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POTASSIUM CHLORIDE EFFECT ON EFFICIENCY OF FINE SLAG USED FOR TREATMENT OF EXPANSIVE SOIL

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The article presents the results of a preliminary investigation carried out to determine the effect of a small amount of potassium chloride (KCl) on the efficiency of fine slag used for treatment of expansive soil. The quantity of KCl has been varied from 0,5 to 1,5 %, while fine slag was varied from 5 to 15 % of the soil weight. It is found that the plasticity and differential free swell of the soil reduces with the addition of KCl as well as fine slag. KCl is more competent in reducing the plasticity and swelling of soil compared to fine slag. Whereas, the enhancement in strength and maximum dry density is relatively large in case of fine slag as compared to KCl added to the soil. The efficiency of fine slag to alter the properties of expansive soil increases significantly in the presence of a small quantity of KCl. The predictive models were also developed to find out the improved properties of expansive soil.

Key words:
Potassium chloride, fine slag, expansive soil, index properties, unconfined compressive strength.

Introduction

Expansive soil, also known as black cotton soil in India, is spread over more than 20 % land cover of India [1]. However, all expansive soils are not black cotton soils and vice versa. These soils suffer from volume expansion and shrinkage in wet and dry state, respectively. Within the last two decades, India has gone through significant advancement and growth in the road network and various other construction activities. Presence of expansive soils often affects the construction activities and performance of structures [2, 3]. In India, these soils have affected the functioning of roads and have hammered construction activities severely. Therefore, it is required to enhance the expansive soil properties before starting any construction activity.

It has been revealed in earlier studies that chemical stabilisation is a relatively more efficient and economical solution to change and enhance the properties of expansive soils [4–6]. The chemical stabilisation using materials like Portland cement, KCl, NaCl, lime, and various other conventional stabilisers are very common. The chemicals undergo cation exchange with the clay minerals; and consequently, reduce the shrinkage and swelling of soils [7]. Many researchers used various combination of chemicals, and some studies used solid waste materials to improve the properties of chemically treated soil [8–10]. Solid waste material improves the strength of soil, and chemical additives reduce the swelling and shrinkage of soil. The solid material interrupts the free flow of moisture and in its turn, reduces the swelling of soil.

R.K. Katti [11] used a number of chemicals to stabilize the expansive soil and revealed that potassium chloride (KCl) is relatively more efficient than other additives such as sodium chloride, barium chloride, calcium chloride, and magnesium chloride. Various other studies have also found KCl to be an effective additive for enhancement of properties of expansive soils [12–14]. A few studies used fine slag (FS) to enhance the strength of the soil. It was found that the addition of FS increased the strength of cohesive soils [1, 15]. The combined effect of FS and KCl is missing in the literature. The main aim of the study is to explore the influence of a small quantity of KCl on the FS efficiency to modify the properties of expansive soil. The soil properties considered in the present study include Atterberg limits, the unconfined compressive strength of soil, water content – dry density relationship, and differential free swell of expansive soil.

Materials used in the present study

The soil used in the present study was collected from Guna city, India. Fig. 1 shows the sampling location (red circle within a square) and the area where the study result can be implemented (blue area). Soils of similar characteristics are spread over more than 40 % area of Madhya Pradesh and a large part of Maharashtra and Rajasthan states of the country. Therefore, the outcome of this study can be utilized for a large area of the country. The properties of soil are presented in Table 1. The finer content is found to be more than 65 %. A small amount of organic materials was also witnessed in the collected soil samples.

FS was used as a primary additive to enhance the soil properties. Potassium chloride was used as secondary material to increase the effectiveness of FS. KCl is available at a very low cost. The description of KCl and FS are presented in Table 2. The powder form of KCl, which has a white crystalline appearance, is used in the study. FS used in the present study is produced through the controlled granulation and possesses good cementitious properties. It has a specific gravity of 2,8.

