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Geotechnical Investigation of Gelatin Biopolymer on Cohesive Soils

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Abstract: Gelatin, a biopolymer derived from animal proteins, has been selected to stabilize three fine-grained soils by determining select index and engineering properties. Specimens for California Bearing Ratio (CBR) were tested using three different curing methods, i.e., thermally cured at 60 °C, unsoaked, and 7 days air-cured submerged specimens. The amount of gelatin added to the soil ranged from 0.5% to 2% by soil weight. The sequence of the interaction between gelatin and the clays is as follows: (A) The biopolymer solution is adsorbed and agglomerated onto the surface of the clay. (B) The presence of Al^{3+}, Si^{4+}, and K^{+} ions on the clay promotes the blending of connective linkages with negatively charged gelatin. (C) The connection reinforcements harden with the curing period and subsequent drying of the stabilized soils. (D) Drying of the gelatin–clay complex also establishes alternative bonding modes such as van der Waals interactions and ligand exchange. The biopolymer formed dry, rigid films after 72 h which were responsible for coating and reinforcing the soil particles. Thermal curing by 1% addition of gelatin yielded the maximum CBR of 91.42%, 141.1%, and 122.3% for high compressible clay, low compressible clay, and low compressible silt, respectively, and a maximum Unconfined Compressive Strength (UCS) of 3968 kN/m^2 for the low compressible clay. The UCS results revealed that brittle failure was predominant for the gelatin-amended soils after 28 days of curing while shear failure was observed for the treated soils tested 2 h after sample preparation. Tests on pH revealed that the gelatin-stabilized soils displayed marginal variations after 28 days. Spectroscopic analysis revealed the various types of bonds between gelatin and the clays. A reduction in mass of 9% was observed for the alternate wetting and drying of the high compressible clay after a period of 12 cycles. The adsorption of the clay–gelatin complex was indicated by variation in average particle diameter and specific surface. Savings in 450 m^3 and 93.75 m^3 of coarse aggregates and dense bituminous macadam, respectively, were observed for a 1 km pavement for the stabilized low compressible clay.

Keywords: biopolymer; gelatin; soil improvement; thermal curing; unconfined compressive strength

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1. Introduction

In recognition of the contamination effects of chemical soil modifiers on soil and groundwater, the assessment of the ability of biopolymers to improve the engineering properties of soils has gained attention in the last decade. Capable of forming hydrogels, having a high molecular weight, and reducing carbon dioxide emission when compared to conventional chemical binders, biopolymers and recycled waste products have been widely adopted by researchers in the last decade to enhance the geotechnical properties of coarse and fine-grained soils [1]. Sustainability in soil stabilization helps to achieve a reduced carbon footprint, reduced utilization of resources, and elimination of hazardous stabilizers. Other than biopolymers, sustainable stabilization has been demonstrated by Ijaz et al. [2] by the adoption of limestone calcined clay cement in the treatment of high-swelling clay. The UCS of the high swelling clay was enhanced by 500%, and the reductions in carbon content, thermal energy, and electrical energy for a 1 km pavement was found to be 27,420 kg, 350 GJ, and 4,612,594 kWh, respectively. Ijaz et al. [3] emphasized the efficient utilization of lignosulphonate, an industrial by-product, with lime. Sustainable stabilization not only eliminated the swelling potential of the clay but also effectively decreased the adoption of lime while minimizing the impact of landfill disposals. Ijaz et al. [4] reduced the ground heaving of a surficial slope of an unsaturated swelling clay from 4.08 cm to 1.05 cm by utilizing a lignosulphonate-based composite cementing additive. Ijaz et al. [5] neutralized the expansion capability of an expansive clay by treatment with lignosulphonate-based composite cementing additive, an industrial by-product-based composite additive. Reclaimed subbase materials were found to be sustainable stabilizers when mixed with stone dust due to the enhancement in engineering properties while paving the way for field application in pavement sub-soil layers [6]. Ijaz et al. treated problematic clay soil with lignosulphonate, an industrial by-product, and minimized volumetric shrinkage by 90% in addition to enhancing the CBR by 151% [7].

As a soil additive, biopolymers have the potential to solve the trilemma of sustainability, price, and soil suitability. The typical origin of the various polysaccharide and protein biopolymers are microbes, plants, and animals [8]. Some of the microbial polysaccharides used in the improvement of soil properties are as follows. Ham et al. [9] increased the surface erosion resistance and critical shear stress of coarse-grained soil by 800% and 100%, respectively, by the addition of dextran biopolymer. Im et al. [10] observed a 50% improvement in the shear modulus of gellan gum-stabilized kaolin clay due to the amplifying speed of the transverse waves. The blending of xanthan gum with low plastic clay increased fracture toughness and fracture energy by 289% and 489% respectively [11]. Soldo et al. [12] asserted the influence of strain localization on the addition of xanthan gum biopolymer to a low compressible silty soil and inferred that it is possible to advance or postpone the strain localization of the treated soil which in turn promotes the in-situ application of the treatment.

Some of the plant-based polysaccharides used in the improvement of soil properties are as follows. UCS of lignin-treated low plastic silty soil resulted in its improvement from 230 kN/m^2 to 1100 kN/m^2 for a 7-day curing period and the stability of the treated soil fabric enhanced after 28 days of curing [13]. A wind tunnel test on pectin-treated sand revealed no crack formation on the surface, emphasizing the stability of the soil's resistance against erosion [14]. The addition of glucomannan biopolymer increased the cohesion and angle of internal friction of a poorly graded sand from 0 to 34.5 kPa and from 34° to 44° respectively under soaked curing conditions [15]. Soldo et al. [16] observed a 33% increase in the tensile strength of the β-glucan-treated silty sand. The addition of locust bean gum to saline sand and sand containing 10% iron oxide increased the UCS from 0 to 3713 kN/m^2 and 83 kN/m^2 to 4510 kN/m^2, respectively [17]. To increase the durability and engineering behavior among the treated biopolymer soils, two different biopolymers have been combined for soil stabilization. Ni et al. [18] observed an 87% reduction in the coefficient of consolidation and volume compressibility in the treatment of sandy lean clay with a carrageenan–casein biopolymer combination. The stability of poly-glutamic acid and xanthan gum biopolymers at varying temperatures and pH prohibited the movement of fluid through the soil pores, which led to the isolation of underground contaminants. Cross-linking of guar gum with xanthan gum biopolymer resulted in 264% and 21% improvement in the tensile strength of clayey sand compared to the individual stabilization of guar gum and xanthan gum, respectively. Cross-linking of biopolymers enhanced the stability of the hydrogel, thereby increasing the strength of the treated soil [19].

Among the protein biopolymers, the utilization of casein on granular sand increased the cohesion intercept of submerged specimens and dried specimens by five times and 14 times respectively. The collapse potential of the casein-treated soils decreased by 80%. Ni et al. [18] reduced the compression index of a sandy lean clay at all vertical stresses through treatment with casein biopolymer. Subjecting the casein-treated sand samples to a wind speed of 150 km/h resulted in a 69% reduction in loss of mass [20].

Gelatin, a hydrophilic protein biopolymer capable of forming strong, stable gels and exhibiting surface-active characteristics, has been used in this study to understand the effect of protein-based biopolymers on the geotechnical properties of soil. Gelatin is obtained by overheating collagen until denaturation takes place. The denaturation temperature of fish collagen to obtain gelatin is 5 °C to 30 °C. However, the thermal stability of the resulting gelatin is 240 °C. Hence, it is sustainable. It belongs to a class of thermoplastic hetero-polymers and is being used in the photographic and cosmetic industries among other miscellaneous applications [21]. Owing to collagen's triple helix complex network, the gels produced by gelatin are sturdy even with reduced water intake [21]. The gelatin biopolymer used in the study is obtained from fish bones. The mechanism of clay–gelatin interaction and its effects on the soil's performance under different periods are crucial for stabilization [1]. The adoption of protein biopolymers in soil stabilization is relatively lesser than that of polysaccharides, and biopolymers from animal sources have scarcely been applied in soil treatment as compared to microbial and plant sources. Limited literature has investigated the applicability of gelatin in soil strengthening. Thermal treatment in the biopolymer stabilization of soils has been reported to increase durability and better resistance to compressive loadings [22]. The World Health Organization (WHO) conducted toxicology studies on xanthan gum and guar gum biopolymers and concluded that they did not pose health risks. Gelatin is widely used in the packing of pharmaceutical medicines among other applications. Certain chemical additives improve the strength of the soil while impacting its pH whereas the pH of the gelatin stabilized soil showed marginal variations even after 28 days of curing. The present study aims to ascertain the strengthening potential of gelatin-treated soils under varying curing methods and curing periods, and analyzes the effect of stabilization on the UCS and CBR of the soils.

2. Materials and Methods

Highly compressible clay, low compressible clay, and low compressible silt were used for the study. The highly compressible kaolin clay is primarily composed of kaolinite minerals possessing the following elements: carbon (15.85%), oxygen (60.09%), aluminum (11.6%), and trace elements. The chief elements present in the low plastic clay are oxygen (65.08%), silicon (17.58%), and aluminum (9.28%), along with trace elements. The major elements in the low plastic silt are carbon (14.82%), oxygen (54.69%), calcium (13.5%), silica (6.93%), and aluminum (3.11%), along with trace elements. The geotechnical properties of the soils used for the study are presented in Table 1. The molecular structure of the gelatin biopolymer is shown in Figure 1.

