ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Thermo-hydraulic performance of zeolite-bentonite mixtures stabilized with Zostera marina biomass

Esra Güneri [1]

[1] Department of Civil Engineering, Izmir Democracy University, Izmir (Türkiye); esra.guneri@idu.edu.tr
*Correspondence: esra.guneri@idu.edu.tr

Received: 22.11.24; **Accepted:** 19.02.26; **Published:** 10.03.26

Citation: Güneri, E. (2026). Thermo-hydraulic performance of zeolite-bentonite mixtures stabilized with Zostera marina biomass. Revista de la Construcción. Journal of Construction, 25(1), 218-234. https://doi.org/10.7764/RDLC.25.1.218

Graphical abstract:

Highlights:

- Additives are needed that soils maintain their engineering properties as temperatures rise.
- Environmentally friendly seaweed is an alternative material in this regard.
- A novel mixture was created using seaweed dried at high temperatures.

Abstract: Geotechnical engineering frequently encounters soils exhibiting insufficient mechanical strength or undesirable hydraulic properties, necessitating the implementation of soil improvement techniques. In the contemporary context of escalating global energy demands and rapid population growth, the selection of stabilization materials must rigorously prioritize sustainability, environmental compatibility, and cost-effectiveness. Furthermore, the expansion of energy infrastructure, often involving near-surface heat transfer mechanisms, requires a comprehensive understanding of soil behavior under elevated thermal regimes. This study investigates the potential of dried Zostera marina (seaweed) biomass as a novel, sustainable, and low-cost alternative additive for soil stabilization. Historically recognized for its thermal insulation capabilities in cold climates, Zostera marina represents a readily available waste product of marine origin. The research focused on evaluating the thermo-hydraulic conductivity performance of mixtures formulated by incorporating Zostera marina into a base matrix of zeolite and bentonite. Hydraulic conductivity tests were systematically conducted under two distinct thermal conditions: ambient laboratory temperature (RT) and an elevated temperature of 40 °C, allowing for the isolation of additive and thermal influences on permeability. The experimental results demonstrate a critical dual behavior. At ambient temperature, the inclusion of Zostera marina effectively reduced the hydraulic conductivity of the mixtures. However, under the 40 °C thermal regime, a discernible increase in permeability was recorded, a finding consistent with established literature concerning the temperature-dependent hydro-mechanical response of organic-rich or clay-based matrices. These findings highlight the necessity of considering service temperature when developing sustainable stabilization techniques utilizing marine biomass additives.

Keywords: bentonite, hydraulic conductivity, seaweed, temperature, zeolite.

List of abbreviations:

XRD: X-Ray Diffraction Analysis

w_{opt}: Optimum water content

$\gamma_{dry, max}$: Maximum dry unit weight

SEM: Scanning electron microscope

1. Introduction

Determining the engineering properties of soils and improving the existing properties is important in terms of the safe existence of the structures to be built. Soil stabilization is a method consisting of procedures aimed at improving the condition of the soil in cases where it is not possible to replace the soil due to technical or environmental reasons, and even if it is, the cost is not low (Nwonu et. al.,2021; Liu et. al.,2019; McDowell, 1959). In order to optimize parameters such as shear strength, compression and permeability of the soils, currently used iron slag (Winterkorn and Pamukcu, 1991), steel slag (Kang et. al., 2016), fiber group and chemicals are used (Yoobanpot et. al., 2017). Additives used in soil improvement develop different engineering properties under different conditions depending on soil type, mineralogy, usage rate, temperature and many other factors. The targeted improvements can be listed as filling the voids, increasing the shear strength (Zinchenko et. al., 2022), creating lateral balance (Kaminskas and Barauskas, 2014), increasing the resistance of the soils to liquefaction (Firoozi et. al., 2014), reducing the masses that expose them to excessive pressure, controlling deformations, increasing the bearing capacity, managing soil plasticity and limiting important properties such as swelling and shrinkage (Abu-Farsakh et. al., 2015).

One of the most important factors to consider when applying improvement methods is temperature. The acceleration of energy production in response to the rapid increase in the world population and, as a result, the increase in the number of energy structures and facilities, causes the interaction of soils with temperature to increase. Thermal piles, buried power cables, etc. are among the most common energy structures, and since they interact with the surrounding soil, they cause negative changes in the engineering properties of the soil at the design stage (Laloui, 2001). In addition, as a result of the effects of global warming, the soil temperatures began to overheat, only going beyond seasonal temperatures, depending on seasonal changes. These mentioned factors reveal that the engineering properties of soils should also be examined in the presence of high temperatures.

In addition to the method used in improvement, it is very important that the additive materials chosen are sustainable, environmentally friendly and low-cost. Considering environmental factors such as increasing world population, decreasing natural resources and environmental pollution, it seems that there is a need for alternative additive materials. Zostera marina, or seaweed, with its terminological name, has been used for insulation (roof) purposes in countries where rain prevails, such as Japan, and cold, such as Denmark, for years (Liu et. al., 2023). In our country, it is used in many different areas such as insulation, filling material, pharmaceutical industry, medicine and toy making. It is known that this type of seaweed has a healing effect on human health due to the iodine it secretes.

Seagrasses are a polyphyletic group of flowering plants that have successfully recolonized the marine environment approximately 100 million years ago (Orth et al., 2006). Among them, Zostera marina is one of the most widespread and wellstudied species, forming underwater meadows that are among the most productive ecosystems on earth. The ecological value of these meadows is profound; they act as significant carbon sinks (blue carbon), oxygenate the water, stabilize sediments, and provide essential habitat and food for a diverse array of marine organisms, including commercially important fish and invertebrates (Duarte et al., 2005). Thriving in a submerged, saline environment presents unique physiological challenges. Unlike terrestrial plants, seagrasses must cope with high ionic strength, which can lead to osmotic stress and ion toxicity, limited light availability, and a high propensity for epiphytic growth and microbial infection. To overcome these challenges, Z. marina has evolved a suite of specialized morphological, physiological, and, most critically, chemical adaptations. Similar to brown algae and some invertebrates, Z. marina synthesizes a sulfated galactan, often referred to as zosterin (Pfeifer et al., 2020). These polysaccharides are heavily esterified with sulfate groups, which confer a strong negative charge. This anionic nature is critical for ionic balance, helping to manage osmotic pressure by binding cations from the surrounding seawater (Scheller and Ulvskov, 2010). Furthermore, unlike terrestrial vascular plants, the supportive tissues of *Z. marina* are not lignified. Lignin, a complex polymer of monolignols that provides rigidity and waterproofing to terrestrial vasculature, is largely absent or present in only trace amounts in seagrass cell walls (Martone et al., 2009). This is a key adaptation to life in a buoyant aqueous medium, where heavy, rigid structures are energetically costly and unnecessary. Instead, structural support is achieved through thickened cell walls rich in hemicelluloses and the turgor pressure maintained by osmotic regulation.

Figure 1. Dried seaweed used in experiments.

