behaviours suggest that gelation pathways and polymer-soil interaction dynamics may govern the time-dependent evolution of strength. Further controlled studies are warranted to isolate and quantify the individual effects of gelation method and mixing approach on UCS development.

The effect of curing temperature on compressive strength development in alginate-treated sandy soils has been investigated in four studies, with results summarized in Figure 6C. Likewise, a general increase in curing temperature to approximately 35–50 °C is associated with improved UCS performance. However, the impacts of application methods are less discernible. Wen et al. [15] and Li et al. [117], both employing wet mixing and external gelation via direct CaCl_2 application, reported UCS gains continuing up to 50 °C. In contrast, Arab et al. [118], who also used external gelation but via enzymatically induced calcium precipitation (EICP), observed peak UCS at approximately 35 °C. The differing thermal response in this case may be attributed to the enzymatic sensitivity to elevated temperatures, which can reduce urease activity and limit calcium availability. Lemboye et al. [81], using dry mixing and uncontrolled gelation, recorded peak strength at higher curing temperatures than Fatehi et al. [16], despite comparable application conditions. This discrepancy likely reflects variations in alginate properties or the mineralogical composition of the treated sand samples, both of which influence gelation kinetics and strength development at elevated temperatures.

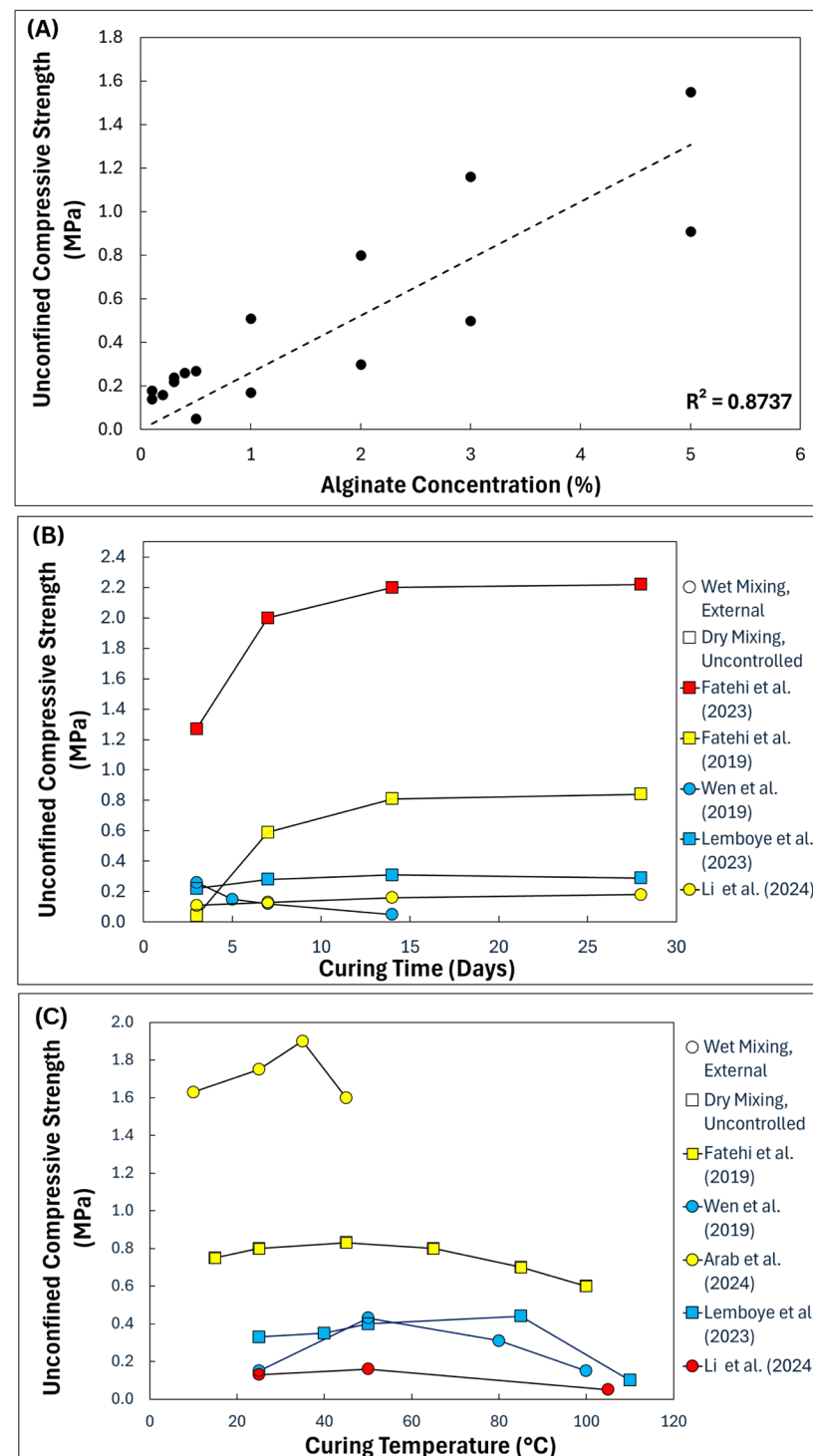


Figure 6. (A) UCS vs. concentration of alginate at optimal curing conditions, linear regression analysis fitted to data, (B) UCS vs. curing time at optimal concentrations and curing temperatures of alginate [13,15,16,81,117], (C) UCS vs. curing temperature in sandy soils at optimal concentrations and curing times of alginate [15,16,81,117,118]. Note: Data points are compiled from methodologically heterogeneous studies. The linear fit is presented to illustrate a general positive trend and is not a predictive model. The alginate concentration unit is w/w% of the dry soil's mass.

7.2. Alginate-Clay Interactions

The efficacy of alginate as a clay soil stabilizer is fundamentally governed by its interactions with specific clay minerals, which dictate resultant hydro-mechanical behaviour. For expansive smectite clays like montmorillonite, SA can form composite matrices

where the biopolymer interacts with clay surfaces through hydrogen bonding and electrostatic forces [119]. Studies on SA-montmorillonite composites for adsorption indicate a special mechanism where alginate gel can bind to external surfaces and facilitate interlayer adsorption at higher concentrations [119]. This interaction suggests that alginate treatment could restrict interlayer water uptake and limit swelling, while simultaneously reducing permeability by clogging pore networks. This observation is supported by molecular dynamics simulations, which indicate that alginate polymers adsorb onto clay-like surfaces primarily through hydrogen bonding and van der Waals forces, providing reasoning for the observed modification of plasticity and swelling [120]. For kaolinite, the interaction is highly sensitive to pore water chemistry: SA acts as a dispersant in the presence of monovalent Na^+ or Mg^{2+} but becomes a flocculant when cross-linked by divalent Ca^{2+} or trivalent Al^{3+} ions [121]. This ion-dependent flocculation mechanism controls clay permeability and shear strength development.

