Long Term Strength Development of Lime Stabilized Soils

A Thesis
by
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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Dedicated

to

My Wife and Children

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ABSTRACT

To study the long term strength development of lime stabilized soils, samples were prepared using different types of soil and varying lime content and compaction condition. The unconfined compression tests were carried out on stabilized samples at 7, 28, 90, 180 and 360 days. The unconfined compressive strength of stabilized soil was also determined after soaking the specimen in water. Three types of soil, collected from Dhaka and adjacent areas, were used for the research work. Two soils were ML/CL type and the other one was CL type according to Unified Soil Classification System. Slaked lime was used as a stabilizer.

The unconfined compressive strength of the soil was increased when it was stabilized with lime. The gain in strength was found to depend on a number of factors, such as lime content, soil type, curing time, mellowing time, compaction energy etc. For a particular curing period soil stabilized with higher percentages of lime showed higher compressive strength.

The CL type soil was found more suitable for lime stabilization. It attained reasonably high strength with small quantity of lime. The unconfined compressive strength of lime treated CL type soil was higher than ML/CL type soil for a given lime content and curing period. Soil containing organic matters (about 2%) need high lime content and longer curing period for stabilization.

The strength of lime stabilized soil continued to increase with curing period. The rate of gain in strength was not constant with time. Initially the rate of gain in strength was high, after that the rate decreased. The soils stabilized with lower amount (3%) of lime did not show increase of strength after 180 days of curing period. But with higher amount of lime (5%, 7%), the strength increased beyond 180 days. The 360-day strength of the lime stabilized soil was appreciably higher than the 28-day strength. This was pronounced when stabilized with higher percentages of lime.

The decrease in strength due to compaction delay was seen to depend on soil type. The decrease in strength was less in CL type soil than that of ML/CL type soil. The reduction in 28-day strength is about 15% for 24 hours (1 day) delay in compaction. Whereas for 336 hours (14 days) delay in compaction, the reduction in strength was approximately 50% when CL type soil was stabilized with 3% lime. The decrease in strength due to retempering was found to be similar to that of compaction delay.

There was a small loss of strength of lime stabilized soil when they were immersed in water, for 7 days. For CL type soil, the ratio of soaked to unsoaked unconfined compressive strength was observed to vary between 0.71 to 0.85 depending on lime content and curing period.

CONTENTS

CHAPTER ONE

INTRODUCTION

CHAPTER TWO

LITERATURE REVIEW

CHAPTER THREE

EXPERIMENTAL INVESTIGATION

CHAPTER FOUR

RESULTS AND DISCUSSIONS

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

List of Figures

List of Tables

Notations

ASTM	American Society for Testing and Materials
AASHTO	American Association of State Highways and Transportation Officials
c	Cohesion
CBR	California Bearing Ratio
kPa	Kilopascal
kN/m^3	Kilonewton per cubic meter
LL	Liquid limit
PI	Plasticity index
PL	Plastic limit
psi	Pound per square inch
q_u	Unconfined compressive strength
w	Water content
w_n	Natural water content
γ	Unit weight
γ_d	Dry unit weight
t/m^2	Ton per square meter

CHAPTER ONE

INTRODUCTION

1.1 General

Improving in situ soil by using additives is generally referred to as stabilization (Das, 1984). The main purposes of soil stabilization are to modify engineering properties of the soil, expedite construction, improve the strength and durability of soil and reduce sensitivity to moisture (Little, 1995). In stabilizing the soil, the additive lime is often used for fine-grained soil and cement is used for coarse-grained soil. Lime stabilization has some advantages over cement stabilization. The reaction of lime with soil is slow which enables flexibility in construction (NLA, 1987). The problems of rain are also minimized as substantial proportion of the strength of lime treated soil is retained when they become saturated with water (TRL, 1993).

In Bangladesh land development activities have been increased significantly in the recent time. Every year new residential, commercial and recreational areas are being developed by raising low lands. Houses, Markets, Roads etc. are frequently being constructed on newly reclaimed ground. In the reclamation process, filling soils are generally collected from readily available borrow pits. But the properties of these soils do not always comply with the specified requirements and thus create problems in the construction phase. Longer monsoon, heavy rainfall and flood are other problems in land development works in Bangladesh. To mitigate the problems it is necessary to improve the properties of in-situ soil and filling soil. Lime stabilization could play a vital role in this process.

Chemical reaction of lime with clayey soils is two folds. First, it agglomerates the fine clay particles into coarse, friable particles (silt and sand sizes) through a phenomenon called 'Base Exchange'. Next it produces a definite "cementing" or hardening action in which the lime reacts chemically with available silica and some alumina in the raw soil (or with pozzolan additives, like fly ash), forming calcium silicates and aluminates.

In general, lime reacts readily with most plastic soils containing clay, either the fine grained clays, or clay-gravel types. The only exception would be organic matter. Soils with a plasticity index lower then 10 do not react as readily with lime, although there are numerous exceptions (NLA, 1987).

1.2 Effect of lime on Clay Soils

Lime change the characteristics of most clay soils in varying degrees, as follows:

1. The plasticity index drops sharply with the addition of lime. This is generally due to the liquid limit decreasing and the plastic limit increasing.
2. The soil is agglomerated, decreasing the soil binder content (minus No. 40 mesh particles) substantially.
3. Lime (and water) accelerates the disintegration (breaking up) of clay clods during mixing. As a result the soil becomes friable and can be worked readily.
4. Lime aids in drying out wet soils quickly, thus speeding up compaction.
5. The shrinkage and swell characteristic of clay soils is reduced markedly.
6. After curing unconfined compressive strength increases considerably.
7. Load bearing values increase substantially.
8. The lime-stabilized layer forms a water-resistant barrier by impeding penetration of gravity water from above and capillary moisture from below. Thus, the layer becomes a firm "working table," shedding rainwater readily and remaining stable, thereby minimizing construction delays.

1.3 Objectives of the Present Research

A lot of research works on lime stabilization have been performed in developed countries (Ingles and Metcalf, 1972; Kezdi, 1979; NAASARA, 1985; Bell, 1988; TRB, 1987; Jacques, 1990; Bordem, 1991; TRL, 1993). In Bangladesh some research works have also been carried out to investigative the properties of lime stabilized soils (Ahmed, 1984; Serajuddin, 1992; Molla, 1997; Rajbongshi, 1997).

However little research has been done to investigate the long term effect of lime on soil.

This research work intends to investigate the long term strength gain of lime treated soils; using variables such as base soil, lime content, mellowing time and compaction energy. Unconfined compressive strengths of re-tempered and soaked samples have also been determined.

The main objectives of this research work are as follows:

i) To study the long term strength of lime treated soil, stabilized with different base soils and with different lime contents.

ii) To examine the effect of compaction energy on long term strength and dry density of lime stabilized soil.

iii) To investigate the effect of mellowing time (compaction delay) on the strength of lime stabilized soil.

iv) To investigate the strength of re-tempered or re-worked lime treated samples.

1.4 The Research Scheme

In order to achieve the above objects the following investigations were performed. Three types of soil have been used in this research work. The investigation were carried out according to the following phases:

i) Firstly, the grain size distribution, optimum moisture contents and the Atterberg's limit tests of the base soils were performed. Mineralogical composition of clay fraction, organic matter content and pH values of the soils were also determined.

ii) Samples for Unconfined Compression Test using the selected soils were prepared with the following variables:

a) Percentage of lime

b) Compaction energy and moisture content

c) Mellowing time

d) Re-worked (previously compacted and cured) sample.

iii) Finally unconfined compression tests on prepared samples at different ages (7 days, 28 days, 90 days, 180 days and 360 days) were carried out.

1.5 Thesis Layout

A review on lime stabilization of fine-grained soil is presented in chapter 2. The review mainly includes the mechanism of lime stabilization, properties of lime stabilized soils, factors influencing lime soil interactions, mixture design procedure and durability of lime treated soils.

In chapter 3, a comprehensive description of the details of the experimental investigations is presented.

The results of the testing programme are contained in chapter 4, in which much attention is given to explain the influence of lime content and curing time on the strength of the lime stabilized soil.

Chapter 5 presents the conclusions and recommendations for further research in this field.

Brief descriptions on procedures of determining chemical and mineralogical properties of soil are presented in appendices.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

This chapter provides a comprehensive literature review on the basic concepts and mechanisms of lime stabilization, properties of lime stabilized soil, factors affecting lime soil interaction. The discussions were obtained mainly from a large number of published papers that dealt with shallow and deep stabilization.

2.2 Mechanism of Soil Lime Reactions

The basic mechanism of soil lime reactions have been described by Eades and Grim (1960), Compendium (1987), IRC (1973 a), Hausmann (1990) and Little (1995). The basic mechanisms that have been identified in soil-lime interaction are

a) Cation exchange,

b) Flocculation and agglomeration,

c) Pozzolanic reaction and

d) Carbonation.

2.2.1 Cation Exchange

Within a period of couple of minutes up to some hours after mixing, the calcium hydroxide transformed into Ca^{++} (or Mg^{++}) and $(OH)^-$ due to the presence of carbonic acid (H_2Co_3) in the soil (Kezdi, 1979). The presence of carbonic acid is due to the reaction of carbondioxide of the air in the soil and the free water. These dissociated divalent calcium cations always replace the univalent alkali ions that normally adsorbed at the negatively charged clay surface. This cation exchange occurs because divalent calcium cations can normally replace cations of single valance and ions in a high concentration will replace those in a lower concentration. The most common cations found in soil are sodium (Na^+), potassium (K^+), calcium (Ca^{++}), magnesium (Mg^{++}), aluminium (Al^{+3}) and the general order of replacebility

of the common cations associated with soil is given by the lyotropic series as:
$Na^{+} < K^{+} < Mg^{++} < Ca^{++} < Al^{+++}$

Many natural soils are largely cation saturated. In some cases the exchange complex is particularly Ca^{++} saturated before the lime addition. But cation exchange may still take place because the cation exchange capacity will increase as the pH of the soil increases. The cation exchange capacity highly depends on the pH of soil water and on the type of clay mineral in the soil. Among the types of clay minerals, montmorilonites have the highest and kaolinites have the lowest (low to non-existent) cation exchange capacities (ASSARSON et. al, 1974). Brandle (1981) concluded that cation exchange capacity of a soil is not a criteria for its reactivity with lime and instead suggested that amount of semi-removal silica is useful criteria of lime reactivity for practical purpose.

2.2.2 Flocculation and Agglomeration

Cation exchange, due to the addition of lime, results in stabilization of the diffused water layer and a dramatic reduction in its size (Fig. 2.1). When the clay particles are allowed to approach each other more closely due to reduction in the size of the water layer an edge-to-face attraction or flocculation occurs.

The edge-to-face attraction is probably partly due to the attraction of broken bonds at the edge of the clay particles to the oppositely charged surfaces of neighboring clay particles. Flocculation is additionally enhanced due to a high electrolyte concentration and high pH environment existing in the lime-soil-water system (Little, 1995).

Thompson (1966) indicated that flocculation and agglomeration are primarily responsible for the change in plasticity, shrinkage and workability characteristics of soil lime mixture.

Mitchel et al. (1961) demonstrated that the introduction of lime in moist soil increase the pH of the soil and release Ca^{++} ions into the pore water. This phenomenon reduces the forces of repulsion and encourages compression of the diffused double layers. Mitchell (1981) stated that less tendency of repulsion for particles in double layer resulting in a flocculated structure. These reaction results to an apparent change in texture — the clay particles "clumping" into to larger sized "aggregate".

Full Hydration

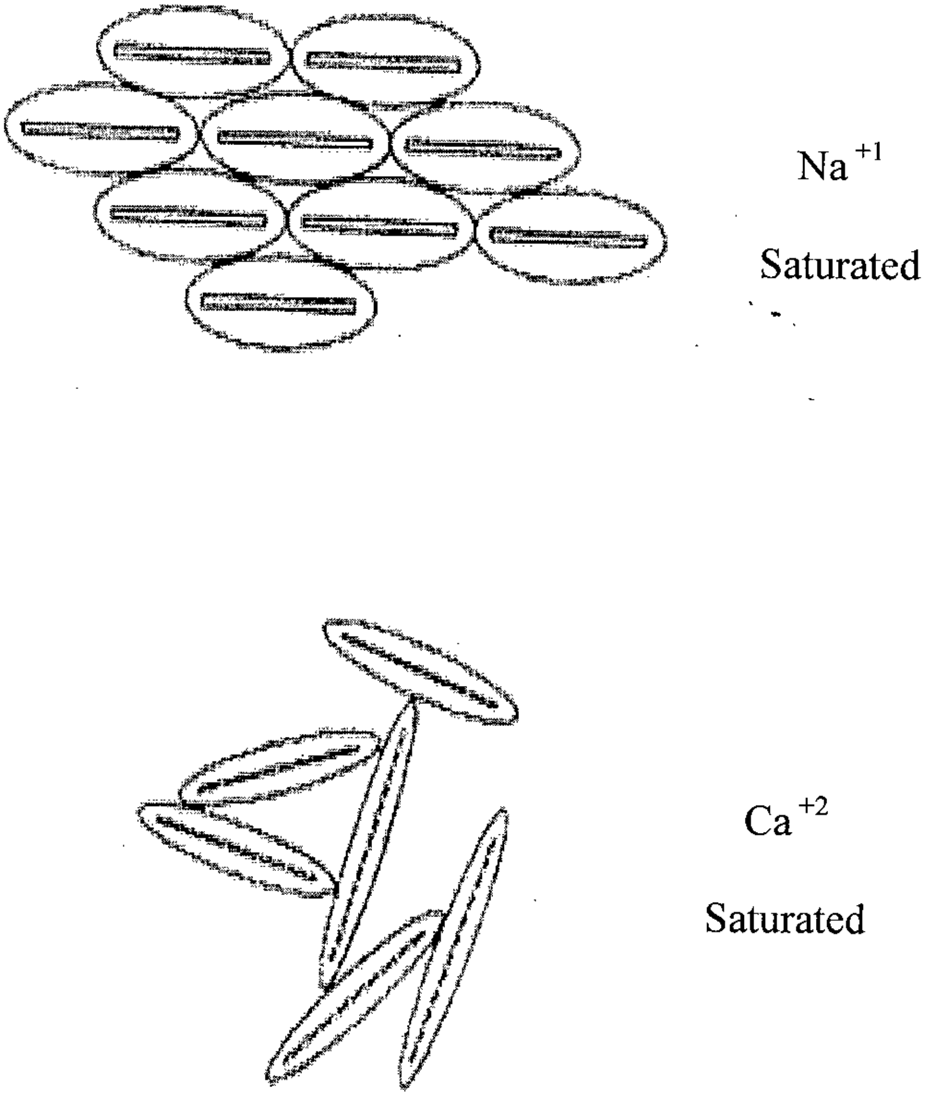


Fig. 2.1 The effect of exchangeable cations on the size of diffused water layer (after Little, 1995)

Some researchers, such as Diamond and Kinter (1965), explain that the immediate textural changes, plasticity changes and short-term strength gains are artifacts of the crowding of calcium hydroxide molecule along the surface of the clay. This crowding results in an attack on the clay mineral surface and the formation of calcium-aluminate and calcium silicate minerals, which help bond the mineral surfaces together. Diamond and Kinter (1965) argued that although calcium saturation is required for stabilization, many natural soils that are largely calcium saturated still exhibit deficiencies associated with problematic soil for use as subgrades and thus require stabilization. Furthermore, many chemical agents other than lime induce immediate flocculation when mixed with clays (Brandle, 1981), yet are valueless for stabilization.

2.2.3 Pozzolanic Reaction

Lime reacts with many compounds and elements including sulfur compounds, acid gases, halogen, magnesiam compounds, phosphorous, silica and alumina and metals (Boyonton, 1979). The most important reaction among these in terms of soil and aggregate stabilization is the reaction between lime and silica and alumina compound in presence of water is referred to pozzolanic reaction.

A pozzolan is defined as a finely divided silicious or aluminous material, which in the presence of water and calcium hydroxide will form a cemented product. The cemented products are calcium-silicate-hydrates and calcium-aluminate-hydrates. These are essentially the same hydrates that form during the hydration of Portland cement (Little, 1995).

Clay is a pozzolan as it is a source of silica and alumina for the pozzolanic reaction. Clay-silica and clay-alumina become soluble or available in a high pH environment (Fig. 2.2). The pH of water saturated with lime is 12.45 at 25° C. Thus a soil-lime-water system has a pH high enough to solubilize silica and alumina for pozzolanic reaction.

What is unique about the pozzolanic phenomenon is the cooperative reaction between the lime and the clay. The lime induces the high pH environment, which solubilizes the silica and alumina. The lime also provides the residual free calcium,

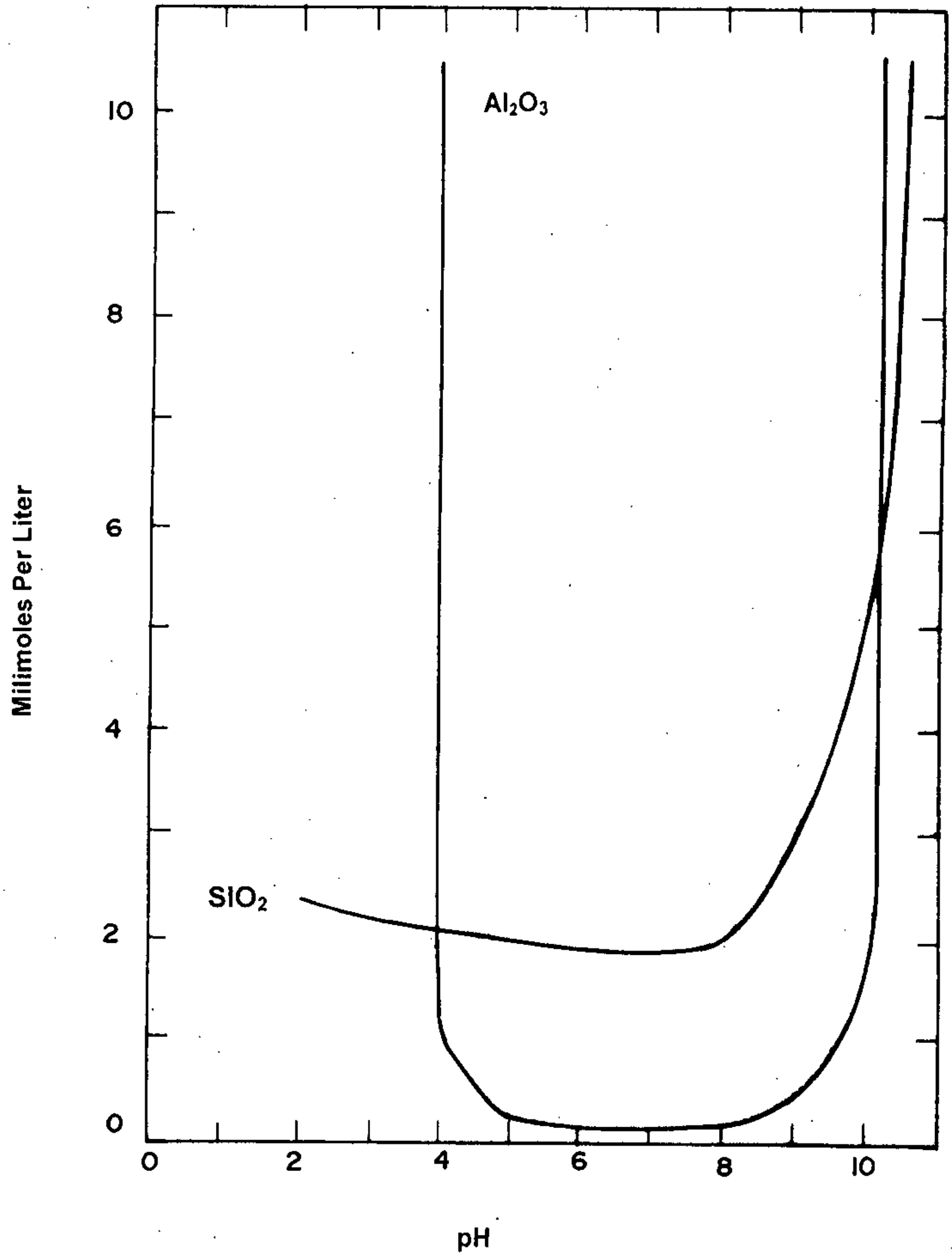


Fig. 2.2 The effect of pH on release of silica and alumina from the clay surface (after Keller, 1964)

which combines with silica and alumina supplied by the clay to produce the pozzolanic reaction.

The reaction between lime and available silica and alumina are quite complex, and there is no complete agreement on all aspects of the systems that form as a result of these reactions.

However it has been well documented that lime reacts with silica, alumina and water at elevated temperature to form hydrated compounds (Broms; 1984; Boyonton, 1979). The pozzolanic reaction is illustrated by the following equation:

$$Ca^{++} + OH^{-} + \text{soluble clay silica} \longrightarrow \text{Calcium silicate hydrate (CSH)}$$

$$Ca^{++} + OH^{-} + \text{soluble clay alumina} \longrightarrow \text{Calcium aluminate hydrate (CAH)}$$

Kezdi (1979) stated that the dissociation of hydrated lime in to Ca^{++} and OH^{-} ions causes the lime to lose most of its crystallize structure and assume an amorphous form i.e., it creates a transition to gel phase. This semi-crystallize to gel-like amorphous product contributes to the strength enhancing long-term pozzolanic reaction.

Eades and Grim (1965) demonstrated that complex calcium silicates are formed when compacted under optimum moisture conditions and exposed to either normal climatic and temperature conditions or laboratory curing. Eades (1962) reported that the formation to the calcium hydrate compounds were the result of the lime attacking the edges of the clay minerals in the high pH environment of the lime water solution.

The gel of calcium silicates (and or aluminates) cements the soil particles in a similar manner to the effect produced by the hydration of Portland cement, but the lime cementing process is much slower reaction which requires considerably longer time than the hydration of cement. The main part of the reaction does not start until a couple of days after the mixing in of lime (Assarson et al., 1974) and as a rule, is not finished until one to five years later (Diamond and Kinter, 1966).

Doty and Alexander (1978) illustrated the importance of maintaining enough lime and a high enough pH to continue pozzolanic reaction in a reactive soil. As long as this is maintained the pozzolanic reaction and thus the strength gain is continued.

Herzog and Mitchel (1963) indicated that soil lime pozzolanic reaction usually does not appear until after long curing period and than only in cases where a high percentage of lime was added. Pozzlanic materials (Siliceous or Aluminious) possess little or no cementetious value, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementious properties.

2.2.4 Lime Carbonation

The reaction between lime, and carbon dioxide results in the reformation of calcium carbonate. However complete carbonation usually does not occur, even at elevated temperatures. This is because the adsorption of Co_2 on the lime is a surface phenomenon and a shell of calcium carbonate is gradually formed around the CaO or $Ca(OH)_2$ particle (Boynton, 1979). It is important to note that water acts as a catalyst for carbonation, and the process of carbonation is more complete on small-sized, high surface area particles of lime than on larger or courser-sized particles.

Ingles and Metcalf (1972) stated that carbonation forms relatively weak cementing agents. The strength of calcium carbonate formed by this process can generally be discounted, and its significance on stabilization can be dismissed (Broms, 1984). Diamond and Kinter (1966) suggested that carbonation is probably a deleterious rather than a helpful phenomenon in soil stabilization.

2.3 Engineering Properties of Lime Stabilized Soils

Lime treatment results in both immediate and long term effects on soil properties (TRB, 1987). The main effects of lime stabilization are improved workability, increased strength and volume stability and decreased water sensitivity. The properties of soil-lime mix have been summarised by a number of investigators (Ingels and Metcalf, 1972; IRC, 1976; Metcalf, 1981; Kezdi, 1979; NAASRA, 1986; TRB, 1987; Bell, 1993). In the following sections the various physical and engineering properties of lime stabilized soils are reviewed.

2.3.1 Water Content

An immediate reduction of the natural water content occurs when quick lime is mixed with a cohesive soil, as water is consumed in the hydration process.

Assarson et al. (1974) reported that at the slaking of the lime, a part of the soil water about 0.3 kg / kg CaO, is bound. More over a considerably larger amount of pore water evaporates because of the heavy heat release.

According to Broms et al. (1980), the reduction in water content, w_r , can be calculated as:

$$w_r\% = \frac{(W_n + 32) \cdot X}{(100 + X)}$$

Where x is the lime added as a percentage of the weight of the clay, and W_n is the original natural water content, in percent. As a rough estimate, the water content of clay will decrease by about one percent for every one percent addition of quick lime.

2.3.2 Plasticity

Substantial reduction in plasticity is caused by lime treatment and the soil often become non-plastic (Fig. 2.3). Even soils which require long term curing (at least 28 days) to develop significant strength gains demonstrated immediate plasticity index reduction (Little, 1995).

Generally high clay content soils require greater quantities of lime for achieving the non-plastic condition, if it can be achieved. The first increments of lime added are most effective in reducing plasticity (TRB, 1987). The silty and friable texture of the treated soil causes a marked increase in workability.

Both plastic and liquid limits are affected by lime stabilization. The plastic limit of a soil generally increases with the addition of a small amount of lime until a critical lime content (Hilt and Davidson, 1960; Mateos, 1964). The amount of lime at this point was referred to as the “lime fixation point” by Pietsch and Davidson (1965). Mateos (1964) observed that for the lime content beyond the optimum lime content, no further increase in plastic limit occurred.