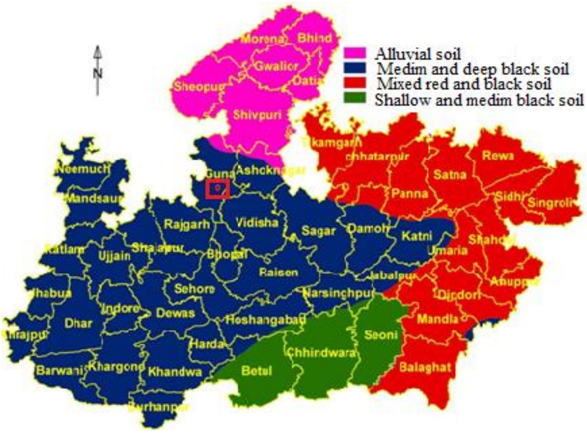


Fig. 1. Distribution of Expansive soil and sampling location (remodified after, MP land report, [16])

Рис. 1. Распределение обширного грунта и места отбора проб (ремодифицировано после отчета МП по земле [16])

Table 1. *Properties of expansive soil used in the study*

Таблица 1. *Свойства экспансивной почвы, использованной в исследовании*

Properties/Свойства	Description/Описание
Specific gravity (G)/Удельный вес (г)	2,42–2,44
Liquid limit (LL)/Предел текучести	53–58 %
Plastic limit (PL)/Предел платичности	30–35 %
Plasticity index (PI)/Индекс пластичности	23–26 %
Optimum moisture content (OMC) Оптимальное содержание влаги	19–21 %
Shrinkage limit (SL)/Предел усадки	10,5–11,5 %
Maximum dry density Максимальная сухая плотность	1,51 gm/cc

Table 2. *Description of KCl and FS used in the study*

Таблица 2. *Описание KCl и FS, используемых в исследовании*

Properties of KCl Свойства хлористого калия	Description Описание	Chemical constituent of FS Химический состав ФС	Amount Сумма (%)
Molar mass Молярная масса	74,56 g/mol	CaO	62,5
Density/Плотность	1,98 gm/cm^3	SiO_2	22
Solubility in water Растворимость в воде	344 g/L	Al_2O_3	5,2
Boiling point Температура кипения	1420 °C	Fe_2O_3	4,25
Odour/Аромат	Odorless Без запаха	SO_3	2,25
Melting point Температура плавления	770 °C	MgO	1,2

Method of testing

The liquid limit of untreated expansive soil and modified soil were determined using the Casagrande apparatus. The plastic limit of soil was evaluated by the thread rolling method. The detailed procedure to determine the LL and PL is given in IS:2720:Part-V [17]. Shrinkage limit of soil samples was determined using the mercury displacement method by following a procedure specified in IS:2720:Part-VI [18]. To determine the Atterberg limits of modified soil, sufficient time was provided to allow the uniform mixing of water within the soil samples. Following the plasticity chart given in the Indian standard, IS 1498 [19], this soil is classified as silt of high plasticity (MH).

The different testing approaches were used to determine the relationship between moisture content and dry density of untreated soil and stabilized soil. For untreated soil samples, Indian standard IS:2720:Part-VII [20] was used, while for the stabilized soil samples, IS:4332:Part III [21] was used. The stabilized soil and water mixture were compacted in the mould of size 1000 ml. The stabilized soil sample added with the varying amount of water content was compacted in the three layers. Each layer was compacted with a hammer (weight of 2,6 kg) falling through a height of 310 mm. The compaction of the stabilized soil sample was completed within 20 minutes as specified in the Indian standard. After this, the compacted soil sample was removed from the mould. To determine the moisture content of compacted soil, the soil samples were taken from the top, center, and bottom of the compacted soil specimen.

The unconfined compressive strength of untreated soil and stabilized soil samples were determined using a method specified in IS 2720:Part X [22]. Soil samples with a diameter of 38 mm and length of 76 mm were used to determine the UCS of soil. All soil samples were made at optimum moisture content and maximum dry density. All samples were compacted and tested under a constant strain of 1,25 mm/min. Stress-strain curves were plotted to determine the peak strength of the soil sample. Indian standard code IS 2720-40 [23] was used to determine the differential free swell of expansive soil. As suggested in the IS code, 10 grams of oven-dried soil sample passing through a 425-micron sieve were poured into two graduated cylinders each of 100 ml capacity. One cylinder was filled with kerosene oil as a non-polar liquid, and the other was filled with distilled water up to the 100 ml mark. The entrapped air was removed from both the cylinders through gentle shaking. After sufficient time (48 hours), when soil samples attained equilibrium condition, the final volume of the soil grains was measured. The differential free swell was determined by the following formula given in IS code IS 2720-40 [23]: differential free swell (DFS)=$[(V_w–V_k)/V_k]\times100$, where V_k and V_w are the final volumes of soil samples in kerosene and distilled water.