Historically, Denmark, the Netherlands, the United Kingdom, Japan, China and other countries have built "seaweed houses"; among them, Denmark and China have typical houses (Fig 2) (Yang and Qian, 2019). Low-carbon and energy-saving, these houses are environmentally friendly. Research has shown that the Zostera marina plant contains zosteric acid and that this acid has protective properties against insects and corrosion. In addition, the fibrous structure of this seaweed has a strength-increasing effect and is affected by wind, temperature, etc. It is effective against environmental factors. While the internal structure of Zostera marina is quite hollow, which creates an advantageous feature in terms of thermal insulation, it is known that its external structure has high-strength colloids (Yang, 2012). Seaweed, which is environmentally friendly and can be destroyed as nutrients for the soil, is an alternative material that can be supported in this respect. Figure 3 overall shows that Zostera marina has a complex interrelated chemistry consisting of both primary and secondary components. It has been revealed that the surface of seaweed is more sensitive to pollution and has a higher defense, and the reason for this is the phenolics on its surface. Phenolics and other compounds are synthesized intracellularly by seaweed and then transported to the surface (Papazian et. al., 2019).

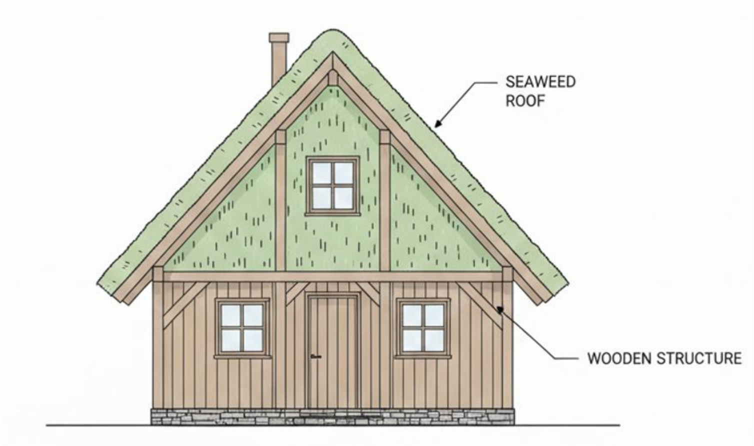

Figure 2. A representative visualization of traditional moss houses inspired by Danish and Japanese rural architecture.

Seaweed, a rich source of various bioactive nutrients (Amir et. al., 2025), yields valuable hydrocolloids like carrageenan, widely utilized in the food industry as thickening, gelling, and stabilizing agents (Muthukumar et. al., 2021; Liao et. al., 2021). Producing commercial carrageenan involves a multi-stage process, including washing, alkaline treatment, hydro extraction, pelletization, drying, and milling (Amir et. al., 2024). While all these stages are essential, drying stands out as particularly critical (Efendy et. al.,2023). This is primarily due to its substantial energy consumption, which directly increases production costs and significantly influences the final product's quality. Furthermore, drying often necessitates high temperatures maintained over extended durations, adding to its operational complexity. The seaweed industry operates through an intricate production system consisting of primary and supporting processes. The primary process involves converting raw seaweed into finished products using specialized equipment such as washers, hydro-extractors, filters, pelletizers, dryers, and mills. Supporting processes provide essential utilities, including heat energy (via boilers) and compressed air (supplied by compressors), which facilitate primary operations. Both stages generate significant waste streams: primary processes yield by-products such as solid residues and wastewater, while supporting processes produce waste materials like fly ash, bottom ash, slag, and flue gas emissions. If left untreated, these by-products and waste materials can lead to severe environmental degradation and public health hazards. Consequently, their proper management or, ideally, their conversion into value added materials is criical. This necessity has positioned waste management and by-product valorization as key priorities in sustainable industrial practices worldwide (Amir et. al., 2025; Abrouki et al., 2021).

The integration of sustainable, bio-derived materials into the construction sector represents a critical area of research aimed at reducing environmental impact (Mohanraj et. al., 2023). Susilorini et al. (2014) investigated the efficacy of natural polymers derived from specific seaweed species, Gracilaria Sp. and Eucheuma cottonii, as modifiers for cementitious mortar. The study utilized Eucheuma cottonii gel and general seaweed powder to enhance mechanical characteristics. The research employed a rigorous dual-phase methodology, initiating with an independent pre-experiment focused on screening the effect of the polymer form (gel versus powder) on compressive strength. The subsequent main experiment optimized the mix proportion and characterized both the compressive and splitting tensile strengths. The findings demonstrated that a natural polymer-modified mortar utilizing seaweed powder, specifically at the optimal mix proportion designated KM-0.5, exhibited substantial improvements in both compressive resistance and resistance to cracking (splitting tensile capabilities). A study in the literature showed that seaweed addition reduced the hydraulic conductivity values of zeolite-bentonite mixtures at room temperature and below 40°C (Güneri, 2024).

Soil improvement is mostly used to improve the geotechnical properties of clays. In this study, the main mixture was formed by combining the properties of bentonite, such as high compression-shrinkage potential and low shear strength, with a certain proportion of zeolite. The aim of this study is to produce materials with low permeability and high resistance to temperature that can be used as buffer materials around energy structures and facilities (such as solid waste storage areas, nuclear waste storage areas (at higher temperatures), buried power cables), considering the changing (increasing) soil temperatures. The alternative is to produce buffer material. At the same time, it is to produce a material that has high performance under room temperature and has an improving effect on soil properties. Within the scope of the study, we focused only on the hydraulic conductivity behavior of seaweed-added mixtures. Hydraulic conductivity tests were carried out at room temperature and under 40°C by adding different amounts of dried seaweed to the additive-free mixtures. The effect of seaweed additive and temperature change on the mixtures was examined.

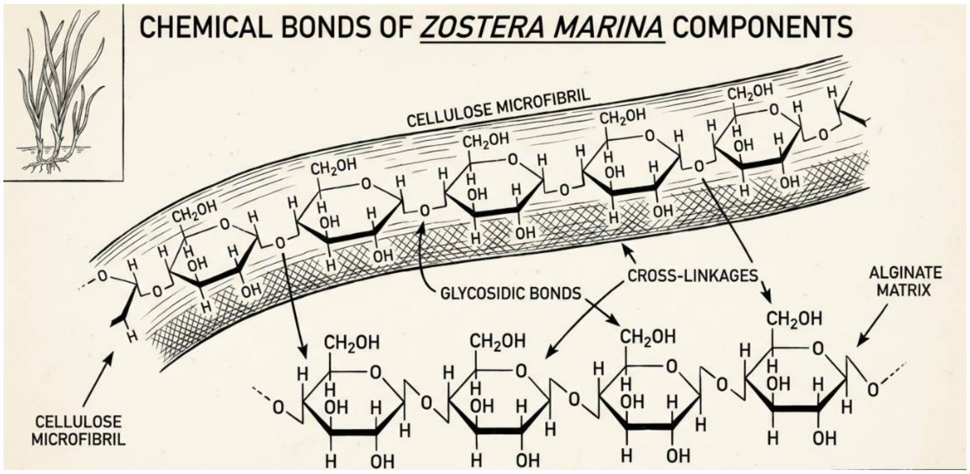

Figure 3. Components contained in seaweed Zostera marina.

2. Materials and methods

2.1. Material characterizations

Within the scope of this study, zeolite-bentonite mixtures were preferred as additive-free mixtures. Dried seaweed and other ingredients were obtained from local companies (Fig 4). Zeolite and bentonite were sifted through no.40 sieves and used. New mixtures were created by adding 10% and 20% dried seaweed to 80% zeolite-20% bentonite mixtures. Abbreviations are used when naming mixtures. For example, 80Z-20B-10SW represents 72% zeolite-18% bentonite and 10% seaweed. The properties of the materials are given in Table 1.

