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Research Article

Effect of Keratin Structures from Chicken Feathers on Expansive Soil Remediation

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Chicken feathers are composed mainly of avian keratin, a fibrillar protein with a complex structure, and important properties such as durability, hydrophobicity, being chemically unreactive, and depending on the specific function can change its morphological and inner structure. This study takes advantage of these features and for the first time the use of keratin from chicken feathers to modify characteristics on expansive soils is reported. Swelling characteristics of remolded expansive soil specimens were studied through varying the percentage of keratin fiber content using 0.25, 0.50, 1.00 and 3.00 wt%. One-dimensional swell-consolidation tests were conducted on oedometric specimens, specific surface area was determined using methylene blue, and degree of saturation was also analyzed. Finally random distribution and interaction between keratin structures and soil were studied by scanning electron microscopy. The results show that randomly distributed fibers are useful in restraining the swelling tendency of expansive soils. The maximum reduction of pressure (43.99%) due to swelling is achieved by reducing the void ratio, which can be reached with the addition of chicken feather keratin structures to the expansive soil. Finally, the mechanism by which discrete and randomly distributed fibers reduce swelling pressure of expansive soil is explained.

1. Introduction

In the field of geotechnical engineering, it has long been known that swelling of expansive soils caused by moisture change results in significant distresses and hence in severe damage to overlying structures. Shrinking and swelling are aggravated by wide swings in the water content, which are due to climatic conditions and wide variations in the rainfall; in addition expansive clays soils are extensively distributed worldwide [1]. These facts cause severe safety and economic problems [2]. For instance, the annual cost of damage is estimated to be around $1000 million in the USA [3]. Therefore, searching for responses to this problem is highly relevant from several points of view.

An interesting alternative is the stabilization of expansive soils by using additives such as lime, fly ash, or cement, which is well documented [1, 4–6]. In recent years, discrete fibers have been added and mixed into soils to improve their strength behavior [3, 7–11]. Unfortunately the interaction mechanisms between reinforcements and soil are complex and depend on their specific features and are necessary to study [12]. An adequate model is presented by Tang et al. [13]; they considered that the bonding force between the fiber and the contact area of soil particles contributes to the

Table 1: Natural fibers used as reinforcement for modified soils.

Natural fiber	Percentage	Effect of reinforcement	Reference
Coconut (coir)	Data not included in reference	Reducing the swelling tendency of the soil.	[9]
	0.5, 1.0, 1.5, and 2	Reducing the resilient strain for soils.	[15]
Sisal	4	Imparted considerable ductility and also increasing slightly its compression strength. Prevention of shrinkage cracks due to the drying process.	[16]
	0.25, 0.5, 0.75, and 1	Reduces the dry density of the soil due to a low specific gravity and unit weight of sisal fiber. The shear stress is increased nonlinearly with increase in length of fiber. Increase in length reduces the shear stress. Cohesion is increased.	[17]
Palm	0.25 and 0.5	Cohesion increases linearly with fiber content. The increase in the length of fiber increases the value of internal friction angle. Coating fibers increase the shear strength of the soil.	[18]
Jute	0.25, 0.5, 0.75, and 1	Contributes to the resilient modulus of native soil under the freezing and thawing conditions.	[19]
	0.2 to 1	Reduces the maximum dry density while increasing the optimum moisture content. California Bearing Ratio value is increased more than 2.5 times.	[9]
Flax	0.6 and 0.8	Enhances the ductility of the material and eliminates the catastrophic failure pattern displayed by specimens without fiber-reinforcement. An enamel paint coating was applied to the fiber surface to increase its interfacial bond strength with the soil.	[20]
Barely straw	1	Decreasing shrinkage, reducing the curing time, and enhancing compressive strength. Flexural and shear strengths were also increased and more ductile.	[9]
Bamboo	Data not included in reference	The root rhizomes of bamboo are excellent soil binders which can prevent erosion.	[9, 21]
Hay	0.5, 1, and 1.5	The dry density decreases. The optimum water content, the unconfined compression strength, shrinkage limit, and the swelling decrease with increasing hay addition.	[22]

interfacial shear resistance. In addition when shear occurs, the interfacial friction also is conditioned by the resistance of soil particle rearrangement and rotation. Besides, an important parameter in expansive soils is the water interaction; this fact is also contemplated by Tang et al. [13], and in this case pore water-fiber contact area also exerts certain influence on the interfacial shear resistance, which could be strongly dependent on the hydrophilic behavior of reinforcement material.

On the other hand, the plastic behavior of fibers also has an interesting effect, since during compaction hard particles in soil can produce deformation of fiber body. This was reported as an additional parameter to take into account since pits and deformations result in an increase in fiber surface roughness an interfacial interlock force [13]. The above considerations are especially important in soil stabilization with natural materials, which recently have received a great attention in reinforcement of soils with natural fibers. In Table 1 some natural fibers used to change the properties of soils and their effects are presented. Then, as it can be observed, in nature, it is possible to find an almost infinite source of high performance materials which are still waiting for serious studies to establish them as basis for innovative technologies and useful raw materials.

