Reduction of the Shrinkage–Swelling Potential with Polymer Nanocomposite Stabilization

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ABSTRACT: This article describes the application of using polymer stabilization to create a new hydrophobic (nanocomposite) material with swollen clay. A series of tests were performed with different polymer contents to study the effect of using polypropylene as a partial soil stabilizer and a shrinkage–swelling modifier for expansive soils. The effect of the obtained clay–polymer nanocomposites on the shear strength of swelling soils was also investigated. The tests showed that the resulting nanocomposites acted as nanofiller materials and decreased both the plasticity index and permeability. The optimum moisture content and dry density decreased relatively with increasing polymer content. The polymer inclusions significantly reduced the free swelling and swelling pressure values. In addition, the produced nanocomposites reduced the volumetric shrinkage of the expansive soils and created isotropic and compressible materials. The unconfined compressive strength of the soil increased significantly with increasing polymer content. The proposed stabilized technique increased the bearing capacity under the model footing and modified the stress settlement relationship. © 2011 Wiley Periodicals, Inc. J Polym Sci Part A: Polym Chem 123: 299–306, 2012

Key words: additives; adhesion; blending

INTRODUCTION

For all engineering structures constructed on clayey soils, these soils cause swelling when they are exposed to water and shrink once water is squeezed out.[1] These volumetric changes cause considerable failure to the foundation and damage to the civil infrastructure.[2,3]

Expansive soil or swelling clays are mostly found in arid and semiarid regions of the world. In Egypt, swelling clays cover most of greater Cairo, including Nasr City, 6th of October City, and Zayed City.

Expansive soils derive their swelling potential mainly from montmorillonite mineral, which is present in these soils.[4,5] Many chemical investigators[6–8] have dealt with the problem of water adsorption through montmorillonite. The modification of the clay microstructure has been done by with the use of polymers to produce nanocomposite materials with components of clay. Polymers are recognized as one of the most promising research areas in science and technology in the 21st century. They are used in a wide range of applications to improve and reinforce several material properties.[9] Polymers can be reinforced with different fillers and enhance the mechanical properties of the virgin polymer. Conventional fillers, such as talc, mica, $CaCO_3$, kaolin, fumed silica, and glass fiber, have been found to increase the mechanical properties with detrimental impacts on the density, transparency, and processability.[10] The most common nanosized fillers are carbon nanotubes, nanosized particles, and intercalated layers. Because nanoparticles have significant surface sizes and quantum effects, their incorporation in a polymer matrix improves several material properties. These improved properties include a high elastic modulus, a lower gas permeability, an increased strength, a lower flammability, and increased biodegradability.[11]

On the other hand, geotechnical investigations have been carried out to study the swollen clay improvement for foundation uses and to control volume changes. Stabilization by admixtures has been used to prevent volume changes or adequately modify volume changes characteristics of such clays. Lime, cement, pozzolonic flay ash, basalt, and furnace slag can be used fairly to stabilize expansive high-plastic clays.[12–17] All of the previous studies have focused on the use of lime flay ash and cement to enhance relatively the geotechnical properties of swollen clay, whereas the application of the use of chemical materials has been limited. In this study, an attempt was made to apply the technique of polymer nanocomposites from the chemical point of view to geotechnical considerations. The use of a polymer to create a new hydrophobic material

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(nanocomposite) with swollen clay was studied. The effect of the use of polypropylene as a partial soil stabilizer and shrinkage–swelling modifier for expansive soils is distinctly explained. In addition, this study included the investigation of the effect of the resulting clay–polymer nanocomposites on the shear strength of swelling soils and induced shear failure.

EXPERIMENTAL

Characterization of the swollen clay and polymer

The initial physical properties of the selected swelling soils were determined according to the American Society for Testing and Materials (ASTM) specifications. The physical properties of the tested soils are shown in Table I. The swelling characteristics of the tested samples were investigated with a standard odometer. The free swelling was found to be 30%; this value agreed with the corresponding value of Phanikumar and Radhey.[12] The swelling pressure was found to be 260 kN/m^2.[18] The swelling of the clay under investigation was classified as marginal swelling. The X-ray diffraction (XRD) results of the tested samples refer to the mineralogical compositions, and the percentages of montmorillonite, kaolinite, and illite were 55, 25, and 17%, respectively.

