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Effect of using polymeric materials in ecological sand-fixing of Kerqin Sandy Land of China

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ABSTRACT: For the first time, the main characteristics of the polymeric materials are considered for understanding their possible application in ecological sand-fixing. In this investigation, two emulsions, named as E2, a poly(vinyl acetate) emulsion, and E7, a vinyl acetate–ethylene copolymer emulsion, have been selected for a series of tests related to the practical requirements for ecological sand-fixing. Besides the sand-fixing properties and the thermal aging and freeze–thaw stabilities of the emulsions, their effects in increasing the growth of both microbes and plants in sandy lands have been evaluated by field experiments in Kerqin Sandy Land of China, and the relationship between the performance and structure of the two emulsions has also been described. The experimental results show that both emulsions could significantly improve the compressive strength of treated sand and could withstand the changes in temperature of the Kerqin Sandy Land. However, different effects were exhibited in promoting the growth of microbes, in facilitating the accumulation of organic fertilizer and soluble salt, and in increasing the crop yield. All of the differences are attributed to their different molecular chain structures. These findings suggest that the structure of a polymeric emulsion should be the first consideration for the materials used in ecological sand-fixing, and ecological sand-fixing is a successful method for the stabilization of sandy land and the restoration of desertified land in semiarid regions. © 2016 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 44102

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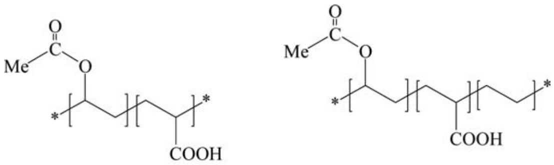
INTRODUCTION

Desertification is one of the most serious environmental and socioeconomic problems worldwide and a major threat to the sustainability of agriculture and economic development.[1–3] In China, the desertification-affected land exceeds 3.9×10^5 km^2, and 61.3% of it was caused by wind erosion.[4] Wind erosion usually results in many negative influences, such as dust storms, desertification, damage of crops, spreading of polluted sediments, loss of fertilizer, and the deposition of soil in ditches.[5–7] Kerqin Sandy Land, located in the agropastoral transition zone between the Inner Mongolian Plateau and the Northeast Plains in China, has suffered severe desertification since the mid-1970s primarily due to improper exploitation and wind erosion. Desertification impedes the growth of grassland vegetation and reduces the yield of crops as a result of wind erosion.[8]

Facing the vast desertified land, humans around the world have needed to consider the control of wind erosion. Many experts have made intensive observations and research studies, and a series of measures have already been adopted or proposed to reduce or prevent the desertification.[9–12] The measures used to control wind erosion mainly include physical fixation, biological fixation, and chemical sand-fixing. However, there are limitations for physical and biological sand-fixing, such as the high cost, noneffectiveness, and inconvenience, which have hindered their application in vast, hostile, desert environments.[13–15] Chemical sand-fixing, therefore, was first proposed in the 1930s,[16] and an increasing number of sand-fixing materials, including natural and synthetic compounds, have been developed and applied to desert control since then.[17–22] However, because of their high cost, environmental toxicity, and damage to vegetation, most of the sand-fixing materials were developed and studied only in laboratories rather than applied in practical sand-fixing on a large scale.[23] Therefore, the ideal ecological sand-fixing materials should be created with the merits of high



E2 E7

Figure 1. Schematic representation of the emulsions used.

erosion resistance, low cost, no additional pollution to sand and environment, promotion of plant cover and crop yield, and ease of production and application.

Based on the above-mentioned problems found in present sand-fixing materials, we have developed a series of polymer emulsions, and after preliminary tests of their basic properties related to sand-fixing, two emulsions, named as E2, a poly(vinyl acetate) emulsion, and E7, a vinyl acetate–ethylene copolymer emulsion, have been selected for sand-fixing in Kerqin Sandy Land, China. The investigation was conducted systematically according to the different geological features, such as mobile dune, semimobile dune, and barren sand soil, and the different plants. Four kinds of psammophytes, including Artemisia songarica Schrenk (*Artemisia oxycephala Kitag.*), caragana *(Caragana microphylla Lam.)*, lespedeza (*Lespedeza bicolor Turcz*), and alfalfa (*Medicago sativa Linn.*), were sowed in mobile and semimobile dunes, and corn was planted in barren sand soil.

