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ORIGINAL PAPER

Evaluating the Influence of Additives on Swelling Characteristics of Expansive Soils

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Abstract Stabilization is one of the most preferred techniques of dealing with expansive soils. Several types of additives have been evolved and are successfully being used for this purpose. This paper evaluates the performance of a variety of additives categorized into (a) cementitious: lime and fly ash (b) non-cementitious: stone dust, and (c) chemical additives: $CaCl_2$ and Na_2SiO_3, when employed to stabilize three types of expansive soils used in the study. Attempts were also made to investigate the influence of valence of cations (viz., monovalent, divalent and trivalent) and mean particle diameter (d_{50}) of additive(s) on percentage reduction of swelling characteristics. Results reveal that each additive exhibits distinct response on the swelling behavior of expansive soils. It has been observed that chemical additives exhibit superior performance over cementitious and non-cementitious additives in reducing the swelling characteristics. Further, it has also been found that valence has profound influence on the swelling characteristics of expansive soils. As such, the degree of reduction of swelling was found significantly high when employed chemical additive consists of trivalent cations than its counterpart additive consists of mono- or divalent cations. Further, efforts were also devoted to correlate mean particle diameter of additives with swelling characteristics, and it was clearly evident from trends that an appreciable decrease in swelling characteristics occurs with decrease in mean particle diameter.

Keywords Expansive soils · Swelling characteristics · Additive · Valence of cations · Mean particle diameter

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List of symbols

d_{50}	Mean particle diameter of additive (mm)
S	Swell potential (%)
S_p	Swell pressure (kPa)
G_s	Specific gravity of soil
γ_d, γ_{dmax}	Maximum dry density (kN/m^3)
ΔH	Change in height of sample during swelling test (mm)
H	Height of the sample (mm)
w_L	Liquid limit (%)
w_P	Plastic limit (%)
w_{PI}	Plasticity index (%)
OMC	Optimum moisture content (%)

Introduction

Damage/distress caused to the infrastructure when constructed on/in expansive soils is significant and is well recognized by the research community [1, 2]. Stabilization of these problematic soils by employing a suitable additive(s) is one of the preferred techniques of dealing with such soils. Numerous additives have been evolved over the past few decades, and their usefulness and efficiency have been well demonstrated by the previous researchers [3–11]. As such, a variety of additives, which are being employed to stabilize the expansive soils for some time, can broadly be classified into three main categories: cementitious, non-cementitious and chemical additives, as listed in Table 1.

Among several additives, lime is the most extensively being used additive, and expansive soil stabilization with this additive is the common traditional practice being followed [12–16]. Although, lime stabilization is well suited

Table 1 Categorization of various additives used for stabilization of expansive soils

Additive	Category
Stone dust, quarry dust, aggregate waste, rock waste powder, crusher dust, granite saw dust, sand	Non-cementitious additives
Lime, fly ash, ground-granulated blast furnace slag (GGBS), cement kiln dust, lime kiln dust, silica fume	Supplementary cementitious additives
$CaCl_2$, KCl, Na_2SiO_3, $FeCl_3$, $Mg(OH)_2$, Na(OH), NaCl, $MgCl_2$, $AlCl_3$	Chemical additives

for almost any type of expansive soil and is economically available additive, constructability issues often make its usage not feasible for all real life conditions. In addition, effective lime-soil reaction demands elevated temperature that is greater than 40 °F. Below this temperature, lime usually remains in a dormant state and does not initiate the reaction.

In order to overcome these limitations, researchers have been resorting to employ chemical additive such as KCl, NaCl, $MgCl_2$, $CaCl_2$, $AlCl_3$, etc., as stabilizing agents [10, 17–22]. The readily soluble capacity in water, which results in supply of adequate number of cations for ion-exchange reaction, is the principal merit of using these chemical additives as compared with the conventional additives [17, 23, 24]. Most importantly, in several field applications, where the soil at the site predominately contains clay size particles, a free passage of liquids and longer wetting periods is essential. Under these circumstances, use of chemical additives are found to be greatly effective than other non-chemical additives [21, 25–28].

Though, chemical additives were proved to be efficient in reducing the swelling characteristics of expansive soils, their utility in an economical way is not justifiable [4, 29, 30]. In this scenario, use of alternate materials such as fly ash, stone dust, quarry dust, cement kiln dust, lime kiln dust, marble dust, granite saw dust, ground granulated blast furnace slag, and so on, which are highly cost-effective and available in abundance, seems to be promising [3, 4, 8, 31]. Moreover, disposal of these waste materials is not only cost-intensive, but also requires usable land that can be utilized for cultivation or for other purposes. Thus, utilization of these wastes and by-products in stabilization of expansive soils could possibly be one of the valuable applications that can be regarded as an economical and effective way of dealing with such materials. As such, efforts were also devoted in this direction, which highlight that these materials can be used either in isolation or in blending with other alternate additives [4].

However, the performance and efficiency of any additive are strongly influenced by chemical and mineralogical composition of soil, properties of additives, and type of construction. Other factors include type and amount of clay mineral, soil–water chemistry, cations, initial moisture content, initial dry density, soil structure and fabric, soil profile, loading conditions and so on, which strongly influence the swelling characteristics of expansive soils [4, 30]. Although, soil stabilization is being practiced for many years, varying degree of success has been reported [16, 32–35]. Furthermore, most of the studies remain confined to employ a single additive either in isolation or mixed with other suitable additive(s). As such, very few efforts were devoted to evaluate the performance among several types of additives that have been employed for stabilization of expansive soils.