The polymer used in this investigation was a polypropylene homopolymer (H030SG) was obtained from the petrochemical factory in Alexandria, Egypt with a melt flow index of 3. This polymer was commercially available, environmentally accepted, and was used as a nanofiller to obtain a nanocomposite material with swollen clay.

TABLE I
Initial Physical and Mechanical Properties of the Swelling Soil

Property	Value
Specific gravity	2.61
Compacted dry density (kN/m^3)	14.8
Initial water content (%)	13
Liquid limit (%)	52
Plasticity index (%)	30
Sand fraction (2 mm - 75i)	5
Silt fraction (75i - 2i)	55
Clay fraction (<2i)	40
Activity	1.3
Permeability (m/s)	14×10^{-4}

Preparation of the polypropylene–clay composites

To prepare the polypropylene–clay composites, physical mixing was adopted.[8] In this method, the clay was dried in an oven at a temperature of 110°C for 24 h. The clay was accurately weighed and mixed with polypropylene in a solution form with xylene as the solvent. Xylene was added to a 1000-mL beaker containing polypropylene. After the mixing process was finished, the beaker was kept open for a few hours to evaporate xylene. Then, the prepared polymer–clay composite was mixed well mechanically.

Testing program

The amounts of polymer added to the swollen clay soil samples, as percentage of the dry soil mass, were 5, 10, and 15%. All of the samples were remolded at their optimum moisture contents (OMCs) and maximum dry densities (MDDs) with the Proctor test according to the ASTM specification of the compaction test. The compaction curves for mixes of different plasticity values prepared with different percentages of polymer are shown in Figure 1. The addition of polymer to form a nanocomposite material with the clay remarkably decreased the resulting dry density with increasing polymer contents. Although there was no wide variation in OMC, it decreased slightly with increasing polymer content. The dry density also decreased gradually in a small range with increasing polymer content because the formed nanocomposites acted as nanofillers; thus, the volume of sample increased.

After the mixing process, the admixture was compacted to the desired density and placed in a PVC cylinder mold (76 mm in height and 38 mm in diameter) and block ($60 \times 60 \times 40$ mm^3) to be tested by an unconfined shear and direct shear testing procedure. A series of tests were conducted to examine the effect of the polymer nanocomposite on the index and mechanical properties in addition to the swelling potential of the stabilized swollen clay with an odometer cell. With a fixed ring odometer, the free-swelling test was performed to determine the swelling potential at different polymer contents (as per ASTM D 4546). Specimens 70 mm in diameter were compacted statically to the relevant MDDs at the corresponding OMCs. To obtain the free swelling, a seating load of 6.9 kPa was first applied, and the specimen was subsequently inundated with distilled water.[15]

Their structures were elucidated by many sophisticated techniques, including scanning electron microscopy (SEM), XRD, transmission electron microscopy (TEM), and atomic force microscopy (AFM). These techniques were done to study and characterize the behavior of the swollen clay samples before and after polymer stabilization and the development of the nanocomposites.

The volumetric shrinkage characteristics of the stabilized samples were measured with proctor molds. This method was earlier proposed by Puppala and Musenda.[19] In this procedure, an oven-dried,

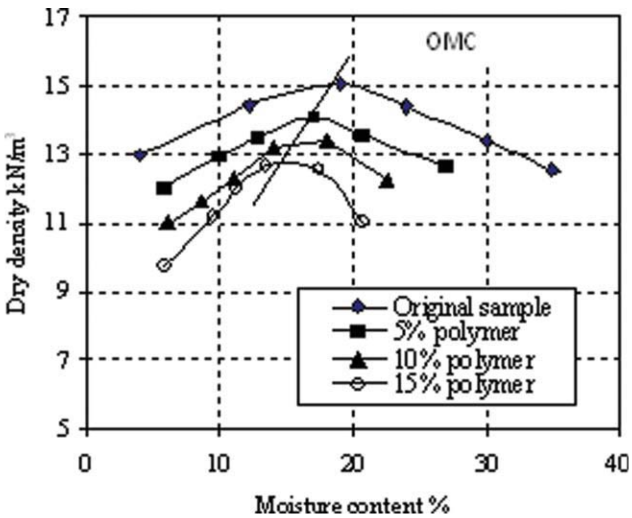

Figure 1 Compaction curves for samples with or without polymer stabilization.

reconstituted soil was mixed with water at the liquid limit state to form a slurry at different polymer contents. The mix was then poured into the mold and lightly tamped. Subsequently, the specimen in the mold was placed in an oven at 80°C for 48 h. During this period, the mold was turned upside down and rotated regularly to allow uniform shrinking and drying of the specimen such that cracks could be avoided or minimized. Thereafter, the diameters and heights were measured at three different locations, and the averages were noted to calculate the volumetric shrinkage strain values.