Figure 4. Images of the samples in dry state.

Table 1. Physico-chemical properties of the materials.

Property	Zeolite	Bentonite	Property	Dried Seaweed
Specific weight	2.40	2.70	Habitat	aquatic
Liquid limit (%)	50.0	476.0	Leaf position	Under water
Plastic limit (%)	N.P.	70.1	Underwater leaf length	Max. 1100mm
pH	7.6	9.5	Underwater leaf blade width	2-12mm

After a sufficient representative volume of the sample was ground to powder size, it was subjected to X-ray diffraction (XRD) analysis in order to reveal the mineral composition. In the XRD analysis, Bruker-DS Advance model X-ray diffractometer was used and CuKά radiation and Ni filter were used and 40Kv - 40mA conditions and the shooting speed was 245 (°20). Semi-quantitative ratios (%, weight) of the minerals are given in XRD pattern obtained by XRD- modal analysis. The XRD analysis results of bentonite and zeolite samples are given in Figure 5. While the bentonite sample contained illite, montmorillonite and quartz minerals, the zeolite sample was determined to contain kljnoptilolite, quartz, feldspar, illite-mica. Kljnoptilolite mineral is the main mineral of zeolite and constitutes 80% of the total.

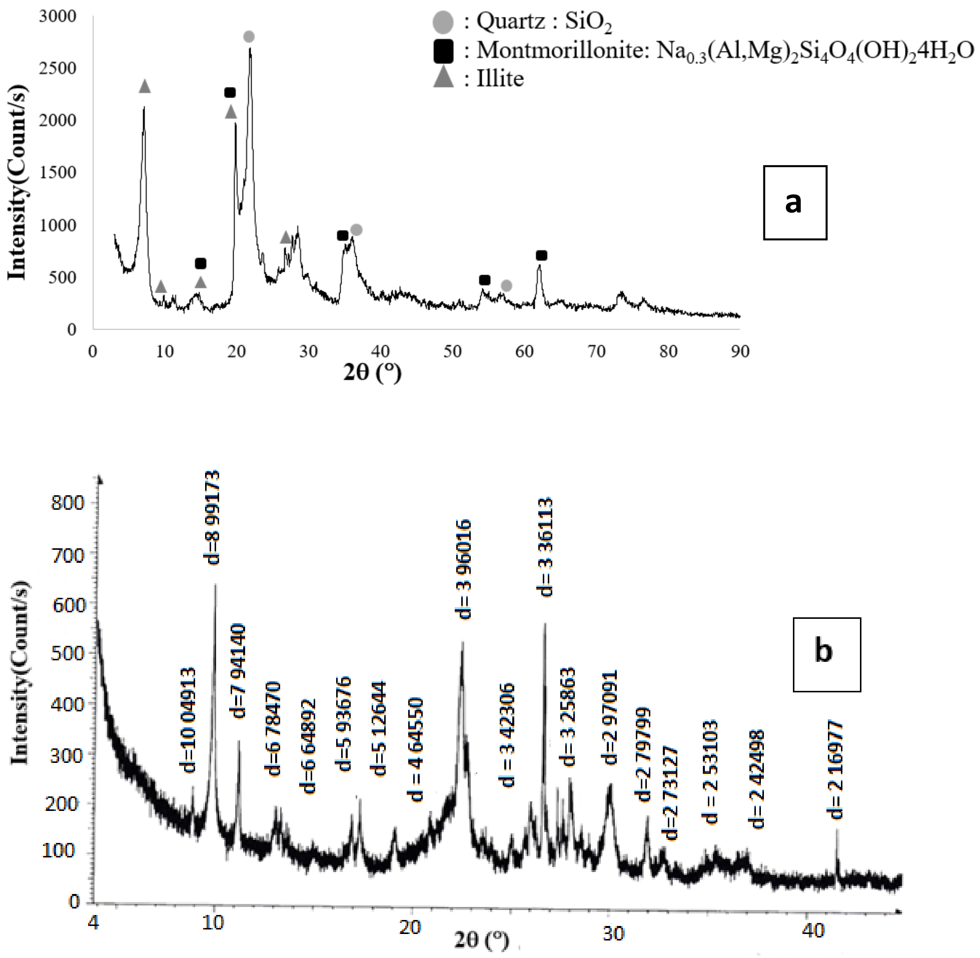

Figure 5. XRD analysis results of (a) bentonite and (b) zeolite samples.

2.2 Methods

2.2.1. Standard Proctor test

In this study, the maximum dry unit volume weight and optimum water content values of the samples were found by the Standard Proctor test according to ASTM D698-Method A (ASTM: D698-12, 2012). Compaction test was carried out in three layers with 25 blows per layer. The samples were first mixed in a dry state and then made wet by adding four different percentages of water. First, the percentage of seaweed in the mixture was determined and 40% of the remaining part was separated as bentonite. The last remaining amount was used as zeolite.

2.2.2. Hydraulic conductivity tests under room and high temperatures

Flexible wall permeameters represent a cornerstone in modern geotechnical and environmental engineering laboratories due to their unparalleled ability to accurately determine the hydraulic conductivity of fine-grained soils and compacted materials. By effectively eliminating sidewall leakage through the application of confining pressure and ensuring full specimen saturation via back pressure, these devices provide reliable data crucial for critical design decisions across a spectrum of applications, from waste containment to water resource management. Hydraulic conductivity, often referred to as permeability (k), quantifies the ease with which water can flow through a porous medium under a hydraulic gradient. This fundamental soil property is indispensable for a myriad of geotechnical engineering and hydrogeological applications, including the design of foundations, earth dams, embankments, landfill liners and covers, roadways, and the prediction of groundwater flow and contaminant migration (Freeze and Cherry, 1979; Terzaghi et al., 1996).

Accurate determination of k is paramount, as even small errors can lead to significant misjudgments in design and risk assessment. Laboratory methods for determining hydraulic conductivity are broadly categorized into rigid wall and flexible wall permeameters. While rigid wall permeameters (e.g., standard compaction mold permeameters) are simpler to operate and often used for coarser-grained soils or quality control of compacted materials, they are prone to significant errors due to sidewall leakage, particularly when testing fine-grained soils (Daniel, 1994). The development of the flexible wall permeameter addressed these limitations by introducing the ability to apply confining pressure to the soil specimen, effectively simulating in-situ stress conditions and preventing flow along the specimen boundaries. Flexible wall permeameters overcome the limitations of rigid wall devices by encapsulating the soil specimen within a flexible membrane (typically latex or another elastic polymer) and applying a uniform confining pressure around the specimen. This confining pressure, which exceeds the pore water pressure within the specimen, effectively forces the membrane to conform tightly to the specimen's sides, preventing sidewall leakage and simulating in-situ confining conditions.

Hydraulic conductivity tests were carried out according to ASTM D5084-16 (ASTM: D5084-16, 2016). The experiments were carried out under two different temperatures: room temperature (25°C) and 40°C. In the tests carried out under room temperature, samples were prepared and compressed according to optimum water content ($w_{opt)}$ and maximum dry unit weight ($\gamma_{dry,max}$) values. It was placed in the permeameters with geotextiles on top and bottom. A membrane was placed on the samples to prevent water from entering them. The membrane was fixed using O-rings to prevent it from slipping as a result of the applied cell pressure. Tests were started under room temperature, and when sufficient and stable flow was achieved, the temperature was increased to 40°C.