Result and discussion

To determine the optimum quantity, the amount of potassium chloride was varied from 0,5 to 1,5 % with an interval of 0,5 %. The amount of KCl at which the properties (in plots) showed a slight crest or displayed a reversal as compared to the previous amounts was considered as optimum quantity. The results of the study show that the optimum quantity of KCl for this particular soil is approximately found to be 1 % of soil weight. The evaluated optimum amount of potassium chloride is also close to the other studies [24, 25] carried out on expansive soils found in India. This amount was added to the soil samples to be treated with FS. To differentiate between the distinct effect of FS and combine effect of KCl and FS, the results are presented in the normalized form as a ratio of the initial value of index property for untreated soil (with a subscript 'i') to the final value of the same property after treatment (with a subscript 'f').

Effect on consistency limit

Liquid limit and plastic limit are crucial index properties to classify finer soils, and it can be correlated with a number of engineering properties and behaviour of soil. The variation in Atterberg limit with KCl and FS is presented in Fig. 2. Fig. 2, *a* shows that the LL of the soil decreases with the increase in the KCl content as well increase in FS content.

The liquid limit indirectly designates the compressibility of soil. Therefore, furthermore reduction in liquid limit with the addition of FS in the KCl treated soil stipulates the additional reduction in soil compressibility. Fig. 2, *b* shows that the plastic limit increases and decreases with the increase in the quantity of KCl and FS, respectively. In the case of KCl, the plastic limit is increased by 25 %, whereas in the case of FS, it decreases by 12 %. A number of other studies used KCl and FS separately to stabilize expansive soil, and made similar observation [12–14, 26].

Fig. 2, *c*, *d* shows the affect of 1 % KCl on FS efficiency to improve LL and PL, respectively. Fig. 2, *c* depicts that the efficiency of FS to reduce the LL enhances due to the presence of KCl. In case of FS added soil, the LL initially decreases with increase in the FS and increase for any quantity greater than 10 %. However, LL reduces continuously, when FS was added along with KCl. However, the PL of soil treated with FS and KCl together always remains more than untreated soil and soil treated with FS alone (Fig. 2, *d*).

The effect of KCl and FS on PI of soil is shown in Fig. 3. Fig. 3, *a* shows that PI reduces significantly in both cases, but the efficiency of KCl is relatively more as compared to FS to reduce the PI of soil. The higher efficiency of KCl shows that it is relatively more flocculation than FS. It can be explained as the better ability of KCl solution to perform electrolytic behaviour where the ions can easily be imparted for better stability of soil grain surface charge.