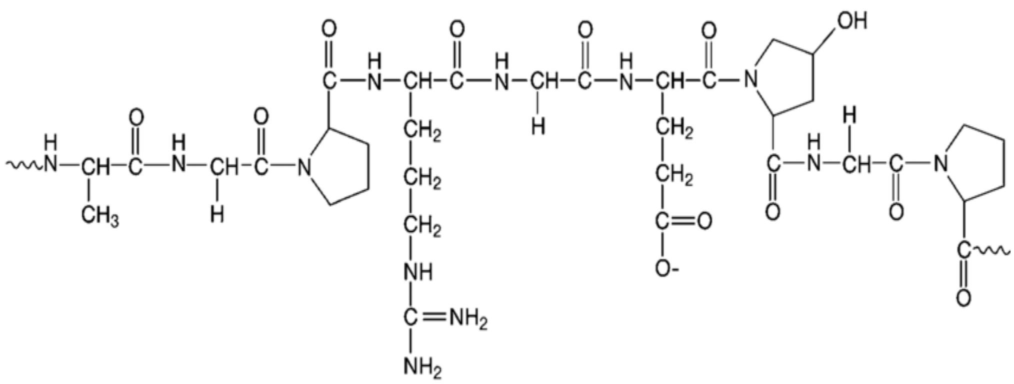

Figure 1. Molecular structure of gelatin [23].

Table 1. Soil properties.

Properties	High Compressible Clay	Low Compressible Clay	Low Compressible Silt
Collection of Soil	Astraa Chemicals, Chennai, TN, India	Srirangam, Trichy, TN, India	Srirangam, Trichy, TN, India
Sand (%)	-	13	17
Clay (%)	100	54	36
Silt (%)	-	33	47
Liquid limit (%)	58.4	34	29
Plasticity index (%)	34.1	14.8	7.7
Classification	CH	CL	ML
Specific Gravity	2.72	2.74	2.71

The gelatin biopolymer was purchased from Alpspure Life sciences, New Delhi. Gelatin is a yellowish coarse powder with a pH of 6.70 and specific gravity of 1.10. Molecular weight and viscosity at 2% concentration were found to be 0.8 million g/mol and 33 cP, respectively. Soil samples for the experimental investigation were prepared by wet mixing [24]. With the addition of water, the gelatin biopolymer forms a gel solution. The amount of water added is close to the dry of optimum moisture content (OMC) i.e., less than 20%, 8%, and 10% of CH, CL and ML soils, respectively, while the remaining water was added during the mixing of the soils with the gel. The mixed soil was sealed for 2 h before molding the samples for the experiments to promote the initial reaction between the biopolymer and the soils.

The experimental program includes the determination of consistency limits, maximum dry unit weight (MDU), OMC, UCS, CBR, permeability, pH, average particle size, specific surface area, durability, and spectroscopic and surface topography of the gelatin-treated soils. The consistency limits were determined by the Casagrande liquid limit apparatus as per the procedure outlined in IS 2720 (Part 5)—1985 [25]. A light compaction test was performed as per the procedure outlined in IS: 2720 (Part 7)—1980 [26]. The UCS for the untreated and gelatin-modified soils was determined as per the procedure outlined in IS: 2720 (Part 10)—1991 [27]. The CBR of the control and modified soils was determined as per the procedure outlined in IS: 2720 (Part 16)—1987 [28]. The pH of the control and gelatin-amended soils were determined as per the procedure outlined in IS: 2720 (Part 26)—1987 [29]. A Scanning Electron Microscope (SEM) of the make and model TESCAN VEGA3 was used to observe the interfacial interactions of the biopolymer-stabilized kaolin. A Perkin Elmer Spectrum One Fourier-transform infrared spectroscopy (FTIR) spectrometer was used for the FTIR analysis of soils. A Malvern Panalytical zetasizer was used to determine the average particle size of the unamended and gelatin-amended soils. The durability of the treated specimens by 12 cycles of submergence and oven drying was performed as per IS: 4332 (Part 4)—1968 [30]. The test for alternate wetting and drying was conducted for cylindrical samples of 38 mm × 76 mm wrapped in a thin polythene film [31]. After a week of air curing, the treated soil specimens were submerged for five hours and oven dried at 70 °C for 42 h. Measurement of mass and specimen dimensions was undertaken after submergence and oven drying. The procedure was repeated for 12 cycles.

In addition to the conventional CBR test for the unsoaked and soaked specimens, the test has been additionally conducted for the thermal curing of 7 days to determine the efficacy of thermal curing in gelatin-treated soils. Furthermore, for the above-soaked CBR condition, the specimens were submerged after only 7 days of air curing because of the consistent findings in multiple literature studies that the first 7 days produced enormous strength gain [32,33]. In addition, thermal curing in the field remains a challenge, and thus air curing was adopted for the initial 7 days before submergence. CBR specimens were thermally cured at 60 °C as demonstrated by Shariatmadari et al. [34] and Bocheńska et al. [35]. Specimens were not subjected to curing temperatures beyond 60 °C due to the potential degradation of the biopolymer and weakening of the bond between the biopolymer and the soil [4]. The methodology involves the determination of CBR by three different curing methods to assess the best curing method and to infer the engineering behavior of the gelatin-treated soils under varying curing conditions. The UCS was determined for 3 days and 7 days for the thermally cured specimens. Thermal curing was not extended beyond 7 days and air curing was adopted from the 8th day to the 28th day to limit the exposure of heat on gelatin linkages with the clays over extended periods. The UCS was additionally determined on the same day of specimen preparation after 2 h of air curing to assess the immediate effect of the biopolymer on the soil.

3. Results

3.1. Liquid and Plastic Limits

The liquid limit of the CH, CL, and ML soils were found to be 58.4%, 34%, and 29%, respectively, and the plasticity index values were observed to be 34.1%, 14.8%, and 7.7%, respectively. The addition of gelatin increases the liquid limit and plasticity of the soils owing to the gelatin's affinity for absorbing water [21]. A linear increase in the liquid limit and plasticity index values was due to the variation in the specific surface, electrostatic attraction in the clay soils, and variations in the double layer of the amended soils [36]. The presence of gelatin increments the unit weight of the diffuse double layer of the clays due to its rheological characteristics [37]. Thus, the clay soil consumes excess water to actualize the double layer, which in turn raises the liquid and plastic limits of the soil. The agglomeration of the clay–gelatin complex was instantaneous during the mixing and testing of the liquid and plastic limits which revealed the adsorption of the gelatin onto the soil. The workability of the treated soil became poorer due to the viscosity and flocculation, which led the hydrophilic biopolymer to take in additional water. This increase in water ameliorated the workability of the treated soils [18]. Seo et al. [38] adopted chitosan biopolymer to improve slope stability by reducing surface erosion by 51%. Figure 2 shows the variations in liquid limit and plasticity index.

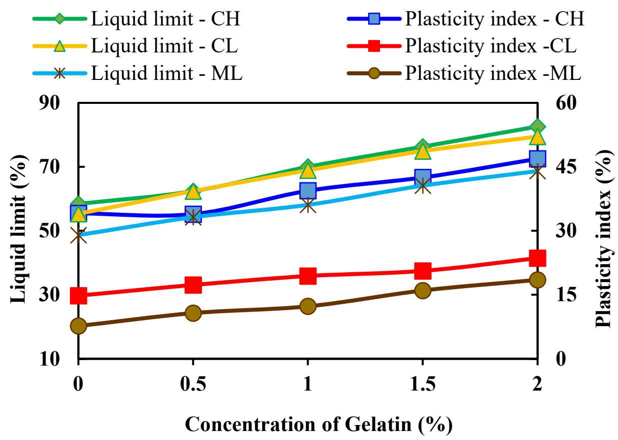

Figure 2. Liquid limit and plasticity index of gelatin-treated soils.

3.2. Compaction Characteristics

The increased requirement of water to achieve the OMC is due to the presence of an OH functional group in gelatin biopolymer. The specific gravity of the gelatin is 59% lower than the specific gravity of the soils, and thus the MDU of the soils reduces with increasing concentration of gelatin. Assimilation of excess moisture further promotes reduction in the dry unit weight of the gelatin-treated soils. When gelatin solution is subjected to fine-grained soils, the soils are instantaneously glued to the hydrophilic biopolymer solution, promoting the further requirement of water on every successive concentration of gelatin. An increase in the viscosity of the gelatin gel was found to be the underlying reason for the reduction in MDU. The viscosity and flocculation of the gelatin-stabilized soils prevented the clay particles from moving to nearer positions, thereby ineffectively filling the pores. Excess water lubricates the soil leading to the decrease in the proximity of the soil particles [39]. A similar finding on a viscous biopolymer was recorded by Kumar et al. [40], who observed a marginal reduction in MDU with the addition of guar gum to an assorted clayey-sandy geomaterial.

Figure 3 displays the variations of OMC and MDU for varying percentages of gelatin.

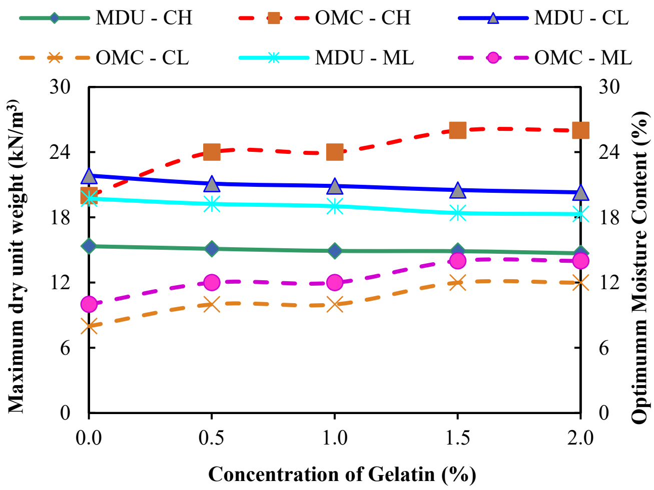

Figure 3. Compaction behavior of gelatin-treated soils.

