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An Experimental Study on Stabilization/Modification of Locally Available Expansive Soil using Industrial Wastes

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ABSTRACT

Expansive soils are produced from the break-down of basic igneous rocks where seasonal variation of weather is extreme. In India, these soils are normally derived from the weathering of basalt rocks. Also, these soil deposits are derived from various other types of rocks including very old sedimentary depositsin the present research, an attempt has been made to study the stabilization of the local soils (high and low expansive) having low bearing strength from two different parts of Bhopal by mixing independently with dolochar and fly ash (plentily available in Bhopal) in the proportions from 5% up to 30% by dry weight of the mixture with increment of 5% with and without lime The experimental programme conducted in this study is comprised of index tests, compaction tests, shear tests, unconfined compressive strength tests, CBR tests and consolidation tests in conformity with approved standards on soil alone and also on stabilised soils to evaluate their individual swelling, compaction, strength, compressibility and drainage characteristics. With addition of fly ash or dolochar, the L.L. and P.I. of soils gradually decreases with the increase of fly ash or dolochar contents. Maximum decrease is observed at 30% fly ash or 30% dolochar content Addition of fly ash or dolochar decreases the free swell index (FSI) of soil, maximum decrease being observed at fly ash or dolochar content of 30%. Addition of lime to the above mixtures, reduces FSI further. The FSI of soil-1 with 30% fly ash or dolochar content is reduced by 100% and 85% for soil-fly ash and soil-dolochar mixture respectively at 4% lime content. CBR of soil-fly ash or soil-dolochar increases with the increase of fly ash or dolochar content. The maximum increase being observed at 30% fly ash or dolochar content. At 30% fly ash content, the 4 days soaked CBR of soil-1 and soil-2 increase by 126% and 117% respectively, whereas, the 4 days soaked CBR of soil-1 and soil-2 at 30% dolochar content increase by 154% and 163% respectively.

KEYWORDS: *Dolochar, Fly Ash, Soil Stabilization, Expansive Soil, CBR. Compressive Strength*

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ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
ASTM	American society for testing and materials
BC	Black cotton
CAH	Calcium aluminate hydrate
CASH	Calcium aluminate silicate hydrate.
CBR	California bearing ratio
CFA	Coal fly ash
CFA	Class-C fly ash

CH	High plasticity/compressible
CKD	Cement kiln dust
CLT	Column leach tests
CSH	Calcium silicate hydrate
CU	Consolidated undrained triaxial compression test
DDL	Diffuse double layer
EDS	Energy dispersive X-ray spectrometry
FA	Fly ash
FSI	Free swell index
GGBS	Ground granulated blast-furnace slag (GGBS)
GI	Group index
HCFA	High carbon fly ashes
IOT	Iron ore tailings
IRC	Indian road congress
IS	Indian standard
L	Lime
LKD	Lime kiln dust
LL	Liquid limit
OI	Loss on ignition
LSD	Limestone dust
LVDT	Linear variable differential transformer
MAPRT	Medium scale accelerated pavement rut tester
MDD	Maximum dry density
MORT&H	Ministry of Road Transport and highways
Mw	Mega Watt
NFA	Neyveli fly ash
NP	Non-Plastic
OMC	Optimum moisture content
OWSA	Optimum wood ash-soil admixture
PI	Plasticity index
PL	Plastic limit
RBI	Road building international
RHA	Rice-husk ash
SEM	Scanning electron microscope
UCS	Unconfined compressive strength
USCS	Unified Soil Classification System
UU	Unconsolidated undrained
VFA	Vijayawada fly ash
WA	Wood Ash
WBM	Water bound macadam
WLT	Water leach tests
XRD	X-ray diffraction

INTRODUCTION

Rapid urbanization coupled with large scale industrialization of the current era has created an unprecedented swell in the demand of infrastructure development in the country. This has practically left the construction sector with no choice but to undertake construction activities on whatever land is available irrespective of suitability etc. Thus the situation has warranted development of land, if found unsuitable, by use of sound and cost effective engineering techniques. In the process hither to unsuitable land (characterized by soft compressive clay, expansive clay, deformable sub-soil etc.) detrimental to typical foundation, could be utilized for construction purposes after appropriate modification of its engineering properties.

Also, these soil deposits are derived from various other types of rocks including very old sedimentary deposits.

Expansive soils are problematic for conventional foundation in the construction of highways, embankment, backfill of retaining walls, etc. These soils are usually found in tropical and temperate zones coupled with low rainfall and poor drainage features.

METHODOLOGY

Introduction

The aim of this study is to look at the effects of industrial wastes like fly ash and dolochar on the stabilisation and alteration of locally usable expansive soil with and without lime. Index tests, compaction tests, shear tests, unconfined compressive strength tests, CBR tests, and consolidation tests were performed in accordance with accepted standards on soil alone and on stabilized soils to determine their individual swelling, compaction, strength, compressibility, and drainage characteristics. The material properties, instrumentation, testing methods, and design of the experimental programme are all covered in the subsequent sections.

Materials used

As parent material, two separate local soils are used, one of which is high expansive (designated as soil-1) and the other is low expansive (designated as soil-2) (designated as soil-2). For the aforementioned study, two industrial wastes, fly ash and dolochar, were obtained from local factories, and lime was purchased from the local market.

Soil – 1

The high expansive soil (Fig.3.1) is collected from Bhopal. The soil-1 is classified as highly compressible clay (CH) as per IS: 1498 – 1970. The soil's mean grain size (D50) is found to be 0.0055 mm. Table 4.1 summarises the geotechnical characteristics of soil-1. The soil- 1 is highly plastic as well as highly swelling, as shown in Table 4.1.

Table 4.1: Geotechnical properties of highly expansive soil, low expansive soil, fly ash anddolochar

Properties	Soil-1	Soil-2	Fly ash	Dolochar
Sieve Analysis				
Gravel (20 mm to 4.75 mm) (%)	0	0	0	0
Sand (4.75 mm to 75 µ) (%)	0.47	35.17	15.5	92.3
Silt (75 µ to 2 µ) (%)	59.53	39.83	77	7.7
Clay (< 2 µ) (%)	40	25	7.5	0
D50 in mm	0.0055	0.04	0.018	1.2
Consistency limit				
Liquid limit (%)	56	33	43	18
Plastic limit (%)	28	18	---	---
Plasticity index (%)	28	15	Non plastic	Non plastic
Shrinkage limit (%)	16.81	11	---	---
Specific gravity	2.69	2.70	2.47	3.21
Free swelling index (%)	60	20	0	0
Compaction OMC (%)	16.1	11.5	35.0	6.7
MDD (kN/m^3)	17.80	18.80	12.20	26.34
CBR				
Un-soaked (%)	16.99	8.22	35.70	40.08
Soaked (%)	3.61	5.25	13.89	38.40
UCS (kPa)	149	110	---	---
Shear strength (UU)	56	44	7	1
c (kPa) (degree)	6	10	44	42
Consolidation C_c	0.298	0.198	---	---
m_v (m^2/kN)	0.39 x 10^{-3}	0.35 x 10^{-3}	---	---
a_v (m^2/kN)	2.43 x 10^{-3}	1.61 x 10^{-3}	---	---
c_v (m^2/min.)	1.31 x 10^{-6}	2.06 x 10^{-6}	---	---
Drainage k (m/min.)	0.51 x 10^{-8}	0.73 x 10^{-8}	---	---

* Soil – 1: High Expansive Soil, Soil – 2: Low Expansive Soil

Fig.4.1 Soil – 1 (Highly expansive soil)

Table 4.2: Elemental composition of soil – 1

Element	% by weight
C as $CaCO_3$	45.68
O as SiO_2	39.54
Na	0.22
Mg as MgO	0.38
Al as Al_2O_3	2.81
Si as SiO_2	7.60
Cl as KCl	0.09
K as Feldspar	0.69
Ca as Wollastonite	0.08
Ti	0.15
Fe	2.55
Cu	0.21

Soil – 2

The soil-2 (Fig.4.2) is collected from Bhopal. As per IS: 1498 – 1970, the collected soil- 2 is classified as low compressible clay (CL). The mean grain size (D50) of the soil is found to be 0.04 mm. The geotechnical characteristics of soil-2 are presented in Table 4.3.

Fig.4.2 Soil – 2 (Low expansive soil)

Table 4.3: Elemental composition of soil – 2

Element	% by weight
O as SiO_2	48.30
Na	0.15
Mg as MgO	0.40
Al as Al_2O_3	8.92
Si as SiO_2	26.55
K as Feldspar	1.58
Ca as Wollastonite	0.50
Ti	1.10
Fe	12.50

Fly ash

The fly ash (Fig.4.3) is collected from the BIRLA Tyres Ltd., India. From Table 4.4, it is open that the fly ash used for the study is found to be non-plastic and non-swelling. The chemical properties of the fly ash are presented in Table 4.4, from which it is classified as Class F fly ash as per ASTM C 618-94a.

Table 4.4: The Chemical characteristics of fly ash

Characteristics	Percent by mass
SiO_2	50.62
Al_2O_3	25.15
Fe_2O_3	3.62
$SiO_2 + Al_2O_3 + Fe_2O_3$	79.39
Total Ca as CaO	0.062
MgO	0.209
Sulphur as SO_3	0.016
Loss of Ignition	3.81
Moisture content	2.04

Fig.4.3 Fly ash

Table 4.5: Elemental composition of fly ash

Element	% by weight
C as $CaCO_3$	56.06
O as SiO_2	35.10
Mg as MgO	0.09
Al as Al_2O_3	2.60
Si as SiO_2	4.55
K as Feldspar	0.21
Ca as Wollastonite	0.16
Ti	0.26
Fe	0.70
Cu	0.27

Dolochar

Dolochar is a by-product of sponge iron plants obtained from the Mandideep Industrial Estate in Bhopal, Madhya Pradesh (Fig.4.4). The collected dolochar is crushed into tiny particles, which are then sieved through a 4.75 mm IS sieve to make the particle size equal to or less than sand size. The material that passes through the 4.75 mm IS sieve is used as a soil stabiliser. The geotechnical properties of dolochar are summarised in Table 4.6, showing that it is non-plastic and non-expansive in nature.

Fig.4.4 Dolochar

Table 4.6: Elemental composition of dolochar

Element	% by weight
C as CaCO3	8.20
O as SiO2	34.88
Mg as MgO	12.83
Al as Al2O3	6.89
Si as SiO2	10.61
Ca as Wollastonite	4.62
Cr	13.35
Fe	7.68
Mo	0.94

Lime

Lime (Quick lime) is collected from the local market (Fig.4.5). The chemical composition of the lime is presented in Table 4.7.

Table 4.7: Chemical characteristics of lime

Characteristics	Percent by mass
Total Ca as CaO	61.38
MgO	0.134
Fe2O3	0.50
Sulphur as SO3	0.24
Carbonate as CaCO3	36.78
Available lime as CaO	34.44
Moisture content	0.46
Volatile matter	13.88
Loss of Ignition	23.19

Fig.4.5 Lime

Table 4.8: Elemental composition of lime

Element	% by weight
C as CaCO3	5.96
O as SiO2	37.12
Mg as MgO	1.28
Al as Al2O3	2.42
Si as SiO2	1.21
K	0.12
Ca as Wollastonite	47.23
Fe	0.32
Yb	4.34

Experimental Programme

The behaviour of soils stabilised with fly ash and dolochar, both with and without lime, has been deliberate using an experimental programme. The physical and chemical properties of soil and additives are determined in the laboratory. The geotechnical characteristics of stabilised samples (soil-fly ash, soil-dolochar, soil-fly ash-lime, and soil-dolochar-lime) are also determined, including consistency, swelling, compaction, and strength (CBR, UCS, and shear strength). Table 4.9 summarises the results of the laboratory experiments performed.

Table 4.9: Summary of test programme

Series No.	Types of material used	Additives used	Proportion
1. Consistency limit test			
1.a. Liquid limit and plastic limit test			
1.	Soil-1	---	100% soil
2.	Soil-2	---	100% soil
3.	Fly ash	---	100% fly ash
4.	Dolochar	---	100% dolochar
5.	Mixture sample = Soil-1 + Fly ash	Fly ash	Addition of fly ash from 5% to 30% bywt. of dry soil mixture with 5% incremental basis.
6.	Mixture sample = Soil-1 +Dolochar	Dolochar	Addition of dolochar from 5% to 30%by wt. of drysoil mixture with 5% incremental basis.
7.	Mixture sample =Soil-2 + Fly ash	Fly ash	Addition of flyash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
8.	Mixture sample =Soil-2 + Dolochar	Dolochar	Addition of dolochar from 5% to 30% by wt. of dry soil mixture with 5%incremental basis.
9.	Stabilized sample = Soil-1 (70%) + Fly ash (30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of fly ash) with 1% incremental basis.
10.	Stabilized sample = Soil-1(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of dolochar) with 1% incremental basis.
11.	Stabilized sample = Soil-2 (70%) + Fly ash (30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of fly ash) with 1% incremental basis.
12.	Stabilized sample = Soil-2(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of dolochar) with 1% incremental basis.
			Total test
2.b. Shrinkage limit test			
1.	Soil-1	---	100% soil
2.	Soil-2	---	100% soil
			Total test

Series No.	Types of material used	Additives used	Proportion
2. Specific gravity test			
1.	Soil-1	---	100% soil
2.	Soil-2	---	100% soil
3.	Fly ash	---	100% fly ash
4.	Dolochar	---	100% dolochar
5.	Mixture sample = Soil-1 + Fly ash	Fly ash	Addition of fly ash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
6.	Mixture sample = Soil-1 +Dolochar	Dolochar	Addition of dolochar from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
7.	Mixture sample = Soil-2 + Fly ash	Fly ash	Addition of fly ash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
8.	Mixture sample = Soil-2 + Dolochar	Dolochar	Addition of dolochar from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
9.	Stabilized sample = Soil-1 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of flyash) with 1% incremental basis.

10.	Stabilized sample = Soil- 1(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of dolochar) with 1% incremental basis.
11.	Stabilized sample = Soil-2 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of fly ash) with 1% incremental basis.
12.	Stabilized sample = Soil- 2(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt.of mixture sample (70% of soil + 30% of dolochar) with 1% incremental basis.
			Total test
3. Free Swelling Index test			
1.	Soil-1	---	100% soil
2.	Soil-2	---	100% soil
3.	Fly ash	---	100% fly ash
4.	Dolochar	---	100% dolochar
5.	Mixture sample = Soil-1 + Fly ash	Fly ash	Addition of fly ash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
6.	Mixture sample = Soil-1 +Dolochar	Dolochar	Addition of dolochar from 5% to 30%by wt. of drysoil mixture with 5% incremental basis.
7.	Mixture sample = Soil-2 + Fly ash	Fly ash	Addition of fly ash from 5% to 30%by wt. of drysoil mixture with 5% incremental basis.
8.	Mixture sample = Soil-2 + Dolochar	Dolochar	Addition of dolochar from 5% to 30% by wt. of dry soil mixture with5% incremental basis.
9.	Stabilized sample = Soil-1 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil +30% of flyash) with 1% incrementalbasis.
10.	Stabilized sample = Soil- 1(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil + 30% of dolochar) with 1% incrementalbasis.
11.	Stabilized sample = Soil-2 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil +30% of flyash) with 1% incrementalbasis.
12.	Stabilized sample = Soil- 2(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil + 30% of dolochar) with 1% incrementalbasis.
			Total test
1.	Soil-1	---	100% soil
2.	Soil-2	---	100% soil
3.	Fly ash	---	100% fly ash
4.	Dolochar	---	100% dolochar
5.	Mixture sample = Soil-1 + Fly ash	Fly ash	Addition of fly ash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
6.	Mixture sample = Soil-1 +Dolochar	Dolochar	Addition of dolochar from 5% to 30%by wt. of drysoil mixture with 5% incremental basis.
7.	Mixture sample = Soil-2 + Fly ash	Fly ash	Addition of flyash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
8.	Mixture sample = Soil-2 + Dolochar	Dolochar	Addition of dolochar from 5% to 30% by wt. of drysoil mixture with5% incremental basis.
9.	Stabilized sample = Soil-1 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% bywt. of mixture sample (70% of soil + 30% of fly ash) with 1%incremental basis.
10.	Stabilized sample = Soil- 1(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% bywt. of mixture sample (70% of soil + 30% of dolochar) with 1%incremental basis.