Lime reduces the liquid limit of highly plastic clays and increases that of low plastic clays (Herrin and Mitchel, 1961; Brandl, 1981). The net effect of adding lime on soil is always a marked decrease in plasticity index of soil. The decrease in plasticity

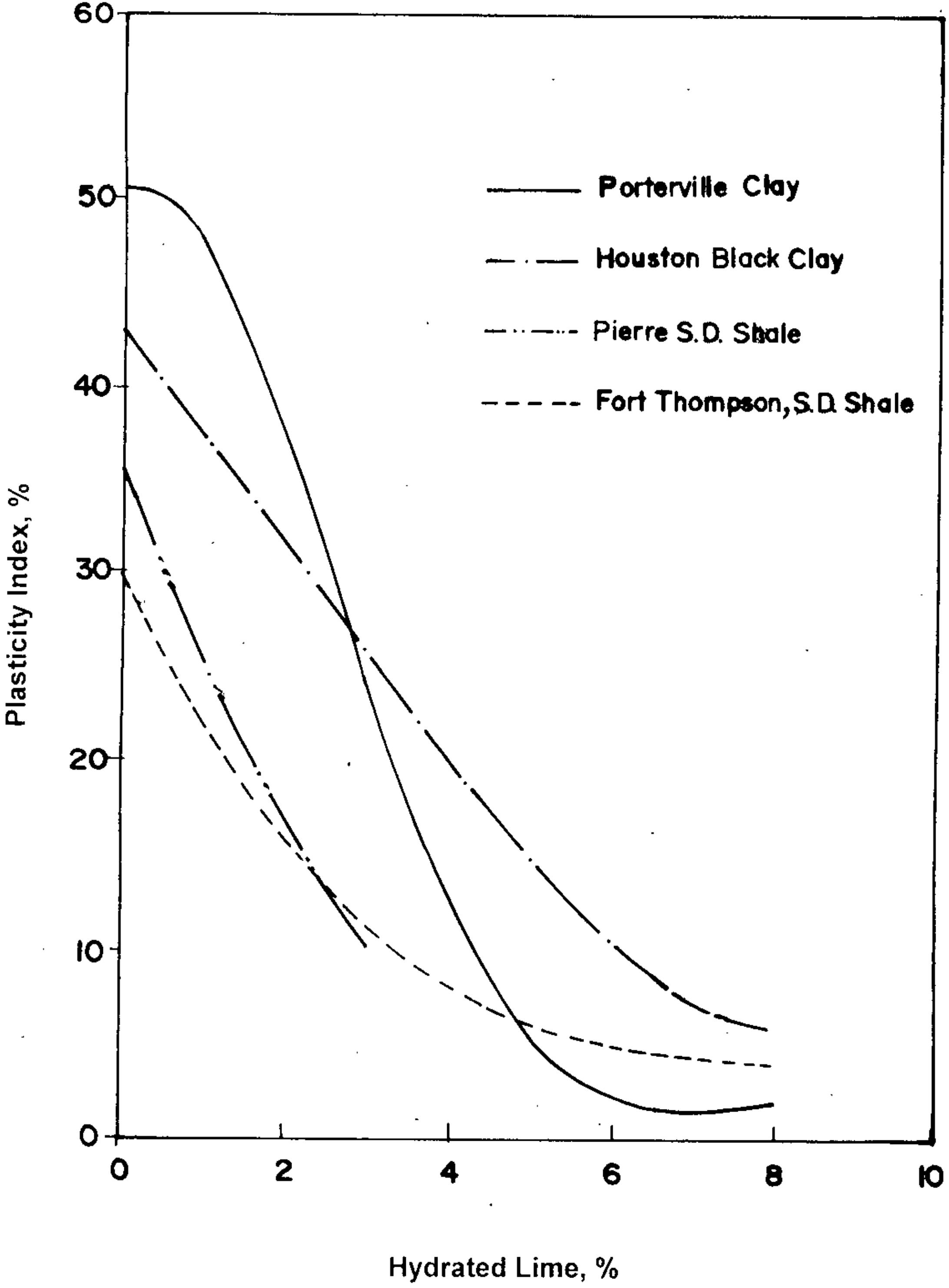


Fig. 2.3 Effect of lime on plasticity for different soils (after Holtz, 1969)

index may be due to the increase in plastic limit or may be due to the decrease in liquid limit (Mateos, 1964; Rodriguez et. al, 1988). The amount of reduction in plasticity index depends on the quantity and type of lime and also type of soil (IRC, 1976).

Ahmed (1984), Rajbongshi (1997) investigated the effect of lime content on the liquid limit, plastic limit and plasticity index of regional soils of Bangladesh. They found an increase in plastic limit while liquid limit and the plasticity index reduce with increasing addition of lime. Hossain (2001) investigated the effect of lime content on the liquid limit, plastic limit and shrinkage limit of an expansive soil from Gazipur, Bangladesh. Hossain (2001) found an increase in plastic limit and shrinkage limit while liquid limit and thus the plasticity index reduce with addition of lime.

2.3.3 Moisture-Density Relationships

For a specific compaction energy, lime treated soil has a lower density and a higher optimum moisture content than does the untreated soil. This phenomenon is presented in Fig. 2.4. The reduction in maximum dry density is typically from 3 to 5 pounds per cubic feet (48-80 kg/m^3) with a typical increase in optimum moisture content of 2-4 percent, Little et al. (1987). If a mixture is allowed to cure and gain strength prior to compaction, further reduction in maximum dry density and an additional increase in optimum moisture content may be noted.

Faisal et al. (1992) stated that the addition of lime leads to decrease the dry density of the soil and an increase in optimum moisture content for the same compaction energy. The decrease in maximum dry density of the treated soil is the reflection of increased resistance offered by the flocculated soil structure to that compaction energy. And the increase in optimum moisture content is probably a consequence of additional water held within the flocculated soil structure resulting from lime interaction with soil. Hansman (1990) also pointed the decrease in maximum dry density as a result of flocculation and cementation of lime mixed soil.

Rajbongshi (1997) and Molla (1997) reported the effect of lime treatment on the maximum dry density and optimum moisture content of regional and coastal soils of Bangladesh. Rajbongshi (1997) and Molla (1997) reported that increment of lime content increases the optimum moisture content and reduces the maximum dry density. The reduction of maximum dry density for a given energy and lime content for a coastal soil is shown in Fig. 2.5. Serajuddin and Azmal (1991) also found that compared with untreated sample, the maximum dry density of lime treated samples of two fine-grained regional soils reduced while optimum moisture content slightly increased.

2.3.4 Swell Potential

Soil swell potential significantly reduced by lime treatment (Thompson, 1966). The reduction in plasticity index (PI) of all fine-grained soil upon the addition of lime is an indication of the reduction of swell potential due to lime stabilization. A relationship between PI and swell potential was developed by Seed, Woodward and Lundgren (1962) that states:

$$\text{Percent swell} = 0.00216 \times \text{PI}^{2.44}$$

Goldberg and Klein (1952) illustrated the influence of compaction density on swell pressure. They demonstrated that an increase in compaction density from 1, 440 kg/m^3 to 1632 kg/m^3 (90 to 102 pcf) increased swell pressure of a Porteville, California clay by 90 percent. However, a similar increase in compaction density had a negligible effect on the same soil when stabilized with 8 percent $Ca(OH)_2$. Basma and Tuncer (1991) showed that swell pressure of a lime treated soil is reduced, as percentage of lime added to the soil and curing time is increased (Fig. 2.6).

2.3.5 Strength and Deformation

Lime treatment of fine-grained soils produce immediate improvement in strength properties of soil-lime mixture. Broms stated that strength increases about one or two hours after mixing. These immediate benefits are evident from CBR, cone index, R-value, static compression and resilient modulus testing. Part of the initial strength increase is due to the formation of gel phase, which possesses cementing properties due to the super saturation of the soil solution (YU Kern 1965). The soaked CBR tests (96-hour soak) in Fig. 2.7 were performed immediately after compactions with out the benefit of long term curing.

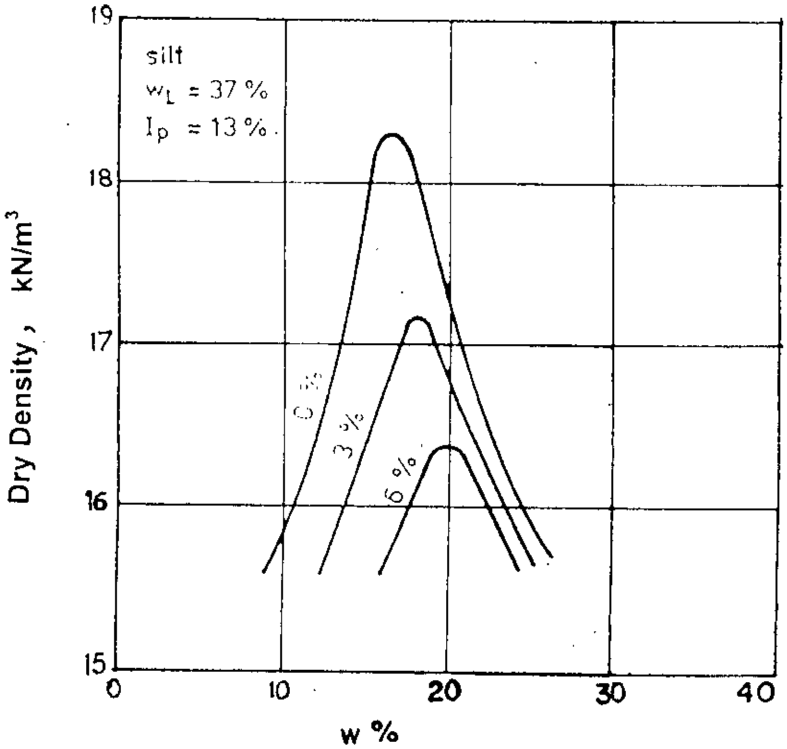


Fig. 2.4 Effect of lime content on maximum dry density and optimum moisture content of a lime treated silt (after Kezdi, 1979)

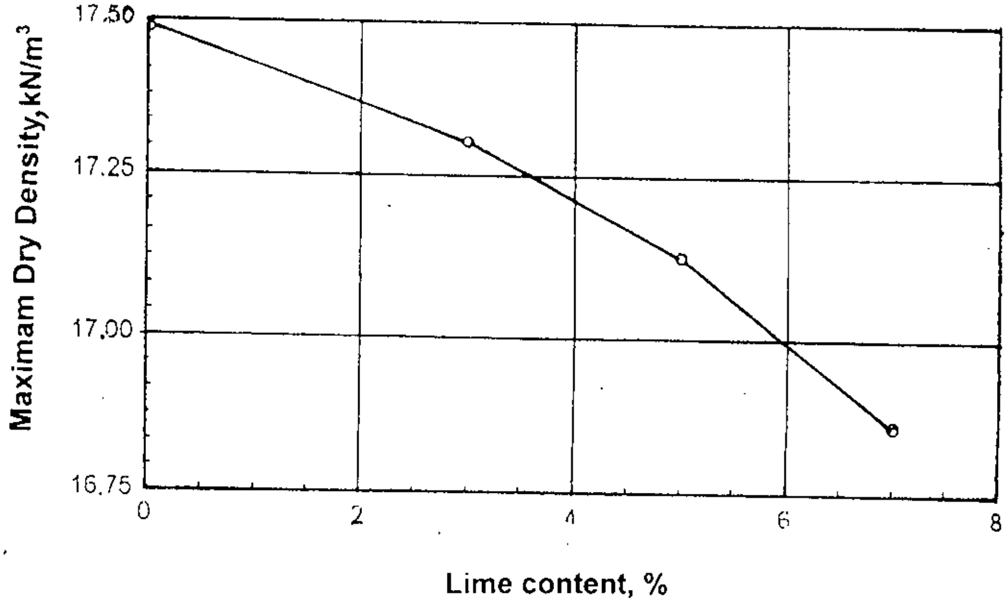


Fig. 2.5 Effect of lime content on maximum dry density of a lime treated coastal soil (after Rajbongshi, 1997)

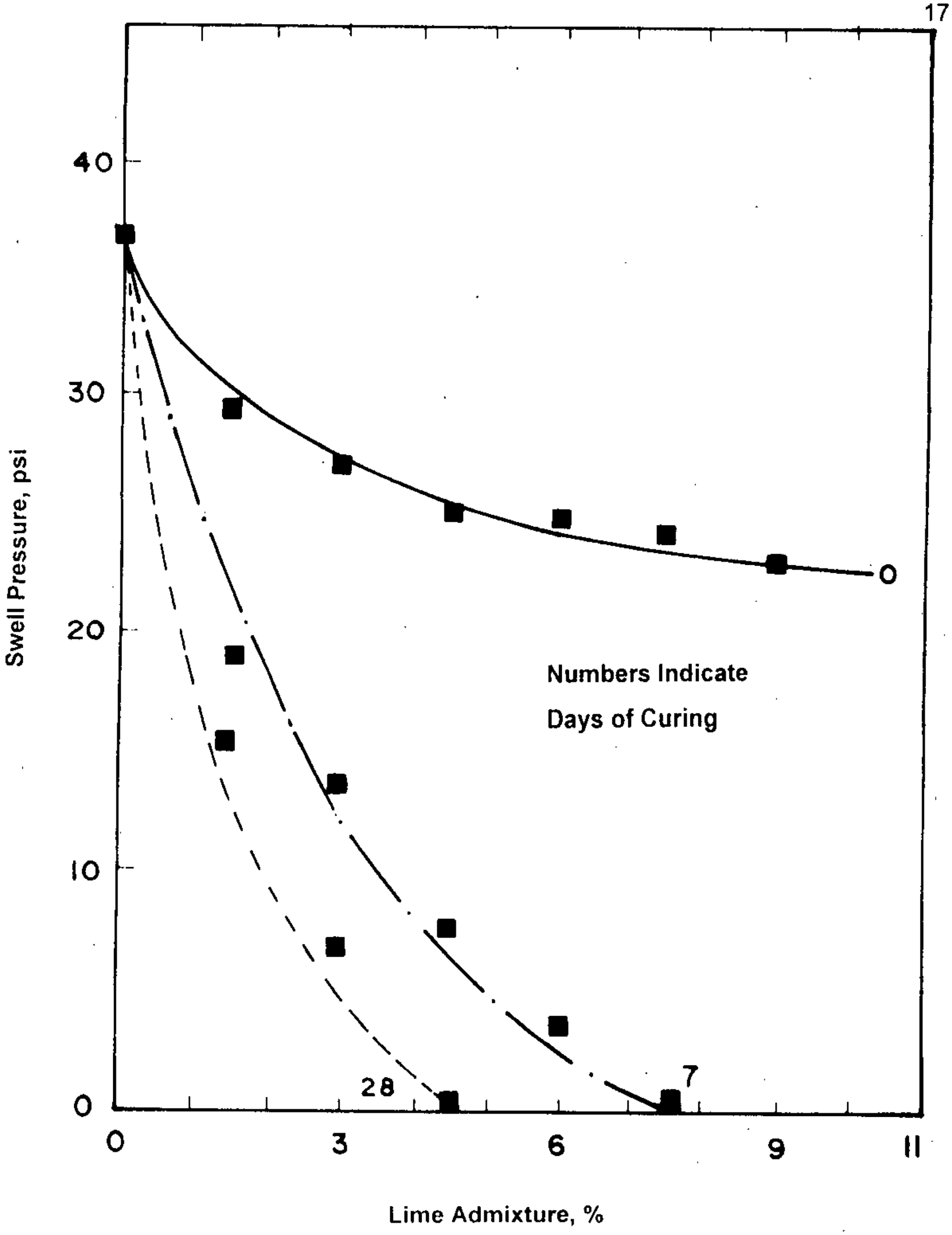


Fig. 2.6 Swell pressure at different lime content and curing period (after Basma and Tuncer, 1991)

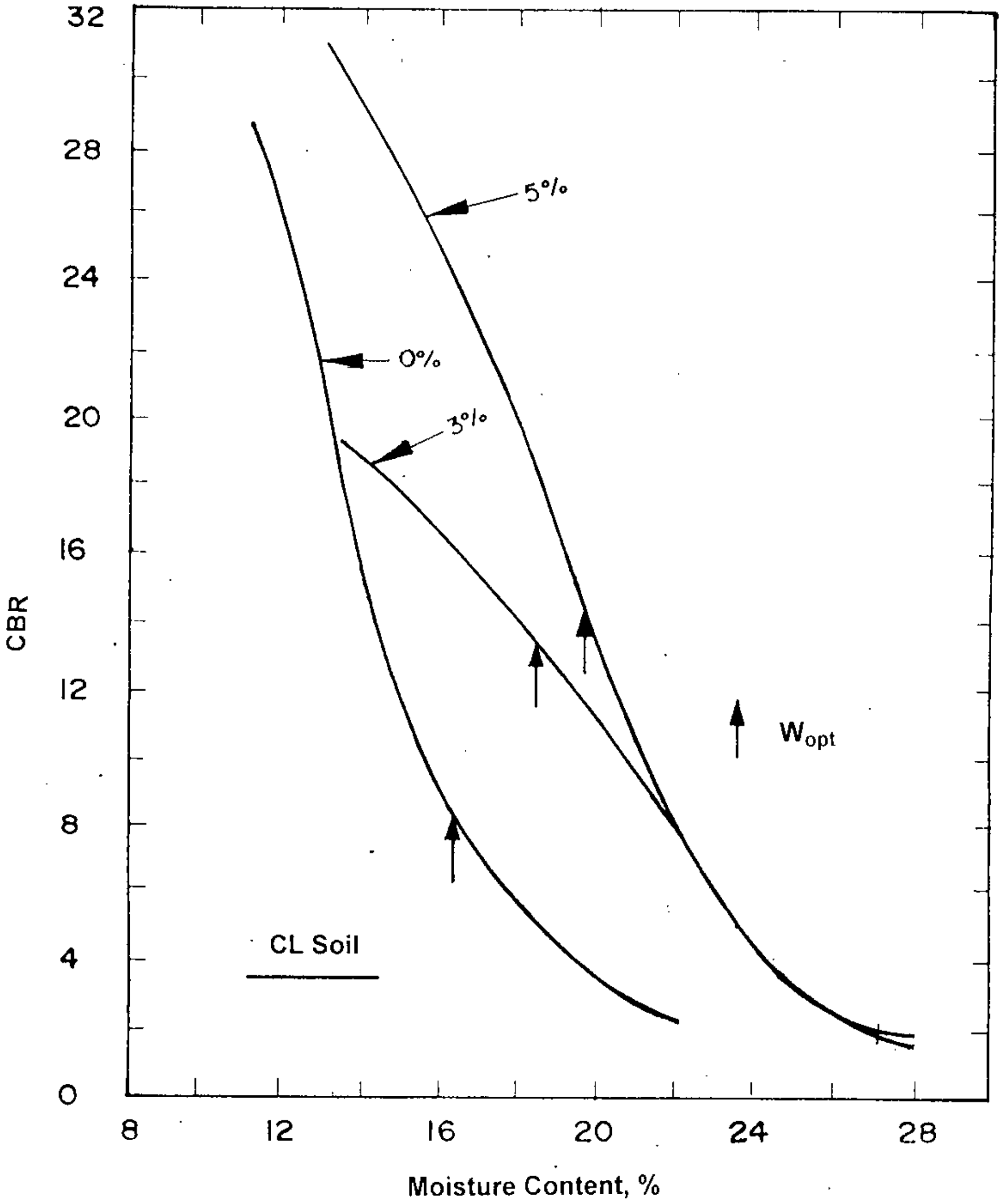


Fig. 2.7 Soaked (96-hour) CBR value of lime treated soil at different moisture content (after Thompson, 1970)

Another part of the increase in shear strength is caused by flocculation of the clay because of cation exchange and by a reduction of the water content and plasticity index (Broms, 1984). Thompson (1970) explained the immediate increase in shear strength where unaltered clay's hydrated diffused water layer is compared to that of the same clay after lime stabilization. The ordered structure of the clay platelets surrounded by the hydrated, diffused water layers provides very little shear strength. The only resistance to relative movement is due to the overlapping and interference among the water layers. On the other hand, in the flocculated structure, the summation of the edge to face contacts provides more substantial shear strength (Fig. 2.1).

The most important effect of long term curing is the development of pozzolanic products. As long as enough residual calcium remains in the system to combine with the clay-silica and clay-alumina and as long as the pH remains high enough to maintain solubility, the pozzolanic reaction will continue. The development of pozzolanic product results in more glue to hold the particles of soil together and a mineralogical change favorable to greater strength. The shear strength of stabilized soil increases through pozzolanic reactions takes place over many month and years (Davidson et al, 1965; Mcdowell, 1966; Brandl, 1981; Broms, 1984).

Lime stabilized soils tend to gain strength at a slower rate than Portland cement stabilized soils. This slower strength gain should be considered in mixture design and pavement design. Long term curing data 28 to 360 days are presented in Table 2.1 for 12 California soils. A very interesting point with these California soils is that most of the soils are relatively low plasticity, clayey silts or silty clays (Doty and Alexander, 1978). Yet they are very reactive as is evidenced by the substantial strength gain.

Although the unconfined compression strength is the most widely used measure of the shear strength of lab-fabricated lime stabilized soils, other measured are also used. Among these are the CBR, California R-value and triaxial shear strength. CBR values for many cured lime-soil mixtures are high (<100) and indicate the extensive development of pozzolanic cementing products (Thompson, 1969). For mixtures with CBR's of 100 or more, test results have title practical significance (TBR, 1987). In this case the unconfined compressive strength is preferred as an indicator of reactivity and of strength.

Table 2.1 Unconfined compressive strength at different curing period for twelve California soils (after Doty and Alexander, 1978)

Soil	AASHTO Classification	Plasticity Index	Unconfined Compressive Strength, psi					
			3 Percent Lime			7 Percent Lime		
			28 day	180 day	360 day	28 day	180 day	360 day
1	A-6 (10)	14	160	210	220	120	210	610
2	A-6 (10)	11	390	410	510	400	120	1410
3	A-7-5 (20)	30	280	360	310	550	1190	1210
4	A-2-4	NP	100	100	100	110	150	180
5	A-7-6 (20)	30	350	450	640	260	1200	1650
6	A-7-5 (13)	15	70	60	70	220	200	220
7	A-4 (5)	7	80	160	280	120	210	400
8	A-6	14	540	700	750	550	1200	1580
9	A-4	7	420	920	1100	350	1250	1900
10	A-7-5 (20)	22	400	760	830	300	950	1200
11	A-4 (2)	10	275	410	900	210	800	1110
12	A-7-5 (20)	22	360	430	520	510	810	1010

Tensile strength

As the unconfined compressive strength of a lime-soil mixture increases the tensile strength does also. Two test procedures are commonly used to measure the tensile strength of lime-soil mixtures: the indirect tensile or splitting tensile test and the flexural beam test. Large variations are common in indirect tensile testing and these variations are dependent on the nature of the lime-soil mixture and the curing conditions.

The ratio of tensile strength to unconfined compressive strength is approximately 0.13, and this is a strong enough correlation to be used for normal design purposes (Little et al., 1987).

The most common method used for evaluating the flexural tensile strength of highway materials is the flexural test (beam strength) as this value can be related to the stabilized slab, which bends under the action of traffic loading in the field. A realistic estimate of the flexural strength (modulus of rupture) is 0.25 times the cured unconfined compressive strength of the mixture (Little et al., 1987).

Deformation

Soil lime mixtures tested in compression are strain sensitive and the ultimate strain is approximately one percent regardless of the soil type or curing period (Thompson, 1966). Brom (1984) stated that the stabilized soil is normally firm to hard and the texture is grainy. Suddath and Thompson (1975) states that as the lime-soil mixture continue to cure, the strength increases, and the strain at failure is reduced (Fig. 2.8).

Benjamin (1990) found nearly 4% failure strain for 1 month of curing and 2% failure strain after 3 months of curing of lime treated soil with 10% lime content. The compressive static modulas of elasticity can be estimated from the unconfined compressive strength of the lime-soil mixture according to the following relation (Thomson, 1966):

$$E \text{ (ksi)} = 10 + 0.124 \text{ (Uc in psi)}$$

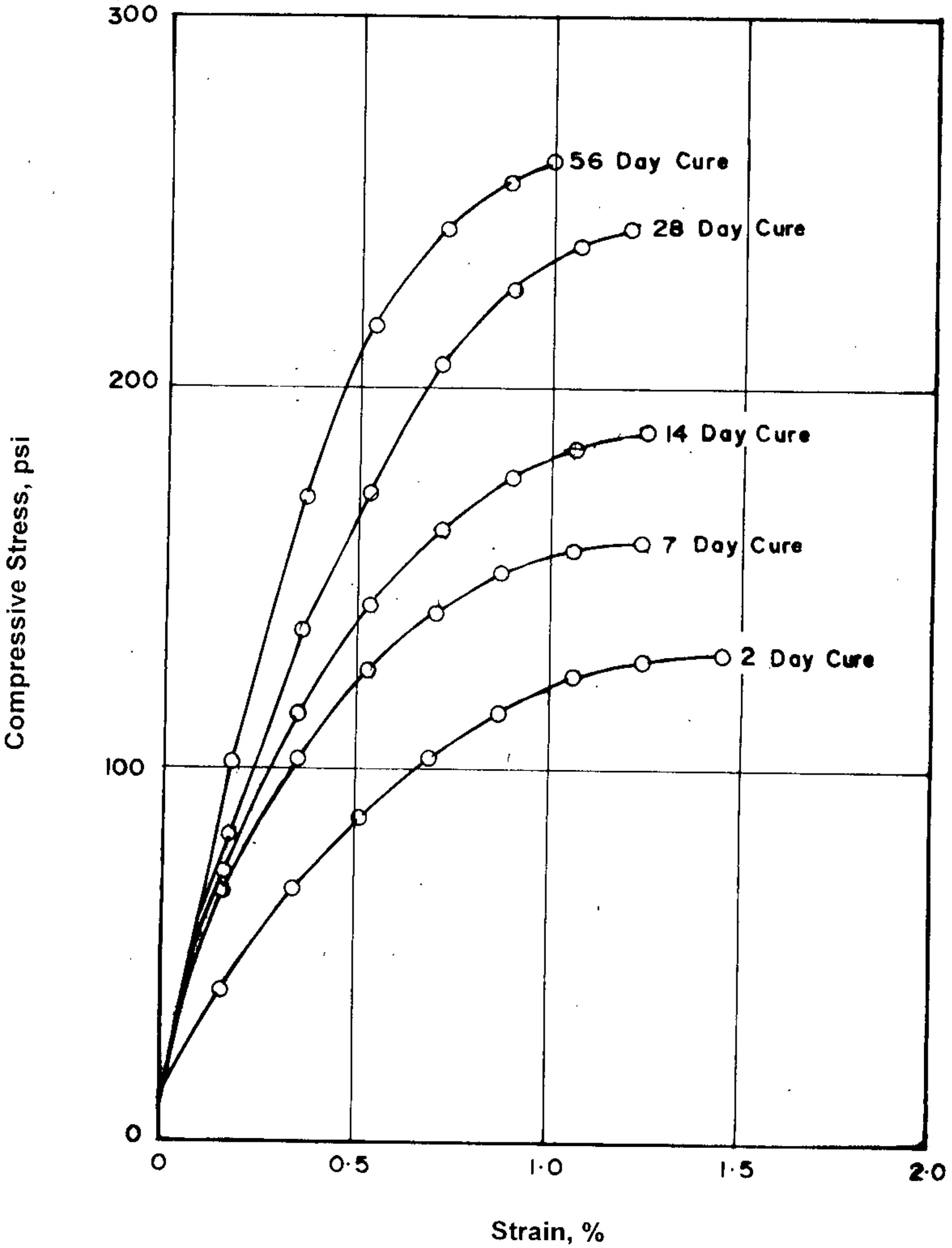


Fig. 2.8 Stress-strain relationship for lime treated clay at various curing time (after Sudath and Thompson, 1975)

Poisson's ratio

Poisson's ratio is a stress dependent property. At low stress levels (less than 50% of the ultimate compressive strength) it is generally in the range of 0.1 to 0.2. At higher levels, poisson's ratio may be closer to the 0.2 to 0.3 range (TRB, 1987).

2.3.6 Permeability

The permeability of soil can change significantly in response to three effects: mineral dissolution, ions exchange reactions and desiccation due to displacement of water by highly organic fluids. The addition of lime to a soil and water system produces the first two effects.

Lime stabilization has been reported to result in an increase in the permeability (Broms and Boman, 1977; Brandl, 1981; Evans and Bell, 1981). The increase in permeability is associated with increase in pore volume due to flocculation (Townsend and Klyn, 1966). McCallister and Petry (1990) have found that initially lime treated soils demonstrate an increase in permeability followed by a decrease because of pozzolanic product, which accumulates in the interstitial regions. They further found that the permeability decrease with leaching, especially if the lime content used to stabilize the soil was a low percentage of lime (3 to 4 percent). However if the lime content was optimum for strength gain (6 to 7 percent), the permeability changes upon leaching were negligible.

Brooms and Boman (1977) found an increase in the permeability of soft clay by 100 to 1000 times or more, which led them to suggest the use of lime columns as vertical drains in the soil to accelerate consolidation settlement.