7.3. Clayey Soils

Calcium alginate has been increasingly investigated for soil stabilization, demonstrating improvements in strength, durability, and swelling reduction across various soil types and treatment methods. Table 8 summarizes the research on the application of sodium alginate for clayey soils, including both clay and silt. The most common application is subgrade stabilization [17,79,120,122], although swelling reduction [18,74,80] and general mechanical reinforcement [10,13] have also been explored. Alginate concentrations ranged from 0.1 w/w% to 4 w/w% of dry soil mass. Calcium sources were primarily internal (i.e., calcium already present in the soil), except for Liu et al. [18], who externally added CaCl_2 . Treatment methods varied, including wet mixing, dry mixing, spraying, and soaking. Studies involving highly plastic clays ($\text{PI} > 40\%$) emphasized swelling reduction and shrinkage control, while those using medium plastic silts ($\text{PI} \approx 15\%$) were more focused on mechanical properties like UCS and shear behaviour.

Table 8. Systematic survey of Ca-alginate-treated clayey soils.

SA Concentration (w/w% of dry soil mass)	Primary Aim	Calcium Source and Gelation Method	Soil Type(s) (USCS)	Treatment Method(s)	Variable(s) Studied	Test(s) Performed	Reference
(1%, 2%, 3%, 4%)	Subgrade Stabilization	CaCl_2 , External	ML (Low plasticity Silt) $\text{PI} = 7.7\%$, CH (Fat Clay) $\text{PI} = 35.8\%$	Wet Mixing, Dry Mixing	Concentration, Curing Time, Treatment Method, Soil Type	UCS, Compaction, Repeated Loading Triaxial	[122]
(0.5%, 1%, 2%, 3%)	Subgrade Stabilization	Soil, Uncontrolled	ML $\text{PI} = 7.6\%$	Dry Mixing	Concentration, Curing Time, Treatment Type	UCS, UU (Unconsolidated Undrained) Direct Shear, Compaction, Wet-Dry	[79]
(0.5%, 1%, 1.5%, 2%, 3%, 4%)	Subgrade Stabilization	Soil, Uncontrolled	CL (Lean Clay) $\text{PI} = 15.8\%$	Dry Mixing	Concentration, Soil type	Compaction, UU Triaxial, California Bearing Ratio (CBR)	[123]
(0.25%, 0.5%, 0.75%, 1%, 1.25%)	Surface Stabilization	Soil, Uncontrolled	CH $\text{PI} = 41\%$	Soaking, Spraying	Concentration, Curing Time, Treatment Method	UCS, Failure Mode	[124]

(0.25%, 0.5%, 0.75%, 1%, 1.5%)	Mechanical Enhancement	CaCl ₂ , External	MH (High plasticity Silt) PI = 16%	Wet Mixing	Concentration, Soil Type	UCS, UU Triaxial	[13]
(0.1%, 0.2%, 0.3%, 0.4%)	Swelling Reduction	CaCl ₂ , External	CH PI = 41%	Wet Mixing	Concentration	UCS, Consolidated Undrained (CU) Triaxial, Swelling, Wet-Dry, Freeze-Thaw	[18]
(1%, 2%, 3%, 4%)	Mechanical Enhancement	Soil, Uncontrolled	MH PI = 14.5%	Wet Mixing	Concentration, Curing Time	UCS, Compaction, Atterberg Limits	[10]
(0.25%, 0.5%, 0.75%, 1%, 1.25%)	Swelling Reduction	Soil, Uncontrolled	CH PI = 41%	Wet Mixing, Spraying	Concentration, Curing Time, Treatment Method	Atterberg Limits, Compaction, Free Swelling	[74]
(1%, 2%, 4%)	Swelling Reduction	Soil, Uncontrolled	ML PI = 15.4%, CH PI = 39.7%	Wet Mixing, Dry Mixing	Concentration, Soil Type, Treatment Method	Compaction, Loaded Swell (LS), CU Triaxial	[80]
(0.25%, 0.5%, 1%, 1.5%, 2%)	Subgrade Stabilization	CaCl ₂ , External	CH PI = 63.4%	Wet Mixing	Concentration	UCS, Compaction	[17]

An analysis is conducted to evaluate the relationship between alginate concentration and UCS improvement across multiple studies on alginate-treated clay soils. The compiled dataset comprises 27 data points, with changes in UCS expressed as the percentage difference relative to untreated controls. Due to variability in alginate sources, soil types, curing conditions, calcium sources, and gelation methods, a non-parametric Spearman rank correlation is used to assess the strength and direction of the monotonic relationship. The analysis yields Spearman's correlation coefficient of $\rho = 0.545$ and is statistically significant ($p = 0.00125$), with a 95% confidence interval of [0.24, 0.75]. The correlation suggests a moderately strong tendency for UCS to improve with increasing alginate concentrations. Figure 7A presents the concentration–performance relationship, although the strength of the effect is greatly influenced by specific experimental conditions relative to each set of datapoints.

In their experiments, Zha et al. [79], Temurayak and Eskisar [10], and Azimi et al. [17] identified an optimal sodium alginate (SA) concentration at which maximum compressive strength was achieved. Conversely, Fatehi et al. [13] observed a continuous increase in UCS across all tested concentrations, suggesting that an optimum may not have been captured within the tested range. However, comparable concentration ranges studied by Bakhshizadeh et al. [124] and Liu et al. [18] yielded divergent outcomes. Bakhshizadeh et al. [124] reported an initial reduction in UCS with increasing SA concentrations (up to 0.75 w/w%), followed by a subsequent increase in UCS, an effect potentially attributed to early-stage gel interference with natural compaction, eventually offset by more effective particle bridging at higher dosages. In contrast, Liu et al. [18] observed a consistent decline in UCS with rising SA content. Their use of external gelation in a dense, low-permeability, high-plasticity clay (PI = 41) may have led to incomplete calcium ion diffusion and heterogeneous gel formation, thereby weakening interparticle bonds at higher concentrations. While both studies employed similar concentration ranges and clay types, their opposing outcomes underscore the influence of initial soil properties, gelation method, and polymer–soil interaction on UCS response. While a moderate to strong monotonic relationship between SA concentration and UCS is supported by the data, the inconsistency of trends across studies suggests that other influencing variables, such as soil plasticity, curing conditions, or gelation method, may play a critical role. With most studies using a wet mixing approach, it is not possible to deduce the impacts of mixing on strength gains. However,

as illustrated in Figure 7B, the highest UCS improvements are observed in high-plasticity silts (MH), reaching increases up to 350%, while high-plasticity clays (CH) exhibit more moderate gains. Although these findings suggest that high clay presence could interfere with the alginate crosslinking mechanisms, further research is needed to confirm this trend. Notably, Arab et al. [122] remains the only study to directly compare UCS improvements in low-plasticity silt (ML) and high-plasticity clay (CH) under controlled conditions, reporting higher strength gains in the latter. Additional studies involving a broader range of soil types, particularly low plasticity silt and clay-classified soils, are recommended to validate this observation.

