

# Modification of Sandy Soil Using Water-Borne Polymer

Abdullah Al-Khanbashi, Maisa El-Gamal

Department of Petroleum and Chemical Engineering, United Arab Emirates University, P.O. Box 17555, Al Ain, United Arab Emirates

Received 7 March 2002; accepted 26 August 2002

**ABSTRACT:** A new polymeric system has been applied for structural modification of (noncompactable) sandy soils. The system is based on a water-borne styrene acrylic polymeric formulation (emulsion) containing varying amounts of solid polymer. The present work deals with system optimization and measurements designed to examine the effects of polymer content on hydraulic conductivity and compressive strength. Samples were prepared from prescribed amounts of polymer, water, and sand by using two different preparations methods (mixing and spraying). Measurements of hydraulic conductivity for both sets of samples were conducted in a flexible membrane test apparatus. For the first set of samples, the permeability coefficient of the sand was noted to be reduced 10-fold (from  $10^{-5}$  to  $10^{-6}$  m  $s^{-1}$ ) upon the incorporation of about 2% polymer. In the second set (samples prepared with the spraying method),

the hydraulic conductivity was further reduced to  $7.2 \times 10^{-7}$  at a polymer concentration of about 2%. Stress-strain measurements made on dry cylindrical specimens disclosed remarkable enhancement in the mechanical behavior of the system. For both types of preparation methods, the compressive strength and modulus of elasticity increased linearly with the polymer concentration in the sample. Scanning electron microscopic examination revealed that the dramatic reduction in the permeability and the improved mechanical properties are attributed to the polymer coverage of the sand particles and the development of interconnecting ties between them. © 2003 Wiley Periodicals, Inc. *J Appl Polym Sci* 88: 2484–2491, 2003

**Key words:** modulus; compression; electron microscopy; mechanical properties; structure-property relations

## INTRODUCTION

The use of polymers in ground modification to enhance mechanical stability and seepage control has become essential in many engineering applications. Among the major technologies benefiting from advances in polymeric materials and processes are geotextiles, permeation grouting, and geomembrane liners.<sup>1–6</sup> Of particular interest is the construction of liners for ponds, waterways, and landfills. In the case of ponds and waterways, liners are designed to diminish water loss; in the case of waste containment landfills, the liners are designed to protect the environment by preventing the release of leachants into the ground water and the surrounding soil.

Material systems used in the construction of liners have evolved over the years from compacted native soils to include polymer-containing admixtures of soil-bentonite, asphalt-concrete, soil-asphalt admixtures, and flexible membranes. The latter is applied in the form of sheet liner commonly manufactured from polyethylene, PVC, butyl rubber, or chlorinated polyethylene. Selection of a particular material system for

liner construction depends on design constraints, location, and economic factors. Stringent environmental liability more often than not demands the construction of multiple membrane systems with a high degree of sophistication.

Admixtures besides being expensive are not impermeable, a limitation that may be controlled by certain polymer additives. Incorporating polymeric additives to admixtures is documented to boost their performance.<sup>7</sup> For instance, it is indicated that the addition of small quantity of specially formulated polymer to marginal-quality bentonite-sand mixtures was found to improve the hydraulic conductivity significantly.<sup>7</sup> Another related report<sup>8</sup> suggests that the addition of low concentration of polyacrylamide, with aluminum citrate as crosslinking agent, to sand was found to produce significant seepage cut-off. These developments prompt the possibility of using polymer formulations to upgrade the mechanical and transport properties of loose sandy soils, which constitute a demanding structural engineering challenge.

Flexible membranes, on the other hand, display the advantage of being resistant to several reactive fluids. However, these membranes are susceptible to mechanical damage due to sharp objects and, to various extent, are prone to crack propagation, particularly at locations of creases, sharp bends, and welding lines. Results of stability assessment of a number of large landfill failures published recently<sup>9</sup> suggest interfacial

Correspondence to: A. Al-Khanbashi (abdullak@uaeu.ac.ae).

Contract grant sponsor: the United Arab Emirates University Research Affairs; contract grant number: 99-12-7-02.

shear strength was found to be the overriding consideration. The triggering mechanisms for failure were related to interfacial mobility associated with clays beneath the geomembranes. Concern of the integrity of the interface between flexible geomembranes and compacted clay is shown in a more recent report.<sup>10</sup> The study indicated that interfacial adhesion was more relevant than the angle of friction in the stability of the system. Furthermore, the clay-polymer adhesion showed little difference on the surface characteristics of the polymer membrane.

The challenge of designing liner systems that are economical, with efficient hydraulic conductivity and interfacial stability, is further accentuated when dealing with loose sand soils. It was this set of issues that occasioned the present research. It constitutes an attempt to design a polymer impregnation system *in situ* to produce desirable enhancements in hydraulic conductivity and mechanical stability of loose sand soils.

