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Assessment of swelling pressure of stabilized Bentonite

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Abstract. In this study, a comprehensive laboratory experimental programme was conducted on expansive soil with a high swelling potential to study the influence of different additive materials on swelling pressure and index properties. Lime, sand, multifilament fiber and fibrillated fiber were used for stabilization of expansive soil. Lime, sand and fibers were respectively added to the expansive soil at 0-7%, 0-80%, 0-0.5%. On each mixture that was prepared by the proportions mentioned above, Atterberg limits, compaction, and swelling pressure tests were conducted. From the result of these experiments, the swelling pressure-time relation could be replaced by a rectangular hyperbola established to facilitate the prediction of ultimate percent swelling with a few initial data points. The best type of additive and its optimum ratio for engineering purposes could be estimated rapidly by this approach.

Keywords: stabilization; expansive soil; swelling pressure; lime; sand; multifilament fiber; fibrillated fiber; rectangular hyperbola

1. Introduction

Since the ancient times, people constructed structures in or on soil even from soil as a construction material for their protection and accommodation. By using soil as a foundation or construction material, many problems have been appeared to be solved. One of the most common problems in these types of constructions is the volume change due to swelling or shrinkage of the clayey soils to make the loading of structures independent. These types of soils are named as swelling soils and when they are allowed to swell freely, large pressure namely swelling pressure appears and causes big damages on structures. For determining the amount of possible potential damage, the amount of swelling pressure must be determined. The amount of swelling pressure will help to predict the amount of possible swelling to prevent the large deformations in structures. Otherwise, it is impossible to have a safe construction site.

For this reason, several researchers have developed correlations to predict swelling pressure and the relation of swelling pressure and dry density, initial moisture content and Atterberg limits (Holtz and Gibbs 1956, Peck *et al*. 1974, Ranganatham and Satyanarayana 1969, Komarnik and David 1969, Vijayvergiya and Ghazzaly 1973, Erzin and Erol 2004, Sridharan and Gurtug 2004, İkizler *et al*. 2010, Türköz and Tosun 2011, Singhal *et al*. 2011, Çimen *et al*. 2012, Vanapalli and Lu 2012, Alonso *et al*. 2013, Zumrawi 2013, İkizler *et al*. 2014, Adem 2015, Han and Vanapalli 2015). Such correlations provided quick estimates of swelling pressures. Also serves as a cross check on field/laboratory tests were conducted on limited number of soils (Rao *et al*. 2006). In many papers, researchers attempted to correlate the engineering properties of the natural soil but very less information about the swelling potential of the treated soil is in the literature. For this reason, in this paper, an attempt has been done to predict the swelling potential of the treated soils with different additives.

It is well known that swelling soils are common engineering problems throughout the world and the controlling of the unwanted behavior of these types of soils are necessary. In this regard many stabilization techniques or replacing the soil with another one have been used to resolve these kinds of soil problems. From the past up to now, stabilization techniques are used with different kinds of additives and become more favorable since they are more economical than replacing the soil with another one.

In the world, type of additives such as lime (Al-Rawas *et al*. 2005, Rushad *et al*. 2011, Al-Mukhtar *et al*. 2010, Çalık and Şadoğlu 2014, Ciancio *et al*. 2014) cement (Al-Rawas *et al*. 2005, Turkoz and Vural 2013, Al Zubaidi 2013, Mahamedi and Khemissa 2015), fly ash (Rushad *et al*. 2011, Rao and Subbarao 2012, Bose 2012, Nalbantoglu 2014, Mir 2015), and sand (Sridharan and Gurtug 2004, Hudyma and Avar 2006, Rao *et al*. 2006, Mishra *et al*. 2008, Ikizler *et al*. 2009, Vanapalli *et al*. 2012, Louafi and Bahar 2012, Rusbintardjo *et al*. 2015) are used for this purpose. Also in the recent years, the additives to increase the bearing capacity of concrete like polypropylene fibers were used for the stabilization of soils in the past studies (Punthutaecha *et al*. 2006). In previous studies, additives mentioned above were used either one by one or a few of them together, and their effects on stabilization were investigated. However, there is no study that uses all of these additives in the same soil and reveals their relative superiorities. In this study, in order to investigate the