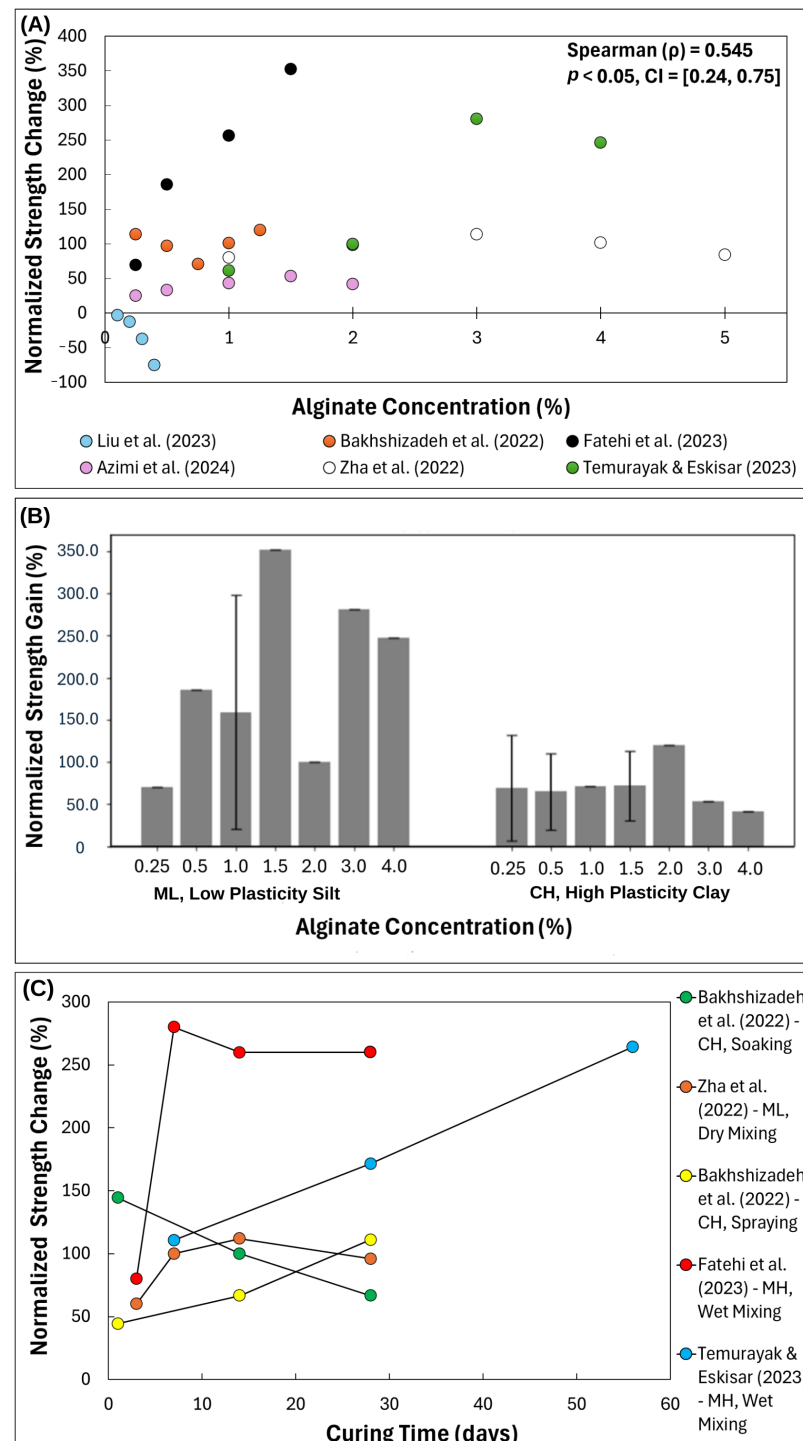


Figure 7. (A) Normalized change in UCS vs. concentration of alginate at optimal curing conditions in clayey soils [9,13,17,18,79,124], (B) Normalized change in UCS vs. increasing concentrations of

alginate in clayey soils at optimal curing conditions, (C) Normalized change in UCS vs. increasing curing time at optimal concentrations and curing temperatures [9,13,79,124]. Note: Data points are compiled from methodologically independent and heterogeneous studies. The correlation coefficient is used to highlight the monotonic trend. The alginate concentration unit is w/w% of the dry soil's mass.

The effect of curing time on compressive strength development in alginate-treated clayey soils has been examined across several studies, with results presented in Figure 7C. While longer curing generally improves UCS, the rate and magnitude of strength gains vary significantly depending on gelation control, application technique, and soil characteristics. Fatehi et al. [13], employing external gelation via CaCl_2 in an MH soil, reported UCS stabilization by 14 days. In contrast, Temurayak and Eskisar [10], using wet mixing under uncontrolled gelation in a similarly classified MH soil, observed continued increases in UCS through 56 days, suggesting extended gelation kinetics and polymer–soil interactions. Zha et al. [79], through dry mixing and uncontrolled gelation in an ML soil, observed a strength peak at 14 days, likely due to more rapid pore stabilization and limited ion exchange in the low-plasticity matrix. Bakhshizadeh et al. [124] further highlight the importance of application technique by comparing soaking and spraying approaches in the same CH soil, both under uncontrolled gelation. The soaking condition produced a sharp UCS peak at 1 day, followed by a decline at 14 and 28 days, possibly due to rapid saturation and structural softening from excess moisture. In contrast, the spraying method yielded a delayed but progressive increase in strength, with the UCS reaching its maximum at 28 days. These outcomes suggest that the mode of polymer delivery influences the rate of water interaction, gel dispersion, and curing uniformity. The discrepancy in results from studies using uncontrolled gelation indicates that application technique, rather than gelation mode alone, also plays a decisive role in shaping strength development timelines. A lack of studies on the impact of curing temperature on the compressive strength of clayey soils was encountered. The only study to have measured this effect is Zha et al. [79], who reported UCS increases of over 100% up to 50 °C, beyond which UCS gains diminish.

The relationship between sodium alginate concentration and compaction properties, namely maximum dry density (MDD) and optimum water content (OWC), is shown in Figure 8A,B. Spearman's rank correlation was employed to quantify monotonic relationships without assuming normality of the data. A moderate negative correlation was found between SA concentration and change in MDD ($\rho = -0.525$, $p < 0.05$, 95% CI $[-0.79, -0.11]$), while a moderate positive correlation was observed with change in OWC ($\rho = 0.551$, $p < 0.05$, 95% CI $[0.14, 0.80]$). These results indicate that, in general, higher SA concentrations lead to lower dry densities and higher water contents required for optimal compaction. It should be noted that these analyses serve as illustrative examples rather than comprehensive correlational models. The variability in methodological conditions amongst studies, including the specific clay type and mineralogy, alginate type and application method, curing regime, and testing techniques, must all be accounted for to accurately detail the relationship between alginate concentration and the MMD and OWC of clay samples.