11.	Stabilized sample = Soil-2 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% bywt. of mixture sample (70% of soil + 30% of fly ash) with 1%incremental basis.
12.	Stabilized sample = Soil- 2(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% bywt. of mixture sample (70% of soil + 30% of dolochar) with 1%incremental basis.
			Total test
5. CBR test			
1.	Soil-1	---	100% soil
2.	Soil-2	---	100% soil
3.	Fly ash	---	100% fly ash
4.	Dolochar	---	100% dolochar
5.	Mixture sample = Soil-1 + Fly ash	Fly ash	Addition of fly ash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
6.	Mixture sample = Soil-1 +Dolochar	Dolochar	Addition of dolochar from 5% to 30% by wt. of drysoil mixture with 5% incremental basis.
7.	Mixture sample = Soil-2 + Fly ash	Fly ash	Addition of flyash from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
8.	Mixture sample = Soil-2 + Dolochar	Dolochar	Addition of dolochar from 5% to 30%by wt. of dry soil mixture with 5% incremental basis.
9.	Stabilized sample = Soil-1 (70%) + Fly ash(30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil +30% of fly ash) with 1% incrementalbasis.
10.	Stabilized sample = Soil- 1(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil +30% of dolochar) with 1% incremental basis.
11.	Stabilized sample = Soil-2 (70%) + Fly ash (30%)	Lime	Addition of lime from 1% to 5% by wt. of mixture sample (70% of soil +30% of fly ash) with 1% incrementalbasis.
12.	Stabilized sample = Soil- 2(70%) + Dolochar (30%)	Lime	Addition of lime from 1% to 5% bywt. of mixture sample (70% of soil + 30% of dolochar) with 1%incremental basis.
			Total tes

Preparation of samples

Until performing the desired laboratory experiments, Every samples are processed and conditioned before being used . In a 105°C oven, soil, fly ash, dolochar, and lime samples aredried. After drying, the soil and dolochar are pulverised separately. The sample that passes through the 4.75 mm IS sieve is used for testing. Separately, fly ash and dolochar are added to soil samples, starting at 5% and working up to 30% by dry weight of the soil mixture with a 5% increment. As a result, a total of 24 soil mixtures (12 for each soil) are produced. The basic gravity, index, swelling, compaction, and strength of test specimens prepared from samples are then resolute in the lab (CBR,). The above characteristics of soil-fly ash and soil-dolochar samples are carefully examined in order to determine the best soil mixture proportion. In this scenario, 70 percent soil + 30 percent fly ash and 70 percent soil + 30 percent dolochar are the best soil mixtures. Furthermore, lime is applied to the soil mixture (70 percent soil + 30 percent fly ash and 70 percent soil + 30 percent dolochar) in increments of 1% by weight of dry mixture samples from 1% to 5%. There will be a total of 20 lime mixed samples (10 for each soil). The geo-tech. properties of lime-mixture samples, such as specific gravity, index, swelling, compaction, and strength (CBR), are determined through a sequence of lab tests after they are prepared. The abstract of sample preparation for testing purposes is shown in Table 4.10.

Table 4.10: Abstract of sample preparation

Sl. No.	Type of samples	Mixture of samples	No. of samples
1	Parent sample	Soil-1	1
		Soil-2	1
		Fly ash	1
		Dolochar	1
		Hydrated lime	1
2	Mixture sample (By addition of fly ashand dolochar)	Soil-1 + Fly ash	6
		Soil-1 + Dolochar	6
		Soil-2 + Fly ash	6
		Soil-2 + Dolochar	6
3	Lime stabilized sample	Soil-1 + Fly ash + Lime	5
		Soil-1 + Dolochar + Lime	5
		Soil-2 + Fly ash + Lime	5
		Soil-2 + Dolochar + Lime	5

Test Methods

Samples prepared under section 3.4 are subjected to successive laboratory tests as prescribed by Bureau of Indian Standards (BIS). Table 4.11 shows the standards followed for the various tests conducted.

Grain Size Analysis

The size-analysis is passed out for soil-1, soil-2, fly ash and dolochar as per IS: 2720 (Part-4)

– 1985. Fraction of materials passing through 4.75 mm and retained on 75 μ IS sieves are subjected to sieve analysis method, whereas, the hydrometer analysis method is adopted for the particles passing through the 75 μ IS sieve.

Table 4.11: Standards follows for the test parameters

Sl. No	Characteristics	Name of the Test	Standards
1	Grain size	Sieve analysis Hydrometer analysis	IS: 2720 (Part-4)-1985
2	Consistency characteristics	Liquid limit, Plastic limit and Plasticityindex. Shrinkage limit	IS: 2720 (Part-5) -1985 IS: 2720 (Part-6) -1972
3		Specific gravity	IS: 2720 (Part 3/Sec. 1)–1980
4	Swelling characteristics	Free swelling index	IS: 2720 (Part-40)-1977
5	Compaction characteristics	Optimum moisture content andMaximum dry density	IS: 2720 (Part-8)-1983
6	Strength Characteristics	California bearing ratio	IS: 2720 (Part-16)-1987

Sieve analysis: The sample that passes through the 4.75 mm IS sieve is dried in an oven at 105 to 110 degrees Celsius. The sample is then measured and immersed in water in aluminium bowlsfor 24 hours. Two grammes of sodium hexametaphosphate are added to the submerged samples to prevent particle coagulation. After the sample has been fully soaked, it is stirred and washed through the 75 μ IS sieve with running water. Samples are continuously washed till clear water through the 75 μ IS sieve is obtained. Then the washed samples are carefully transferred in to theanother dry aluminium bowl and kept in the oven for drying, Samples are dried at 105 to 110 °C temperature till the state of constant mass is obtained After drying, samples are sieved using a series of sieves with sizes of 4.75 mm, 2 mm, 425 mm, and 75 mm.. The fractions retained on the IS sieves are weighed and results noted down to determine the size of the particles. Fig.3.21 shows the view of sieve analysis of samples in progress.

Fig.4.6 Sieve analysis in progress

Specific gravity

IS: 2720 (Part-3/Sec-1)-1980 is used to calculate the real gravity. A 50 mL density bottle with a hole in the cap was used in this experiment. Bottle with a stopper for density is dried and cool in desiccator at 105 to 110 degrees Celsius. Approximately 50 gm of sample is taken (passing through a 2.0 mm IS sieve). A sub-specimen of around 10 gram is take from a 50 gm sample. The density bottle's weight is calculated to near 0.001 gm. (M1). Then sub-specimen is transferred into the density-bottle and weighed the bottle bysub-specimen and stopper is near to 0.001 g (M2).

Fig.4.7 Specific gravity test in progress

By heating the density bottle with the sub-sample and water in the water bath, the trapped airisreleased. After that, the bottle was taken out of the water, dried, and weighed to the nearest

0.001 gramme (M3). The density bottle is then cleaned and filled with airless filtered water. After the density container has been finished, the distilled water stopper is inserted into the mouth. The actual gravity of the sample is then determined using the formula below.

Specific Gravity = G = (M2 - M1) / {(M4-M1) - (M3-M2)} (3.1)

Fig.4.7 shows the photograph of specific gravity test of specimen in progress.

Consistency limit

Samples as prepared under section 3.4 are passed through 425 μ I.S seive and are used for thedetermination of consistency limit.

A. Liquid limit

After that, the soil was allowed to sit for 24 hours to ensure that the moisture inside the samples were uniformly distributed. Following the 24-hour period, the sample was thoroughly re-mixed before the test. While the paste is cut to a depth of one cm at the point offull thickness, and the excess soil is returned to the dish, a portion of the paste is placed in thecup above the point where the cup lies on the base, pressed down, and spread into places withas few strokes of the spatula as possible. Break one straight groove in the centre of the soil paste in the cup, dividing the paste into two equal halves with a 12 mm difference in the middle. After that, the cup of the unit is rotated at a rate of 2 revolutions per second, allowingthe cup to be felt over a 1cm radius. Count and keep track of how many falls (drops/blows) it takes for the spatula groove in the soil cake to close. These blows, which vary from 15 to 35 in number, cause the groove in the specimen cake to close. A portion of the specimen paste is extracted and measured from the moisture can's cup. The intestine's leftover specimen pasteis then carefully mixed with a little more purified water. The operations are repeated four times in all. The number of blows is stated in each case as mentioned above.

A flow curve is plotted on a semi-logarithmic graph sheet using the arithmetical scale for water content and the logarithmic scale for the number of strikes (drops). Near to (as close as possible) and around the five points, a straight line (flow curve) is drawn.

a few points. The specimen's liquid limit is determined by rounding the moisture content measured from the curve for 25 blows (drops) to the nearest whole amount. Figure 4.7 depicts the experimental setup for deciding the liquid boundary.

Fig.4.7 Experimental setup for determination of liquid limit

B. Plastic limit

According to IS: 2720 (Part-5) – 1985, 60 gm of samples are run through a 425 IS sieve to determine the plastic limit. 20 gm of the sample is mixed with distilled water to make a paste that can be moulded with fingers. The rolled specimen is then kept in an airtight jar for 24 hour to ensure uniform moisture distribution . The 8 gram paste is rolled into 3 m.m diameter threads after being moulded into a ball. The threads are rolled between a glass plate and fingers until they are uniformly 3 mm in diameter. Finger transfers (rolling) occur at a rate of 80 strokes per minute. After receiving the yarn, it is kneaded again, and the balls are preparedand rolled into thread in the same manner as before. This process of alternate kneading & rolling is repeated until the threads crumble & the specimen could not be rolled into threads. Then, fragments of crumbled specimen thread are stored in an airtight jar to determine moisture content, which is represented by the specimen's plastic limit (percentage). Figure 4.8 shows an experimental setup for determining the plastic limit.

Fig.4.8 Experimental setup for determination of Plastic limit

C. Shrinkage limit

Soil specimens are checked to assess their shrinkage maximum in accordance with IS: 2720 (Part-6)-1972. For the procedure, 30 gm of samples going through a 425 µ IS Sieve are used. The amount of mercury is obtained by measuring the mercury stored in the shrinkage saucer to a precision of 0.1 gm and dividing the weight by the unit weight of mercury to achieve the power of shrinkage dish/vol. of wet sample pat. The volume of wet sample pat should be registered (V). Tap the shrinkage saucer on a hard surface with a rubber layer to cushion it. Then a portion of specimen paste nearly equal to the first portion is added and tapped until the paste is fully compacted and all included air is carried to the floor, as before. More specimen paste was added, and tapping continued until the shrinkage dish was fully filled andno excess specimen paste could be seen on the exterior. Then excess sample paste is stricken off with a straight edge, and all sample the residue that has adhered to the outside of the shrinkage dish is cleaned down. Immediately the shrinkage dish with wet specimen paste weighed and recorded. The specimen pat is permitted to dry in the open air until it has changed colour from murky to normal. After that, the pat is oven dried to a constant weight using a shrinkagedish at 105 to 110 oC and cooled in a desiccator. The shrinkage saucer with dry specimen pat is weighed and registered immediately after removal from the desiccators. The mercury equation is then used to measure the volume of the dried specimen pat. The volume is measured using the oven-dried specimen pat's volume (V0).

w = moisture content of wet sample pat in percent

V = volume of wet sample pat in ml,

V0 = volume of dry sample pat in ml

W0= Weight of oven-dry sample pat in gm.

Fig.4.9 shows the experimental setup for the determination of shrinkage limit.

Fig.4.9 Experimental setup for determination of Shrinkage limit of specimen

D. Swelling test (Free swell index)

The free swelling index (FSI) measure, performed according to IS: 2720 (Part-40)-1977, determines the swelling characteristics of soil specimens. The specimen for this test is a sample that has passed through a 425 µ IS sieve. The specimen that passes through a 425 µ IS sieve is oven dried and divided into two sections (10 gm each). Two dry weighing cylinders, each with a 100 ml volume and a 1 ml graduation, are used. Each of the 100 ml measurement cylinders is filled with the weighed specimen (10 gm). Following the pouring of the specimens, one measurement cylinder is filled with kerosene, while the other is filled with purified water up to the 100 ml level. Any entrapped air is then collected with gentle shaking and stringing with a glass rod, and the specimens in both cylinders are allowed to stand for 24 hours. Volumes of the specimen under water and kerosene in the cylinders are measured after 24 hours.. The free swell index of specimen is resolute by the following formula.

Free swell index (%) = $\{(V_1 - V_2) / V_2\} \times 100$ (3.3)

Where, V_1 = Volume of sample in distilled water, ml V_2 = Volume of sample in kerosene, ml

Fig.4.10 shows the determination of free swell index of samples.

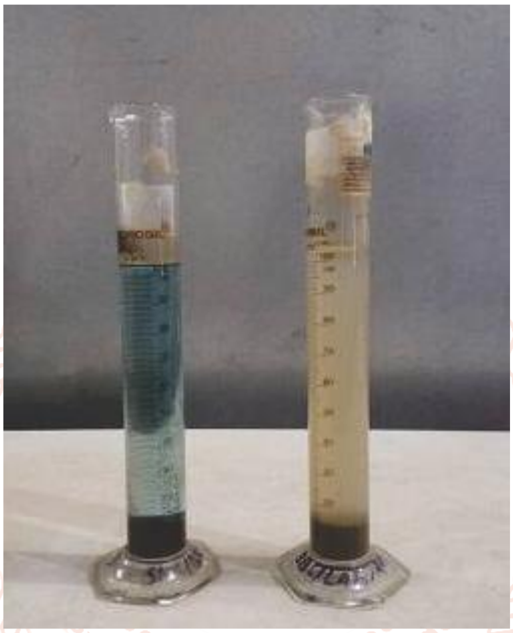

Fig.4.10 Determination of free swell index of specimen

Compaction test

To assess the optimum moisture content (OMC) and optimal dry density, a proctor compaction test is performed on samples according to IS: 2720 (Part-8)-1983 (MDD). The Proctor compaction test is performed on an oven dried sample that has passed through a 19 mm IS sieve. Around 5 kg of oven dried sample is placed in a non-porous metal tray, and water is applied to the samples in stages (starting with 3%). To achieve a homogeneous blend, the specimen and water are carefully combined. The specimen is stored in a closed plastic box in the laboratory for 24 hours at a temperature of 27 2 °C to allow for consistent moisture distribution. The mixture is then compacted in a Proctor's mould (1000 cc capacity) in five equal layers, each layer being evenly compacted with 25 blows from a height of 450 mm with a 4.9 kg rammer, and the bulk density of the compacted specimen is determined.The oven drying process also determines the resulting water content in the specimen. The procedure is repeated more than five times until there is a drop in bulk density. The dry density of specimen is determined as below

Dry density = {100 x (Bulk density)}/ (100+Moisture content) (3.4)

Fig.4.11 Experimental setup of compaction test of specimen

The moisture content and dry densities of each specimen are plotted on compaction curves. The maximal moisture content (OMC) and mean dry density (MDD) was calculated using thecompaction curve. Figure 4.11 shows an experimental configuration for a compaction test.

California bearing ratio (CBR) test

To assess the CBR values of all samples, CBR checks are performed in accordance with IS: 2720 (Part-16)-1987. Using a 4.9 kg rammer descending from a height of 450 mm, samples are compacted to their optimum Proctor density in CBR moulds (150 mm Dia). By using a compaction rammer, each sheet is exposed to 55 blows that are spread uniformly across the layer. After compaction of the last layer, the collar is removed and the excess sample above the top of the mould is evenly trimmed off by means of the straight edge. The compacted samples are checked automatically by the CBR system for unsoaked CBR. The compacted samples with surcharge weights (2x2.5 kg) are kept in a water tank for soaking for soaked CBR. In this case, the compacted specimens of dirt, fly ash, dolochar, soil-fly ash, and soil- dolochar are soaked for 4 days, while the compacted specimens of soil-fly ash-lime and soil- dolochar-lime are soaked for 4, 7, 14, 21, 28, and 56 days. The CBR mould with the specimen is then removed from the water tank and allowed to extract any remaining water. The mould with specimens and surcharge weights is put on the CBR measuring system after excess water has been drained. The plunger of the loading frame is seated in the specimen's centre and is brought into contact with the top rim. The LVDT for calculating the plunger's penetration value has been mounted. The penetration LVDT and the load cell are all set to 0. The unit then applies load to the specimen at a uniform rate of 1.25 mm per minute through the penetration plunger (diameter 50 mm). At penetrations of 0.5, 1.0, 1.5, 2.0, 2.5, 4.0, 5.0, 7.5, 10.0, and 12.5 mm, the load is measured. The load is released and the mould iswithdrawn from the loading system after the final reading. The load vs. penetration curve is measured, and corrected loads for 2.5 mm and 5.0 mm penetration are measured using the formula below.

$$CBR = \frac{\text{Load at 2.5 mm or 5.0 mm penetration}}{\text{Standard load at 2.5 mm or 5.0 mm penetration}} x\ 100 \quad (3.5)$$

Fig.4.12 Experimental setup of CBR test of specimen

At 2.5 mm and 5.0 mm penetration, the unit loads on normal are 1370 kg and 2055 kg, respectively. The higher of the above-mentioned values is taken for each specimen, and the average of three such specimens is stated to the first decimal as CBR for one collection. As a result, the CBR values of all the specimens prepared under section 3.4 have been determined in the manner described above. An experimental setup is presented in Fig.3.29 for reference.

RESULTS AND DISCUSSIONS

General

In this segment, tables and figures display the findings of a series of accuracy tests, free swell index tests, compaction tests, and CBR tests performed on expansive soils with and without additives. The effects of additives such as fly ash, dolochar, and lime on the geotechnical properties of soils are extensively investigated and debated, with references to reported findings.