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Table 1 Physical properties of the Bentonite from laboratory testing

Grain density (kN/m^3)	22.69
Liquid Limit (%)	642
Plastic Limit (%)	71
Plasticity Index (%)	571
Optimum water content (%)	45,45
Maximum dry density (kN/m^3)	11.8
USCS classification	CH

Table 2 Results of chemical analysis of Bentonite

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O
61.28	17.79	3.01	4.54	2.70	2.10	1.24

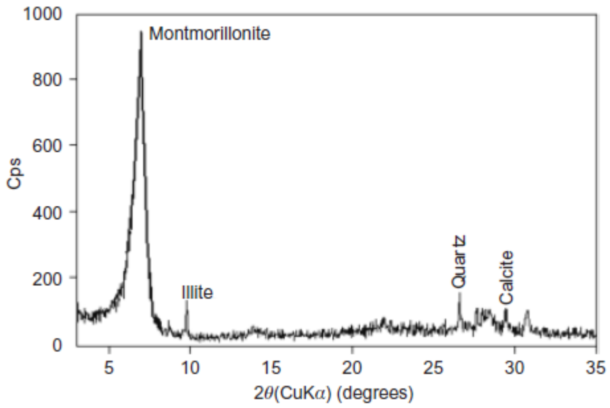

Fig. 1 X-ray diffraction plots of the Bentonite used in this study

effectiveness of different additives on swelling behaviour, Atterberg limits, standart proctor and swelling pressure tests were carried out on an expansive soil specimen having high swelling capacity. Subsequently, 1, 2, 3, 5 and 7% (by weight) lime, 20, 40, 60 and 80% (by weight) sand, 0.2, 0.3, 0.4 and 0.5% (by weight) multifilament and fibrillated fiber additives were added to expansive soil and test results were compared. At second stage of the study, final swelling pressures of the specimen were tried to be estimated by using rectangular hyperbola. Owing to this verification, time/swelling pressure versus time relation could be drawn with first few readings of the time consuming swelling pressure test, and final swelling pressure value could be estimated with great accuracy. The best additive type and optimum ratio for engineering purposes can be determined with this method quickly. Instead of long experimental studies, like highway studies in which many locations should be tested, it is possible to calculate swelling pressure of the soil in a short time by using this methodology.

2. Materials

2.1 Bentonite

Bentonite (B) which had a high swelling potential was used for this study. It was obtained from Karakaya Bentonite Company, Turkey. The physical properties of the

Table 3 Results of chemical analysis of fime

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	Loss on Ignition (%)
2.06	0.54	1.43	69.85	0.76	0.83	0.08	24.45

Table 4 Properties of polypropylene fibers used (as supplied by the manufacturer)

Type and Composition	Polypropylene Fiber	
Fiber Type	Multifilament (M)	Fibrile (F)
Standard	ASTM C-1116-1997	ASTM C-1116-1997
Length	Type III	Type III
Tenacity	12 mm	19 mm
Tensile Strength	7,0 grams/denier	6,0 grams/denier
Young's (Elasticity)	700 N/mm^2	400 N/mm^2
Modulus	3.500 N/mm^2	2.600 N/mm^2
Breaking elongation	% 20	% 15
Density	0,91 $grams/cm^3$	0,91 $grams/cm^3$
Color	Transparent	Transparent
Softening Point	150 Celcius	150 Celcius
Melting Point	160 Celcius	160 Celcius
Acid Resistance	Stable	Stable
Alkali Resistant	Stable	Stable
Ultraviolet Resistance	Optional	Optional

bentonite used in this investigation are summarized in Table 1. Results of chemical analysis of Bentonite are presented in Table 2. The X-ray diffraction plot of the bentonite shown in Fig. 1 indicates that the bentonite was predominantly sodium montmorillonite with some illite, calcite and quartz.