In addition to vegetal reinforcements, fibers from animal origin can be also considered to modify soil properties. This is the case of keratin structures from different animal sources, such as wool and feathers. Keratin is durable, insoluble in the majority of organic solvents, and chemically unreactive, being thus suited to exposure to severe environmental conditions, as can be observed in hair, wool, and feathers. Keratin also provides mechanical strength and elasticity since these are important inherent properties from this fibrillar protein [14].

In the civil engineering field, keratin has found recently interesting research opportunities. For instance, Petric-Gray et al. [10] applied wool to stabilize soils used in the building industry. They used two different percentages, 0.25 and 0.5, in order to modify soil properties. From their results it was observed that wool stabilized soil increases the compressive strength considerably compared with unstabilized soils. Similarly, Galán-Marín et al. [23] studied the stabilization of soils with natural polymers (alginate) and fibers from sheep's wool (0.25 and 0.5%) to produce a composite; their results show that the addition of alginate separately increases compression strength from 2.23 to 3.77 MPa and the addition of wool fiber increases compression strength until 37%. Aymerich et al. [24] investigated the improvements in strength and crack resistance induced by the introduction of 2 and 3% of wool fibers in an earthen material. They show that fibrous reinforcement greatly improved residual strength, ductility, and energy absorption of the reinforced material as compared to unreinforced soil. The results of the study also show that fiber length had a notable influence on the postfracture response of the material at large deformation regimes.

The results using keratin from wool are encouraging; therefore an extensive research field can be predicted in this way. However two important facts deserve to be noted. Firstly wool is a raw material for the textile industry and only a minimal quantity of residues could be used for this purpose. In the second place, it is important to consider that countries such as Scotland or Australia are rich wool producers, but there are others that produce very few quantities of this textile but instead are important consumers of poultry meat. Poultry feathers are considered as a worldwide waste causing serious environmental problems. The feathers, from where keratin fibers can be obtained, have been considered not only a waste, but rather a complicated disposal challenge, in spite of their important characteristics. Keratin, from poultry feathers, is a fibrillar protein that has high stability due to its self-assembled hierarchical structure [25]; in addition feathers have different structural arrangement depending on which part is observed: barbs and barbules, rachis, or quill. Internal structure of feathers rachis was described by Meyers et al. [26]. They observed a cellular core limited by a solid wall, inside an intricate arrangement, similar to a foam, constituting the internal cells. But even these cells are not solid; they are formed by a network of fibers with 200 nm in diameter.

On the other hand, Martínez-Hernández et al. [14] identified that central barbs are hollow and have an irregular, noncylindrical shape [14], whereas barbules are completely full and without free voids inside [27]. This structural dissimilarity provides different mechanical behavior to the feathers [28], which is reflected in the interaction with polymeric matrix, giving a significant variability in thermomechanical response depending on the type and quantity of feather segment reinforcement [29]. Taking into account this influence, we propose that feather segments can contribute positively as reinforcement in expansive soil, considering also that their structural features could produce different effects on mechanical response. Thus this natural material could be applied in soil stabilization and decrease their expansive potential, contributing to the effort to diminish the harmful damage that swelling soils can cause in buildings and constructions.

2. Materials and Methods

2.1. Materials

2.1.1. Chicken Feather Segments. Feather segments were obtained from chicken feathers by the following procedure. After leaving the poultry processing plant, feathers were washed with ethanol and water and finally were dried with an air stream; this allows having clean, sanitized, and odor-free raw material. Then, dried feathers were cut with blades and separated in three segments: barbs (B), rachis or quill (Q), and partially cut feathers which include barbs and quill mixed (T); this last one was called total fiber.

Table 2: Index properties of the expansive soil.

Parameter	Symbol	Value	Norma
Water content	ω	27.86 (%)	ASTM D2216-98 [30]
Unit weight	γ_m	1.69 (T/m^3)	ASTM D7263-09 [31]
Specific gravity	S_s	2.67	ASTM D854-02 [32]
Void ratio	e	1.32	ASTM D7263-09 [31]
Degree of saturation	G_w	75.99 (%)	ASTM D7263-09 [31]
Gravel	G	0.00 (%)	ASTM D2487-00 [33]
Sand	S	2.00 (%)	ASTM D2487-00 [33]
Fine	C	98.00 (%)	ASTM D2487-00 [33]
Liquid limit	LL	85.51 (%)	ASTM D4318-00 [34]
Plastic limit	LP	33.19 (%)	ASTM D4318-00 [34]
Plasticity index	Ip	52.32 (%)	ASTM D4318-00 [34]
Shrinkage limit	SL	14.51 (%)	ASTM D427-04 [35]
Classification	USCS	CH	ASTM D2487-00 [33]

2.1.2. Expansive Soil. The natural soil used for this study is active natural clay obtained from Santa Fe, Queretaro, Mexico, located at 20°35′12.21″N-100°26′50.65″W (about 5 km south of Queretaro City). The climate is considered as semidesert with 780.3 mm of water rain in 2013. Expansive soil samples were obtained from an open cut on the site, sheltered in plastic bags, and transported to the laboratory to be tested. The bags were filled separately with soil samples taken from 0.60 m. Based on the plasticity properties, the soil was classified as CH (clay with high plasticity), according to the Unified Soil Classification System (USCS). The physical properties of soil are given in Table 2. All the experimental determinations of physical properties were realized according to ASTM procedures as is indicated. The mineralogical composition of constituents of the soil, investigated using X-ray diffraction analysis, reveals that the predominant clay minerals are montmorillonite with minor amounts of illite.