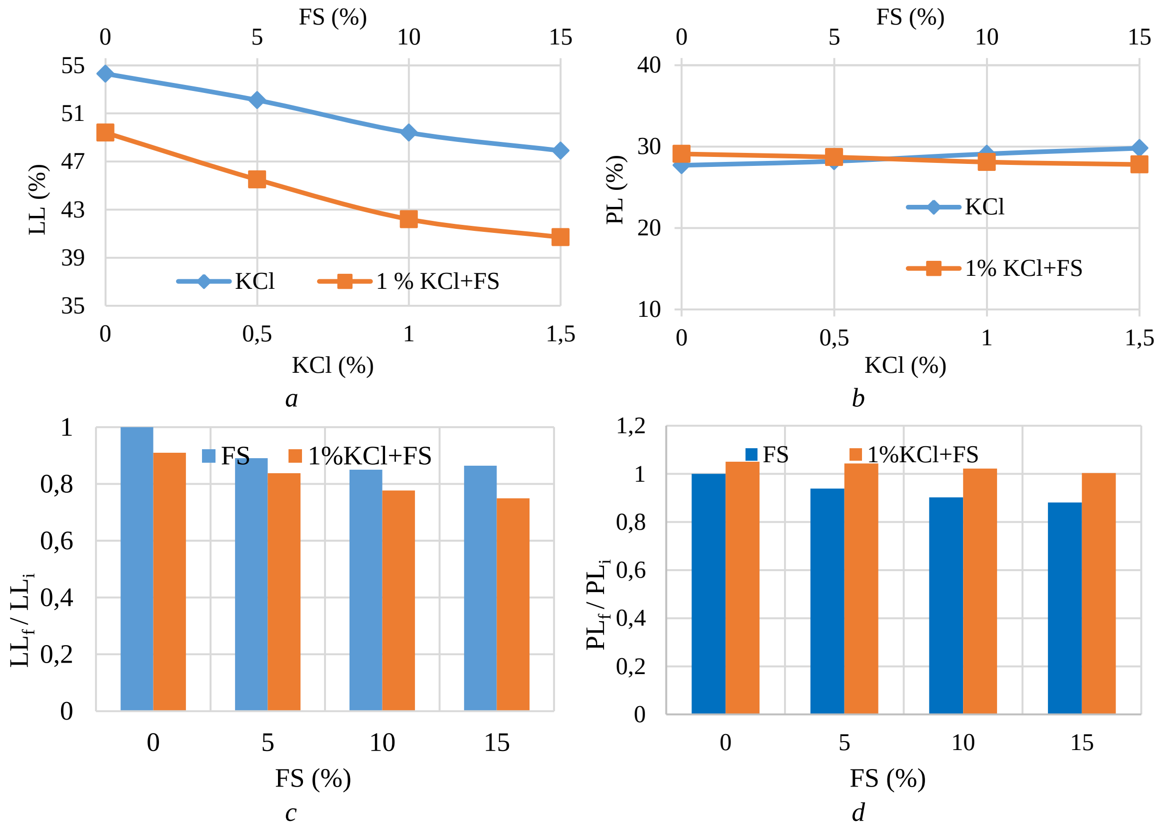
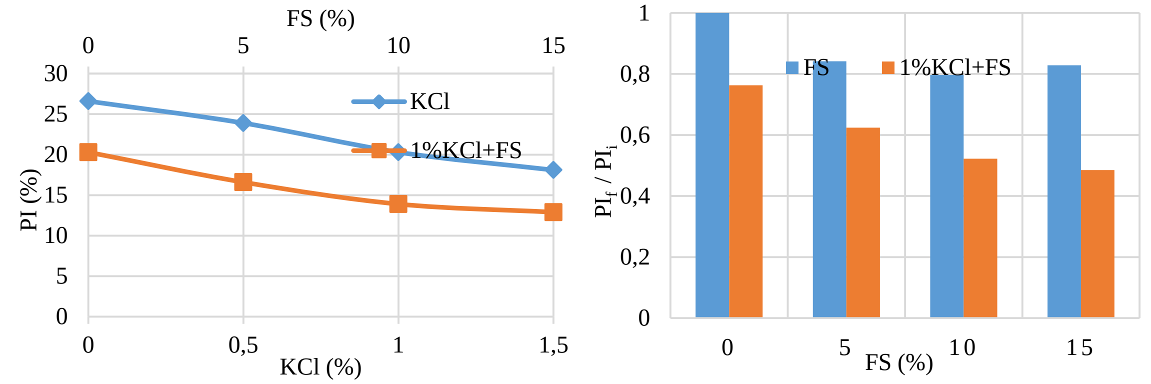


Fig. 2. *Variation in Atterberg limit: a) LL with KCl and FS; b) PL with KCl and FS; c) distinct effect of FS and combine effect of KCl and FS on LL ratio; d) distinct effect of FS and combine effect of KCl and FS on LL ratio and on PL ratio*

Рис. 2. *Изменение предела Аттерберга: a) LL с KCl и FS; b) PL с KCl и FS; c) индивидуальное влияние FS и комбинированное влияние KCl и FS на отношение LL; d) индивидуальное влияние FS и комбинированное влияние KCl и FS на отношение LL и на отношение PL*



a *b*

Fig. 3. *Variation in plasticity index: a) with KCl and FS; b) distinct effect of FS and combine effect of KCl and FS on PI ratio*