Effects of Fly Ash Addition on the Characteristics of Expansive Soil

Table 5.1: Summary of geotechnical properties of soils and soil-fly ash mixture

Geotechnicalproperties	Soil-1	70% soil-1 + 30% fly ash	Soil-2	70% soil-2 + 30% fly ash
Specific gravity	2.69	2.58	2.70	2.61
L. L. (%) P. L. (%) P. I. (%)	56.00 28.00 28.00	48.75 31.96 16.79	33.00 18.00 15.00	22.00 --- NP
FSI (%)	60.00	8.33	20.00	0
OMC (%) MDD (kN/m^3)	16.10 17.80	24.45 15.94	11.50 18.80	15.80 17.52
CBR (%) (4-days Soaking)	3.61	8.16	5.25	11.40
UCS (kPa) (9-days curing)	149.0	108.7	110.0	35.5
c (kPa) (degree) (9-days curing)	56 6	24 15	44 10	18 24
cc *mv* (m^2/kN) av (m^2/kN) *c* (m^2/min.)	0.298 0.39x10^{-3} 2.43x10^{-3} 1.31x10^{-6}	0.136 0.29x10^{-3} 1.11x10^{-3} 3.55x10^{-6}	0.198 0.35x10^{-3} 1.61x10^{-3} 2.09x10^{-6}	0.100 0.19x10^{-3} 0.82x10^{-3} 5.62x10^{-6}
k (m/min.)	0.51x10^{-8}	1.03x10^{-8}	0.73x10^{-8}	1.07x10^{-8}

Effects of Dolochar Addition on the Characteristics of Expansive Soil

Table 5.2: Summary of geotechnical properties of soils and soil-dolochar mixture

Geotechnical properties	Soil-1	70% soil-1 + 30% dolochar	Soil-2	70% soil-2 + 30% dolochar
Specific gravity	2.69	2.88	2.70	3.01
L. L. (%) P. L. (%) P. I. (%)	56 28 28	45 22 23	33 18 15	25 18 7
FSI (%)	60	30	20	0
OMC (%) MDD (kN/m^3)	16.10 17.80	11.20 20.50	11.50 18.80	9.30 21.05
CBR (%) (4-days Soaking)	3.61	9.17	5.25	13.80

Ideal Soil-Fly Ash/Soil-Dolochar Mixture

In the previous pages, the effects of fly ash and dolochar on the geotechnical properties of expansive soils were discussed in different tables (Table 4.1 to Table 4.18) and estimates (Fig.4.1 to Fig.4.30). In the spectrum of fly ash/dolochar content investigated, better results are obtained for soil-fly ash and soil-dolochar mixtures in the proportions 70:30 in terms of consistency, swelling, compaction, weight, consolidation, and drainage. As a result, the above proportion is called the optimal mixture proportion. In the following pages, we providea description of the geotechnical properties, microstructure, and leaching capacity of the soil- fly ash and soil-dolochar mixtures in proportions of 70:30.

Summary of geotechnical properties of ideal mixture

Tables 4.19 and 4.20 summarise the geotechnical properties of soil-fly ash and soil-dolochar mixtures prepared in the proportion 70:30 in comparison to parent expansive soils. The tablesshow a significant change in all geotechnical properties.

Table 5.3: Elemental composition of soil-dolochar mixture in the proportion of 70:30

Element	Soil-1-dolochar (% by weight)	Soil-2-dolochar (% by weight)
O as SiO2	39.75	47.05
Na	0.24	0.16
Mg as MgO	4.31	3.47
Al as Al2O3	5.23	8.75
Si as SiO2	10.94	23.84
K as Feldspar	0.99	1.19
Ca as Wollastonite	1.65	1.41
Ti	0.48	0.83
Cr	2.86	2.21
Fe	5.60	10.33
Mo	0.48	0.60
Mn	0.25	---
Cl as KCl	0.09	---
C as CaCO3	27.13	---
P as GaP	---	0.16

Effects of Fly Ash and Lime Addition on Characteristics of Expansive Soils

This section goes through the effects of lime addition on the geotechnical characteristics of soil-fly ash and soil-dolochar samples prepared in the ideal ratio of 70:30, such as index properties, compaction, weight, consolidation, and drainage.

Specific gravity

Table 4.23 shows the basic gravity of the soil-fly ash-lime mixture. The specific gravity of the soil-fly ash-lime mixture increases as the lime content increases, as shown in the table. At5% lime content, the basic gravities of soil-fly ash-lime mixtures are 2.73 and 2.77 in case of soil-1 and soil-2, respectively.

Table 5.4: Specific gravity of soil-fly ash-lime mixture

Sample reference	Soil – 1	Soil – 2
70% soil + 30% flyash	2.58	2.61
70% soil + 30% fly ash + 1% lime	2.59	2.62
70% soil + 30% fly ash + 2% lime	2.63	2.66
70% soil + 30% fly ash + 3% lime	2.65	2.71
70% soil + 30% fly ash + 4% lime	2.70	2.74
70% soil + 30% fly ash + 5% lime	2.73	2.77

Consistency characteristics

The consistency characteristics such as liquid limit (L.L.), plastic limit (P.L.) and plasticity index (P.I.) of soil-fly ash-lime mixtures are presented in Table 5.5

Table 5.5: Consistency characteristics of soil-fly ash-lime mixture

Sample reference	Soil – 1			Soil – 2		
	L.L. (%)	P.L. (%)	P.I. (%)	L.L. (%)	P.L. (%)	P.I. (%)
70% soil + 30% fly ash	48.75	31.96	16.79	22.00	---	NP
70% soil + 30% fly ash +1% lime	48.00	24.00	24.00	22.00	---	NP
70% soil + 30% fly ash +2% lime	46.00	23.00	23.00	20.00	---	NP
70% soil + 30% fly ash +3% lime	45.00	23.00	22.00	20.00	---	NP
70% soil + 30% fly ash +4% lime	43.00	22.00	21.00	18.00	---	NP
70% soil + 30% fly ash +5% lime	42.00	21.00	21.00	17.00	---	NP

The table shows that as the lime content increases, the liquid limit of the P.L. and P.I. of the soil-fly ash-lime mixture steadily decreases. The following factors can contribute to the reduction of consistency limits:

Swelling characteristics

The characteristics of swelling, i.e. The pozzoloanic reaction of fly ash is increased when the lime content is increased, resulting in more granular formations. The mixed sample of 70% soil-1 + 30% fly ash + 3% lime has an FSI value of 0 percent at a lime content of 3%, and this value remains constant as the lime content is increased, resulting in a 100 percent reduction.

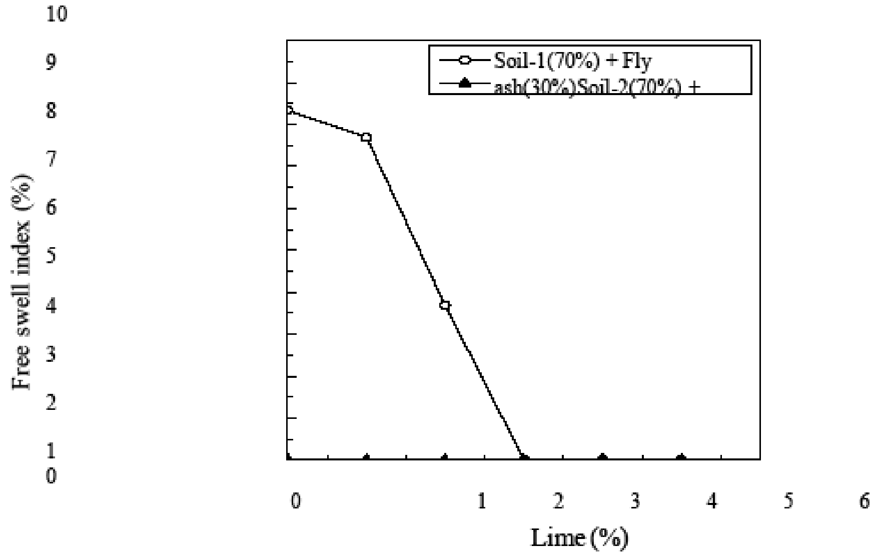

Fig.5.1 Effect of lime on the free swell index of soil-fly ash mixture

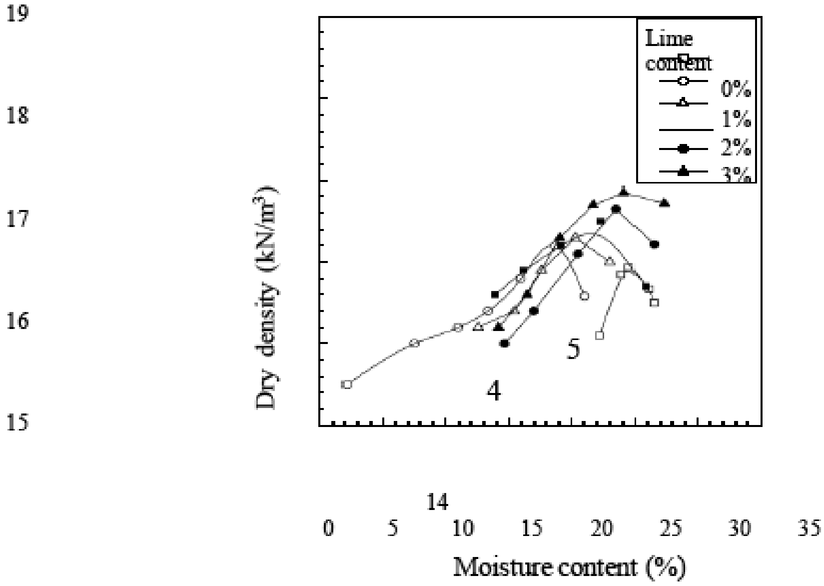

Fig.5.2 Compaction curves of soil-1- fly ash - lime mixture

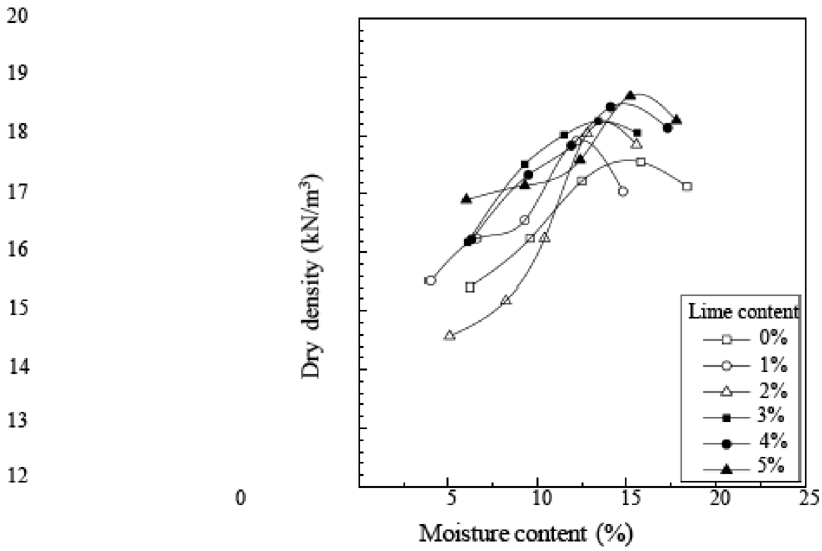

Fig.5.3 Compaction curves of soil-2- fly ash - lime mixture

Table 5.6: Compaction characteristics of soil-fly ash-lime mixture

Sample reference	Soil – 1		Soil – 2	
	OMC(%)	MDD (kN/m^3)	OMC(%)	MDD (kN/m^3)
70% soil + 30% fly ash	24.45	15.94	15.	17.52
30% fly ash + 1% lime	18.8	16.2	12.	17.88
70% soil + 30% fly ash + 2%lime	20.4	16.35	12.	18.01
70% soil + 30% fly ash + 3%lime	22.4	16.55	13.	18.22
70% soil + 30% fly ash + 4%lime	23.6	16.65	14.	18.46
70% soil + 30% fly ash + 5%lime	24.2	16.85	15.	18.65

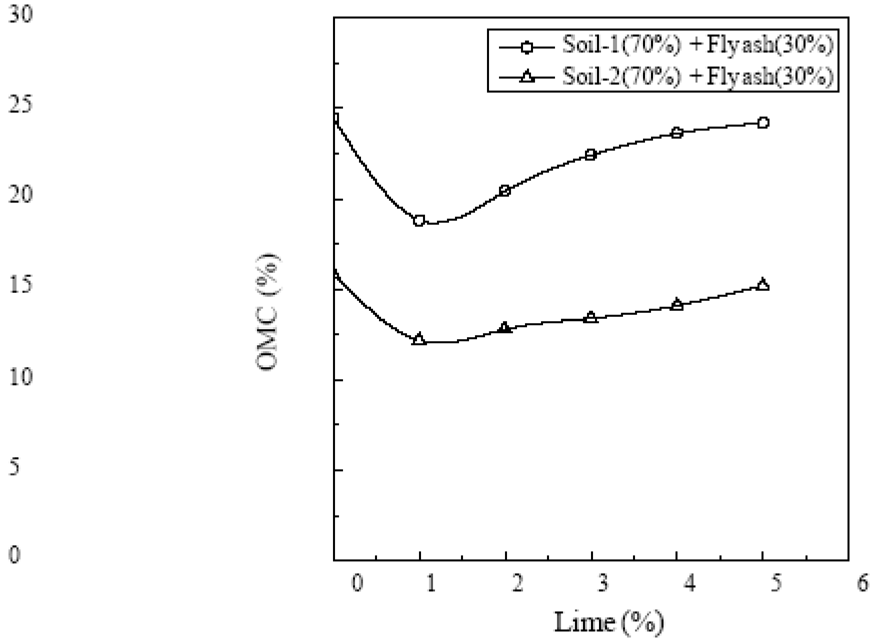

Fig.5.4 Effect of lime on the optimum moisture content of soil-fly ash mixture

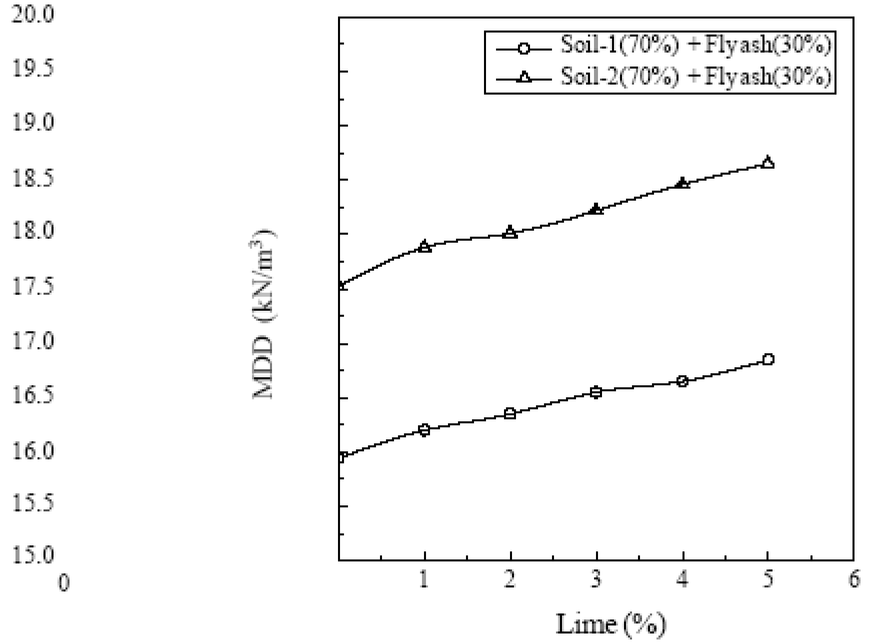

Fig.5.5 Effect of lime on the optimum moisture content of soil-fly ash mixture

Strength characteristics

This section discusses the strength properties of soil-fly ash-lime mixtures, including the California bearing ratio (CBR), unconfined compressive strength (UCS), and shear strength (Triaxial compression).

California bearing ratio (CBR)

At their respective OMC and MDD conditions, the soil-fly ash-lime mixtures are compacted in CBR moulds. After that, the remoulded specimens are immersed in water for 4, 7, 14, 21, 28, and 56 days. CBR tests are performed after the soaking periods are completed to assess the CBR values of the specimen in each soaking state. The specimens were soaked in water for 56 days to determine the effects of lime on CBR values of a soil-fly ash mixture after extended periods of soaking. After various soaking times, the effects of lime on the CBR values of soils-fly ash specimens are investigated. Tables 4.26 and 4.27 showed the CBR values for soil-1 (70 percent) + fly ash (30 percent) and soil-2 (70 percent) + fly ash (30 percent) mixtures of different percentages of lime for various soaking cycles.

Table 5.7: California bearing ratio of soil-1-fly ash-lime mixture

Sample reference	Soaked CBR (%)					
	4 day	7 days	14 days	21 days	28 days	56 days
70% soil + 30%flyash	8.1	---	---	---	---	---
70% soil + 30% fly ash + 1%lime	11.	15.51	17.96	26.43	33.87	41.14
70% soil + 30% fly ash + 2%lime	15.3	18.83	21.47	32.91	37.5	48.66
70% soil + 30% fly ash + 3%lime	20.6	23.5	32.69	38.27	45.29	53.41
70% soil + 30% fly ash + 4 %lime	29.7	35.29	47.76	51.03	56.23	62.54
70% soil + 30% fly ash + 5%lime	28.5	36.8	50.66	56.48	58.42	59.44

Figures 4.40 and 4.41 show the effect of lime on the CBR values of soil-1 (70 percent) + fly ash (30 percent) and soil-2 (70 percent) + fly ash (30 percent) mixtures of different percentages of lime at different soaking times.