The target system is approached through a process similar to one followed in impregnation grouting. However, use is made of an appropriate water-borne polymeric emulsion, thus precluding the negative environmental impact associated with solvents and monomers released during grouting. The hypothesis is that once a water-borne polymer emulsion is impregnated into the sand soil and the water is driven off, the ensuing polymer-sand system would exhibit the desired strength and hydraulic conductivity.

## EXPERIMENTAL

Commercial water-borne styrene acrylic emulsion copolymer was used in this study. The polymer UCAR LATEX D-59 was obtained from Union Carbide (Dubai, United Arab Emirates). The physicochemical properties of the used polymer are shown in Table I. The polymer emulsion was diluted to 15% solid content by the addition of distilled water and used as is to prepare polymer-impregnated samples as outlined below.

The desert sand used in this investigation was obtained from a sandy dunes quarry in the Al Ain area in the United Arab Emirates. The sand is characterized by a grain size ranging from 0.1 to 1 mm and a specific gravity of 2.584. The moisture content, as determined

**TABLE I**  
Physicochemical Properties of Emulsion System

| Parameter                         | Value     |
|-----------------------------------|-----------|
| Total solid content (%)           | 50 ± 2    |
| pH value                          | 8.5–9.5   |
| Viscosity, cps at 26°C            | 1000–4000 |
| Glass-transition temperature (°C) | 13        |
| Specific gravity                  | 1.05      |
| Particle size, μm                 | 0.09–0.12 |

**TABLE II**  
Chemical Composition of Desert Sand

| Compound                       | Weight (%) |
|--------------------------------|------------|
| SiO <sub>2</sub>               | 67.97      |
| Al <sub>2</sub> O <sub>3</sub> | 2.23       |
| Fe <sub>2</sub> O <sub>3</sub> | 2.35       |
| CaO                            | 10.14      |
| MgO                            | 4.79       |
| SO <sub>3</sub>                | 0.24       |
| K <sub>2</sub> O               | 0.80       |
| Na <sub>2</sub> O              | 0.23       |
| Cl                             | 0.00       |
| Loss on ignition               | 11.25      |

by the Modified Proctor Test procedures,<sup>11</sup> was 6% by weight, and the maximum dry density was 1.607 mg m<sup>-3</sup>. The chemical composition of the desert sand was determined using XRF spectrometer; analysis results are shown in Table II.

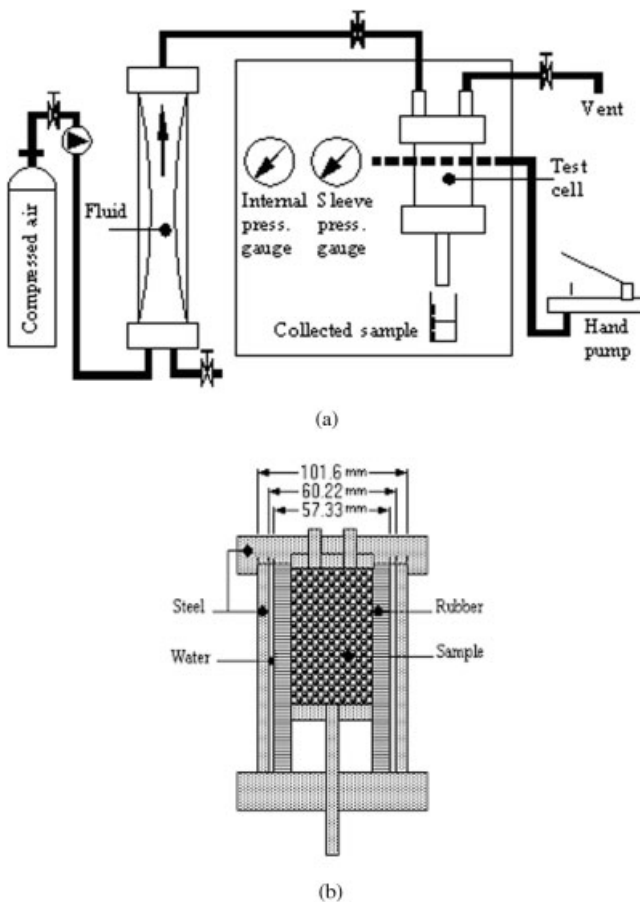
## Specimen preparation

The present study aims at exploring the use of water-borne polymer emulsion as an agent to improve sandy soils in terms of hydraulic conductivity and mechanical strength. Accordingly, the method of sample preparation was designed with this application in mind. A direct method involved spraying the polymer emulsion (15 wt % in distilled water) on top of a sand column, contained within a mold. Specimens were then dried at 60°C in a forced air oven to produce specimens containing 0.5, 1, 1.5, and 2 wt % polymer. Because the spraying method is likely to produce polymer concentration gradient profile, it is useful to prepare a parallel set of samples with known and uniform polymer composition. A set of specimens was prepared by processing the polymer-soil-water mixture into dough using a mechanical kneader. The uniformly mixed dough was subsequently molded into a steel mold and dried at 60°C in a forced air oven. Specimens containing 0.5, 1, 1.5, and 2 wt % polymer were prepared using this method.