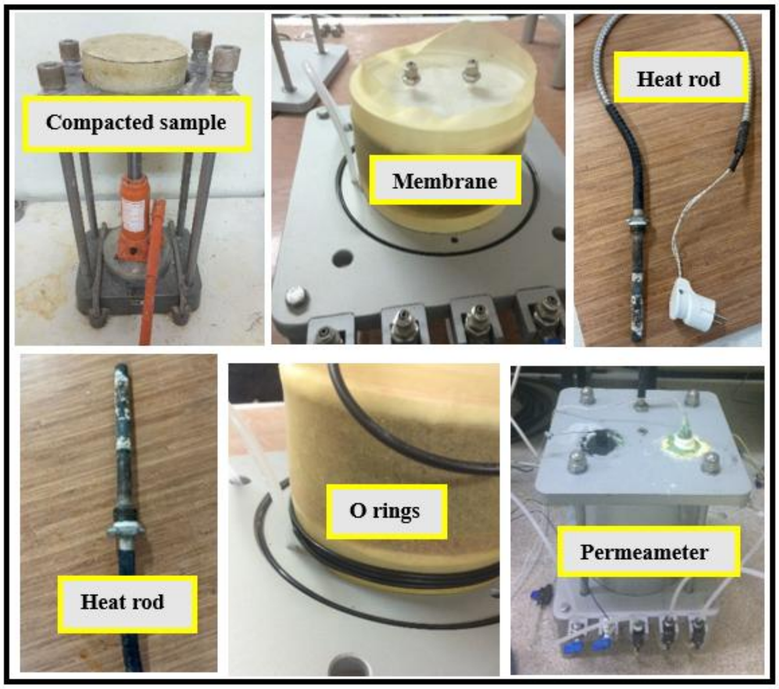

Figure 6. The system used in hydraulic conductivity tests in the presence of temperature.

Aluminum cells were used in tests carried out under high temperatures. Some additions were made to the same system as in the tests carried out at room temperature. In order to measure the soil temperature, a small diameter hole was opened in the bottom geotextile and a thermocouple was passed through it. In this way, it was possible to check whether the soil temperature reached 40°C. The water temperature was measured by placing a thermocouple inside the cell. Thermostat was used to stabilize the temperature at 40°C. A heat rod was used to provide temperature (Fig 6). The heat rod was sent into the cell by drilling a hole in the head of the cell in a way that would not cause any gaps or leaks. The temperature is fixed at the desired degree with the thermostat.

2.2.3. Thermal conductivity measurements

Within the scope of this study, thermal conductivity values of pure and dried seaweed-added zeolite-bentonite mixtures were measured. Samples prepared according to optimum water content and maximum dry unit weight values were compressed in thermal conductivity measurement molds (r = 7 cm, L = 14 cm and V = 538 cm^3). Before the measurement, the samples were first weighed in dry form, then mixed when the required amount of water was added according to wopt, and left for 24 hours with the mouth closed to ensure homogeneity. At the end of this period, measurements were made with a Tempos thermal analyzer. The appropriate probe was selected for the measurement. By determining the thermal conductivity values correctly, the effect of the seaweed additive on the conductivity or insulation behavior of the additive free mixtures can be examined.

Figure 7. The **s**ystem used in thermal conductivity tests and the sample.

3. Experimental results

3.1. Standard Proctor test

Within the scope of this study, hydraulic conductivity tests of additive free zeolite-bentonite mixtures and mixtures with dried seaweed additives were carried out at room temperature and under 40°C. Thermal conductivity values of the mixtures were determined under room temperature. Experimental studies were started with the compaction test. Compaction curves of the mixtures are given in Figure 8. Standard Proctor test results showed that the optimum water content of the 20B-80Z mixture was 55% and the maximum dry unit weight value was 11.3 kN/m^3. It was observed that with 10% and 20% dried seaweed additives, the water content values increased to 57% and 60%, respectively. Maximum dry unit weight values decreased to 10.2 kN/m^3 and 9.4 kN/m^3, respectively. An increase in water content was observed because of the fact that seaweed is a material with a lower specific gravity than zeolite and bentonite, and also that the structure of seaweed is quite porous (Yang et. al., 2012) and can fill these voids with water.

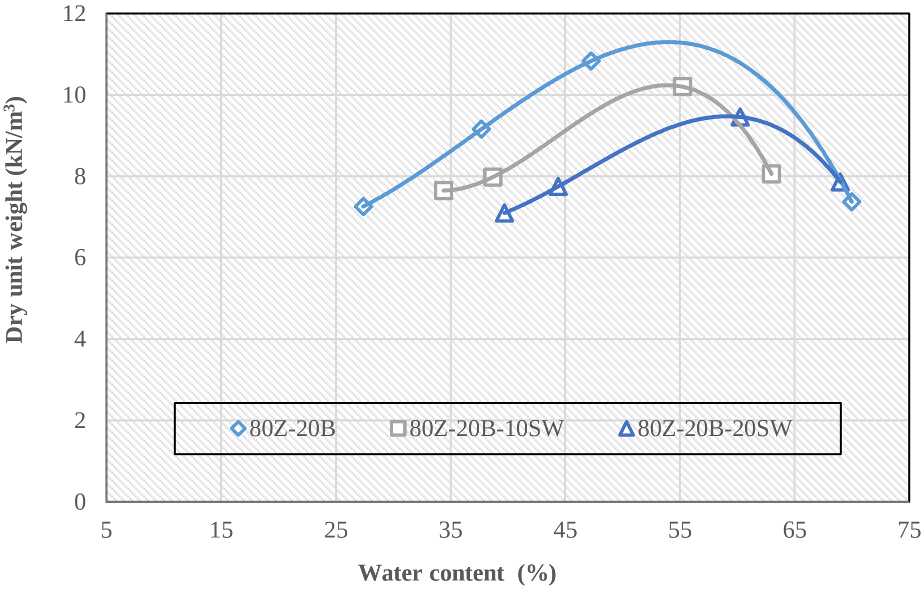

Figure 8. Compaction curves of the mixtures.

3.2. Hydraulic conductivity tests under room and high temperatures

Within the scope of this study, hydraulic conductivity tests of 20B-80Z, 20B-80Z-10SW and 20B-80Z-20SW mixtures were carried out under 25°C and 40°C. The test results showed that the hydraulic conductivity value of the additive free zeolite-bentonite mixture was determined as 3.8×10^{-12} m/s under room temperature and 6.0×10^{-12} m/s under high temperature. With the addition of 10% and 20% dried seaweed, the permeability coefficients under room temperature were measured as 8.9×10^{-12} m/s and 8.0×10^{-12} m/s, respectively. The k values determined for the additive mixtures under 40°C were 1.9×10^{-11} m/s and 2.4×10^{-11} m/s, respectively. When the samples were examined under room temperature, it was observed that seaweed caused an increasing effect on hydraulic conductivity due to its porous structure (Yang et. al., 2012). However, it was determined that by increasing the 10% seaweed additive to 20%, the “k” coefficient decreased by 1.1 times, reducing the permeability (Fig 9). When the test results performed at high temperatures are examined, it is seen that the permeability of each mixture increases. For example, while the additive free mixture 20B-80Z increased approximately 1.6 times with the increase in temperature, the mixture with 10% additive increased its permeability by 2.1 times and with 20% additive increased its permeability by 3 times.