The more cohesive and reactive the clay, the higher is the increase in permeability of the material according to the flocculation reaction (Brandl, 1981). McCallister and Petry (1990) found that the permeability's of three expansive soils were from 7 to 300 times higher after lime treatment than for the natural clays without lime stabilization. Ranganathan (1961) found a 10-fold increase in permeability in lime treated expansive clays.

2.4 Factors Influencing Lime-Soil Interactions

A number of factors influence lime-soil reactions. These factors are broadly classified as material factors and production factors. Material factors are the characteristics of the untreated soil and the production factors include the quality and quantity of lime and the type and condition of mixing, compacting and curing. The factors of major consequence in terms of their influence in strength are described in the following section.

2.4.1 Soil

Lime is an effective stabilizer for a wide range of soils. Actually, two phases of stabilization occur in a lime-soil system. The first involves the practically immediate reactions of cation exchange and flocculation-agglomeration. These reactions occur to some extent that with medium, moderately fine and fine grained soils. The second is the lime-soil pozzolanic reactions, which occur between soil silica and or soil alumina to form cementing agents. The clay minerals, quartz, feldspar, micas and other silicates or aluminasilicate minerals in the soil are possible sources of silica and alumina. Since the clay minerals are the most abundant source of readily available silica and alumina adequate clay content must be present to provide a source for the pozzalanic reaction (Little, 1995).

Some researchers divide the lime treated soils into two categories: reactive and modified. The reactive soils are those which demonstrate an unconfined compressive strength gain of at least 345 kpa (50 psi) over the untreated soil and the modified refers to soil with limited strength gain (less than 345 kpa (50 psi)) with significant physical property changes (Thompson, 1966).

Although lime can not react pozzolanically with sands, lime may be an effective stabilizer with sandy or silty soils which have a clay content as low as 7% and a PI as low as 10 (Little, et al., 1987). In the case of plasticity indices above 30 and greater than 25 percent material passing the number 200 sieve, the selection criteria recommended by Currin et al. (1976) is the use of lime either as the stabilizer of choice or as a pre-treatment to reduce the plasticity index below 30 followed by Portland cement stabilization (Fig. 2.9).

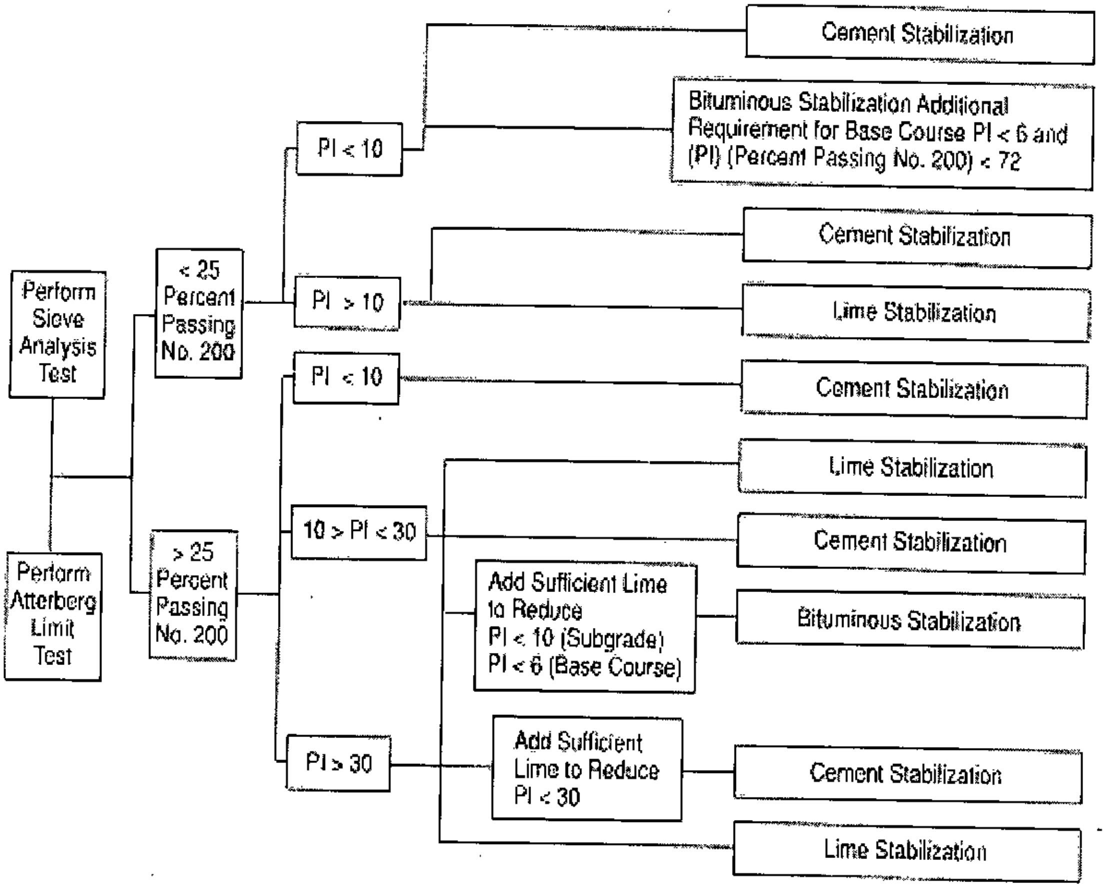


Fig. 2.9 Selection of the appropriate stabilizer for a certain soil based on index properties (after Currin et al. 1976)

NASSARA stated that soil having plasticity index in the range of 10 to over 50 are suitable for lime stabilization. Soils with plasticity index lower than 10 do not generally react with lime.

Broms (1984) stated that the clay content of the soil should not be less than 20% and the sum of the silt and clay fractions should preferably exceed 35%, which is normally the case when the plasticity index of the soil is larger than 10. Ahmed (1984) reported that for successful stabilization of soil, a certain minimum clay fraction in soil is always needed.

Kezdi (1979) showed the effect of grain size distribution on the applicability of lime stabilization (Fig. 2.10). He also showed that the strength of lime stabilized silty clay is higher than clay and silt (Fig. 2.11).

Broms (1984) and Ingels et al. (1972) reported that the increase in strength of lime stabilized silty clay is higher than the other types of soils.

Rodriguez et al. (1988) noted that the strength increase due to lime stabilization on clayey gravel soil is such that the stabilized soil becomes stronger than those that would be obtained with cement. He also added that lime has more frequently been used with plastic clays, which become more workable and easy to compact.

Locat et al. (1990) studied the effect of lime on different type of soil. It has been found that the higher strength is gained by the soil with higher clay content (Fig. 2.12).

Serajuddin (1992) observed that stabilized silty soil has much lower strength than stabilized clay types of soil.

The major soil properties, which influence the lime-reactivity of a soil, are clay mineralogy, soil pH, degree of weathering, natural drainage, organic matter content, exchangeable cation, extractable iron, silica-sesquioxide ratio and silica-alumina ratio (Little, 1995).

Nature of clay (Mineralogy)

Generally, the most pozzolanically reactive clay minerals are the montmorillonitic

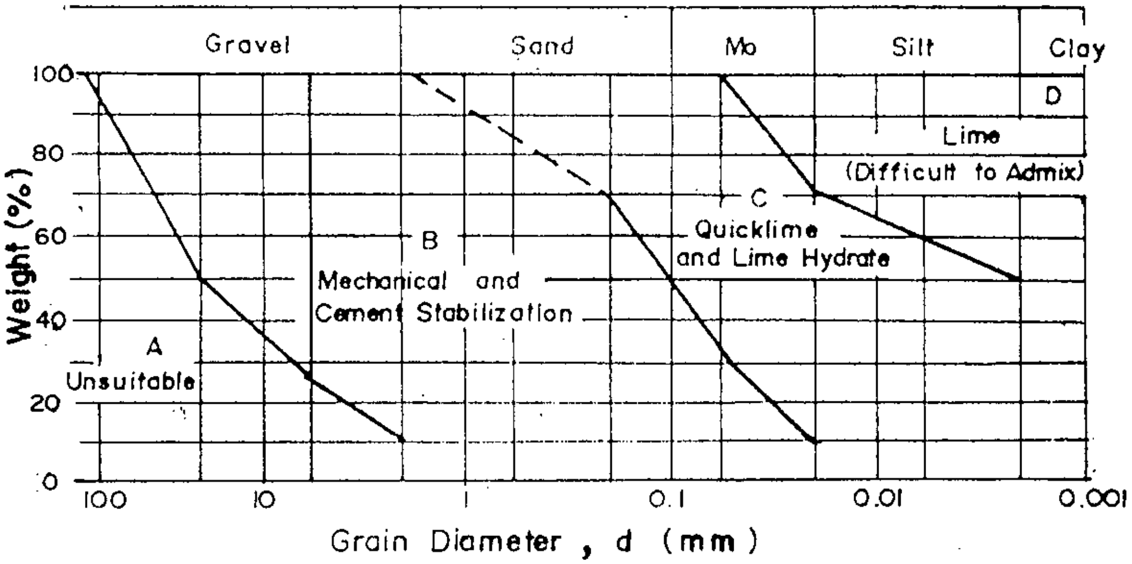


Fig. 2.10 Effect of grain size distribution on the applicability of lime stabilization (after Kezdi, 1979)

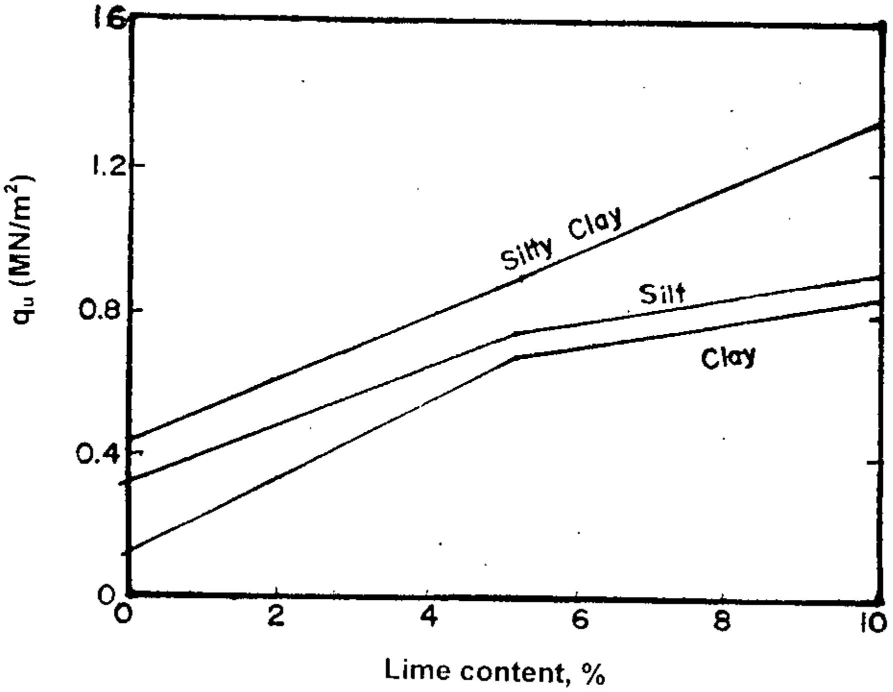


Fig. 2.11 Effect of lime treatment on the strength of various types of soil (after Kezdi, 1979)

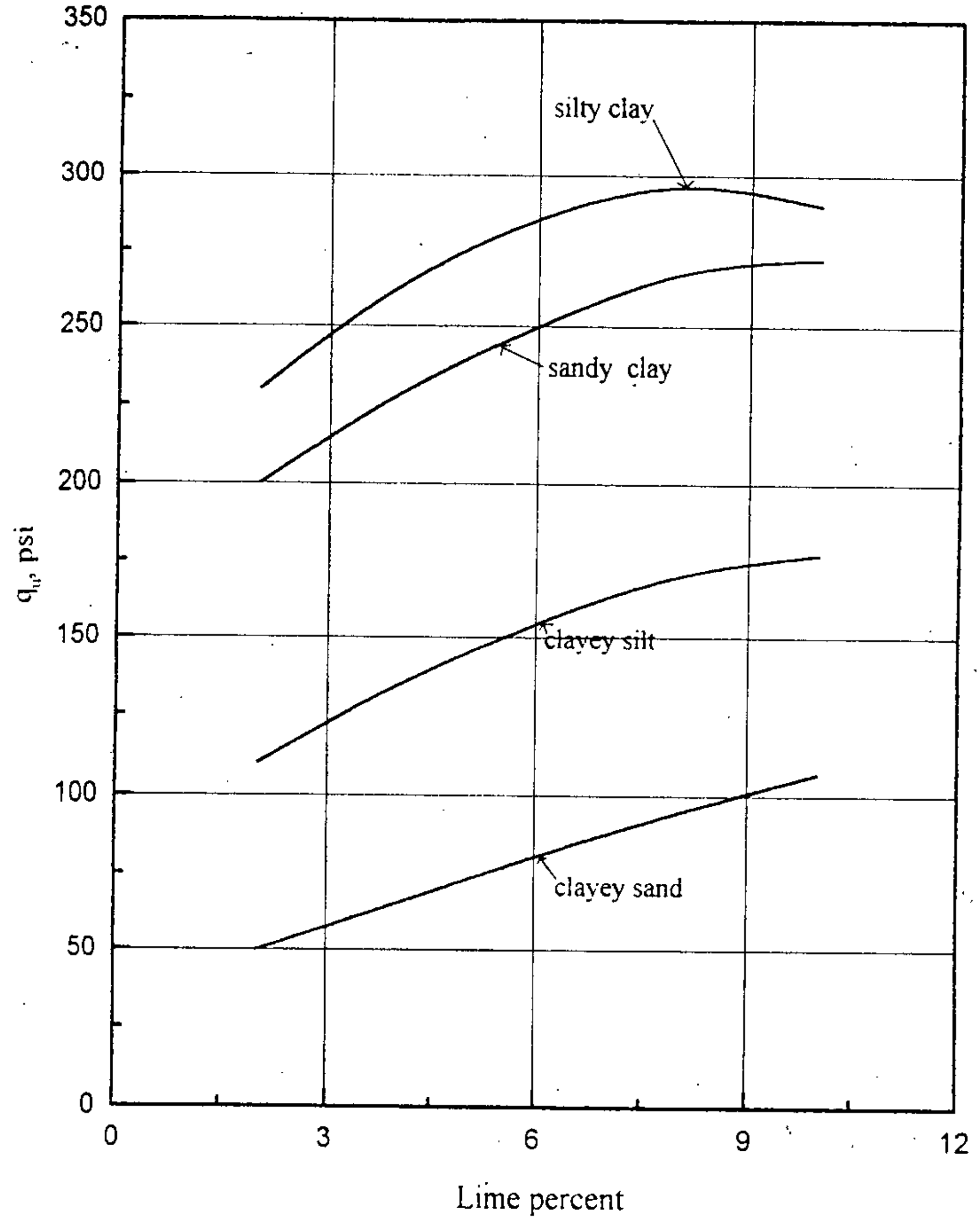


Fig. 2.12 Variation of unconfined compressive strength (q_u) with lime content for various types of soil at 28 days of curing (after Locat et al., 1990)

and mixed layered clay minerals. This is probably due to the greater specific surfaces of smectite and mixed layer material with increased availability of silicates and aluminates. These minerals are more freely attacked and dissolved in the lime-induced high pH environment (Lee et al. 1982). It is important to remember that even though the smecite and mixed layer clay minerals may be more reactive, other clay minerals still frequently exhibit high reactivity (Little, 1995).

Eades and Grim (1965) described the reaction between lime and kaolinite clays as one in which the lime "eats into the kaolinite around the edges with a new phase forming around the core of kaolinite as a result". In contrast, reaction of lime with montmorillonite (smectite) begins with replacement of the naturally occurring cations with calcium, which is provided in abundance with lime stabilization. Once enough calcium is provided to saturate interlayer positions, the clay mineral structure deteriorates, and new minerals are formed which account for strength gain and textural chances.

The findings of Eades and Grim (1965) document a very important point in the practice of lime-soil stabilization: the amount of lime necessary to initiate and "drive" lime-soil reactions which are responsible for long-term compressive strength gain and pozzolanic reactivity is soil dependent and varies considerably from soil-to soil.

A basic understanding of clay mineralogy and mechanics of lime-soil reactivity provides a clearer recognition of the importance of proper lime-soil mixture design and insurance that adequate quantities of lime are added to satisfy all cation replacement and exchange reactions and provide yet enough residual lime to "drive" the pozzolanic reactions (Little, 1995).

pH of soil

Thompson's work (1966) reveals the validity of pH, weathering and soil drainage as indicators of lime-soil reactivity. Generally high natural pH's (above 7) indicated good lime reactivity. Soil pH's below 7 indicated poorer reactivity. Eades and Grim (1966) and Broms (1984) recommended that a high pH value (pH > 12) is favorable for long-term chemical reactions in lime stabilized soils.

In poorly drained soils, break down and removal of soil constituents are retarded and leaching effects are minimized (Thompson, 1966) maintaining a high pH level.

Relatively unweathered soil minerals in poorly drained soils a re a readily available silica and or alumina or pozzolan source to react with lime. Highly weathered soils, indicated by low soil pH should be less reactive.

Organic content

Organic material can inhibit the reaction between calcium and the clay mineral surface. This occurs generally because the organic molecule is quite complex and can adsorb calcium cations or interact with soil exchange sites and hence prevent them from reacting with the soil. It is difficult to predict exactly what level of organic material is enough to substantially interfere with soil-lime reactivity. Hardy (1970) found that organic carbon in excess of one percent hindered stabilization.

Arman and Muhfakh (1972) studied the effect of the percent of organic matter on the unconfined compressive strength of the lime stabilized soil. It has been found that the presence of organic matter in the soil reduces the strength of the stabilized soil to a large extent. As the organic content on the soil increase, unconfined compressive strength continues to decrease as shown in Fig. 2.13.

Benjamin (1990) found negligible strength increase of soil stabilized with 2.5% lime whereas a 5% lime caused moderate strength increase of soil containing 4.3% organic matter after 8 weeks of curing.

NASSARA (1970) stated that soil containing more than 3% organic matter is deleterious to strength development of the stabilized soil. Holm et al. (1983) stated that the strength increase of lime stabilized organic soil is very low. According to them as lime is added to organic soils, some of the Ca^{++} ions are used to satisfy the high exchange capacity of organic matter thus depriving the clay minerals of calcium ions for pozzolanic reactions.

Geological and climatic effects

Hardy (1970) stated that no single soil property proved to be an accurate predictor of lime reactivity for tropical and subtropical soils. Two or more soil properties or characteristics are required. Lime requirements to maximize the strength of lime treated tropical and subtropical soils are generally higher than those of temperate zone soils.

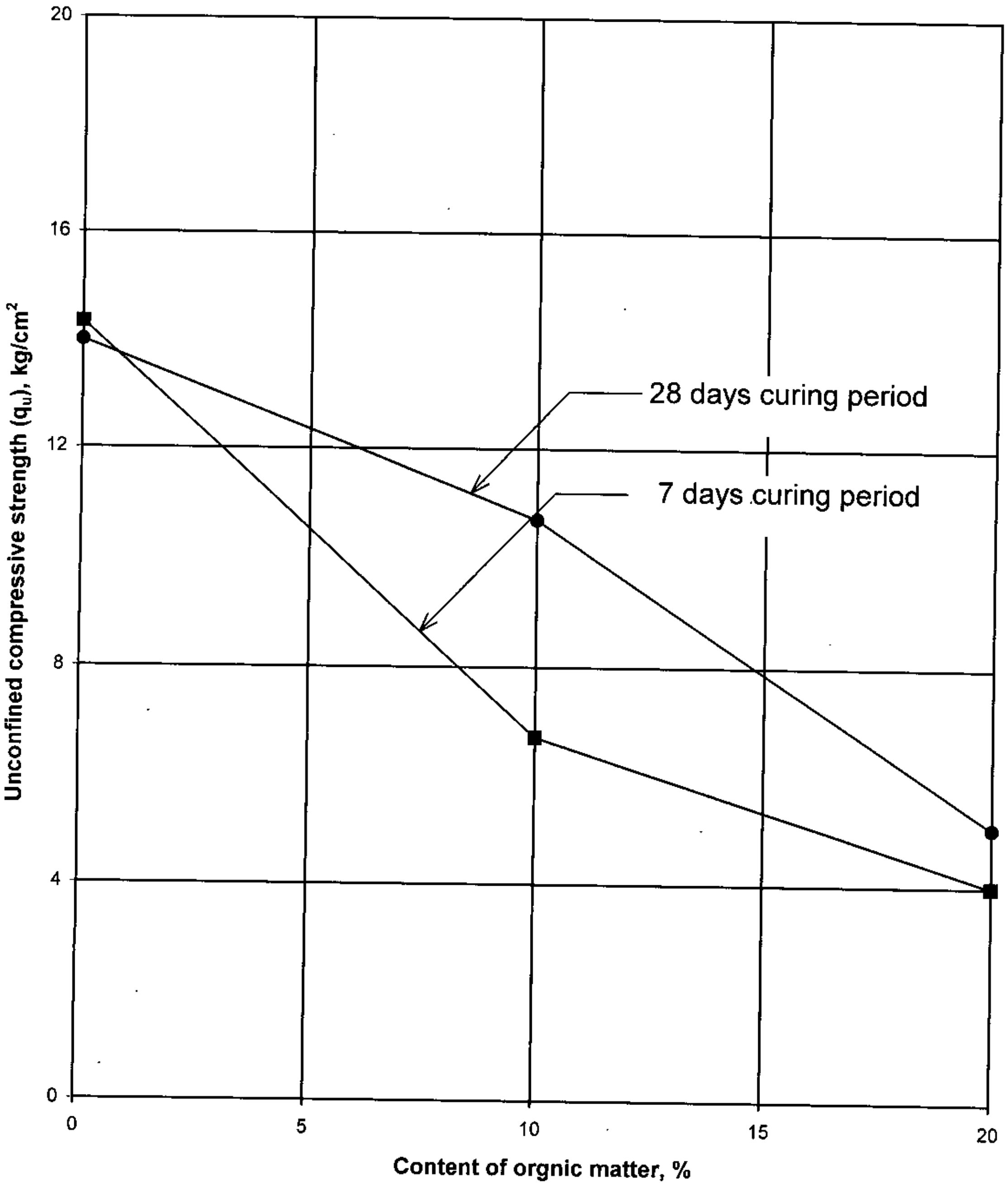


Fig. 2.13 Effect of organic matter on unconfined compressive strength of lime treated soil (after Arman and Muhfakh, 1972)

Hardy, (1970) showed that soil pH, cation exchange capacity and percent base saturation are useful indices of lime reactivities within tropical and subtropical ultisols. High pH and base saturation values indicated good ultisols reactivity. Low cation exchange capacity (CEC) indicated poor ultisol reactivity.

The best index of lime reactivity for tropical and subtropical oxisols is the relative concentration of the base soil constituents as measured by the silica sesquioxide (Where a sesquioxide is a compound in which two metal cations are combined with three oxygen atoms) ratio and to a lesser extent the silica alumina ratio. Low silica sesquioxide and silica alumina ratios indicate good oxisol-lime reactivity (Hardy, 1970).

2.4.2 Lime and Lime Content

Lime

Various forms of lime have been successfully used for soil stabilization. Normally, finely pulverized quick lime is used for soil stabilization of clay with high water contents (BROMS and BOMAN, 1997). If the water content is low, hydrated lime is preferable. On an equivalent basis quick lime is cheaper than hydrated lime but hydrated lime has an advantage of safety and convenience in handling.

Quicklime and hydrated lime are reasonable stable compounds. However, quicklime is vulnerable to water; even the moisture in the air produces a destabilizing effect by air slaking. Hydrated lime is more stable since water does not cause a change in its composition. The primary factor influencing the stability of hydrated lime is carbon dioxide, which reacts with either quicklime or hydrated lime to form calcium carbonate (Boynton, 1979), generally at a slow rate.

Obviously, a relationship exists between hydrated lime and the quicklime from which it was derived. The chemical composition of the hydrated lime reflects this relationship. A high calcium quicklime will produce a high calcium hydrated lime containing 72 to 74 percent calcium oxide and 23 to 24 percent water in combination with the calcium oxide. A dolomitic quicklime will produce a dolomitic hydrate. Under normal hydrating conditions the calcium oxide fraction of the dolomitic quicklime completely hydrates, but generally only a small portion of the magnesium oxide hydrates (about 5 to 20 percent). The composition of a normal dolomitic hydrate will be 46 to 48 percent calcium oxide, 33 to 34 percent magnesium oxide and 15 to 17 percent water in chemical combination with calcium oxide (Boynton, 1979).

Lime content

Lime content is defined as the ratio of the weight of lime used to the dry weight of the base soil, which is to be treated, expressed in percent. The strength of lime-soil mixture increases as the lime content is increased. Researchers stated different criteria for optimum lime content. Herrin and Mitchell (1961) pointed that there is no optimum lime content, which produces a maximum strength in a lime stabilized soil under all conditions. However, for a particular condition of curing time and soil type, there is a corresponding optimum lime content, which causes the maximum strength increase.

Eades and Grim (1966) suggested that the lowest percentage of lime required to maintain a pH of 12.40 is the optimum percentage required stabilizing the soil. The pH procedure is based on the philosophy of adding sufficient lime to a soil to satisfy cation exchange capacity of the soil and satisfy all initial or short term reactions and yet still provide enough lime and a high enough pH to sustain the strength producing lime-soil pozzolanic reactions.

Ingles and Metcalf (1972) suggested that the addition of up to 3% lime would modify well-graded clay gravels, while 2% to 4% was required for the stabilization of silty clay and 3% to 8% was proposed for stabilization of clays and heavy clays. They further suggested that a useful guide is to allow 1% of lime (By weight of dry soil) for each 10% of clay in the soil. Hausman (1990) stated that the practical lime content for lime stabilization varies from 2% to 8%. He showed that the unconfined compressive strength of lime stabilized soil increases with increasing lime content up to 8% after which it decreases. The unconfined compressive strength of the lime stabilized soil at different lime content as found by Serajuddin (1992) is shown in Fig. 2.14. It can be seen from the figure that the unconfined compressive strength of the lime stabilized soil increases with the increase of lime content.