Since the polymer emulsion contains significant amount of water, its percentage was included in the moisture content calculations, for both types of samples, to give the optimum moisture content of 6%. Also, during the drying process, the weight loss was recorded as a function of time until steady state was reached to ensure complete removal of water.

## Characterization

The hydraulic conductivity for the unmodified sand was determined using the constant-head method. Briefly, this method entails the use of a poly(vinylchloride) cell with internal diameter of 7.6 cm and height of 21 cm. The sand sample is charged into the cell and



**Figure 1** Flexible membrane testing apparatus for hydraulic conductivity measurements (A). Flexible membrane testing cell (B).

the water flow is adjusted to maintain a constant head of about 93 cm above the top of the sand. The water drainage through was collected and its volume was measured as a function of time. The hydraulic conductivity of unmodified sand specimens was determined by applying Darcy's Law,

$$Q = KiA$$

where  $Q$  is the water flow rate,  $K$  the hydraulic conductivity,  $i$  the hydraulic gradient, and  $A$  the cross-sectional area.

Hydraulic conductivity of polymer-modified sand was measured using a flexible-membrane test apparatus because of their solid nature. A sketch of the apparatus is shown in Figure 1. Samples 8.5 cm in length and 3.8 cm in diameter were first saturated in distilled water for 24 h under room temperature and pressure and then placed in a rubber stopper with a diameter of 3.81 cm. Water pressure was applied around the rubber to prevent side leakage during hydraulic conductivity measurements. Then a water pressure gradient of 1.7 psi was applied across the tested specimen and the quantity of passing water was

recorded as a function of time. The hydraulic conductivity was calculated using the following equation:

$$K = \frac{Q\mu L}{A\Delta P}$$

where  $\mu$  is the water viscosity,  $L$  the sample length, and  $\Delta P$  the pressure drop.

Improvement in the mechanical strength of the sand-polymer composite was monitored through measurements of stress-strain behavior in compression. The unconfined compression tests were conducted using an MTS tensile testing machine. The system is equipped with universal testing software (TestWorks) capable of graphic and numerical analysis of the test data. All tests were conducted at constant cross-head speed of  $5 \times 10^{-3} \text{ m s}^{-1}$ . The compressive strength and modulus of elasticity were selected to investigate the mechanical properties of sand-polymer prepared specimens.

Microscopic examination was achieved using JSM-5600 Joel microscope equipped with X-ray diffraction attachment for chemical analysis. Several samples were examined to ascertain the observed phenomena.

## RESULTS AND DISCUSSION

All polymer-impregnated samples when dried were cohesive solid materials, a noticeable change from the loose characteristic of the sandy soil. In this section, we present results of measurements of the hydraulic conductivity and mechanical behavior of the new material systems. Results of SEM examinations are also presented to help develop a mechanistic view of the introduced improvements.

Figure 2 presents the hydraulic conductivity results. The sand sample exhibited hydraulic conductivity of  $3 \times 10^{-5} \text{ m s}^{-1}$ , a value that falls in the general range reported in the literature.<sup>3</sup> The hydraulic conductivity for both types of specimens (mixed and sprayed) decreased with increasing the polymer concentration. Significant reduction in hydraulic conductivity was observed for systems containing 0.5 wt % polymer for both types of specimens. At this polymer concentration, the hydraulic conductivity of both types of samples is practically comparable. At polymer concentration of 1 wt % or more, the hydraulic conductivity continue to decrease but at a much lower rate. Considering the reduction of the variance of the data at and above 1 wt % polymer concentration, it is reasonable to conclude that the hydraulic conductivity of the sprayed samples is always lower than the mixed samples. As seen in Figure 2, the hydraulic conductivity recorded at 1 wt % polymer concentration was approximately  $6.1 \times 10^{-6}$  and  $3.4 \times 10^{-6}$  for the mixed and sprayed specimens, respectively. The maximum

decrease in hydraulic conductivity for both types of specimens was observed at 2 wt % polymer concentrations. For the mixed specimens, the hydraulic conductivity was  $2.1 \times 10^{-6} \text{ m s}^{-1}$  and for the sprayed specimens the hydraulic conductivity was  $7.2 \times 10^{-7} \text{ m s}^{-1}$  at 2 wt % polymer concentrations. For this polymer-soil system, attempts to incorporate more than 2 wt % polymer by mixing produced nonhomogeneous polymer-sand mixture, which was not suitable for hydraulic conductivity measurements. This mixture exhibited large-scale phase segregation, producing lumps of polymer-rich domains. The phase separation experienced during mixing could be attributed to the doughy nature of the mix. This limitation can possibly be overcome by significant increase in the volume fraction of the water phase to transform the ternary system into a slurry that is more susceptible to mixing than the dough.