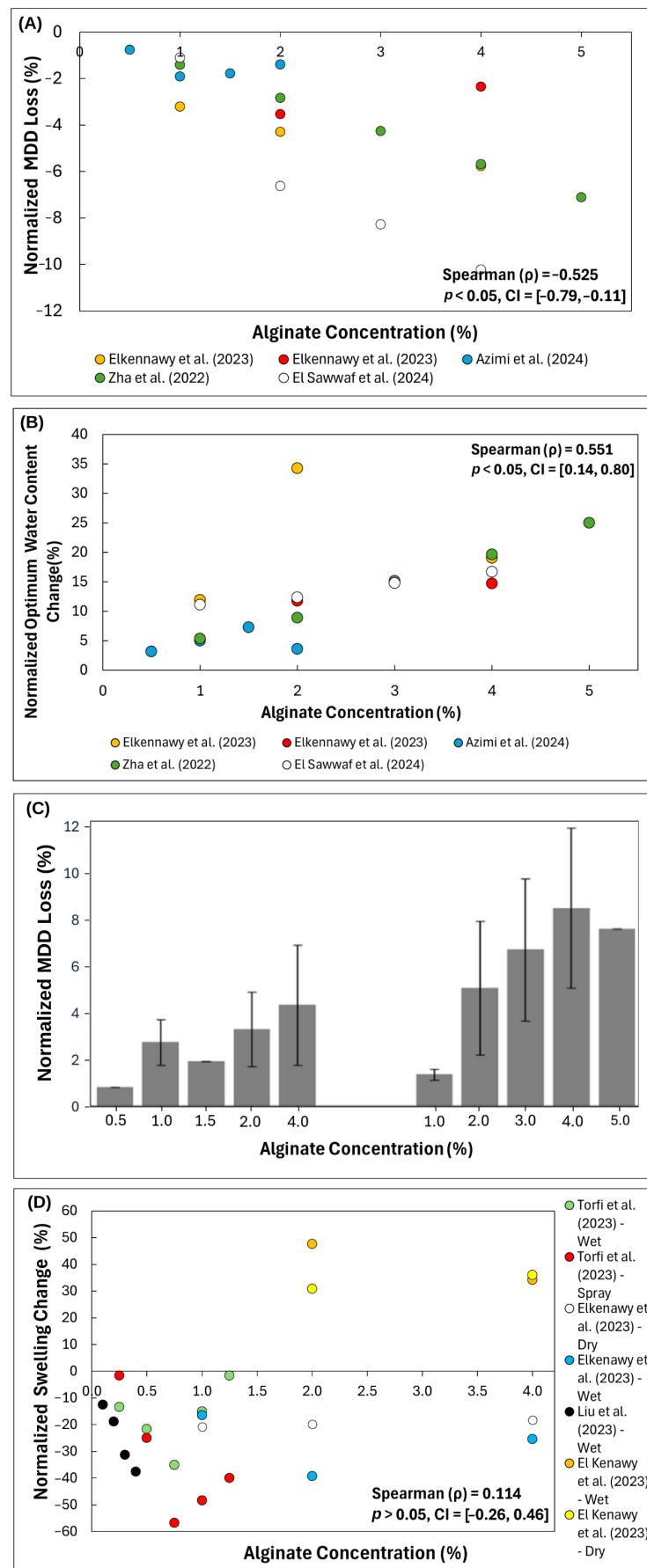


Figure 8. (A) Change in maximum dry density with increasing concentrations of SA in clayey soils at optimal curing [17,79,80,123], (B) Normalized change in optimal water content vs. concentration

of SA in clayey soils at optimal curing conditions [17,79,80,123], (C) Normalized change in maximum dry density vs. concentration of SA in clayey soils at optimal curing conditions by mixing method, (D) Normalized change in swelling vs. concentration of SA in clayey soils at optimal curing conditions [18,74,80]. Note: Data points are compiled from methodologically independent and heterogeneous studies. The correlation coefficient is used to highlight the monotonic trend.

Across all soil types, mixing method consistently emerges as the dominant factor influencing changes in maximum dry density (MDD), as shown in Figure 8C. Studies employing dry mixing, such as Zha et al. [79] and El Sawwaf et al. [123], reported the largest reductions in MDD (up to -10.22%), regardless of soil plasticity. The likely mechanism involves uneven distribution of sodium alginate (SA) and rapid water uptake upon compaction, which promotes the formation of bulky gels and pore expansion, disrupting soil particle packing. In contrast, wet mixing yielded more moderate reductions or even gains in MDD. For instance, Arab et al. [122] reported a rare increase in MDD ($+3.29\%$) using external CaCl_2 gelation with wet mixing, suggesting that controlled gelation and uniform particle coating can enhance packing efficiency. Azimi et al. [17], who also employed wet mixing with external gelation, reported minimal MDD reductions (-1.4% to -1.9%), reinforcing this stabilizing effect. However, despite using wet mixing, Elkenawy et al. [80] reported larger MDD reductions (as low as -5.77%), likely due to their use of uncontrolled gelation, which may result in premature swelling and less uniform polymer dispersion.

Regarding OWC, the increase is more pronounced in high-plasticity soils under uncontrolled gelation, as reported by Elkenawy et al. [80], who observed up to a 34% increase in OWC in CH soils. This is consistent with alginate's water affinity and swelling capacity, which elevate the moisture demand during compaction. The modest OWC increase in external gelation studies supports the interpretation that controlled crosslinking of alginate gels limits water availability and gel expansion, leading to more compacted matrices. In summary, while increasing SA content generally reduces MDD and increases OWC, these effects are strongly modulated by application technique, gelation method, and soil type. These findings suggest that while the mixing method plays a central role, gelation control may also modulate the compaction response. Therefore, a controlled study isolating the influence of gelation and mixing processes could be useful to disentangle their individual and interactive effects on compaction behaviour.

Swelling reduction in alginate-treated clays showed high variability across studies, with no statistically significant monotonic correlation found between concentration and swelling change (Spearman $\rho = 0.114$, $p > 0.05$, $\text{CI} = [-0.26, 0.46]$), as shown in Figure 8D. This weak non-parametric association highlights the complex interplay between alginate concentration and soil response, influenced by factors such as application method, gelation control, and soil plasticity. Among the datasets, Torfi et al. [74] reported the greatest reduction in swelling (as low as -56.7%), notably under spraying application on CH clay. This high variability could be explained by the clay-specific mechanisms detailed in Section 7.2. The potential for alginate to restrict interlayer water uptake in expansive smectites (such as montmorillonite in CH clays) could lead to significant swell reduction, whereas its primary effect on lower-activity clays would be fabric modification, resulting in more inconsistent outcomes. Compared to wet mixing on the same soil type, spraying produced more consistent and substantial reductions, likely due to its ability to ensure more uniform surface coating and delay premature hydration, thus enhancing the effectiveness of alginate distribution and particle interaction. This underscores the importance of application techniques in swelling control. Most studies in the dataset were conducted on CH clays. However, Elkenawy et al. [80] uniquely included both CH and ML soils. In his ML cases, the addition of alginate led to positive swelling values (up to 47.7%), in contrast to the consistent reduction observed in CH. This divergence may reflect the

higher permeability and lower surface activity of ML soils, which diminishes alginate's ability to form stable gels. These contrasting outcomes emphasize the need for more investigations across diverse soil types, especially LP silts and CL clays, to generalize the effectiveness of alginate treatment in mitigating swelling.

A general lack of study on the influence of alginate on the Atterberg limits of clayey soils was encountered. Torfi et al. [74] and Temurayak and Eskisar [10], using similar alginate application methods on differing clay types, were the only studies to gauge the impact of alginate concentration on Atterberg limits. While both experiments resulted in comparable trends to the plasticity index of soil samples, with liquid limits increasing and minimal change to plastic limits, it is not possible to verify the consistency of their findings due to data insufficiency. Contrarily, Arab et al. [122] measured Atterberg limit changes for single concentrations of alginate across varying soil types and found a decrease in the plasticity index for all soil samples tested.