RESULTS AND DISCUSSION

Polymer–clay nanocomposite mechanism

Clay–polymer stabilization with polypropylene is a recent field of stabilization and was applied in this research to improve and modify the behavior of the

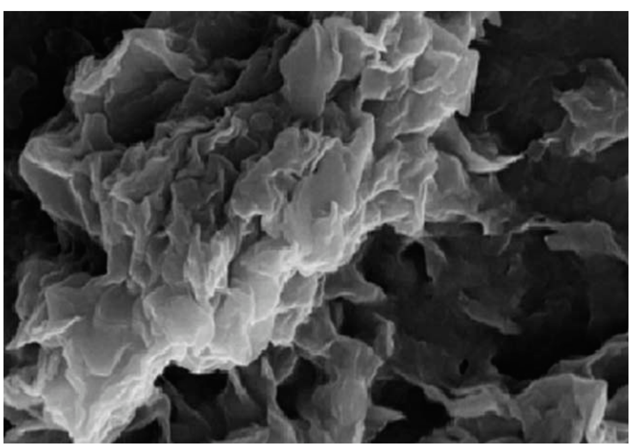

Figure 2 SEM image of the layered, exfoliated structure of a swollen clay sample.

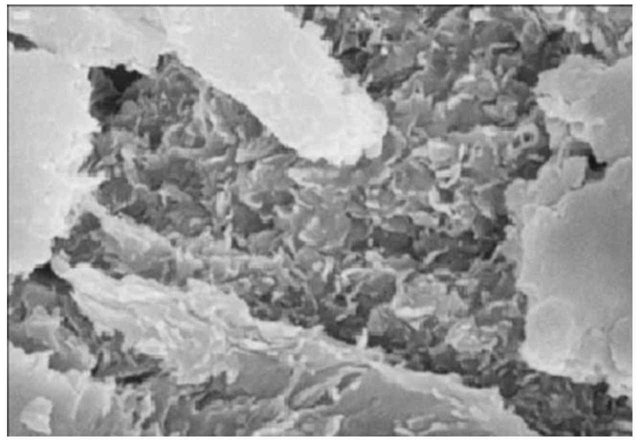

Figure 3 SEM image of the fractured surface of a polymer–clay nanocomposite (polymer concentration = 10%).

swollen clay. Figure 2 presents the SEM image of the pristine swollen clay. It shows an aggregate of montmorillonite platelets exfoliated during dispersion in water during sample preparation. The fractured surface of the swollen clay composite with polymer (Fig. 3) showed that the clay dispersed in the polymer matrix in aggregates of different sizes; this indicated an inhomogeneous distribution of clay. The polymer stabilization increased the net electrical attraction between adjacent grain particles. It also improved the grain surface of the swollen clay against water by constructing the nanocomposite as a hydrophobic material and preventing the affectivity of the montmorillonite (ion exchange). The polymer here modified the microstructure of the soil-like nanofiller to produce a new skeleton and altered the texture of the clay by reducing the fine particles. Furthermore, it produced nanocomposite materials. The ion-change phenomena distinctly describes this mechanism.[7,8,10]

The absence of a characteristics peak at 75° for the clay–polymer stabilized sample in the region 2–10° in XRD, as shown in Figure 4(a), indicated the total dispersion and delimitation (exfoliation) of the fine nanoclay layers in the matrix. Interestingly, the polymer clearly was able to exfoliate both the pure clay and modified clays (at 10% polymer content), as evident from the XRD studies. However, the particle size was much lower in the case of the sample without polymer and the distribution was also better in this particular sample, as shown in the TEM micrograph [Fig. 4(b,c)].

Thus, the TEM image shows that the clay was not evenly dispersed throughout the matrix. In fact, although some tactics were found, most of the clay stacks were confined to clusters.