3.3. UCS

The UCS of the CH, CL, and ML was found to be 140 kN/m^2, 196 kN/m^2 and 217 kN/m^2, respectively. After a week of thermal curing, the untreated specimens exhibited 189 kN/m^2, 316 kN/m^2 and 268 kN/m^2 for CH, CL, and ML soils, respectively. In addition to gelatin biopolymer, the UCS of thermally cured specimens was found to be higher than the UCS of air-cured specimens tested after two hours of sample preparation on the same day. Maximum UCS of 271 kN/m^2, 345 kN/m^2, and 436 kN/m^2 were observed for air-cured specimens of CH, CL, and ML soils at 1% gelatin addition, respectively. On thermal curing, the maximum UCS was achieved first for CL soil, followed by ML and CH soils respectively. The 3-day and 7-day strength of CL soil was found to be 1869 kN/m^2 and 3719 kN/m^2, respectively. Figure 4 shows the UCS of treated soil after 2 h of curing (non-thermal), thermally cured soil specimens (3, 7 days), and thermally cured and air-cured specimens (28 days).

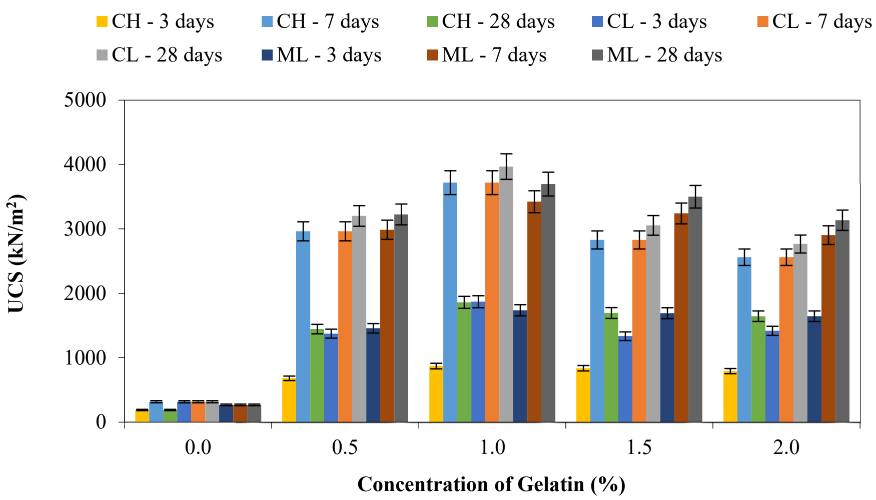

Figure 4. UCS of gelatin-treated soils.

The provision of curing time and selection of curing methods enhanced the strength of the soils. An increase in strength with an increase in curing days was observed, but the percentage of strength increase after 7 days of curing was observed to be less than the first week of curing. Loss of water during drying transforms the gelatin gel into a sharp, prickly gelatin film which not only coats the surface of the soil but also entwines the soil particles and fills the gaps in the soil particles. A similar observation was reported by Barani and Barfar [11] regarding the transmutation of gel into a glassy state. The curing of the specimens is responsible for the above transformation and the stiffness. In the case of gelatin, the transformation into sharp, prickly films was rapid and occurred in less than 72 h. Reddy et al. [41] reported that the biopolymer films do not deteriorate even after many years after adsorption with the soils. However, a detailed study on the long-term durability assessment of the gelatin-treated soil is necessary [6]. Enhanced co-action between gelatin and the soils is also due to the establishment of chemical bonds by the functional groups of the biopolymer with the soil. Covalent amide bonds, hydrogen bonds, and Van der Waals forces contributed to the strengthening of the soils [42]. A similar finding of strength increase has been reported for an anionic biopolymer in contact with clay soil by Bozyigit et al. [43] in which the efficacy of xanthan gum in treatment with kaolin increased the UCS by 423%. The existence of nitrogen in the gelatin promotes the long-term durability of the stabilized soil [44]. Figure 5 reveals the stress–strain curves of UCS tests.

Improved areal extent under the UCS curves was higher for thermally cured specimens at all concentrations, indicating the toughness of the treated soils over control soil samples. Agglomeration of the soils at the bonding sites alters the soil structure, and brittle failure was observed for the gelatin-treated soils which were thermally cured [45]. The UCS of the specimens tested after two hours did not exhibit brittle failure. Barani et al. [11] observed similar trends for peak strength corresponding to varying water contents. An increase in UCS is a direct product of the cohesive and binding attributes of gelatin onto the soils. The presence of biopolymers increased the stiffness of the soils in a non-linear manner in the air-cured specimens tested after 2 h [16]. The modulus of elasticity increased with increasing concentration in the thermally cured specimens. Chang and Cho [46] showed the effects of the application of heat on compressive strength and ascribed the superlative results to the rigidity of the specimens upon depletion of water. The removal of water during thermal curing is responsible for the brittle failure of the soil [11]. In thermal treatment, the percentage reduction in UCS with a higher gelatin concentration was found to be less than the percentage reduction in UCS of the non-thermally treated soils. Chang et al. [22] demonstrated that the submergence of a thermo-gelation biopolymer after the process of air drying helped the amended soil regain its strength, even after submergence, as compared to unmodified soil. Untreated soils do not bear large strains even after thermal treatment. Non-thermal soils fail relatively quickly compared to thermally cured specimens. When thermally cured, higher percentage additions of gelatin biopolymer resist the compressive stresses irrespective of the optimum percentages. Mujtaba et al. [47] utilized pulverized glass wastes to stabilize expansive clay soil, strengthening the soaked CBR by 288% and decreasing the swelling potential by 87%. Figure 6a–c, shown below, reveal the brittle failure of the UCS specimens under thermal curing after 28 days, while Figure 6d reveals the shear failure of untreated low plastic clay.

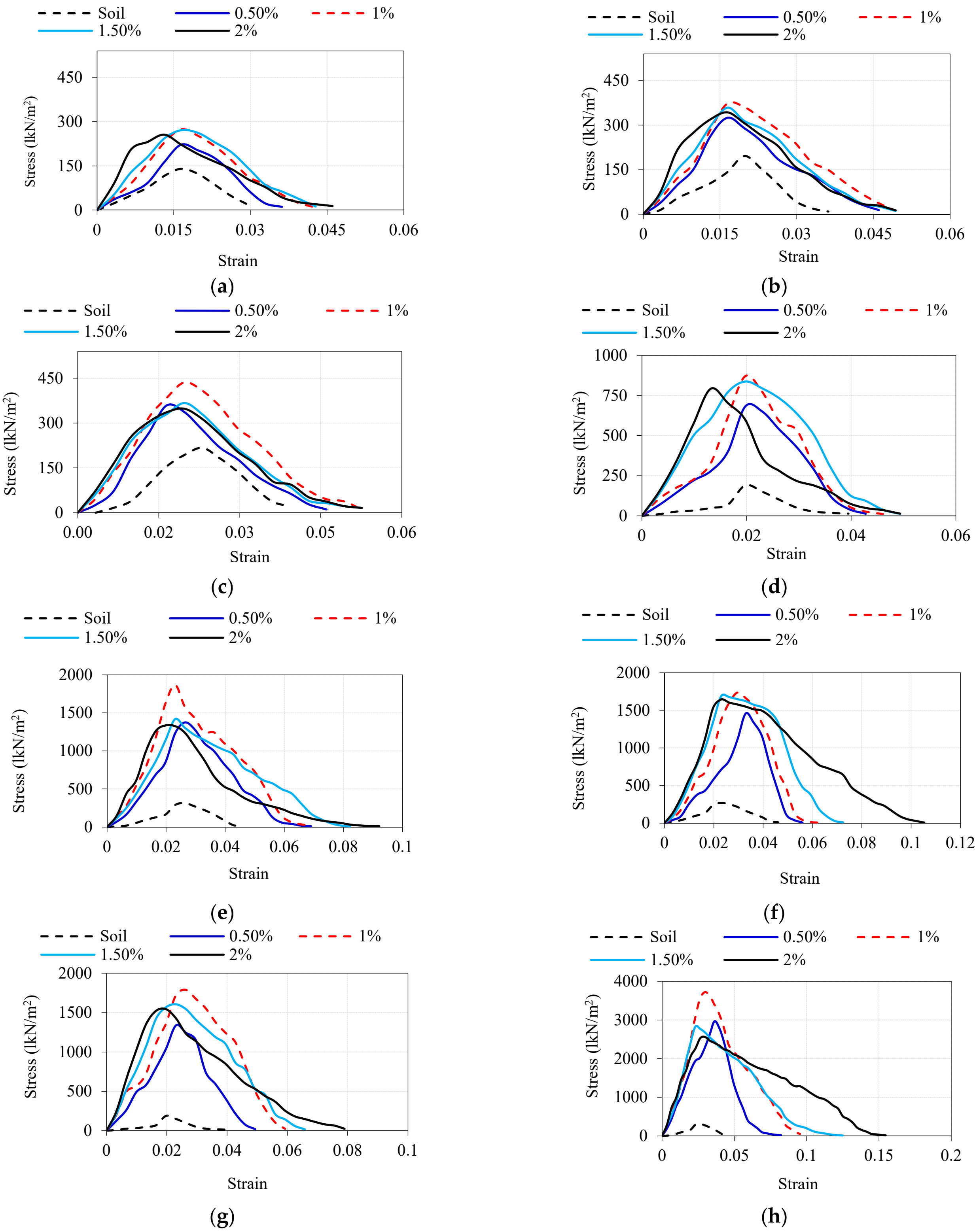

Figure 5. *Cont*.