2.2 Lime

In order to improve the swelling properties of the bentonite, lime (L) was used with 1, 2, 3, 5 and 7% by dry weight. The chemical analyses of the lime was supplied by Barkisan Lime Company in Trabzon is given in Table 3.

2.3 Sand

Sand was supplied by Set Cement Company was added to the bentonite at 20, 40, 60 and 80% (by weight). Specific gravity of sand used in the experiments was sieved on sieve No. 40 is 2.66.

2.4 Polypropylene fiber

Polyfiber that made of polypropylene fiber is an engineering product. It is a production for structural materials that were explored by the test results of engineering researches in the USA in 1960s. Polypropylene fiber is the most common synthetic material used to reinforce concrete and soil. The primary attraction is that of low cost (Miller and Rifai 2004). In this study, two types of fibers including fibrillated fiber (F) and multifilament fiber (M) were used for evaluating as potential stabilizers in enhancing swelling characteristics of expansive soil. The fibers were supplied by Polypropylene Fiber Industry in Istanbul, Northwest Turkey. Properties of the selected

(M)

(F)

Fig. 2 Multifilament fiber (M) and fibrillated fiber (F) used in this study (as supplied by the manufacturer)

polypropylene fibers are presented in Table 4. The fiber content used in this study was varied as 0.2 %, 0.3, 0.4, and 0.5 by dry weight of expansive soil. Fig. 2 shows photographs of fibrillated fiber (F) and multifilament fiber (M).

2.2 Test procedure

The purpose of the experimental work is to investigate the effect of adding lime, sand, multifilament fiber (M) and fibrillated fiber (F) on the swelling pressure of a potentially expansive soil estimate the swelling pressures for all doses by making only few of these tests.

Laboratory experimental program was used expansive soil with a high swelling potential as expansive soil. 18 samples were prepared by adding lime, sand, multifilament fiber (M) and fibrillated fiber (F), by dry weight of the soil to expansive soil with predetermined percentage of stabilizer (Table 5). All of the materials were oven dried for 24 h at 50℃. Mixtures were prepared by hands until reaching a uniform mixture. Atterberg and standard proctor compaction tests of samples were conducted to measure both plasticity and compaction characteristics. The liquid limit and plastic limit values of the samples were determined according to the procedure outlined in British Standard (BS) 1377 (BS 1990) and summarized in Table 5. The liquid limit values of the expansive soil decreased with an increasing amount of stabilizer. It may be seen that the liquid limit varied from 316% to 642% (2-folds) at the addition of lime, varied from 91% to 642% (7.1-folds) at the addition of sand, varied from 464% to 642% (1.4-folds) at the addition of fibrillated fiber and varied from 461% to 642% (1.4 -folds) at the addition of multifilament fiber. The plasticity index varied from 225% to 571% (2.5-folds) at the addition of lime, varied from 67% to 571% (8-folds) at the addition of sand, varied from 420% to 571% (1.36-folds) at the addition of fibrillated fiber and varied from 413% to 571% (1.38 -folds) at the addition of multifilament fiber. Standard proctor tests (BS 1377 1990) were conducted on lime, sand and polypropylene fiber blended expansive soil (Table 5). The standard proctor test consists of a mould of volume 944 cm^3 (1/30 ft^3), internal diameter of 10 cm (4 in.), and a height of 11.68 cm (4.6 in.) in which the soil is compacted in three layers, giving each layer 25 blows by a metal hammer weighing 2.5 kg (5.5 lbs) falling through 30.5 cm (12 in.). The compaction energy works out to be 593.7 kJ/m^3. A summary of the optimum moisture content and maximum dry density results is given in Table 5. Table 5 shows that optimum moisture content value of expansive soil decreased with an increasing amount of lime. On the contrary, a clear difference isn't observed maximum dry density values. Optimum moisture content values were observed to decrease as the maximum dry density values were increased with an increasing amount of sand. The optimum moisture content was reduced with the addition of polipropilen fiber. On the contrary, a clear difference isn't observed maximum dry density values. The optimum moisture content was reduced with the addition of fibrillated fiber and multifilament fiber. On the contrary, a clear difference isn't observed maximum dry density values.