Table 5.8: California bearing ratio of soil-2-fly ash-lime mixture

Sample reference	Soaked CBR (%)					
	4 days	7 days	14 days	21 days	28 days	56 days
% soil + 30% fly ash	11.40	---	---	---	---	---
70% soil + 30% fly ash + 1%lime	16.40	22.52	25.66	33.18	41.52	53.25
70% soil + 30% fly ash + 2%lime	21.66	26.62	31.55	38.92	45.66	57.19
70% soil + 30% fly ash + 3%lime	26.34	29.55	38.88	46.62	51.15	63.22
70% soil + 30% fly ash + 4%lime	35.33	41.10	51.11	61.15	66.34	68.15
70% soil + 30% fly ash + 5%lime	39.60	43.22	54.52	60.18	65.56	66.50

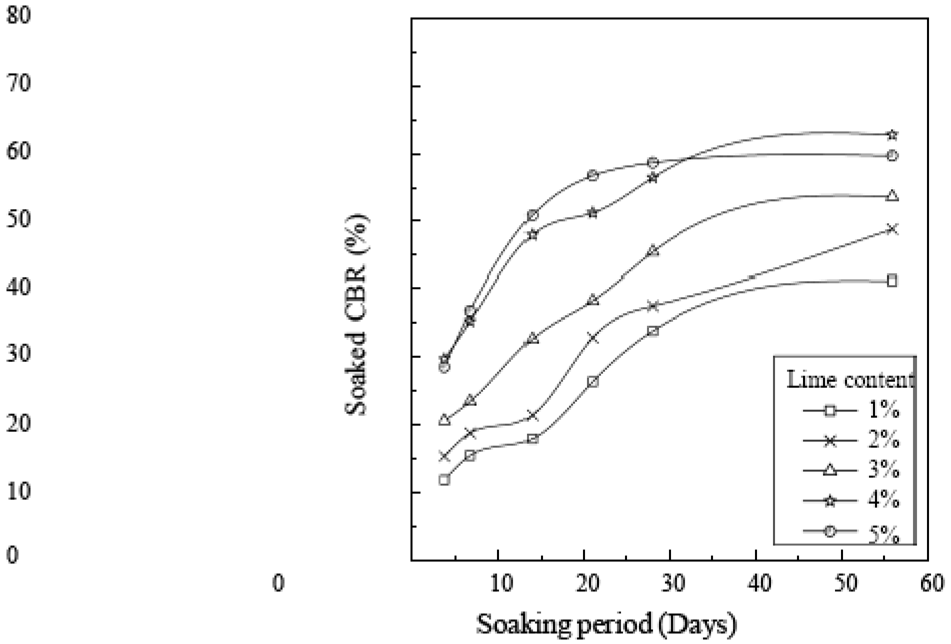

Fig.5.6 Effect of lime on the CBR at different soaking periods of soil-1 - fly ash mixture

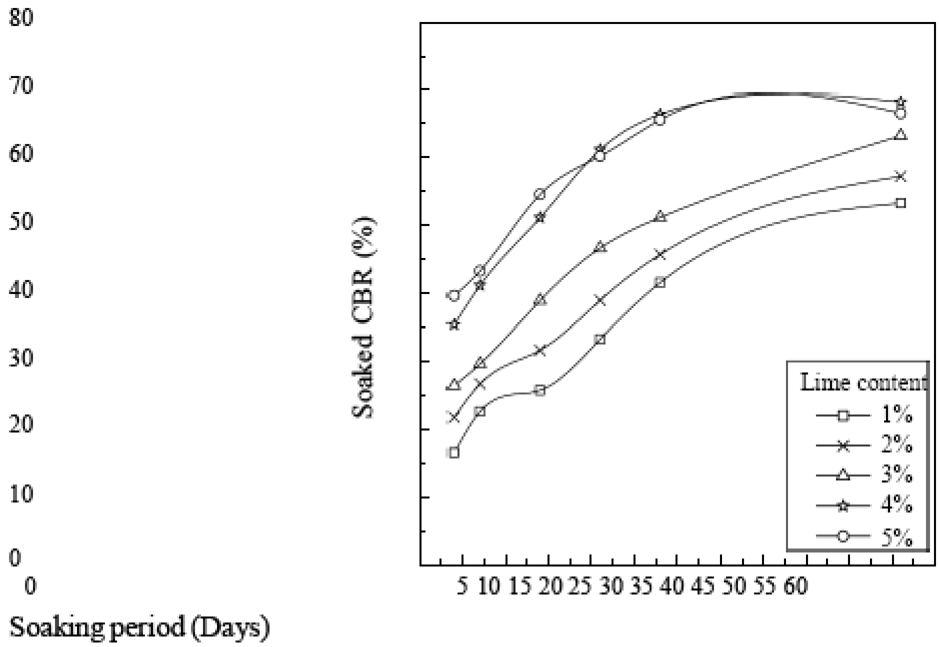

Fig.5.7 Effect of lime on the CBR at different soaking periods of soil-2 - fly ash mixture

Unconfined compressive strength (UCS)

Unconfined compressive strength tests are performed on remoulded soil-fly ash-lime specimens, as described in section 3.5.9. Tables 4.28 and 4.29 show the results of UCS tests on soil-1 (70 percent) + fly ash (30 percent) and soil-2 (70 percent) + fly ash (30 percent) samples with various percentages of lime at various curing times.

Table 5.9: UCS of soil-1-fly ash-lime mixture

Sample reference	UCS (kPa) At the different periods (days) of moist curing					
	4 days	7 days	14 days	21 days	28 days	56 days
70% soil + 30% fly ash + 1%lime	23	27	49	53	61	86
70% soil + 30% fly ash + 2%lime	32	35	54	55	66	90
70% soil + 30% fly ash + 3%lime	50	69	109	110	119	165
70% soil + 30% fly ash + 4%lime	88	112	132	150	170	286
70% soil + 30% fly ash + 5%lime	73	100	122	140	158	229

Figs. 4.42 and 4.43 present the effects of lime on the UCS values of soil-1 (70%) + fly ash (30%) and soil-2 (70%) + fly ash (30%) samples with different percentage of lime at differentcuring periods respectively. Addition of lime beyond 5% lime, reduces theUCS.

Table 5.10: UCS of soil-2-fly ash-lime mixture

Sample reference	UCS (kPa) At the different periods (days) of moist curing					
	4 days	7 days	14 days	21 days	28 days	56 days
70% soil + 30% fly ash + 1%lime	20	25	38	48	57	72
70% soil + 30% fly ash + 2%lime	28	33	42	53	62	78
70% soil + 30% fly ash + 3%lime	44	55	79	92	105	122
70% soil + 30% fly ash + 4%lime	66	82	108	125	164	192
70% soil + 30% fly ash + 5%lime	53	78	98	112	148	170

The increased of UCS by the addition of lime may be due the following reasons;

A. A physicochemical bond is formed between soils and fly ash particles as a result of the pozzolanic reaction (cation exchange process) between the two. In the presence of lime, these physicochemical bonds are strengthened.

B. In the presence of water, lime's cementitious properties create a much stronger bond between soil and fly ash particles. The strength of the bonds improves as the curing time increases.

C. As the lime content increases, the cementitious property of the lime increases as well, eventually reaching its maximum value. With increasing lime content, this cementitious property decreases. The formation of non-cohesive characteristics in soil-flyash-lime samplesis to blame.

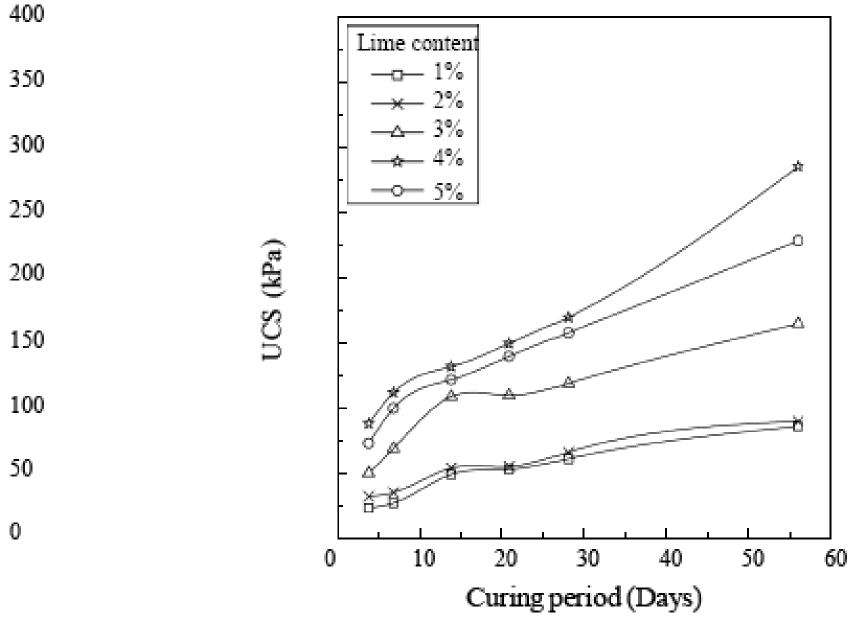

Fig.5.8 Effect of lime on the UCS at different curing periods of soil-1 - fly ash mixture

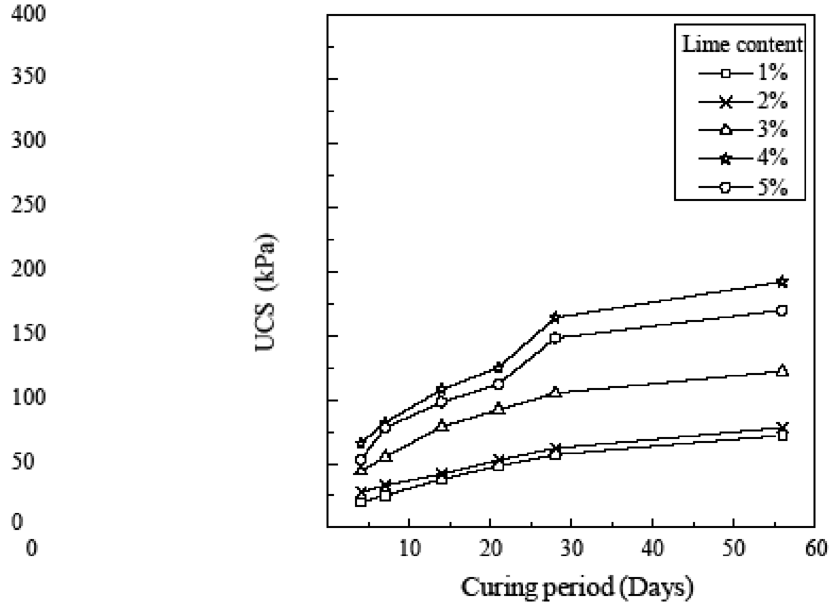

Fig.5.9 Effect of lime on the UCS at different curing periods of soil-2 - fly ash mixture

Similar trends of increase in UCS with the increase of lime content and curing periods hadalso been noticed by Sridharan *et at.* (1997), Zha *et al.* (2008), Solanki *et al.* (2009), Sahoo *et al*. (2010) and Kang *et al.* (2015). In the present investigation, the UCS of soil-1 (70%) + fly ash (30%) + lime (4%) mixture is more than the UCS of soil-2 (70%) + fly ash (30%) + lime (4%) mixture, it may be soil-1 has more clay content than soil- 2.

Shear strength (Triaxial compression)

The triaxial compression test results for different percentage of lime contents are reported in Table 4.30. The effects of lime on the cohesion (c) of soil-fly ash mixtures are presented in

Fig.4.44 and the effects of lime on the angle of shearing resistance (mixture are shown by Fig.5.10.

Table 5.11: Shear strength of soil-fly ash-lime mixture

Sample reference	Soil – 1		Soil – 2	
	C (kPa)	⌡ (degree)	*C* (kPa)	⌡ (degree)
70% soil + 30% fly ash	24	15	18	24
70% soil + 30% fly ash + 1%lime	72.5	14	42	22
70% soil + 30% fly ash + 2%lime	87.5	15	50	27
70% soil + 30% fly ash + 3%lime	117.5	18	58	30
70% soil + 30% fly ash + 4%lime	122.5	19	65	31
70% soil + 30% fly ash + 5%lime	120	18	61	31

When lime is applied to a soil-fly ash mixture (in a 70:30 ratio), the cohesion of the soil-flyash-lime specimen increases as the lime content increases, reaching its highest value at 4% lime content. The addition of another 5% of lime reduces cohesion. But the initially decreases at 1% lime content and then increases with the increase of lime content up to 4%.Beyond 4% lime content,

remain constant. Lime exhibits the cementitious properties in the presence of water. Due to this cementitious property of lime, it creates a bond with the soil-fly ash particles. The strength ofthe bond increases with the increase of lime content with curing which attains a maximum value at optimum lime content.

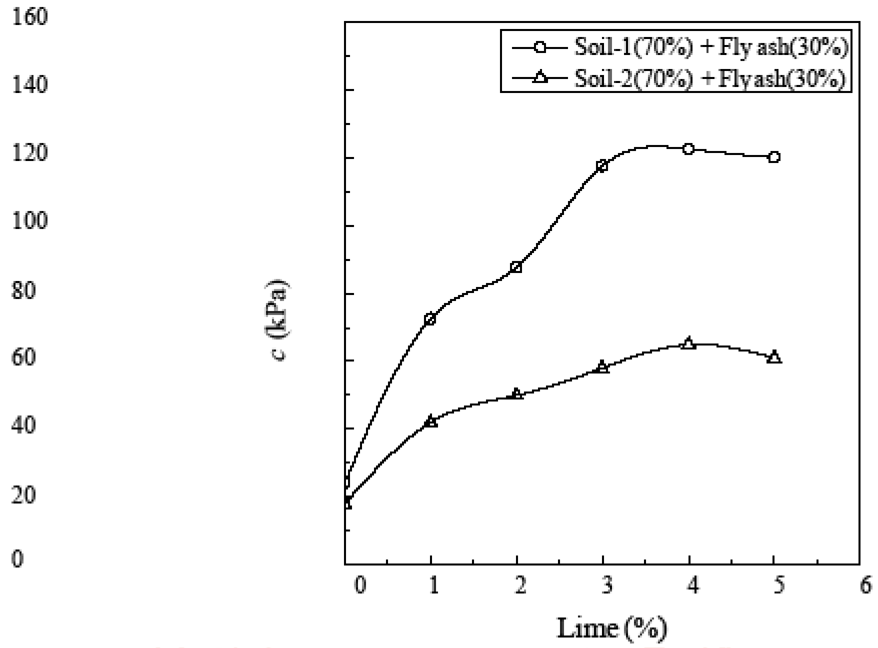

Fig.5.10 Effect of lime on the cohesion of soil-fly ash mixture

Similar observation was noticed by Sahoo *et al.* (2010). They revealed that the *c* and increase with the increase of lime content and observed optimum value at 15% fly ash and 4% lime content. In the present study, the *c* and of 70% soil-1 + 30% fly ash + 4% lime mixture are increased by 2.19 and 3.17 times respectively as compared to soil-1 alone, whereas the *c* and of 70% soil-2 + 30% fly ash + 4% lime mixture are increased by 1.48 and 3.1 times respectively as compared to soil-2 alone.

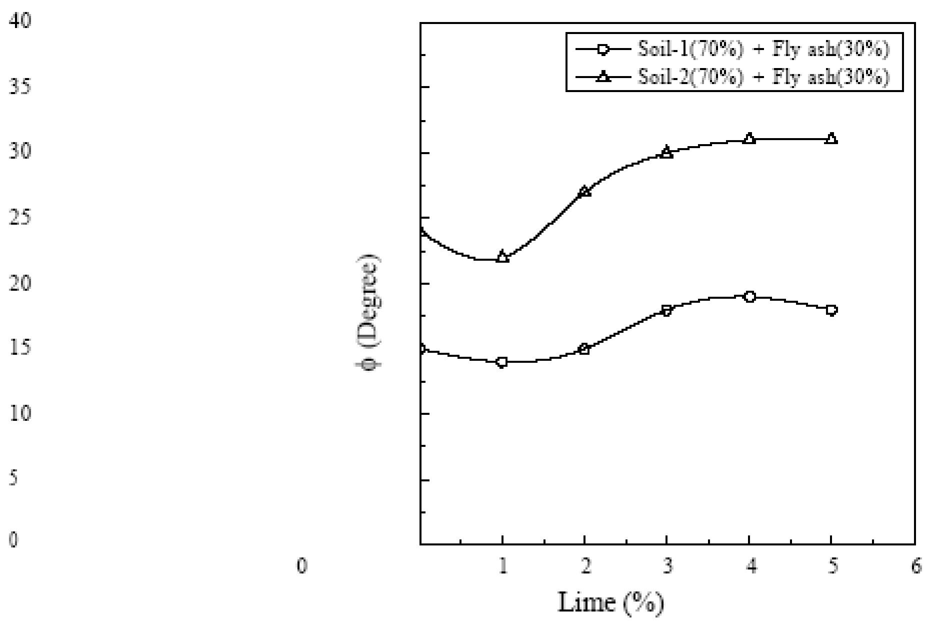

Fig.5.11 Effect of lime on the angle of shearing resistance of soil-fly ash mixture

Consolidation characteristics

The consolidation characteristics such as compression index (c_c), coefficient of volumechange (m_v), coefficient of compressibility (a_v) and coefficient of consolidation (c_v) of soil- fly ash-lime mixture are studied by conducting a series of consolidation test.

Table 4.31: Consolidation characteristics of soil-1-fly ash-lime mixture

Sample reference	c_c	m_v (m^2/kN)	a_v (m^2/kN)	c_v (m^2/min.)
70% soil + 30% flyash	0.136	0.29×10^{-3}	1.11×10^{-3}	$3.55 \times 10^{-}$
70% soil + 30% flyash + 1% lime	0.199	0.24×10^{-3}	1.62×10^{-3}	$4.9 \times 10^{-}$
70% soil + 30% flyash + 2% lime	0.147	0.18×10^{-3}	1.2×10^{-3}	$3.99 \times 10^{-}$
70% soil + 30% flyash + 3% lime	0.144	0.17×10^{-3}	1.17×10^{-3}	$3.64 \times 10^{-}$
70% soil + 30% flyash + 4% lime	0.114	0.10×10^{-3}	0.93×10^{-3}	$3.31 \times 10^{-}$
70% soil + 30% flyash + 5% lime	0.101	0.11×10^{-3}	0.82×10^{-3}	$0.86 \times 10^{-}$

The test results of consolidation tests of soil-fly ash-lime mixtures are reported in Table 5.13 and Table 5.13. When lime is added to the soil-fly ash mixture, the c_c, m_v, a_v and c_v of soil-fly ash-lime mixture decreases gradually with the increase of lime content.