In this study, attempts were made to evaluate the performance of a variety of additives ranging from cementitious to non-cementitious to chemical additives when employed to stabilize three types of expansive soils. Five types of additives such as fly ash, lime (categorized as cementitious additives), stone dust (categorized as non-cementitious additive), and $CaCl_2$ and Na_2SiO_3 (categorized as chemical additives) were used. Results reveal that all the five additives are effective in reducing the swelling characteristics of expansive soils and each additive exhibits entirely different response. In general, it has been observed that the swelling characteristics of expansive soils decrease with an increase in additive content. Further, the performance of chemical additives is observed to be superior over other two categories of additives. Efforts were also made to study the influence of (a) valence of cations (i.e. monovalent, divalent and trivalent) and (b) mean particle diameter (d_{50}) of additive(s) on swelling characteristics of expansive soils. Trends plotted between valence and swelling characteristics clearly indicate the influence of valence such that the chemical additives consisting of higher valence (i.e. trivalent) exhibit greater efficiency than those additives consisting of lower valence (i.e. mono-and divalent). In addition, attempts were also made to correlate the mean particle diameter of additive(s) with swelling characteristics of expansive soils. A linear variation when plotted for mean particle diameter of additive against swelling characteristics was noticed with a considerable reduction in swelling characteristics with decrease in mean particle diameter of additive. The results clearly highlight that variety of additives can be employed for stabilization of three expansive soils used in the study. But, factors such as cost, benefit, practicality, and availability shall be taken into account when selecting a particular type of additive for stabilization of expansive soils.

Experimental Investigations

Soil Sample Collection

Expansive soils were collected from Amalapuram (denoted as AM) and Bhimavaram (denoted as BV) regions of Andhra Pradesh state, India, and Warangal (denoted as W) region of Telengana state, India. All samples were collected in their disturbed state and from a sufficient depth below the ground surface (i.e. 0.8–1.0 m) in order to avoid grabbing of roots and vegetation during sample collection. These samples were later dried and processed by pulverizing with the help of a wooden mallet. The processed samples were then subjected to various experimental investigations to establish their physical, chemical, geotechnical, and swelling characteristics.

Physical Characteristics

The specific gravity, G_s, of a sample was determined by pycnometer bottle method in accordance with the ASTM standard [36]. For the sake of accuracy, average value obtained from tests conducted in triplicate was considered representative, as listed in Table 2. Grain size distribution characteristics and consistency limits of soils used in the study were established in accordance with the ASTM standards [37, 38]. The results obtained are presented in Table 2. These soils have been classified as per unified soil classification system (in accordance with the ASTM standard [39], and the same has been reported in Table 2. It has been found that all the three soils fall under the category of highly compressible clays (i.e. CH).

Table 2 Physical and geotechnical characteristics of three expansive soils used in the study

Parameter	AM	BV	W	Fly ash	Stone dust
G_s	2.56	2.60	2.58	2.55	2.68
Grain size distribution (%)					
Gravel	2	2	3	0	0
Sand	25	26	26	28	96
Silt and clay	73	72	71	72	4
Atterberg's limits					
w_L (%)	98	76	64	30	NP
w_P (%)	36	30	26	–	
w_{PI}	62	46	38	–	
Compaction characteristics					
γ_d (kN/m^3)	16.2	16	16.4	14	–
OMC (%)	26	25	23	18	–
USCS[a]	CH	CH	CH	SM	SW

[a] [39]

Additives Used and Mix Proportions

In the present study, five different types of additives such as fly ash, lime, stone dust, $CaCl_2$, and Na_2SiO_3, respectively, were used to stabilize three expansive soils. Based on their nature and characteristics, these additives have been categorized into (a) cementitious additives: fly ash and lime, (b) non-cementitious additives: stone dust, and (c) chemical additives: $CaCl_2$ and Na_2SiO_3. The fly ash used was collected from Vijayawada thermal power station, Vijayawada, Andhra Pradesh, India. Stone dust and lime were collected from manufacturing units located in the region of Guntur, Andhra Pradesh, India. The chemical compositions of fly ash and lime are listed in Table 3. The solutions of $CaCl_2$ and Na_2SiO_3 have been prepared from the analytical grade salts. For stabilization of expansive soils, each additive in isolation, but in varying proportions, was mixed with expansive soil during stabilization. Table 4 presents list of various additives and the corresponding proportions in percentages adopted for stabilization of expansive soils.

Compaction Characteristics

The compaction characteristics of (a) three virgin expansive soils and (b) expansive soil blended with an additive in various mix proportions were established by adopting standard Proctor compaction technique in accordance with the ASTM standard [40]. Results obtained are presented in Table 5. However, the compaction characteristics of soils

Table 3 Chemical composition of fly ash and lime used in the study (% by weight)

Oxide	Value
Fly ash	
SiO_2	61–64.29
Al_2O	21.6–27.04
Fe_2O	3.09–3.86
TiO_2	1.25–1.69
MgO	0–0.05
CaO	1.02–3.39
P_2O_5	0.02–0.14
SO_3	0–0.07
K_2O	0.08–1.83
Na_2O	0.26–0.48
Lime	
CaO	58.64
SiO_2	7.3

Table 4 Percentage proportion of various additives adopted for stabilization of three expansive soils

Name of additive	% Added
Lime	0, 2, 4, 6, 8, 10, and 12
Fly ash	0, 10, 15, 20, 25, 30, 40, and 50
Stone dust	0, 10, 15, 20, 25, 30, 40, and 50
$CaCl_2$	0, 0.5, 1.0, 1.5, and 2.0
Na_2SiO_3	0, 0.5, 1.0, 1.5, and 2.0

blended with chemical additives such as $CaCl_2$ and Na_2SiO_3, were not established.