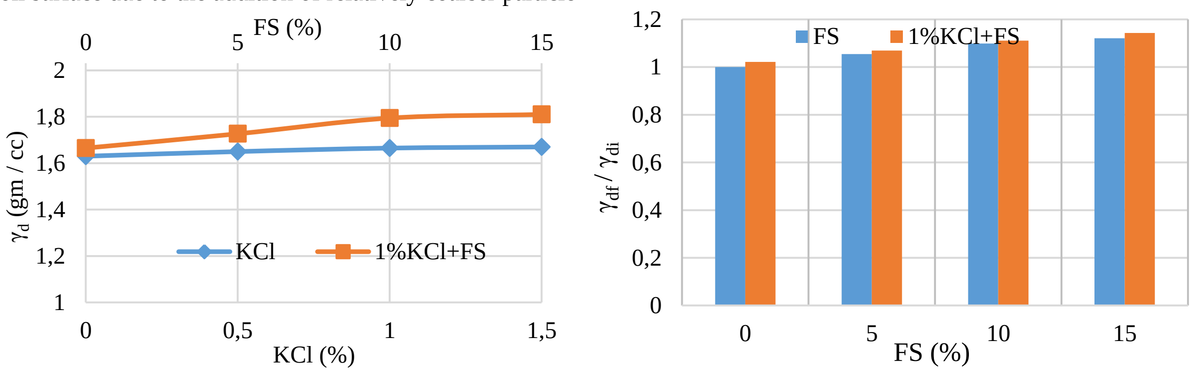
Рис. 3. *Изменение индекса пластичности: a) с KCl и FS; b) индивидуальное влияние FS и комбинированное влияние KCl и FS на отношение PI*

The addition of FS to KCl treated soil reduces the PI from the 14,7 to 11,2 % for FS content of 10 %, and furthermore, the addition of FS does not have any influence on PI of soil. The stabilized soil became low plastic with the addition of FS in KCl treated soil. Fig. 3, *b* shows a significant reduction in PI in case of KCl and FS added to soil as compared to the soil in which only FS was added. Presence of small amount of KCl increases the efficiency of FS approximately two times. In stabilized soil, FS acts as a diluent, and decreases LL. The presence of 1 % KCl in expansive soil increases the efficiency of FS significantly, which indicates the increase of diluent factor. Addition of coarser particles as additives decreases the thickness of diffused double layer and flocculation of clay particles and contributes to reduction of soil PI [27].

Effect on density and optimum moisture content

The effect of FS and KCl on soil dry density is presented in Fig. 4. The increase in maximum dry density is very nominal with the addition of KCl and FS. However, the increase in the density is comparatively more noteworthy in case of FS added soil due to the higher specific gravity of FS. Moreover, the FS particles are believed to form a dense cohesive matrix with the finer ones. The density increases due to change in soil gradation and a decrease in soil surface due to the addition of relatively coarser particle of FS. It decreases the micro-pores in expansive soil and decreases water holding capacity of expansive soil [1, 29]. Therefore, there is a reduction in OMC, and it can be observed in Fig. 5. The OMC of soil is reducing with the increase of KCl. It also decreases with the addition of FS content in KCl added to the soil. The reduction in the OMC is quite significant when FS is added to KCl treated soil. Fig. 5, *b* shows that the change in OMC of soil is insignificant in FS-treated soil. However, the OMC reduced significantly when the soil is treated with KCl and FS together.

The affinity of soil for water reduces with the addition of KCl, and the addition of FS further reduces the ability of expansive soil to absorb moisture from the surroundings. This reduces the moisture content in the soil admixture matrix and causes a significant increase in the density of soil. Earlier studies found that the chemical reduces the thickness of water around the soil particles, which also helps in higher concentration and better packing of grains, and hence OMC reduces and density increases with the addition of chemicals [13]. The reaction between anions of additives and cations of soil creates a condition in which the small soil particles group together to the bulky particle, and it finally increases the density of soil. The decrease in concentration of cations in expansive soil causes the reduction in affinity of soil particles to water [30].



a *b*

Fig. 4. *Variation in maximum dry density: a) with KCl and FS; b) distinct effect of FS and combine effect of KCl and FS on γ_d ratio*

Рис. 4. *Изменение максимальной сухой плотности: a) с KCl и FS; b) индивидуальное влияние FS и комбинированное влияние KCl и FS на соотношение γ_d*