The generally observed decrease in hydraulic conductivity for both types of specimens (Fig. 2) may be explained by examination of scanning electron micrographs. The question here is what is the structure origin by which the incorporation of 0.5% polymer caused an order-of-magnitude reduction in hydraulic conductivity. Figure 3 shows a micrograph of a sand sample without any treatment. As expected, the particles appear smooth and unconnected. The addition of 0.5% by weight of polymer (Fig. 4) results in partial coverage of the sand particles by a polymer film. The polymer apparently has acted as adhesive ties to the soil particles, even at this very low polymer concentration. This is illustrated by the polymer patches in the figure. This tie mechanism is speculated to per-

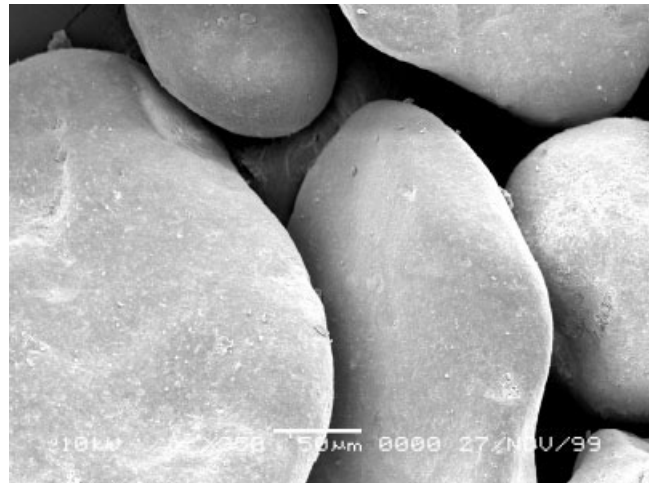


Figure 3 Scanning electron micrograph of natural desert sand.

form two functions leading to the reduction of hydraulic conductivity. On the one hand, the polymer ties must have held adjacent sand particles together, thus limiting particle movement under applied hydraulic pressure. In the meantime, the polymer ties possibly acted as partial constraint to inhibit the water flow through the interparticle spacing. The total effect must have given rise to the observed reduction of hydraulic conductivity. It should be noted, however, that the polymer did not seal off relatively large pores such as those shown in the figure for both methods of applications. This is perhaps associated with the lack of excess polymer to fill the large-volume pores. It should be emphasized that each of the samples at hand (Fig. 4) contains only 0.5 wt % polymer concentration. Most of this amount of polymer has been consumed on the partial coverage of the sand particles as shown in Figure 4. The fact that the amount and morphology of polymer coverage are similar in both samples (mixed and sprayed) rationalizes the similarity in hydraulic conductivity (Fig. 2).

The sprayed samples showed better reduction in hydraulic conductivity relative to samples prepared by mixing with the increase in polymer content, as shown in Figure 2. Figure 5 shows SEM micrograph of fractured surface of a sample containing 1 wt % polymer concentration prepared by the mixed method. Examination of the figure shows that the majority of the polymer is consumed to cover the surface of the sand particles and less polymer resides as interparticle ties. Compared with Figure 4, it can be noted that the fraction of interparticle ties, which are believed to constrain the flow, did not increase significantly. This explains the modest reduction of hydraulic conductivity relative to doubling the amount of polymer.

Attention now is turned to the observation that samples prepared by spraying method at 1 wt % and