Topographic and phase imaging in tapping-mode AFM was performed to investigate the size of the clay-platelets, the polymer–filler interface, and the

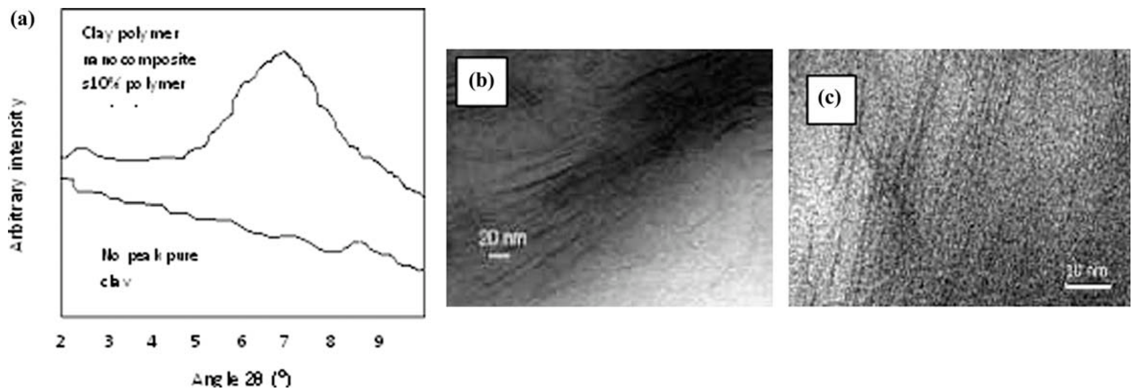

Figure 4 (a) XRD diffractogram of nanocomposites with the pure clay, (b) TEM micrograph of the pure clay, and (c) TEM micrograph of the clay stabilized with the polymer (polymer concentration = 10%).

spatial distribution of the nanoparticles (unmodified and modified clays) in the fluoroelastomer. The phase images (Fig. 5) of the pure clay and modified polymer–clay nanocomposites revealed that the width of the clay particles was lower in the case of the unmodified-clay-filled system (10 ± 3 nm) versus that of the modified system (15 ± 2 nm). This was in accordance with the TEM and SEM morphological results. This may have been due to better polymer–filler interaction in the case of the polar natural clay. We concluded that studies by XRD and TEM confirmed the AFM results and showed the effectiveness of constructing the new inclusions or nanoparticles because of proper polymer–clay interaction.

On the other hand, these nanofiller materials significantly modified and decreased both the plasticity index and the permeability of the soil, according to percentage of polymer, as presented in Table II. This also confirmed the produced nanocomposites

Swelling potential

Figure 6 shows typical swelling curves for samples with different polymer contents; the figure indicates that even after a period at which the swelling reading was constant, swelling still occurred, although at a much lower rate. Hence, hyperbolic modeling was used to obtain the maximum free-swelling values. It is also shown in this figure that at 0% polymer content, the mix produced a free-swelling value of 30%, which was significantly higher than the value predicted for the stabilized sample. The polymer stabilization generally decreased the free swelling by about 16–60% (with a higher value for a higher polymer content).

Figure 7 again indicates that the polymer significantly controlled and reduced the free swelling and had a considerable effect on the modification of the swelling potential in the resulting polymer–clay nanocomposites.

Similarly, the variation of the swelling pressure with polymer content (Fig. 8) indicated that at a maximum polymer content of 15%, the swelling pressure was reduced by as much as 70%. This suggested that the adopted polymer also worked as a compressible inclusion within the soil. Additionally, although this figure seems to suggest that the swelling pressure could be totally eliminated, the