Table 5 Atterberg limits and compaction properties of soils studied

Samples	% Additive	*LL* (%)	*PL* (%)	I_p (%)	Optimum Moisture Content (%)	Maksimum Dry Density (kN/m^3)
Untreated Soil	Bentonite	642	71	571	43,49	11,1
Lime (L)	1%L	482	74	408	42	11,5
	2%L	517	52	465	40	11,6
	3%L	565	61	504	37	11,7
	5%L	492	98	394	32	11,9
	7%L	316	91	225	29,8	12
Sand (S)	20% S	471	46	425	37,2	13,1
	40% S	343	43	300	19,25	14,2
	60% S	210	27	183	17,52	15,5
	80% S	91	24	67	15,62	16,7
Fibrillated Fiber (F)	0.2% F	489	53	436	37,45	11,9
	0.3% F	478	49	429	34,06	12,4
	0.4% F	464	44	420	33,89	12,8
	0.5% F	467	47	420	29,34	13,5
Multifilament Fiber (M)	0.2% M	461	47	414	38,56	11,3
	0.3% M	464	51	413	36,37	11,4
	0.4% M	501	53	448	36,00	11,7
	0.5% M	534	57	477	35,70	12

2.3 Swelling pressure test

Standard Proctor test result was also used to compact and prepare soil specimens for swelling pressure tests. The swelling pressure tests were performed according to ASTM D4546 (2003) for measuring the maximum swelling pressures. The swelling tests were carried out in the conventional oedometer apparatus. The specimens were compacted at their optimum water content and maximum dry density in the consolidation ring of mm. 50.8 mm. in diameter and 20 mm. in thickness (1.99 in. diameter and 0.79 in. thickness). For the porous stone placements and to take care of swelling, the samples were trimmed to 14.88 mm height. The inside of the rings was lubricated with silicone grease to minimise side friction between the ring and the soil specimen. Filter papers were placed on top and bottom of the soil specimen to prevent finer particles from being forced into the pores of the porous stones placed on