Swelling Characteristics

Swelling characteristics such as swell potential, *S*, and swell pressure, S_p, of each soil were determined with the help of a conventional oedometer apparatus, which consists of a metallic cylindrical ring of internal diameter 60 mm and height 20 mm. It has been well documented that expansive soils undergo maximum volume change when compacted at a maximum dry density (γ_{dmax}) with optimum moisture content (OMC) [41]. Thus, all swell tests were conducted considering the compaction state of γ_{dmax} and OMC (refer to Table 5).

Soil samples on which swelling tests to be carried out were oven dried and pulverized such that all particles are passing through 425 µm sieve. Initially, the prepared soil sample was mixed with respective additive (viz., fly ash or lime or stone dust or $CaCl_2$ or Na_2SiO_3) and blended thoroughly in their dry state. Subsequently, desired amount of distilled water was added to this mixture and the process of blending was continued again until a uniform consistency in the soil sample was ensured. The prepared sample was then compacted in the consolidation ring up to the desired height, *H*. It can be noted here that *H* shall not be exceeding that of the height of the ring. Such arrangement avoids swelling of soil sample beyond the height of the ring and also facilitates compression of the soil sample to its original height when applying swell pressure. The ring with soil sample was then placed in the consolidation set-up to proceed for the swelling experimentation. Prior to commencement of the test, porous stones, saturated by boiling in distilled water for about 15 min, were placed on both side of the sample. In addition, pair of filter papers (make, Whatman No. 1) was also inserted between soil sample and porous stone in order to avoid intrusion of soil particles into the porous stone.

After ensuring the entire assembly of the ring was properly placed in the set-up, the loading block was positioned centrally on top of the porous stone such that the vertical compressive load when applied was transmitted to the soil specimen through the loading cap uniformly. As the lever loading system was used the apparatus was

Table 5 Compaction characteristics of various mix proportions

Additive	% Added	AM		BV		W	
		OMC (%)	γ_d (kN/m^3)	OMC (%)	γ_d (kN/m^3)	OMC (%)	γ_d (kN/m^3)
Fly ash	10	23.65	16.5	22.6	16.3	21.15	16.7
	15	22.75	16.7	22.6	16.7	20.25	16.9
	20	22.3	17.1	22.15	16.95	19.8	17.44
	25	21.35	17.6	22.1	17.51	19.2	18
	30	20.95	17.7	20.66	17.62	18.4	18.1
	40	20.1	17.8	19.76	17.72	17.2	18.2
	50	19.7	17.9	18.9	17.79	16.6	18.3
Lime	2	26.9	16.73	25.8	16.7	25.6	16.8
	4	27.3	17.6	26.1	18	28.1	18.3
	6	27.65	17.7	26.5	18.1	27.4	18.54
	8	27.85	17.8	26.85	18.2	28.85	18.57
	10	27.9	17.9	26.98	18.3	29.19	18.6
	12	27.86	17.8	27.12	18.2	29.05	18.65
Stone dust	10	19.9	16.7	20.42	16.5	17.1	17
	15	19.15	17	19.61	16.9	16.39	17.5
	20	18.4	17.5	18.93	17.4	15.65	17.9
	25	18	17.9	17.83	17.8	14.35	18.4
	30	17.65	18.5	17.53	18.3	14.08	18.9
	40	16.4	18.6	14.9	18.4	12.41	18.94
	50	13.84	18.61	13	18.42	11	18.99

properly counterbalanced. Dial gauge, which measures the progressive vertical heave of the specimen, was fastened to the stand with its end-release touching perfectly on the loading block. An initial seating pressure of 5 kPa was placed on the loading hanger and the initial reading of the dial gauge was noted. The system was then connected to water reservoir to allow water ingress into the sample, which accelerates the swelling process. The free swell readings shown by the dial gauge were recorded at regular intervals of time. The swelling test was continued until there was no change in three consecutive dial gauge readings, which can be designated as a state of equilibrium, was recorded. For the samples used in the study, the state of equilibrium was noticed after about 3 days of experimentation. After successful completion of the test, the difference in height, ΔH, was computed by subtracting the initial height from the final height of the sample. Thus, swell potential of a sample can be computed using the following equation:

$$S(\%) = \frac{\Delta H}{H} \times 100, \quad (1)$$

where, S is the swell potential, H is the initial height of the sample, and ΔH is the difference in height of sample.

From the stage of equilibrium, which would represent the maximum swell potential of a soil, vertical compressive load was applied to determine the swell pressure exhibited by a soil. This was achieved by applying a vertical compressive load in increments. Each imposed load was maintained until no change in dial gauge reading was recorded. Loading on the sample was continued till heave becomes zero or the sample has been compressed to its initial height. The load at which the sample is compressed to its initial height can be designated as the swelling pressure of a soil.

Following the above procedure, swelling characteristics have been established on all soil samples prepared with the composition and mix proportions, as listed in Tables 4 and 5, respectively.

Results and Discussion

The degree of expansive potential of three soils (AM, BV and W) used in the present study was identified as per the classification system proposed by Snethen [42], Dakshanamurthy and Ramana [43], Sowers and Sowers [44], and Grabowska-Olszeawska [45]. These classification systems primarily employ consistency limits as input parameters. All the methods predominantly classify that the soils are to be 'very high expansive potential' in nature, as depicted in Table 6. Since, the soils were identified as expansive in nature they were stabilized with the help of various additives such as stone dust, fly ash, lime, $CaCl_2$, and Na_2SiO_3.