From May to October of 2014, we observed the growth of psammophytes and corn, determined the changes in organic content of the dunes and soil, and examined the microbial ecology of the dunes and soil after the sand-fixing. We have gathered the necessary data to try to find the relationship between the structure of E2 and E7 emulsions and their anti-wind-erosion ability, as well the effect on the sandy land's restoration.

This paper provides a preliminary summary of the experiment, showing not only that the E2 and E7 emulsions could effectively stabilize the Kerqin Sandy Land, but also discussing the mechanism of their different performances. These results will inform the main consideration when a material will be developed or used for ecological sand-fixing in arid and semiarid areas.

EXPERIMENTAL

Laboratory Tests

Preparation of the Emulsions. In this study, two emulsions were used with different chemical structures, as shown in Figure 1 and Table I. E2 is a poly(vinyl acetate) emulsion, and E7 is a vinyl acetate–ethylene copolymer emulsion. They were prepared by Anhui WanWei Updated High-Tech Materials Co. (Hefei, Anhui, China). The E2 is synthesized with a conventional emulsion polymerization process, and the preparation of E7 is based on the high-pressure polymerization technique.

Basic Properties of the Emulsions. Generally, the basic parameters of the emulsions that are connected to the sand-fixing performance are the viscosity, the size and size distribution of latex particles, and the zeta potential values. They were measured by an LVDV-C viscometer (Brookfield, MA) and by dynamic light scattering and laser Doppler electrophoresis using a Zetasizer-HS (Malvern Instruments, Malvern, UK).

Preparation of Fixed Sand Specimens. The sand specimens were prepared with identical volumes but different concentrations of E2 and E7 emulsions as follows: 10 g sand (from Kerqin Sandy Land with particle size between 0.2 and 0.45 mm) and 1 g emulsion with a concentration of 2.0% were mixed homogeneously and then transferred into a mold to make a sand column (2.2 cm in height and 2.0 cm in diameter) for the compressive strength test. The sand volumes were held at room temperature for 4 h, followed by 24 h in an oven at 60 °C for complete drying.

Compressive Strength of Fixed Sand Specimens. The compressive strength is a key parameter for evaluating the effectiveness of sand fixatives. Compressive strength is described as the hardness of a specimen that is, in fact, attributed to the fixing ability of materials. In this test, the completely dried sand column was put in an electronic tensile testing machine (WDW-5, Jinan Chuanbai Instrument Co. Ltd., Jinan, China) with a compression rate of 100 mm/min, and the value was recorded as the compressive strength (MPa). The compressive strength was tested with three replicate samples for each measurement.

Thermal Aging Ability of Fixed Sand Specimens. The specimen column was subjected to heat aging in an air circulation oven at 60 °C for a continual period of 10 days, regarding one day as a cycle. The compressive strength of each sample was measured as above after every cycle to evaluate the thermal stability of the sand-fixing material.

Freeze–Thaw Property of Fixed Sand Specimens. One cycle of a freeze–thaw process involves 22 h of freezing at −18 °C and 2 h of thawing at 25°C. The specimen column was put through 10 cycles and then was subjected to the compressive strength test to obtain its freeze–thaw stability related to the sand-fixing material used.

Field Experiments

Procedure of Applying Emulsions in Sand-Fixing. The experimental zone, about 6.66×10^4 m^2 of area in Kerqin Sandy Land, covered different geological features, such as mobile dune, semimobile dunes, and barren sand soil. The procedure of applying the emulsion for sand-fixing was that the mixed psammophytes were sown in dunes, and the corn was sown in barren sand soil, respectively. The emulsions were sprayed with concentrations of 2% with a volume of about 1.0 L/m^2. A hard crust on the sand surface 0.3–0.8 cm thick formed rapidly after the spraying, which could protect the sand from being blown away, even by a strong wind.