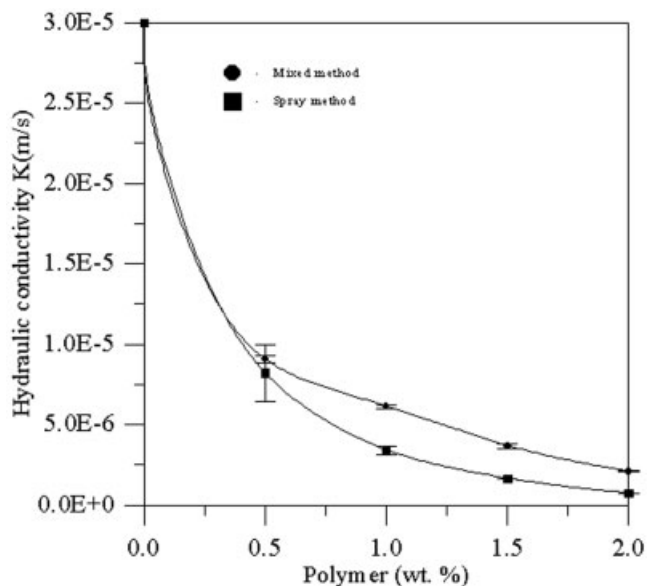


Figure 2 Transport data for mixed and sprayed samples as a function of polymer content. The error bars represent the variance of three identical measurements at each point.



(a)



(b)

**Figure 4** Scanning electron micrograph for natural desert sand containing 0.5% polymer by mixed method (A) and spray method (B).

higher polymer concentration always exhibit lower hydraulic conductivity in comparison to those prepared by the mixing method, as seen in Figure 2. Examination of the top surface of the sprayed sample in Figure 6(A) shows the formation of nearly continuous polymer film (crust) covering the sand particles. This crust seems to seal the top surface of the sample with the exemption of few large holes. A view of a fractured surface of the same sample at a depth of 1 cm below the surface is shown in Figure 6(B). This micrograph shows that the amount of surface coverage and the fraction of interparticle ties appear similar to that shown in Figure 5. Hence, it is reasonable to suggest that the extra reduction in the hydraulic conductivity associated with the spraying method is attributed to the crust morphology clearly shown in Figure 6(A) and to the subsurface profile of polymer concentration. The latter is examined below.

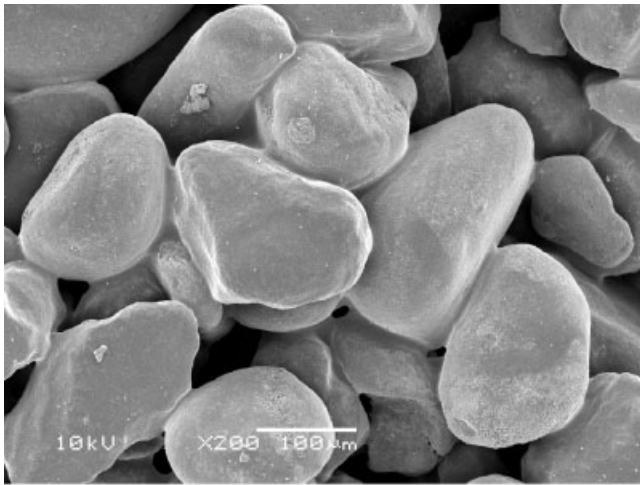
Thermogravimetric results of the axial polymer concentration for sprayed samples are shown in Figure 7. The cylindrical sample was cut using a diamond knife into seven sections. Each section was ground and ashed. The polymer content in weight percentage was then plotted as a function of depth, as shown in the figure. The concentration profiles of all samples appear similar and were found to be described by power decay function of the form  $Y = aX^{-m}$ . Using this function, we may obtain the polymer concentration in the crust zone (within the top 1.0 mm). The extrapolated values are plotted as a function of the overall polymer concentration within the sample in Figure 8. Clearly, the polymer concentration within the top 1.0 mm (crust) is a linear function of the overall polymer concentration of the sample. The relationship is linear, i.e.,  $Y = 10.5X$  with  $R^2 = 0.97$ . That the crust zone does not contain a continuous polymer film (100% polymer) is further indicated by the unfilled pores displayed in the surface micrograph shown in Figure 6(A). Similar and more numerous pores must exist in the subsurface in view of the concentration profiles shown in Figure 7. The pores are likely interconnected and tortuous, an attribute that accounts for the observed hydraulic conductivity of the system.

At this junction, it is useful to elucidate the mechanism by which surface coverage of the sand particles through which the water-borne polymer takes place. It is recognized that the polymer used in this study is comprised of latex particles in the range of 0.09–0.12  $\mu\text{m}$ . The formation of a latex film arises from the coalescence of the individual latex particles, which are normally held apart by stabilizing forces (electrostatic and/or steric) resulting from the charged polymer chain end groups or surfactant. These forces are overcome by the evaporation of the continuous phase (water). As the water-borne polymer latex is driven into



**Figure 5** Scanning electron micrograph of a fractured surface of a sample containing 1 wt % polymer prepared by the mixed method.

the pores between the sand particles, the water phase is progressively lost by evaporation and by wetting the large surface area of the sand particles. This results in increased latex concentration that likely produces high viscosity material. As further water loss continues, the high-viscosity syrup creates the interparticle ties. Adhesion of the polymer film to the sand surface is possibly related to the surface energy of the polymer and that of the solid surface, assuming surface cleanliness. Considering the generic chemical nature of the polymer and the sand surface, wetting conditions are likely to be favored. The critical surface tension of the type of acrylic polymer used in this study is reported<sup>12</sup> to be in the range of 40 dynes cm<sup>-2</sup>, which should not inhibit wetting of silicate sand surface. At this point, it is useful to note that the scenario presented above is a proposed rationale for the experimental observations.