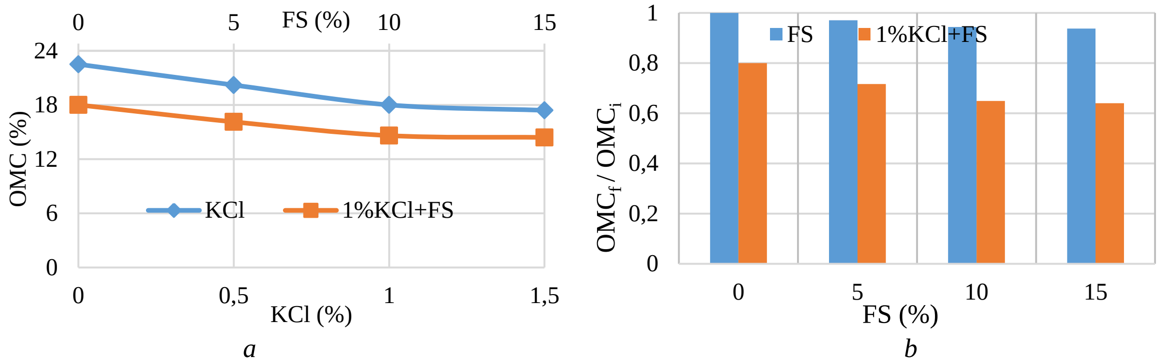


Fig. 5. Variation in optimum moisture content: a) with KCl and FS; b) distinct effect of FS and combine effect of KCl and FS on OMC ratio

Рис. 5. Изменение в оптимальном содержании влаги: a) с KCl и FS; b) индивидуальное влияние FS и комбинированное влияние KCl и FS на коэффициент OMC

Effect on soil strength

The effect of KCl and FS on the strength of expansive soil is shown in Fig. 6. The strength of soil increases with an increase in KCl and FS quantity. The strength increases by the 1,3 times of the unaltered soil for the KCl content of 1,5 %. The addition of FS increases the strength of untreated soil by 2,4 times when added at 5 % of the soil content and beyond. However, the strength of the soil increases by 3,5 times after addition of FS with KCl. The strength of soil increases due to reduction in the thickness of double layer of water around the soil particles [1, 14, 29]. It causes the increase in shearing resistance between soil particles [28–31].

The distinct effect of potassium chloride on the strength of expansive soil is relatively small as compared to FS. However, a small amount of potassium chloride influences the efficiency of FS significantly (Fig. 6, *b*). It may be attributed to the competency of KCl to decrease the double layer repulsive force significantly [28]. Strength enhancement can also be noted due to FS alone seizes after 10 % concentration, but the same continues rising with the increasing content of FS when used in combination with KCl. It indicates the significance of using two different natures of additives to the soil.

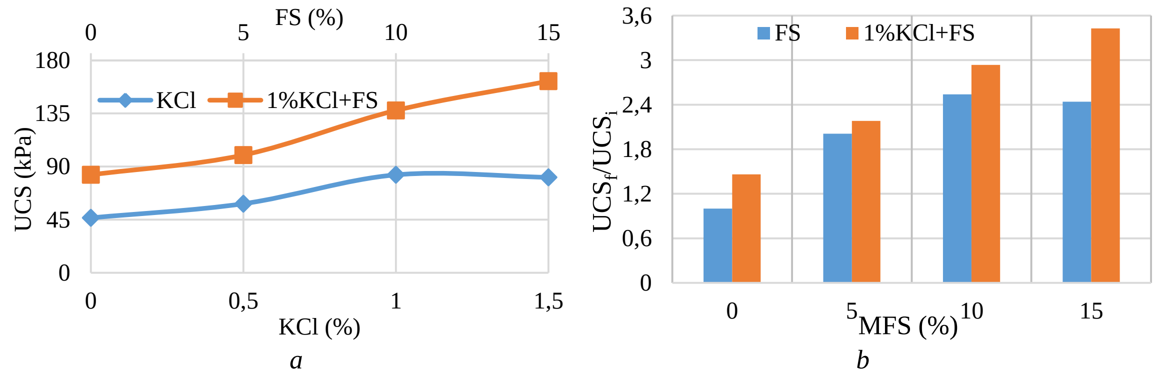


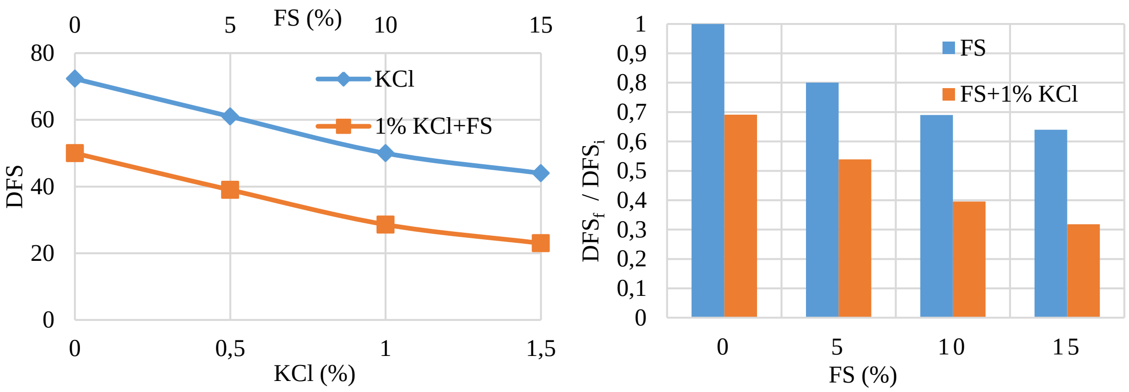
Fig. 6. Variation in unconfined compressive strength: a) with KCl and FS; b) distinct effect of FS and combine effect of KCl and FS on UCS ratio