Changes of Sand Soil. The sand soil, 3 months after the sand-fixing, was picked from 0–20 cm depth in each site with three replicates to examine the changes in soil properties. The sand and soil samples were air-dried and passed through a 2-mm sieve before the test. The pH and soluble salt of the soil after

Table I. Contents of Structure Units in E2 and E7

Emulsion type	Vinyl acetate (%)	Acyclic acid (%)	Ethylene (%)
E2	95-98	2-5	0
E7	77-85	2-5	13-18

Table II. Basic Property Parameters of the Ecological Sand-Fixing Emulsions

Emulsion	Particle size (nm)	Particle size distribution	Viscosity (mPa s)	Zeta potential (mV)
E2	2381	0.241	162.4	−3.59
E7	1576	0.335	144.2	−12.6

the sand-fixing were determined by pH meter measurement and the weight difference method, and the results were then calculated.[24,25] The soil organic carbon was determined by Walkley–Black dichromate oxidation.[26]

Analysis of Microbial Growth in Sand Soil. The changes in microbes in the sand soil 3 months after sand-fixing were estimated by the plate count method and presented as the number of microbes in the sand.[27,28]

Plant Growth. Before fixing the sand with the E2 and E7 emulsions, four kinds of psammophytes, artemesia, caragana, lespedeza, and alfalfa, were sowed in mobile and semimobile dunes, and corn was planted in barren sand soil. The growth of psammophytes and corn was observed along their growing, and the corn yield was calculated after the harvest by the weighing method.

RESULTS AND DISCUSSION

For practical purposes, ecological sand-fixing materials should be nontoxic, nonpolluting, and adaptable to the climatic and environmental conditions in the treated area. At the same time, these materials should be widely available, effective in the long term, and inexpensive. According to these principles, we tested a range of alternatives in the laboratory and finally selected the E2 and E7 emulsions for the subsequent field investigation because of their good performance. The further consideration was based on the different structures of the E2 and E7 emulsions, which would offer the expected understanding of the sand-fixing mechanism from the view of materials.

Basic Properties of the Emulsions

Droplet Size, Polydispersity Index, and Zeta Potential. The particle size and polydispersity (PDI) of emulsions are physical indices of their dispersion homogeneity, possible indicating the internal effect of emulsions on their ability in sand-fixing. The data for the particle sizes and PDI of the two emulsions were determined and are listed in Table II. It is well known that the pore space among sands is approximately 8 μm,[29] and we can find that the particle sizes of E2 and E7 were much smaller than 8 μm, telling us they could easily seep into the pore space in a typical aeolian sand. In addition, the average values of PDI were lower than 0.5, which showed that the particles of the emulsions are monodisperse due to a successful polymerization process.[30]

The zeta potential of an emulsion usually indicates the degree of repulsion between adjacent, similarly charged particles in a dispersion. Generally, if the particles have a higher negative or positive zeta potential, they will make the dispersion stable because of their repellency to each other; therefore, for emulsions, it means good stability. In contrast, a low zeta potential will result in aggregation of the colloid particles because of the attractive forces.[31] Additionally, the zeta potential of an emulsion will affect the growth and activity of microbes in its environment, especially when the emulsion possesses a high positive zeta potential. The main parameters of E2 and E7 emulsions are shown in Table II. We can see that both E2 and E7 have the negative charge, and the zeta potential of E2 is smaller than E7, suggesting E2 would have a stronger cementing ability to aggregate sand particles against wind erosion.

Viscosity. The binding strength of sand-fixing emulsions normally increases with their increasing viscosity, but for the penetration rate and depth the situation is just the reverse. As a result, a highly viscous emulsion will be left on the sand surface to form a thin binding layer, and an emulsion with low viscosity tends to prevent the formation of a crust because of its faster penetration rate and deeper penetration depth. Therefore, the proper viscosity of emulsions also seems to be a key factor for successful sand fixation. In our study, we have found that a suitable viscosity for sand-fixing is in the range of 100–500 mPa s. Therefore the measured viscosities of the E2 and E7 emulsions are suitable for sand-fixing (Table II).