2.2. Methods

2.2.1. Sample Preparation. Dry soil was initially conditioned with water in order to maintain the natural features of unit weight and moisture; for this, dry soil samples were mixed with water corresponding to the natural moisture. After, wet soil samples were mixed separately with three kinds of feather segments: quill, barbs, and partially cut feathers (total fiber). These segments are shown in Figure 1. Four different contents of feather segments were used as soil modifiers: 0.25, 0.50, 1.00, and 3.00 wt%; additionally soil without modification was maintained as control sample. Once mixed, the feather segments-soil samples were preserved at room temperature until they were required for the different analysis. The nomenclature used for each sample is described in Table 3.

2.2.2. Tests Conducted. One-dimensional swell-consolidation tests were performed on compacted mixtures of fibers

Table 3: Nomenclature adopted for feather segments-soil mixtures.

Type of fiber	Feather segment (wt %)	Nomenclature
Natural Soil	0.00	SN
Barbs	0.25	SMB-0.25%
Barbs	0.50	SMB-0.5%
Barbs	1.00	SMB-1%
Barbs	3.00	SMB-3%
Quill	0.25	SMQ-0.25%
Quill	0.50	SMQ-0.5%
Quill	1.00	SMQ-1%
Quill	3.00	SMQ-3%
Total fiber	0.25	SMT-0.25%
Total fiber	0.50	SMT-0.5%
Total fiber	1.00	SMT-1%
Total fiber	3.00	SMT-3%

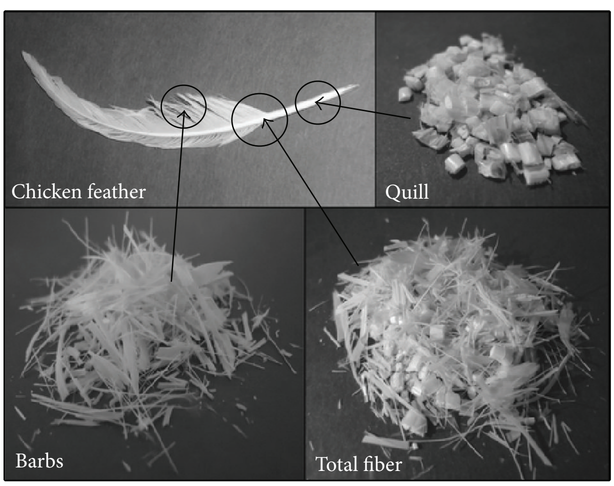


Figure 1: Kinds of feather segments: quill, barbs, and partially cut feathers (total fiber).

and expansive soil to assert the optimum fiber content and aspect ratio for maximum heave reduction. Swell-consolidation tests were conducted in a conventional oedometer (Controls model 26-T0326) with 75 mm in diameter and 20 mm in thickness (H). The specimens (feather segments-soil) were statically compacted inside the oedometer ring by stacking three layers, each one around 7 mm in thickness, to ensure uniform density. In all samples, a random distribution of fiber was maintained. For each sample, heave was allowed under a seating surcharge of 1 kPa by free inundation or by allowing water continuously into the soil specimen. After final heave (ΔH) was reached, the sample was compressed with incremented vertical loads until initial void ratio (e) was attained. Swelling pressure (p_s) was determined as the pressure corresponding to the initial void ratio (e) of the specimens; the p_s values were obtained from the e-log p curve depicted for each type of feather segment used as modifier. These evaluations were made following the standard test

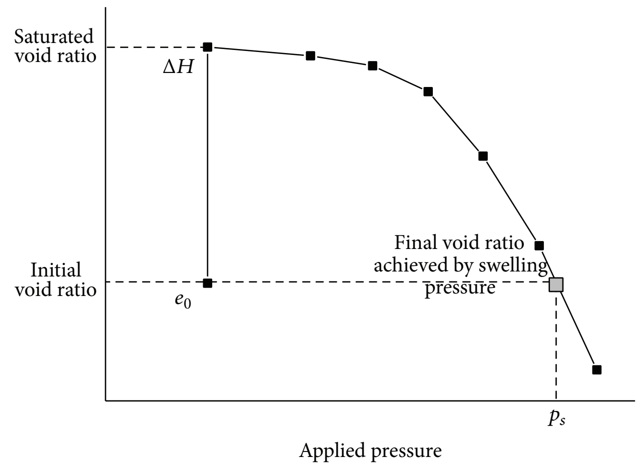


Figure 2: Graphic explanation of swelling pressure.

methods ASTM D4546-03 [36]. The swelling pressure (p_s) corresponds to the necessary value to return soil sample towards its initial void ratio after it was completely saturated with water. Figure 2 shows a graphic explanation of the method followed to establish the swelling pressure and its relation with void ratios.