As depicted in Figs. 1 and 2, respectively, variations of S and S_p with percentage additive content was obtained corresponding to three soils AM, BV and W used in the study. In general, it can be seen from the plots that both S and S_p decrease with increase in percentage additive content indicating their usefulness in stabilizing three types of expansive soils. As depicted in the figures, it is clearly evident that the type and nature of additive (i.e. cementitious, non-cementitious or chemical) have a significant influence on stabilization of an expansive soil and results also reveal that percentage of additive required for stabilization of soils AM, BV and W is different for different additives. Further, it can also be noticed that each additive exhibits distinct response showing its effect on the swelling behavior of expansive soils. As depicted in Figs. 1 and 2, respectively, trends show that approximately 30, 10, 40, 1.0, and 1.5 %, respectively, correspond to fly ash, lime, stone dust, $CaCl_2$, and Na_2SiO_3, respectively, both S and S_p attained constant values. The findings are in good agreement with those results reported by other researchers [31, 46, 47] for similar types of additives. Incidentally, for all the three soils, as there is no significant change in their physical and compaction characteristics, the percentage of additive content found to be almost similar. Figure 3 shows the maximum percentage of additives required for stabilization of soils AM, BV and W, respectively.

From the Figs. 1 and 2, respectively, it is obvious that efficiency among cementitious additives like fly ash and lime, the performance of fly ash is significantly lower than that of lime in reducing S and S_p. When lime is added to the soil, it causes (a) cation exchange, in which the positively charged ions react with negatively charged clay particles, and (b) flocculation-agglomeration. The combination of these two phenomena in tandem allows the small clay particles to floc together resulting agglomerate into larger clay flocs [4, 26, 48–50]. In addition, the addition of lime to soil provides an adequate number of cations, which can readily take part in exchange of cations present on clay

Table 6 Classification of degree of swell potential of soils used in the study

Soil	Snethen [42]	Dakshanamurthy and Ramana [43]	Sowers and Sowers [44]	Grabowska-Olszeawska [45]
AM	VH	VH	H	VH
BV	VH	VH	H	H
W	VH	VH	H	H

H high, *VH* very high

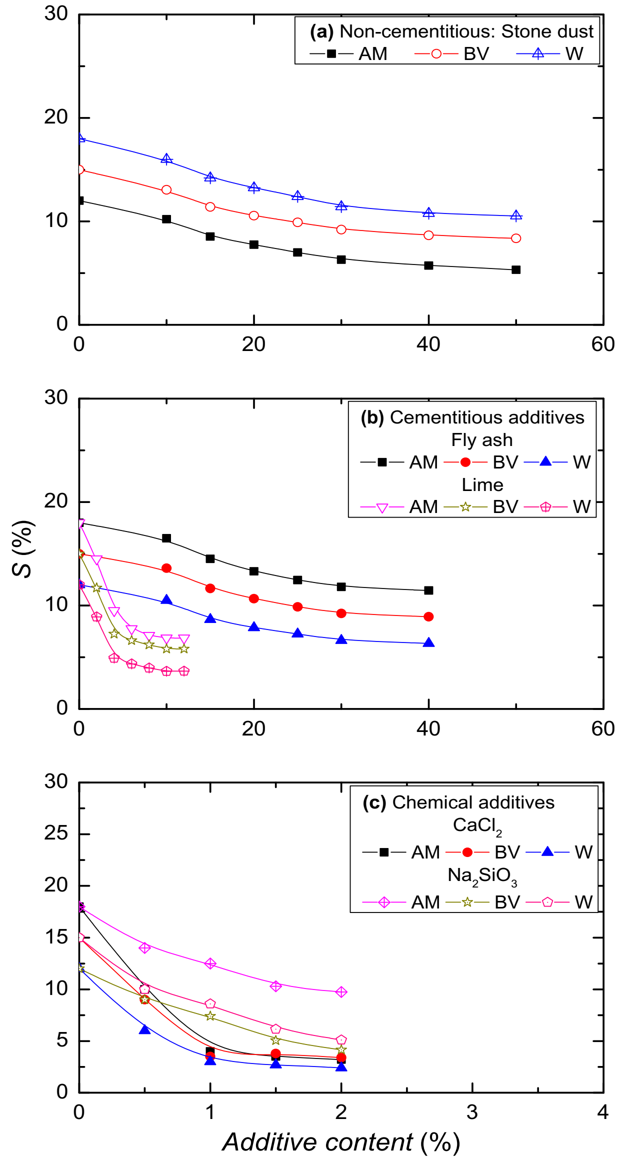


Fig. 1 Reduction in swell potential with varying proportions of additive content **a** non-cementitious additive **b** cementitious additives and **c** chemical additives

