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ORIGINAL PAPER

The effects of chemical admixtures and physical factors on the treatment of dispersive soils

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Abstract Dispersive soils are very abundant around the world; upon contact with water, the clay minerals in dispersive soils become strongly repulsed by each other and remain suspended apart from each other, a dangerous trend which has led to a number of irreparable damages. The soil used in this test was completely virgin and could be classified as a dispersive soil. In the first section of this study, the pinhole test was conducted on more than 20 selected additives; the results of these tests demonstrated that the best amending agents were calcium oxide and calcium hydroxide salts, in addition to polymer and cement compounds. A closer examination of the results obtained from the pinhole test for the six ideal additives, used at different percentages, revealed that even low percentages of lime, cement, and calcium hydroxide would dramatically reduce soil dispersivity. The combined effect of lime compounds with any of the (high pH) additives, including aluminum sulfate, pozzolan, and sulfur, at identical ratios represents their cumulative effect on the amendment intensity. The second section simultaneously explores the effects of several physical parameters of the amended soil including density, moisture, and time, through the test design method. The results obtained from this phase suggested that both increasing soil density and time would effectively amend the soil if used within their respective ranges, the former directly and the latter to a certain extent.

Keywords Dispersive soil · Chemical treatment · Physical treatment · Pinhole

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Introduction

Dispersive soils are found across different geographical and climatic conditions around the world, including Australia, Brazil, Iran, New Zealand, USA, Thailand, and South Africa, among other countries (Ouhadi and Goodarzi 2006). Upon contact with water, the clay minerals in this type of soil disintegrate and are suspended in repulsion from each other, due to magnetic charges. This can lead to the formation of piping in embankment dams, erosion, and the subsequent destruction of roads, water supply channels, and building foundations. An insufficient amount of attention has been paid to this issue and has resulted in instances of vast and often irreparable damage (Moein and Shoaee 2011; Sherard et al. 1976; Ingles 1985). In the past, it was strongly recommended that dispersive soils be avoided. However, today, due to the significant increase in construction as well as the development of new land use models, soil amendment is being considered as a necessary alternative (Umesha et al. 2009).

Dispersive soils can be identified through both field and laboratory testing methods. Field methods include the observation of objective evidence available at the site (including large holes, pitcher-shaped scours, deep narrow channels, and turbid waters) and the Crumb test. The laboratory identification methods include the pinhole test, measuring the sodium absorption ratio (SAR) based on Sherard's chart, the exchangeable sodium percentage (ESP) method, and the double hydrometry method (Askari and Fakher 1991; Bazargan and Ismaili 2010). In spite of the extensive research conducted so far, many characteristics of dispersive soils remain unknown, and the results obtained from different dispersivity diagnostic methods are not consistent enough to be conclusive. As a result, none of the dispersivity tests proposed so far can produce definitive criteria for soil dispersivity (Rahimi et al. 2008).

Dispersive soils can amended via both transitional and the in situ methods. Transition, the most common amendment method, involves extracting virgin soil and mixing in suitable additives. Electrokinetic injection (Mosavat et al. 2012) is among the most important in situ amendment methods. It should be noted that in both methods, identification and application of suitable and effective chemical compounds are of particular significance. There have been a limited number of studies carried out so far on the type of additives applied in dispersive soil amendment. This study separately examined several different compounds, including lime, aluminum sulfate, pozzolan, gypsum, fly ash, and occasionally polymer compounds like polyvinyl alcohol. It should be noted that identification in most previous studies was based on different tests conducted under non-identical conditions, thus failing to provide an ideal ground for comparison (Askari and Fakher 1991; Jafari and Hassanlou 2012; Vakili et al. 2013).

Dispersive soils are characterized by the presence of a higher percentage of sodium ions in their pore water compared to the percentage of other cations generally found in montmorillonite clay minerals. Since montmorillonite contains more water particles between its plates, it subsequently exhibits greater dispersivity potential and high swelling rates upon contact and absorption of water.