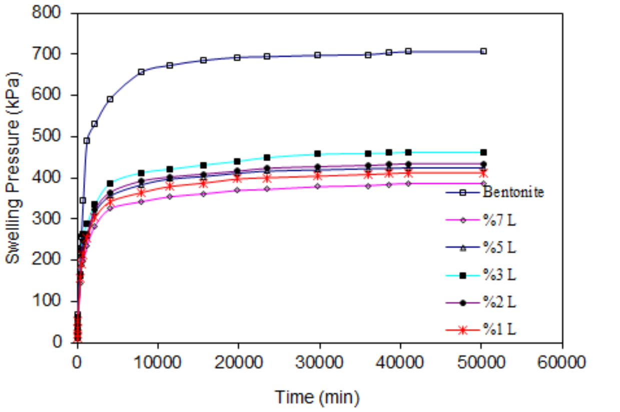

Fig. 3 Swelling pressure versus time for bentonite-lime mixture

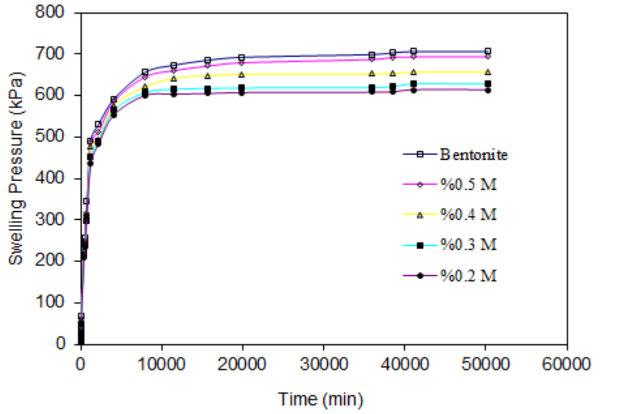

Fig. 5 Swelling pressure versus time for bentonite-multifilament fiber mixture

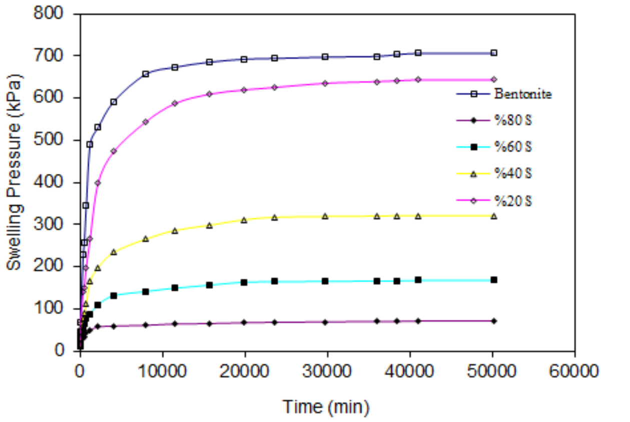

Fig. 4 Swelling pressure versus time for bentonite-sand mixture

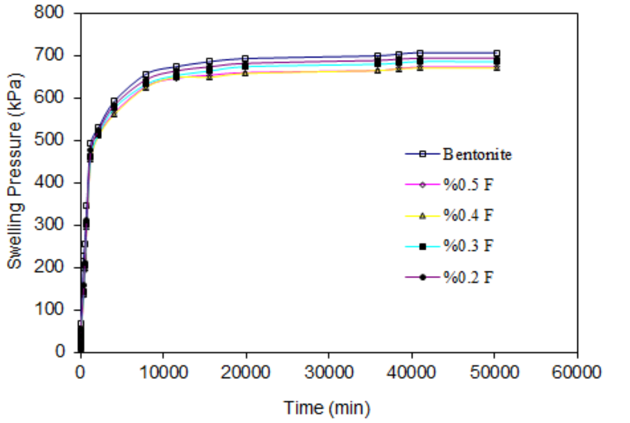

Fig. 6 Swelling pressure versus time for bentonite-fibrillated fiber mixture

both sides of the specimen. The swelling tests were conducted in a temperature-controlled room maintained at 25±1℃. After specimens were placed in to consolidometer, they were maintained at constant volume by adjustments in vertical pressure after the specimens were inundated in free water to subject swelling pressure. Experiment was stopped when the dial gauge no longer indicated any swell movements for more than 3 days.

2.3.1 Swelling pressure test results

The swelling pressure test results of bentonite stabilized with lime, sand and multifilament fiber and fibrillated fiber are presented in Figs. 3-6 as the swell pressure versus time. It can be seen that the increase in swelling pressure is quite rapid at the initial stages, and it gradually reaches the asymptotic level. Even after a lapse of 14-28 days (20.000-40.000 min), there is a gradual and slow increase in swelling pressure. Maximum swelling pressures of bentonite stabilized with 0, 1, 2, 3, 5, and 7% of lime were 706, 412, 434, 462, 424, and 386 kPa (Fig. 3), and with 0, 20, 40, 60 and 80% of sand were 706, 643, 321, 167 and 71 kPa (Fig. 4), and with 0, 0.2, 0.3, 0.4 and 0.5% of multifilament fiber were 706, 614, 628, 656, and 693 kPa (Fig. 5), and with 0, 0.2, 0.3, 0.4 and 0.5% of fibrillated fiber were 706, 693, 685, 670, and 672 kPa (Fig. 6), respectively. Soil specimens with no stabilizers exhibited large swell pressures, while stabilized specimens yielded low swell pressures. The amount of reduction in swelling pressure magnitudes with fiber reinforcement was small when compared to lime and sand stabilized soils. In summary, lime and sand improvement resulted in moderate to high reductions of swelling pressures, and fibers resulted in low reductions. The low reductions in swelling pressures due to fiber treatment can be attributed to the presence of fibers, which create drainage paths for the dissipation of pore pressures in a loaded soil specimen. Another reason could be that the fibers, being tensile elements, restrain the swell pressures generated during soaking. Fiber reinforcement effects on swell pressures are a positive contribution, though the contributions can be small to moderate in magnitude.