Specific surface area (SSA) of soils is a very important index soil property since it is directly related to the amount of expansion [37, 38]. It can be calculated by determining the amount of an adsorbed substance such as methylene blue (MB), ethylene glycol monoethyl ether, or water required to form a monolayer [39]. In this research SSA was determined using MB; the tests were realized in samples modified with the feather segments at the weight percentages described in Table 3. This test was realized in basis to the norm AASHTO TP 57-06 [40].

The shrinkage limit (SL) is an important parameter for expansive soils due to the fact that it represents the water content in soil, which through a dry process does not undergo any change in volume. The procedure to determine this parameter was according to ASTM D427-04 [35] method.

The modified soils with 3 wt% of feather segments were analyzed by scanning electron microscopy (SEM) in a JEOL model SM-6060LV microscope at 5–20 kV and high vacuum. Before analyzing the morphological surface, the soil samples were fastened to a double-sided adhesive tape attached to copper stubs and vacuum-coated with gold at 7×10^{-2} mBar using Argon in a Sputter Coater EMS 550 with a final coat of 120 nm. Soil samples with 3 wt% of feather segments were chosen for SEM analysis due to the fact that these samples have more feasibility to found zones with feather-soil interactions.

3. Results and Discussion

The value of void ratio depends on volumetric changes of soils; then in order to evaluate the effect of keratin over these parameters in soils, void ratios were studied in all samples as well as swelling pressure. Figure 3 shows the void ratio curves as function of log of applied pressure for natural soil and

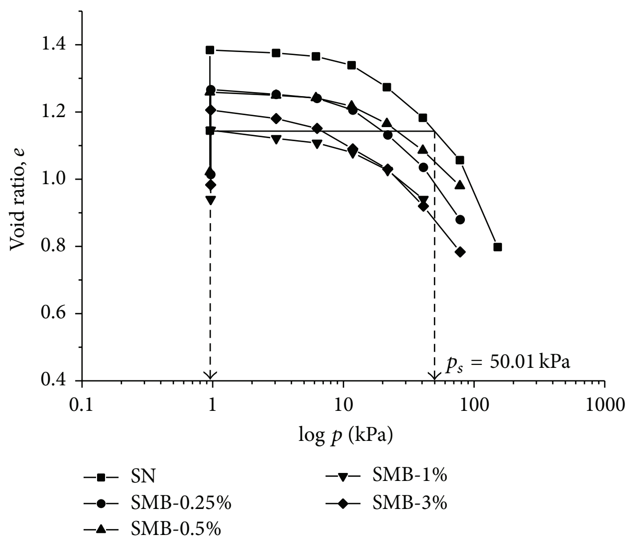


FIGURE 3: e-log p curves of soil modified with barb fibers.

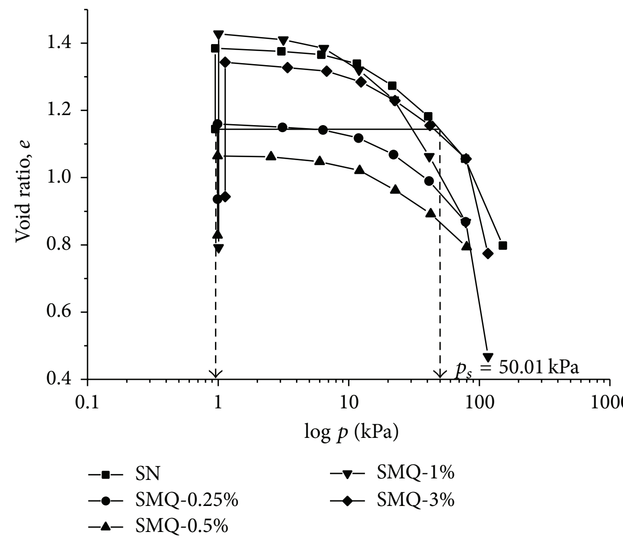


FIGURE 4: e-log p curves of soil modified with quill segments.

TABLE 4: p_s and G_w values presented by soil modified with barbs.