Because of the small atomic radius and high charge density, the sodium found in mineral plates forms a large hydration layer around itself in the presence of water molecules. As the large layer forms around sodium ions at high frequency, a repulsive force far stronger than the van der Waals attractive force is created between these plates, leading to the breakdown of the mineral structure and suspension of the plates with equal electrical charges in water (Bazargan and Ismaili 2010; Sherard et al. 1976). Therefore, one of the amendment methods for dispersive soils involves exchanging sodium cations with cations that have a smaller hydration radius and a larger electric charge. An increase in electric charge results in lower concentration of cations between the negatively charged plates in clay minerals.

With this in mind, it is important to examine a classification of ions known as the *lyotropic series*. This series (Eq. 1) compares the capabilities and speeds of different cations in attracting negatively charged surfaces based on load density and hydraulic radius. The most important replaceable cations in terms of the lyotropic series include Ca^{2+} and Al^{3+}(Rahimi et al. 2008; Spangler and Handy 1982; Nori and Neishaburi 2008).

$$\begin{aligned} Al^{3+} &> Ba^{2+} > Pb^{2+} > Ca^{2+} > Ni^{2+} > Cd^{2+} > Cu^{2+} \\ &> Co^{2+} > Zn^{2+} > Mg^{2+} > Ag^{+} > Cs^{+} > K^{+} \\ &> NH_4{}^{+} > Na^{+} > Li^{+} \end{aligned} \quad (1)$$

The first stage of this study attempted to provide accurate and applicable comparisons for a wide range of suitable amendment additives, using numerous soil dispersivity measurement tests. Based on factors like cationic substitution, cementation capability, and conclusions from our literature review, the following potential additives were selected for testing: calcium, aluminum, potassium, ammonium, iron, several polymeric compounds, a number of cement compounds, pozzolan, and sulfur minerals. Then, a few more effective compounds were selected, examined separately in different mixture percentages, and combined through various dispersivity identification methods. During the second stage, using the experiment design method, the effects on the physical parameters of amended soil were studied through analysis of variables including density, moisture, time passed since inclusion of additives, and type of chemical additive.

Materials, tools, and test procedures

Materials and tools

Dispersive soil

The dispersive soil used in this study was obtained from a site 20 km from Torbat Heidarieyh-Mashahad Road, Iran. Table 1 lists the dispersivity and physical properties of the studied soil. As can be seen in Table 1, the sample soils are fully dispersive (based on the results obtained from the existing dispersivity tests). For this reason, no chemicals were added to the soil to induce artificial dispersivity.

Additives

The purity of the additives used in this section was between 90 and 95% on an industrial scale. The lime and portland cement type I were supplied by East Mashhad Cement Co., whereas other additives were supplied by Dr. Mojallali Chemical Industry Co. Additionally, double-distilled water with conductivity of less than 4 μS/cm was used in all the experimental stages.

Table 1 Physical and dispersivity specifications of soil sample used in conjunction with standards in several tests

Parameter	Soil sample	Reference (ASTM)
Grading	CL-lean clay	D422-63
Plasticity index	12	D4318-84
Dry density (KN.m-3)	1.86 With optimum moisture 15.4%	D698-78
Pinhole[a]	D1	D4647
[Na+] (mg/KgSoil)	4010	D4647-87
ESP	13.2	(Richards 1954)

[a] At carved hunk compaction for pinhole test

Instrumentation

- The pinhole apparatus (manufactured by Iran Abzar-e Khak Co.) was employed in accordance with the ASTM standards (ASTM D4647-93 2009).
- The flame photometer apparatus was manufactured by Iran Fater Electronic Co.