A limited number of studies have investigated the effect of alginate concentrations on the modulus of elasticity of clayey soils. With different soil types and methods of alginate application, it is not possible to deduce any trends. Fatehi et al. [13] found a significant increase in elasticity at the highest alginate concentration studied (1.5 w/w%), which was greater than two-fold that of the lowest concentration of alginate tested (100% increase at 0.25 w/w%). El Sawwaf et al. [123] encountered dissimilar results, with the elastic modulus of their clayey sample decreasing linearly with increasing concentrations of alginate (−30% at 4 w/w%). On the other hand, Elkenawy et al. [80] managed to obtain an optimal value for improvement in the elasticity of their sample at 2 w/w% alginate.

As shown in Figure 9, more reliable trends are observed in the triaxial shear strength parameters of alginate-treated clayey soils. Cohesion generally tends to increase regardless of alginate concentration and experimental conditions, with the largest gains reported by El Sawwaf et al. [123] at over 150% increase at 4 w/w% alginate. This strengthening can be attributed to the fundamental alginate-clay interactions described in Section 7.2, where ionic bridging and the formation of a composite matrix enhance interparticle bonding.

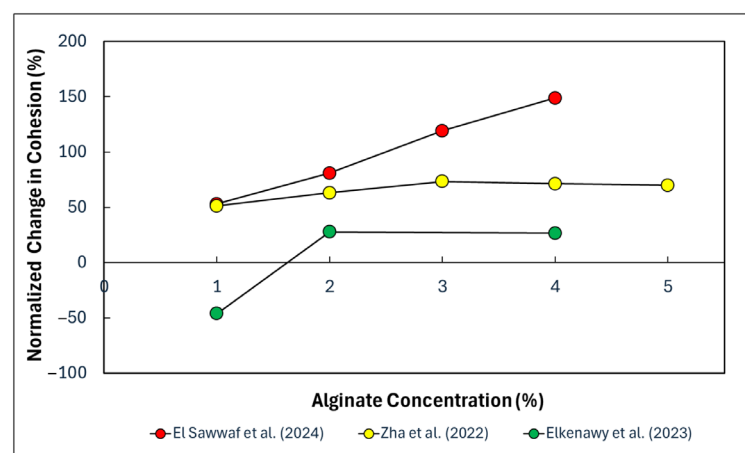


Figure 9. Normalized change in cohesion based on shear testing of alginate-treated clayey soil samples vs. alginate concentration [18,79,123].

8. Cement Mixtures

The integration of alginate into cementitious materials has been investigated by various authors. The most employed application of alginate is to facilitate self-healing of cracks and defects through encapsulation of bacterial strains for controlled release upon cracking. Alginate concentration is expressed as a weight-to-weight percentage (w/w%) by weight of the cementitious binder.

8.1. Comparison of Biopolymers

The performance of SA is contextualized by other natural polymers used as sustainable cement admixtures, each with distinct rheological behaviours and dosage-dependent effects. Cellulose-derived polymers primarily act as physical thickeners and water retainers. Their effectiveness increases linearly with dosage but plateaus, and excessive amounts significantly retard setting, a key limitation compared to SA's ionic gelation [125,126]. Microbial polysaccharides, like xanthan gum, exhibit high efficiency, where minimal dosages (0.05–0.2%) drastically increase yield stress and viscosity. However, beyond a critical point, their effect diminishes, and they do not exhibit ionic gelation like SA [127,128]. Other ionic biopolymers, such as chitosan and carrageenan, also show strong dosage-dependent gelling. Still, chitosan requires acidic dissolution, complicating its use in cement, while carrageenan's gelling is highly ion-specific [129,130]. In summary, while these biopolymers modify rheology in a dosage-sensitive manner, SA's unique advantage is its controllable, calcium-activated ionic crosslinking. This makes it uniquely suited for applications requiring in situ gelation, whereas cellulose and microbial gums are preferred for predictable physical thickening and stabilization.

8.2. Case Study Results

Table 9 presents a range of studies exploring alginate's application in cementitious systems, with a primary focus on self-healing in OPC matrices through microbial encapsulation. Most studies adopted microbial-induced calcium carbonate precipitation (MICP), using bacterial strains such as *Bacillus* spp. while one study utilized *Lysinibacillus sphaericus* [131]. Encapsulation was consistently used to protect microbial viability during mixing, with sodium alginate concentrations ranging from as low as 0.1 w/w% of cementitious binder [132] to as high as 25 w/w% [133], reflecting different performance goals and microbial loading requirements. While most studies used MICP, Feng et al. [74] employed polyethylene glycol as the encapsulant, signalling an interest in non-biological healing approaches. Variables such as curing time, capsule composition, and mixture content were commonly studied to optimize healing and mechanical recovery.

Table 9. Systematic survey of Ca-alginate-treated cement mixtures.

SA Concentration (w/w% of Cementitious Binder)	Primary Aim	Calcium Source and Gelation Method	Material Type	Treatment Method(s)	Variable(s) Studied	Test(s) Performed	Reference
(2.53%)	Microbial Self-healing	CaCl ₂ , External	OPC	MICP, <i>Bacillus pseudofirmus</i> Encapsulation	Concentration, Curing Time, Capsule Composition	Healing	[134]
(0.1%, 0.2%)	Hydration Enhancement	Cement, Internal	Calcium Aluminate Cement	Dry Mixing	Concentration	Compression, Tensile	[135]
(1%, 1.5%, 2%)	Microbial Self-healing	CaCl ₂ , External	OPC, Sand	MICP, <i>Bacillus sphaericus</i> Encapsulation	Concentration, Mixture Composition	Flexure, Tensile	[136]
(0.5%, 1%)	Microbial Self-healing	CaCl ₂ , External	OPC, Sand	MICP, <i>Bacillus sphaericus</i> Encapsulation	Concentration, Capsule Composition	Compression, Tensile, Water Absorption	[137]
(5%, 10%)	Ca-alginate Self-healing	Cement, Internal	OPC, Sand, Polyethylene Glycol	Sodium Alginate Encapsulation	Concentration, Healing Time	Compression, Flexure, Permeability	[74]

(0.5%, 1%)	Microbial Self-healing	CaCl ₂ , External	OPC, Sand	MICP, Lysinibacillus sphaericus Encapsulation	Concentration	Compression, Flexure	[131]
(10%, 15%, 25%)	Microbial Self-healing	CaCl ₂ , External	Portland Pozzolana Cement, Sand	MICP, Bacillus megaterium Encapsulation	Concentration, Mixture Composition	Compression	[133]
(0.1%)	Microbial Self-healing	Cement, Internal	OPC, Sand	MICP, Bacillus sphaericus Encapsulation	Capsule Composition	Compression	[132]