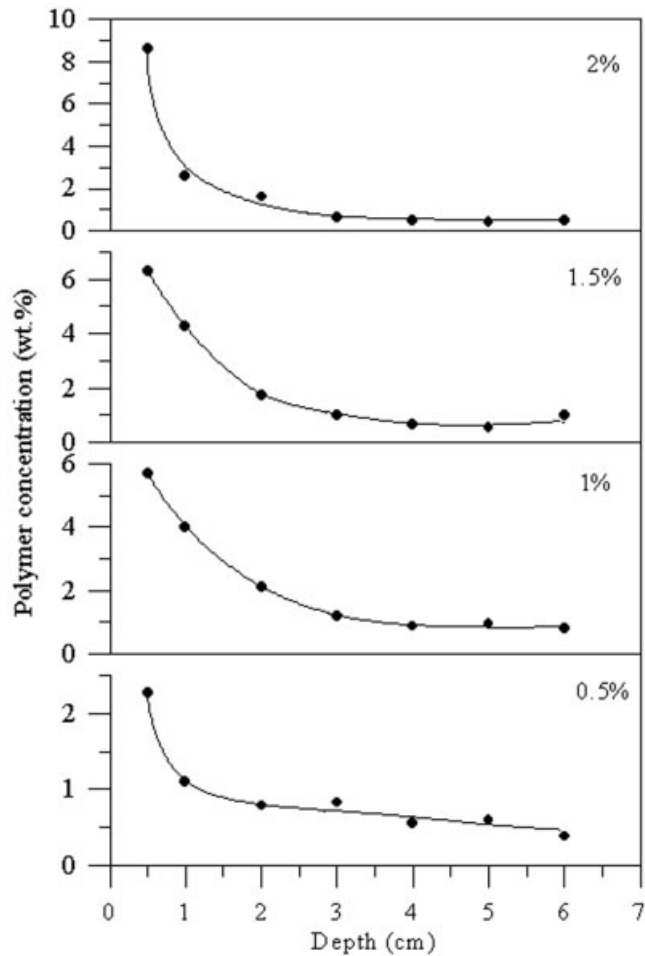


(a)



(b)

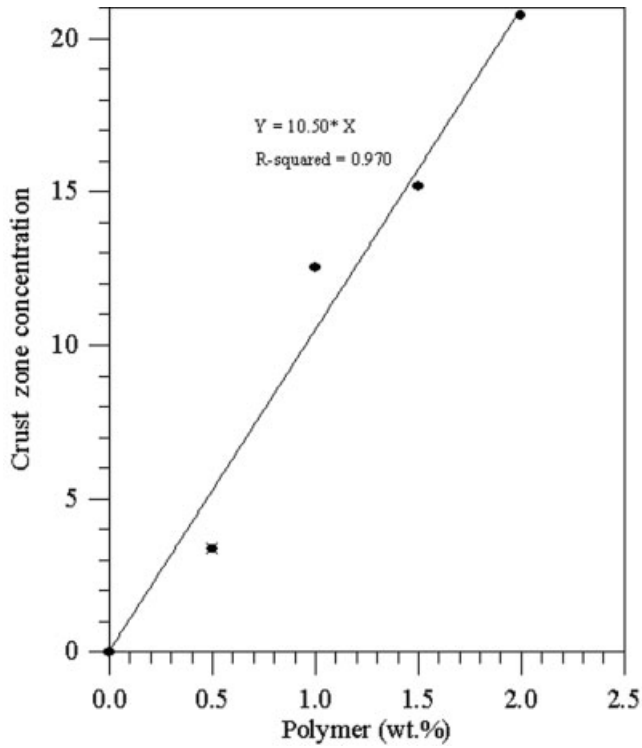
**Figure 6** Scanning electron micrograph for natural sand containing 1% polymer prepared by the spraying method. Fine film on top surface [crust (A)]. Polymer distribution at 1 cm depth for the same sample (B).



**Figure 7** Thermogravimetric analysis of sections prepared from sprayed samples.

Direct evidence would be needed to substantiate the present explanation, the generation of which is beyond the scope of the present study.