Table 5.12: Consolidation characteristics of soil-2-fly ash-lime mixture

Sample reference	c_c	m_v (m^2/kN)	a_v (m^2/kN)	c_v (m^2/min.)
70% soil + 30% fly ash	0.100	$0.19 \times 10^{-}$	0.82×10^{-3}	5.62×10^{-6}
il + 30% flyash + 1% lime	0.162	$0.18 \times 10^{-}$	1.32×10^{-3}	4.25×10^{-6}
il + 30% flyash + 2 % lime	0.150	$0.15 \times 10^{-}$	1.22×10^{-3}	3.20×10^{-6}
il + 30% flyash + 3% lime	0.140	$0.12 \times 10^{-}$	1.10×10^{-3}	2.92×10^{-6}
il + 30% flyash + 4% lime	0.120	$0.12 \times 10^{-}$	0.88×10^{-3}	2.66×10^{-6}
il + 30% flyash + 5% lime	0.098	$0.10 \times 10^{-}$	0.75×10^{-3}	0.80×10^{-6}

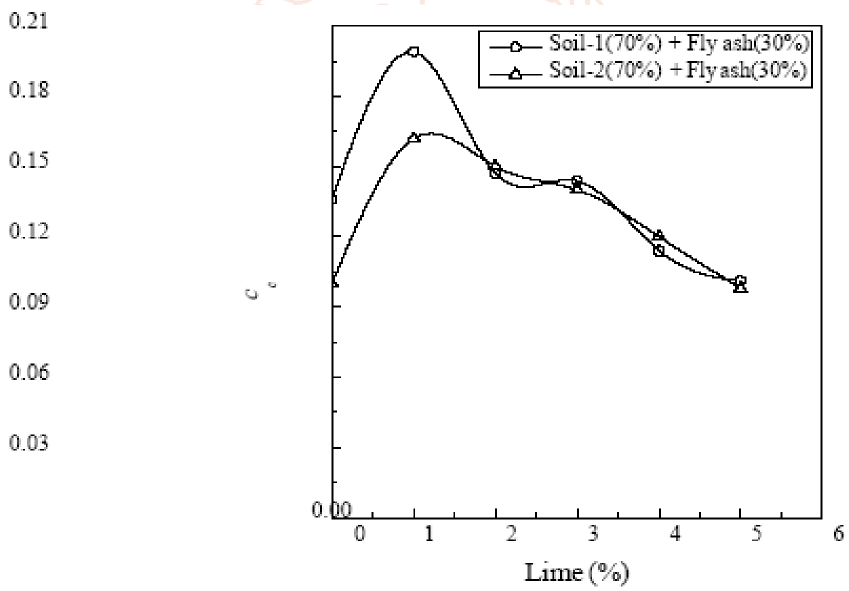

Fig.5.12 Effect of lime on the compression index of soil-fly ash mixture

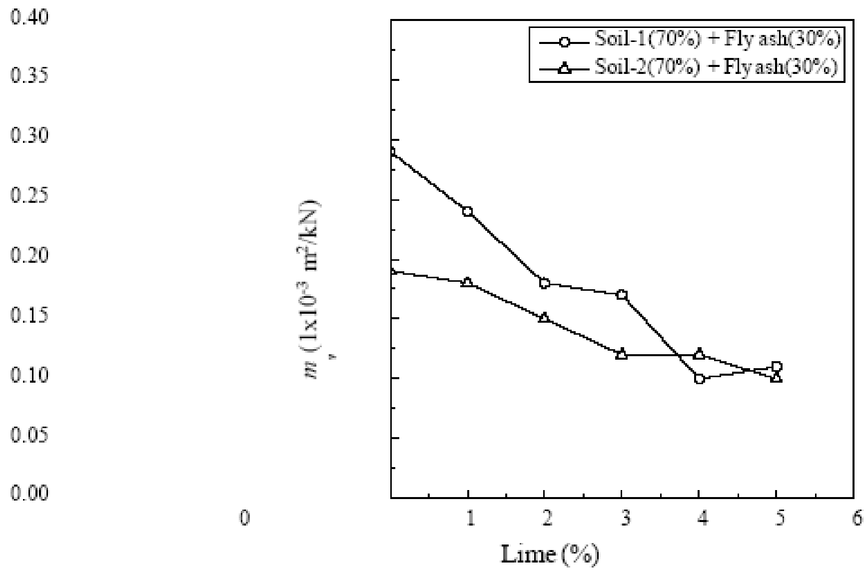

Fig.5.13 Effect of lime on the coefficient of volume change of soil-fly ash mixture

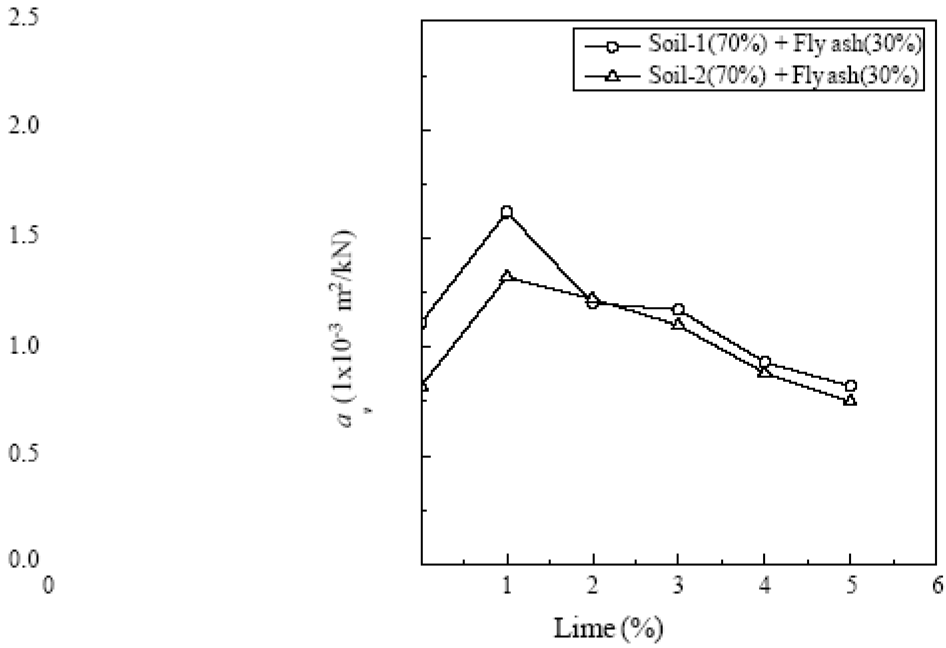

Fig.5.14 Effect of lime on the coefficient of compressibility of soil-fly ash mixture

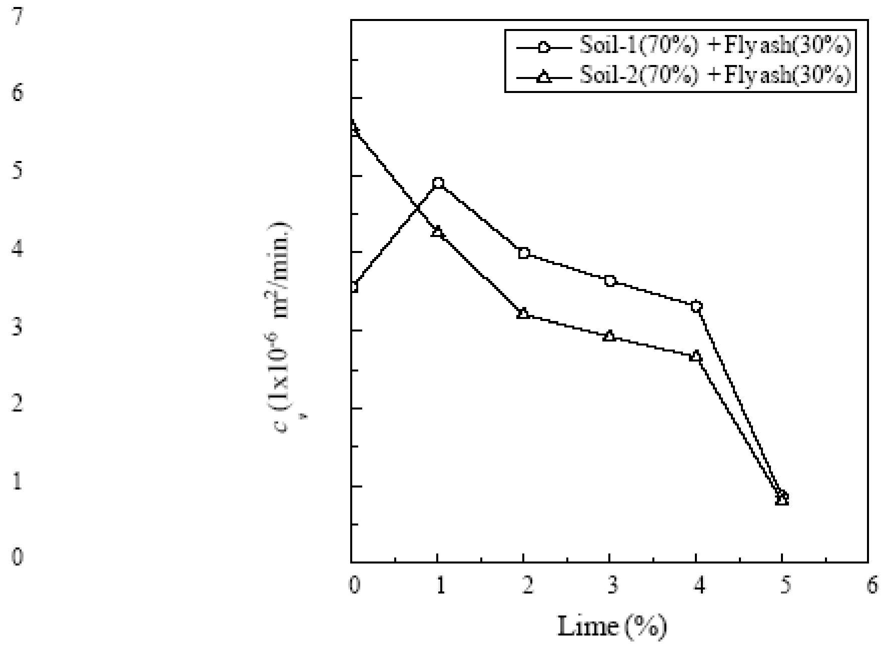

Fig.5.15 Effect of lime on the coefficient of consolidation of soil-fly ash mixture

Pozzolanic reaction between fly ash and soil particles, form granular particles by which the plasticity and liquid limit of the mixture decreases. When lime is added to the soil-fly ash mixture, the lime enters in to the soil-fly ash particles and fills the pore spaces between the particles. As a result, the voids inside the mixture reduce. Again by addition of lime, the compressibility characteristics of the mixture gets reduced, this is due to the agglomeration formations of soils treated with fly ash and lime, which results in stronger lime particle agglomerates giving higher resistance to compression. Due to the above reasons the c_c, m_v, a_v and c_v of soil-fly ash-lime samples decreased gradually with the increase of lime content (Figs. 4.46 to 4.49).

Kumar and Janewo (2016) noticed the similar trends of decreasing of voids ratio (e), c_c, m_v and a_v by the increase of percentage of cement kiln dust (CKD) and RBI grade 81 (stabilizer) in the clayey soil. They reported that the values of compression index and void ratio decrease for the mix of 81% clay + 15% CKD + 4% RBI Grade 81 as compared to original clayey soil.

Drainage characteristics

The coefficient of permeability (*k*) of soil-fly ash-lime mixtures are reported in Table 4.33. The Fig.4.50 shows the effect of lime on the coefficient of permeability of soil-fly ash specimen.

Table 5.13: Coefficient of permeability of soil-fly ash-lime mixture

Sample reference	Soil – 1	Soil – 2
	k (m/min.)	*k* (m/min.)
70% soil + 30% fly ash	1.03 x 10^{-8}	1.07 x 10^{-8}
70% soil + 30% fly ash + 1% lime	1.176 x 10^{-8}	0.765 x 10^{-8}
70% soil + 30% fly ash + 2% lime	0.718 x 10^{-8}	0.48 x 10^{-8}
70% soil + 30% fly ash + 3% lime	0.62 x 10^{-8}	0.35 x 10^{-8}
70% soil + 30% fly ash + 4% lime	0.331 x 10^{-8}	0.32 x 10^{-8}
70% soil + 30% fly ash + 5% lime	0.095 x 10^{-8}	0.08 x 10^{-8}

The coefficient of permeability of soil-fly ash-lime samples gradually decrease with increase in lime content. It may be due to the pozzolanic reaction of fly ash with the soil particles forming granular particles which allow the water to flow. But by addition of lime to the soil- fly ash mixtures, the lime enters in to the soil-fly ash particles, reduces the effective void space and develops cementitious bond.

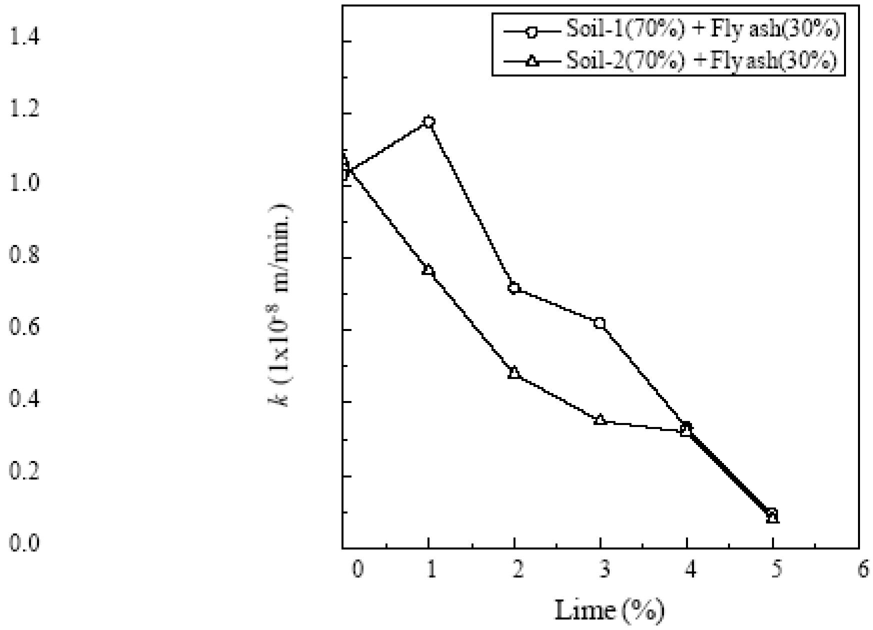

Fig.5.16 Effect of lime on the coefficient of permeability of soil-fly ash mixture

Effects of Dolochar and Lime Addition on Characteristics of ExpansiveSoils

Specific gravity

Table 4.34 shows the specific gravity of soil-dolochar-lime mixtures. Like soil-fly ash-lime mixture, the specific gravity of soil-dolochar-lime mixture increases with the increase of limecontent.

Table 5.14: Specific gravity of soil-dolochar-lime mixture

Sample reference	Soil – 1	Soil – 2
70% soil + 30% dolochar	2.88	3.01
70% soil + 30% dolochar + 1% lime	2.91	3.08
70% soil + 30% dolochar + 2% lime	2.93	3.10
70% soil + 30% dolochar + 3% lime	2.95	3.11
70% soil + 30% dolochar + 4% lime	2.98	3.12
70% soil + 30% dolochar + 5% lime	3.07	3.16

Consistency characteristics

The liquid limit (L.L.), plastic limit (P.L.) and plasticity index (P.I.)of soil-dolochar- lime mixtures are reported in the Table 5.15. The liquid limit, plastic limit and plasticity index of soil-dolochar-lime mixtures decrease with the increase in lime contents. Due to slow pozzolanic reaction of dolochar, decrease in consistency limit is not so high as in soil-fly ash-lime case.

Table 5.15: Consistency characteristics of soil-dolochar-lime mixture

Sample reference	Soil – 1			Soil – 2		
	L.L. (%)	P.L. (%)	P.I. (%)	L.L. (%)	P.L. (%)	P.I. (%)
% soil + 30% dolochar	45	22	23	25	1	7
70% soil + 30% dolochar + 1% lime	46	24	22	24	1	7
70% soil + 30% dolochar + 2% lime	44	23	21	22	1	6
70% soil + 30% dolochar + 3% lime	42	22	20	21	1	5
70% soil + 30% dolochar + 4% lime	41	21	20	20	--	NP
70% soil + 30% dolochar + 5% lime	39	20	19	19	--	NP

The decrease in consistency limit (L.L, P.L. and P.I.) with the increase of lime content may be due to the following causes;

a. Addition of lime and water to soil-dolochar mixed samples leads to cation exchange reaction,resulting the flocculation and agglomeration of clay particles.

The present study revealed that, at 5% lime content, the L.L., P.L. and P.I. of soil-1- dolochar-lime are decreased by 30%, 29% and 32% as compare to soil-1 alone,

whereas the soil-2 shows non-plastic characteristic at 30% dolochar and 5% of lime content.

Swelling characteristics

The swelling characteristics of soil-dolochar-lime mixtures have been studied through free swell index (FSI) tests. The effects of lime on the FSI values of soil- dolochar-lime samples are shown in Fig.5.17. From the figure it is observed that the FSI of soil-dolochar-lime mixtures decrease with the increase in lime content in the mixture.

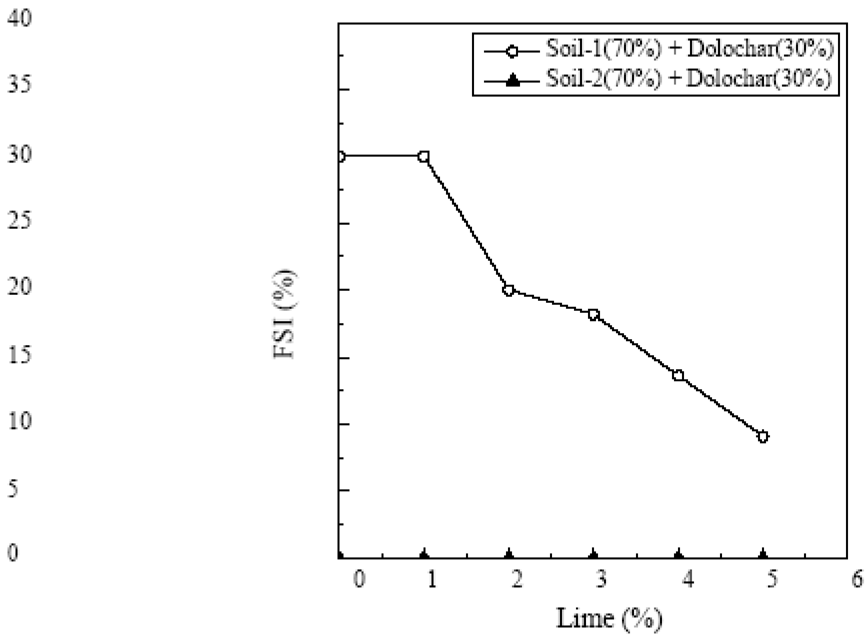

Fig.5.17 Effect of lime on the free swell index of soil-dolochar mixture

In case of soil-1, at 1% lime content, the FSI value of soil-dolochar-lime sample of soil-1 has no change. But further increase in lime content the FSI of soil-dolochar- lime samples of soil-1 is gradually reduced to 9.09% at 5% lime content. In case of soil-2, no FSI is observed withaddition of lime to soil-dolochar mixed samples. The reduction in free swell index of the soil may be due to the physico-chemical reaction between the soil and the dolochar/lime blend, which leads to the formation of calcium silicate in the soil, resulting the neutralization of the net clay layer,

The similar trend of decrease in FSI was reported by Etim (2015). In the present study, at 30% dolochar and 5% lime content, the FSI of soil-1 and soil-2 are decreased by 85% and 100% respectively as compared to soil alone.