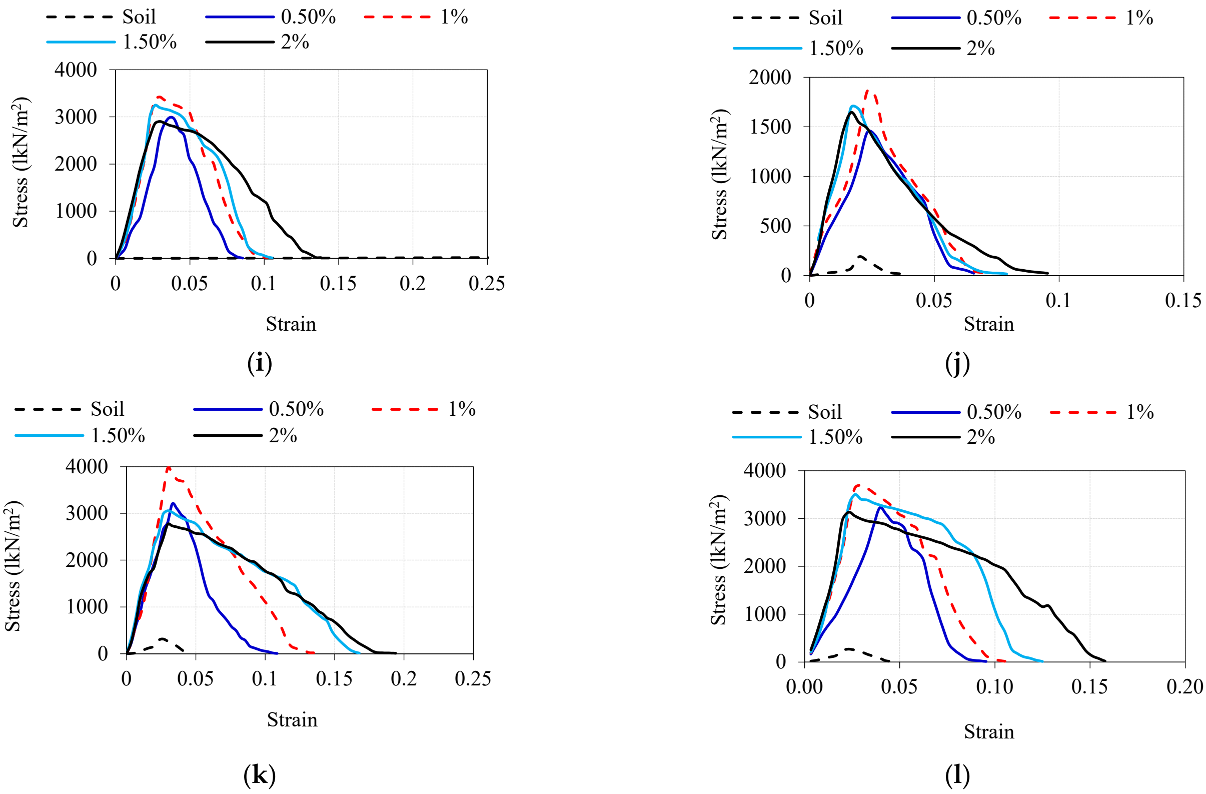

Figure 5. Stress-strain curves of UCS tests: (**a**) CH + Gelatin—2 h; (**b**) CL + Gelatin—2 h; (**c**) ML + Gelatin—2 h; (**d**) CH + Gelatin—3 days; (**e**) CL + Gelatin—3 days; (**f**) ML + Gelatin—3 days; (**g**) CH + Gelatin—7 days; (**h**) CL + Gelatin—7 days; (**i**) ML + Gelatin—7 days; (**j**) CH + Gelatin—28 days; (**k**) CL + Gelatin—28 days; (**l**) ML + Gelatin—28 days.

3.4. CBR

The test finds application in the design of flexible pavements by empirical and mechanistic design methodologies and assesses the choice of soil for the suitability of foundation soil for the pavement. Air curing of specimens for one week facilitated bonding between the soils and the gelatin biopolymer. After 7 days of air curing, the specimens were submerged for 96 h before the test. Resistance to penetration is high under dried conditions due to the higher frictional resistance compared to in submerged conditions [48]. The microstructural modifications during the curing days enhanced the resistance of the soil to penetration [1]. Both the unsoaked and thermally cured CBR specimens fared better than the air-cured and submerged CBR specimens. After 7 days' thermal curing, the CBR of CH, CL, and ML soils was increased by 1224.9%, 1056.6%, and 963.5%, respectively, after a 1% optimum addition of gelatin. The unsoaked CBR of CH, CL, and ML soils increased by 614.6%, 658.9%, and 527.2%, respectively, after a 1% addition of gelatin. The submerged CBR percentage of CH, CL, and ML soils increased by 118.7%, 84.3%, and 82.2%, respectively, after the optimum addition of gelatin. The interaction mechanism involving gelatin with the clays is as follows. The clayey and silty soils comprise Al^{3+}, Si^{4+}, and K^{+} ions, which promote the blending of connective linkages with the negatively charged gelatin. The connection reinforcements harden with the curing period and subsequent drying of the stabilized soils. Drying of the gelatin–clay complex due to thermal curing promotes alternative bonding modes of short-range order, such as van der Waals interactions [43]. There is also the bond formed by a process known as "ligand exchange," in which the negatively charged gelatin moves into the inner coordination layer of the edge aluminum and forms a stable complex with it. For kaolin clay, the negatively charged gelatin could be repelled from the surface of the clay, resulting in relatively minimal adsorption. This is also a reason for the relative reduction in CBR when compared to the other two-clay soils. The underperformance of the biopolymer-treated soils under submerged conditions could be due to the non-uniform, modified gel matrix in the treated soil [49]. For CL and ML soils, electrostatic interaction and adsorption were greater due to the opposing charges of the clay–gelatin complex. The molecular interactions in the three treated soils are illustrated in Section 3.6.1 of FTIR.

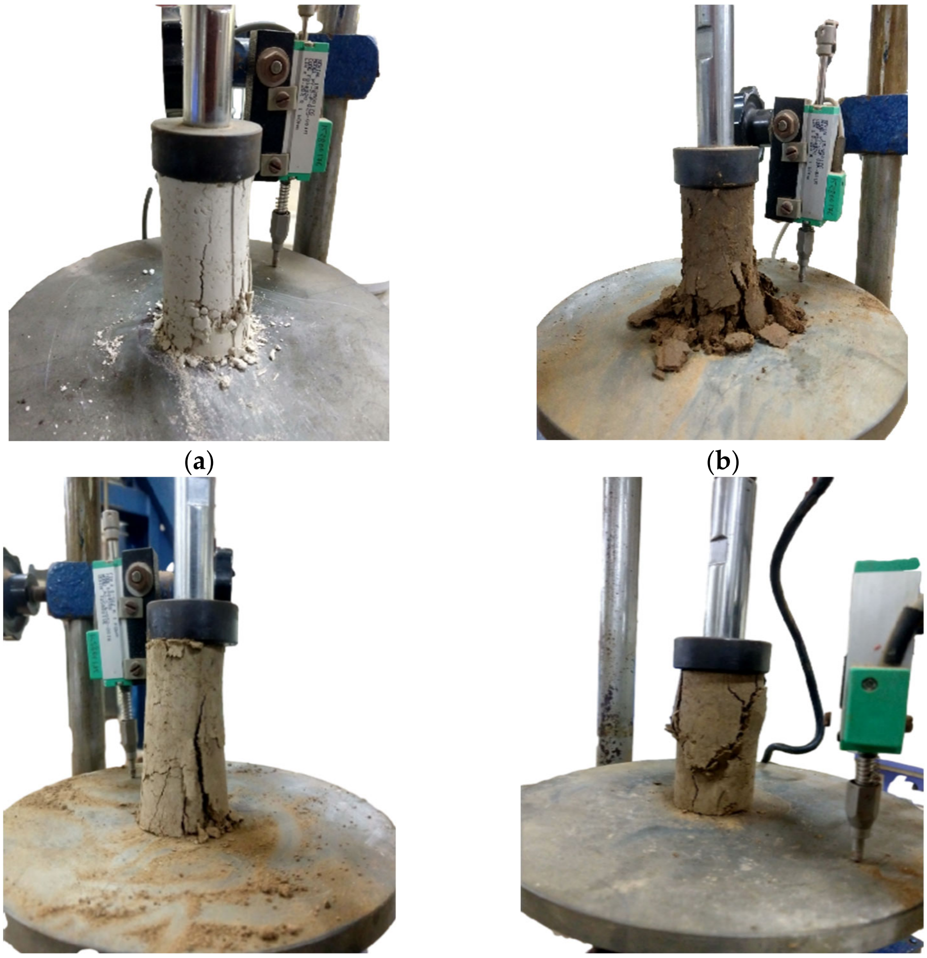
(a) (b) (c) (d)

Figure 6. Failure of UCS specimens: (**a**) CH + Gelatin; (**b**) CL + Gelatin; (**c**) ML + Gelatin; (**d**) CL.

Increasing the amounts of gelatin above 1% tends to push the clay particle due to the lubricating effect of the biopolymer on the soil, which in turn reduces hydrogen covalent bonding in soils [50]. Improvement in the CBR of the soil after biopolymer treatment has been noted by Elkafoury et al. [51], Mohan et al. [52], Hamza et al. [53], Arab et al. [45], etc. Reduction in the voids of the soils by the presence of biopolymer linkages decreases the deformation of the soils and contributes to an increase in CBR values. Figure 7 displays the results of CBR for the treated soils.