Investigation of Figs. 3-6 shows that the shape of time vs. swelling pressure is similar to that of a rectangular hyperbola. Figs. 7-10 show the time-swelling pressure data plotted (time/swelling pressure) vs. time. An almost perfect linear relationship is obtained for all the cases, justifying that the shape of the time-swelling pressure curve can be treated as a rectangular hyperbola. Thus, one can write

$$\frac{t}{SP} = a + bt \tag{1}$$

Table 6 Actual swelling pressure and predicted swelling pressure of soils studied

Samples	% Additive	Actual Swelling Pressure (kPa)	Predicted Swelling Pressure (kPa)
Untreated Soil	Bentonite	706	714.29
Lime	1%L	412	416.67
	2%L	434	434.78
	3%L	462	476.19
	5%L	424	434.78
	7%L	386	384.62
Sand	20% S	643	666.67
	40% S	321	333.33
	60% S	167	169.49
	80% S	71	70.92
Fibrillated Fiber (F)	0.2% F	693	714.29
	0.3% F	685	714.29
	0.4% F	670	666.67
	0.5% F	672	666.67
Multifilament Fiber (M)	0.2% M	614	625
	0.3% M	628	625
	0.4% M	656	666.67
	0.5% M	693	714.29

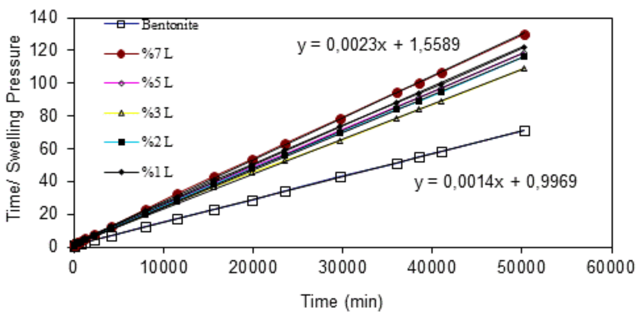

Fig. 7 Time/swelling pressure versus time for Bentonite-lime mixture

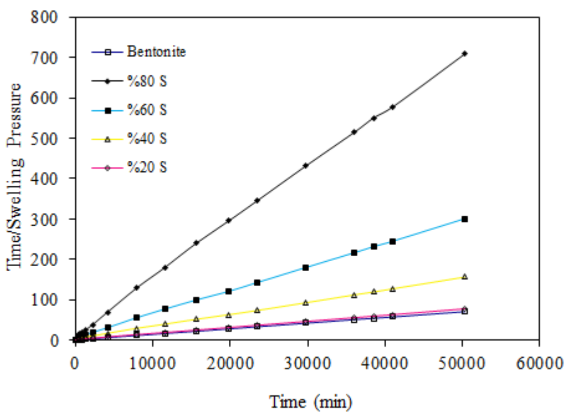

Fig. 8 Time/swelling pressure versus time for Bentonite-sand mixture

where t is the time, SP is swelling pressure. a and b are the intercept and the slope of the straight line, respectively. $1/b$ gives the ultimate swelling pressure. Earlier, attempts have been made to predict swelling pressure magnitude using