Compressive Strength. The compressive strength is defined as the hardness of a sand specimen for evaluation of the bonding force or cohesion between the sand particles after being fixed with materials. The sand, from a mobile dune in the Kerqin land, was fixed with a 2% concentration of the E2 and E7 emulsions according to the procedure described in the section Laboratory Tests, and the compressive strengths of the fixed sand specimens were measured and are listed in Table III. The specimens treated with E2 and E7 generated compressive strengths of 0.63 and 0.34 MPa, respectively. This showed that the emulsion used certainly affected the compressive strength of the treated sand, which is dependent on its structure and physical parameters. However, the results also pointed out that the emulsion, even in a low concentration, could offer sand the desired strength to resist the outside mechanical action.

Table III shows that there was a difference in compressive strength of the sand specimens fixed with E2 and E7. Obviously, the E2-treated sand has a compressive strength almost double that of E7. This could be attributed to the structure difference of the two emulsions. The flexibility of the E7 molecular chain is higher than that of E2 because of the internal plasticization

Table III. Mechanical Properties of the Fixed Sand Specimen

Sample	Average compressive strength (MPa)
Control	0.0015
E2	0.63
E7	0.34

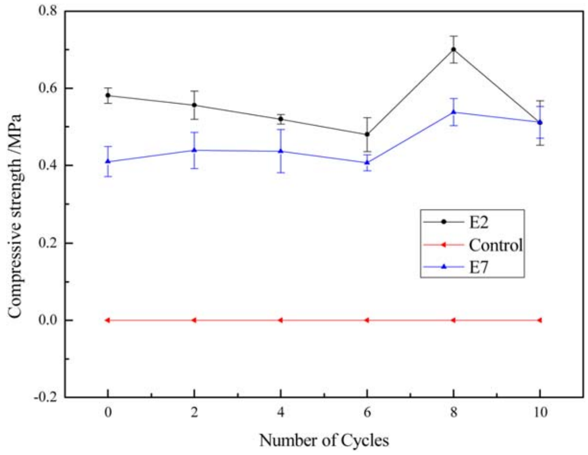


Figure 2. Compressive strength change of sand-fixing specimens with thermal cycle frequency. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

of polyethylene, which is beneficial to the movement of the molecular chain. However, the rigid molecular chain of E2 can offer better cementing ability to aggregate sand particles, resulting in the higher compressive strength of E2-treated sand. The particle size, viscosity, and zeta potential of E2 also endow it with higher compressive strength, according to the analysis in the previous section.

Thermal Aging and Freeze–Thaw Ability of Emulsions. In the natural environment, the chemical components of the sand-fixing materials may be greatly changed because of solar radiation, oxidation, wind erosion, leaching by rainwater, and other factors. With the passage of time, the mentioned environmental factors could shorten the life span of sand-fixing materials, especially in desert regions with such harsh natural conditions. Therefore, the thermal aging ability of the specimens treated with E2 and E7 were tested. The dependence of compressive strength on the cycle of the thermal aging test is shown in Figure 2. The results show that there are no visible changes in the compressive strength with the increasing number of thermal aging cycles from 1 to 10, which indicates that both the E2 and E7 emulsions have good thermal stability.[22]

For the same reason, the resistance of two emulsions to freezing was also determined in order to know their suitability for use in a low-temperature environment. The compressive strength of the fixed sand specimens with increasing freeze–thaw cycles was measured, and the obtained data are illustrated in Figure 3. The results showed that there are no obvious changes in the compressive strength of freeze–thaw specimens during the 10 aging cycles.

Based on the tests, we know that both the E2 and E7 emulsions can withstand the climatic changes of the desert and can be used for the sand-fixing in Kerqin Sandy Land.