It was revealed in previous studies that the viscosity of soils decreases as the temperature increases and therefore the permeability increases (Sultan, 1997; Delage et.al., 2000; Chen et. al., 2014). In addition to viscosity, fabric changes and pore structure reshaping that occur with temperature increase can also affect hydraulic conductivity (Romero et. al., 2001).

The hydraulic conductivity of bentonite has been observed to increase with escalating temperature, particularly up to 80 °C (Pusch, 1980; Cho et.al., 1999). This phenomenon is primarily attributed to the concomitant reduction in water viscosity with rising temperatures (Cho et.al., 1999). However, research by Zihms and Harrington (2015) suggests that changes in water viscosity alone may not fully account for the observed sensitivity of bentonite permeability to temperature variations. These temperature-dependent behaviors necessitate careful consideration in repository design, particularly concerning potential thermal variations at disposal sites to ensure maximum design temperatures are not exceeded (IAEA, 2006; NDA, 2010). Studies consistently indicate that below a critical threshold of 100 °C, the intrinsic sealing performance of bentonite clays remains largely unaffected (Zihms and Harrington, 2015; Cho et.al., 2000; Jacinto et.al., 2007). Conversely, temperatures exceeding 100 °C pose a significant challenge, potentially inducing detrimental processes such as illitization and mechanical degradation, which could severely compromise the clay's long-term barrier function (Daniels et.al., 2017). Furthermore, at these elevated temperatures, a more pronounced increase in clay permeability has been reported (Cho et.al., 2000), exacerbating concerns regarding repository integrity.

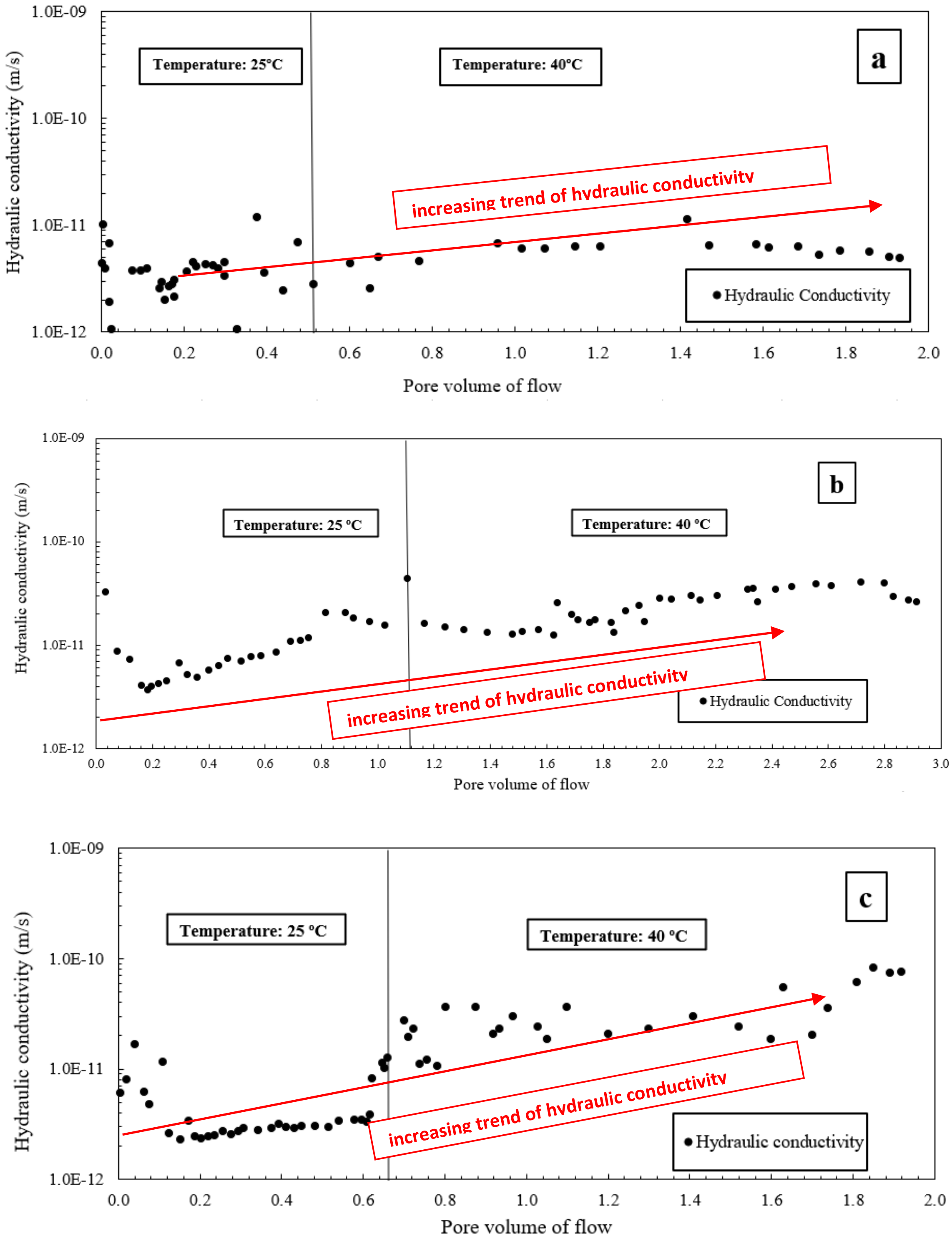

Figure 9. Hydraulic conductivity graphs of the mixtures in terms of pore volume of flow: a) 20B-80Z b) 20B-80Z-10SW c) 20B-80Z-20SW at room and high temperatures.

Within the scope of this study, SEM images of the zeolite-bentonite mixtures were analyzed. In Figure 10a, if it is assumed that mixture has a leafy appearance under room temperature, it was seen that the leaves of this leafy appearance became lighter. At room temperature, the zeolite sample is under minimum thermal stress and its structure reflects the ideal state obtained after synthesis. At room temperature SEM images show the ideal, sharp, and distinct crystal structure of zeolites. Figure 10b shows the SEM image of bentonite. It was seen that zeolite has a more granular structure than bentonite and bentonite is more homogeneous.