Test procedures

The more common Classification A method was used in the pinhole test (ASTM D4647-93 2009). In order to provide the possibility of a relatively qualitative comparison, in addition to the dispersivity class, a graph was presented for each test based on the average water flow rate at different heights (Vakili et al. 2013). The sample for the pinhole test was prepared by passing the soil through a 2-mm sieve and dry-mixing it with 21 identified additives at weight percentages of 1.75%. The sample was then tested at the relative density of soil at the site (77% standard proctor) and optimum moisture content after 72 h. In the next stage, six candidate additives with percentages between 0.5 and 4.5 were selected under optimum soil moisture conditions, 90% standard density, and time of 12 days.

During the relative combination stage, three main additives with several other desirable types, the amendment agents, were applied at 1 wt% (either combined or in equal ratios) under the same conditions as in the previous stage.

The mixture percentages of substances were reduced at different stages of the testing to increase the efficiency of the candidate compounds and to set a basis for a more transparent comparison.

All of the experiments in this study (except the design phase test which had its own particular confidence level) were replicated three times, and their mean values were reported. The Minitab 17 (via Taguchi's approach and selection of four variables at four levels (L16)) was used to design the experiments (Table 2).

Results and discussion

Comparison of the effects of 21 desirable chemical additives on soil dispersivity amendments

The results of the pinhole tests on the 21 initially identified compounds, shown in Fig. 1, cover all categories of non-dispersive (ND2), semi-dispersive (ND3 and ND4), and fully dispersive (D2) soils. According to this figure, polymeric compounds, cement, aluminum chloride, and different types of lime produced the best responses. At their respective percentages, these compounds placed the soil under the non-dispersive group (marked in green).

At the next stage, the pozzolanic and cement, calcium carbonate, barium chloride, aluminum sulfate, and pozzolan compounds are used to amend the soil to the semi-dispersive phase.

However, regarding the average output flow from the cell, a significant difference is observed between these results and those obtained for the control sample (marked in red).

One drawback of this identification method is that the samples cannot be separated into their specific dispersivity classes. No significant difference was observed between the results obtained for the other compounds in the semi-dispersive class and those obtained for the control sample in terms of average output flow. As can be observed in the diagram, the application of compounds in the fully dispersive class (marked in purple) can aggravate the soil dispersivity.

Table 2 Factors and levels applied in the Taguchi design of experiments

Levels	Type of variable			
	Type of admixture	Moisture (%)	Compaction percent by standard Proctor test ($\rho = 1.86$ g/cm^3) (%)	Time (day)
1	CaO	5	70	7
2	$Ca(OH)_2$	10	80	15
3	Portland cement	15	90	23
4	$Al_2(SO_4)_3$	Saturated	100	33

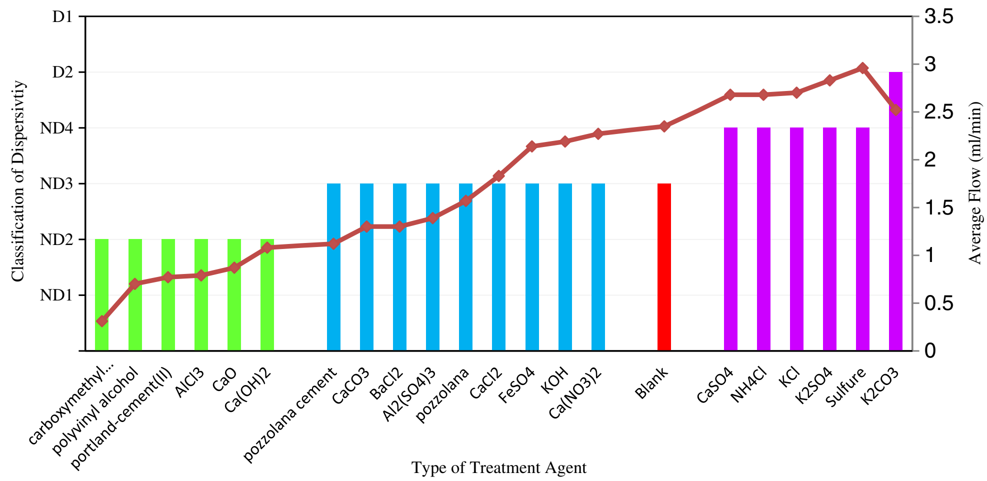

Fig. 1 Combinational figure for the results of pinhole tests on 21 compounds identified in the treatment of dispersive soils in terms of dispersivity class and average output flow