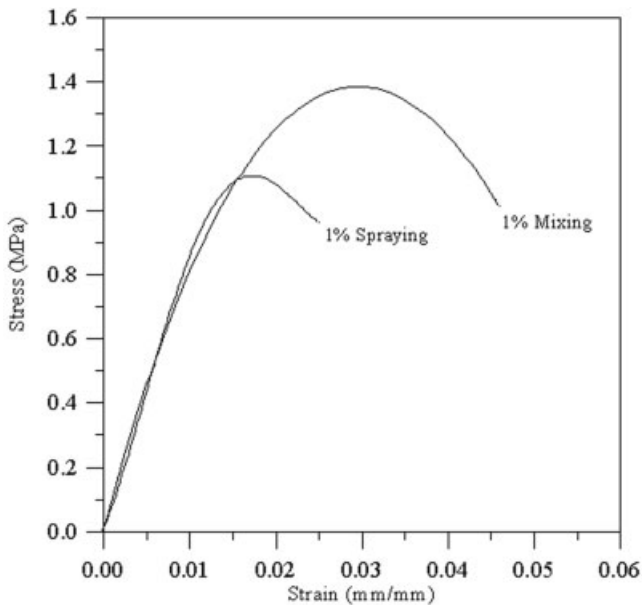
Typical unconfined compressive stress-strain curves of specimens containing different polymer concentrations are shown in Figure 9. The curves clearly indicate that the polymer treatment, even at the lowest concentration, transformed the loose sand into a solid material. All curves exhibit a linear region from which the modulus of elasticity can be determined and a yield zone the maximum of which has been taken as the compressive strength. Figures 10 and 11 show the variation of modulus of elasticity and compressive strength of sand-polymer composite as a function of polymer concentration. The modulus of elasticity and compressive strength increase linearly with polymer concentration for both types of preparation methods. Starting from sand with negligible mechanical properties, at 2% by weight of polymer content, the compressive strength was about 2 MPa and the modulus of elasticity was about 0.12 GPa for sprayed sample. For mixed sample, at the same concentration, the compressive strength was about 2.7 MPa and the modulus



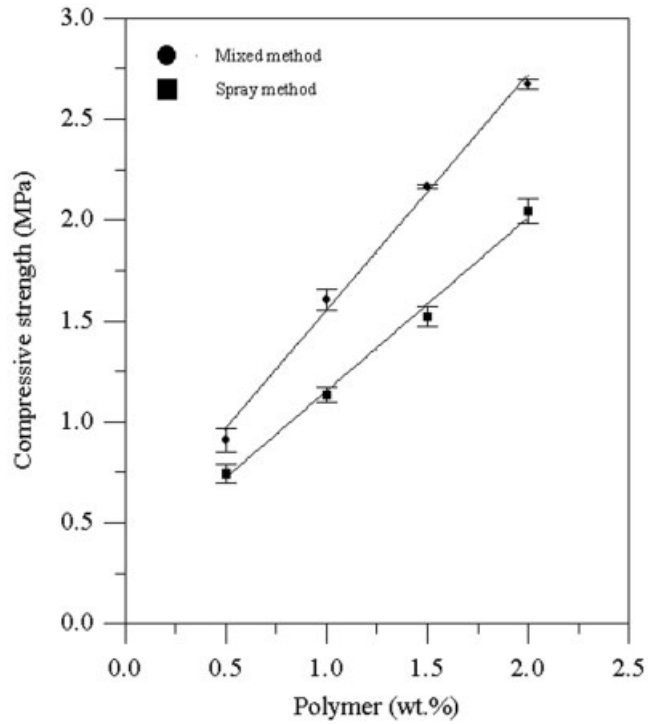
**Figure 8** Sprayed sample crust concentration as a function of overall polymer content.

of elasticity was about 0.17 GPa. This increase in mechanical properties is attributed to the increased inter-particles friction associated with the deposited polymer film and to the interparticle ties (Fig. 6).

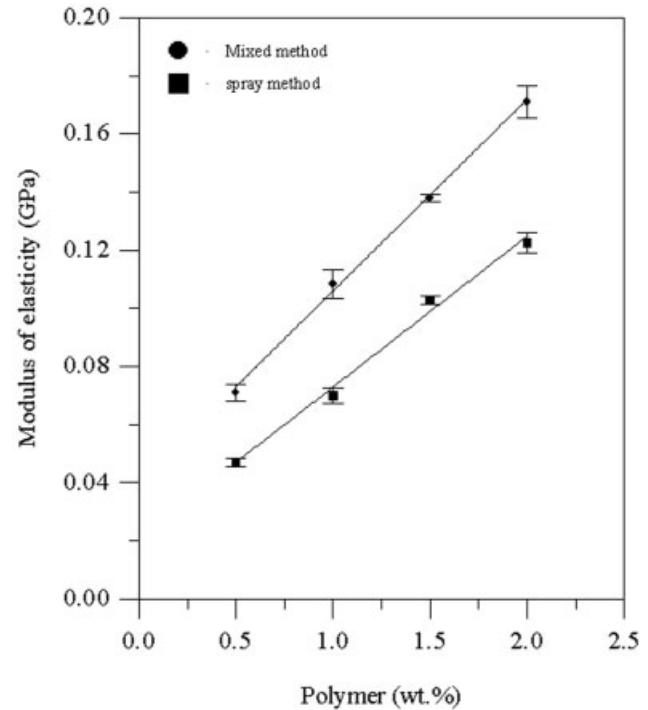
The property improvements achieved in this study offer interesting prospects for field applications and raise important questions. The results suggest the use-