Mohan and Adarsh [52] observed an increase in the CBR of highly compressible clay soil after treatment with guar gum biopolymer and added that extending the soaked curing period up to 28 days further enhanced the CBR values by 500%. Onah et al. [49] improved the CBR of a low plastic clay soil from 11.9% to 121% with the addition of lime and guar gum biopolymer. A similar finding of CBR increase has been reported for an anionic biopolymer in contact with clay soil by Hamza et al. [54], who improved the CBR of fat clay with xanthan gum biopolymer by 848%.

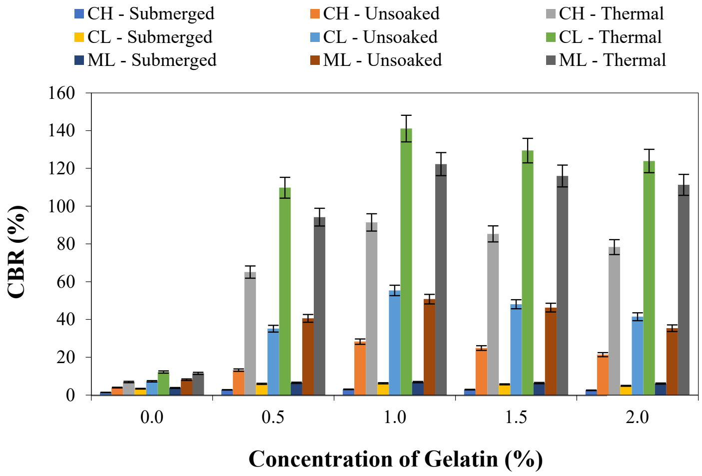

Figure 7. CBR of gelatin-treated soils.

3.5. Durability

The encouraging results of the 28-day UCS test reveal that the decomposition of the biopolymer had not taken place. Exposure to water during the wetting cycle disrupts the stability of hardened gelatin hydrogel present within the soil pores. With the increase in the number of cycles, the connection linkages of clay–gelatin were affected, which in turn influenced the loss in weight for each cycle. A higher dosage of gelatin (2%) resists the degradation of the gelatin effectively when compared to the lower concentration (0.5%) due to adequate interparticle bonding and amide bond. Cyclical alternate heating partially restored the hardening and stability of the gel–soil matrix. The reduction in mass for the treated soils was 9%, 7.8%, and 7.9% for CH, CL, and ML soils, respectively. Figure 8 highlights the results of the durability test. Chang et al. [55] and Reddy et al. [56] recorded the biopolymer-treated clay soils' resistance against weathering and revealed that the treated soils were durable after cyclical wetting and drying. Figure 8 highlights the results of the durability test.

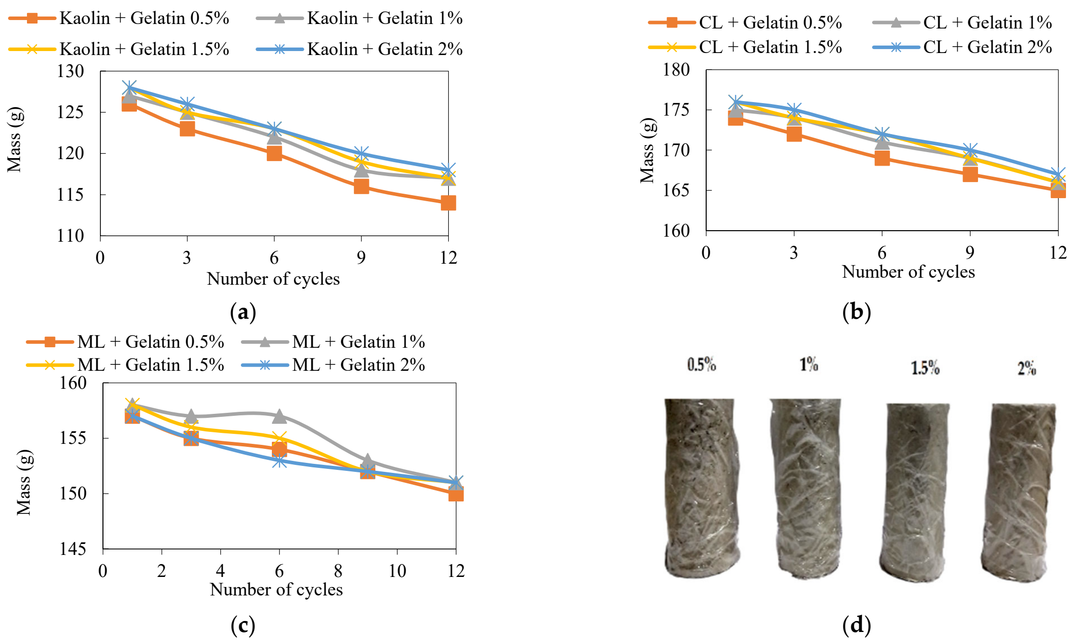

Figure 8. Durability test. (**a**) CH + Gelatin; (**b**) CL + Gelatin; (**c**) ML + Gelatin; (**d**) Durability specimens after 12 cycles.

3.6. Gelatin-Soil Mechanism

3.6.1. FTIR

Gelatin biopolymer contains diverse functional groups involving carbon, oxygen, and hydrogen which offer multiple reaction sites for chemical bonding with the clay and silt soils. Figure 9 highlights the wavenumbers for the FTIR curves of the gelatin-treated soils.

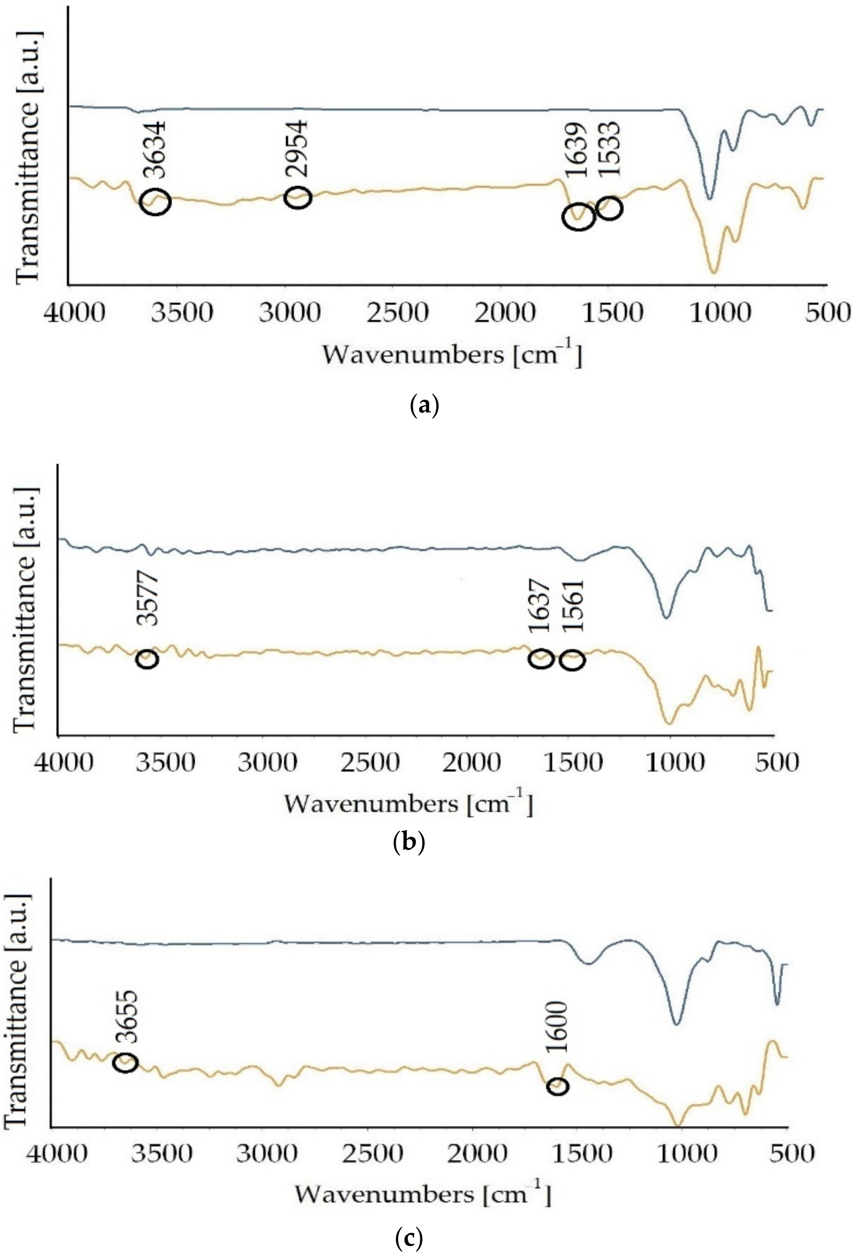

Figure 9. FTIR of Gelatin treated soils: (**a**) CH + Gelatin; (**b**) CL + Gelatin; (**c**) ML + Gelatin. Blue line represents soil. Orange colored line indicates gelatin stabilized soils.