Type of soil	p_s (kPa)	G_w (%)
SN	50.01	64.63
SMB-0.25%	45.03	69.70
SMB-0.5%	61.71	68.93
SMB-1%	41.11	71.61
SMB-3%	28.01	67.86

for samples modified with barb fibers varying the contents. In this graph it is possible to appreciate that keratin barbs diminish the values of pressure needed to return to initial void ratio in the soil, since all curves with modified soils are below the natural soil. The curve in which p_s presents the lower value corresponds to soil with 3 wt% of barb fibers. In addition, it is also important to observe that the initial void ratio (e) for the modified soils is lower than e for natural soil (all the values for e are shown in Table 4). This variation is due to the influence of keratin barbs exerted on soils, since unit weight and moisture were reproduced in modified soils as they were obtained in soil *in situ*; therefore no changes in this sense are expected due to the effect of these control parameters. This diminishing in e values is because the specific gravity is smaller for barb fibers (0.796) [41] than for soil sample (1.69) and these keratin materials occupy the voids which were previously occupied by air, decreasing the volume of voids and increasing the volume of solids in the total volume.

In Figure 3, it is also appreciated that swelling pressure (p_s) decreases as the fiber content is increased. The corresponding values of p_s for the modified soils are shown in Table 4. This behavior is due to the fact that barb fibers are hydrophobic and their internal structure is compact and close [14]. These features do not allow the fact that fibers can absorb water. In spite of the fact that barbs can produce a decreasing in swelling pressure, the inherent characteristics and variability of the natural material are reflected in the absence of a clear tendency according to the increment of concentration of barb fiber.

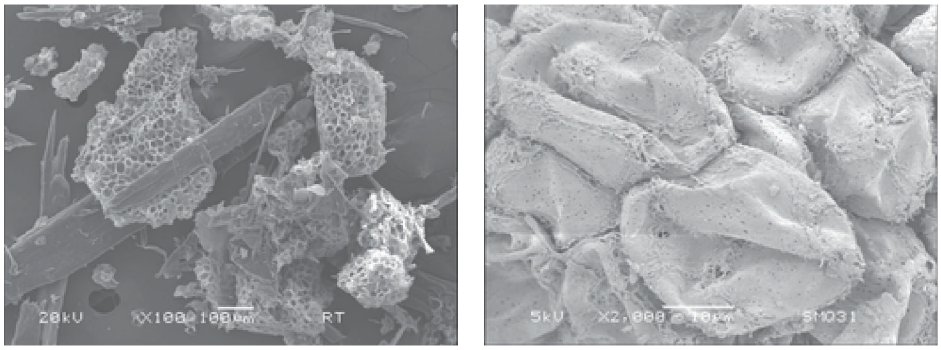
The effect caused by hydrophobic nature of keratin barbs is also observed in the initial degree of saturation values (G_w), showed in Table 4. These are slightly higher for the modified soils than for that corresponding to the natural soil, which is in agreement with e results and is related also with the specific gravity. Take into account the so-called basic volume-mass relationship for soils that establishes [42]

$$G_w e = \omega S_s, \tag{1}$$

where G_w corresponds to initial degree of saturation, e is initial void ratio, ω is water content, and S_s is specific gravity. This equation implies that G_w can be considered as the inverse of e.

In our samples, specific gravity diminishes as fiber contents are increased as it is shown in Table 4, and this is reflected in G_w response. In addition, the increasing in G_w values is explained considering that modified soils were obtained first by dry weight of keratin barb and soil; later the necessary quantity of water to maintain 28% of water content was added to a complete saturation of the sample. Therefore as fiber content is increased, a lower quantity of soil is included, and this must absorb all the added water; besides the minimum interaction between keratin fiber and water due to the hydrophobic character of keratin feathers [14] must be considered.

Figure 4 shows the e-log$p$ curves for the natural soil sample and for samples modified with quill varying the contents with 0.25, 0.50, 1.00 or 3.00 wt%. In this figure the void ratio performance was similar to that presented by soil modified with barbs. However, this type of segment had a higher swelling pressure in all cases, compared to natural soil, as can be observed in Table 5. This is due to the fact that quill segments have an internal structure like a honeycomb (Figure 5). This particular morphology allows an internal adsorption of water, which means that soil could have access



(a) (b)

FIGURE 5: SEM micrographs of quill to 100x (a) and 2000x (b).

TABLE 5: p_s and G_w values presented by soil modified with quill.

Type of soil	p_s (kPa)	G_w (%)
SN	50.01	64.63
SMQ-0.25%	54.75	72.80
SMQ-0.5%	65.23	81.27
SMQ-1%	86.47	76.18
SMQ-3%	92.58	70.50

to the retained water inside the quill. Thus soil modified with quill has the possibility to use this water and avoid the volumetric changes that expansive soils undergo during dry seasons. It is worthy to mention that quill fragments are also easily collapsed and because of their empty cells have even lower values in specific gravity than barbs, as it is observed in Table 5.

Table 5 shows the values corresponding to p_s and G_w for soil modified with quill. As it is observed the p_s value for soil modified with 0.25 wt% of quill segment is the closest to the natural soil; then taking into account this parameter the most recommendable modification for this series is with 0.25 wt% of quill.

The corresponding G_w values were higher than that observed for natural soil, a similar behavior observed also for soil modified with barbs. As can be perceived the G_w values are even higher for quill as modifier than those for barbs. This performance is completely logic if the honeycomb structure of quill is considered, since due to this internal structure free voids are more evident.