Compaction characteristics

The compaction curves of soil-dolochar-lime mixtures of soil-1 and soil-2 are presented in Figs. 5.18 and 5.19 respectively.

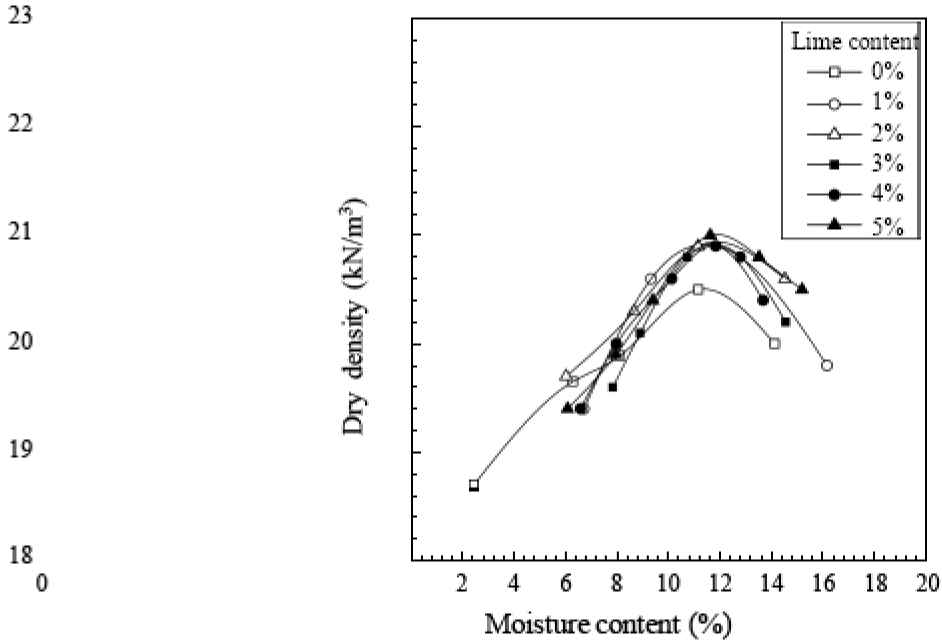

Fig.5.18 Compaction curves of soil-1- dolochar - lime mixture

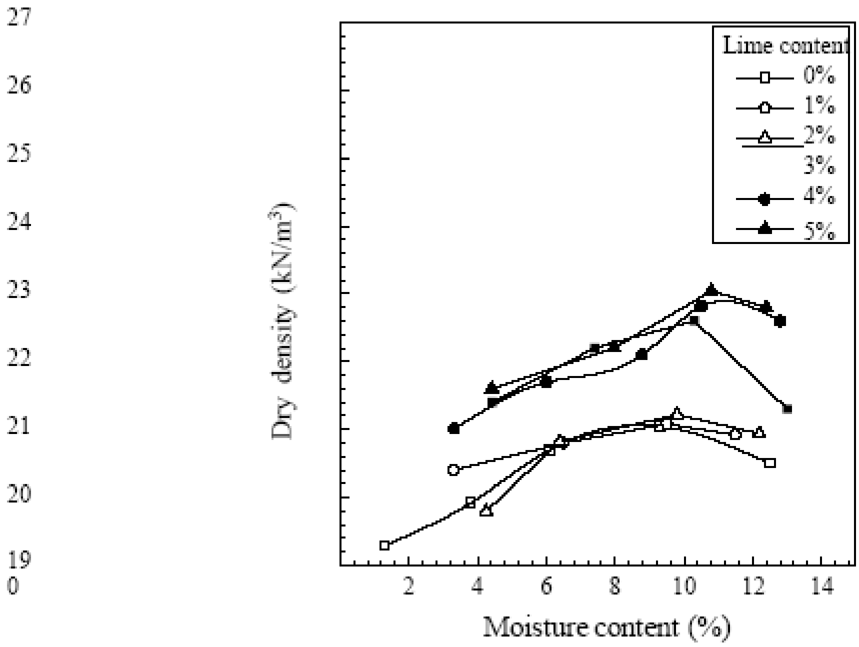

Fig.5.19 Compaction curves of soil-2 - dolochar - lime mixture

Table 5.16: Compaction characteristics of soil-dolochar-lime mixture

Sample reference	Soil – 1		Soil – 2	
	OMC (%)	MDD (kN/m^3)	OMC (%)	MDD (kN/m^3)
70% soil + 30% dolochar	11.2	20.5	9.3	21.05
70% soil + 30% dolochar + 1%lime	11.9	20.85	9.5	21.08
70% soil + 30% dolochar + 2%lime	11.9	20.86	9.8	21.22
70% soil + 30% dolochar + 3%lime	12.0	20.88	10.3	22.60
0% dolochar + 4% lime	12.1	20.90	10.5	22.82
70% soil + 30% dolochar + 5%lime	12.4	20.93	10.8	23.04

The compaction characteristics of soil-dolochar-lime mixtures are reported in Table.

5.16. The OMC and MDD of soil-1 with 30% dolochar content are 11.2% and

20.5 kN/m^3 respectively, whereas, the OMC and MDD of soil-2 with 30% dolochar content are 9.3% and 21.05 kN/m^3 respectively. With the increase in lime content in the soil- dolochar-lime samples, the OMC and MDD gradually increases.

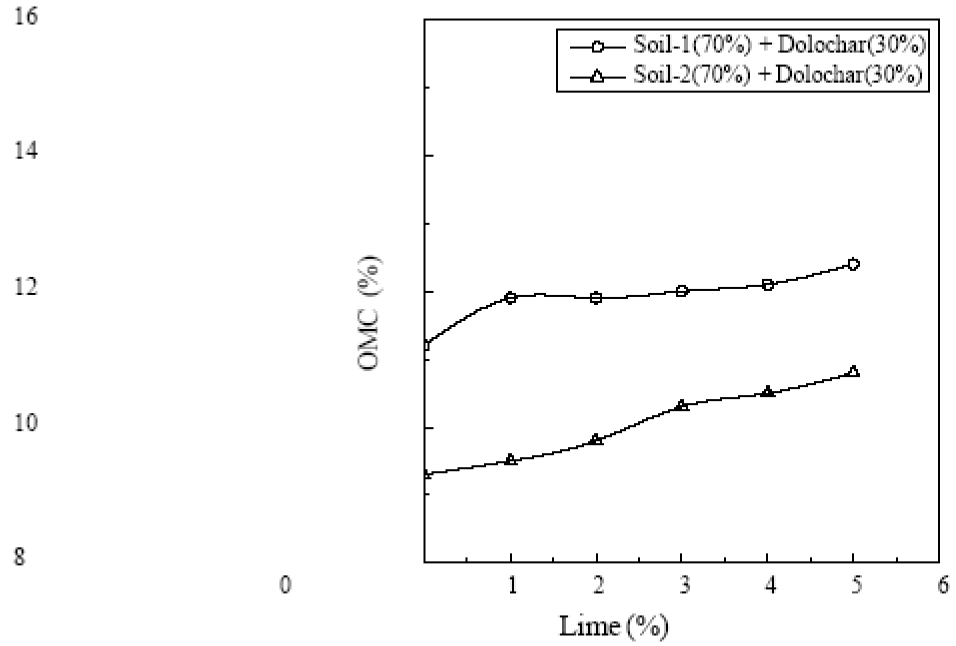

Fig.5.20 Effect of lime on the optimum moisture content of soil-dolochar mixture

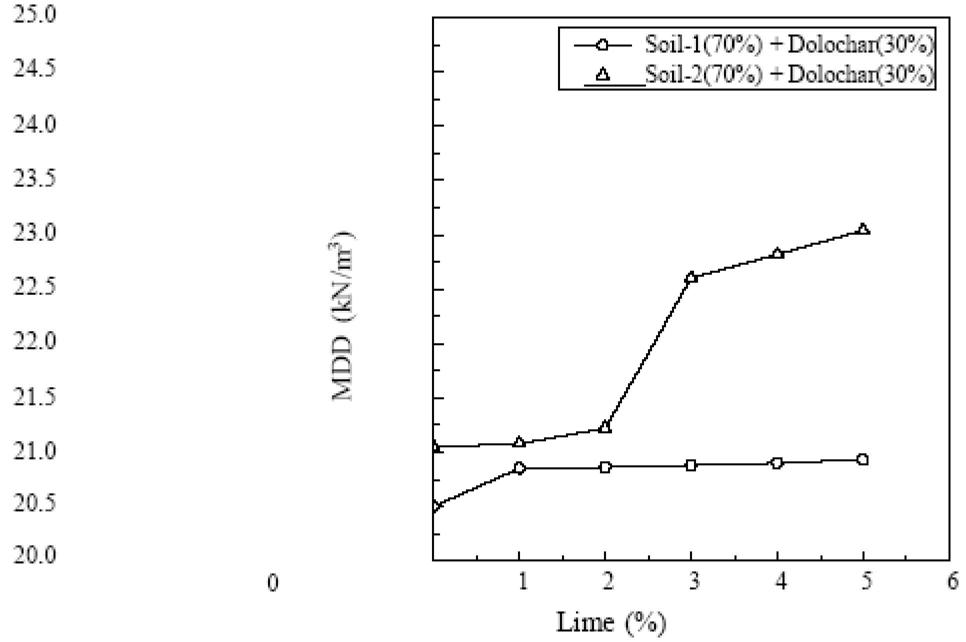

Fig.5.21 Effect of lime on the maximum dry density of soil-dolochar mixture

Figs. 4.54 and 4.55 presented the effects of lime on OMC and MDD of soil- dolochar-lime mixtures respectively. The increase of MDD may be due to the increase of specific gravity of soil-dolochar-lime mixture with the increase of lime content. At 30% dolochar and 5% lime, the MDD of soil-1 and soil-2 is increased by 18% and 23% respectively compared to that of the soil.

Strength characteristics

The strength characteristics of soil-dolochar-lime samples are studied by conducting a series of California bearing ratio (CBR), unconfined compressive strength (UCS) and shear strength(Triaxial compression) tests and the effect of lime on such strength characteristics is discussed in the following sections.

California bearing ratio (CBR)

Remoulded specimens of soil-dolochar-lime at different percentages of lime are subjected to CBR tests as per procedure elaborated at section 3.5.6. The soaked CBR of stabilized soil mixtures at different soaking periods are reported in Table 5.17 and Table 5.18. Figs. 5.22 and 5.23 indicated the effects of lime on the CBR at different soaking periods of soil- dolochar mixture with different percentage of lime. For a given percentage of lime content, the soaked CBR increases with the increase of soaking periods. Again this soaked CBR of soil-dolochar-lime mixtures increases with the increase in lime content and achieves the maximum value at 4% lime content. Addition of lime beyond 4% doesn‘t cause any significant change in CBR values.

The increase of CBR with the increase of lime content and soaking periods may be due thefollowing reasons;

A. Lime enhances the pozzolanic reaction between soil and dolochar particles, resultingformation of granular particles.
B. Again, the lime entering in to the voids of soil-dolochar particles makes a cementitious bondwhich is much stronger,
C. In presence of water, the strength of the cementitious bond increases with the increase ofsoaking periods.

Table 5.17: California bearing ratio of soil-1-dolochar-lime mixture

Sample reference	Soaked CBR (%)					
	4 days	7 days	14 days	21 days	28 days	56 days
70% soil + 30%dolochar	9.17	---	---	---	---	---
70% soil + 30% dolochar + 1% lime	14.54	19.16	32.73	39.6	51.33	59.91
70% soil + 30% dolochar + 2% lime	16.5	24.22	36.49	44.16	54.80	63.26
70% soil + 30% dolochar + 3% lime	21.89	37.33	41.64	49.94	61.99	65.9
70% soil + 30% dolochar + 4% lime	27.86	41.97	59.1	65.86	69.27	75.57
70% soil + 30% dolochar + 5% lime	30.23	45.62	61.47	66.86	68.23	71.59

Table 5.18: California bearing ratio of soil-2-dolochar-lime mixture

Sample reference	Soaked CBR (%)					
	4 days	7 days	14 days	21 days	28 days	56 days
70% soil + 30%dolochar	13.8	---	---	---	---	---
70% soil + 30% dolochar + 1% lime	20.42	28.92	38.60	49.70	58.63	68.44
70% soil + 30% dolochar + 2% lime	26.88	39.60	47.55	55.78	64.52	73.88
70% soil + 30% dolochar + 3% lime	31.60	47.22	53.32	62.88	72.80	78.62
70% soil + 30% dolochar + 4% lime	37.22	51.60	61.20	78.42	82.55	85.60
70% soil + 30% dolochar + 5% lime	40.15	55.28	64.75	76.60	80.10	82.22

In the present study, the 4 days soaked CBR of virgin soil-1 increase from 3.61 to 27.86% (increase by 672%) by the addition of 30% dolochar and 4% lime. Whereas, the 4 days soaked CBR of virgin soil-2 increase from 5.25 to 37.22% (increase by 609%) for the mixture containing 30% dolochar and 4% lime.

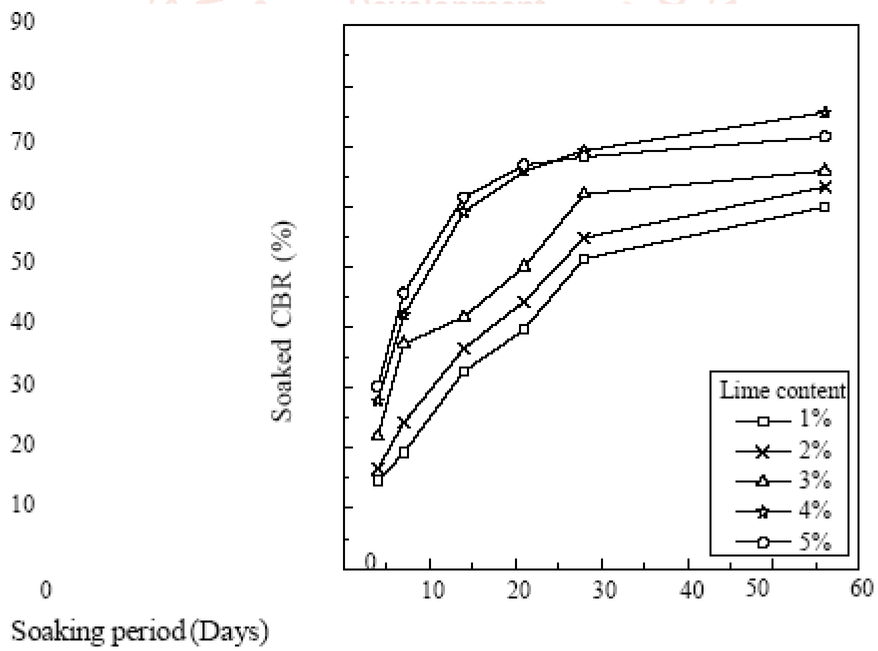

Fig.5.22 Effect of lime on the CBR at different soaking periods of soil-1 - dolochar mixture

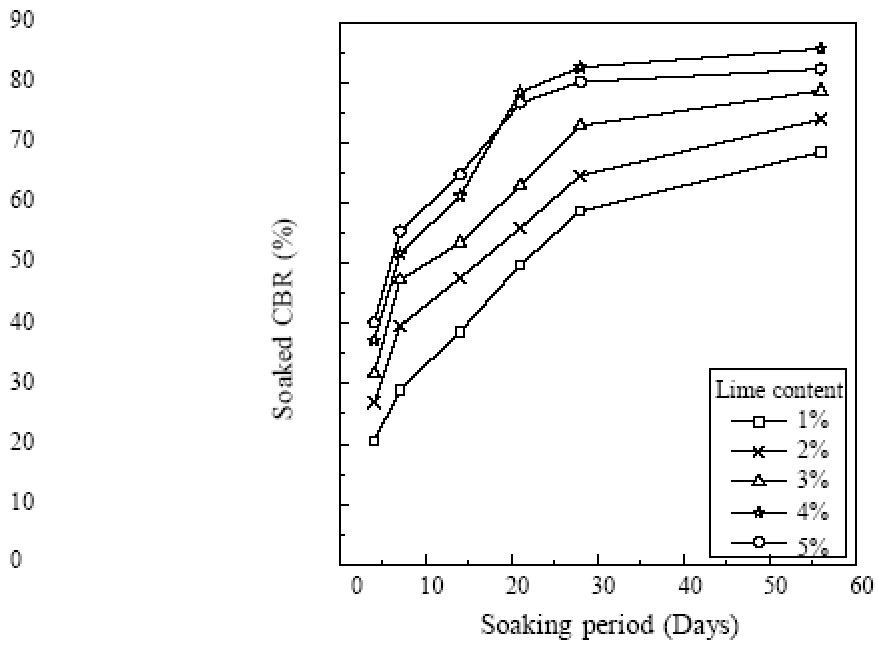

Fig.5.23 Effect of lime on the CBR at different soaking periods of soil-2 - dolochar mixture

Unconfined compressive strength (UCS)

The UCS of soil-dolochar-lime mixtures at different curing periods as per test conducted are reported in Table 5.18 and Table 5.19. The effects of lime on the UCS soil-dolochar-lime mixture at different curing periods are presented in Figs. 5.24 and

5.25. For a given percentage of lime content, the UCS of soil-dolochar-lime mixture increases with the increase of curing periods. It is also noticed that the UCS of soil- dolochar-lime mixture increases with the increase of lime content and achieve maximum value at 4% lime content after which UCS decreases with any further increase of lime.