A closer examination of the effects of selected additives on soil dispersivity using the pinhole test

In the following stage of this experiment, we studied six of our compound candidates in greater detail, namely lime, cement, calcium hydroxide, pozzolan, aluminum sulfate, and calcium carbonate, used at different percentages. This examination not only looked at the amendment levels of various compounds, but also factors like accessibility and affordability of the aforementioned compounds.

According to the diagrams in Fig. 2, the addition of lime, cement, and calcium hydroxide resulted in the reclassification of amended soil in the non-dispersive class; these amended soils mitigated dispersivity at even lower concentrations under experimental conditions as well. Calcium carbonate, in spite of relatively lower efficiency when compared to some other compounds, steadily reduced the output flow rate from the cell, a trajectory which was directly correlated with increases in the percentage rates of calcium carbonate.

At the same time, the addition of aluminum sulfate and pozzolan did not produce particularly favorable results for elimination of soil dispersivity.

Relative combinations of lime additives with several other desirable elements

Although lime compounds displayed higher levels of efficiency when compared to other additives, they also introduce several limitations, including:

1. Lime compounds increase the soil pH; cation substitution efficiency decreases, as does soil alkalinity.
2. Using lime in high sulfate soils, particularly chalky soils, could aggravate the soil conditions in terms of swelling (Grant et al. 1977).

Given the objective of examining the combined amendment additives in conjunction with the first case, it seems appropriate to employ compounds that increase soil pH simultaneously with the main three additives already introduced. For this purpose, the soil pH variations were measured after the addition of the 21 initial amendment types (Fig. 3). Among the additives leading to lower pH, the sulfur compound is more important, owing to its availability and reasonable price.

Other appropriate measures in this regard involve application of pozzolan or sulfate-resistant cement. According to previous studies, pozzolans are made of silica or silicification aluminate with no adhesive value per se. However, fine pozzolan particles react chemically with calcium hydroxide in moist environments at room temperature, producing compounds with high adhesion and cementitious properties (Mallela et al. 2004; Ramezanpur et al. 1998).

In addition to sulfur compounds, the pozzolan additive was combined with the three main compounds at a ratio of 50% for the purpose of comparison. Table 3 provides a schematic view of the compound types tested.

Pinhole test results for combined amendment types

According to the diagram in Fig. 4, all the combined options (except the lime and pozzolan compounds) exhibited favorable and sometimes better results than the individual compounds in terms of average output flow rate. Although all the compounds (except one) were classified as fully non-dispersive (ND1), and although comparison of results based on average output flow in a single classification category lacks necessary consistency, we can generally conclude that the addition of sulfur, aluminum sulfate, and pozzolan (except in one case) at a weight ratio of 50% to lime, hydrated lime, and cement would significantly amend the soil.