Cruz et al. [131] incorporated sodium alginate capsules containing *Lysinibacillus sphaericus* to induce biomineralization-based crack healing. Their formulation, incorporating up to 1 w/w% capsules, resulted in workable mortars (flow around 190–194 mm) and maintained flexural and compressive strengths statistically equal or superior to the reference mortar after 91 days. Their method preserved bacterial viability and facilitated CaCO₃ precipitation, allowing cracks to self-seal while maintaining the mortar's original rheological and mechanical properties. Fahimizadeh et al. [134] similarly encapsulated non-ureolytic bacteria in alginate hydrogels for self-healing cement paste and mortar. Their results showed a flexural strength regain of up to 39.6% for mortar and 32.5% for cement paste after 56 days, demonstrating alginate's effectiveness in protecting bio-agents while facilitating crack healing of cracks initially ~1 mm wide that shrink to 0.1–0.3 mm, with complete closure observed at 28 days. In a related approach, Risdanareni et al. [132] immobilized *Bacillus sphaericus* spores in alginate-coated alkali-activated lightweight aggregate. Their study found that while the coating prevented bacterial leakage and improved crack healing efficiency at 90 days, achieving 100% closure for cracks of 0.3–0.4 mm, it also led to an 11% decrease in compressive strength, emphasizing a trade-off between healing performance and mechanical properties. Further advancing microbial self-healing applications, Rong et al. [136] utilized sodium alginate as a carrier for microbial repair materials. Their coating-based approach facilitated the formation of a calcium alginate-CaCO₃ composite within cracks, leading to a 67% reduction in surface water absorption after repair, demonstrating significant improvements in durability for cracks with an average width of approximately 0.2 mm. Similarly, Soda et al. [133] explored cement-coated alginate beads (CCAB) containing *Bacillus megaterium* to induce calcite precipitation. Their results indicated that replacing 20% of fine aggregate with CCAB (containing 5% nano-silica) was optimal, achieving 93.96% crack healing efficiency while maintaining structural performance for cracks averaging 0.13 to 0.25 mm in width. Wang et al. [137] also employed modified-alginate encapsulated bacteria for crack self-healing, demonstrating 70% CaCO₃ precipitation efficiency within the hydrogel and a reduction in mortar compressive strength of 16–23% with a 1 w/w% hydrogel dosage. Meanwhile, Feng et al. [74] introduced a novel self-sealing approach using in situ calcium alginate crosslinking. By embedding sodium alginate in polyethylene glycol granules within mortar specimens, their system allowed for the formation of hydrogels upon cracking, effectively sealing macro-cracks up to 4 mm wide within one day and drastically reducing water permeability by achieving complete closure of 1–4 mm wide cracks. Research has also explored alginate's chemical interactions with cement hydration processes. Engbert et al. [135] investigated the hydration of calcium aluminate cement (CAC) in the presence of sodium alginate. Contrary to expectations, they found that alginate acted as an accelerator, promoting earlier heat release and increasing early-stage strength. Their analysis suggested that alginate's strong calcium ion complexation promoted the formation of C-A-H phases, enhancing cement setting and early strength development.

Adding alginate into cementitious systems creates significant microstructural changes that underpin the observed macro-scale improvements in mechanical

performance, durability, and self-healing. These modifications occur through several interconnected mechanisms. When used as a capsule for healing agents like bacteria or as a direct additive, the resulting hydrogel effectively fills pores and microcracks. Scanning Electron Microscopy (SEM) analyses reveal that this leads to a denser, more homogeneous matrix, which is a direct contributor to reduced permeability and enhanced durability [136]. Secondly, alginate creates a bridging interface between the additive and the cement hydrate phases. This interfacial zone enhances bonding and cohesion within the composite, improving stress transfer and overall mechanical integrity [138]. Similarly, in microbial repair, sodium alginate forms a mixed matrix of calcium alginate and calcium carbonate that closely adheres to crack walls, allowing for durable repair [136].

8.3. Variability of Results

The literature on alginate in cementitious materials shows significant contradictions. These discrepancies likely stem from the complex interplay between the biopolymer's intrinsic properties and the challenging environment of a hydrating cement matrix. Unreported alginate sources and compositional variability are major contributing factors. These parameters, which are rarely characterized in these studies, create a primary source of irreproducible results. This directly manifests in contradictory experimental findings regarding mechanical strength. For instance, while some self-healing studies report that alginate capsules maintain compressive strength [131,133], others document significant strength reductions of 11–23% [132,137]. Another factor could be the ionic cementitious environments rich in Ca^{2+} , creating complex competitive interactions. As demonstrated by Li et al. [139], low SA dosages (<0.01 g) can improve particle dispersion via synergy with superplasticizers, while higher dosages (>0.2 g) worsen dispersion and increase viscosity. Contradictory mechanical and physical outcomes are therefore highly probable to be a direct consequence of studies using different, uncharacterized commercial alginate blends and the high Ca^{2+} concentrations present in cement prematurely crosslinking calcium alginate beads, diminishing their designed swelling capacity.

9. Asphalt Mixtures

Several studies have explored the use of alginate in asphalt applications, focusing on its role in encapsulating rejuvenators and oils to enhance durability, fatigue resistance, and self-healing properties. Table 10 compiles a range of investigations that use sodium alginate (SA) to encapsulate oils or rejuvenators in asphalt binders. Each entry lists the SA concentration, asphalt material type, the treatment method, key variables studied, and the tests performed. The majority of studies examine how altering the percentage of alginate in the mixture affects the binder's mechanical behaviour or thermal stability. Meanwhile, others vary the asphalt grade or introduce basalt fibres to test their effects on crack healing and fatigue damage reduction. To assess mechanical and self-healing performance, most studies employed standard testing methods for asphalt or polymer-modified mixtures, including indirect tensile strength (ASTM D6931 or equivalent), flexural testing of beam specimens (e.g., three-point bending, adapted from ASTM D790 or comparable methods), and fatigue tests, typically under cyclic or static loading conditions depending on the study. Some studies adopted more specialized procedures (such as linear amplitude sweep (LAS) as per AASHTO TP 101 and multiple creep stress recovery (MSCR) as per AASHTO T350) to capture nuanced viscoelastic responses under cyclic or thermal loading. Significant methodological variations exist that complicate comparability, due to differences in loading rates, test temperatures, specimen geometries, and healing approaches. These differences must be considered when interpreting the compiled results. Alginate concentration is expressed as a weight-to-weight percentage (w/w%) by weight of the asphalt/bituminous binder.

Table 10. Systematic survey of Ca-alginate-treated asphalt concrete.