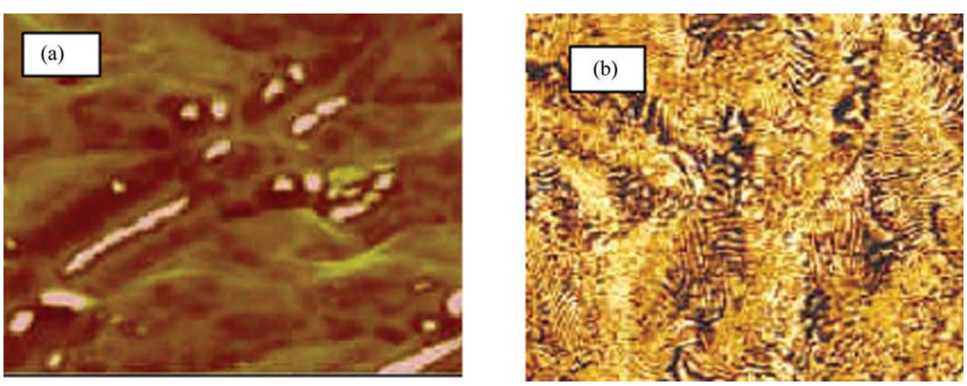

Figure 5 Tapping-mode AFM phase images of (a) the pure clay sample and (b) the clay–polymer nanocomposite (polymer concentration = 10%, scale = 100 nm). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE II
Effects of the Polymer Content on the Permeability and Plasticity Index

Polymer content (%)	Permeability (m/s)	Plasticity index (%)
0	14×10^{-4}	30
5	5×10^{-6}	25
10	1×10^{-7}	20
15	30×10^{-7}	17
100 (pure)	1.25×10^{-2}	18

polymer content required for that purpose (>15%) would cause difficulties in mixing and compaction and would not be economical.

In agreement with Erguler and Ulusay,[20] we found that exponential equations could be used to model the variations of the swelling pressure with the calculated maximum free swelling at different polymer contents (Fig. 9). The figure demonstrates the effectiveness of the polymer as a swelling reducer and confirms the produced nanocomposites as filling materials.

Volumetric shrinkage

The variations in volumetric shrinkage strain with polymer content are shown in Figure 10. From this figure, we concluded that the addition of polymer to form nanocomposite materials considerably reduced the volumetric shrinkage strain of the expansive soils. In general, the use of such polymers for stabilization processes shows relatively isotropic behavior with respect to both the diametrical and axial shrinkages because there is a trivial difference in the obtained values, as obviously shown in Figure 10.

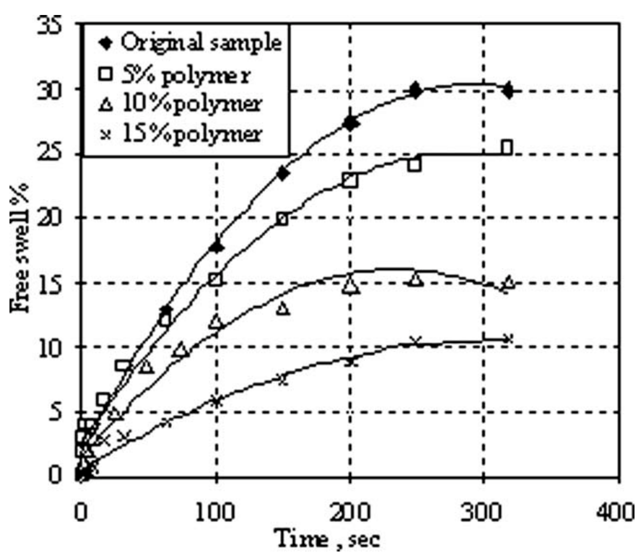

Figure 6 Free swelling of the stabilized samples versus time.

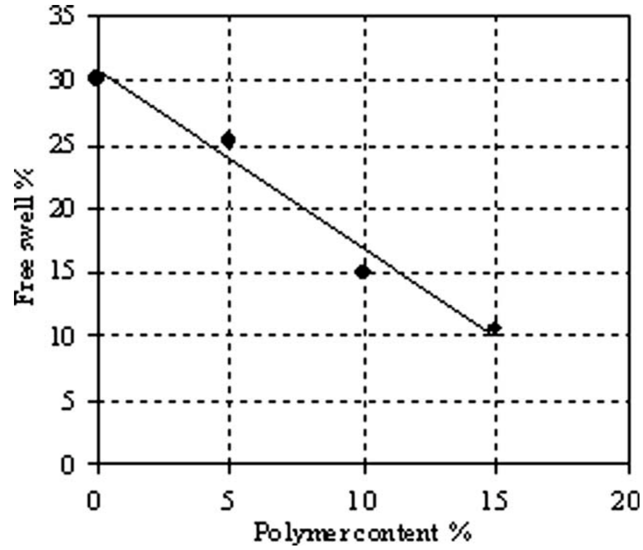

Figure 7 Free swelling of the stabilized samples versus the polymer content.