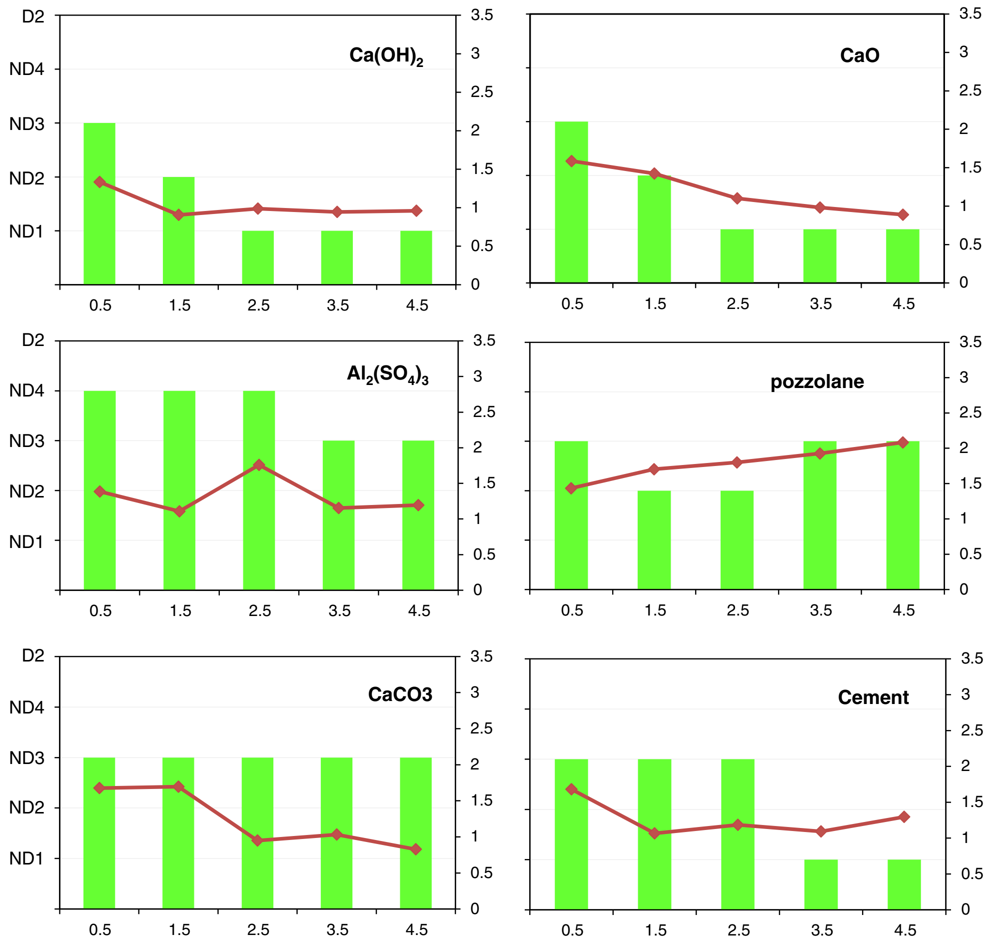

Fig. 2 Changes in soil dispersivity treated with six candidate compounds at varying percentages depending on dispersivity class and average output flow

Using the test design method to examine the physical factors influencing soil amendment

Previous studies have generally focused on the type and percentage of additives. However, soil amended by adding a percentage of a specific additive is also the function of several other variables. This section explores a number of fundamental variables (listed below) from a practical perspective, through the Taguchi test design method:

- Density of amended soil
- Moisture of amended soil

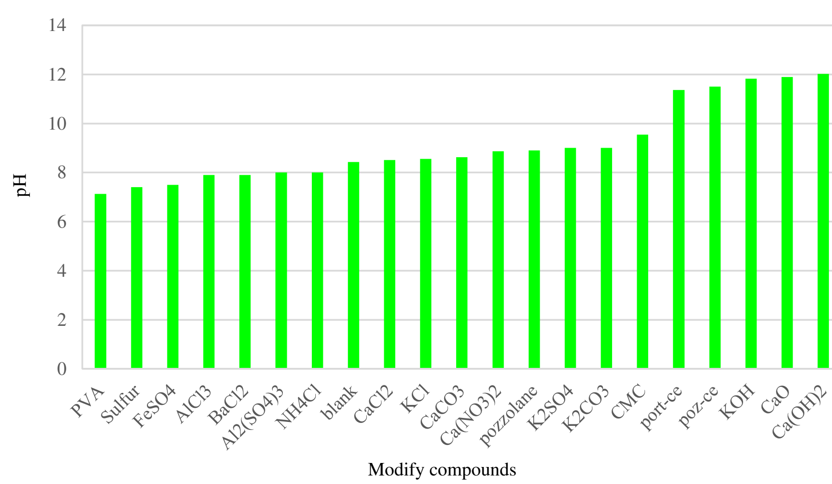

Fig. 3 Changes in soil pH after the addition of modified varieties (1/75% *w/w*)