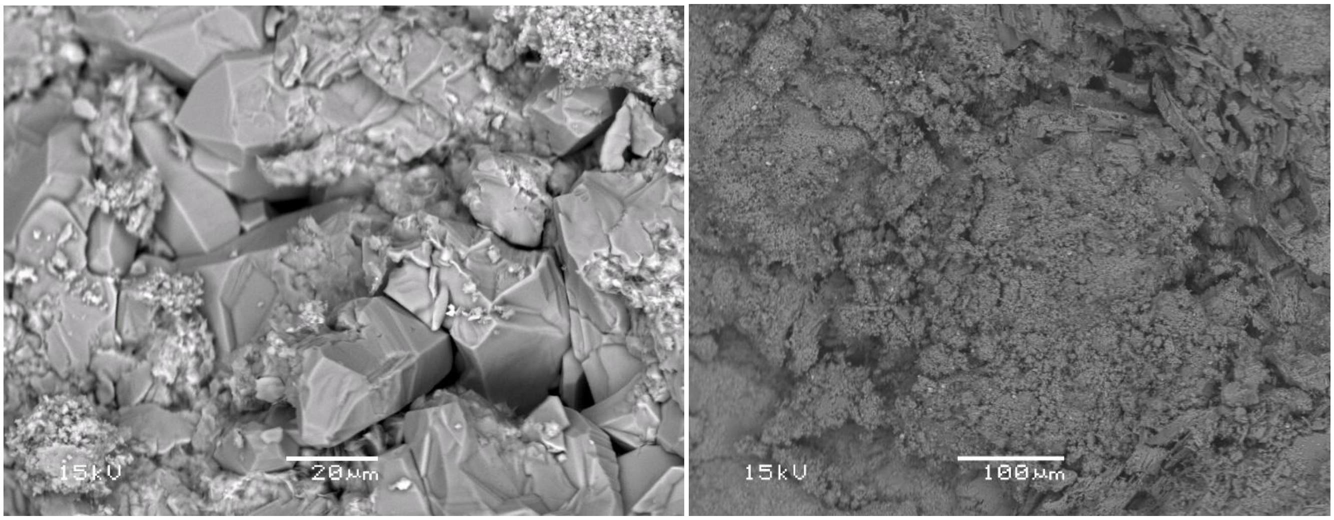

Figure 10. Electron microscopy image of (a) zeolite sample at 20 µm, (b) bentonite sample at 100 µm.

Figure 11 shows that although dried seaweed slightly increases hydraulic conductivity under room temperature, it has a reducing effect with a 20% contribution rate. Data under high temperatures show parallelism with the literature and reveal that decreasing viscosity increases permeability (Duley and Domingo, 1943; Constantz and Murphy, 1991; Hopmans and Dane, 1986).

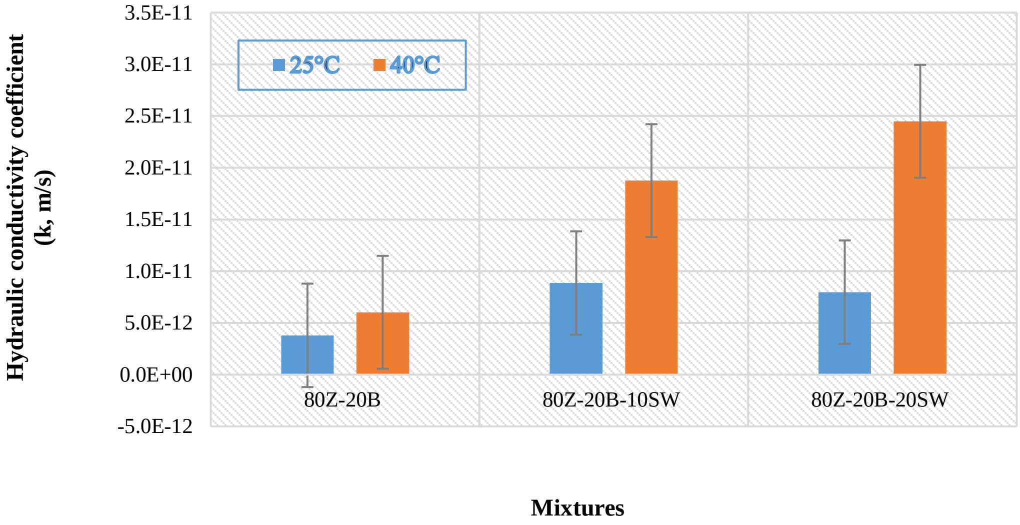

Figure 11. Variation of hydraulic conductivity depending on temperature and seaweed addition.

3.3. Thermal conductivity

Thermal conductivity is the amount of heat passing through unit area in unit time under the effect of thermal gradient. Thermal parameters include heat capacity and is the amount of heat required to change the temperature of a material by one degree kelvin (Andersland and Ladanyi, 1994). Thermal conductivity of soil depends on various factors such as soil type, temperature, particle size, degree of saturation, soil structure, porosity. Each material has a different thermal conductivity coefficient. For example: the thermal conductivity of water is higher than that of air, which means that soils with higher water content have higher thermal values (Garcia-Gutierrez and Espinosa-Paredes, 2004).

As a result of the thermal conductivity measurements, it was seen that the algae additive had an increasing effect on the thermal conductivity of mixtures without additives. While the thermal conductivity value of the additive free zeolite-bentonite mixture was 0.911 W/mK, with 10% and 20% additive, this value increased by approximately 23% and 6%, respectively (Table 2). While the seaweed additive's capacity to carry thermal conduction initially had a higher percentage, increasing the seaweed additive increased the capacity of this conduction at a relatively lower rate. One of the main reasons for this is that the seaweed increases the conduction by filling the gaps in the zeolite-bentonite mixtures, and then the increasing contribution rate has a negligible effect on the gaps.

Table 2. λ values of the mixtures.

Mixtures	Thermal conductivity (λ, W/mK)
20B-80Z	0.911
20B-80Z-10SW	1.124
20B-80Z-20SW	1.189

4. Conclusions and comments

This study investigates the modification of engineered composite mixtures specifically, those composed of zeolite and bentonite through the incorporation of dried seaweed biomass. Such mixtures are commonly employed in barrier systems (e.g., sanitary landfills or thermal storage systems) due to their high sorption capacity and low hydraulic conductivity. Given the growing need for sustainable and low-cost additive materials, dried seaweed was evaluated as a partial replacement binder. Standard geotechnical tests, including compaction (Proctor) and hydraulic conductivity, were performed. Hydraulic conductivity tests were conducted under two critical thermal regimes: ambient temperature and elevated temperature conditions, to simulate operational scenarios. Furthermore, the thermal conductivity coefficient λ was determined for varying mixture formulations. The results demonstrate significant interactions between the organic fraction and the mineral matrix, revealing specific trade-offs regarding optimal moisture content, maximum dry density, and heat transfer efficiency.

1. As the seaweed contribution increased, the w_{opt} value of the mixtures increased, while the $\gamma_{dry,max}$ values decreased. Dried seaweed possesses a significantly lower specific gravity compared to bentonite and zeolite. Introducing this low-density, bulky, highly porous material effectively replaces denser mineral particles within the matrix. Even when maximum compaction effort is applied, the overall mass per unit volume decreases, leading to a reduction in $\gamma_{dry,max}$. Seaweed biomass is highly hydrophilic, primarily composed of polymeric materials (e.g., alginate, cellulose) capable of substantial water absorption and retention. To achieve optimal sliding and particle rearrangement (necessary for maximum density), a greater volume of water is required to satisfy the combined hydration demands of the bentonite, the zeolite, and the highly absorbent organic fraction. The increased w_{opt} reflects this higher water demand necessary for optimal particle lubrication during compaction.

2. The seaweed additive had a slightly increasing effect on permeability under both temperature values. Under room temperature, it was observed that increasing the seaweed additive from 10% to 20% showed a tendency for the hydraulic conductivity value to decrease. The general trend of a slight increase in k with seaweed addition can be attributed to the physical disruption of the dense, low-permeability bentonite framework. The inclusion of organic fibers and particles can create micro-pathways or macropores, increasing the void ratio and reducing the tortuosity

of the flow paths, thereby elevating k above the baseline mineral mixture value. The observed decrease in k when moving from 10% to 20% seaweed at room temperature is a crucial finding, suggesting an optimal threshold for barrier performance. At low percentages (e.g., 5-10%), the seaweed might act primarily as isolated conduits or disruptors. At higher critical concentrations (e.g., 20%), the increased volume of the organic fraction, coupled with the high wopt, may lead to a point where the swollen organic material begins to effectively fill the inter-aggregate voids and micro-cracks. This void filling mechanism can increase the flow path tortuosity and reduce the effective pore throat size, resulting in a marginal decrease in k compared to the peak permeability observed at intermediate concentrations.