Shear strength behavior

Studies were carried out to examine the effect of the polymer that produced the nanocomposites on the unconfined compressive strength of the swelling soil samples. Figure 11 shows the stress–strain curves of samples stabilized by the polymer at different contents. The achieved nanocomposite (polymer effect) significantly modified the stress–strain relationship. The induced nanofiller distinctly increased the stress and decreased the vertical strain with the increasing polymer content. Also, at polymer contents of 10% or greater, there no peak failure was exhibited because the induced nanocomposites acted as a compressible isotropic and ductile inclusions, as confirmed before. In addition, the executed nanocomposites significantly increased the initial tangent

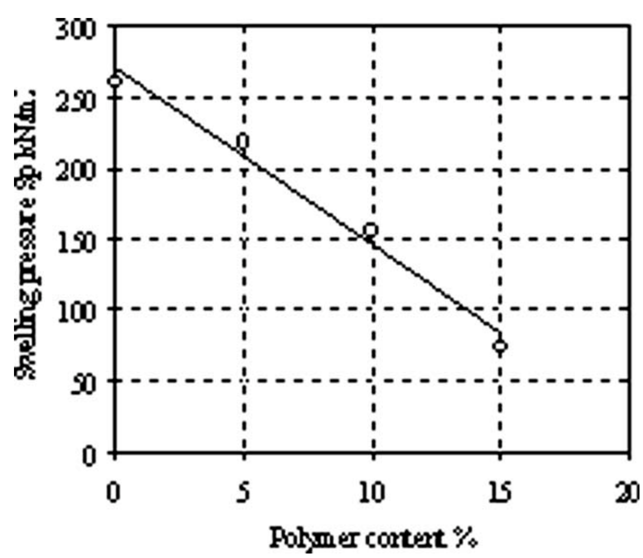

Figure 8 Swelling pressure versus the polymer content.

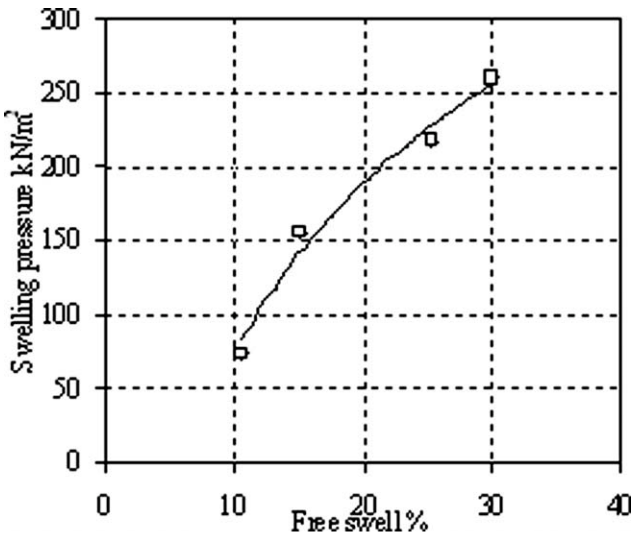

Figure 9 Swelling pressure versus free swelling with the same polymer content

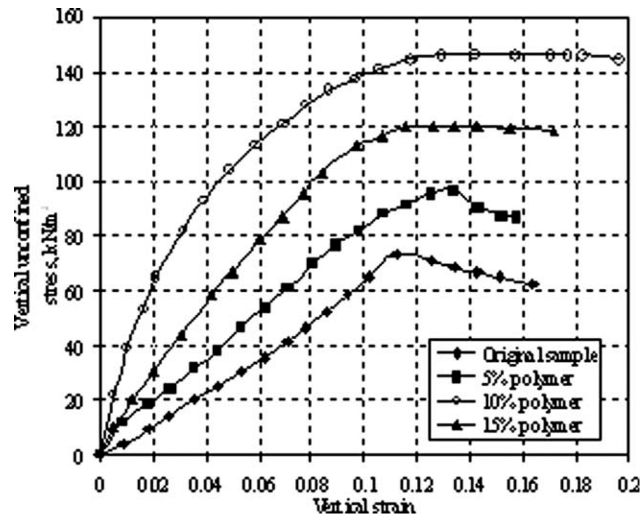

Figure 11 Stress–strain curves of the stabilized samples with different polymer contents.

modulus, as illustrated in Figure 11. Moreover, the formation of the nanocomposites diverted the failure pattern in the unconfined compression test from brittle failure (well-defined shear plan) to plastic failure. This also verified that the clay–polymer produced an isotropic and compressible material. On the other hand, the plot of the unconfined compressive strength with polymer content is shown in Figure 12. Increasing the polymer content increased the unconfined compressive of the soil samples in a linear relationship. This increase was backed to the effect of achieving nanocomposites with the soil particles. In addition, the polymer had a considerable effect on increasing the shear strength of the expansive clay.