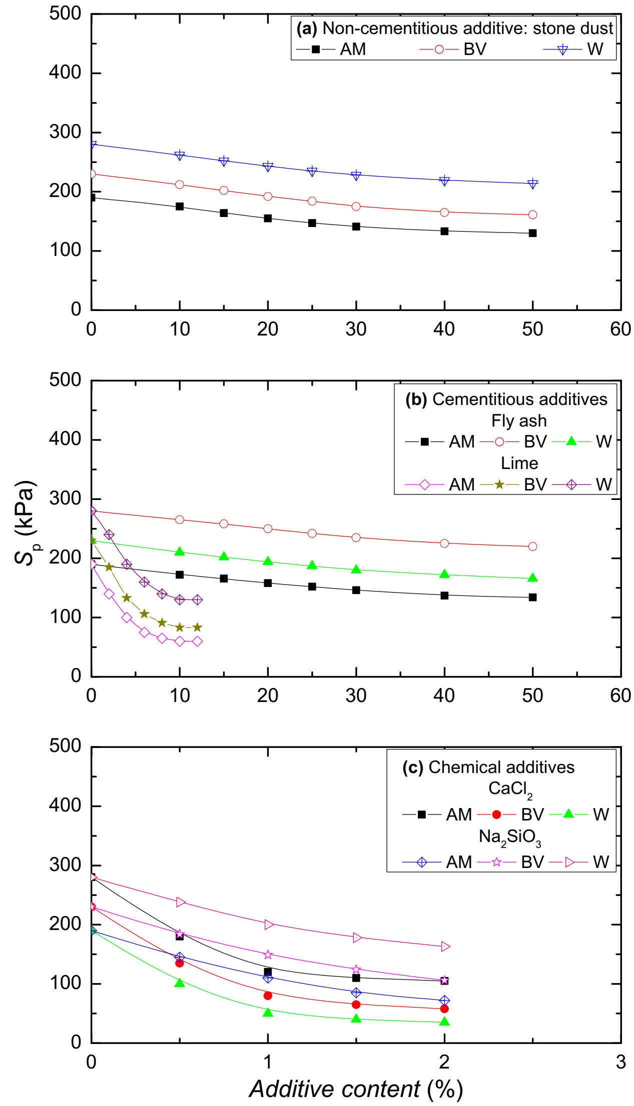


Fig. 2 Reduction in swell pressure with variation of additive content **a** non-cementitious additive **b** cementitious additives and **c** chemical additives

particles surface. Thus, the net result is a substantial decrease in swelling characteristics of expansive soils. Moreover, the reaction between lime and water, which usually occurs after sufficiently long time, forms a cementitious matrix resulting resistance to volumetric expansion of soil to an appreciable extent [51]. Overall, when lime is added to soil, reduction in S and S_p occurs primarily because of alteration in clay structure.

However, the reaction between fly ash and soil is a complex phenomenon as it contains an array of cations (like Na^+, Ca^{2+}, K^+, Fe^{3+}, and so on) and a considerable amount of silt size particles. Thus, when fly ash is added to the soil, reduction in swell behavior is attributed to the presence of silt size particle, to some extent, and due to the immediate effect of chemical reactions because of an array of cations present in fly ash, to the rest, [3]. As such, the amount of free lime available in fly ash is quite less and hence, ion-exchange occurrence between fly ash and soil is negligible. Thus, less reduction in S and S_p of expansive soils can be expected as compared to lime [52]. Similarly, the performance of non-cementitious additive like stone dust in reducing S and S_p also observed to be low when compared to its counterpart additives. This may be because stone dust merely acts as a fill material within the pore space of the soil mass as it does not show affinity to water, and it also creates a contrast in density of particles between additive and parent soil [53].

Attempts were made to highlight the relative performance among a variety of additives, as depicted in Fig. 4, which shows the percentage reduction of both S and S_p with additive type. It is apparent from the chart that the performance of chemical additives in reducing the swelling behavior of expansive soils is superior over its counterparts like cementitious and/or non-cementitious additives. As such, Figs. 1 and 2, respectively, also confirm similar such findings. Interestingly, all the additives show better performance in reducing S_p than S of a soil. Further, to comprehend the influence of various categories of additives on the stabilization process in a much better way, the results of both S and S_p in their reduced percentage intensity form were superimposed into a single graph, as depicted in Fig. 5. From the graph, it is evident that the performance efficiency increases in the order of non-cementitious to cementitious to chemical additives.

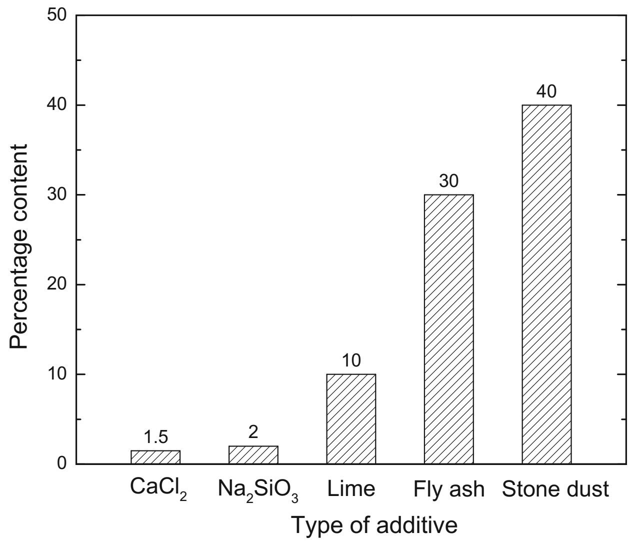


Fig. 3 Maximum percentage of additive for stabilization of expansive soils used in the study

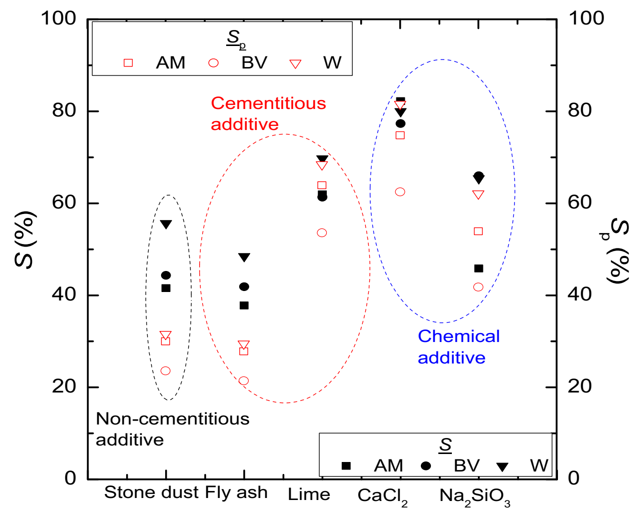


Fig. 5 Influence of category of additives on the swelling characteristics of expansive soils