3. As the seaweed contribution increased, the thermal conductivity coefficients of the mixtures increased. The dominant factor driving the increase in the bulk thermal conductivity lambda is the higher equilibrium moisture content required for optimal compaction, overriding the insulating effect of the organic solids themselves. This suggests a critical thermal trade-off: using seaweed improves water retention, which enhances heat transfer capability, but at the cost of requiring a higher initial moisture content.

Hydraulic conductivity is overwhelmingly sensitive to the distribution and connectivity of macropores pores typically greater than 75 µm in diameter (Beven and Germann, 2013). Water flow in saturated soil is predominantly governed by the Hagen Poiseuille equation principles, where flow velocity is proportional to the square of the pore radius. Consequently, a small increase in the number or size of macro-aggregates dramatically increases k, as water bypasses the slow flow through the soil matrix and utilizes preferential pathways. Organic amendments improve k primarily by acting as binding agents that stabilize clay and silt particles into larger, water-stable aggregates.

The effectiveness of an amendment depends heavily on its decomposition rate and the quality of the binding agents it releases (Six et al., 2004). Seaweed excels in this role due to its unique chemical profile, which is dominated by highly effective, fast-acting biopolymers not found in most terrestrial plants. Seaweed biochar typically exhibits a high degree of intrinsic porosity (surface area ranging from 100 to 500 m^2/g) (Albalasmeh et al., 2022). When incorporated into the soil matrix, these highly stable carbon structures function as long-term, artificial macro-pores and micro-reservoirs, maintaining open channels for water movement even under compaction stress (Lehmann et al., 2015).

The findings of this study demonstrate that seaweed-amended zeolite-bentonite mixtures exhibit properties suitable for application as a novel, sustainable, and eco-friendly buffer material in engineered barriers, particularly for thermal and hydraulic containment systems. Given their enhanced thermal conductivity and controlled hydraulic permeability under elevated temperatures, these composites present a viable solution for use in high-temperature environments, such as encapsulation layers for solid waste repositories or subsurface thermal energy storage structures, where effective sealing and thermal regulation are critical performance requirements.

Author contributions: The author contributed to the study conception and design. Material preparation and data collection were performed by Esra Güneri. The first draft of the manuscript was written by Esra Güneri and the author commented on previous versions of the manuscript. The author read and approved the final manuscript.

Funding: No funding was received for conducting this study.

Conflicts of interest: The author declare that has no conflicts of interest regarding the publication of this paper.

References

Abrouki, Y., Mabrouki, J., Anouzla, A., Rifi, S. K., Zahiri, Y., Nehhal, S., ... and Souabi, S. (2021). Optimization and modeling of a fixed-bed biosorption of textile dye using agricultural biomass from the Moroccan Sahara. Desalination and Water Treatment, 240, 144-151.

Abu-Farsakh M., Dhakal S., Chen Q., Laboratory characterization of cementitiously treated/stabilized very weak subgrade soil under cyclic loading, Soils Found. 55 (3) (2015) 504–516.

Albalasmeh, A. A., Ghorbani, A., and Papanikolaou, G. (2022). Seaweed biochar combined with organic amendments enhances soil water retention and hydraulic conductivity in degraded agricultural soils. *Soil and Tillage Research*, *215*, 105202.

Amir, N., Hussin, F., Aroua, M. K., and Gozan, M. (2024). Greener lightweight foam concrete using seaweed industrial by-product to replace natural sand with inorganic salt as a stabilizer. Journal of Building Engineering, 97, 110815.

Amir, N. and Gozan, M. and Aroua, M. and Alhamid, M. (2025). Development and performance evaluation of a novel industrial-scale fixed bed dryer for alkali-treated eucheuma cottonii chips. Sustainable Energy Technologies and Assessments. 81. 104453. 10.1016/j.seta.2025.104453.

Andersland, 0. B. and Ladanyi, B., (1994). An Introduction to Frozen Ground Engineering, Chapman and Hall, New York.

ASTM: D698-12 (2012) Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM Int. https://doi. org/ 10. 1520/ D0698- 12.1.4

ASTM (2001) ASTM D5084-16 “Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter.” ASTM Int. https:// doi. org/ 10. 1520/D5084- 16A.1

Beven, K., and Germann, P. (2013). Macropores and water flow in soils revisited. *Water Resources Research*, *49*(6), 3071–3078.

Chen, G.J., Maes, T., Vandervoort, F., Sillen, X., Van Marcke, P., Honty, M., and Vanderniepen, P., (2014) Thermal impact on damaged Boom Clay and Opalinus Clay: permeameter and isostatic tests with μCT scanning. Rock Mech. Rock. Eng.47 (1), 87–99.

Cho, W.J.; Lee, J.O.; Chun, K.S. The temperature effects on hydraulic conductivity of compacted bentonite. Appl. Clay Sci. 1999, 14, 47–58.

Cho, W.J.; Lee, J.O.; Chun, K.S. Influence of temperature elevation on the sealing performance of a potential buffer material for a high-level radioactive waste repository. Ann. Nucl. Energy 2000, 27, 1271–1284

Constantz J., Murphy F. (1991) The temperature dependence of ponded infiltration under isothermal conditions. J Hydrol 122:119–128

Daniel, D. E. (1994). State of the Art: Hydraulic Conductivity of Compacted Clay. *Journal of Geotechnical Engineering, 120*(2), 487-505.

Daniels, K. A., Harrington, J. F., Zihms, S. G., and Wiseall, A. C. (2017). Bentonite Permeability at Elevated Temperature. *Geosciences*, *7*(1), 3. https://doi.org/10.3390/geosciences7010003

Delage, P., Sultan, N., Cui, Y. J., (2000) On the thermal consolidation of boom clay. Canadian Geotechnical Journal 37, 343–354.

Duarte, C. M., Middelburg, J. J., and Caraco, N. (2005). Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, *2*(1), 1–8. https://doi.org/10.5194/bg-2-1-2005

Duley F-L, Domingo C-E (1943). Effect of water temperature on rate of infiltration. Soil Sci Soc proc 31:129–131

Efendy, M., Syarif, M., Amir, N., and Hidayat, R. (2023). Economic feasibility case study of developing a salt production plant. The Engineering Economist, 68(2), 99-121.

Firoozi A.A., et al., Assessment of nano-zeolite on soil properties, Aust. J. Basic Appl. Sci. 8 (19) (2014) 292–298.

Freeze, R. A., and Cherry, J. A. (1979). *Groundwater*. Prentice-Hall.

Garcia-Gutierrez A., Espinosa-Paredes G., Energy Conversion and Management, 45, 755-764 (2004).