Application of polymer stabilization for footing

In this part of study, loading tests for model circular steel footing resting on stabilized swollen clay were studied. A series of loading tests for footing on stabilized clay at different polymer contents was carried out. The testing model consisted of a rigid cylindrical steel tank 40 cm in diameter and 50 cm in height. The tank had a 0.5-mm wall thickness and was built rigidly to resist the lateral deformation to satisfy the plain strain conditions. A circular footing model made of steel with a hole in its center was adopted. The footing was 75 mm in diameter and 10 mm in thickness. The load was transferred from the steel frame over the tank to the footing through a

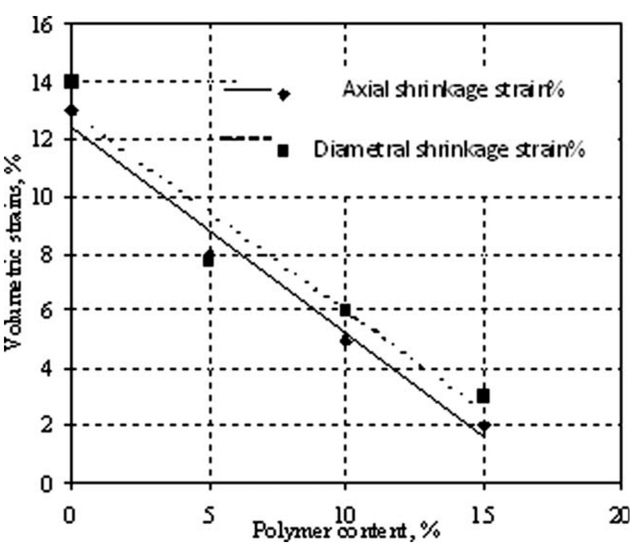

Figure 10 Variation of the axial and diametral shrinkage strains with the polymer content.

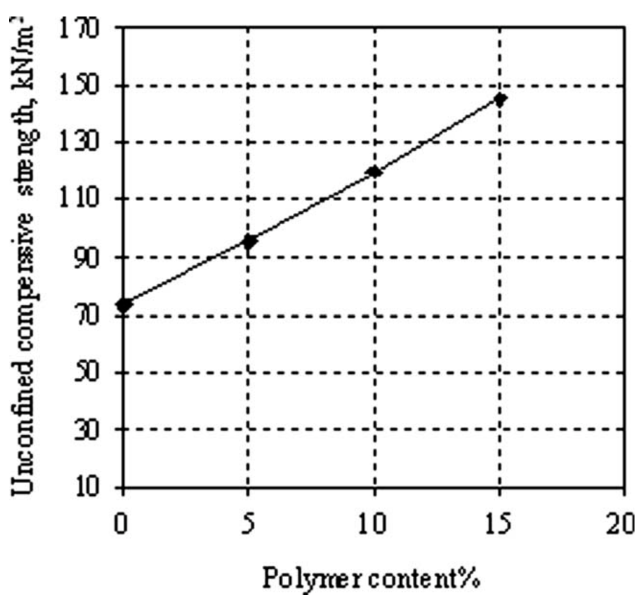

Figure 12 Unconfined compressive strength versus the polymer content.