The e-log$p$ curves for samples modified with total fibers are showed in Figure 6. These samples have a better performance than soil modified with quill, but not as good as soil modified with barbs.

As in the other two modifications, the void ratios of modified soils are smaller than the value determined for natural soil (Figure 6), and as it is observed in Table 6 the smaller value for p_s corresponds to the sample with 0.25 wt% of total fiber included. It is noteworthy that this is even smaller than natural soil. Regarding the p_s of the other samples with total fiber, the values observed were very close

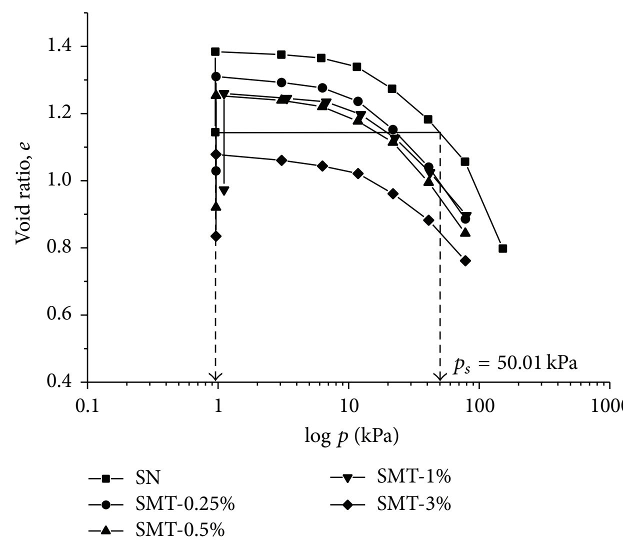


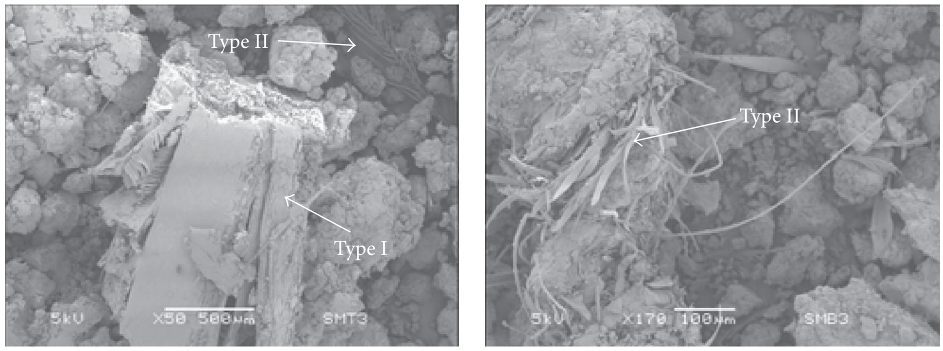
FIGURE 6: e-log p curves of soil modified with total fiber feathers.

TABLE 6: p_s and G_w values presented by soil modified with total feathers.

Type of soil	p_s (kPa)	G_w (%)
SN	50.01	64.63
SMT-0.25%	43.76	60.89
SMT-0.5%	56.11	69.82
SMT-1%	54.84	66.46
SMT-3%	50.96	74.80

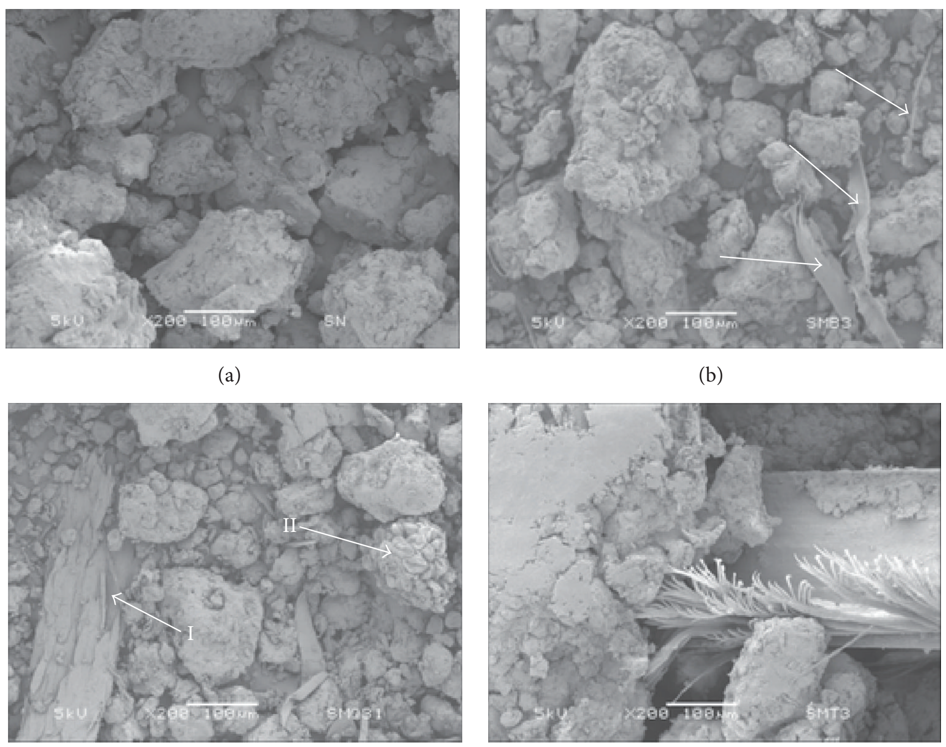
to natural soil; despite the fact that they are larger, the general performance is acceptable.