Benjamin (1990) found on the observations up to six months curing time, the range of effective lime content for soft organic clay was from 5% to 10%. A 5% lime content was sufficient to cause moderate strength increase, while 10% was

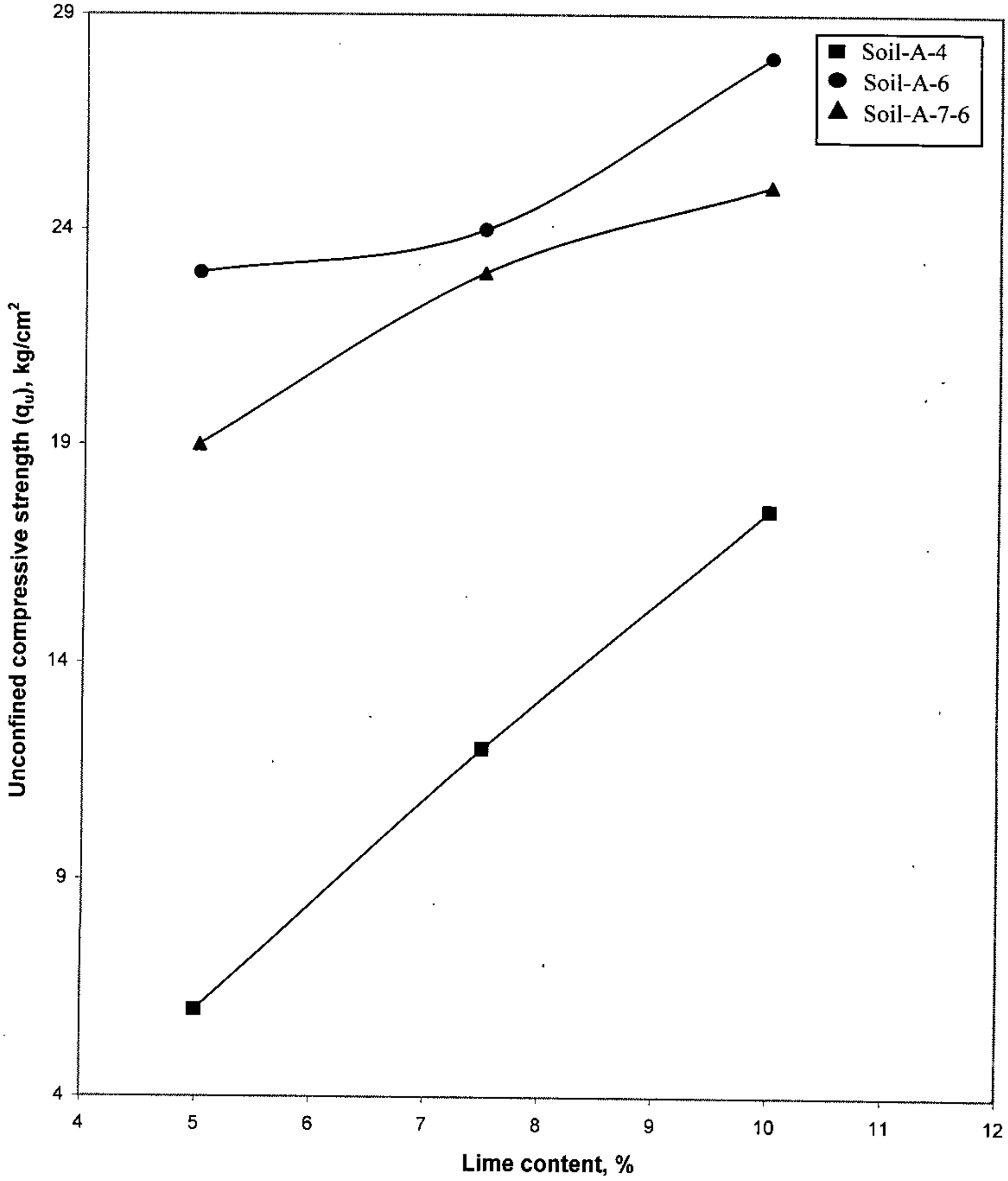


Fig. 2.14 Effect of lime content on unconfined compressive strength of 28 day cure lime stabilized soils (after Serajuddin, 1992)

established to be the optimum lime content for maximum improvement in strength.

Townsend and Klym (1962) recommended stabilization with a lime content of at least 4 percent in excess of the lime fixation percentage. This lime fixation percentage is defined as that percentage of lime, which causes the soil's plastic limit to reach a stable value, i.e. no appreciable changes with further addition of lime.

2.4.3 Mixing

The success of lime stabilization technique depends to a great extent on proper mixing and compaction. In general the more the degree of mixing, the greater the strength of soil.

While most soils may only require one stage mixing, more plastic soils require two-stage mixing (TRB, 1983). NLA (1987) states that incase of extremely plastic gumbo clay (PI of 50 +), it is advantageous to add the requisite amount of lime in two increments to facilitate adequate pulverization and obtain complete stabilization. Compendium (1987) stated that due to two stage of mixing, unconfined compressive strength of the stabilized soil increases. The reason for the increase in strength is that after first stage of mixing the soil become more friable and the soil becomes more effective in lime stabilization.

Khan (1989) pointed out that an intimate mix of water and soil is necessary for maximum utilization of cementing properties of lime. Since lime reaction is slow prolonged mixing is not objectionable. Chew et al. (1955) indicate that increasing mixing time gives increased unconfined compressive strength.

2.4.4 Compaction Delay (mellowing time)

Compaction delay is the time interval between final mixing and compaction. There are controversies on the effect of compaction delay on strength. Fine-grained soil has less effect on the compaction delay time than course grained soil.

Mateos and Davidson (1962) stated that delay of 24 hours had no significant effect on the density and strength for clay type of soil. They recommended an additional small amount (0.5%) of lime into the mixture to compensate for loss due to carbonation and erosion when longer compaction delays (two weeks or more) cannot be avoided.

NLA (1987) reported that granular soil-lime mixture should be compacted as soon as possible after mixing, although delays of up to two days are not detrimental, especially if the soil is not allowed to dry out. For clayey soil delays of up to four days are not injurious. They have also suggested to add 0.5% extra lime in lime-soil mix for longer delays.

Metcalf (1977) stated that the effect of delay in compaction is less pronounced, as lime stabilized soil has no rapid cementing action. Rodrigues et al. (1988) observed that only 3% decrease of unconfined compressive strength and about 2% decrease in dry density for a compaction delay period of 6 hours. They observed that after a few hours, lime mixture require more water for compaction. They explained that some water react with soil lime mixture, so the water content of the mixture is reduced before compaction.

Boominathan and Prasad (1992) stated that compaction delay of 24 hrs could decrease the strength from 30% to 70%. They pointed out that the reduction in strength and density are attributed to granulation of loose soil particles by week cementation as the soil mellows.

Mitchell and Hopper (1961) found that the unconfined compressive strength of the lime stabilized soil decreased 30% for compaction delay of 24 hours.

Townsend et al. (1970) also observed up to 30% reduction in strength for compaction delay of 24 hour.

Sastry et al. (1987) observed that for a delay period of two hours, between mixing and compaction, there is practically no reduction in strength. But for further delay the strength of soil lime mixture continues to fall. Fig. 2.15 shows the variation of unconfined compressive strength of the lime stabilized soil due to the variation of compaction delay. The unconfined compressive strength was measured at 28 days of curing.

TRL (1993) recommend that a stabilized layer must be compacted as soon as possible in order that the full strength potential can be realized and density can be achieved without over stressing the material. If the layer is overstressed, shear

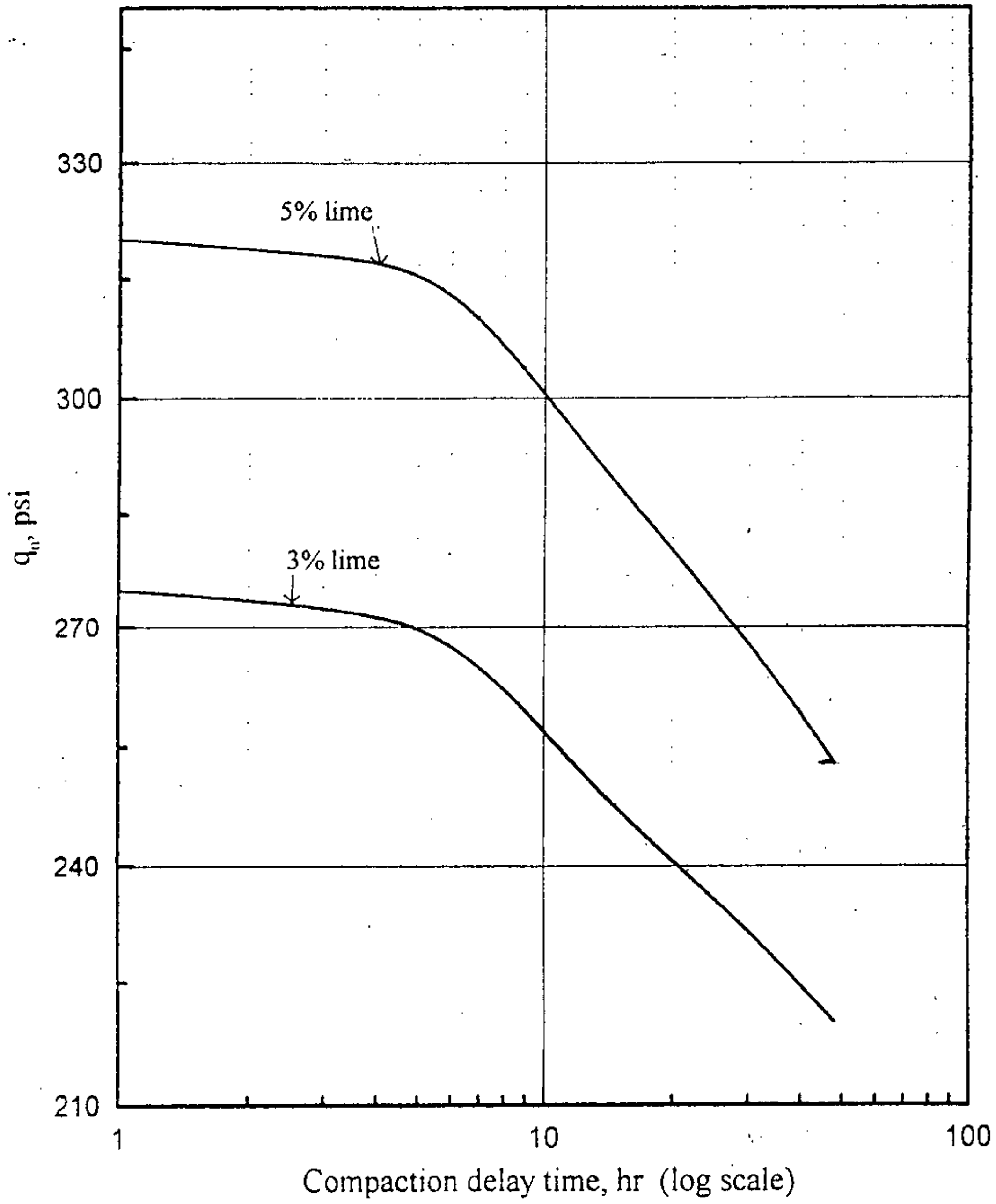


Fig. 2.15 **Variation of unconfined compressive strength (q_u) with compaction delay (after Sastry et al., 1987)**

planes will be formed near the top of the layer and premature failure along this plane is likely, particularly when the layer is only covered by a surface dressing.

Molla (1997) investigated the effect of compaction delay time on unconfined compressive strength of three regional soils of Bangladesh. Molla (1997) stated that unconfined compressive strength decreases with the increase of compaction delay time. This trend is presented in Fig. 2.16 The soils were stabilized with 3%, 4% and 5% lime and were cured for 28 days.

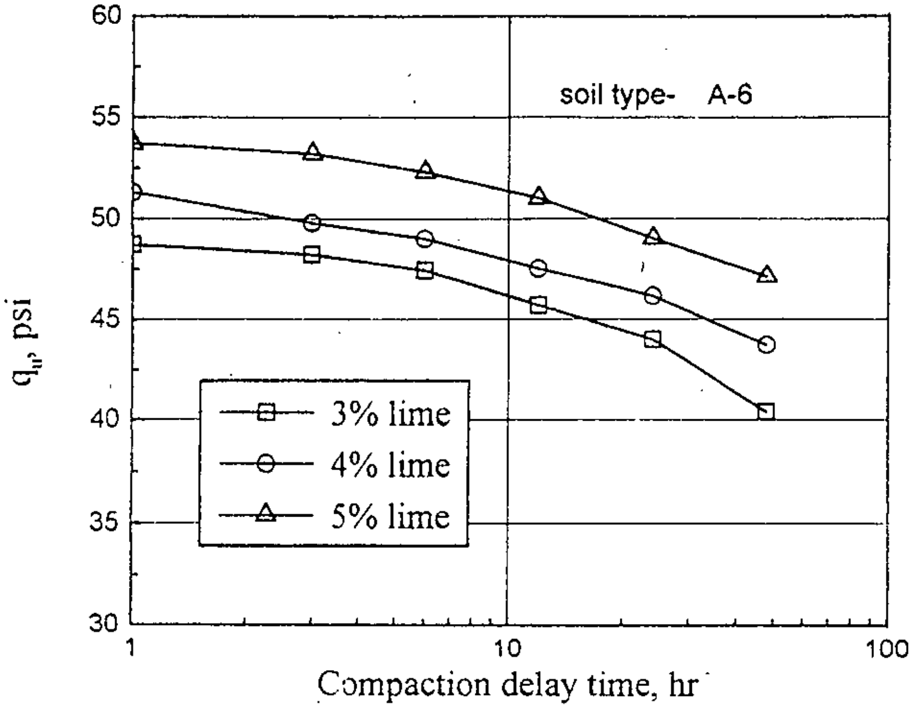
2.4.5 Compaction

Compaction brings the clay minerals into close and intimate contact with the lime particles (Craft, 1964). The greater the compaction effort, the more is the strength attained (Remus and Davidson, 1961; Dunlop, 1977; Serajuddin, 1991; Molla, 1997).

Herrin and Mitchel (1961) stated that a minimum amount of energy is essential for properly stabilize soil with lime. They mentioned that the required compaction effort depends upon the soil type. For the fine-grained soil required compaction energy is lower than the other types of soil. Ei- Rawi (1968) found that the kneading compaction produce stronger specimen. He also stated that lime reacts slowly with soil particles and this phenomenon is more evident for specimens at reduced compaction. Very low-density specimens are not well stabilized. Unconfined compressive strength of lime stabilized soil compacted by modified proctor test method is about 15% higher than that of standardproctor test method (Dunlop, 1977). He also stated that strength of stabilized soil is also dependent upon the uniformity of the compaction.

Serajuddin (1991) observed that the compaction energy has a large effect on unconfined compressive strength and on the CBR value of the lime stabilized soil. He found with lime stabilized soil that the CBR value was increased by about 100% and unconfined compressive strength by about 25% in the modified proctor test method than the standard proctor test method.

Molla (1997) stated that the strength of the stabilized soil increases rapidly with the increase of compaction energy up to a certain level. After that the rate of increase is gradual (Fig. 2.17).



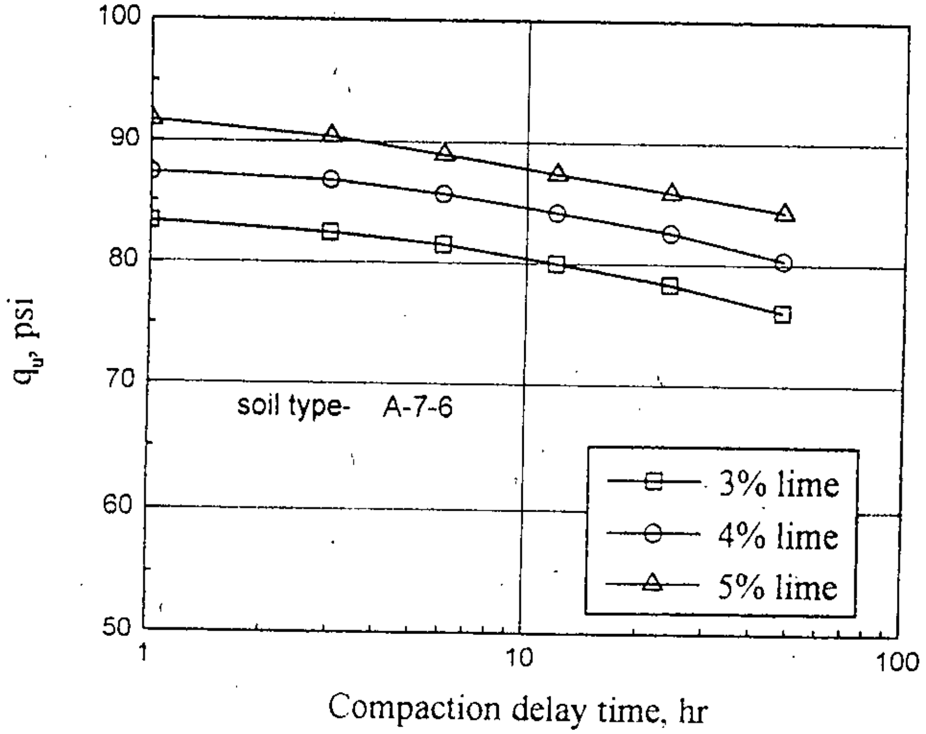


Fig. 2.16 **Variation of unconfined compressive strength (q_u) with compaction delay at different lime contents (after Molla, 1997)**

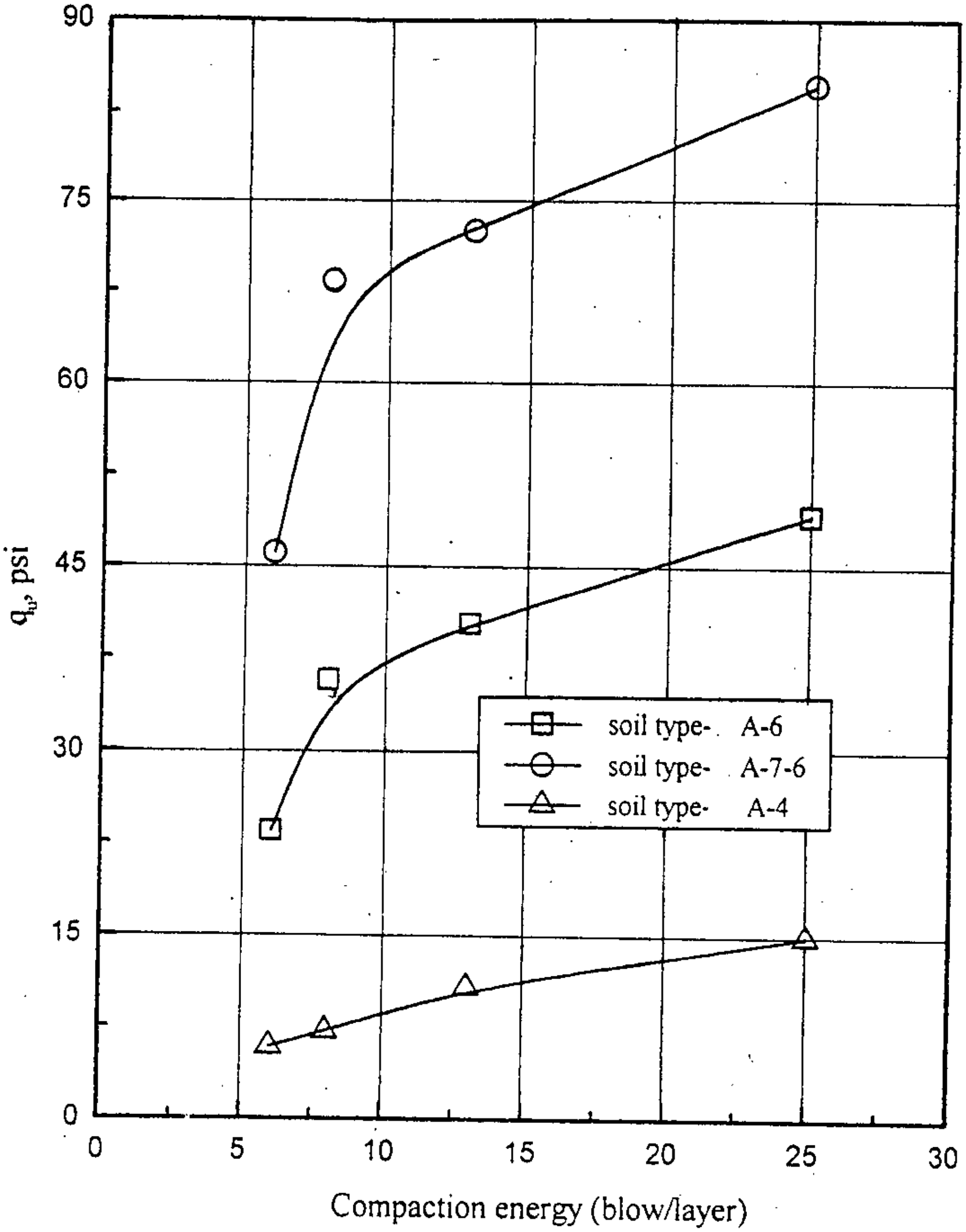


Fig. 2.17 **Unconfined compressive strength (q_u) at different blows per layer at 3% lime using standard proctor equipment (after Molla, 1997)**

2.4.6 Moisture Content

Soil attains maximum dry density at the optimum moisture content, which varies with compaction energy (Chu et al., 1955). Felt (1965), Molla (1997) observed that the strength of the stabilized soil initially increases with the increase of water content. After certain water content, the strength decreases Fig. 2.18 Matos et al. (1962) indicates that the unconfined compressive strength is higher for moisture content slightly on the wet side of clay soil. Rajbongshi (1997) also found that the unconfined compressive strength of lime stabilized soil is higher for moisture content on the wet side of optimum moisture content (Fig. 2.19).

On the long term, high water content may perform better than stabilized soil of low water content; likely because of the movement of solutes is eased with in the pore space (Choquette, 1987).

Locat et al. (1990) stated that for soils with high water content, lower strength development could be partly associated with fewer lime particles per unit volume. On the other hand, for high water content, the easier the mixing and the better the dispersion should be. The lower strength development was observed at high water content is mostly attributed the fact that more cementing products between the more distant soil particles before there is any significant strength increase.

2.4.7 Curing

Proper curing is very important to retain sufficient moisture in the layer so that the stabilizer can continue to hydrate. It reduces shrinkage and reduces the risk of carbonation from the top of the layer (TRL, 1991).

In hot and dry climate the prevention of moisture loss is difficult. If the surface is sprayed constantly and kept damp, the moisture content in the main portion of the layer will remain stable but the operation is likely to leach stabilizer from the top portion of the layer. TRL (1991) recommends an alternate method is to first apply a very light spray of water followed by a viscous cutback bitumin or a slow setting emulsion.

Little (1995) suggested that the laboratory curing condition should be correlated with field condition. Specimen should be kept in sealed container such as metal

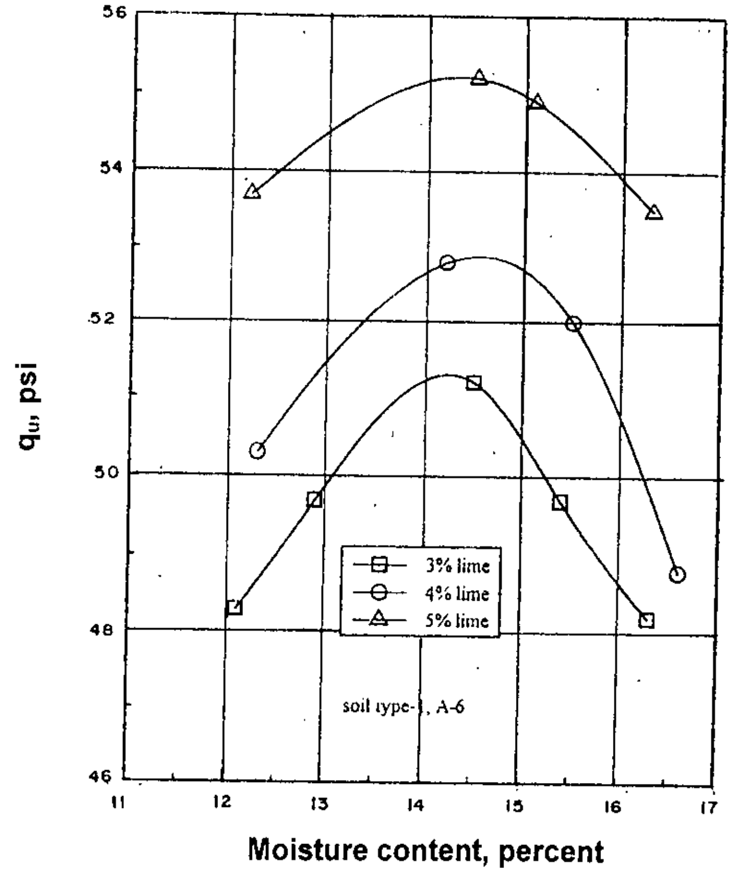


Fig. 2.18 Moisture-unconfined compressive strength relation- ship for the stabilized soil at different lime contents (after Molla, 1997)

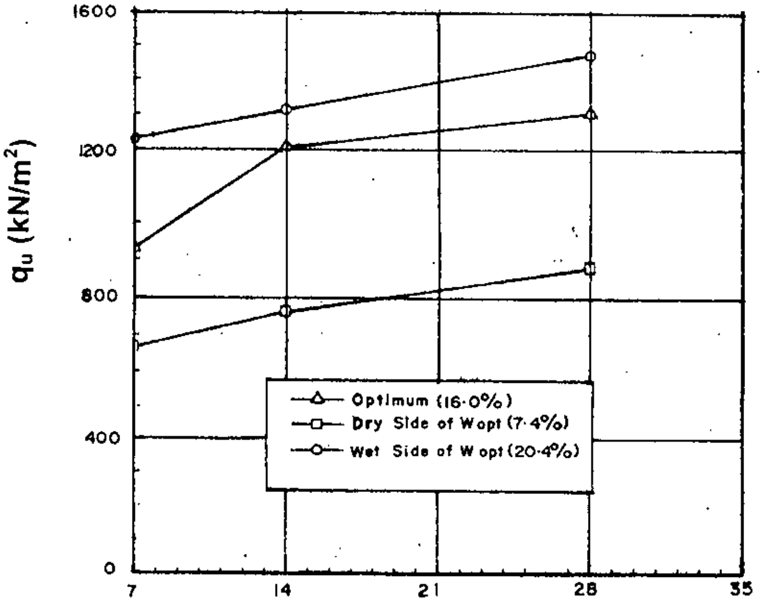


Fig. 2.19 Variation of unconfined compressive strength with euring age for a CL soil treated with 3% lime and at different moulding water contents (after Rajbongshi, 1997)

plastic bag to prevent moisture loss and lime carbonation.

Ramle (1987) has pointed out that the warped specimen maintains a slightly higher moisture content and then higher strength than duplicate unwrapped specimen.

Broms (1984) stated that the shear strength of stabilized clays would normally be higher than that of the untreated clay after the mixing. The initial reaction between lime and soil takes place during the first 48-72 hours after mixing and a secondary reaction, which starts after this period and continues indefinitely (Taylor and Arman, 1960).

Benjamin (1990) found the highest relative increase in strength occurred after 8 weeks of curing for lime contents from 5 to 15% with soil containing 4.3% organic matter. For the optimum lime content (10% in this case), the relative strength increases were 5, 14 and 30 times at 4, 8 and 16 weeks respectively (Fig. 2.20).

Davidson et al. (1965) found that the rate of strength gain was relatively constant up to curing time of 150 days, after which the rate slowed down. Brend (1981) found that the time dependent increase in shear strength is approximately linear with the logarithm of time. Townsend et al. (1970) observed that longer curing period is necessary for specimen compacted at reduced level of compaction.

Broms and Boman (1977) reported that approximately one-third of the increase in shear strength after one year is usually gained after a month and approximately three-quarters after three months.

Doty and Alexander (1978) studied the strength gain over a one-year period and found that the long-term strength can be several times as high as 28 days strengths, but in order for this to occur adequate lime must be used to allow full pozzolanic strength gain (Table 2.1).