Table 3 Composition of suitable compounds (50% weight percentage)

Basic Compound / Acidic Compound	Portland cement	CaO	$Ca(OH)_2$
Sulfur	S + cement	S + CaO	S + $Ca(OH)_2$
Pozzolan	Pozzolan + cement	Pozzolan + CaO	Pozzolan + $Ca(OH)_2$

- Time

It should be noted that Taguchi's method is based on application of orthogonal arrays where a large number of variables can be analyzed through a few experiments. The results of this limited set of experiments can be generalized to the entire possible space of design parameters (Roy 2010).

The major effects of varying factors on the pinhole test and a statistical analysis of the results

The results of the experiments were summed up and then divided by the total number of experiments in an effort to calculate the average performance of each factor at the desired level.

The *factorial effect* refers to the measurable differences between the average effects of each parameter at the desired level, representing the relative impact of each factor. The higher the value of difference, the greater the effect of that factor (variable). The diagrams in Fig. 5 display the average response for each of the factors based on the pinhole tests.

The statistical analysis of variance for the collected data serves to evaluate the effect of each variable on the dispersivity trend in terms of contribution percentage and confidence level (Table 4) (Roy 2010). As can be observed in the ANOVA table and in Fig. 5, with a contribution percentage of 34.5%, the "additive type" parameter has the greatest impact among the selected parameters. According to the diagram, calcium hydroxide, cement, and lime yielded more positive responses than aluminum sulfate did. After additive type, density, time, and moisture content had the most noticeable effects. When the sample density was expanded from 70 to 100%, the average flow sharply dropped, thus significantly enhancing the efficiency of the amended soil under similar conditions. Concerning time, it was observed that dispersivity decreased during the first 24 days and that there was no significant change thereafter. Moisture was statistically less significant than the other factors tested.

Conclusions

1- The results of the pinhole tests showed that among various salts, from aluminum, calcium, potassium, ammonium, and chloride cations, the best response was obtained from calcium oxide and calcium hydroxide. In addition, application of salts from other cations had no positive effect on the amendment of dispersive soils, and potassium ion salts even enhanced the soil's dispersivity. This result can also be explained by considering cation substitution in the lyotropic series (Nori and Neishaburi 2008; Ryker 1977). Additionally, it was observed that polymeric and cement compounds such as CMC, PVA, and portland had greater capabilities than other additives in terms of