SA Concentration (w/w% of Total Binder)	Primary Aim	Crosslinker and Gelation Method	Material Type	Treatment Method	Variables Studied	Tests Performed	Reference
(0.1%, 0.25%, 0.5%)	Oil Self-Healing	CaCl ₂ , External	Asphalt AC-20, Bitumen, Limestone Aggregate	Oil Encapsulation	Concentration, Temperature	3PB, Fracture Loading, UCS, Thermal Stability	[140]
(0.5%)	Oil Self-Healing	CaCl ₂ , External	Asphalt Binder AC-13	Oil Encapsulation	Bead Usage, Bead Contents	3PB, Fatigue Loading, Thermal Stability	[141]
(0.5%)	Oil Self-Healing	CaCl ₂ , External	Stone Mastic Asphalt	Oil Encapsulation	Healing Time, Temperature	Indirect Tensile, Fatigue Loading	[142]
(2%)	Rejuvenator Self-Healing	CaCl ₂ , External	Asphalt Binder 70#	Rejuvenator Encapsulation	Fibre Type	3PB, Tensile Stress-Recovery, Fatigue Loading, Thermal Stability	[143]
(1%, 3%, 5%)	Rejuvenator Self-Healing	CaCl ₂ , External	Asphalt Binder 70#	Rejuvenator Encapsulation	Concentration, Treatment Type	Tensile Stress-Recovery, Thermal Stability	[144]
(0.5%)	Oil Self-Healing	CaCl ₂ , External	Asphalt Binder 70#, Basalt Aggregate	Oil Encapsulation	Temperature	3PB, Fatigue Loading	[69]
(5%, 10%, 15%)	Rejuvenator Self-Healing	CaCl ₂ , External	Asphalt Binder (Various Grades)	Rejuvenator mixture	Concentration, Binder Grade	3PB, Tensile, Fracture Resistance, Dynamic Shear Rheometer, MSCR, LAS	[145]
(0.25%, 0.5%, 0.75%, 1%)	Oil Self-Healing	CaCl ₂ ,	Asphalt AC-20, Bitumen, Limestone Aggregate	Oil Encapsulation	Concentration, Capsule Contents	Indirect Tensile, Fatigue Loading, Dynamic Creep	[146]
(0.5%)	Oil Self-Healing	CaCl ₂ , External	Asphalt AC-13, Basalt Aggregate	Oil Encapsulation	Treatment Time	3PB, Fracture Loading, UCS, Thermal Stability	[147]
(3%, 5%, 10%)	Rejuvenator Self-Healing	CaCl ₂ , External	Asphalt Binder (Various Grades)	Rejuvenator Encapsulation	Concentration, Binder Grade	MSCR, LAS	[148]

Studies investigating oil encapsulation in asphalt aimed at improving self-healing and fracture resistance. Al-Mansoori et al. [140] tested alginate at 0.1–0.5 w/w% of total binder in AC-20 asphalt with limestone aggregates, demonstrating that alginate enhanced thermal stability and fracture resistance, as confirmed through 3PB and compression tests. Similarly, Zhang et al. [141] examined 0.5 w/w% alginate in AC-13 asphalt, reporting fatigue resistance improvements and higher retention of encapsulated oil. Norambuena-Contreras et al. [142] extended this by testing stone mastic asphalt (0.5 w/w%), showing that oil encapsulation significantly improved healing times, particularly under elevated temperatures, as confirmed through indirect tensile and fatigue loading tests. Meanwhile, Bao et al. [69] applied 0.5 w/w% alginate in asphalt binder 70# with basalt aggregates, revealing that encapsulated oil contributed to increased fatigue resistance and better fracture performance under cyclic loading. Another group of studies focused on rejuvenator encapsulation to restore aged asphalt properties. Aguirre et al. [148] tested 3–10 w/w% alginate in variable binder grades, showing that higher concentrations provided better stress recovery (MSCR test) and increased fatigue life (LAS test). Similarly, Shu et al. [143] examined 2 w/w% alginate in basalt-reinforced asphalt, emphasizing how fibre type influenced tensile and fatigue properties. In a related study, Shu et al. [144] tested 1–5 w/w% alginate in asphalt binder 70#, finding that higher alginate concentrations improved

tensile strength but negatively affected thermal stability at 5 w/w%. Zaremotekhas et al. [145] analyzed 5–15 w/w% alginate with variable binder grades, demonstrating that rejuvenator encapsulation significantly enhanced binder flexibility and stress relaxation. Lastly, studies comparing capsule content effects focused on optimizing encapsulation efficiency. Ozdemir et al. [146] investigated 0.25–1 w/w% alginate in AC-20 asphalt and found that higher capsule content enhanced dynamic creep resistance and fatigue performance. Yu et al. [147] studied 0.5 w/w% alginate in a dense-graded AC-13 asphalt concrete, incorporating 70 # virgin asphalt as the binder, and basalt aggregates. They concluded that treatment time influenced fracture resistance and compression stability, making alginate-encapsulated binders more effective under prolonged loading conditions.

10. Thermal Insulation

Rising pressures to reduce the environmental impact of buildings have spurred interest in bio-based insulation materials that are both effective and renewable. Alginate offers a stable and renewable polymer backbone that can be readily crosslinked to form porous and lightweight networks, a feature that is especially desirable for insulating structures. Table 11 outlines several central aspects of recent sodium alginate insulation research, including the choice of concentration, filler material, crosslinking approach, and overall processing route. Alginate concentration is expressed as a weight-to-volume percentage (w/v%) by weight of the composite mix or solution.

Table 11. Systematic survey of Ca-alginate-treated thermal insulation materials.

SA Concentration (w/v% of Composite Mix)	Primary Aim	Crosslinker and Gelation Method	Material Type	Treatment Method	Variables Studied	Tests Performed	Reference
(4%)	Thermal Insulation	Glutaraldehyde, N/A	SA, Wood Fibre, Waste Textile Fiber Composite	Calcium or Aldehyde Crosslinking, Air Drying	Ratio of Fibre, Crosslinker Type, Pressing Temperature and Time	UCS, Thermal Conductivity, 3PB	[67]
(0.1%, 0.25%, 0.5%, 1%, 2%)	Thermal Insulation	CaCO ₃ and CaHPO ₄ , Internal	SA-Clay Aerogel	Calcium Crosslinking, Freeze Drying	Concentration, Clay Type, Alginate Type	UCS, 3PB, Atterberg Limits, Hygroscopicity	[149]
(20%)	Thermal Insulation	Glyoxal, Glutaraldehyde, N/A	SA, Wood Fibre, Straw Fiber Composite	Glyoxal or Glutaraldehyde Crosslinking, Air Drying	Fibre Type, Fiber Ratio, Crosslinker Type, Curing Conditions	UCS, Thermal Conductivity, 3PB	[150]
(2%)	Thermal Insulation	H ₃ BO ₃ , External	SA-Hydroxyapatite Nanorods (HANRs) Aerogel	Calcium from HANRs and Boric Acid Crosslinking, Freeze Drying	Amount of HANRs, Boric Acid Concentration, Freeze-Drying Conditions	UCS, Thermal Conductivity, Cone Calorimeter	[151]
(2%)	Thermal Insulation	Silane, N/A	SA Aerogel	Silane MTMS Crosslinking, Unidirectional Freeze Drying	Silane MTMS Ratio, Freezing Direction and Temperature, Curing Conditions	UCS, Thermal Conductivity, Fatigue	[152]

(2%)	Thermal Insulation	Ammonium Polyphosphate, N/A	SA-Ammonium Polyphosphate (APP) Aerogel	Calcium Crosslinking, Directional Freeze Drying	Flame Retardant Loading, APP Type, Freeze-Drying Temperature and Direction	UCS, Limiting Oxygen Index (LOI), UL94, Thermal Conductivity	[153]
(2%)	Thermal Insulation	CaCO ₃ , Internal	SA-Grapefruit Peel Aerogel	Calcium Crosslinking, Freeze Drying	Ratio of Grapefruit Peel Precursor to SA	UCS, Thermal Conductivity	[154]
(2%)	Thermal Insulation	CaCO ₃ , Internal	SA-Al ₂ O ₃ Fibre Nano-composite Aerogel	Calcium Crosslinking, Freeze Drying	Al ₂ O ₃ Fibre Concentration, Ratio of Al ₂ O ₃ Fiber to SA	UCS, LOI Thermal Conductivity	[155]
(2%)	Thermal Insulation	CaCl ₂ , External	SA-3D Printed Fumed Silica Aerogel	Calcium Crosslinking, Freeze Drying	Fumed Silica Loading, Printing Viscosity	UCS, Thermal Conductivity	[156]