The time required to reach a certain percentage of curing can be accelerated by curing at a higher temperature (Fig. 2.21). The higher temperature accelerates the formation of pozzolanic reaction products. However, if accelerated curing temperatures are too high, the pozzolanic compounds formed during laboratory curing can differ substantially from those that would normally develop in the field. Research evidence indicates that 40 ^{0}C at various curing times is a more

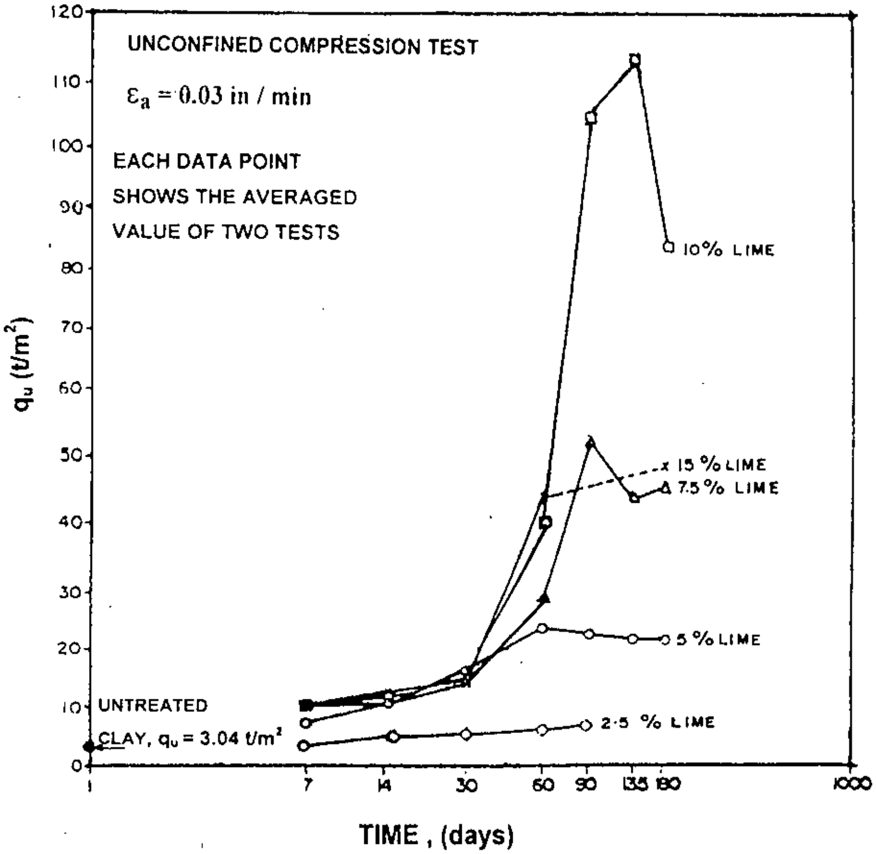


Fig. 2.20 Change of unconfined compressive strength with curing time (after Benjamin, 1990)

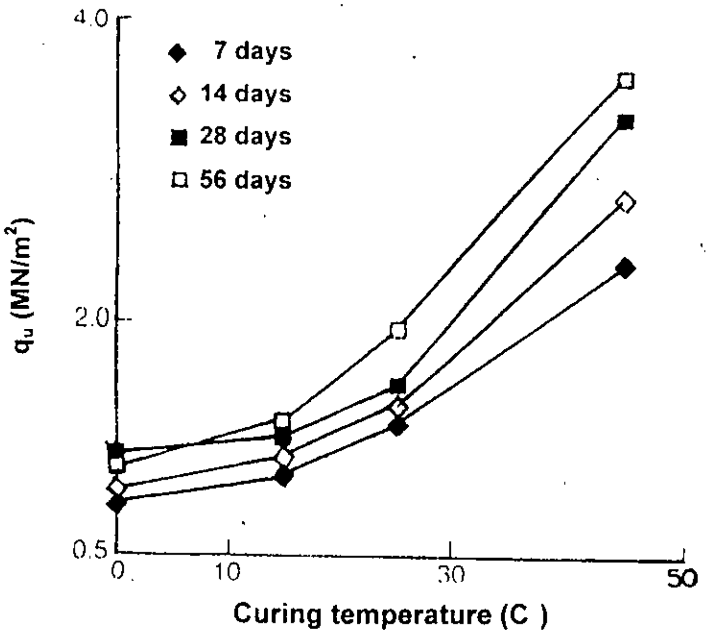


Fig. 2.21 Effect of curing temperature and curing age on unconfined compressive strength of a clay stabilized with 5% lime (after Bell, 1988)

appropriate temperature which accelerates curing without introducing pozzolanic product that may significantly differ from those expected during field curing. Generally elevated temperatures in excess of 49 ^{0} C should be avoided (Little, 1995).

2.5 Mix Design Procedure

A large number of mixture design procedures exist. This is primarily because various countries and agencies have developed particular criteria and procedures to fit their specific design need and lime-soil mixture property objectives. Mixture design criteria have been validated on the basis of field performance in various states and by various agencies. Since various mixture design procedures are developed to meet specific user objectives and are validated for specific geographic regions, indiscriminate application of mixture design procedures to areas other than for which they were designed is discouraged.

Several mixture design procedures are summarized in a number of publications. The TRB State of the Art Report 5 (1987) summarizes the California procedure, Eades and Grim procedure, Illinois procedure, Oklahoma procedure, South Dakota procedure, Thompson procedure and Virginia procedure. Three procedures, which illustrate three sound approaches to mixture design, are presented below. These are the Thompson procedure, the Eades and Grim Procedure and the Texas procedure. The TRB Lime Stabilization State of the Art Report 5 (1987) has used extensively as a reference in summarizing these procedures.

2.5.1 Thompson Procedure

Treatment level

Most fine-grained soils can be effectively stabilized with 3 to 10 percent lime (on a dry weight basis of soil). Under normal field conditions, approximately 2 percent lime is the minimum quantity that can be effectively distributed and mixed with a fine-grained soil.

Mix design protocol

The basic components of mixture design are:

1. Method of preparing the soil-lime mixture,

2. Procedures for compacting and curing specimens,

3. Testing procedures for evaluating a selected property or properties of the soil lime mixture and

4. Appropriate criteria for establishing the design lime content.

Mix preparation

Lime content is specified as a percentage of the dry weight of soil. Soil-lime mixtures are prepared by dry mixing the proper amount of soil and lime and blending the required amount of water into the mixture. ASTM D-3551 should be followed. The mixture should be allowed to mellow for approximately one-hour prior to specimen preparation. Mixtures are normally prepared at or near optimum moisture content as determined by ASTM D-698 or D-1557. Other moisture contents may also be used. In some situations a moisture content may be selected to represent an in situ field condition (TRB Report 5, 1987).

Density control

The density of the compacted specimens must be carefully controlled. The strength of a cured soil-lime mixture is greatly influenced by density and small density variations make it difficult to accurately evaluate the effect of other variables such as lime percentages and curing conditions. Thus, the compaction energy should always be specified. ASTM D-698 or equivalent density is recommended for normal mixture design purposes. Other compaction energy may be used to simulate anticipated field conditions (TRB Report 5, 1987).

Curing conditions

Time, temperature and moisture must be controlled. For stabilization applications where "immediate" strength is an important factor, specimens can be tested immediately after compaction. Ambient temperature or accelerated (high temperature) curing is used for applications where field curing can be achieved prior to use for the stabilized layer.

Laboratory curing conditions should be correlated with field conditions. Because the first winter's exposure is most critical, for freeze-thaw zones, it is important to approximate the "field strength" of the mixtures before the beginning of the winter.

Normal curing conditions are 21^0C (72^0F) for 28 days. Accelerated curing conditions are 49^0C (120^0F) for 48 hours (Little et al. (1987).

Specimens should be cured in a "sealed container" to prevent moisture loss and lime carbonation. Sealed metal cans, plastic bags, etc. are satisfactory.

Disparities in curing conditions make it difficult to compare the results obtained from different testing methods. Mixture quality criteria developed for a particular test procedure should not be arbitrarily adopted for analyzing test results obtained from a different test method.

Testing procedures

Moisture-density relations, plasticity characteristics, swell potential, uncured strength and cured strength are significant soil-lime mixture properties. Recommended testing procedures are presented below.

a. Moisture-density relations: - Utilize ASTM D-698. In many instances lime stabilization is used under conditions (wet soils, poor support, etc.) Where it may be very difficult to achieve a high percentage of specification density, but adequate soil-lime mixture properties are obtained at lower densities.

b. Atterberg limits: - ASTM D-4318 should be used to determine the plasticity characteristics of the soil-lime mixture. The mixture should not be cured prior to determining the PI since the field objective is related to obtaining immediate improvement and substantial pozzolanic strength development is not required.

c. Swell potential: - Use ASTM D-3668 to evaluate swell potential.

d. CBR Test: - The CBR test is appropriate for the following conditions:

   (1) "Immediate" (uncured) strength is a major factor. In this situation, the soil-lime mixture is not highly cemented.

   (2) The soil-lime mixture does not gain significant cured strength due to limited soil-lime-pozzolanic cementing reactions, and the mixture is considered a "modified" soil.

CBR test would be conducted in accordance with ASTM D-3668. The specimens may be either soaked or unsoaked depending on the stabilization objective. Unsoaked conditions may be appropriate for some "immediate strength" evaluation purposes.

For expedient, comparative testing procedures, CBR penetration tests (as per ASTM D-3668) can be conducted on "proctor-sized" (101.6-mm diameter by 114.3-mm, 4-inch diameter by 4.6-inch) specimens prepared in the process of determining the moisture-density relation of a soil-lime mixture. The data provide comprehensive moisture-density and "immediate CBR" information for the soil-lime mixture.

e. Unconfined Compression Test:- Unconfined compression test (ASTM D-5102) procedures should be used to evaluate soil-lime mixtures, which develop significant cured strength. A strength gain of 345 kPa (50 psi) cured (28 days at 21^0C (72^0F) or equivalent) indicates that the soil-lime pozzolanic cementing reaction is proceeding.

Mix design criteria

Mixture design criteria are used to evaluate the adequacy of a given soil-lime mixture. Criteria vary depending on the stabilization objectives and anticipated field service conditions i.e., environmental factors, loading considerations, design life, etc. Mixture design criteria may, thus range over a broad scale and are based on careful considerations of the specific considerations associated with the stabilization project. For soil-lime mixtures used in structural layer applications, minimum strength requirements are specified. Design lime content is normally that percentage which produces maximum strength for given curing conditions. Strength criteria are specified in terms of compressive strength. Minimum strength requirements for base material is 1034 kpa (150 psi) and for subbase material is 689 kpa (100 psi).

Lime modification is used to expedite construction (improve workability, facilitate drying and form a "working platform") or to modify the in situ subgrade or embankment soil properties (increase CBR, decrease swell potential, decrease plasticity).

For construction expedient and subgrade modification purposes, design lime content can be based on an evaluation of the effect of lime content on the "uncured" CBR strength and swell values and /or the PI (an indirect indication of the "swell potential" and "workability").

An "uncured" CBR of 12 to 15 is adequate for much construction expediting applications where the stabilized layer is to serve as a "working platform". Lower CBR values (but not less than approximately 8) may be satisfactory in some situations.

For PI reduction and workability improvement applications, design lime content is the lime percentage beyond which further increases in lime content do not effect significant changes in PI. In some instances lower lime contents may produce acceptable PI reduction and satisfactory workability. Generally the first increment of lime (< 3 percent) produces very substantial decreases in PI with increased percentages (> 3 percent) being less beneficial. Many soil-lime mixtures are non-plastics with 3 percent lime while others retain PI at increased treatment levels. It should be noted that soil modification with low percentages of lime might not provide permanent effects. Stabilization permanency requires a strength evaluation.

2.5.2 Eades and Grim Procedure

The pH procedure, developed by Eades and Grim (1966), is based on the philosophy of adding sufficient lime to a soil to satisfy cation exchange capacity of the soil and satisfy all initial or short term reactions and yet still provide enough lime and a high enough pH to sustain the strength- producing lime- soil pozzolanic reactions. These reactions continue for essentially as long as the pH remains high and lime and pozzolans are available. The procedure is presented in the appendix to ASTM C-977 and is summarized below:

1. Representative samples of air- dried, minus No. 40 soil to equal 20 grams of oven- dried soil are weighed to the nearest 0.1 gram and poured into 150 ml (or larger) plastic bottles with screw tops.
2. Because most soils require between 2 and 5 percent lime, it is advisable to set up five bottles with lime percentages of 2, 3, 4, 5 and 6. This will ensure, in most

cases, that the percentage of lime required can be determined in 1 hour. The lime is weighed to the nearest 0.01-gram and it is added to the soil. The dry soil and lime are shaked to mix.

3. 100 ml of Co_2 - free distilled water is then added to the bottles.

4. The lime-soil-water mix is shaked, for a minimum of 30 seconds, until there is no evidence of dry material on the bottom.

5. At every 10 minutes the bottle is shaked for 30 second.

6. After 1 hour, part of the slurry is transferred to a plastic beaker and the pH is measured. The pH meter must be equipped with a Hyalk electrode and standardized with a buffer solution with a pH of 12.00.

7. The pH for each of the soil-lime mixtures is recorded. If the pH readings go to 12.40, the lowest percentage of lime that gives a pH of 12.40 is the percentage required stabilizing the soil. If the pH does not go beyond 12.30 and 2 percent lime gives the same reading, the lowest percentage that gives a pH of 12.30 is that required stabilizing the soil. If the highest pH is 12.30 and only 1 percent lime gives a pH of 12.30, additional test bottles should be started with larger percentages of lime. Fig. 2.22 demonstrates the results of a pH test for a Burlson, Texas clay.

The pH test is a good test to use as a starting point for optimum lime content selection. The pH test has been shown to provide optimum lime contents that correlate well with optimum lime contents selected from strength testing for soils form Illinois (Thompson and Eades, 1970) and from other regions of the country (Haston and Wohlgemuth, 1985). However, Hardy (1970) demonstrated that the pH test is not as effective in predicting the optimum lime content for ultisols and oxisols of the tropics and subtropics when optimum lime content is defined as the lime content which provides the maximum strength.

The major limitations of the pH test are: (a) the technique does not establish whether the soil will react with lime to produce a substantial strength increase, and (b) strength data are not generated for use in evaluating mixture quality.

2.5.3 Texas Procedure

The soil-lime mixture design procedure used by the Texas Department of Transportation is AASHTO T-220, which provides for the determination of the unconfined compressive strength of the lime-soil mixture. The procedure suggests strength criteria of 690 kPa (100 psi) for base construction and 345 kPa (50 psi) for subbase construction.

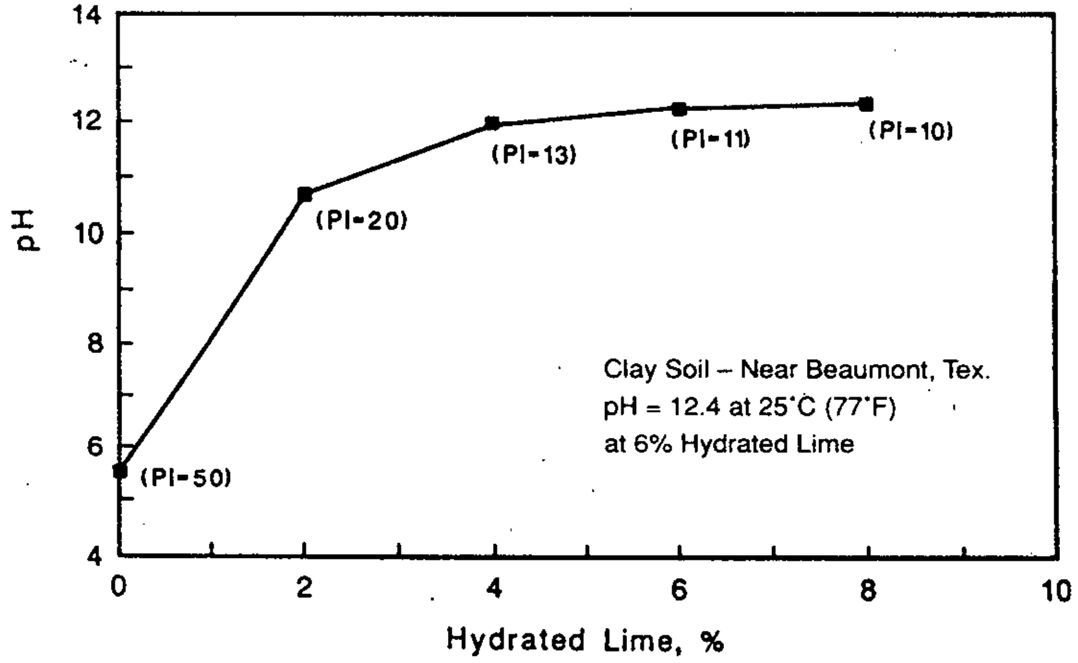
Details of the procedure are presented in AASHTO-220. A summary of the procedure is presented as follows:

1. Based on the grain size and PI data, the lime percentage is selected using Fig. 2.23. The percentages in this figure should be substantiated by approved testing methods on any particular soil material. Use of the chart for materials with less than 10 percent No. 40 and cohesionless materials (PI of less than 3) is prohibited. A relatively high purity lime, usually 90 percent or more of Ca and Mg hydroxides, or both, and 85 percent or more of which passes the No. 200 sieve is required for stabilization. Percentages shown are for stabilizing subgrades and base courses where lasting effects are desired. Satisfactory temporary results are sometimes obtained by the use of as little as one-half of the aforementioned percentages.

2. Optimum moisture and maximum dry density of the mixing are determined in accordance with appropriate sections of AASHTO T-212 and Tex-212 and Tex-113-E. The compaction energy is 50 blows of a 44.5 N (10 pound) hammer with a 45.7-cm (18-inch) drop.

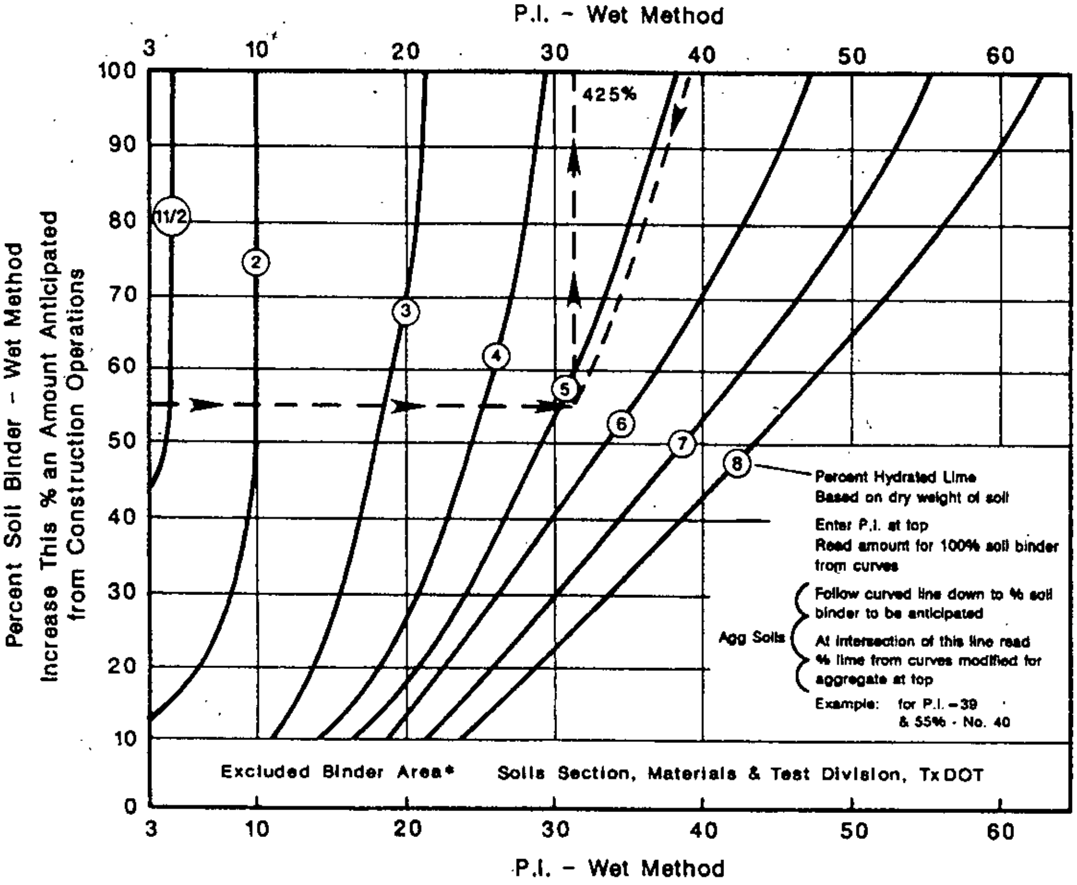
3. Test specimens 152-cm (6-inches) in diameter and 203-cm (8-inches) in height are compacted at optimum moisture content and maximum dry density.

4. The specimens are placed in a triaxial cell (AASHTO T-212 or Tex-121-E) and cured in the following manner:
    a. The specimens are cooled for at least 8-hours and
    b. The specimens are subjected to capillarity (AASHTO T-212 Section 6 or Tex-121-E) for 10 days.



Clay Soil – Near Beaumont, Tex.
pH = 12.4 at 25°C (77°F)
at 6% Hydrated Lime

Fig. 2.22 The Eades and Grim pH procedure to determine optimum lime content (after Little,1995)



Percent Hydrated Lime
Based on dry weight of soil

Enter P.I. at top
Read amount for 100% soil binder from curves

Follow curved line down to % soil binder to be anticipated

At intersection of this line read % lime from curves modified for aggregate at top

Example: for P.I. – 39
& 55% - No. 40

Fig. 2.23 The Texas procedure, based on soil index properties, to select optimum lime content (after Little, 1995)

5. The cured specimens are tested in unconfined compression in accordance with AASHTO T-212 sections 7 and 8 or Tex-117-E.

The results of the unconfined compressive strength testing can be used for substantiation of optimum lime content.

Summary

The primary objective of mixture design is to identify an optimum lime content to be used during construction to modify or stabilize the soil or aggregate. The optimum lime content is a function of the expectations of how the stabilized material will be used. This is because a fairly wide range of lime contents can be used based on the desired engineering properties of the lime-soil/aggregate mixture. The desired objectives may range from a reduction in plasticity and construction expediency to permanent engineering changes which affect the strength of the mixture and performance of the treated layer (Little, 1995).

Haston and Wohlgemuth (1985) tested 29 different soils from different locations in Texas. They compacted the optimum binder contents determined for these soils using the criteria of (1) Atterberg limits, (2) soil-water-lime mixture pH and (3) unconfined compressive strength. They also considered the Texas method (Tex-121-E) for determining the optimum lime content. The conclusions of Haston and Wohlgement were:

1. Strength tests are the best indicator of the amount of lime to use for stabilization.
2. The pH test using the Eades and Grim procedure (ASTM C-977-83a) is a better predictor of peak strength than Atterberg limits tests.
3. Tex-121-E method for optimum lime content is often significantly below the strength test optimum, and this is often a surprise to practicing engineers who have, in the past, considered the Tex-121-E method to be conservative.

The work by Haston and Wohgemuth (1985) is in agreement with the extensive work performed by Currin, Allen and Little (1976).

Because of the importance of selecting an optimum lime content based on the criterion of strength, the Thompson procedure is recommended as an acceptable procedure for mix design. This procedure incorporates the pH test for estimation of the optimum lime content followed by verification of the optimum lime content based on the criterion of strength (Little, 1995).

The differentiation between lime modification and lime stabilization of soils cannot be overemphasized in mixture design. McCallister and Petry (1991) clearly demonstrated the importance of optimum lime content based on the lime content the produces optimum strength. Their data on over 1,700 samples subjected to serve leaching demonstrated that lime contents based on optimum strength are required for permanency. Similar findings are presented by Townsend and Klym (1965) in their suggestions for stabilizing Canadian soils to withstand freeze induced heave. They recommend a lime content of 4 percent above the lime fixation point (the point at which PI is reduced the maximum amount for the soil in question) to insure durability in a freeze-thaw environment.

2.6 Durability of Lime Treated Soils

The primary durability considerations concerning lime-soil mixture deals with prolonged exposure to moisture. Extensive work by Thompson and Dempsy (1969) on Illinois soils reveals that the ratio of soaked to unsoaked compressive strengths for lime soil mixtures is typically between 0.7 and 0.85. Lime-soil mixture seldom reaches 100 percent saturation. The maximum degree of saturation is typically in the range of 90 to 95 percent.

Eades and Grim (1960) questioned permanency of lime in soil and conducted experiments with lime in pure clay minerals. They speculated that if stabilization was due to only flocculation and ion exchange, percolation of ground water could replace calcium. However they also concluded that the formation of new compounds such as silicate and aluminate hydrates are permanent reaction products and are not susceptible to leaching. Kennedy (1984) further substantiated this conclusion by stating that once calcium silicate hydrates are formed in the stabilization process, they are permanent and do not revert. However, Kennedy did not dispute the possibility of reversal or degeneration of soil-lime effects for areas where smaller quantities of lime have been added than that, which is necessary to fully stabilize the soil.

Mc. Callister and Petry (1990) stated that in order to provide the greatest safeguard possible against leachate damage and moisture damage in general, the proper strategy is to use the optimum lime content to produce optimum strength in the mixture design process.

Kelly's (1977) study demonstrated that soil with PI's of from 12 to 50 can be stabilized permanently to develop high compressive strength and demonstrated continued strength increase with time.

Doty and Alexander (1978) pointed out that the substantial long-term strength gain could result in autogenous healing of well-designed mixture. The mixture can continually resist fatigue damage and other form of distress, which occur in period of low level or no pozzolanic reactivity by reestablishing the pozzolanic reaction during the favourable curing periods.

CHAPTER THREE

EXPERIMENTAL INVESTIGATION

3.1 General

The experimental investigations carried out on the untreated and treated samples have been described in this chapter. Thompson procedure, described in chapter-II, was used as a guide in preparing the sample and evaluating the properties of the soil lime mixtures. The unconfined compression test was done in order to study the relative increase in strength of lime treated soils as affected by curing time and molding conditions.

Three types of soil of Dhaka and adjacent areas were used in this research work. The samples were collected from a depth of about 1.5-meter. Care was taken to remove any loose material, debris, coarse aggregates and vegetation.

All samples were packed in large polythene bags covered by gunny bags and transported to the Geotechnical laboratory of BUET. The soil samples are designated as follows:

Soil 'A' : Collected from Bilamalia, Savar,
Soil 'B' : Collected from Beraid, Badda,
Soil 'C' : Collected from Patira, Rupgonj.

The lime was collected from open market and it was kept sealed to prevent carbonation until immediately before use. To study the effect of lime on strength of stabilized soil, 3%, 5% and 7% lime were used. Lime content is defined as the ratio of the weight of lime to the dry weight of soil expressed in percent. To study the long term strength of lime stabilized soil unconfined compression test was performed on soil specimen cured for 7 days, 28 days, 90 days, 180 days and 360 days.

3.2 Laboratory Test on Base Soils

The soils collected from the fields were air-dried and the soil lumps were broken down with a wooden mallet. The following tests were performed in determining the properties of the untreated soil.

i) Liquid limit and Plastic limit	ASTM D4318
ii) Grain size analysis	ASTM D422
iii) Optimum moisture content and maximum dry density	ASTM D698

The chemical properties investigated are the soil pH and organic content. The soil pH was determined by using pH meter with glass electrode (Metrohm 691) from extraction of soil: water 1: 2.5. Organic matter content was determined by dry combustion method. Details of the pH determination and organic matter determination are given in appendix-A and appendix-B respectively.