Field Experiments

An appraisal of whether a material could be used in the ecological restoration of a desert mainly depends on its performance in practical applications. The E2 and E7 emulsions, even though selected in the lab from a series of emulsions based on the above-mentioned principles, should also undergo a more severe test: the field experiment. The Kerqin Sandy Land, located in Inner Mongolia of China, is of special interest for the ecology of northern and northeastern China. Because of the hostile climate and year-round strong winds, there are mobile and semi-mobile dunes as well as poor soil presented, providing us with a most effective field for investigation. After the sandy land was fixed by E2 and E7, a set of measures were carried out 3 or 5 months later to find changes such as the sand soil properties and the microbe numbers.

Changes of Sand Soil Properties Caused by E2 and E7 Fixation. From May to August of 2014, we determined the particle size distribution, organic carbon content, pH, and soluble salt of the sand soil after the sand-fixing. The results obtained are listed in Table IV and Table V. As we know, the soil particle size distribution usually reflects the extent of soil erosion by wind. Generally, the higher the erosion extent, the smaller the soil particle size is. The experimental results show that, after fixation, the soil particle average size of sand was increased, indicating the wind erosion rate of sand was decreased because of the coarser surface of the sand caused by the increasing sand particle size.

We also can see that, after applying the sand-fixing emulsions, the sand soil's organic carbon content increased from 0.357% to 0.421% for E2 and to 0.601% for E7; the soluble salt of sand soil increased from 1.52 g/kg to 2.02 g/kg for E2 and to 2.25 g/kg for E7, which resulted from the decreased wind erosion rate of sand. And the obtained results are in good agreement with each other, that is, the larger the sand soil's particle size, the coarser the surface of the sand, the lower the erosion extent, and the higher the content of organic carbon and soluble salt the sand soil has. Assuredly, the increased difference in both the organic carbon content and soluble salt of sand soil is assigned to the structure difference of E2 and E7 emulsions: E7 has a more flexible molecular chain than E2.

Changes of Sand Microecology Caused by E2 and E7. Microbes play a considerable role in sand fertility and plant nutrition,

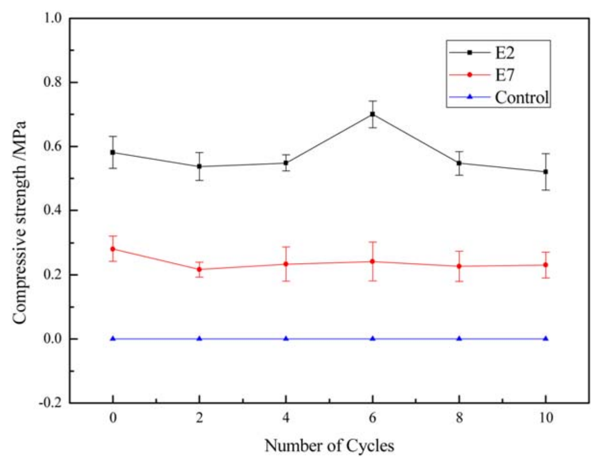


Figure 3. Compressive strength change of sand-fixing specimens with freeze–thaw cycle frequency. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table IV. Changes in Soil Particle Size Distribution of Sand-Fixed Sandy Land after Three Months

	Grain-size distribution of surface sand (%)				
Sample	>0.9 mm	0.45–0.9 mm	0.3–0.45 mm	0.15–0.3 mm	<0.15 mm
Control	0.02	0.65	4.4	73.03	21.9
E2	8.86	12.3	9.33	56.01	13.5
E7	66.1	3.24	4.19	19.38	7.18