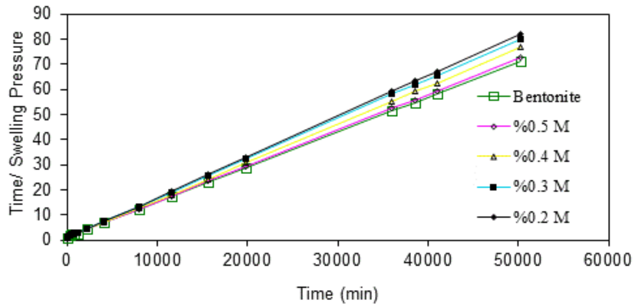

Fig. 9 Time/swelling pressure versus time for Bentonite-multifilament fiber mixture

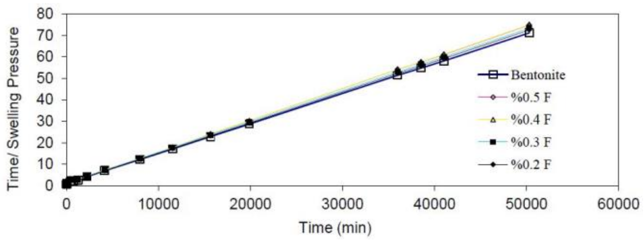

Fig. 10 Time/swelling pressure versus time for Bentonite-fibrillated fiber mixture

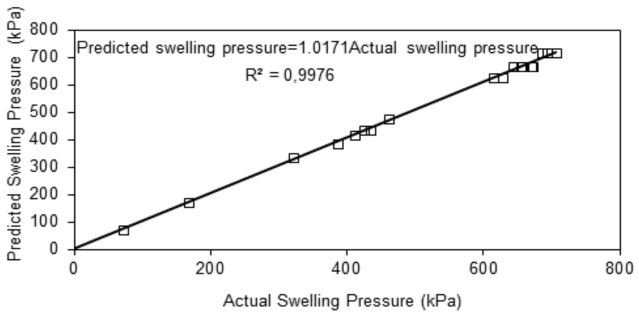

Fig. 11 Actual swelling pressure vs. predicted swelling pressure for all the test results

rectangular hyperbola (Dakshinamurthy 1978, Rao and Kodandaramaswamy 1981, Sridharan *et al*. 1986, Sridharan and Gurtug 2004).

Fig. 11 shows the experimentally obtained ultimate swelling pressure vs. the predicted value, i.e., $1/b$. The predicted swelling pressure is 1.0171 times of the actual swelling pressure with a correlation coefficient of R^2= 0.9976 which means approximately R^2=1 and proves that correlation is extremely well (Table 6). It ought to be more because the predicted swelling pressure is the asymptotic value of the time vs. swelling pressure plot. The asymptotic value obtained is more than the value obtained from the experimental results taken up to a finite time. Theoretically, it takes infinite time to attain the asymptotic value.

3. Conclusions

A significant number of researches have been conducted to develop several treatment methods to stabilize expansive soils and to reduce the damaging effects of expansive soils. In recent years, the most commonly used method is addition of stabilizing materials, such as lime, cement, sand or polypropylene fiber to the expansive soil. In this study, lime, sand, multifilament and fibrillated fiber were selected and used to investigate their potential for reducing swelling pressures. Expansive soil-lime, expansive soil-sand, expansive soil- multifilament fiber and expansive soil-fibrillated fiber mixtures are evaluated. Laboratory experimental program was conducted on bentonite with a high swelling potential for studying the influence of additive materials on swelling pressures and index properties. The major conclusions obtained from the laboratory tests, and analyses of test results can be drawn as follows.