The determination of the clay mineralogy of the untreated clay was done by X-ray diffraction analysis, and was carried out at the laboratory of the Soil Research Development Institute, Dhaka, an organization of Agriculture ministry. The procedure involved in the mineral content determination is described briefly in appendix-C.

3.3 Tests on Lime Stabilized Soils

Compaction tests were performed on lime-soil mix with different lime content and compaction energy. Unconfined compressive tests were performed at different curing days.

3.3.1 Compaction Test

The optimum moisture content and maximum dry density of the lime treated soils were determined by Standard Proctor test method. A cylindrical mold of 4 inch inside diameter and 4.60-inch height was used. The volume of the mold was 1/30 cu. ft. The weight of the rammer used was 5.5 lbs and the face diameter was 2 inch.

Air-dried soils passing through No. 4 sieve were mixed with desired quantity of lime. The mixture was blended until it formed a uniform color. The water was then added and it was thoroughly mixed to ensure even distribution. After applying the first increment of water, the soil-lime-water mix was placed in a desiccator and allowed to stand for 1 hour.

A series of soil-lime mixture of varying moisture contents were prepared. These samples were compacted in 3 (three) layers of approximately equal height.

Each layer was compacted by 25 blows with the rammer, falling from a free height of 12 inch. The amount of used soil-lime was such that the third compacted layer was slightly above the top of mold by not exceeding 6 mm. Moisture content and dry density were determined for each compacted sample.

3%, 5%, and 7% lime were mixed separately with the three type of soil and optimum moisture content and maximum dry density of lime-soil mix were determined. These optimum moisture contents were used in preparing the lime stabilized soil samples for compression test.

3.3.2 Preparation of Lime Stabilized Samples

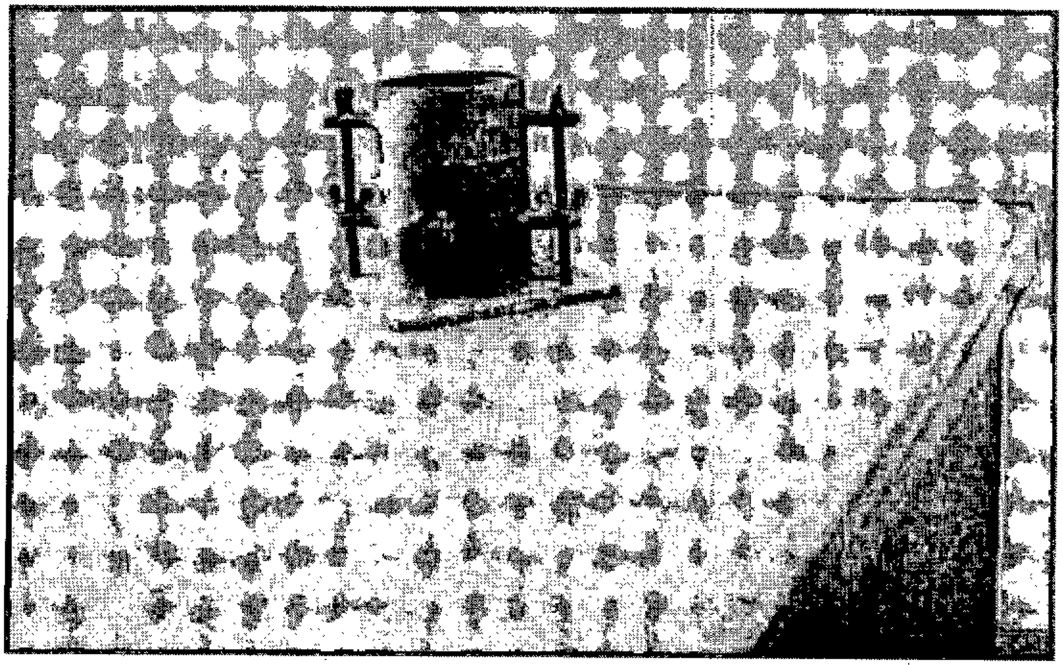
In order to prepare test samples for strength test of this research work a compaction mold was fabricated.

Compaction mold

The mold used for compacting untreated soil and treated soil (soil-lime mix) were fabricated using mild steel seamless pipe. The mold is 4.6-inch high and 4.0-inch in diameter composed of two longitudinal halves joined with nut-bolts. The removable collar and base plate are similar to that of used for Standard Proctor Test (ASTM D698). Standard Proctor Test hammer was used for compacting the soil-lime mix. The mold is shown in Fig. 3.1.

Soil-lime mixing

The soil-lime mixtures were prepared by dry mixing the proper amount of soil and lime in batches. Before mixing, the water content of the air-dry soil was determined. The mixing was done thoroughly in a steel pan. Then required quantity of water was added in to the soil mass and was blended. Mixtures were prepared at or near optimum moisture content as determined by the procedure described in section



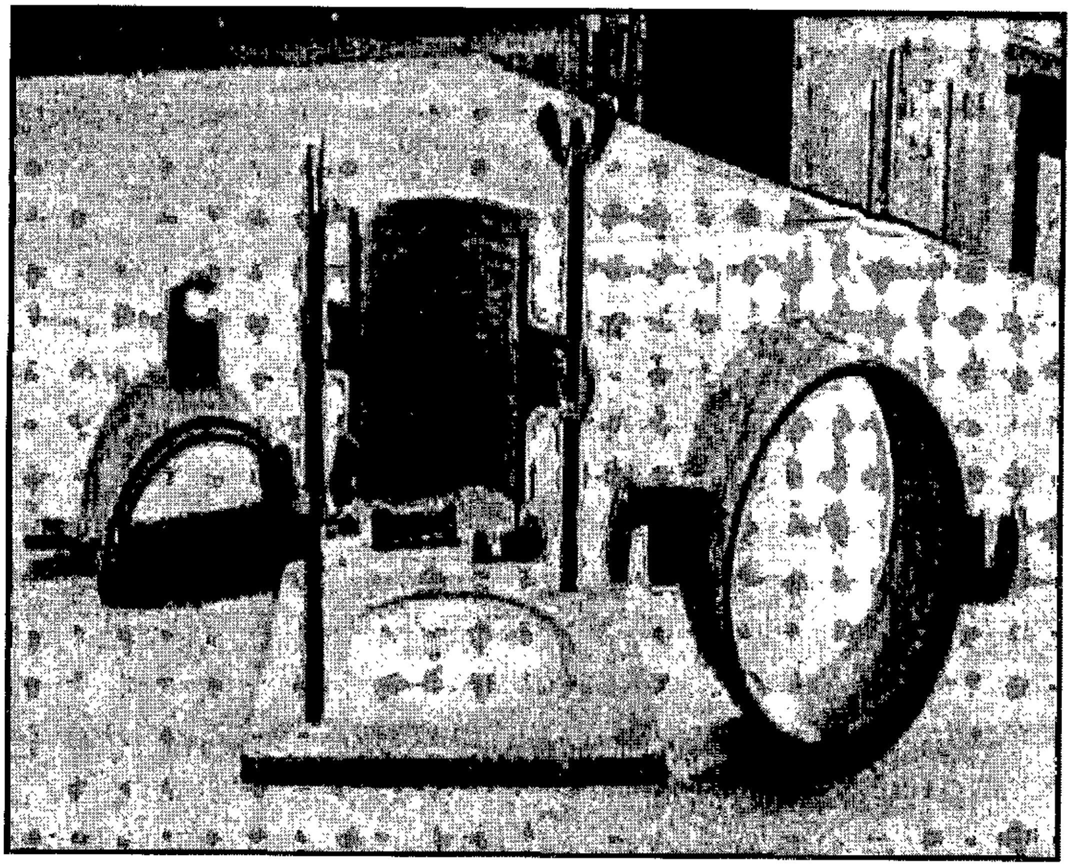


Fig. 3.1 Compaction mold for preparing test sample

3.3.1. Soil lime mixtures were allowed to mellow for 1 (one)-hour prior to compaction.

Compaction

The soils were compacted in the mold with evenly distributed blows of the hammer using a one feet drop in approximately 3 (three) equal layers and it were compacted by 25 blows in each layer. The surfaces of the first two layers were scarified to promote bonding between adjacent layers. The compacted soil lime mix were removed from the mold by unscrew the nut-bolts and thus separating the halves. A representative sample of approximately 100-gm was obtained for water content determination.

The compaction was performed as the procedure described above. To investigate the effect of compaction energy, compaction delay (mellowing time) and retempering (reworking) the test samples were prepared as follows:

a) Compaction energy

To observe the effect of compaction energy on the lime treated soil, specimens were prepared by using 8, 15 and 25 blows per layer. The maximum dry density and optimum moisture content of soil 'C' mixed with 3% and 7% lime by using 8, 15 and 25 blows per layer were also determined. Mixtures were prepared at or near of this optimum moisture content and the soil-lime mix were allowed to mellow for 1 hour.

b) Compaction delay (mellowing time)

Compaction delay is the time interval between the mixing of soil-lime and the compaction of the mix. After thorough mixing, it was placed in a plastic bag with seal and stored in a humid chamber. As mentioned earlier the mixture was generally allowed to mellow for 1 hour. To study the effect of compaction delay (mellowing time) the lime soil mix was kept in the humid chamber for 24 hours (1 day), 72 hours (3 days), 168 hours (7 days) and 336 hours (14 days). After the mellowing time, the soil-lime was compacted accordingly.

c) Reworked or retempered sample

Compacted stabilized soils sometimes needed to repair or retemper in the field due to various reasons. To study the effect of retempering on strength of stabilized soil retempered samples were prepared. The soil-lime mixtures were compacted in the mold by 25 (twenty-five) blows in each layer keeping moisture content near optimum. Then they were removed from the mold and poured in airtight bag and kept in sealed container for 24 hours (1 day), 72 hours (3 days), 168 hours (7 days) and 336 hours (14 days). After the desired period the tempered soils were broken down and pulverized to passing # 4 sieve. They were then again compacted in the mold with 25 (twenty-five) blows in each layer following normal procedure described earlier.

3.3.3 Strength Test

Unconfined compression tests were used to measure the strength of the lab-fabricated lime stabilized soils.

Preparation of test specimen for unconfined compression test

The compacted (in the mold) soil-lime mixtures were immediately removed from the mold and they were divided in to four parts. Each part was trimmed to circular cross-section keeping the ends parallel by making them perpendicular to one of the sides. When the soil sample became about a size of 1.5 inch diameter, it was placed in to a cylindrical split type form of 3 inch height and 1.5 inch diameter and the sample was trimmed again to get the specimen of form size.

Curing of specimen

After preparing the test specimen, they were kept in airtight balloons and then in a desiccator sealed with paraffin wax for a period of 7 days, 28 days, 90 days, 180 days and 360 days.

Soaking of specimen

After wrapping with filter paper the cured test specimens were immersed in a jar filled with water for 7 days. During these periods, the water in the jar was maintained approximately 1 inch above the top of the specimen. For this purpose 21-day, 83-day and 173-day old (cure) samples were used.

Unconfined compression test

After the desired curing period the unconfined compression tests were carried out to study the strength gain of lime treated samples. The tests were conducted according to ASTM D 2166-85-test procedure. The unconfined compression testing programme is presented in table 3.1.

The prepared specimen was placed on a loading platform of a compression machine immediately after removing from the curing chamber or soaking jar. The specimen was carefully aligned in the compression machine and the loading device was adjusted carefully such that the upper platoon just makes contact with the specimen. Then the proving ring and the deformation dials were set to zero.

The rate of deformation during testing for stabilized soil was chosen to be 0.15 mm per minute. The rate was calculated taking 0.2% of the height of the specimen per minute.

The axial deformation of the specimen and the corresponding load applied were recorded at frequent intervals. The compression was continued until cracks have definitely developed. The maximum load causing failure of the specimen was taken as the unconfined compressive strength of the sample.

Flow chart for the preparation of unconfined compression test specimen

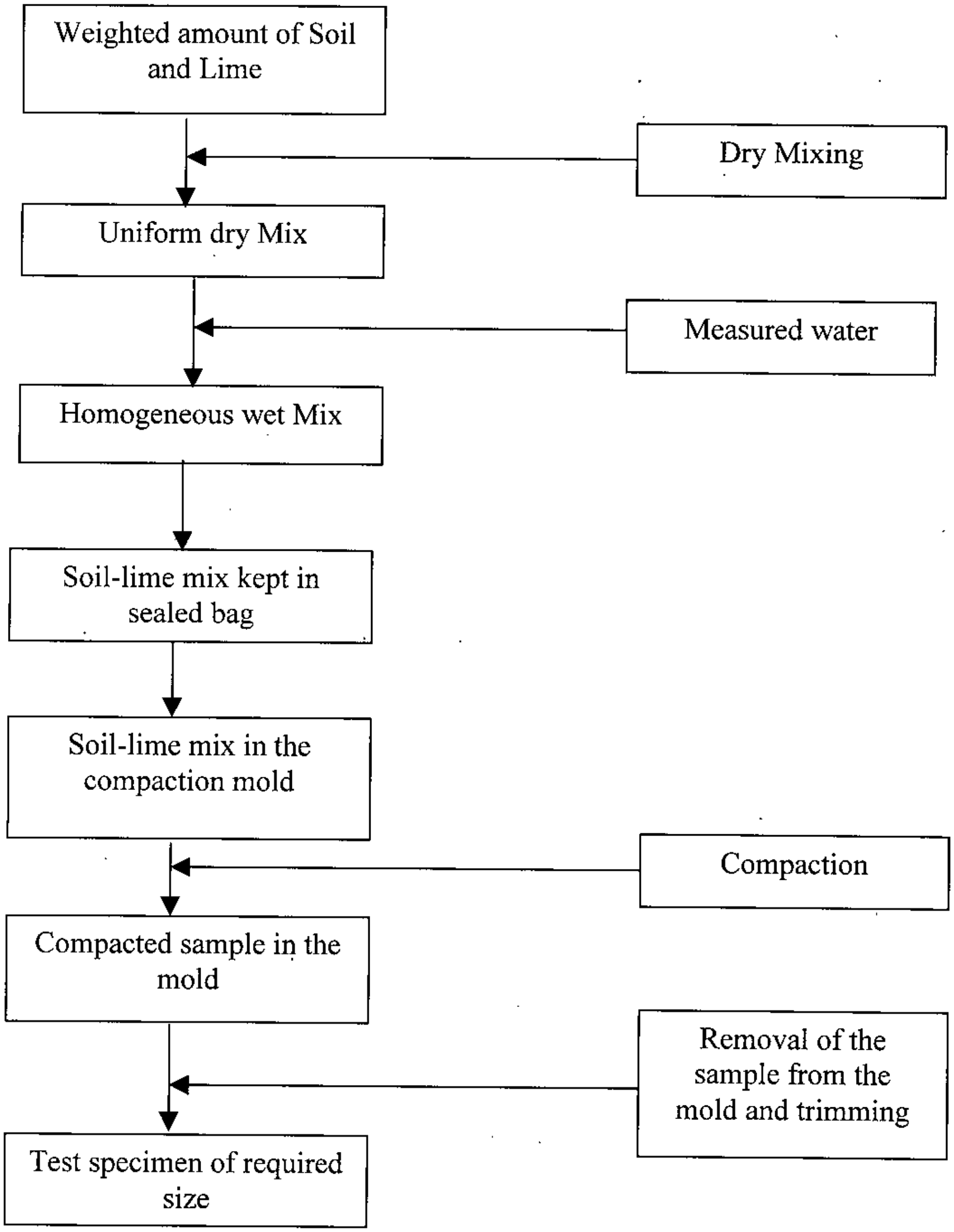


Fig. 3.2 The different stages for the preparation of soil specimen for unconfined compression test

Table 3.1 The unconfined compression testing programme

Sample Type	**Lime Content**	**Number of tests ***		
		Soil 'A'	**Soil 'B'**	**Soil 'C'**
Base soil	0%	2	2	2
1 hour mellowing using Standard Proctor energy	3%	10	10	10
	5%	10	10	10
	7%	10	10	10
1 hour mellowing using reduced energy	3%	—	—	12
	7%	—	—	12
Compaction delay sample	3%	—	—	24
	7%	18	—	24
Retempered sample	3%	—	—	24
	7%	18	—	24
7 days soaked sample	3%	—	—	6
	5%	—	—	6
	7%	—	—	6

* Tests were repeated and average values used

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 General

This chapter deals with the experimental results and discussions from the tests conducted on the base soils and lime stabilized soils. The properties of the base soils used in the study are first presented, it include the physical, chemical and mineralogical properties. The effect of lime treatment on the properties of soil is presented next. The variables, which are considered, are soil, lime content, compaction energy, compaction delay (mellowing time) and curing time. Test samples were also prepared by using tempered (worked) lime treated soil.

4.2 Properties of the Soils Used

The properties of the three types of soil are presented in Table 4.1. It is seen from the table that the liquid limit of the soil 'A', 'B' and 'C' are 46%, 48% and 40% and the plasticity index are 19%, 20% and 17%. The soil 'A' contains 24% clay and 72% silt size particle and soil 'B' contains 26% clay and 71% silt size particle. Where as soil 'C' contains 20% clay, 64% silt and 16% sand size particle. It is evident from the table that the soils 'A' and 'B' have almost similar physical properties. According to Unified System of Soil Classification (ASTM, D2487), soil 'A' and soil 'B' are ML/CL type and soil 'C' is CL type. According to AASHTO (M145) soil 'A' and soil 'B' are A-7-6 type and soil 'C' is A-6 type.

The pH value of soil 'A', 'B' and 'C' are 6.9, 5.6 and 6.1 respectively. The organic matter content of soil 'A' is 1.10%, soil 'B' is 2.38% and soil 'C' is 0.37%. The important property, which has a significant influence on the effectiveness of lime treatment, are the organic content and the acidity (low pH) of the soil. The clay, which is high in organic matter, has a large reserve of potential acidity or buffering capacity. Buffering capacity was defined by TAN (1982) as the capacity of the soil to release exchangeable H^+ in to the soil solution to restore the equilibrium pH and due to which there is no soil reaction until the reserve in H^+ is exhausted. Thus an

Table 4.1 Characteristic values of the initial properties of the base soils

Properties	Characteristic Values		
	Soil 'A'	Soil 'B'	Soil 'C'
Physical properties :			
Liquid limit, (%)	46	48	40
Plastic limit, (%)	27	28	23
Plasticity Index, (%)	19	20	17
Grain size distribution :			
% Clay (< 0.002 mm)	24	26	20
% Silt (0.002 mm to 0.075 mm)	72	71	64
% Sand (0.075 mm to 2.00 mm)	4	3	16
Optimum moisture content (%)	21.70	22.10	18.40
Maximum dry unit weight, (pcf)	104.40	102.70	110.30
Color	Gray	Dark gray	Redish brown
Classification :			
Unfined (ASTM, D2487)	ML/CL	ML/CL	CL
AASHTO (M145)	A-7-6	A-7-6	A-6
Chemical Properties :			
Soil pH (1:2.5, Soil: Water Ratio)	6.90	5.60	6.10
Organic Carbon, (%)	0.64	1.39	0.21
Organic Matter, (%)	1.10	2.38	0.37
Mineralogical Composition :			
Clay Fraction :			
Mica, (%)	45	47	60
Vermiculite, (%)	7	9	21
Chlorite, (%)	18	Trace	—
Kaolinite, (%)	10	37	15
Gibbsite, (%)	7	—	—
Quartz (%)	13	7	4
Silt Fraction :	Mainly quartz	Quartz & feldspar	Mainly quartz

amount of lime is needed to first exhaust the reserve acidity, and thereafter, to raise the pH to the desired level at which lime-clay reactions are enhanced.

NASARA (1970) stated that soil containing more than 3% organic matter is very harmful to the strength development of the stabilized soil. However IRC (1973a) recommended a maximum limit of 2% organic content for lime stabilization.

From the mineralogical analysis it is seen that a substantial portion of the clay fraction of the soils are mica. Other than mica, soil 'A' contains 18% chlorite, 10% kaolinite and 13% quartz, soil 'B' contains 37% kaolinite and low amount of vermiculite (9%) and quartz (7%), and soil 'C' contains 21% vermiculite and 15% kaolinite.

Silt fraction contains large amount of quartz and small amount of feldspar.

4.3 Maximum Dry Density and Optimum Moisture Content of Base Soils and Lime Stabilized Soils

The optimum moisture content and maximum dry density of the base soils and lime stabilized soils were determined using Standard Proctor method.

The relationships between moisture content and dry density for three different soils are shown in Fig. 4.1(a), Fig. 4.1(b) and Fig. 4.1(c). It can be observed from the figures that the maximum dry density of the lime stabilized soils decrease due to the addition of lime and the dry density continues to decrease with the further addition of lime. On the other hand optimum moisture content increases in both the cases. Serajuddin and Azmal (1991), Rajbongshi (1997), Molla (1997) found similar results from their study with different regional fine-grained soils of Bangladesh. Faisal et al. (1992) describes the above phenomena as a result of flocculation of the soil structure caused by the addition of lime. The increase in optimum moisture content is probably the consequence of the additional water held with in the flocculated soil structure resulting from lime-soil interaction.

It can also be observed from the figures that the moisture-density curves become flat due to the addition of lime. With this flat shape it is possible to compact the soil-lime mix in a wider range of moisture content. Again as the optimum moisture content of the lime stabilized soil increases, it is possible to compact the soil when

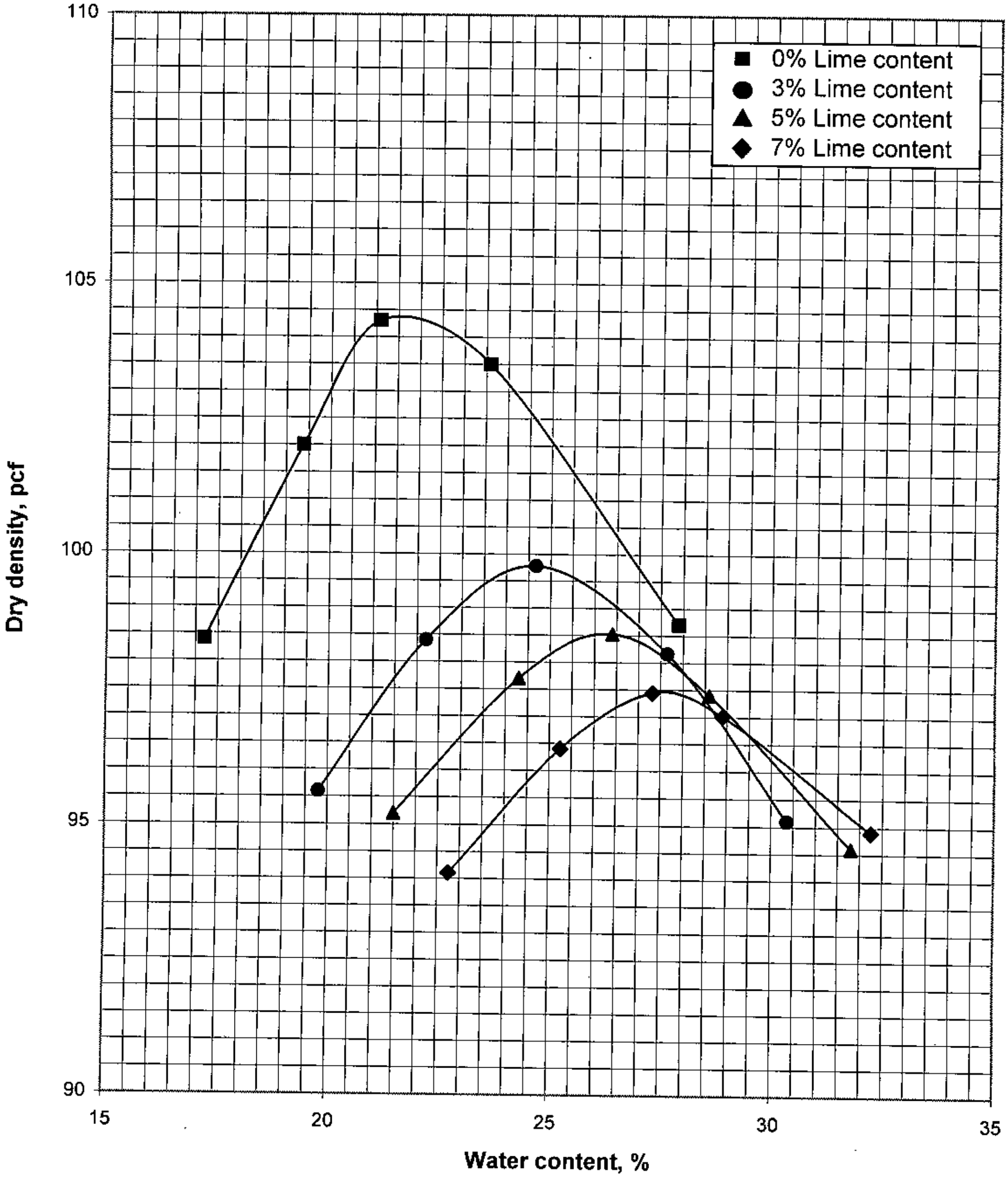


Fig. 4.1.(a) Moisture-density relationship for stabilized soil 'A' (ML/CL) at different lime contents

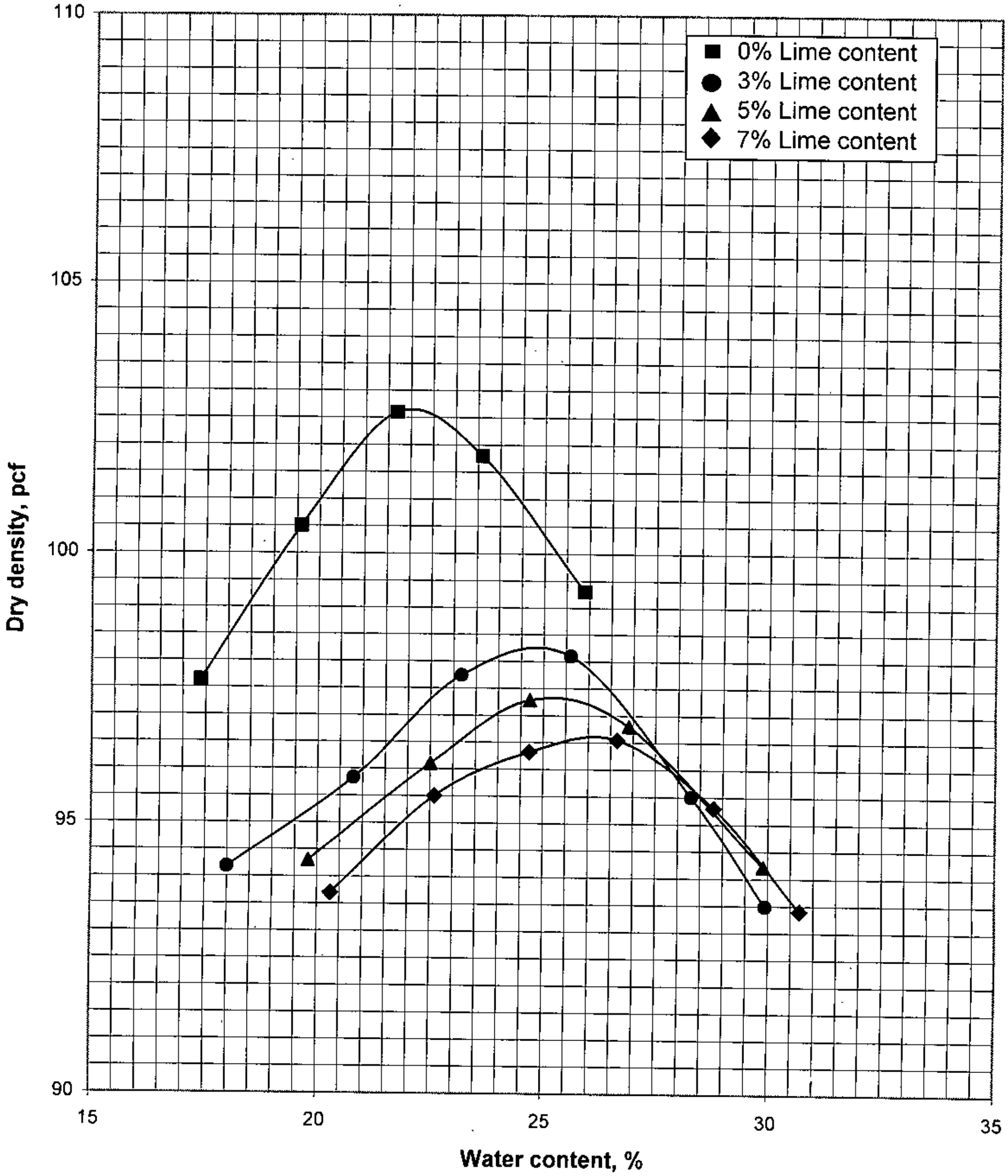


Fig. 4.1.(b) Moisture-density relationship for stabilized soil 'B' (ML/CL) at different lime contents