and they can speed up the transformation of sand to the soil, being the most active composition in the land ecological system. So the microbial ecosystem of sand is a primary parameter used to evaluate the effectiveness of the sandy land's recovery. Table VI shows the result that the microbial biomass of the barren sand soil was well developed during the experimental period. As shown in Table VI, because these are desert regions with such a harsh environment, the quantity of actinomycetes was significantly higher than that of the bacteria and fungi. Meanwhile, we observed that the increase in average growth rate of bacteria by E7 fixing was much higher than by E2 fixing; this could first be attributable to the stable living environment for bacteria growth provided by the increased sand surface roughness that hinders the wind erosion. The second is the longer sand-fixing cycle offered by E7 because of its better flexibility. The third is the self-plasticizing action of E7 owing to the inserted ethylene fragments in the main chain of the molecule, so no additional plasticizer is added to gain the required flexibility in the final emulsion. However, E2 is a poly(vinyl acetate) emulsion, and usually plasticizers have to be used to soften its rigid molecule chain. The most-used plasticizers are *n*-butyl phthalate and dioctyl phthalate, and, as we know, they are somewhat toxic for organisms. Even though the contribution of E2 is less than E7 in the growth of bacteria, it behaves well in the growth of actinomycetes and fungi, and besides it does much better than the control, meaning the plasticizer of E2 has little positive effect on the multiplication of microbes in sand soil.

Significantly, along with the increased quantity of microbes in the sandy land, the ability to effectively decompose plant residues is improved, which in turn increases the organic matter content of sandy land and then promotes the growth of plants. However, it is not clear yet why the fungi in the sand were inhibited by E7 fixing; its expected study is essential for the emulsions' wide application.

Changes of Sand Land Vegetation Caused by E2 and E7. One of the most important considerations in ecological sand-fixing is the vegetation restoration of sandy land.[29,30] Figure 4 showed the growth of Artemisia songarica Schrenk, a kind of psammophyte, on sand-fixed mobile dunes with E2 and E7 emulsions after 3 months. From Figure 4, we can find an apparent disparity in the growth of psammophyte on the sand-fixed and unfixed mobile dune. Figure 4(a) presents the growth of artemisia on an unfixed mobile dune, and Figure 4(b) and Figure 4(c) represent the growth of artemisia in mobile dunes fixed by E2 and E7, respectively. The artemisia thrived in the fixed mobile dune with E2 and E7; the luxuriant growth of the plants implied the effectiveness of sand-fixing materials on the sandy land restoration. In our mind, however, what is most expected is the lasting flourishing of plants in a sand-fixed mobile dune. Surely, further research is needed and should be related to both the materials and the psammophytes.

We have mentioned that the corn was planted in barren sand soil, followed by spraying the E2 and E7 on the seeded sand soil. The observations of the growth of corn 3 months later are presented in Figure 5. Comparing the pictures of (a), (b), and (c) in Figure 5, we see that the growth of corn in fixed barren sand soil was very different from that in unfixed land, showing that the application of sand-fixing materials is more effective in increasing corn average cover and crop yield.

The difference in corn growth in fixed and unfixed barren sand soil is probably caused by the relatively stable soil environment generated after the fixation with E2 and E7. Obviously, the growing environment of corn in unfixed barren sandy soils is unstable, meaning not only the seeds of corn and organic matter would be blown away by the year-round strong wind, but also the growth of corn and soil microbes was disturbed, which will surely impede the biotransformation of the system in barren sandy soils. Therefore, we can say that E2 and E7 are ecological sand-fixing materials, for they are able to provide the vegetation with stable growing conditions and enhance top-soil development on the sandy land surface. This also has been proved by the testing results of soil properties and the corn yield of fixed soil.

Table V. Changes in Soil Organic Carbon Content, pH, and Soluble Salt of Sand-Fixed Sandy Land after Three Months

Sample	Soil organic carbon content (%)	pH	Soluble salt (g/kg)
Control	0.357	6.45	1.52
E2	0.421	6.54	2.02
E7	0.601	6.40	2.25

Table VI. Number of Microbes in Sand Fixed with E2 and E7 Emulsions after Three Months

Sample	Bacteria (per g)	Actinomycetes (per g)	Fungi (per g)
Control	2.50×10^6	2.25×10^7	1.53×10^5
E2	4.95×10^6	1.06×10^8	4.88×10^5
E7	2.58×10^7	6.98×10^7	8.50×10^4