Güneri, E. (2024). Determination of the Hydraulic Conductivity Behavior of Seaweed Added Zeolite-Bentonite Mixtures in the Presence of Temperature with Empirical Relationships. Çukurova Üniversitesi Mühendislik Fakültesi Dergisi, 39(3), 617-623. https://doi.org/10.21605/cukurovaumfd.1559943

Hopmans J, Dane J (1986). Temperature dependence of soil hydraulic properties. Soil Sci Soc Am J 50:4–9

International Atomic Energy Agency (IAEA). Storage of Radioactive Waste: Safety Guide; IAEA Safety Standards Series No. WS-G-6.1; IAEA: Vienna, Austria, 2006.

Jacinto, A.; Gomez-Espina, R.; Villar, M.V.; Ledesma, A. Effect of temperature on the retention capacity of compacted bentonite: An experimental and numerical investigation. In Proceedings of the International Meeting on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Lille, France, 17–20 September 2007.

Kaminskas, Rimvydas and Barauskas, Irmantas. (2014). Influence of pozzolana on sulfate attack of cement stone affected by chloride ions. Materials and Structures. 47. 1901-1910. 10.1617/s11527-013-0159-5.

Kang, G., Tsuchida, T., Athapaththu, A.M.R.G. (2016). Engineering behavior of cement-treated marine dredged clay during early and later stages of curing. Eng. Geol. 209, 163–174.

Laloui, L. (2001). Thermo-Mechanical Behaviour of Soils. Revue Française de Génie Civ-il. 5:6, 809-843, DOI: 10.1080/12795119.2001.9692328.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, S. A., Hockaday, D. K., and Crowley, D. (2015). Biochar effects on soil biota—A review. *Soil Biology and Biochemistry*, *88*, 78–103.

Liao, Y. C., Chang, C. C., Nagarajan, D., Chen, C. Y., and Chang, J. S. (2021). Algae-derived hydrocolloids in foods: applications and health-related issues. Bioengineered, 12(1), 3787-3801.

Liu Y., et al., Utilization of cementitious material from residual rice husk ash and lime in stabilization of expansive soil, Adv. Civ. Eng. 2019 (2019).

Liu Y., Gao W. and Wang X., (2023) Research on the history, ecology, and design of folk houses:A review of the literature on seaweed houses in China, Journal of Asian Architecture and Building Engineering, 22:6, 3414-3434, DOI: 10.1080/13467581.2023.2213293

Martone, P. T., Estevez, J. M., Lu, F., Ruel, K., Denny, M. W., Somerville, C., and Ralph, J. (2009). Discovery of lignin in seaweed reveals convergent evolution of cell-wall architecture. *Current Biology*, *19*(2), 169–175. https://doi.org/10.1016/j.cub.2008.12.031

Masri, M., Younes, S. and Haack, M. and Qoura, F. and Mehlmer, N. and Brück, T. (2017). A Seagrass-Based Biorefinery for Generation of Single-Cell Oils for Biofuel and Oleochemical Production. Energy Technology. 6. 10.1002/ente.201700919.

McDowell C., Stabilization of soils with lime, lime-flyash, and other lime reactive materials, Highw. Res. Board Bull. 231 (1) (1959) 60–66.

Mohanraj R.,Senthilkumar S., Goel Prince, Bharti Ronak,A state-of-the-art review of Euphorbia Tortilis cactus as a bio-additive for sustainable construction materials, Materials Today: Proceedings,2023,ISSN 2214-7853,https://doi.org/10.1016/j.matpr.2023.03.762.

Muthukumar, J., Chidambaram, R., and Sukumaran, S. (2021). Sulfated polysaccharides and its commercial applications in food industries—A review. Journal of Food Science and Technology, 58(7), 2453-2466.

Nuclear Decommissioning Authority (NDA). The UK Radioactive Waste Inventory; NDA Report No. NDA/ST/STY(11)0004; NDA: Cumbria, UK, 2010.

Nwonu D.C., Ikeagwuani C.C., Evaluating the effect of agro-based admixture on lime-treated expansive soil for subgrade material, Int. J. Pavement Eng. 22 (12) (2021) 1541–1555.

Orth, R. J., Carruthers, T. J. B., Dennison, W. C., Duarte, C. M., Fourqurean, J. W., Heck, K. L., Hughes, A. R., Kendrick, G. A., Kenworthy, W. J., Olyarnik, S., Short, F. T., Waycott, M., and Williams, S. L. (2006). A global crisis for seagrass ecosystems. *BioScience, 56*(12), 987–996. https://doi.org/10.1641/0006-3568(2006)56[987:AGCFSE]2.0.CO;2

Papazian, S., Parrot, D., Burýšková, B. et al. Surface chemical defence of the eelgrass Zostera marina against microbial foulers. Sci Rep 9, 3323 (2019). https://doi.org/10.1038/s41598-019-39212-3.

Pusch, R. Permeability of Highly Compacted Bentonite; Technical Report TR-80-16; Svensk Kärnbränslehantering AB (SKB): Stockholm, Sweden, 1980. [Google Scholar]

Romero E, Gens A, Lloret A (2001) Temperature effects on the hydraulic behaviour of an unsaturated clay. Geotech Geol Eng 19:311–332

Scheller, H. V., and Ulvskov, P. (2010). Hemicelluloses. *Annual Review of Plant Biology, 61*, 263–289. https://doi.org/10.1146/annurev-arplant-042809-112315

Six, J., Frey, S. D., Thomsen, I. K., and Christensen, B. T. (2004). Assessing the potential for soil carbon sequestration via aggregate stabilization in the Nordic and Baltic regions. *Journal of Environmental Quality*, *33*(1), 16–22.

Sultan, N., (1997) Etude du comportement thermo-mécanique de l'argile de Boom:expériences et modélisation (PhD thesis) Ecole Nationale des Ponts et Chaussées, p.217.

Susilorini, R. M. R., Hardjasaputra, H., Tudjono, S., Hapsari, G., Wahyu, S. R., Hadikusumo, G., and Sucipto, J. (2014). The advantage of natural polymer modified mortar with seaweed: green construction material innovation for sustainable concrete. Procedia Engineering, 95, 419-425.

Terzaghi, K., Peck, R. B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice* (3rd ed.). John Wiley and Sons.

Winterkorn, H.F., and Pamukcu, S. (1991). Soil Stabilization and Grouting.

Yang, J. 2012. "Properties Analysis of Seaweed as a Traditional Building Material." Advanced Materials Research 450–451: 154–157. doi:10.4028/www.scientific. net/AMR.450-451.154.

Yang, J., and Y. Qian. 2019. "Experimental Analysis and Utilization of Seaweed Materials." New Building Materials 46: 91–94. doi:10.3969/j.issn.1001-702X.2019.04.023.

Yoobanpot, N., Jamsawang, P., Horpibulsuk, S. (2017). Strength behavior and microstruc-tural characteristics of soft clay stabilized with cement kiln dust and fly ash residue. Appl. Clay Sci. 141, 146–156.

Zihms, S.G.; Harrington, J.F. Thermal cycling: impact on bentonite permeability. Mineral. Mag. 2015, 79, 1543–1550.

Zinchenko A., et al., Efficient stabilization of soil, sand, and clay by a polymer network of biomass-derived chitosan and carboxymethyl cellulose, J. Environ. Chem. Eng. 10 (1) (2022), 107084.

Copyright (c) 2026 Güneri, E. This work is licensed under a Creative Commons Attribution-Noncommercial-No Derivatives 4.0 International License.