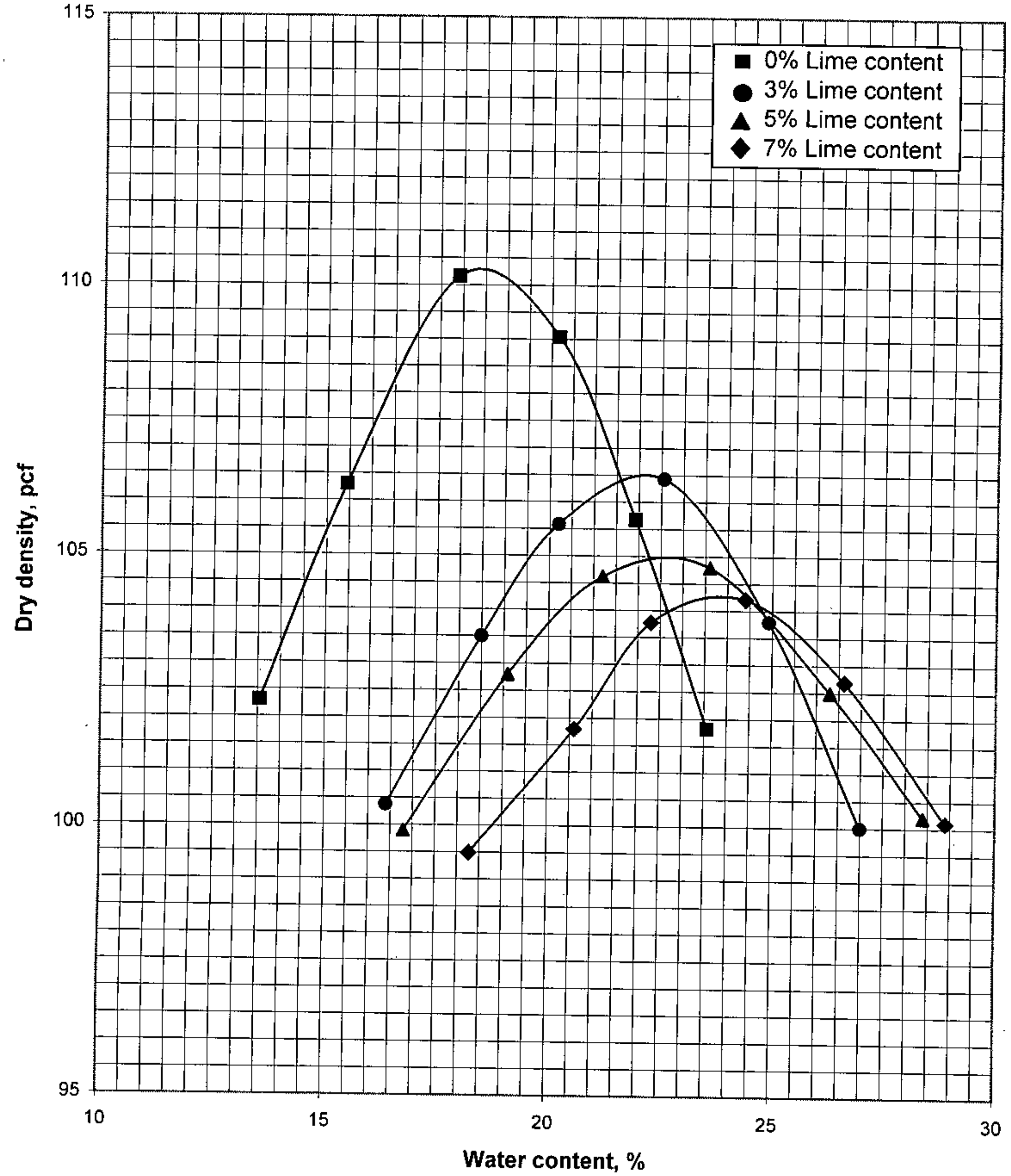


Fig. 4.1.(c) Moisture-density relationship for stabilized soil 'C' (CL) at different lime contents

Table 4.2 Optimum moisture content and maximum dry density of the soils with different lime contents

Soil type	Lime content, %	Optimum moisture content, w_{opt}, %	Maximum dry density, γ_d max, pcf (kN/m^3)
Soil 'A' (ML/CL)	0	21.7	104.4 (16.39)
	3	24.6	99.8 (15.67)
	5	26.3	98.7 (15.50)
	7	27.5	97.5 (15.31)
Soil 'B' (ML/CL)	0	22.1	102.7 (16.12)
	3	24.7	98.3 (15.43)
	5	25.5	97.3 (15.28)
	7	26.4	96.6 (15.17)
Soil 'C' (CL)	0	18.4	110.3 (17.32)
	3	22.2	106.6 (16.74)
	5	22.8	104.9 (16.47)
	7	24.1	104.2 (16.36)

Note: Value in parentheses represents the value in SI unit

the natural moisture content of the soil is high.

4.4 Effect of Different Variables on Unconfined Compressive strength of Lime Stabilized Soil

The test samples were prepared using different type of soils, lime content, compaction energy, mellowing time and by retempering at different time.

4.4.1 Effect of Soil Type and Lime Content on 28-Day Strength

The test samples were prepared with the 3 (three) types of soil and they were stabilized with 3%, 5% and 7% lime and at optimum moisture content of soil-lime mix. The soil-lime mixtures were allowed to mellow for 1 hour after mixing. They were compacted in 3 (three) approximately equal layers and by 25 blows in each layer by following Standard Proctor compaction method.

The unconfined compressive strength of the lime stabilized soils cured for 28 days are presented graphically in Fig. 4.2 For a given lime content a marked difference in strength is observed for the three types of soil.

It can be seen from the figures that the increase in strength of soil 'A' (ML/CL) and 'B' (ML/CL) are negligible when they are stabilized with 3% lime. At 5% and 7% lime content soil 'A' shows a marked increase in strength where as soil 'B' does not.

For soil 'C' (CL) the strength increases greatly when it is stabilized with only 3% lime and the strength continues to increase with subsequent increment of lime content. But with these higher lime contents, 5% and 7%, the difference in strength increment is small.

From the Table 4.3 it is seen that the unconfined compressive strength of the soils stabilized with 7% lime is nearly 3 times for soil 'A', 1.6 times for soil 'B' and 5.4 times for soil 'C' of that of the base soil. In addition to physical properties, the chemical properties and mineralogical properties favour the greater strength increment of soil 'C'.

It is interesting to note that although the soil 'A' and soil 'B' are clayey silt (ML/CL), with similar physical properties, the increase in strength of soil 'A' is higher than soil 'B' at the same lime content. As mentioned earlier the probable reason of this may

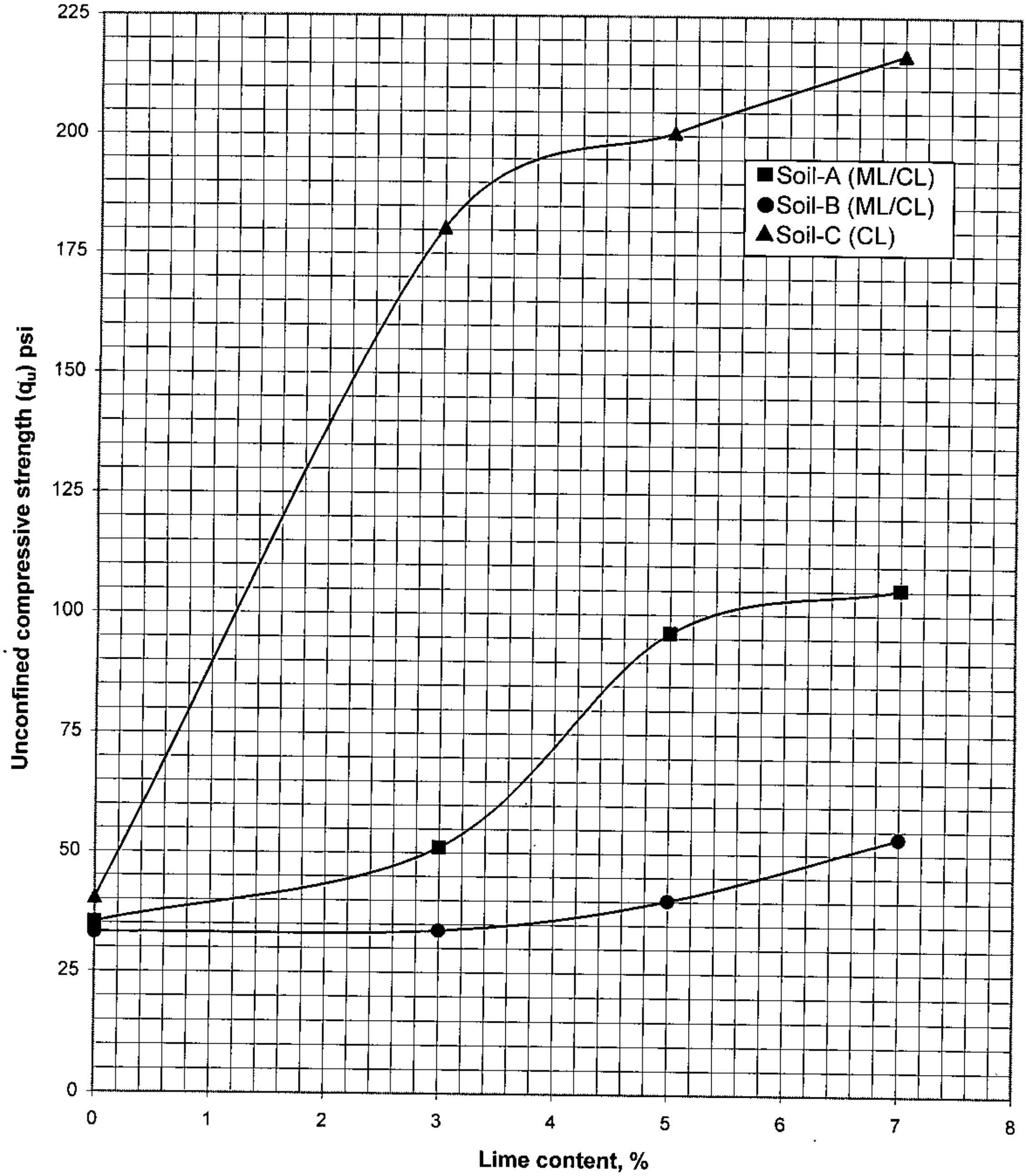


Fig. 4.2 Effect of lime content on unconfined compressive strength of different types of soil at 28 days of curing

Table: 4.3 Unconfined compressive strength of 28 day cure lime stabilized soils

Lime content, %	Soil type	Mixing water content, w%	Unconfined compressive strength, q_u, psi (kPa)	$\frac{q_u}{q_{u}, 0\% \text{ lime}}$
0	'A' (ML/CL)	21.20	35.28 (243.22)	1.00
	'B' (ML/CL)	21.90	33.16 (228.61)	1.00
	'C' (CL)	18.60	40.34 (278.10)	1.00
3	'A' (ML/CL)	25.10	51.14 (352.56)	1.45
	'B' (ML/CL)	25.40	33.76 (232.74)	1.02
	'C' (CL)	22.30	180.44 (1243.95)	4.47
5	'A' (ML/CL)	26.60	96.13 (662.72)	2.72
	'B' (ML/CL)	26.00	40.17 (276.93)	1.21
	'C' (CL)	23.10	200.69 (1383.56)	4.97
7	'A' (ML/CL)	27.90	105.29 (725.87)	2.98
	'B' (ML/CL)	26.70	53.42 (368.28)	1.61
	'C' (CL)	24.30	217.4 (1498.76)	5.39

Note: Value in parentheses represents the value in SI unit

be as soil 'B' is acidic (pH 5.6) and it contains 2.38% organic matter (1.39% organic carbon) where as soil 'A' contains 1.10% organic matter (0.64% organic carbon).

Hardy (1970) found that organic carbon in excess of 1% hindered stabilization. Holm et al. (1983) stated that as some of the Ca^{++} ions of dissociated lime are used to satisfy the high exchange capacity of organic matter thus depriving the clay minerals of calcium ions for pozzolanic reactions.

4.4.2 Long Term Strength Gain of Lime Treated Soils

A series of unconfined compression tests were performed to study the strength gain of lime stabilized soils with time. Three types of soil stabilized with 3%, 5% and 7% lime were used for preparing the sample and the lime stabilized soil were cured for a period of 7 days, 28 days, 90 days, 180 days and 360 days.

The test results are illustrated in Fig. 4.3 (a), Fig. 4.3 (b), Fig. 4.3 (c), Fig. 4.4 (a), Fig. 4.4 (b) and Fig. 4.4 (c).

28-day cure sample strengths are usually used in designing the lime stabilized soil structural layer. But the above curves show that the strengths of all the lime stabilized soils increase substantially after that period.

Soil 'A' (ML/CL):

It is seen from the Fig. 4.3 (a) that for 3% lime content the unconfined compressive strength of the stabilized soil at 7 days of curing is increased and it continued to increase up to 180 days of curing.

At 5% lime content substantial increase in strength occurred. The rate of increase of strength is high up to 90 days of curing after that the rate is low.

From the figure it is seen that up to 28 days of curing time the strengths of the stabilized soil with 7% lime are slightly higher than that with 5% lime. But after 28 days the strengths increased greatly and it continued to increase up to 360 days.

It can be observed from the Table 4.4 (a) that at 3% lime content the 28-day strength is 51% of 360-day strength, at 5% lime content it is 47% of 360-day strength and at 7% lime content the strength is only 30% of 360-day strength. It demonstrates that the higher lime content yield higher strength gain in long term curing.

Soil 'B' (ML/CL):

The effect of varying the lime content and the curing time on the strengths of stabilized soil 'B' (ML/CL) is shown in Fig. 4.3 (b) and Fig. 4.4 (b).

A lime content of 3% does not result in any significant strength increase, even in longer curing period.

With 5% lime content the increase in strength of the stabilized soil up to 28 days are negligible. The rate of increase in strength is high after 90 days of curing. After 180 days the strength increase is small.

The unconfined compressive strength of the soil stabilized with 7% lime is prominent after 28 days of curing and it increases at a higher rate up to 180 days. After 180 days the rate of increase in strength slows down slightly.

It can be seen from the Table 4.4 (b) that the 28-day strengths of the stabilized soil are very small in comparison to 360-day strength. The 28-day strength are only 38%, 19% and 17% of 360-day strength for 3%, 5% and 7% lime content respectively.

It is evident from the above that soil 'B' (ML/CL), containing organic matter (2.38%) and having low pH (5.6), requires higher percentage of lime for strength gain. The strength of the stabilized soil at 28 days is negligible. But the strength beyond 90 days is reasonably high with higher percentage of lime (5% and 7%).

Soil 'C' (CL):

From Fig. 4.3 (c) it is seen that the strength-time curves (time in log scale) are nearly linear at various lime content. The unconfined compressive strength of the stabilized soil with 3% lime content increases significantly at the early days of curing and continues to increase up to 180 days of curing period. With 5% lime content the strength is higher than that of 3% lime content. 7% lime content does not cause any appreciable difference with 5% lime content in strength gain up to 90 days of curing. After 90 days the unconfined compressive strength of the stabilized soil treated with 7% lime continue to increase linearly but it slows down gradually for the soil with 5% lime content.

It can be observed from the Table 4.4 (c) that the 28-day strengths of the stabilized soil are 55%, 47% and 42% of 360-day strength for 3%, 5% and 7% lime content respectively.

It is seen from the Fig. 4.4 (a), Fig. 4.4 (b) and Fig. 4.4 (c) that the 28-day strength of the lime stabilized soil is relatively small to 360-day strength for all the three types of soil. This is more pronounced with higher percentage of lime.

The unconfined compressive strength of lime stabilized soil increases with increasing lime content, however is not proportional to the lime content. The effect of increasing the lime content becomes evident at 90 days and more so at longer curing period.

The increases in strengths, at any curing time, of soil 'C' (CL) are higher than that of soil 'A' and 'B' (ML/CL) when both are stabilized with equal lime content. Soil containing organic matter and having low pH (Soil 'B') requires higher amount of lime to achieve reasonable strength increase. Benjamin (1990) found similar results studying with soil containing organic matter.

The rate of increase in strength is not constant with time. Initially the rate of increase in strength is high, after that the rate decreases gradually. Hilt and Davidson (1962) stated that apparently strength develops at a rate that parallel the rate of reaction. As the lime combine with soils, the amount of free lime decreases, the rate of strength increase gradually slows.

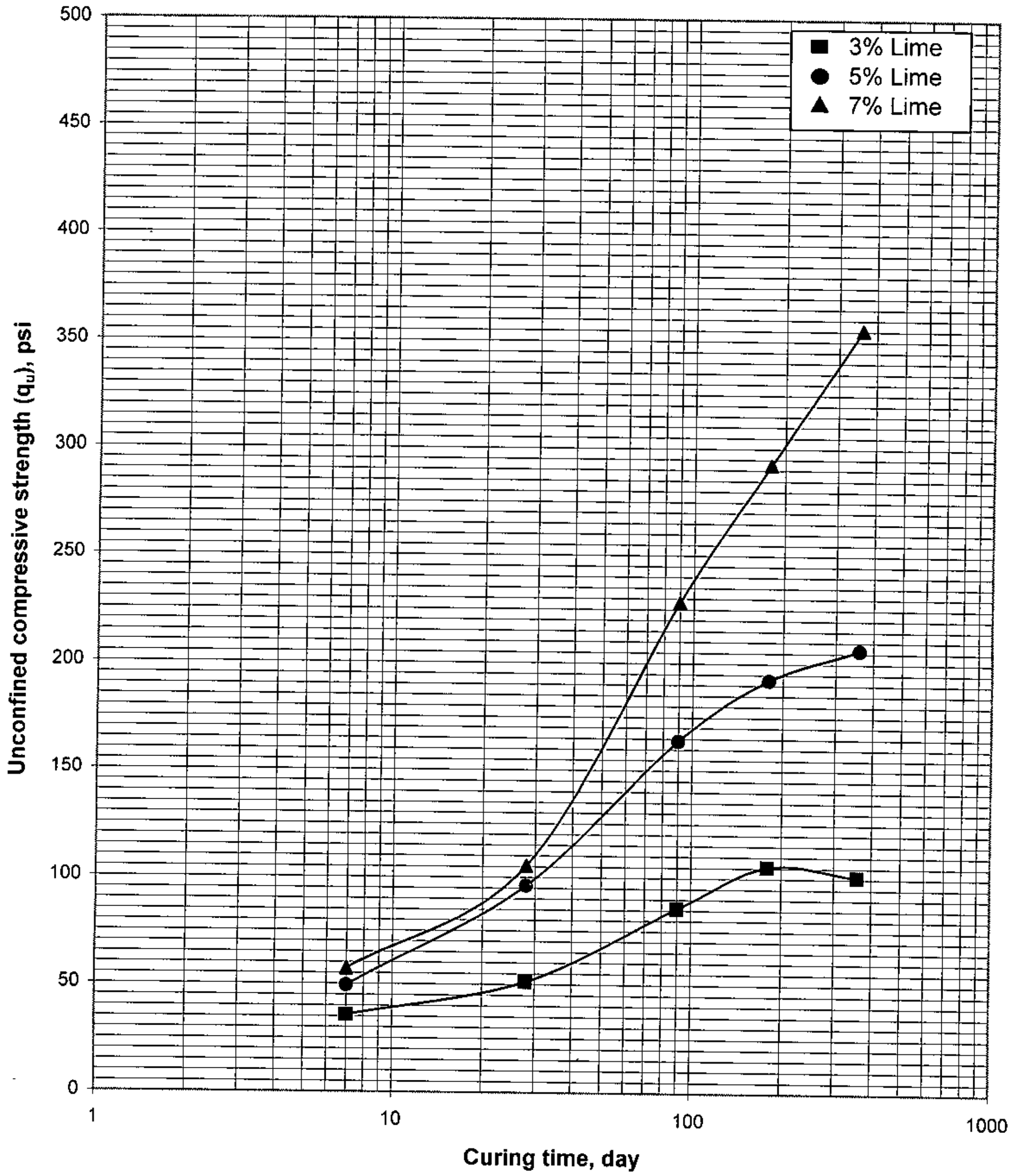


Fig. 4.3.(a) Effect of curing time on unconfined compressive strength of lime stabilized soil 'A' (ML/CL) at different lime contents

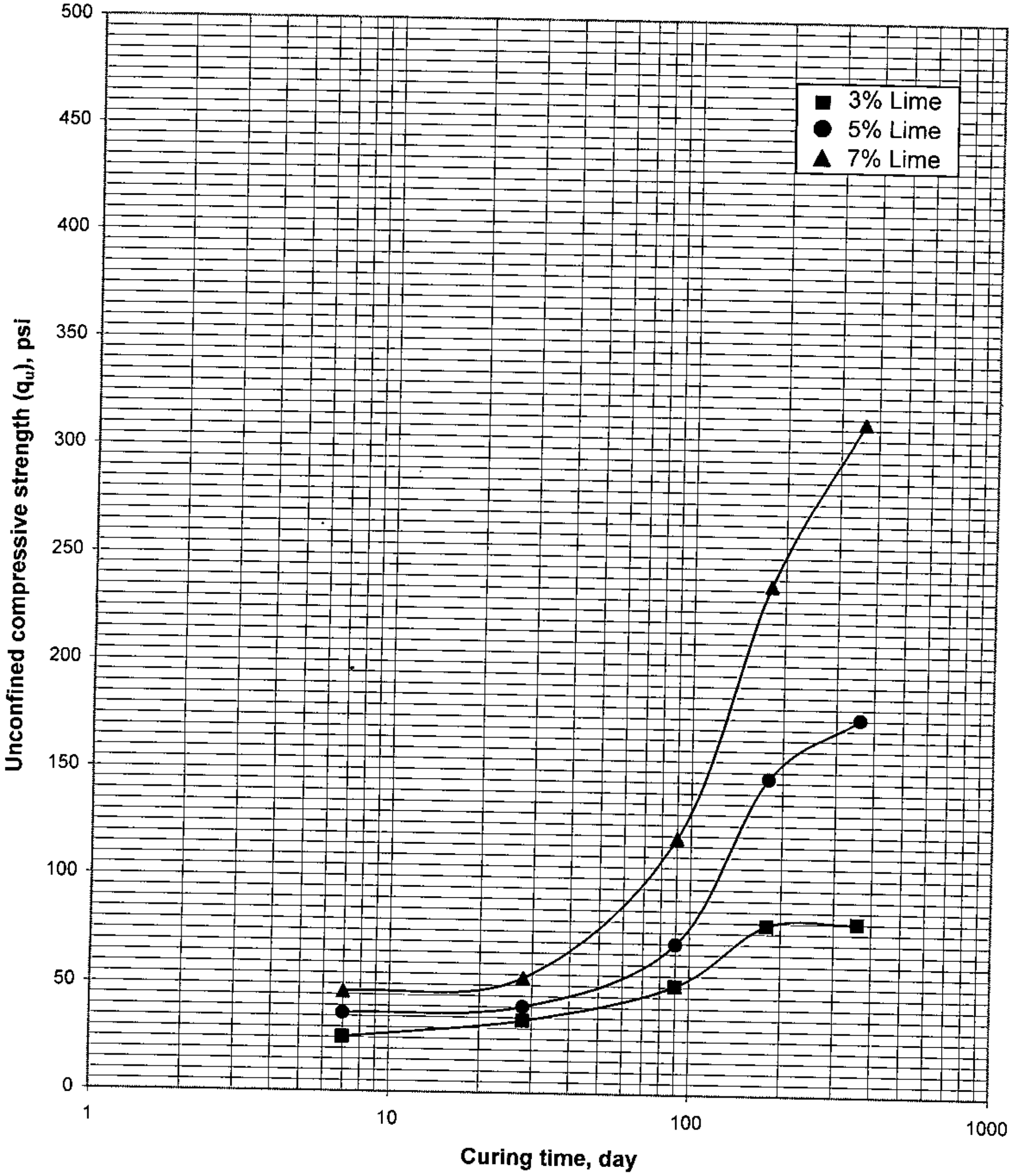


Fig. 4.3.(b) Effect of curing time on unconfined compressive strength of lime stabilized soil 'B' (ML/CL) at different lime contents