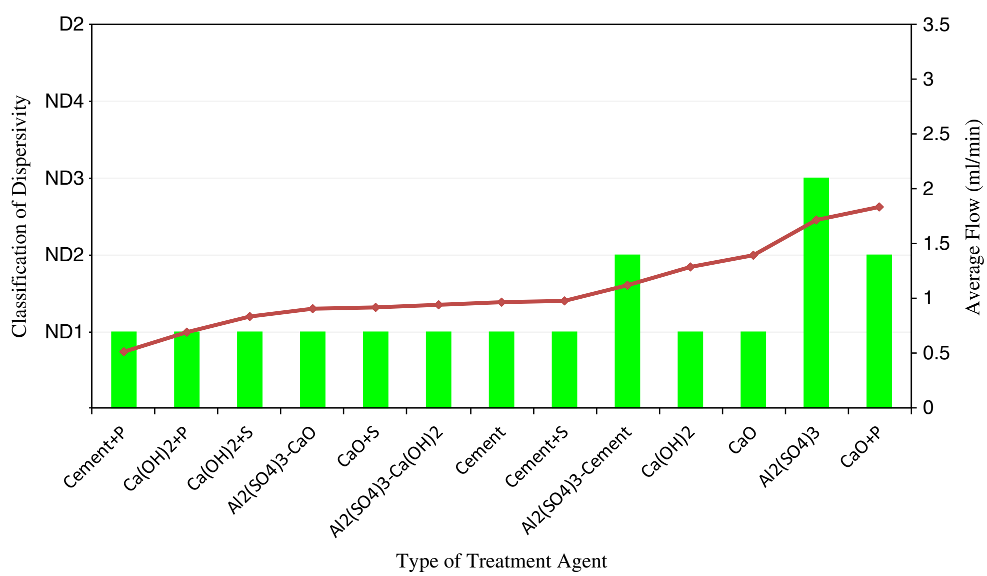

Fig. 4 Changes in dispersivity of combined and separate candidate treatment agents in terms of dispersivity class and average output flow

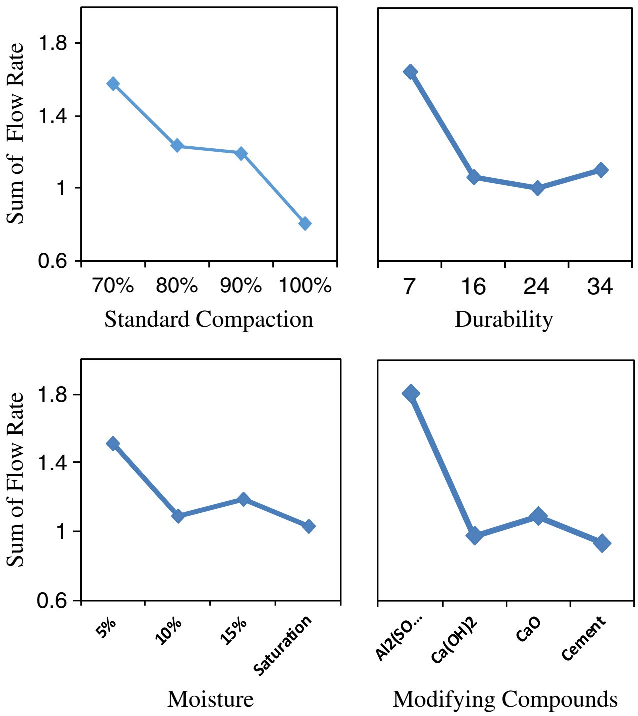

Fig. 5 Figures for the impact of physical factors with type of admixture on soil treatment through the pinhole method

reducing soil dispersivity. It should be noted, however, that polymeric additives are more expensive and less durable than other mineral additives.

2- A closer examination of the six ideal additives (added at different percentages) revealed that lime, cement, and calcium hydroxide severely reduced soil dispersivity (to "non-dispersive" ranking) even at low concentrations, based on the results of both pinhole tests. The effect of the relative composition of these three efficient lime-based additives with several other pertinent additives can enhance the efficiency and lower the required percentage rate of the additives. Using acidic additives, including aluminum sulfate, pozzolan, and sulfur at equal ratios with each of the three main compounds can often improve the intensity of the soil amendment. As previously described, this effect can be attributed to the ability of sulfur to reduce soil pH, as well as to the increase in adhesion and strength of lime compounds and pozzolan (Mallela et al. 2004; Ramezanpur et al. 1998).

3- Other factors affecting the amendment of dispersive soil were density and time. Increasing soil density and time within a given range can directly enhance the amendment process at a confidence level of over 95%.

Table 4 F Values and Contribution Percentage of Factors in Taguchi Test

Type of parameter	Pinhole test	
	F value	Contribution percentage
Compactions	1.45	21.1
Type of admixture	2.36	34.5
Durability	1.36	19.7
Moisture	0.67	9.7
Residual error	–	14.4

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