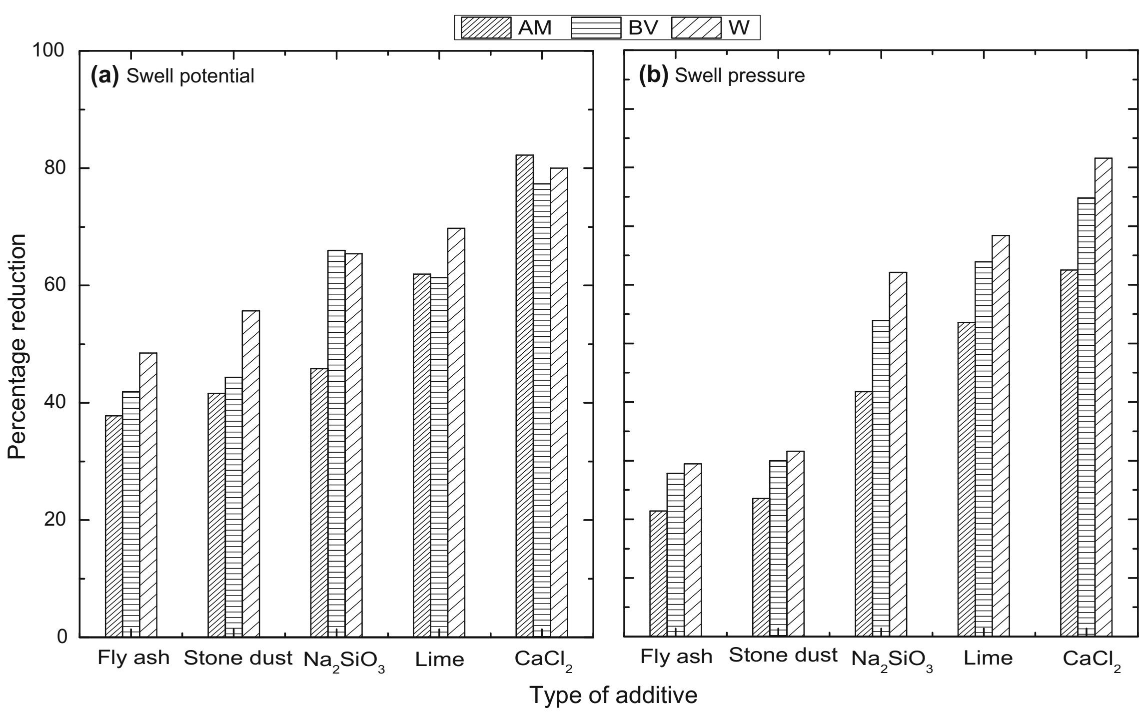


Fig. 4 Percentage reduction of S and S_p with additive content

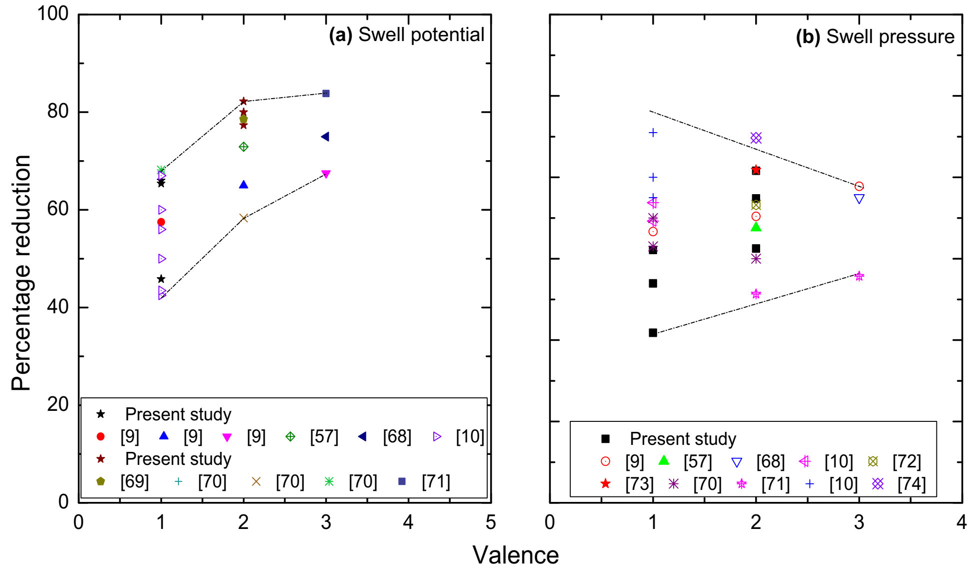


Fig. 6 Influence of valence on the swelling characteristics of expansive soils

As such, Figs. 1, 2, 3 also show that the quantity of additive content in case of chemical category is significantly lesser as compared with those of cementitious or non-cementitious categories. This may be attributed to the fact that the salts in chemical additives are readily soluble (solubility of $CaCl_2 = 745$ g/l, and $Na_2SiO_3 = 610$ g/l) in water as compared with lime (soluble capacity = 1.65 g/l). Petry and Armstrong [25] reported that when calcium chloride electrolyte is added to soil, it easily made into the calcium charged supernatant, which helps in ready cation exchange reactions with clay particles. While those of cementitious/non-cementitious additives like fly ash and stone dust, their solubility capacity in water is almost zero. Thus, the mechanism involved in reducing S and S_p of soil when employed these additives is majorly due to mechanical bonding or cementation instead of an ion-exchange phenomenon [54]. As such, when chemical additives are employed in place of cementitious/non-cementitious additives, because of their instantaneous solubility supply an adequate numbers of cations for exchange with ions available on the surface of soil particles, which in turn leads to increase or decrease in thickness of the diffuse double layer [9, 27]. Thus, chemical additives exhibit better performance at an accelerated rate that too in substantial lesser quantity than their counterparts would do so. Incidentally, results of lime additive in reducing S and S_p are very close to that of chemical additives. This may because, lime contains a considerable amount of CaO, which in turn makes it highly reactive in nature, while a limited amount of CaO is available in fly ash and negligible in stone dust additives [55]. Further, a partial amount of CaO in the lime also exists as non-exchanged calcium ions, which may be adsorbed onto soil particles resulting low base-exchange reaction and hence, insignificant volume change potential. In addition, the reaction between lime and water is exothermic in nature, which releases a good amount of heat energy into the soil mass resulting in evaporation of water at a faster rate, which in turn reduces the swell properties of expansive soils, rapidly [56].

Influence of Valence on Swelling Characteristics

It can be seen from Figs. 1, 2 and 5, respectively, among $CaCl_2$ and Na_2SiO_3 additives, the efficiency of former one in reducing S and S_p is prominently better than later one. This finding was in agreement with those results reported by Murty and Praveen [57] and Srinivas and Raju [9]. This is due to the fact that the additive $CaCl_2$ contains divalent cations (i.e. Ca^{2+}) as against Na_2SiO_3, which contains monovalent (i.e. Na^+) cations. A base exchange occurs with the strong calcium ions replacing the weaker sodium ions (typical cation's replaceability is: $Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Al^{3+} < Fe^{3+}$), which in turn results decrease in thickness of the diffuse double layer develops on the surface of clay particles. This alteration in electrical charge around a clay particle reduces the spacing between clay particles resulting creation of flocculated structure, which in turn reduces the swell percent and swell pressure of a soil [58–60]. Moreover, according to Gouy-Chapman theory, thickness of diffuse double layer varies inversely with valence [61]. Thus, it can be established that the chemical additive with higher valence of cations (like $CaCl_2$) performs superior to than those additives with lower valence (like Na_2SiO_3) in reducing the swelling