(a) without sand-fixing (b) fixed with E2 (c) fixed with E7

Figure 4. The growth of Artemisia songarica Schrenk in sand-fixed mobile dune 3 months later (a) without sand-fixing, (b) fixed with E2, and (c) fixed with E7. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

(a) without sand-fixing (b) treated with E2 (c) treated with E7

Figure 5. Comparison of corn growth after sand-fixing with E2 and E7 after 3 months: (a) without sand-fixing, (b) treated with E2, (c) treated with E7. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

As presented in Table VII, the values of average height and diameter of growing corn showed overall increasing trends in both the E2 and E7 fixed barren sand soil. The only difference was the differing increase in corn yield caused by E2 and E7, that is, the 9.4% increase from E2 and 32.7% from E7, which were attributable to their different structure.

Here let us make a detailed description based on the data obtained. First, the soil average particle size in the E7-fixed soil was larger and the soil surface coarser than in the E2-fixed soil, indicating more nutrient substances and a more stable living environment for corn growth than for E2 fixation. Second, the E7 molecular chain is more flexible than that of E2, providing better and longer growing conditions for the multiplication of the soil's microorganisms, which in turn promote the corn growth and consequently result in the higher yields than for the E2 fixed soil. The excellent performance of E7 makes it clear that it is a better prospective candidate than E2 for ecological sand-fixing in relatively arid and semiarid areas.

Table VII. Changes in Plant Height, Plant Diameter, and Crop Yield of Sand-Fixed Sandy Land after Five Months

Sample	Plant height (cm)	Plant diameter (cm)	Maximal growth of crop yield (%)
Control	164.8–224.0	1.82–2.78	0
E2	191.4–242.0	2.31–2.72	9.4
E7	197.3–246.6	2.51–2.69	32.7

Comprehensive Analysis

When the E2 and E7 emulsions were used in sand-fixing, the obtained positive effects rely on the adhesive force of E2 and E7 emulsions, which makes the sand particles larger and the sand surface coarser, resulting in a stronger wind resistance and leading to collection of fine wind-blown materials by entrapment and deposition of dust. These accumulations contributed to increases in clay in the topsoil, significantly increased the soil organic carbon and soluble salt on the sandy land, and facilitated the deposition of wind-dispersed seed. As a result, vegetation cover and plant density can increase over time. Moreover, vegetation restoration can accelerate an increase in microbes, which effectively improves fertility over time. This change also facilitates seedling growth in nutrient-poor environments.

Although both of the emulsions could significantly improve the microbe growth and vegetation restoration of the fixed sand land or sand soil, a difference in effects is presented that is due to the differing structures of the E2 and E7 emulsions. The flexible molecular chain of E7 is helpful for the aggregation of soil particles to increase the roughness of the sand land surface, followed by reduced wind erosion and then by more detained soil organic carbon content and soluble salt on the surface of the sandy land. And it is also favorable to promoting the growth of sand microbes. Therefore, the accumulated nutrients and faster-multiplying sand microbes can assuredly increase the height and diameter of plants and the yield of corn.

CONCLUSIONS

Owing to such extensive desertified saline soil in the world, we have successfully developed the E2 and E7 emulsions used as ecological sand-fixing materials for the sand in the Kerqin Sandy Land of China. Also, in the lab and field experiments, it was found that the addition of a low content of the emulsion could obtain the desired sand-fixing properties, such as outstanding sand-fixing ability, thermal aging resistance, and freeze–thaw stabilities to withstand the temperature changes in desert. In addition, the growth of plant and soil microbes proved its ecological effects. Moreover, a relationship has been established tentatively between the performance in ecological sand-fixing and the structure of the materials. All the findings will be helpful for the application of conscientious and judicious knowledge in sand-fixing. All of these results indicated that E2 and E7 are prospective candidates for ecological sand-fixing materials and could be used for the ecological restoration of sandy land.

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