**Figure 9** Stress–strain behaviors of typical specimens containing polymer.



**Figure 10** Variation of compressive strength for mixed and sprayed samples as a function of polymer concentration. The error bars represent the variance of three identical measurements at each point.



**Figure 11** Variation of modulus of elasticity for mixed and sprayed samples as a function of polymer concentration. The error bars represent the variance of three identical measurements at each point.

fulness of the polymer modification technique for field applications requiring stabilization of desert sand. The simplicity of its application and the limited polymer fraction needed lead to cost reduction and therefore enhance the economic feasibility of the system. Most important is that the polymer is delivered to the soil structure through water that eliminates the environmental concerns associated with other solvents. In the meantime, the durability of the polymer-soil system and whether the polymer degrades to release the polymer with time are pertinent questions if the system is to be adopted for field applications. A study is being carried out in our laboratory to address these questions.

### CONCLUSIONS

A system based on water-borne polymer has been introduced to enhance mechanical stability and hydraulic conductivity of loose sand soil. At a polymer concentration of 2%, the hydraulic conductivity for mixed materials was  $2.1 \times 10^{-6} \text{ m s}^{-1}$  and for the sprayed specimens the hydraulic conductivity was  $7.2 \times 10^{-7} \text{ m s}^{-1}$ , which is a significant improvement of the sand. The polymer treatment even at the lowest concentration transformed the loose sand into a solid material. For both types of preparation methods, the modulus of elasticity and compressive strength increased linearly with polymer concentration. For mixed samples at a polymer concentration of 2%, the compressive strength was about 2.7 MPa and the modulus of elasticity was about 0.17 GPa. For sprayed samples at the same concentration, the compressive strength was 2 MPa and the modulus of elasticity was about 0.12 GPa. It is shown that the improved hydraulic conductivity and mechanical properties are attrib-

uted to the polymer coverage of the sand particles and to the development of the interconnecting ties between them.

The authors are particularly grateful to the guidance of Prof. A. Moet, Department of Petroleum and Chemical Engineering, United Arab Emirates University. Also, the authors thank Dr. A. M. O. Mohsen, Department of Civil Engineering, United Arab Emirates University, for useful discussions. The polymer used was kindly provided by the Union Carbide Corporation, Dubai, United Arab Emirates.

### References

1. Koerner, R. M.; Welsh, J. P. *Construction and Geotechnical Engineering Using Synthetic Fabrics*; John Wiley and Sons: New York, 1980.
2. Karol, R. H. *Chemical Grouting*; Marcel-Dekker: New York, 1983.
3. Hausmann, M. R. *Engineering Principles of Ground Modification*; McGraw-Hill: New York, 1990; p 144.
4. Greenwood, D. A.; Thomson, G. H. *ICE Works Construction Guide*; Thomson Telford: London, 1984.
5. Wrigley, N. *Chem Indust* 1988, 13, 414.
6. Kirzhner, F. *J Polym Eng* 1999, 19, 53.
7. Haug, M. D.; Boldt-Leppin, B. *ASTM Special Technical Publication: Proceedings of the Symposium on Hydraulic Conductivity and Waste Containment Transport in Soil*; ASTM: Philadelphia, 1993; p 407.
8. Khedr, S. A. *Transport Res Rec* 1985, 1043, 131.
9. Koerner, R. M.; Yang, T. Y. *Geotechnical Special Publication: GeoDenver 2000 Congress Advances in Transportation and Geoenvironmental Systems Using Geosynthetics*; ASCE: Reston, VA, 2000.
10. Ling, H. I.; Pamuk, A.; Dechaskulsom, M.; Mohri, Y.; Burke, C. *J Geotech Geoenviron Eng* 2001, 127, 950.
11. *Modified Moisture Content Test*. ASTM D 1557; ASTM: Philadelphia, 2001.
12. Skeist, I. *Handbook of Adhesives*; Van Nostrand Reinhold: New York, 1977.