Lacoste et al. [67] included alginate as an adhesive binder for a wood fibre and textile waste bio-composite. Their material met the requirements for building insulation, with a thermal conductivity of 0.078–0.089 W/m·K. However, the flexural strength of 0.84 MPa and the compressive strength of 0.44 MPa were far lower than those of typical polymer foams. Chen [150] consolidated the former by developing a wood and straw fibre-alginate bio-composite with similar thermal conductivity values. These findings demonstrate the thermal feasibility of alginate as an eco-friendly binder for sustainable building materials. Zhu et al. [151], utilizing a double-crosslinked hydroxyapatite nanorod–alginate composite, exhibited a notably low thermal conductivity of 0.035 W/m·K and exceptional flame retardancy. The denser, more uniform pore network, reinforced by nanorod alignment paired with a dual boric acid crosslinking approach, appeared to minimize heat transfer to a greater extent than in previous alginate aerogels. Guan et al. [152] manufactured a silane crosslinked-alginate aerogel with a thermal conductivity of 0.069 W/m·K and outstanding fatigue resistance (100-cycle at 50% strain). Their anisotropic property gains were attributed to silane crosslinking in combination with unidirectional freeze-drying during aerogel manufacturing. Of particular interest is Zhan et al. [153], whose ammonium polyphosphate-alginate aerogel resulted in thermal conductivity values as low as 0.028 W/m·K and excellent flame retarding properties (UL-94 rating of V-0). Jing et al. [154] achieved a similar thermal conductivity of 0.028 W/m·K and excellent compressive strength properties using grapefruit peels, showcasing the versatility of alginate as a thermal insulator and the potential for simple yet effective combinations. Guo et al. [156] employed 3D printing to fabricate fumed silica–alginate aerogels, resulting in a thermal conductivity of 0.032 W/m·K alongside shape customization. These novel approaches emphasize the growing diversity and evolving breadth of advancements in the application of alginate for building energy conservation. Dove et al. [149] investigated the economic and environmental viability of alginate as a sustainable additive for the manufacturing of aerogel composites at the lab scale. The developed low-density bentonite-alginate composite was tested against varying types of alginate and clay-biopolymer ratios, measuring a flexural and compressive strength up to 1 MPa and 33 MPa, respectively, for the ideal mixing ratio (0% clay) and alginate composition (highest viscosity and relatively lower M/G ratio). While the aerogel specimen performed well mechanically, its economic analysis revealed that the highest costs are attributed to the freeze-drying process for aerogel manufacturing. Although the analysis costs were relatively high, it was anticipated that field-scale adoption of the aerogel would considerably lower these costs through scaling revisions. An environmental analysis revealed that the developed clay-alginate aerogel performed significantly poorly compared to commercial silica-based aerogels (~10× increase in

embodied energy). The authors recommend conducting a more detailed investigation, using precise thermal-conductivity data, to better assess the commercial feasibility of alginate-based aerogels.

11. Conclusions and Future Research Needs

Alginate, a seaweed-derived biopolymer, has emerged as a promising sustainable material in geotechnical and construction engineering. Its ability to form hydrogels via ionic crosslinking with calcium enhances the mechanical strength, water retention, and durability of earthen and cementitious materials, offering notable advantages in sustainability and environmental compatibility over traditional stabilizers like cement and lime. This review consolidates current knowledge on the use of SA across a broad range of applications. Alginate has been shown to enhance the mechanical and physical properties of various soil-based materials, namely unfired earth blocks, sandy soils, and clayey soils, and can be effectively combined with other enhancement techniques to produce an optimized cementitious or bituminous product.

The mechanical performance of alginate-based treatments is highly dependent on the gelation mechanism (internal, external, or uncontrolled), availability of calcium ions, and the specific characteristics of alginate (viscosity, molecular weight, M/G ratio). These factors govern the structure, stiffness, and moisture behaviour of the resulting hydrogel matrix. The analysis on cohesionless, fine sands has shown that alginate acts as a pure binder, with UCS typically increasing monotonically with dosage. In contrast, clayey soils exhibit more complex responses, typically exhibiting an optimal concentration range beyond which strength gains diminish, highlighting the role of clay-mineral interactions, pore structure, and water retention effects. Alginate can be integrated into several novel systems, such as biopolymer-assisted EICP/MICP, self-healing concretes, and earthen materials, where it contributes as a modifier of both physical and mechanical properties. In biopolymer-assisted EICP/MICP, alginate was found to enhance strength and durability and to influence microstructural development through its gelation and ion-binding capabilities. Alginate improves calcium ion retention and distribution, leading to more uniform precipitation and increased compressive strength. In self-healing concrete, encapsulation ability supports the controlled release of healing agents, prolonging the functional service life. For earthen materials, alginate improves cohesion and water resistance, making it a suitable additive for sustainable construction.

Despite generally positive outcomes, considerable variability in experimental methods (particularly in calcium sourcing, alginate properties, curing conditions, mixing techniques, and gelation approaches) hampers cross-comparison and scalability. Critical knowledge gaps remain, especially regarding the effects of alginate concentration on modulus of elasticity, shear strength, and Atterberg limits, as well as the role of curing conditions in the effects of alginate treatment on controlling erosion and permeability. Another vital research gap is the lack of formal techno-economic analyses for civil engineering applications. The economic viability of sodium alginate as a construction material is defined by its high performance-to-cost ratio rather than direct material cost. Industrial sodium alginate is substantially more expensive per kilogram than conventional Portland cement. However, its application is highly efficient, with effective dosages for soil stabilization typically below 5 w/w% by soil mass and as low as 0.1–0.2 w/w% by total soil or binder mass for certain hydrogel applications. This low dosage makes the total binder cost per unit volume competitive while enabling significant property enhancements. The economic case for alginate is built on its multi-functionality, which can reduce or eliminate the need for multiple admixtures. In soils, it concurrently improves unconfined compressive strength, shear modulus, and erosion resistance. Its superior water retention and hydrogel-forming properties offer direct benefits for internal curing in concrete and drought

resilience in agriculture. As a natural, biodegradable polymer, it also aligns with sustainable construction regulations, providing an environmental premium. Key challenges for large-scale adoption include securing a high-volume, cost-stable supply chain and developing standardized field application protocols. Future feasibility research must model full-process economics, from raw material sourcing and processing to in situ performance and lifecycle durability, to provide definitive financial projections for industry adoption.

To conclude, while promising progress has been made, fully unlocking alginate's potential in civil engineering requires continuous exploration and standardization. Advancement depends on establishing standardized testing protocols and clearer reporting of alginate characteristics, calcium sources, soil mineralogy, and gelling techniques, which will significantly strengthen the reliability of quantitative models. A deeper understanding of alginate's interactions at the microstructural level is also essential to guide formulation and predict long-term behaviour. Furthermore, comprehensive Life Cycle Assessments addressing environmental and economic feasibility, as well as product lifespan, are imperative for scaling alginate applications, particularly in ground-based engineering and construction. The path forward holds abundant opportunities for sustainability, refinement, and impactful real-world implementation.

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