Table 6 also presents the corresponding values of G_w, as it can be appreciated that only the value for 3 wt% of total fiber included has a very dissimilar behavior, since its value is 13.60% higher. This unusual value can be attributed to the honeycomb structure and the free voids, which in this sample could be more abundant according to the higher percentage of quill segments included as part of total fiber. This behavior is nonhomogeneous due to the fact that



(a) (b)

Figure 7: SEM micrographs of modified soil with total fibers 50x (a) and barbs 170x (b).



(a) (b)

(c) (d)

Figure 8: SEM micrographs of SN (a); SMB-3% (b); SMQ-3% (c); and SMT-3% (d).

reinforcement is a natural material, and its structure can vary causing unexpected responses.

The internal structures of quill segment were observed in Figure 5, and additionally Figure 7(a) shows a SEM image of total fiber segment included in the soil modified with 3 wt%. This figure shows two different types of structures; one is a clear segment of quill with some fine barbs attached, indicated as type I. This has the honeycomb structure. Type II can be considered similar to the hierarchical morphology shared by barbs in Figure 7(b).

The SEM micrographs presented in Figure 8 show the physical distribution of feather segments in soil. All samples have the characteristic lumps observed in natural soil (Figure 8(a)), which interact with feather segments depending on their shape and size. Among the three keratin materials studied, barbs are the most uniform and thinnest material used to modify the soil; consequently they were perfectly covered by lumps, as can be observed by the fibers signed by arrows in Figure 8(b). This interaction is similar to that presented by Tang et al. [13] and represented in their model. In contrast quill and total fiber present a wide variety of forms and sizes. For instance, quill is fragmented producing segments from the outer cortex (indicated as I in Figure 8(c)) and the internal structure (II in Figure 8(c)). Both have different grade of interaction with soil, since their morphology is a key parameter, as it was described taking into account the

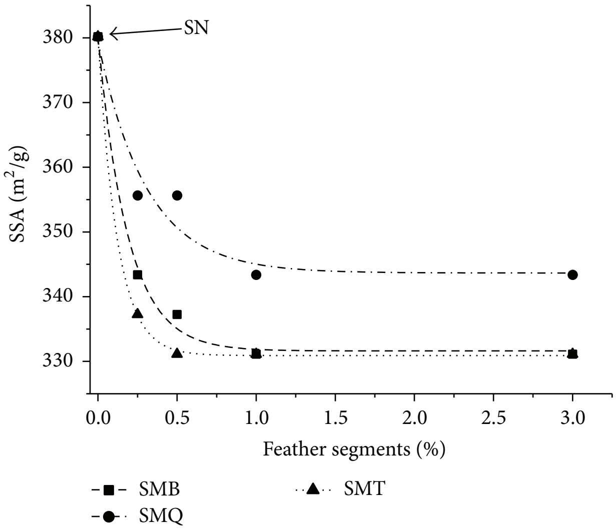


Figure 9: Specific surface areas (SSA) for the different percentages of keratin segments used as soil modifiers.

honeycomb structure. The presence of fine fibers and quill in the total fiber is a useful advantage in the adhesion of fine particles of soil over the surface of total fiber as can be appreciated in Figure 8(d). The morphological features and interaction between the three types of segments and soil are reflected in final swelling properties, since soil modified with barbs shows the highest degree of modification as was discussed before.

Taking into account that specific surface area of soils (SSA) is an important parameter to quantify interaction processes at the liquid-solid interface [43], it is very useful to corroborate the results explained above, since SSA is related to the capability of soil to adsorb water and therefore involves free swell index and liquid limit of soil [39]. Thus, if SSA values are high, then the expansive potential is higher too. The SSA results obtained from natural soil and soil modified with the three types of feather segments are showed in Figure 9. It is clearly appreciated that SSA values decrease as the percentage in keratin segments is increased. In addition the type of segments also has a noticeable effect on the SSA behavior. Total fiber and barbs have similar tendencies, although the lowest value was obtained with total fiber. The soil modified with quill presents the highest values; this is consequence of the free voids observed in the internal structure that can retain water as was explained before.

4. Conclusions

In agreement with the results obtained in the oedometer (e-log$p$ curves), it was concluded that soils modified with barbs present the lower values in swelling pressure. The soil modified with 3% of barbs has a value of 28.01 kPa; this is the smallest value found in our soil samples, and it represents a reduction of 44% in swelling pressure compared to natural soil without reinforcement.