Рис. 6. Изменение в неограниченной удельной работе разрыва: a) с KCl и FS; b) индивидуальное влияние FS и комбинированное влияние KCl и FS на коэффициент UCS

Effect on soil differential free swell

The effect of FS and KCl on differential free swell (DFS) is presented in Fig. 7. The differential free swell of plain soil lies close to 80 %, which shows that the soil belongs to the very high expansive group [32]. Fig. 7, *a* shows that the differential free swell reduces significantly with an increase in KCl and FS quantity. However, the rate of decrease in the DFS is nominally higher in KCl as in solution form it has a better reactivity with the mineral content in the soil. Fig. 7, *b* shows that the addition of 1 % KCl increased the efficiency of FS significantly. The formation of cementitious leads to decrease of soil swelling [33, 34].

The quantity of cementitious products increases with the increase of FS and KCl content. However, the rate of formation of the cementitious product reduces at higher contents of FS and KCl. Therefore, the differential free swell of the soil decreases with an increase in the amount of FS and KCl, but the rate of decrease in DFS reduces with an increasing amount of these additives. The DFS also decreases due to decrease in thickness of the diffused double layer of water due to the supply of cations by FS and KCl in the soil structure. It can be noted that the soil became low expansive after modification with KCl and FS as the DFS reduces to 50 % after treatment with KCl and further reduces to 25 % on the combined effect of both additives.



a *b*

Fig. 7. *Variation in differential free swell: a) with KCl and FS; b) distinct effect of FS and combine effect of KCl and FS on DFS ratio*

Рис. 7. *Различия в дифференциальной бесплатные отекать: а) с KCl и FS; б) индивидуальное влияние FS и комбинированное влияние KCl и FS на коэффициент DFS*

The addition of chemicals and FS causes cation exchange and flocculation of particles and consequently increases the strength of soil [1, 12–14]. The enhancement in strength of swelling soil might be observed due to reduction in plasticity of swelling soil (liquid limit and plasticity index). However, the overdose of chemicals and FS increases the cation concentration and reduces the efficiency of chemical and FS. It is also possible that the excess compound formation due to excessive addition of FS (content >10 %) would have caused the weakening of bonds between the soil particles and the formed cementitious compound as observed from the various previous studies [32, 34].

Predictive models

Nowadays, regression analysis is very popular in civil engineering to predict the influence of various parameters on soil properties. From the experimental study, it is observed that the liquid limit, plastic limit and compaction parameters are varying more or less linearly with change in FS content, while, plasticity index, unconfined compressive strength and free swelling are varying nonlinearly with the change in amount of FS. However, to accurately predict the variation in soil properties with addition of FS, the relationship between FS content and soil properties was assumed to be varying nonlinearly. The equation (1) was used to predict the modified soil properties due to FS addition. Though the equation (1) is nonlinear, it can be changed to linear equation by changing the form of equation (1) to equation (2).

$$\frac{\text{Index properties of treated soil}}{\text{Index properties of untreated soil}} = A_0 + A_1(FS) + A_2(FS)^2 + \ldots A_n(FS)^n; \quad (1)$$

$$\frac{\text{Index properties of treated soil}}{\text{Index properties of untreated soil}} = A_0 + A_1(FS_1) + A_2(FS_2) + \ldots A_n(FS_n). \quad (2)$$

Table 3 shows the predictive models, developed to predict various index properties of treated expansive soil with R^2. These models use the index properties in dimensionless forms as a ratio of initial value of index property for untreated soil (with a subscript 'i') to the final value of the same property after treatment (with a subscript 'f').