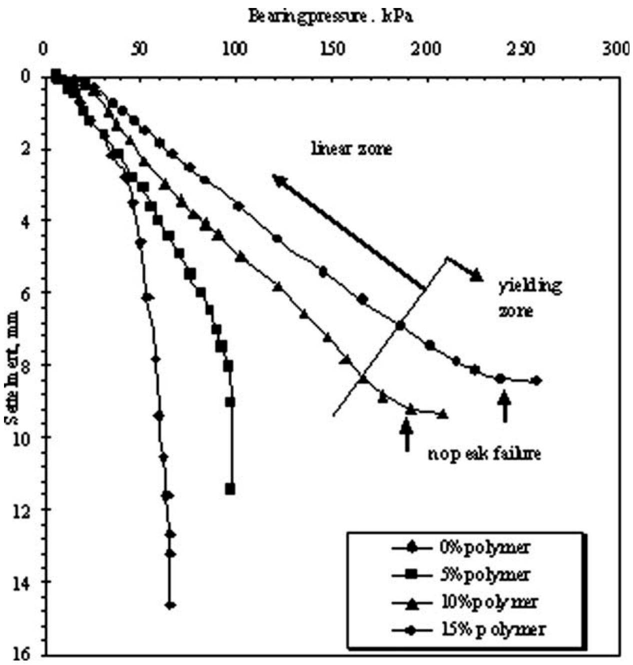

Figure 13 Variation of the bearing pressure with different polymer contents.

ball bearing, which was placed between the footing and the proving ring. The load was applied by a manual hydraulic jack. The soil model thickness was taken as four times the footing width. The tested soil was prepared at different polymer contents, as mentioned before. All of the samples were remolded at their OMC and MDD. The footing was placed at the top surface and incrementally loaded up to failure with proving ring, and the settlement of the footing was measured at each increment with a dial gage. The stress settlement relationship of the model footing resting on stabilized swelling soil at different polymer contents is shown in Figure 13. The ultimate bearing capacity of the footing soil system for each test was estimated from the stress displacement curves, where the slope of the load displacement curves first reached zero or a steady minimum value. The polymer stabilization significantly modified the stress settlement curves; this modification backed the polymer effect. Where the developed nanocomposite was made, the subgrade under the footing as a one united and totally deformed. Also, the figure again showed that the ductility of the supporting stabilized soil was increased with increasing polymer content. On the other hand, at higher values of polymer content (>5%), the linear stress settlement relationship was obtained until it reached failure compared with the other case. At polymer contents of 10 and 15%, the stress settlement curves started to change their direction, and no peak failure was distinctly exhibited. This also showed that at this polymer contents, the subgrade was linearly compressed, and the failure took place at a lower variation in the settlement value, as illustrated in Figure 13. The bearing capacity failure mode of the footing on stabilized soil was modified to punching shear failure with a lower variation in the settlement rate.

It can be concluded that the polymer stabilization had a considerable effect on increasing the bearing capacity of the expansive clay and on the control of the vertical footing settlement. This technique could be considered for local stabilization only for one-footing structures, such as single-column piers/bridges without the excavation and stabilization of the whole site. This study suggests that one can carry out such polymer stabilizations by excavating and stabilizing the soil only under the footing positions. This technique should be compared with other methods for the improvement of the soil-bearing capacity, such as in soil reinforcements or pile foundations in which soil reinforcement is not economical and needs more installation efforts. This method is economical and capable of providing bearing-capacity improvements.

CONCLUSIONS

From the results of this study, the following conclusions can be drawn:

1. Stabilizing the swollen clay by polypropylene modified the microstructure of soil as a nanofiller and altered the texture of clay by producing nanocomposite hydrophobic materials.
2. The polymer stabilization generally reduced the free swelling by about 16–60% (a higher value for a higher polymer content). The polymer significantly controlled and reduced the free swelling and had a considerable effect on the modification of the swelling potential due to the resulting polymer–clay nanocomposites.
3. The addition of polymer to form nanocomposite materials considerably reduced the volumetric shrinkage strain of the expansive soils and acted as compressible materials.
4. At a maximum polymer content of 15%, the swelling pressure was reduced by as much as 70%. This again illustrated that the adopted polymer also worked as a compressible inclusion within the soil.
5. The adopted stabilization process showed isotropic behavior with respect to both the diametrical and axial shrinkages.
6. The induced nanofiller distinctly increased the unconfined compressive stress and decreased the vertical strain with increasing polymer content. At polymer contents of 10% or more, no peak failure was exhibited.

7. Increasing the polymer content increased the unconfined compressive of the swelling soil samples in a linear relationship and modified the brittle shear failure to plastic shear failure.
8. This method was also considered to be an effective technique for increasing the bearing capacity of the footing and for controlling the settlement.

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