Table 5.19: UCS of soil-1-dolochar-lime mixture

Sample reference	UCS (kPa) At the different periods (days) of moist curing					
	4 days	7 days	14 days	21 days	28 days	56 days
70% soil + 30% dolochar + 1% lime	30	33	53	60	72	84
70% soil + 30% dolochar + 2% lime	34	45	56	68	78	95
70% soil + 30% dolochar + 3% lime	52	72	114	118	125	155
70% soil + 30% dolochar + 4% lime	60	115	138	162	180	220
70% soil + 30% dolochar + 5% lime	75	108	132	153	170	192

The following may be the causes for the increasing of UCS of samples;

A. Due to the physico-chemical reaction of lime, a cementitious bond with the soil and dolocharparticles in the presence of water is achieved.
B. The strength of the cementitious bonds increase with the increase of lime content and curingperiods.
C. With curing, compounds like calcium silicate hydrate and calcium aluminate hydrate areformed,
D. In presence of excess lime (more than the optimum quantity), a non-cohesive characteristic isdeveloped which reduces the strength among particles of soil-dolochar-lime mixture.

Table 5.20: UCS of soil-2-dolochar-lime mixture

Sample reference	UCS (kPa) At the different periods (days) of moist curing					
	4 days	7 days	14 days	21 days	28 days	56 days
70% soil + 30% dolochar + 1% lime	22	27	35	46	58	77
70% soil + 30% dolochar + 2% lime	25	28	40	51	62	82
70% soil + 30% dolochar + 3% lime	35	58	89	102	115	145
70% soil + 30% dolochar + 4% lime	72	101	109	140	161	185
70% soil + 30% dolochar + 5% lime	60	92	102	133	150	171

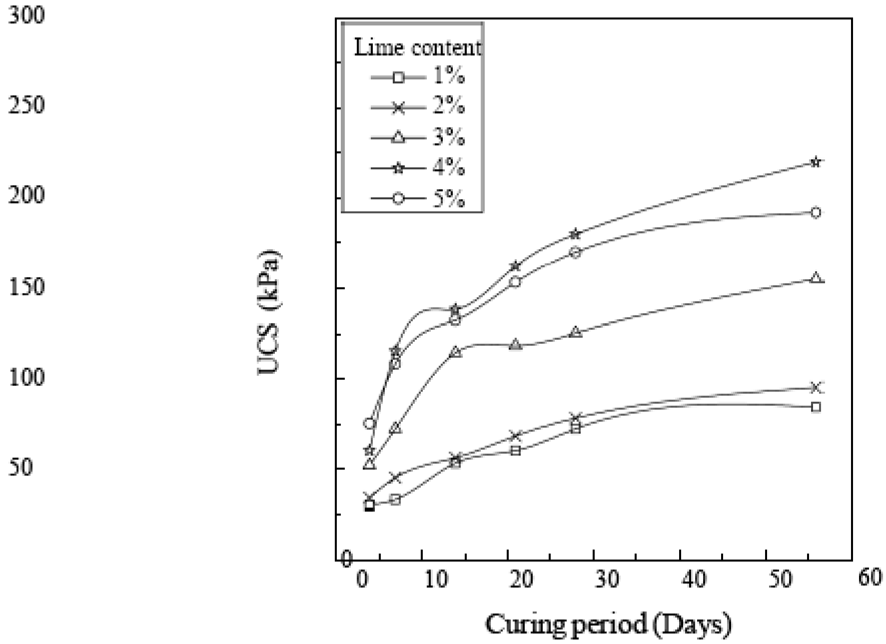

Fig.5.24 Effect of lime on the UCS at different curing periods of soil-1 - dolochar mixture

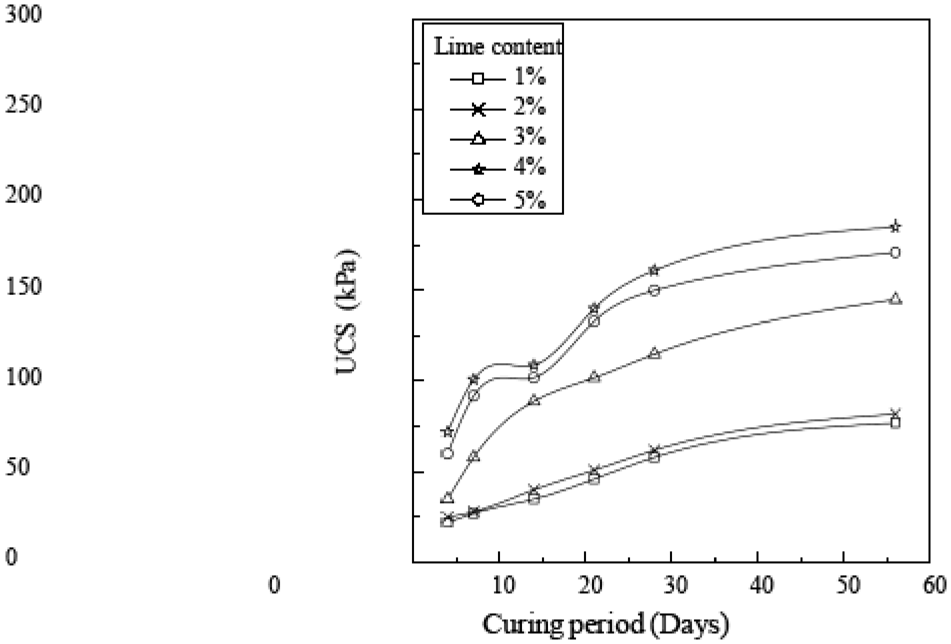

Fig.5.25 Effect of lime on the UCS at different curing periods of soil-2 - dolochar mixture

In the present study, the UCS of soil-dolochar-lime mixture of soil-1 is more than that ofsoil-dolochar-lime mixture of soil-2, it may be soil-1 has more clay content than that of soil-

2. At 56 day moist curing, the UCS of soil-1 (70%) + dolochar (30%) + lime (4%) is 220kPa, whereas, the UCS of soil-2 (70%) + dolochar (30%)

+ lime (4%) is 185 kPa.

Shear strength (Triaxial compression)

Table 5.21 indicates the shear strength characteristics of soil-dolochar-lime mixtures. The effects of lime on the cohesion (*c*) and angle of shearing resistance ( ) of soil-dolochar-lime mixtures are presented in Figs. 5.26 and 5.27 respectively. The cohesion of the soil-dolochar-lime mixture increases with the increase in lime content and attains an optimum value at 4% lime content and thereafter decreases at 5% lime content. But the angle of shearing resistanceof soil-dolochar-lime mixture increases with the increase in the lime content.

Table 5.21: Shear strength of soil-dolochar-lime mixture

Sample reference	Soil – 1		Soil – 2	
	c (kPa)	φ (degree)	*c* (kPa)	φ (degree)
% soil + 30% dolochar	30	15	21	25
70% soil + 30% dolochar + 1%lime	75	16	38	25
70% soil + 30% dolochar + 2%lime	82.	20	50	28
70% soil + 30% dolochar + 3%lime	95	20	60	35
70% soil + 30% dolochar + 4%lime	117.	22	75	38
70% soil + 30% dolochar + 5%lime	105	24	71	40

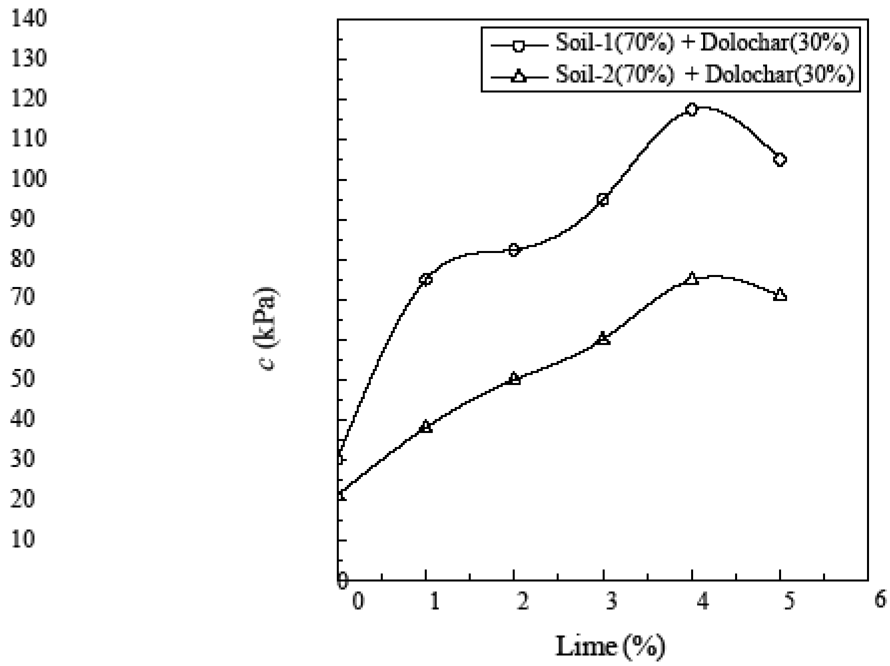

Fig.5.26 Effect of lime on the cohesion of soil-dolochar mixture

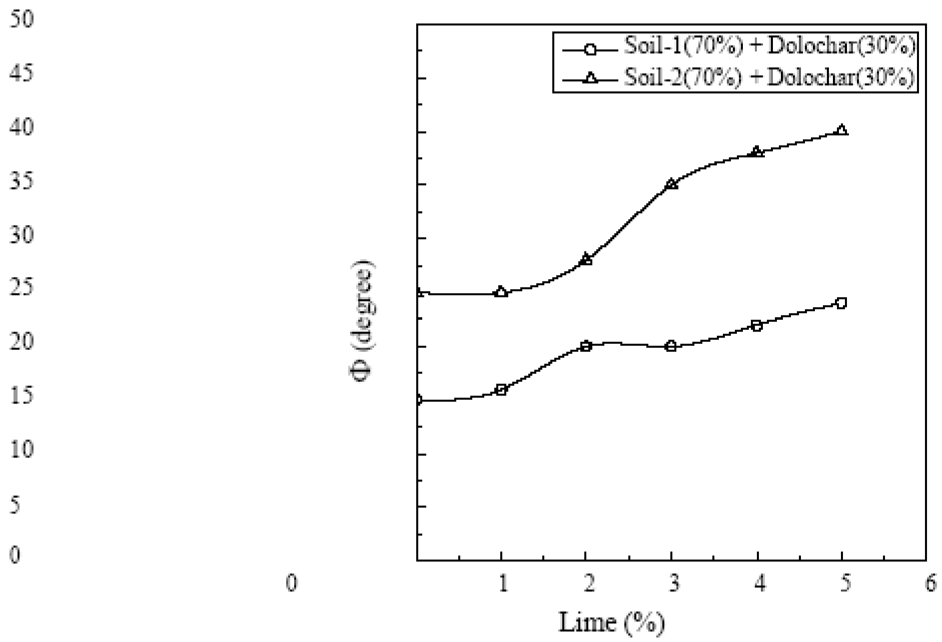

Fig.5.27 Effect of lime on the angle of shearing resistance of soil-dolochar mixture

The increase and decrease of shear strength may be due to the following causes;

A. Due to the pozzolanic reaction of lime and dolochar, granular particles are created with the soil mass, thereby the angle of shearing resistance is increased.
B. In the presence of water, lime makes a cementitious bond with the soil and dolochar.
C. The strength of the cementitious bond increases with the increase of lime and curing periodsin water.
D. Presence of more lime than the optimum content, develops the non-cohesive characteristic which eventually decreases the cohesion between the soil particles.

In the present investigation, it is seen that the cohesion of soil-dolochar-lime mixture increases at 4% lime content. At 30% dolochar and 4% lime content, the cohesion of soil-1 and soil-2 are increased by 2.1 and 1.7 times respectively, whereas the angle of shearing resistance of soil-1 and soil-2 increased by 3.67 and 3.8 times respectively as compared to soil alone.

Consolidation characteristics

The consolidation properties such as compression index (c_C), coefficient of volume change (m_V), coefficient of compressibility (a_V) and coefficient of consolidation (c_V) of soil-dolochar- lime mixtures are reported in Table 5.22 and Table 5.23. The effects of lime on the different consolidation properties of soil-dolochar-lime mixtures are presented in Figs. 5.28 to 5.31. The c_C, m_V, a_V and c_V of soil-dolochar-lime mixtures decrease with the increase of lime content.

Table 5.22: Consolidation characteristics of soil-1-dolochar-lime mixture

Sample reference	c_C	m_V (m^2/kN)	a_V (m^2/kN)	c_V (m^2/min.)
70% soil + 30% dolochar	0.155	0.30 x 10^{-3}	1.26 x 10^{-3}	3.75 x 10^{-}
70% soil + 30% dolochar + 1% lime	0.161	0.22 x 10^{-3}	1.31 x 10^{-3}	2.65 x 10^{-}
70% soil + 30% dolochar + 2% lime	0.121	0.17 x 10^{-3}	0.99 x 10^{-3}	2.41 x 10^{-}
70% soil + 30% dolochar + 3% lime	0.114	0.14 x 10^{-3}	0.93 x 10^{-3}	1.10 x 10^{-}
70% soil + 30% dolochar + 4% lime	0.111	0.10 x 10^{-3}	0.91 x 10^{-3}	0.96 x 10^{-}
70% soil + 30% dolochar + 5% lime	0.101	0.11 x 10^{-3}	0.82 x 10^{-3}	0.59 x 10^{-}

The decrease of c_C, m_V, a_V and c_V of soil-dolochar-lime samples with increase of lime contents have the same reasons as in the case of soil-fly ash-lime samples. Lime particles enter in to the soil-dolochar particles and fill the pore spaces between the particles by which the voids inside the mixtures decrease. As a result, particles are closely packed with each other and create a strong bond. Due to the cementitious property of lime, these bonds become stronger in presence of water. As a result it gives higher resistance to compression which increases with the increase in lime content.

Table 5.23: Consolidation characteristics of soil-2-dolochar-lime mixture

Sample reference	c_C	m_V (m^2/kN)	a_V (m^2/kN)	c_V (m^2/min.)
70% soil + 30% dolochar	0.120	0.17 x 10^{-3}	0.98 x 10^{-}	7.34 x 10^{-}
70% soil + 30% dolochar + 1% lime	0.140	0.20 x 10^{-3}	1.10 x 10^{-}	3.65 x 10^{-}
70% soil + 30% dolochar + 2% lime	0.132	0.18 x 10^{-3}	0.92 x 10^{-}	2.88 x 10^{-}
70% soil + 30% dolochar + 3% lime	0.120	0.15 x 10^{-3}	0.84 x 10^{-}	2.10 x 10^{-}
70% soil + 30% dolochar + 4% lime	0.100	0.14 x 10^{-3}	0.78 x 10^{-}	1.31 x 10^{-}
70% soil + 30% dolochar + 5% lime	0.098	0.10 x 10^{-3}	0.66 x 10^{-}	1.20 x 10^{-}