Si-OH stretching was observed for the wavenumbers 3634 cm^{-1}, 3577 cm^{-1}, and 3655 cm^{-1} for CH, CL, and ML soils, respectively [57]. The wavenumbers 1639 cm^{-1}, 1637 cm^{-1}, and 1600 cm^{-1} promoted stretching of CO for CH, CL, and ML soils, respectively [42]. The presence of a hydroxyl functional group indicates the hydrogen bonding of the clay–gelatin complex. Covalent amide bonds were formed by the bending of NH and stretching of CN for CH and CL soils at wavenumbers 1533 cm^{-1} and 1561 cm^{-1}, respectively [42]. Kaolin clay exhibited an additional CH_3 stretching at 2954 cm^{-1} which was not observed for the other two soils, thus highlighting the prevalence of covalent and hydrogen bonding [58]. These covalent amide bonds possess more stability and better adsorption characteristics than hydrogen and Van der Waals interactions. The bonding of CH and OH contributed to the submerged strength while the bonding of CO contributed to the dry strength of the soil [59]. Bending and stretching molecular vibrations were prevalent for all the stabilized soils, thus promoting the bridging of the clay–biopolymer matrix.

3.6.2. SEM

Visual topographical observation of the stabilization at the micro level was carried out with Scanning Electron Microscopy (SEM). The analysis involved a magnification and an applied voltage of 5 kx and 10 kV, respectively, and was carried out by mounting samples by stub and gold coating by sputter. The test was conducted from the failed UCS samples after 28 days of curing. The structure of the untreated low plastic clay reveals a loose porous structure when observed through SEM. Changes in macro engineering properties are due to modifications in the microstructural properties. The gelatin biopolymer not only adsorbed onto the surface layer of the soil but also plugged the soil with filiform linkages. The solidification of the biopolymer solution clusters the clay particles, which strengthens the chemical bonds established by the clay–polymer interaction. The distinctions between the SEM micrographs is concordant with the widely available literature studies for clayey, silty, and sandy soils [1]. Hydration and drying lead to bio-cementation in the treated soil composite [43]. The structural configuration of the resulting treated products at the micro scale induces modifications in their engineering properties [1]. Figure 10 shows the images from SEM for the soils treated with gelatin.

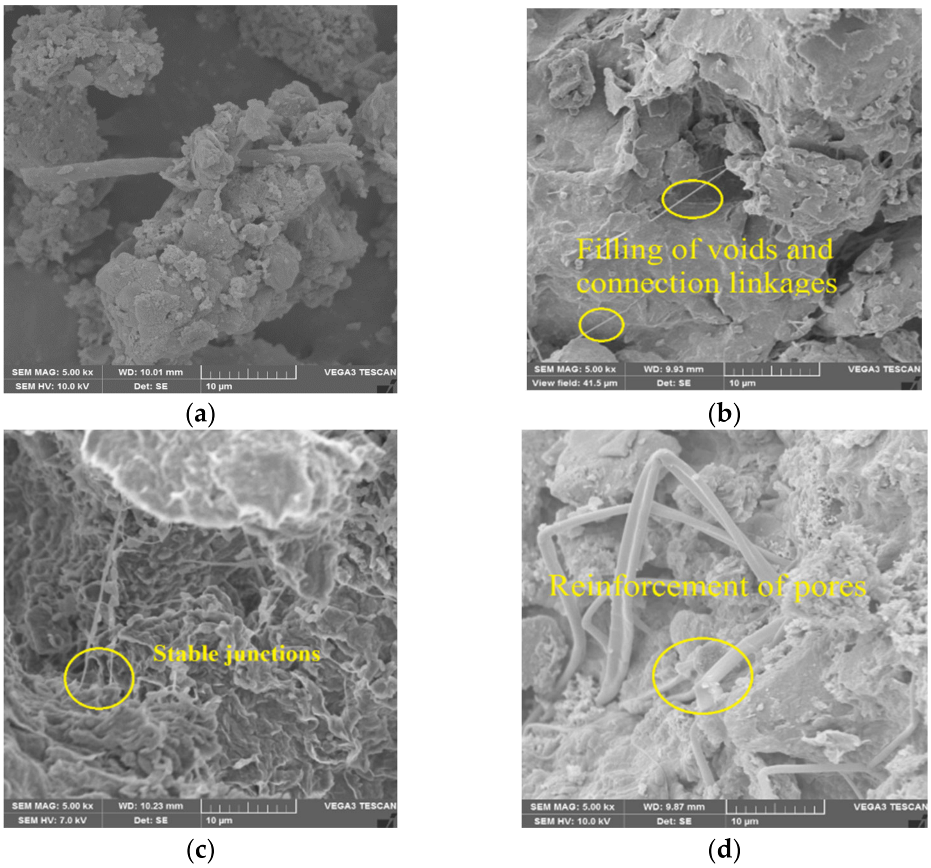

Figure 10. SEM of Gelatin treated soils: (**a**) Untreated CL; (**b**) Gelatin treated CH; (**c**) Gelatin treated CL; (**d**) Gelatin treated ML.

3.6.3. Average Particle Size Determination

The average particle size of CH, CL, and ML soils was found to be 441 nm, 521 nm, and 632 nm, respectively. The particle size of the gelatin-stabilized soils increased with the curing period. The specific surface of the CH, CL, and ML soils increased to 532 nm, 651 nm, and 682 nm, respectively, after 28 days of curing. The increase in particle size is a reflection of the adsorption and agglomeration of the gelatin solution on the soils; the amount of adsorption was measured with Brunauer–Emmett–Teller (BET) analysis. The specific surface area was reduced from 16.5 m^2/g to 14.2 m^2/g, 9.7 m^2/g to 9.2 m^2/g, and 1.7 m^2/g to 1.6 m^2/g for CH, CL, and ML soils, respectively. Nugent et al. [36] opined that this modification in the double layer of the biopolymer-treated soil induced the accumulation of bio-cementitious adsorption on the soil surface. Ghasemzadeh and Modiri [60] noted a reduction in specific surface area by 37.5% and 6%, respectively, in the treatment of kaolinite soil with Persian gum and xanthan gum.

3.6.4. Permeability

The coefficient of permeability of the CH, CL, and ML soils was found to be 2.91×10^{-7} cm/s, 7.3×10^{-5} cm/s, and 2.6×10^{-4} cm/s, respectively. The addition of biopolymers plugs the pores of the soils and thereby reduces the course for pore fluid to travel [40]. This leads to a decrease in the permeability of biopolymer-stabilized soils with increasing concentration. Maximum reduction was observed for the 2% addition of gelatin, and the corresponding values of CH, CL, and ML soils were 1.1×10^{-8} cm/s, 3.8×10^{-6} cm/s, and 1.6×10^{-5} cm/s, respectively.

3.6.5. pH

The pH of CH, CL, and ML soils was found to be 6.10, 7.32, and 7.48, respectively, while the pH of the gelatin biopolymer was determined to be 6.70. The pH of the treated soils displayed a marginal increase of 1.5% up to the highest concentration of gelatin. Hydrogen ion concentration influences the functional groups of the gelatin biopolymer and thus the binding of gelatin with the clay soil is influenced by the pH. High pH variation is not preferable as the risk of contamination for the sub-soil and the water table does exist. Even after 28 days, the pH of the stabilized soils did not vary, which is a good indicator from an environmental perspective [61].

3.6.6. Viscosity

The gelatin biopolymer solution exhibited marginal viscosity from 0.5% to 2% concentration. A maximum of 33 cP was observed at the highest concentration of gelatin. Viscosity enhances the UCS of the soils by promoting the bonds between gelatin and the clay soils [40]. Kumar et al. [40] emphasized the combined outcomes of viscosity and molecular weight by the enhanced shear resistance of the soil due to the strengthening of the connecting bridges between the soil grains and the biopolymer. Figure 11 shows the viscosity of the gelatin biopolymer.

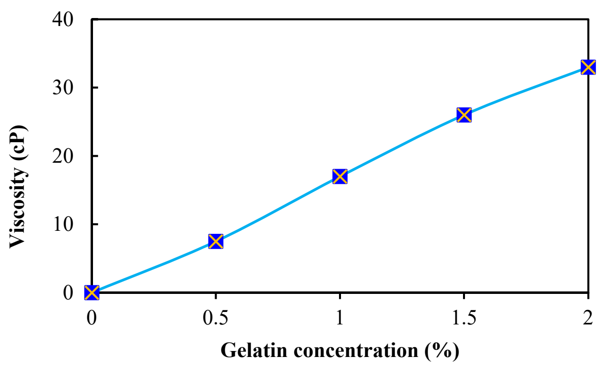

Figure 11. Viscosity of gelatin.

3.6.7. Future Perspectives

Sustainability in a road network is essential because it ensures the fulfillment of present requirements for development without compromising the resources of future requirements. The conservation of energy and resources is important for achieving sustainability in the construction sector. Sustainability in ground improvement by economizing on energy and resources ought not to cause the pollution of underground natural resources. Based on the CBR values under soaked conditions, IRC 37:2001 [62] recommends suitable thickness values for the top three layers of flexible pavement. A reduction in the thickness of the base course, the sub-base course, and the bituminous course was noted for the gelatin-treated soils. The thickness of the granular layer, the bituminous concrete (BC), and the dense bituminous macadam (DBM) for CL soil was found to be 120 mm, 0 mm, and 35 mm respectively. The thickness of the granular layer, the bituminous concrete (BC), and the dense bituminous macadam (DBM) for ML soil was found to be 100 mm, 0 mm, and 20 mm, respectively. The untreated CBR of CH soil was less than 2 and design thickness values were not specified for the CBR. For 1 km of pavement for a width of 3.75 m, this results in respective savings of coarse aggregates and dense bituminous macadam of 450 m^3 and 93.75 m^3 for CL soil. Cost efficiency is worked out for the soil with the best performance, which is CL. The savings in the cost of the top two layers of the pavement were found to be 11.57%, as highlighted in Table 2 below.

Table 2. Cost Comparison.