On the other hand, void ratio is also an important parameter, since if it decreases the possible expansion is also diminished. This response is produced due to the fact that the space between the particles is reduced and the possibility to infiltrate water is also reduced. In this case, the behavior of void ratio is strongly influenced by the structural features of feather segments, since quill fragments are hollow. Thus the order of initial void ratio behavior was quill > total fiber > barbs > natural soil.

Modification with quill also provides a good performance taking into account the results of degree of saturation. Higher values reached for this parameter imply that soil is less susceptible to undergoing harmful expansion. The results allow observing that general performance of degree of saturation was following the next order: quill > barbs > total fiber > natural soil.

On the other hand, specific surface area results show also a better behavior for soil modified with feather segments, since all modified samples present lower values than natural soil.

Therefore it is possible to conclude that the proven feather segments effectively can be used as ecological modifiers for expansive soils, taking advantage of this structural material obtained from chicken feathers and changing natural properties of soil.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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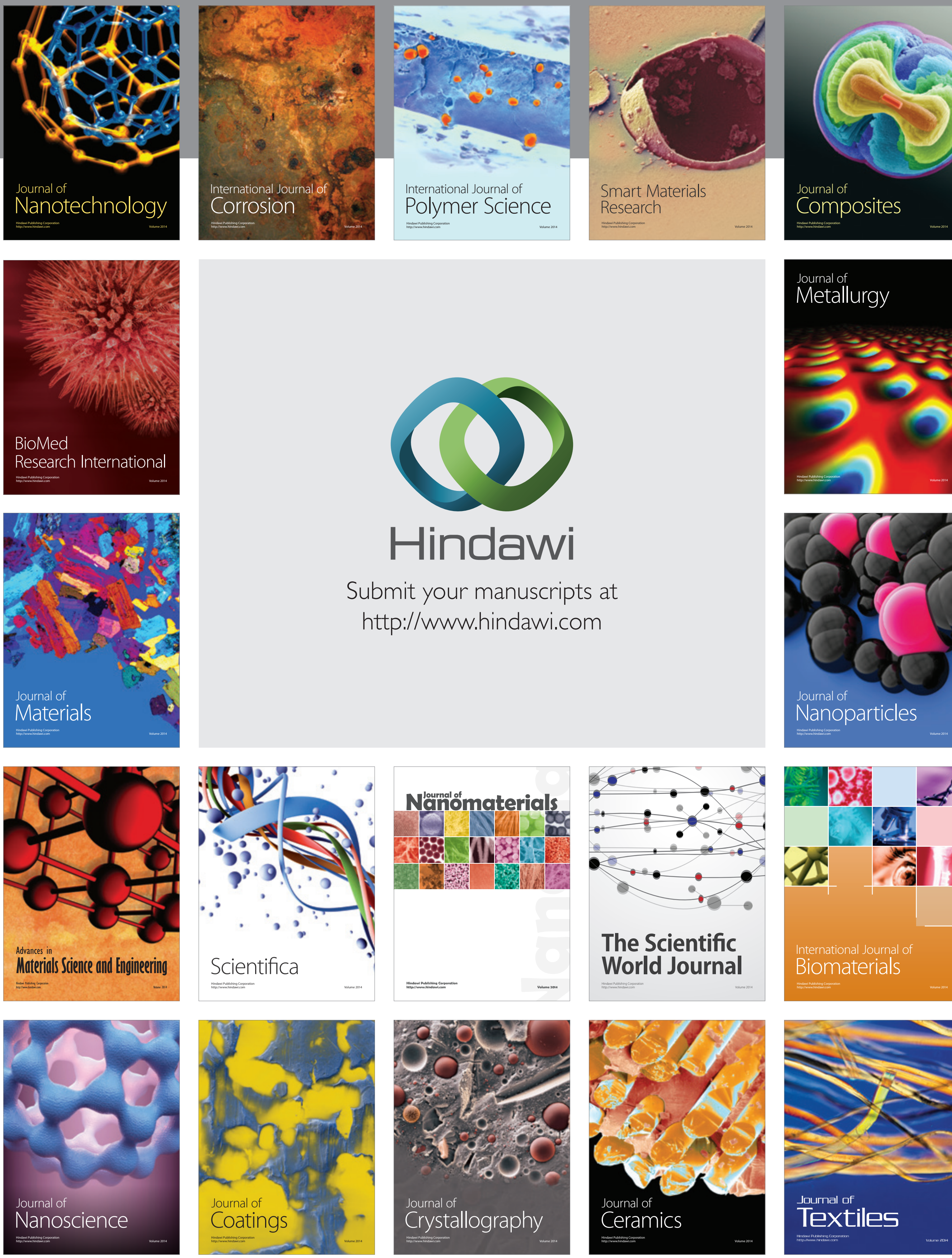
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