1. All four stabilizers, lime, sand and multifilament fiber and fibrillated fiber improved soil properties including liquid limit, plastic limit, and optimum moisture content and maximum dry density of bentonite.
2. 25-51% decrease in liquid limit value and 29-61% decrease in plasticity index value occurred with lime addition. A decrease was observed in optimum water content of the bentonite with increasing amount of lime ratio. On the other hand, any significant variation didn't occurred in maximum dry density value of the bentonite. In case of lime use as additive, 42-45% decrease occured in swelling pressure values. This decrease in swelling pressure increases up to 3% additive ratio and decreases after 3%. This indicates that the optimum lime ratio for application may be 1%.
3. 26-86% decrease in liquid limit value and 27-86% decrease in plasticity index value occurred with sand addition. A decrease was observed in optimum water content of the bentonite with increasing amount of sand ratio. It is observed that maximum dry density of the bentonite increases with increasing amount of sand ratio. In case of sand use as additive material, 9-90% decrease occured in swelling pressure values. It is observed that addition of 20% sand is not effective in reducing swelling pressure value of the bentonite. When a 55% reduction in swelling pressure for the addion of 40% sand was compared for addition of 60% and 80% sand it was obvious that due to the difficulty of application, addition of 20% sand can be recommended as a more effective stabilization material.
4. 17-28% decrease in liquid limit value and 16-28% decrease in plasticity index value occurred with multifilament fiber addition. A decrease was observed in optimum water content of the bentonite with increasing amount of multifilament fiber ratio. It is observed that maximum dry density of the bentonite increases with increasing amount of multifilament fiber ratio. On the other hand, any significant variation didn't occurred in maximum dry density value of the bentonite. In case of multifilament fiber use as additive, 2-13% decrease occured in swelling pressure values. Swelling pressures are increased when higher dosages of multifilament fiber are used. In fact, swelling pressure may be higher then that of bentonite with no additives beyond the dosage level of 0.5%. Thus, dosage level between 0.2% and 0.3% would be best for the treatment of bentonite on the reduction of swelling pressure.
5. 24-27% decrease in liquid limit value and 24-26% decrease in plasticity index value occurred with fibrillated fiber addition. A decrease was observed in optimum water content of the bentonite with increasing amount of fibrillated fiber ratio. On the other hand, any significant variation didn't occurred in maximum dry density value of the bentonite. 3-5% decrease occured in swelling pressure values with an increasing amount of fibrillated fiber ratio. From these results, it is seen that fibriilated fiber addition is not very effective in reducing swelling pressure. This phenomenon can be explained fibrillated fibers (F) at higher dosage are difficult to mixed with bentonite because of texture of fibrillated fiber.
6. All of the additives investigated in this study give positive results on decreasing swelling pressures. However, each of the additives and their ratio has different effects on swelling pressure decrease. Bentonite exhibited large swelling pressures, while stabilized specimens yielded low swelling pressures. The amount of reduction in swelling pressure magnitudes with fiber reinforcement was small when compared to lime and sand stabilized soils. The swelling pressure test results of bentonite stabilized with lime, sand and multifilament fiber and fibrillated fiber show that the increase in swelling pressure is quite rapid at the initial stages, and it gradually reaches the asymptotic level. Even after a lapse of 14-28 days (20.000-40.000 min), there is a gradual and slow increase in swelling pressure.
7. The swelling pressure-time relationship of bentonite stabilized with lime, sand and multifilament fiber and fibrillated fiber has the shape of a rectangular hyperbola and hence, the time over swelling pressure vs. time bears a good linear relationship. The ultimate swelling pressure could be obtained from the initial readings. The predicted swelling pressure is 1.0171 times of the actual swelling pressure with a correlation coefficient of R^2= 0.9976 which means approximately R^2=1 and proves that correlation is extremely well. From this verification results, it is seen that lime and sand addition give successive results. In the verifications made for multifilament fiber and fibrillated fiber, swelling pressure values for 0.2% and 0.3% additive ratios are equal. Situation is same for the 0.4 and 0.5%. Ratios being very close and additives being ineffective are thought as the reason for this situation.
8. Thanks to these estimations, the best additive type and optimum ratio for engineering purposes can be determined with this method quickly. Instead of long experimental studies, like highway studies in which many points should be tested, it is possible to calculate swelling pressure of the soil in a short time by using this methodology.

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