% of Gelatin	CBR of CL Soils (%)	Cost of Bituminous Surfacing (INR)	Cost of the Granular Layer (INR)	Transportation Cost of the Granular Layer (INR 50/m^3)	Total Cost (INR)
0	3.37	10,125,000	2,492,674	118,125	31,963,780
1	6.21	7,802,183	2,017,879	95,625	28,266,877

One of the major reasons for the successful application of biopolymers in various sectors is their biodegradability. However, for civil engineering purposes, the biodegradable trait of the biopolymers should not compromise the long-term durability of their intended applications. Chang et al. [63] reported the integrity of polysaccharides with granular soil over 2 years. There are challenges in thermal application in practical field implementation, especially if the treatment warrants a larger area. The adoption of a biomaterial for soil strengthening depends on its cost, environmental friendliness, and technical feasibility. Medicinal-grade biopolymers may not be required for soil applications and thus customized manufacturing for specific applications could lead to a decline in prices. Soil is a natural material functioning as an engineering material and can be a vital contributor to sustainable infrastructure growth. The price of biopolymers has dropped significantly over the years due to their widespread adoption in the pharmaceutical, printing, textile, and construction sectors. The grade of a biopolymer influences its price, and the inverse relationship between the demand and the price of the biopolymer is further expected to lower prices due to custom-grade manufacturing and technological advances.

4. Conclusions

The maximum liquid limit of 82.4% was observed for the CH soil in treatment with gelatin. The overall increase in the liquid limit and plasticity index of the gelatin stabilized soils is due to the variation in specific surface and hydration of the gelatin. Thus, the addition of excess water and the tendency of the biopolymer solution to marginally displace the nearby surrounding soil particles due to its lubricative texture reduces the MDU of all the soils. The 1% addition of gelatin has been effective in achieving the optimum UCS and CBR of the soils. Thermally cured specimens recorded the maximum UCS and CBR of 3968 kN/m^2 and 141.1%, respectively, for the low plastic clay soil. The maximum reduction in permeability was found to be 96% for the kaolin clay. The maximum percentage increase of 24.95% was observed for the average particle diameter of the treated CL soil, while a

5.1% reduction in specific surface area was noted for the specific surface area of the treated CL soil after 28 days. Negligible changes in the pH and stability of the treated soils against wetting and drying highlight the durability of gelatin-stabilized soils with a maximum weight loss of 9% for CH soil. Savings in 450 m^3 and 93.75 m^3 of coarse aggregates and dense bituminous macadam were observed for a 1 km pavement for the stabilized low plastic clay. The filling of voids by the gelatin gel and the formation of hydrogen amide covalent bonds in the gelatin–clay matrix by adsorption and agglomeration are responsible for the strengthening of soils, and the strength increases with dehydration.

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References

1. Latifi, N.; Horpibulsuk, S.; Meehan, C.L.; Abd Majid, M.Z.; Tahir, M.M.; Mohamad, E.T. Improvement of Problematic Soils with Biopolymer—An Environmentally Friendly Soil Stabilizer. *J. Mater. Civ. Eng.* **2017**, *29*, 04016204. [CrossRef]
2. Ijaz, N.; Ye, W.; ur Rehman, Z.; Ijaz, Z. Novel Application of Low Carbon Limestone Calcined Clay Cement (LC3) in Expansive Soil Stabilization: An Eco-Efficient Approach. *J. Clean Prod.* **2022**, *371*, 133492. [CrossRef]
3. Ijaz, N.; Dai, F.; ur Rehman, Z. Paper and Wood Industry Waste as a Sustainable Solution for Environmental Vulnerabilities of Expansive Soil: A Novel Approach. *J. Env. Manag.* **2020**, *262*, 110285. [CrossRef]
4. Ijaz, N.; Ye, W.; ur Rehman, Z.; Dai, F.; Ijaz, Z. Numerical Study on Stability of Lignosulphonate-Based Stabilized Surficial Layer of Unsaturated Expansive Soil Slope Considering Hydro-Mechanical Effect. *Transp. Geotech.* **2022**, *32*, 100697. [CrossRef]
5. Ijaz, N.; ur Rehman, Z.; Ijaz, Z. Recycling of Paper/Wood Industry Waste for Hydromechanical Stability of Expansive Soils: A Novel Approach. *J. Clean Prod.* **2022**, *348*, 131345. [CrossRef]
6. Mujtaba, H.; Khalid, U.; ur Rehman, Z.; Farooq, K. Recycling of Reclaimed Subbase Materials in Flexible Pavement Design. *Road Mater. Pavement Des.* **2022**, *23*, 2713–2732. [CrossRef]
7. Ijaz, N.; Ye, W.; ur Rehman, Z.; Ijaz, Z.; Junaid, M.F. New Binary Paper/Wood Industry Waste Blend for Solidification/Stabilisation of Problematic Soil Subgrade: Macro-Micro Study. *Road Mater. Pavement Des.* **2022**, 1–17. [CrossRef]
8. Cortés-Morales, E.A.; Mendez-Montealvo, G.; Velazquez, G. Interactions of the Molecular Assembly of Polysaccharide-Protein Systems as Encapsulation Materials. A Review. *Adv. Colloid. Interface Sci.* **2021**, *295*, 102398. [CrossRef]
9. Ham, S.-M.; Chang, I.; Noh, D.-H.; Kwon, T.-H.; Muhunthan, B. Improvement of Surface Erosion Resistance of Sand by Microbial Biopolymer Formation. *J. Geotech. Geoenvironmental Eng.* **2018**, *144*, 06018004. [CrossRef]
10. Im, J.; Chang, I.; Cho, G.-C. Small Strain Stiffness and Elastic Behavior of Gellan Treated Soils with Confinement. In *Geotechnical Frontiers 2017*; American Society of Civil Engineers: Orlando, FL, USA, 2017; pp. 834–841.
11. Barani, O.R.; Barfar, P. Effect of Xanthan Gum Biopolymer on Fracture Properties of Clay. *J. Mater. Civ. Eng.* **2021**, *33*, 04020426. [CrossRef]
12. Soldo, A.; Aguilar, V.; Miletić, M. Macroscopic Stress-Strain Response and Strain-Localization Behavior of Biopolymer-Treated Soil. *Polymers* **2022**, *14*, 997. [CrossRef]
13. Zhang, T.; Yang, Y.-L.; Liu, S.-Y. Application of Biomass By-Product Lignin Stabilized Soils as Sustainable Geomaterials: A Review. *Sci. Total Environ.* **2020**, *728*, 138830. [CrossRef]
14. Lemboye, K.; Almajed, A.; Hamid, W.; Arab, M. Permeability Investigation on Sand Treated Using Enzyme-Induced Carbonate Precipitation and Biopolymers. *Innov. Infrastruct. Solut.* **2021**, *6*, 1–8. [CrossRef]
15. Lim, A.; Iskandar, M.R.; Albrecht, Y. Improvement of Soil Shear Strength Using Glucomannan Biopolymer for Loose Sand. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Bristol, UK, 2021; Volume 871.