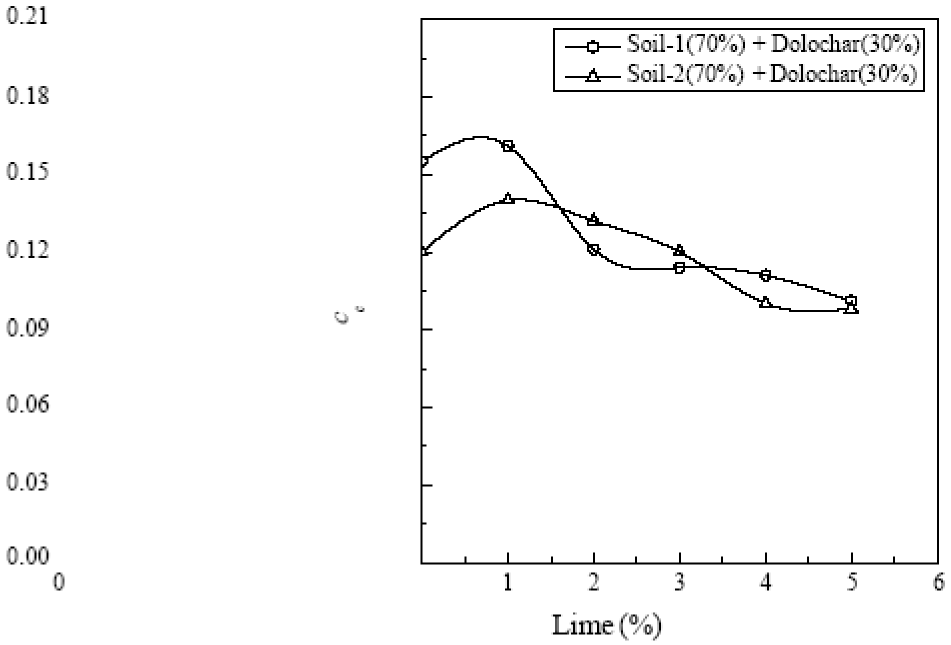

Fig.5.28 Effect of lime on the compression index of soil-dolochar mixture

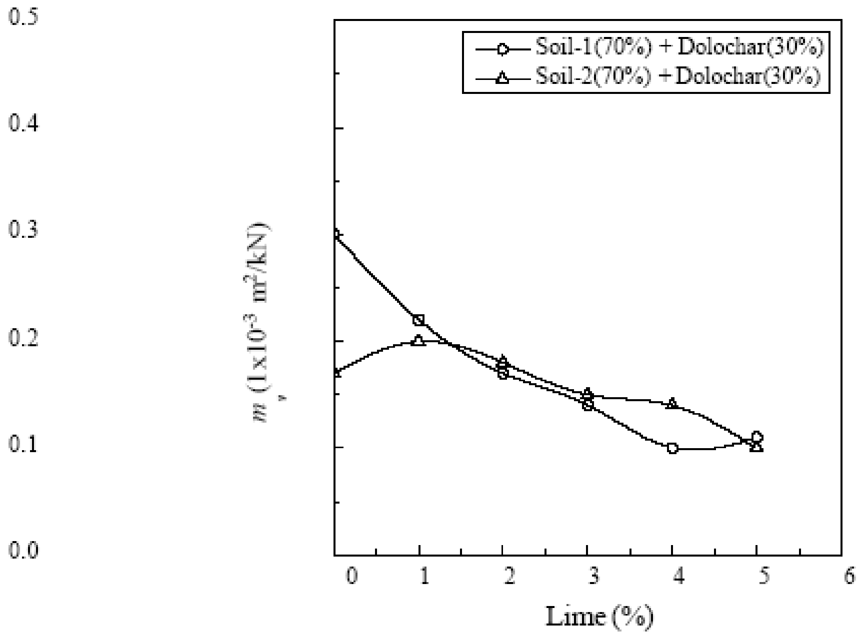

Fig.5.29 Effect of lime on the coefficient of volume of soil-dolochar mixture

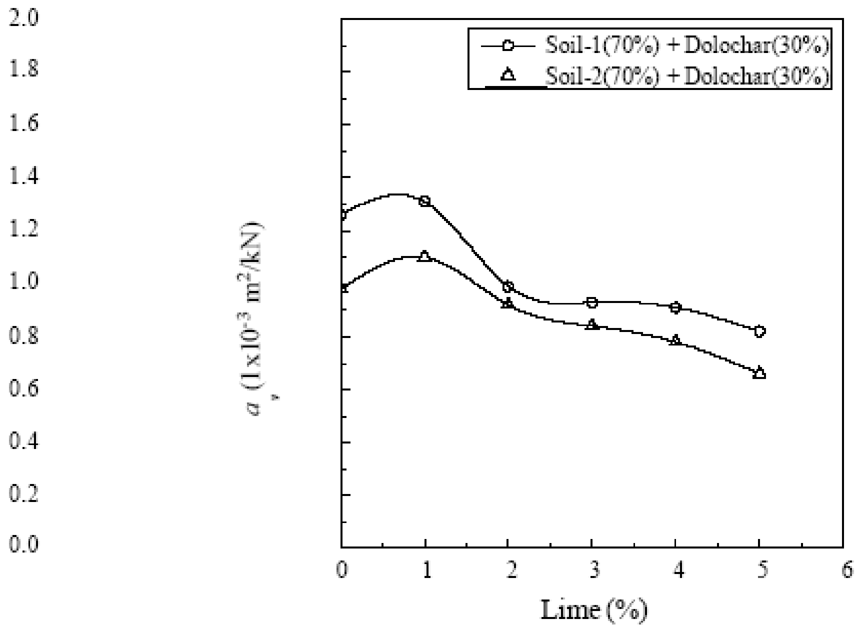

Fig.5.30 Effect of lime on the coefficient of compressibility of soil-dolochar mixture

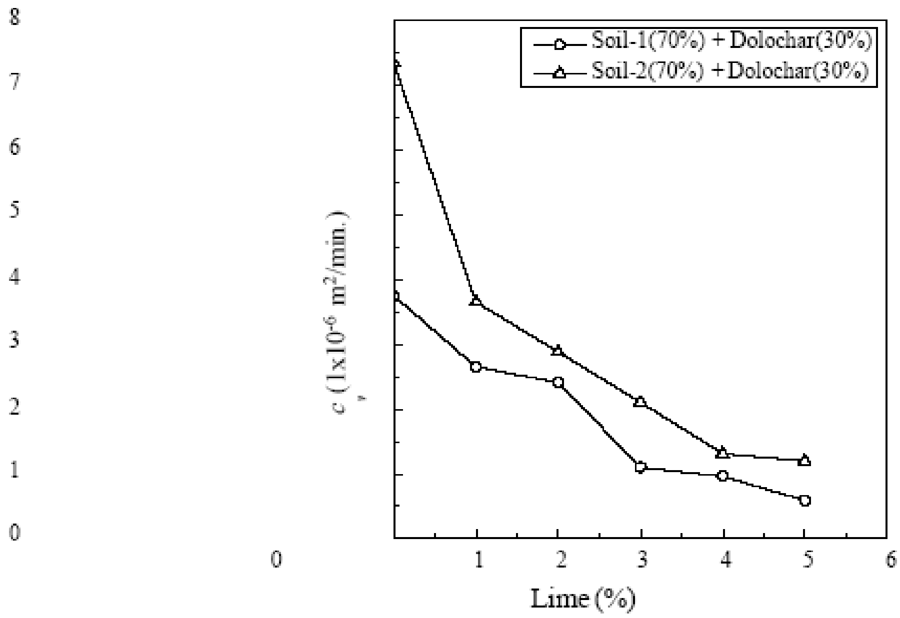

Fig.5.31 Effect of lime on the coefficient of consolidation of soil-dolochar mixture

Drainage characteristics

The coefficient of permeability (*k*) of soil-dolochar-lime mixtures of soil-1 and soil-2 are reported in Table 5.24. The effects of lime on the coefficient of permeability of soil- dolochar-lime mixture are shown in Fig.5.32.

Table 5.24: Coefficient of permeability of soil-dolochar-lime mixture

Sample reference	Soil – 1	Soil – 2
	k (m/min.)	*k* (m/min.)
70% soil + 30% dolochar	1.12×10^{-8}	1.25×10^{-8}
70% soil + 30% dolochar + 1%lime	0.58×10^{-8}	0.83×10^{-8}
0% dolochar + 2% lime	0.41×10^{-8}	0.52×10^{-8}
0% dolochar + 3% lime	0.15×10^{-8}	0.32×10^{-8}
70% soil + 30% dolochar + 4%lime	0.10×10^{-8}	0.18×10^{-8}
70% soil + 30% dolochar + 5%lime	0.06×10^{-8}	0.12×10^{-8}

It is seen that the coefficient of permeability of soil-dolochar-lime mixtures decrease with increase in lime content. The lime enters in to the soil-dolochar particles and influences the pore size distribution of the mixtures. As a result, particles of the soil mixture get compacted and thereby resist the flow of water through it. Since the soil- 1 has more clay content than that of soil-2, the coefficient of permeability of soil- dolochar-lime mixture of soil-1 is less than that of soil-2.

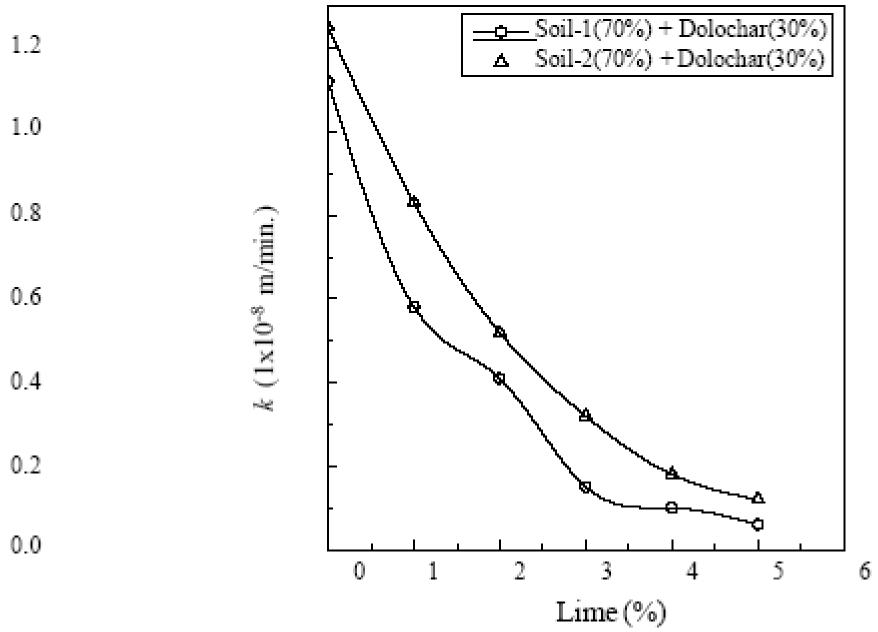

Fig.5.32 Effect of lime on the coefficient of permeability of soil-dolochar mixture

Optimum Soil-Fly Ash-Lime/Soil-Dolochar-Lime Mixture

The effect of lime on the geotechnical characteristics of soil-fly ash and soil- dolochar samples are reported in the previous sections through various tables

and figures. Considering the consistency, swelling, compaction and strength characteristicsof soil-fly ash-lime and soil- dolochar-lime mixtures, the better results are obtained both for soil-fly ash-lime and soil-dolochar-lime mixtures in the proportions of 70:30:4. Thus the 70:30:4 proportions for soil-fly ash-lime or soil-dolochar-lime mixture is considered as optimum proportion of the mixtures. The summary of geotechnical properties, microstructure and the leaching potential of the soil-fly ash-lime and soil-dolochar- lime mixtures in the proportions of 70:30:4 are reported separately in subsequent sections.

Summary of geotechnical properties of optimum mixture

The summary of geotechnical properties of soil-fly ash-lime and soil-dolochar-lime mixtures at the proportion of 70:30:4 vis-à-vis parent expansive soils and ideal mixture of soil with fly ash and dolochar are reported in Table 5.25 to Table 5.28. From the tables appreciable improvement in all geotechnical properties are observed

Table 5.25: Summary of geotechnical properties of soil-fly ash and soil-fly ash-lime mixture for soil-1

Geotechnicalproperties	Soil-1	70% soil-1 + 30% flyash	70% soil-1 + 30% fly ash + 4% lime
Specific gravity	2.69	2.58	2.70
L. L. (%) P. L. (%) P. I. (%)	56.00 28.00 28.00	48.75 31.96 16.79	43.00 22.00 21.00
FSI (%)	60.00	8.33	0
OMC (%) MDD (kN/m^3)	16.10 17.80	24.45 15.94	23.60 16.65
CBR (%) (4-days Soaking)	3.61	8.16	29.74
UCS (kPa) (9-days curing)	149.0	108.7	112.0 (7-days curing)
c (kPa) (degree) (9-days curing)	56.0 6	24.0 15	122.5 19
c_c m_v (m^2/kN) a_v (m^2/kN) c_v (m^2/min.)	0.298 $0.39x10^{-3}$ $2.43x10^{-3}$ $1.31x10^{-6}$	0.136 $0.29x10^{-3}$ $1.11x10^{-3}$ $3.55x10^{-6}$	0.114 $0.10x10^{-3}$ $0.93x10^{-3}$ $3.31x10^{-6}$
k (m/min.)	$0.51x10^{-8}$	$1.03x10^{-8}$	$0.331x10^{-8}$

Table 5.26: Summary of geotechnical properties of soil-fly ash and soil-fly ash-lime mixture for soil-2

Geotechnicalproperties	Soil-2	70% soil-2 + 30% fly ash	70% soil-2 + 30% fly ash + 4% lime
Specific gravity	2.70	2.61	2.74
L. L. (%) P. L. (%) P. I. (%)	33 18 15	22 --- NP	18 --- NP
FSI (%)	20	0	0
OMC (%) MDD (kN/m^3)	11.5 18.80	15.8 17.52	14.1 18.46
CBR (%) (4-days Soaking)	5.25	11.40	35.33
UCS (kPa) (9-days curing)	110.0	35.5	82.0 (7-days curing)
c (kPa) (degree) (9-days curing)	44 10	18 24	65 31
c_c m_v (m^2/kN) a_v (m^2/kN) c_v (m^2/min.)	0.198 $0.35x10^{-3}$ $1.61x10^{-3}$ $2.09x10^{-6}$	0.100 $0.19x10^{-3}$ $0.82x10^{-3}$ $5.62x10^{-6}$	0.120 $0.12x10^{-3}$ $0.88x10^{-3}$ $2.66x10^{-6}$
k (m/min.)	$0.73x10^{-8}$	$1.07x10^{-8}$	$0.32x10^{-8}$

Table 5.27: Summary of geotechnical properties of soil-dolochar and soil-dolochar-lime mixture for soil-1

Geotechnical properties	Soil-1	% soil-1 + 30% dolochar	70% soil-1 + 30% dolochar + 4% lime
Specific gravity	2.69	2.88	2.98
L. L. (%) P. L. (%) P. I. (%)	56 28 28	45 22 23	41 21 20
FSI (%)	60	30	13.63
OMC (%) MDD (kN/m^3)	16.1 17.8	11.2 20.5	12.1 20.9
CBR (%) (4-days Soaking)	3.61	9.17	27.86

UCS (kPa) (9-days curing)	149	150	115 (7-days curing)
c (kPa) (degree) (9-days curing)	56 6	70 5	117.5 22
cc *mv* (m^2/kN) *av* (m^2/kN *cv* (m^2/min.)	0.298 0.39×10^{-3} 2.43×10^{-3} 1.31×10^{-6}	0.155 0.30×10^{-3} 1.26×10^{-3} 3.75×10^{-6}	0.111 0.10×10^{-3} 0.91×10^{-3} 0.96×10^{-6}
k (m/min.)	0.51×10^{-8}	1.12×10^{-8}	0.10×10^{-8}

Table 5.28: Summary of geotechnical properties of soil-dolochar and soil-dolochar-lime mixture for soil-2

Geotechnical properties	Soil-2	% soil-2 + 30% dolochar	70% soil-2 + 30% dolochar + 4% lime
Specific gravity	2.70	3.01	3.12
L. L. (%) P. L. (%) P. I. (%)	33 18 15	25 18 7	20 --- NP
FSI (%)	20	0	0
OMC (%) MDD (kN/m^3)	11.5 18.8	9.3 21.05	10.5 22.82
CBR (%) (4-days Soaking)	5.25	13.8	37.22
UCS (kPa) (9-days curing)	110	32.5	101 (7-days curing)
c (kPa) (degree) (9-days curing)	44 10	21 25	75 38
cc *mv* (m^2/kN) *av* (m^2/kN) *cv* (m^2/min.)	0.198 0.35×10^{-3} 1.61×10^{-3} 2.09×10^{-6}	0.120 0.17×10^{-3} 0.98×10^{-3} 7.34×10^{-6}	0.100 0.14×10^{-3} 0.78×10^{-3} 1.31×10^{-6}
k (m/min.)	0.73×10^{-8}	1.25×10^{-8}	0.18×10^{-8}

Concluding Remarks

The results have duly been discussed at length and the probable causes of changes in the geotechnical properties due to inclusion of additives have been explained adequately. From the experimental studies, a set of conclusions has however been arrived at from the in-depth studies elaborated above and the concluding remarks are presented under Chapter V which is a part of literature on

–Stabilization of Expansive Soil‖.

CONCLUSIONS AND FUTURE SCOPE OF WORK

As a prelude to the actual investigation, the related experimental investigations including the effect of various types of additives for improving geotechnical properties of weak soil in general and expansive soil in particular, carried out by past researchers have been critically reviewed in chapter II. This review has given an insight in to the existing knowledge as well as its limitations/inadequacies, thus enabling to draw the scope and inspirations for the present study. According to the literature reviews, few studies have been done on stabilising local expansive soil with industrial wastes produced by nearby factories, and still less studies have been done on stabilising expansive soil using dolochar as an additive.

In terms of the use of dolochar, it can be said that, since all local supplies of fly ash have been exhausted, the addition of dolochar as a strengthening additive could open up vast new avenues in the engineering effort to profitably turn poor soil into a productive construction base (foundation).

A rigorous and thorough experimental investigation has been carried out in accordance with the guidelines prescribed by the Bureau of Indian Standards out came of which along with details are presented in chapter III in an exhaustive manner. The results of the above investigation have also been studied critically and have been discussed elaborately in chapter V.

The present work offers opportunity to convert waste (fly ash and dolochar) in to durable construction material through careful and appropriates blending which is substantiated adequately and elaborated substantially in the fore-going chapters, salient concluding points of which are enumerated below. .

The addition of lime to the above mixtures lowers the FSI even further. At 4% lime content, the FSI of soil-1 with 30% fly ash or dolochar content is decreased by 100% and 85% for soil-fly ash and soil-dolochar mixtures, respectively.

1. A rise in soil fly ash content raises OMC and lowers MDD. OMC improves by 52% & 37% for soil-1 and soil-2, respectively, and MDD declines by 10% & 7% for soil-1 and soil-2 at 30% fly ash content. In the case of a soil-dolochar combination, though, the pattern is in the opposite direction. OMC declines by 30% and 19% for soil-1 and soil-2, respectively, and MDD rises by 15% and 12% for soil-1 and soil-2, respectively, at 30% dolochar content.
2. As lime is added to the above mixture, the k values steadily decrease as the lime content increases.
3. The ideal mixture design proportions of soil-fly ash-lime and soil-dolochar-lime for the products used in this case were found to be 70:30:04 for the soils, fly ash, dolochar, lime, and other materials.
4. Heavy metal concentrations leached from stabilised soil with an optimal combination were found to be below reasonable limits..
5. The addition of 30% fly ash or 30% dolochar with 4% lime would significantly boost the local expansive soil for long-term use in the building of bridges, pavements, and foundations, lowering construction costs and reducing the issue of toxic waste management, which would otherwise result in environmental hazards.

Scope for Future Study

1. The characteristics of stabilised soil were investigated in this study under OMC and MDD conditions of modified Proctor compaction. The same can be investigated using moisture content other than OMC, as well as normal Proctor compaction.
2. At 7, 14, 21, 28, and 56 days of soaking, the CBR and UCS characteristics of soil-fly ash and soil-dolochar samples can be investigated.
3. To stabilise the soil-fly ash and soil-dolochar mixtures, stabilisers such as cement, bitumen, and other chemicals could be used.
4. A cost analysis of the recommended design mixture can be performed to investigate its economic aspects.

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