Table 3. *Predictive models to predict the Index properties of soil*

Таблица 3. *Прогностические модели для прогнозирования индекса свойств почвы*

Index properties Свойства	KCl (%)	Model/Модель	R^2
LL_f/LL_i	0	$1–0.275(FS)+0.0012(FS)^2$	0,999
	1	$0.91–0.0175(FS)+0.0004(FS)^2$	0,998
PL_f/PL_i	0	$1–0.0031(FS)$	0,985
	1	$0.98–0.0079(FS)$	0,951
PI_f/PI_i	0	$1–0.04(FS)–0.002(FS)^2$	0,997
	1	$0.75–0.034(FS)+0.001(FS)^2$	0,999
MDD_f/MDD_i	0	$1+0.013(FS)–0.003(FS)^2$	0,999
	1	$1.02+0.11(FS)–0.0001(FS)^2$	0,998
OMC_f/OMC_i	0	$1+0.25(FS)–0.01(FS)^2$	0,998
	1	$0.80–0.024(FS)^2+0.001(FS)$	0,991
UCS_f/UCS_i	0	$1–0.04(FS)–0.002(FS)^2$	0,999
	1	$1.43+0.16(FS)–0.001(FS)^2$	0,998
FSI_f/FSI_i	0	$1–0.1(FS)+0.005(FS)^2$	0,998
	1	$1.625–0.4(FS)–0.0012(FS)^2$	0,978

These models are developed using Microsoft excel. The coefficient of determination (R^2) was used as a criterion to define the best fit. The R^2 value close to 1 shows the good predictive capacity and 0 shows low predictive capacity. From Table 1, it can be observed that the R^2 value is ranging from 0,95 to 0,999, which shows good capacity of the developed model. However, a large number of tests are needed to be carried out in order to increase the reliability of the predictive model. The presented model may predict the variation in index properties for other expansive as well. However, there are chances that the accuracy might not be similar to the present case as the test are carried out on particular soil. This limitation can be omitted by carrying out the tests for other expansive soils with different plasticity.

Conclusions

The efficiency of FS increases with the presence of a small quantity of potassium chloride. The plasticity index, flow index, liquid limit and OMC of potassium chloride treated expansive soil reduces significantly with the addition of FS. The plasticity of soil is reduced from high to low due to the combined effect of potassium chloride and FS. Potassium chloride is found to be more efficient in improving the Atterberg limits and reducing the optimum moisture content of the soil, whereas the FS is more efficient in improving the density and unconfined compressive strength of soil. The addition of potassium chloride alone increases the strength of soil by nearly 30 % of the initial strength of the soil. The addition of FS with KCl treated soil results in increase in the strength to 300 % of untreated soil. The differential free swell of soil reduces to 50 and 25 % respectively for soils treated with FS alone and FS with KCl as compared to that of untreated soil. The efficiency of FS to modify the soil properties enhances with KCl addition to expansive soil. The significant improvement in soil behaviour supports the use of a small quantity of KCl with FS. Finally, based on experimental results, the predictive models are developed to determine the influence of FS on index properties of soil used in the present study.

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ВЛИЯНИЕ ХЛОРИДА КАЛИЯ НА ЭФФЕКТИВНОСТЬ МЕЛКОГО ШЛАКА, ИСПОЛЬЗУЕМОГО ДЛЯ ОБРАБОТКИ ДОРОЖНЫХ ПОЧВ

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Представлены результаты предварительного исследования, проведенного для определения влияния небольшого количества хлорида калия (KCl) на эффективность мелкого шлака, используемого для обработки обширных почв. Количество KCl варьировалось от 0,5 до 1,5 %, в то время как количество мелкого шлака варьировалось от 5 до 15 % от веса почвы. Установлено, что пластичность и дифференциальное свободное набухание почвы снижается при добавлении KCl, а также мелкого шлака. KCl более компетентен в снижении пластичности и набухания почвы по сравнению с мелким шлаком. Увеличение прочности и максимальной сухой плотности относительно велико в случае с мелким шлаком по сравнению с KCl, добавленным в почву. Эффективность мелкозернистого шлака для изменения свойств обширного грунта значительно возрастает в присутствии небольшого количества KCl. Прогнозные модели также разрабатываются, чтобы выяснить улучшенные свойства обширной почвы.

Ключевые слова:
Хлорид калия, мелкий шлак, экспансивная почва, индексные свойства, неограниченная прочность на сжатие.

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