16. Soldo, A.; Miletić, M.; Auad, M.L. Biopolymers as a Sustainable Solution for the Enhancement of Soil Mechanical Properties. *Sci. Rep.* **2020**, *10*, 1–13. [CrossRef]
17. Armistead, S.J.; Smith, C.C.; Staniland, S.S. Sustainable Biopolymer Soil Stabilization in Saline Rich, Arid Conditions: A 'Micro to Macro' Approach. *Sci. Rep.* **2022**, *12*, 1–11. [CrossRef]
18. Ni, J.; Li, S.-S.; Geng, X.-Y. Mechanical and Biodeterioration Behaviours of a Clayey Soil Strengthened with Combined Carrageenan and Casein. *Acta Geotech* **2022**, *17*, 5411–5427. [CrossRef]
19. Muguda, S.; Hughes, P.N.; Augarde, C.E.; Perlot, C.; Walter Bruno, A.; Gallipoli, D. Cross-Linking of Biopolymers for Stabilizing Earthen Construction Materials. *Build. Res. Inf.* **2022**, *50*, 502–514. [CrossRef]
20. Nouri, H.; Ghadir, P.; Fatehi, H.; Shariatmadari, N.; Saberian, M. Effects of Protein-Based Biopolymer on Geotechnical Properties of Salt-Affected Sandy Soil. *Geotech. Geol. Eng.* **2022**, *40*, 5739–5753. [CrossRef]
21. Kasapis, S.; Norton, I.T.; Johan, B. *Modern Biopolymer Science: Bridging the Divide between Fundamental Treatise and Industrial Application*; Academic Press: Cambridge, MA, USA, 2009; ISBN 0080921140.
22. Chang, I.; Prasidhi, A.K.; Im, J.; Cho, G.-C. Soil Strengthening Using Thermo-Gelation Biopolymers. *Constr. Build. Mater.* **2015**, *77*, 430–438. [CrossRef]
23. Kommareddy, S.; Shenoy, D.B.; Amiji, M.M. Gelatin Nanoparticles and Their Biofunctionalization. In *Nanotechnologies for the Life Sciences*; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2007.
24. Rezaeimalek, S.; Nasouri, N.; Huang, J.; Shafique, S.B.; Gilazghi, S.T. Comparison of Short-Term and Long-Term Performances for Polymer-Stabilized Sand and Clay. *J. TrafficTransp. Eng.* **2017**, *4*, 145–155. [CrossRef]
25. *IS 2720-5*; Methods of Test for Soils, Part 5: Determination of Liquid and Plastic Limit. Indian Standards Institution: New Delhi, India, 1985.
26. *IS 2720-7*; Methods of Test for Soils, Part 7: Determination of Water Content-Dry Density Relation Using Light Compaction. Indian Standards Institution: New Delhi, India, 1980.
27. *IS 2720-10*; Methods of Test for Soils, Part 10: Determination of Unconfined Compressive Strength. Indian Standards Institution: New Delhi, India, 1991.
28. *IS 2720-16*; Methods of Test for Soils, Part 16: Laboratory Determination of CBR. Indian Standards Institution: New Delhi, India, 1987.
29. *IS 2720-26*; Method of Test for Soils, Part 26: Determination of PH Value. Indian Standards Institution: New Delhi, India, 1987.
30. *IS 4332-4*; Methods of Test for Stabilized Soils, Part 4: Wetting and Drying, and Freezing and Thawing Tests for Compacted Soil-Cement Mixtures. Indian Standards Institution: New Delhi, India, 1968.
31. Noolu, V.; Mallikarjuna Rao, G.; Sudheer kumar reddy, B.; Chavali, R.V.P. Strength and Durability Characteristics of GGBS Geopolymer Stabilized Black Cotton Soil. *Mater. Today Proc.* **2021**, *43*, 2373–2376. [CrossRef]
32. Joga, J.R.; Varaprasad, B.J.S. Sustainable Improvement of Expansive Clays Using Xanthan Gum as a Biopolymer. *Civ. Eng. J.* **2019**, *5*, 1893–1903. [CrossRef]
33. Ramachandran, A.L.; Dubey, A.A.; Dhami, N.K.; Mukherjee, A. Multiscale Study of Soil Stabilization Using Bacterial Biopolymers. *J. Geotech. Geoenvironmental Eng.* **2021**, *147*, 04021074. [CrossRef]
34. Shariatmadari, N.; Reza, M.; Tasuji, A.; Ghadir, P.; Javadi, A.A. Experimental Study on the Effect of Chitosan Biopolymer on Sandy Soil Stabilization. In *Proceedings of 4th European Conference on Unsaturated Soils (E-UNSAT 2020), Lisboa, Portugal, 19–21 October 2020*; EDP Sciences: Les Ulis, Fance, 2020; Volume 195.
35. Bocheńska, M.; Bujko, M.; Dyka, I.; Srokosz, P.; Ossowski, R. Effect of Chitosan Solution on Low-Cohesive Soil's Shear Modulus G Determined through Resonant Column and Torsional Shearing Tests. *Appl. Sci.* **2022**, *12*, 5332. [CrossRef]
36. Nugent, R.; Zhang, G.; Gambrell, R. Effect of Exopolymers on the Liquid Limit of Clays and Its Engineering Implications. *Transp. Res. Rec.* **2010**, *2101*, 34–43. [CrossRef]
37. Chen, C.; Wu, L.; Harbottle, M. Exploring the Effect of Biopolymers in Near-Surface Soils Using Xanthan Gum–Modified Sand under Shear. *Can. Geotech. J.* **2020**, *57*, 1109–1118. [CrossRef]
38. Seo, S.; Lee, M.; Im, J.; Kwon, Y.-M.; Chung, M.-K.; Cho, G.-C.; Chang, I. Site Application of Biopolymer-Based Soil Treatment (BPST) for Slope Surface Protection: In-Situ Wet-Spraying Method and Strengthening Effect Verification. *Constr. Build. Mater.* **2021**, *307*, 124983. [CrossRef]
39. Adabi, M.; Darvishan, E.; Eyvazi, G.; Jahanbaksh Motlagh, H. Geoenvironmental Application of Novel Persian Gum Biopolymer in Sandy Soil Stabilization. *Arab J. Sci. Eng.* **2022**, *47*, 12915–12929. [CrossRef]
40. Anandha Kumar, S.; Sujatha, E.R.; Pugazhendi, A.; Jamal, M.T. Guar Gum-Stabilized Soil: A Clean, Sustainable and Economic Alternative Liner Material for Landfills. *Clean Technol. Env. Policy* **2021**. [CrossRef]
41. Reddy, N.G.; Nongmaithem, R.S.; Basu, D.; Rao, B.H. Application of Biopolymers for Improving the Strength Characteristics of Red Mud Waste. *Environ. Geotech.* **2020**, *40*, 1–20. [CrossRef]
42. Kuptsov, A.H.; Zhizhin, G.N. *Handbook of Fourier Transform Raman and Infrared Spectra of Polymers*; Elsevier: Amsterdam, The Netherlands, 1998; ISBN 0080531946.
43. Bozyigit, I.; Javadi, A.; Altun, S. Strength Properties of Xanthan Gum and Guar Gum Treated Kaolin at Different Water Contents. *J. Rock Mech. Geotech. Eng.* **2021**, *13*, 1160–1172. [CrossRef]
44. Skujins, J.J.; McLaren, A.D. Persistence of Enzymatic Activities in Stored and Geologically Preserved Soils. *Enzymologia* **1968**, *34*, 213–225.

45. Arab, M.G.; Mousa, R.A.; Gabr, A.R.; Azam, A.M.; El-Badawy, S.M.; Hassan, A.F. Resilient Behavior of Sodium Alginate–Treated Cohesive Soils for Pavement Applications. *J. Mater. Civ. Eng.* **2019**, *31*, 04018361. [CrossRef]
46. Chang, I.; Cho, G.-C. Strengthening of Korean Residual Soil with β-1,3/1,6-Glucan Biopolymer. *Constr Build Mater* **2012**, *30*, 30–35. [CrossRef]
47. Mujtaba, H.; Khalid, U.; Farooq, K.; Elahi, M.; Rehman, Z.; Shahzad, H.M. Sustainable Utilization of Powdered Glass to Improve the Mechanical Behavior of Fat Clay. *KSCE J. Civ. Eng.* **2020**, *24*, 3628–3639. [CrossRef]
48. Fatehi, H.; Ong, D.E.L.; Yu, J.; Chang, I. Biopolymers as Green Binders for Soil Improvement in Geotechnical Applications: A Review. *Geosciences* **2021**, *11*, 291. [CrossRef]
49. Onah, H.N.; Nwonu, D.C.; Ikeagwuani, C.C. Feasibility of Lime and Biopolymer Treatment for Soft Clay Improvement: A Comparative and Complementary Approach. *Arab. J. Geosci.* **2022**, *15*, 337. [CrossRef]
50. Singh, S.P.; Das, R. Geo-Engineering Properties of Expansive Soil Treated with Xanthan Gum Biopolymer. *Geomech. Geoengin.* **2020**, *15*, 107–122. [CrossRef]
51. Elkafoury, A.; Azzam, W. Utilize Xanthan Gum for Enhancing CBR Value of Used Cooking Oil-Contaminated Fine Sand Subgrade Soil for Pavement Structures. *Innov. Infrastruct. Solut.* **2021**, *6*, 1–10. [CrossRef]
52. Mohan, R.P.; Adarsh, P. Strength Characteristics of Kuttanad Soil Stabilized with a Biopolymer Guar Gum. In *Ground Improvement and Reinforced Soil Structures. Lecture Notes in Civil Engineering*; Springer: Singapore, 2022; pp. 423–431.
53. Hamza, M.; Nie, Z.; Aziz, M.; Ijaz, N.; Ameer, M.F.; Ijaz, Z. Geotechnical Properties of Problematic Expansive Subgrade Stabilized with Xanthan Gum Biopolymer. *Road Mater. Pavement Des.* **2022**, 1–15. [CrossRef]
54. Hamza, M.; Nie, Z.; Aziz, M.; Ijaz, N.; Ijaz, Z.; ur Rehman, Z. Strengthening Potential of Xanthan Gum Biopolymer in Stabilizing Weak Subgrade Soil. *Clean Technol. Env. Policy* **2022**, *24*, 2719–2738. [CrossRef]
55. Chang, I.; Lee, M.; Tran, A.T.P.; Lee, S.; Kwon, Y.-M.; Im, J.; Cho, G.-C. Review on Biopolymer-Based Soil Treatment (BPST) Technology in Geotechnical Engineering Practices. *Transp. Geotech.* **2020**, *24*, 100385. [CrossRef]
56. Reddy, J.J.; Varaprasad, B.J.S. Long-Term and Durability Properties of Xanthan Gum Treated Dispersive Soils–An Eco-Friendly Material. *Mater. Today Proc.* **2021**, *44*, 309–314. [CrossRef]
57. Nikolic, G. *Fourier Transforms: New Analytical Approaches and FTIR Strategies*; BoD–Books on Demand: Rijeka, Croatia, 2011; ISBN 9533072326.
58. Abidi, N. *FTIR Microspectroscopy*; Springer International Publishing: Cham, Switzerland, 2021; ISBN 978-3-030-84424-0.
59. Cole, D.M.; Ringelberg, D.B.; Reynolds, C.M. Small-Scale Mechanical Properties of Biopolymers. *J. Geotech. Geoenviron. Eng.* **2012**, *138*, 1063–1074. [CrossRef]
60. Ghasemzadeh, H.; Modiri, F. Application of Novel Persian Gum Hydrocolloid in Soil Stabilization. *Carbohydr. Polym.* **2020**, *246*, 116639. [CrossRef]
61. Theng, B.K.G. Clay-Polymer Interactions: Summary and Perspectives. *Clays Clay Min.* **1982**, *30*, 1–10. [CrossRef]
62. Indian Roads Congress Guidelines for the Design of Flexible Pavements. 2001. Available online: http://sscnagpur.ac.in/Department/Civil%20Engineering/IRC-37-2001.pdf (accessed on 13 January 2023).
63. Chang, I.; Im, J.; Prasidhi, A.K.; Cho, G.C. Effects of Xanthan Gum Biopolymer on Soil Strengthening. *Constr. Build Mater.* **2015**, *74*, 65–72. [CrossRef]