Table 7 Legend of references used in Figs. 6 and 7

Reference	Legend	Additive
Present study	–	$CaCl_2$, Na_2SiO_3, stone dust, lime, fly ash
Cokca et al. (2009)	[8]	Granulated blast furnace slag, granulated blast furnace slag cement
Srinivas and Raju (2010)	[9]	$CaCl_2$, KCl, $FeCl_3$
Gueddouda et al. (2011)	[10]	NaCl, lime
Cetiner (2004)	[16]	Fly ash, lime
Murty and Praveen (2008)	[57]	$CaCl_2$
Rao et al. (2012)	[68]	$FeCl_3$
Abdullah and Al-Abadi (2009)	[69]	$CaCl_2$
Belabbaci et al. (2013)	[70]	KCl, $MgCl_2$
Radhakrishnan et al. (2014)	[71]	$AlCl_3$, fly ash
Heeralal et al. (2012)	[72]	$CaCl_2$
Urena et al. (2013)	[73]	$Mg(OH)_2$
Azam et al. (2000)	[74]	Calcium sulfate
Cai et al. (2006)	[75]	Polypropylene fiber
Kalkan (2009)	[76]	Silica fume
Nalbantoglu and Gucbilmez (2002)	[77]	Fly ash
Nalbantoglu (2004)	[78]	Fly ash
Zhang and Cao (2002)	[79]	Fly ash, lime
Negi et al. (2013)	[80]	Silica fume
ElKholy (2008)	[81]	Sand
Siddique and Hossain (2011)	[51]	Lime
Al-Rawas et al. (2005)	[82]	Lime
Phanikumar (2009)	[83]	Lime
Mousa and Al-Sharif (1998)	[84]	Burned olive waste
Mollamahmutoglu and Yilmaz (2001)	[85]	Fly ash
Sabat (2012)	[86]	Ceramic dust
Bose (2012)	[87]	Fly ash
Kalkan and Akbulut (2004)	[88]	Silica fume

characteristics of expansive soils. Results also highlight that cation exchange is one of the dominants phenomena in mitigating the swelling characteristics of expansive soils.

With this in view, attempts were made to investigate the influence of valence in reducing both S and S_p of expansive soils. Figure 6 depicts the variation of percentage reduction of S and S_p when plotted against valence of cations of $CaCl_2$ and Na_2SiO_3. In order to validate the findings of the study, data available in the literature (refer to Table 7) correspond to various other chemical additives, which consist of either monovalent or divalent or trivalent cations, were collected and presented in the form of Fig. 6. It can be observed from Fig. 6 that, in general, both percentage reductions of S and S_p vary linearly with increase in valence such that higher degree of reduction was exhibited by higher valence cations and vice versa. However, it can be noted from the trends depicted in the figure that the percentage reduction range is marginal for S, while it is drastic in case of S_p with an increase in valence. Results reveal that valence has phenomenal influence in reducing S_p than S of a soil. As depicted in the Fig. 6, the scatter in the results of S_p exhibited by monovalent cations is appreciably higher than trivalent cations. The order of efficiency of valence in its increasing form is found to be monovalent to divalent to trivalent. The maximum and minimum percentages reduction of both S and S_p observed from the graphs are listed in Table 8. The range can be bracketed between 84–40 % and 78–42 %, corresponding to S and S_p, respectively.

Influence of Mean Particle Diameter of Additive on Swelling Characteristics

The physical characteristics such as grain size, shape and particle size distribution of various additives are usually quite distinct, and they show significant change in the behavior of expansive soils. The chemical reactions include pozzolanic reactions, cation exchange capacity, carbonation

Table 8 Range of maximum and minimum percentage reduction of S and S_p for different valence of cations

Valence	Swelling characteristic (minimum–maximum)	
	S (%)	S_p (%)
Monovalent	42–68	42–80
Divalent	58–82	60–82
Trivalent	67–84	75–78

and cementation, and microfiller effects, which dominantly influence the efficacy of the stabilization process, largely controlled by particles composition of an additive(s) [62–65]. Stalin [66] reported that presence of coarser fraction of an additive and its size considerably affects the swelling behavior of an expansive soil. Further, the size of particles has direct bearing on the formation of the number of bonds between clay and additive and water absorption properties [29, 67]. However, no effort was devoted to investigate the influence of gradational characteristics of additives on the swelling behavior of expansive soils.

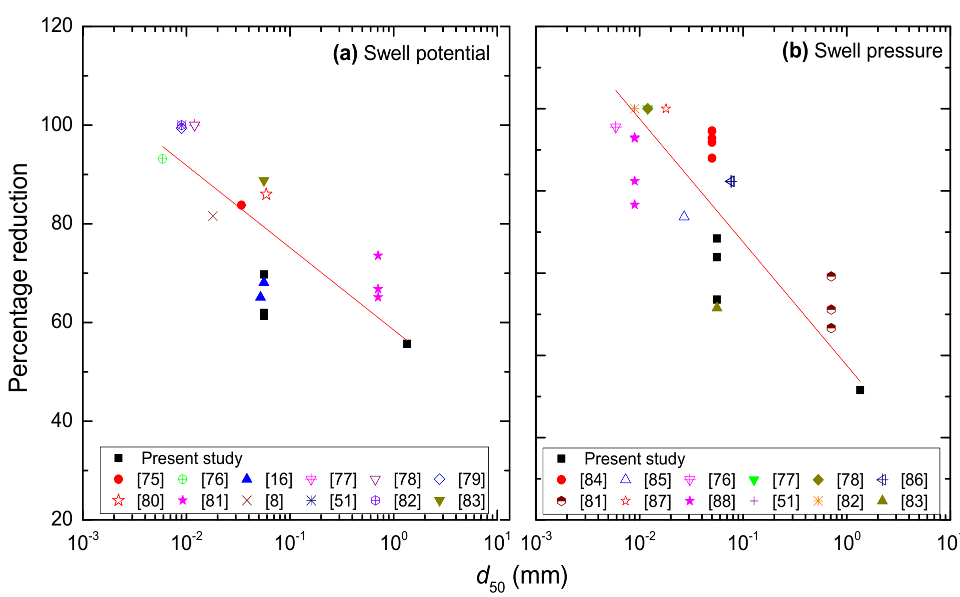
With this in view, efforts were also made in this study to evaluate the influence of mean particle diameter, d_{50}, of additives on the swelling behavior of expansive soils. Figure 7 depicts the relationship of d_{50} when plotted against S and S_p. In order to generalize this relationship, data collected from the literature corresponding to a variety of additives (refer to Table 7) were also superimposed on the plot. It can be noted that the minimum value of d_{50} was obtained for lime, while the maximum value of d_{50} was found for stone dust or quarry dust additives. As depicted in the figure, it can be observed that d_{50} varies linearly with S and S_p such that decrease in the mean particle diameter decreases the percentage reduction of S and S_p. As such, trends display similar influence of d_{50} on both S and S_p. It can also be noticed from the figures that the smaller is the mean particle diameter of an additive, greater is the percentage reduction of S and S_p and hence, its effectiveness on a soil. Results reveal that up to 100 % reduction in S and S_p can be achieved when employed additives comprising mean particle diameter of lesser than 0.01 mm. As such, results show marginal scatter in the data, although the entire data are fitting well within the 90 % prediction band. This may be attributed to (a) difference in degree of swell potential (viz., low, medium, high, or extremely high) exhibited by a soil mass, (b) distinction in the methodology that can be employed to determine S and S_p, (c) type of clay mineral and its percentage content in a given soil mass, etc.

As such, the results suggest that the better correlation between d_{50} and swelling characteristics can be developed when adopted system based on the swell potential like low, medium, high, very high, etc., of soils. Thus, results demonstrate that the mean particle diameter of additive has a definite influence on swelling characteristics of expansive soils.

Concluding Remarks

This paper demonstrates the performance of a variety of additives such as non-cementitious: stone dust, cementitious: lime and fly ash, and chemical additives: $CaCl_2$ and Na_2SiO_3, in reducing the swelling behavior of expansive soils. Results highlight that all the additives are effective in reducing swelling characteristics, and each additive showed its distinct response in stabilizing the expansive

Fig. 7 Percentage reduction versus mean particle diameter of additive **a** swell potential and **b** swell pressure



soils. Among the three categories of additives that have been employed for stabilization of three expansive soils, chemical additives exhibit better performance over its counterparts. Efforts were also made in the present study, to investigate the influence of valence of cations and mean particle diameter of additive on swelling characteristics. It has been observed that both valence of cation and the mean particle diameter of additive significantly affect the swelling characteristics. Further, trends clearly show that with increase in valence of cations and decrease in mean particle diameter, both S and S_p decreased to a significant level. As such, results demonstrate that varieties of additives are effective in stabilization of expansive soils, but the selection of a particular additive type seems to be prudent if set on the basis of the prevailing site conditions.

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