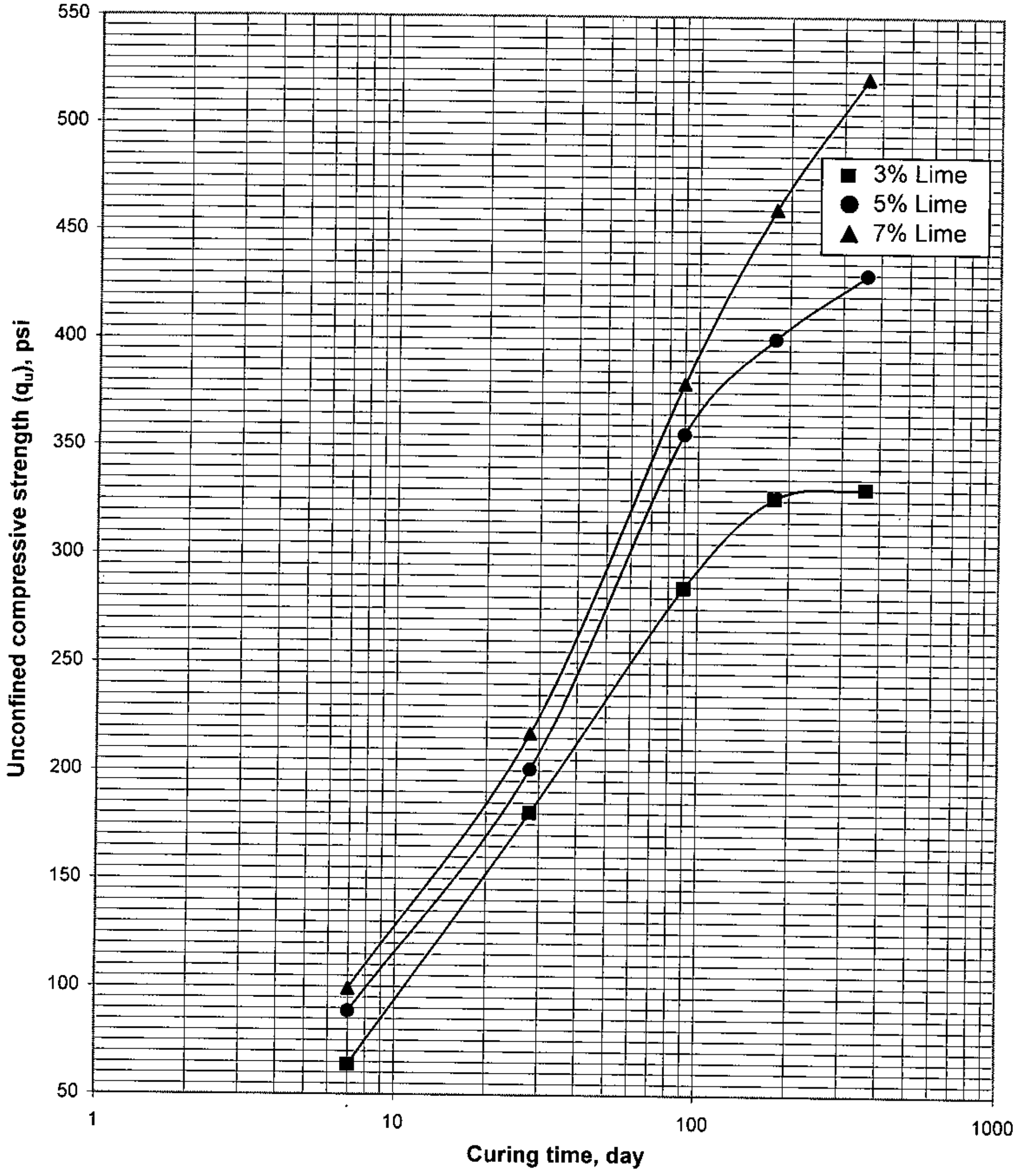


Fig. 4.3.(c) Effect of curing time on unconfined compressive strength of lime stabilized soil 'C' (CL) at different lime contents

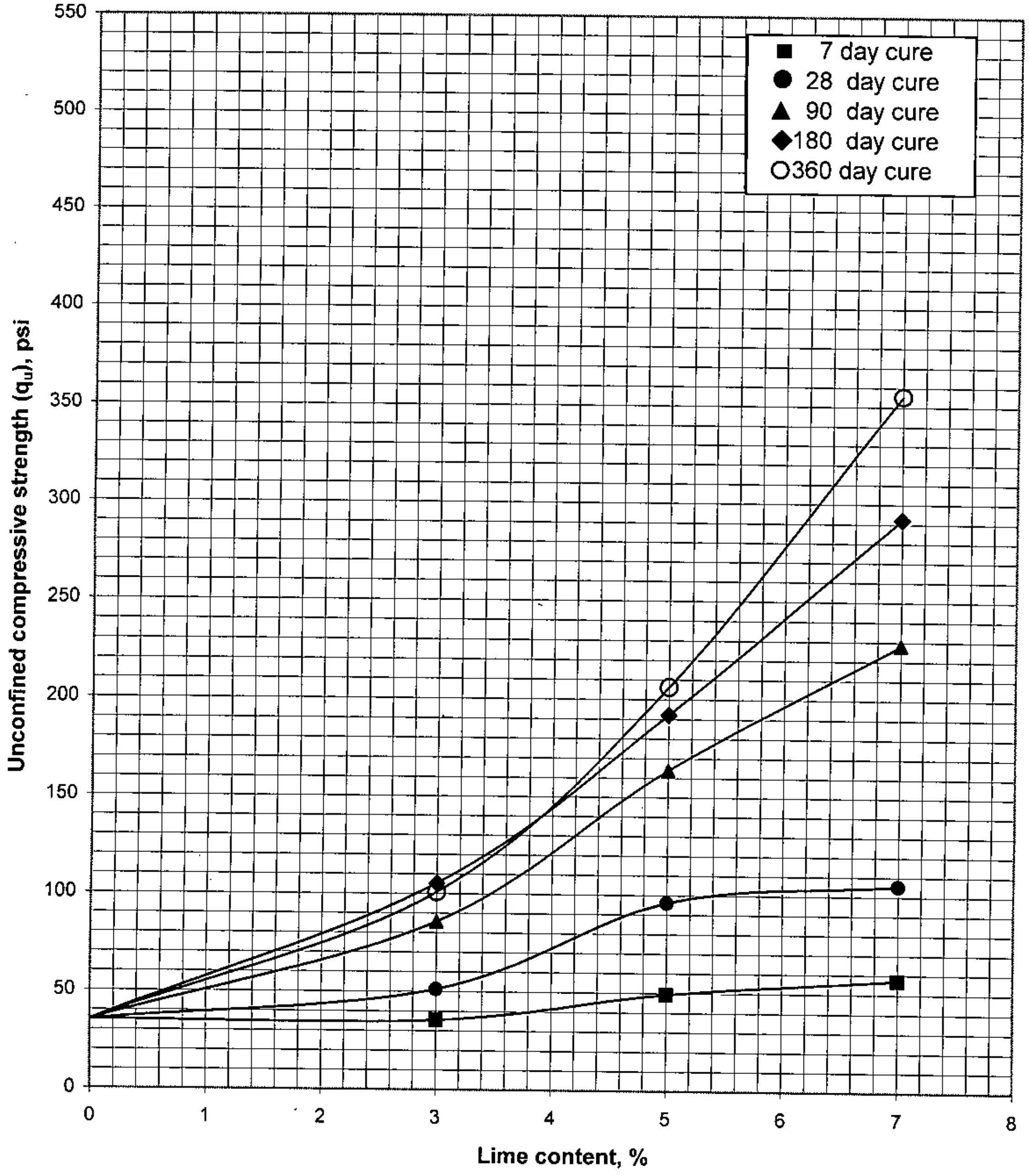


Fig. 4.4.(a) Variation of unconfined compressive strength with lime content of stabilized soil 'A' (ML/CL) at different curing days

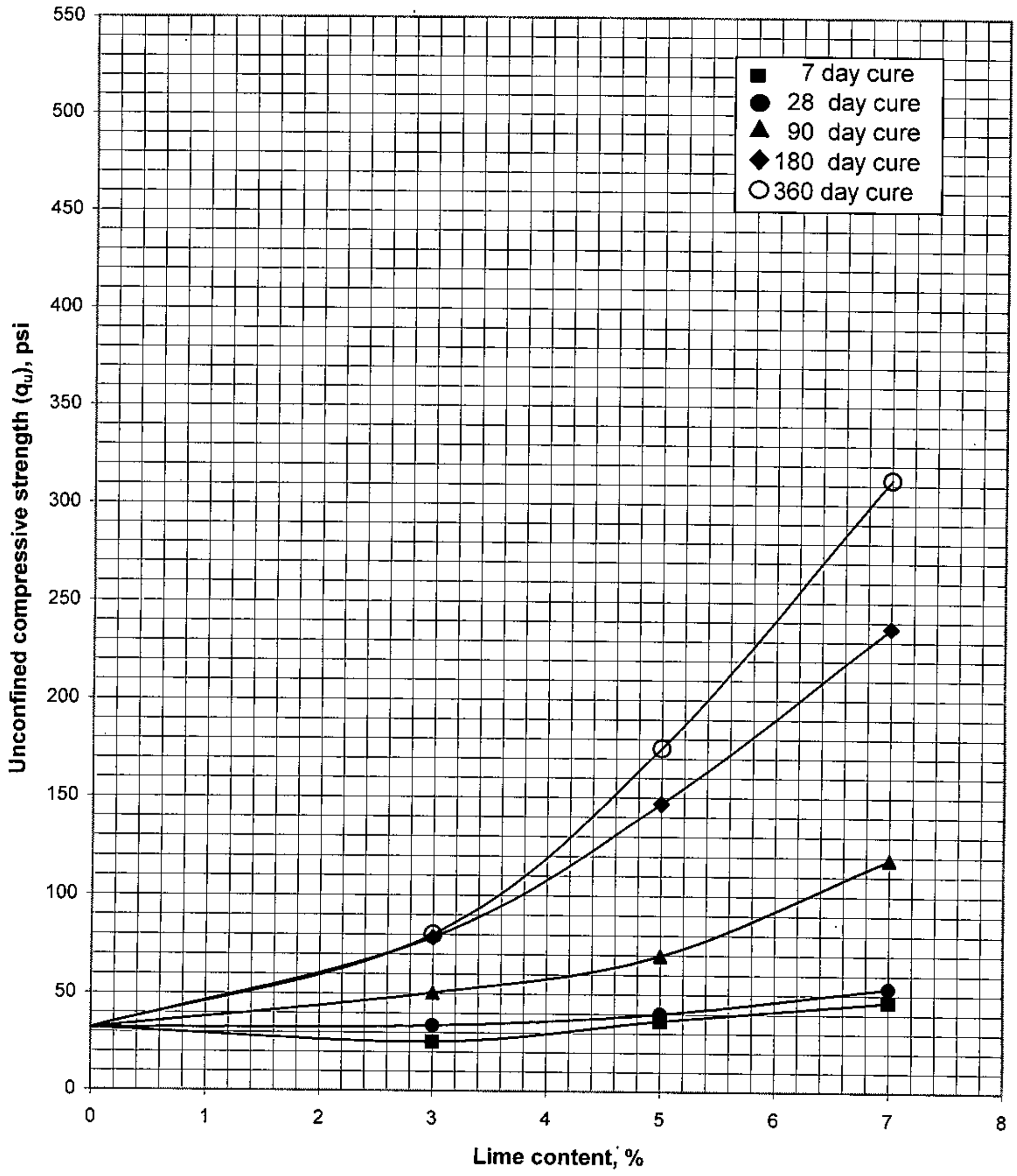


Fig. 4.4.(b) Variation of unconfined compressive strength with lime content of stabilized soil 'B' (ML/CL) at different curing days

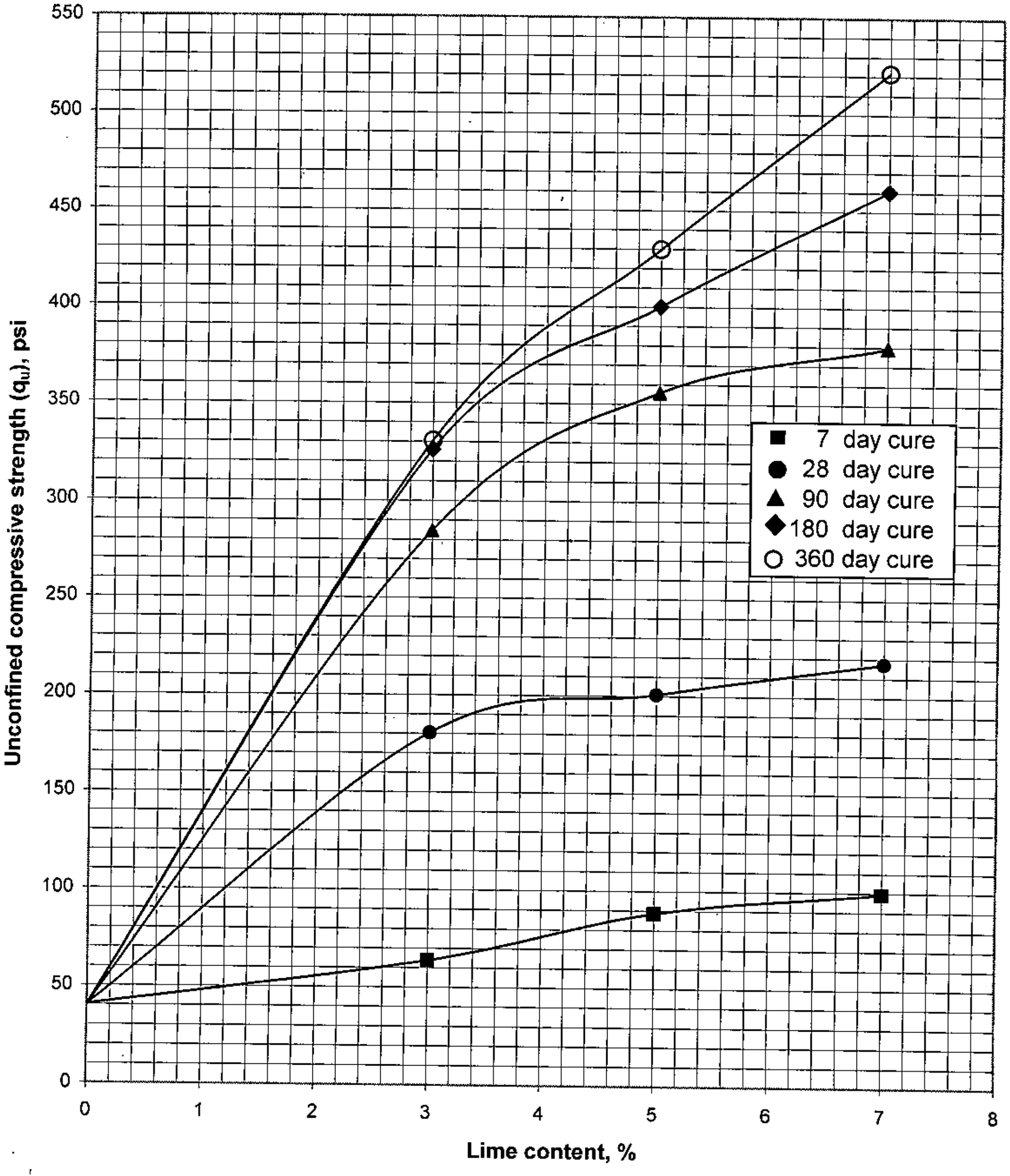


Fig. 4.4.(c) Variation of unconfined compressive strength with lime content of stabilized soil 'C' (CL) at different curing days

Table: 4.4 (a) Unconfined compressive strength of lime stabilized soil 'A' (ML/CL) at different curing time

Lime content, %	Mixing water content, %	Curing time, day	Unconfined compressive strength, q_u, psi (kPa)	$\frac{q_u}{q_u, 28\ day}$	$\frac{q_u}{q_u, 360\ day}$
0	21.20	—	35.28 (243.22)	—	—
3	25.10	7	35.64 (245.70)	0.70	0.35
		28	51.14 (352.56)	1.00	0.51
		90	85.73 (591.02)	1.68	0.85
		180	105.29 (725.87)	2.06	1.04
		360	100.81 (694.98)	1.97	1.00
5	26.60	7	49.27 (339.67)	0.51	0.24
		28	96.13 (662.72)	1.00	0.47
		90	163.84 (1129.51)	1.70	0.79
		180	192.28 (1325.58)	2.00	0.93
		360	206.3 (1422.23)	2.15	1.00
7	27.90	7	57.04 (393.23)	0.54	0.16
		28	105.29 (725.87)	1.00	0.30
		90	228.09 (1572.45)	2.17	0.64
		180	292.26 (2014.84)	2.78	0.82
		360	355.4 (2450.13)	3.38	1.00

Note: Value in parentheses represents the value in SI unit

Table: 4.4 (b) Unconfined compressive strength of lime stabilized soil 'B' at different curing time

Lime content, %	Mixing water content, %	Curing time, day	Unconfined compressive strength, q_u, psi (kPa)	$\frac{q_u}{q_u\text{, 28 day}}$	$\frac{q_u}{q_u\text{, 360 day}}$
0	21.90	—	33.16 (228.61)	—	—
3	25.40	7	25.33 (174.63)	0.75	0.32
		28	33.76 (232.74)	1.00	0.38
		90	50.42 (347.60)	1.49	0.63
		180	78.74 (542.83)	2.33	0.98
		360	80.15 (552.55)	2.37	1.00
5	26.00	7	36.48 (251.49)	0.91	0.15
		28	40.17 (276.93)	1.00	0.19
		90	69.74 (480.79)	1.74	0.40
		180	146.97 (1013.21)	3.66	0.84
		360	175.38 (1209.70)	4.37	1.00
7	26.70	7	46.41 (319.95)	0.87	0.15
		28	53.42 (368.28)	1.00	0.17
		90	118.72 (818.46)	2.22	0.38
		180	237 (1633.88)	4.44	0.76
		360	312.84 (2156.72)	5.86	1.00

Note: Value in parentheses represents the value in SI unit

Table: 4.4 (c) Unconfined compressive strength of lime stabilized soil 'C' (CL) at different curing time

Lime content, %	Mixing water content, %	Curing time, day	Unconfined compressive strength, q_u, psi (kPa)	$\frac{q_u}{q_u, 28\ day}$	$\frac{q_u}{q_u, 360\ day}$
0	18.60	—	40.34 (278.10)	—	—
3	22.30	7	63.78 (439.70)	0.35	0.19
		28	180.44 (1243.95)	1.00	0.55
		90	284.58 (1961.89)	1.58	0.86
		180	326.16 (2248.55)	1.81	0.99
		360	330.52 (2278.60)	1.83	1.00
5	23.10	7	88.60 (610.81)	0.44	0.21
		28	200.69 (1383.56)	1.00	0.47
		90	355.73 (2452.40)	1.77	0.83
		180	400.18 (2758.84)	1.99	0.93
		360	429.75 (2962.70)	2.14	1.00
7	24.30	7	99.16 (683.61)	0.46	0.19
		28	217.14 (1496.96)	1.00	0.42
		90	379.20 (2614.20)	1.75	0.73
		180	460.37 (3173.79)	2.12	0.88
		360	521.45 (3594.88)	2.40	1.00

Note: Value in parentheses represents the value in SI unit

4.4.3 Effect of Compaction Delay (mellowing time)

To observe the effect of compaction delay (mellowing time), soil lime mixtures were left in desiccators for 24 hours (1 day), 72 hours (3 days), 168 hours (7 days) and 336 hours (14 days) before compaction. Soil 'A' with 7% lime and soil 'C' with 3% and 7% lime were used for preparing the sample. The specimens were prepared using water content, which is equal or nearly equal to optimum moisture content of the soil-lime mix. The unconfined compression tests were performed on stabilized soil samples cured for 28 days, 90 days and 180 days.

Unconfined compressive strengths of lime stabilized soil samples prepared at different mellowing time are shown in Fig. 4.5 (a), Fig. 4.5 (b) and Fig. 4.5 (c). The values of the unconfined compressive strengths are presented in Table 4.5. These values are compared with the unconfined compressive values obtained from sample prepared after 1 hour mellowing time.

It can be seen from the table that the 28-day strength of soil 'A' with 7% lime is reduced by 25% for 24 hours compaction delay. In soil 'C' with 3% lime content, 24 hours delay in compaction caused 11% reduction of strength, with 7% lime the reduction in strength is 25%. For silty soil with 5% lime content Mitchell and Hopper (1961) found that a 24 hours compaction delay time causes 30% strength decrease. For 72 hours (3 days) compaction delay, the decrease in strength of soil 'A' with 7% lime is 34%, soil 'C' with 3% lime is 21% and soil 'C' with 7% lime is 28%. Molla (1997) found 8% to 17% reductions in strength for 48 hours delay period.

For a delay period of 336 hours (14 days) the reduction in strength is nearly 50%.

It may be observed from the figure that the strength of the lime stabilized soil decreases with increasing mellowing time. The amount of decrease of strength due to mellowing time depends on soil type. The decrease in strength due to compaction delay (mellowing time) is less in soil 'C' (CL) than soil 'A' (ML/CL).

Rodrigueze et al. (1988) observed that compaction delay is not so critical for lime as critical for cement. Mitchell and Hopper (1961) stated that the decrease in

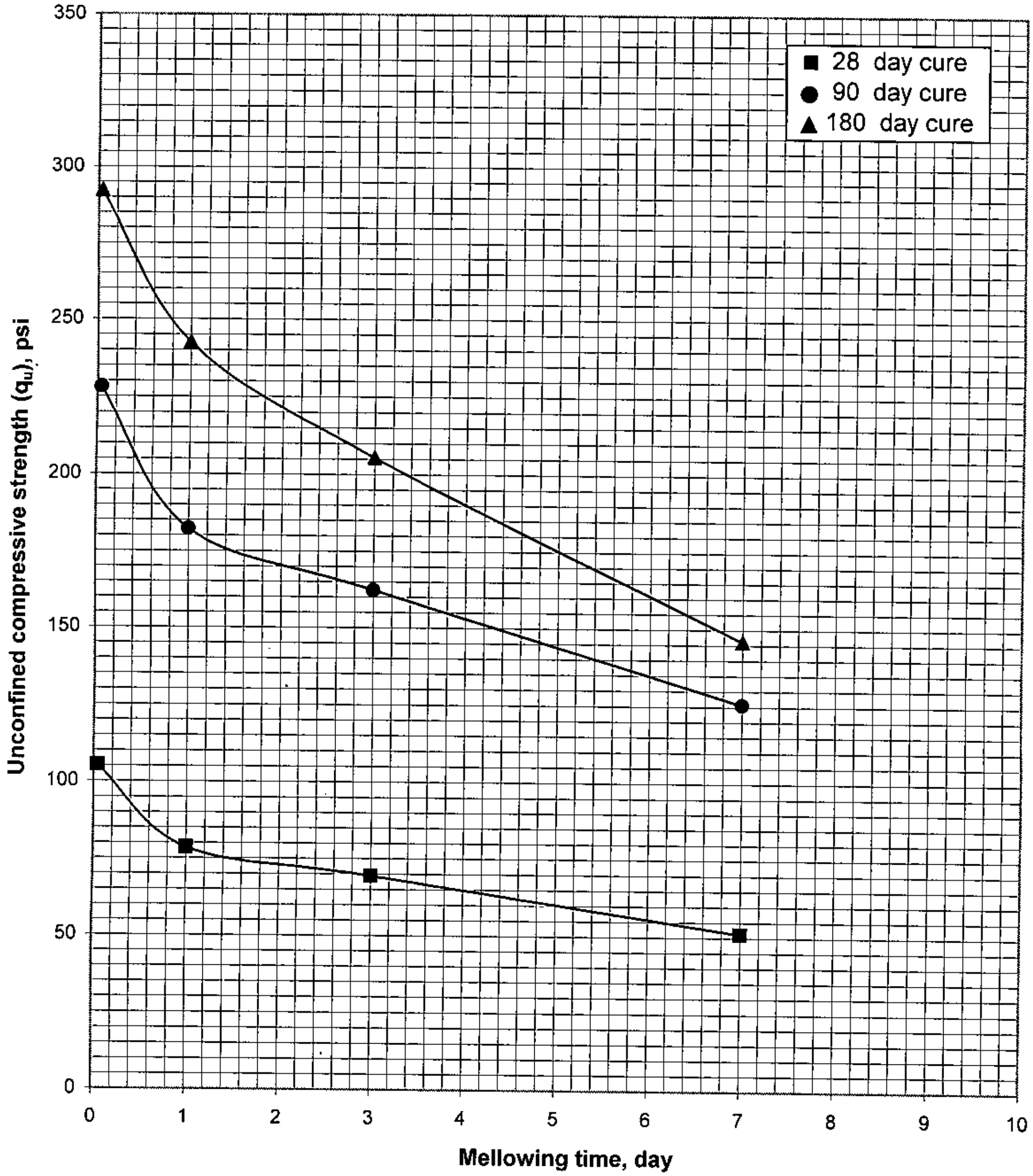


Fig. 4.5 (a) Effect of mellowing time on unconfined compressive strength of soil 'A' (ML/CL) stabilized with 7% lime

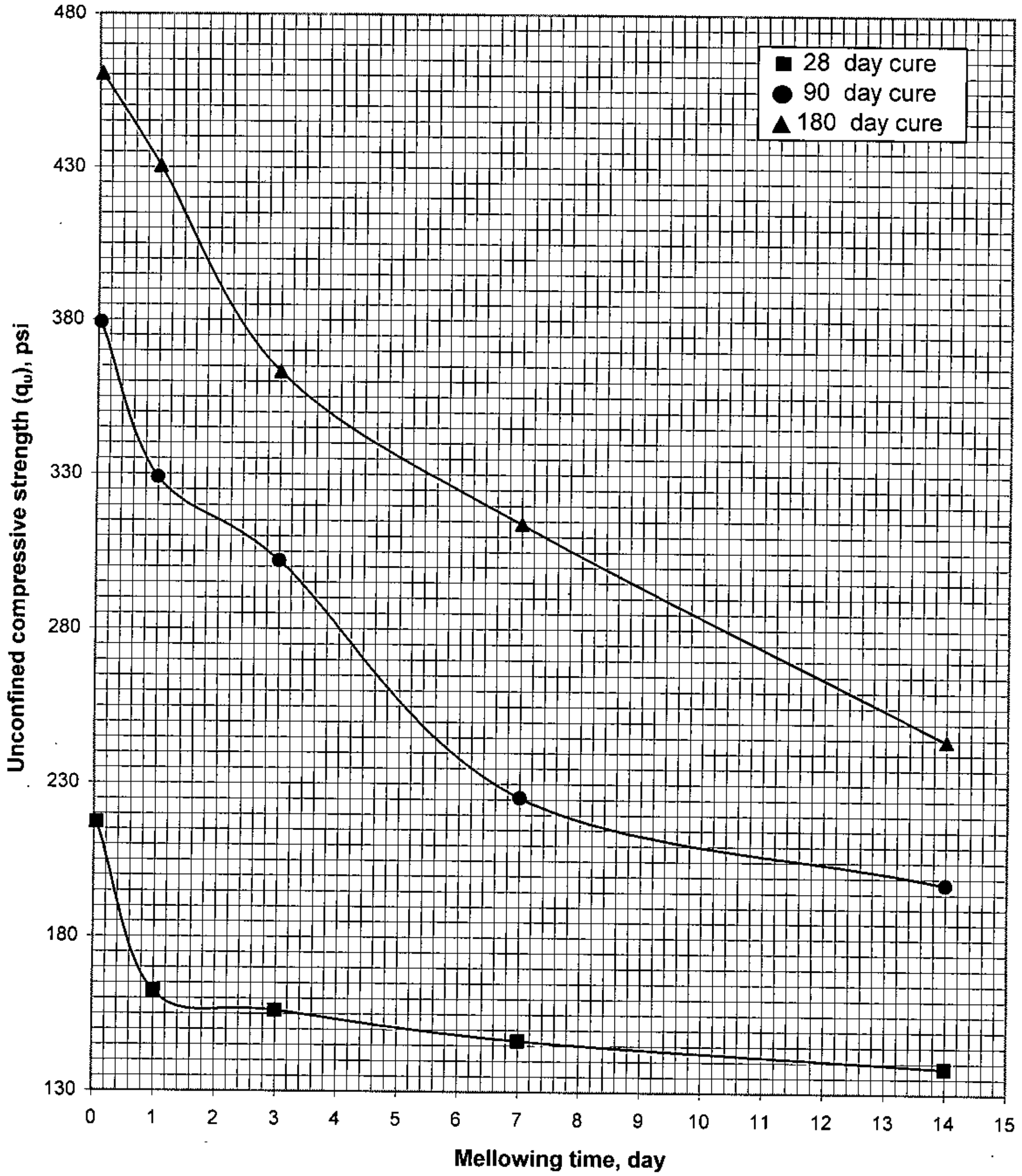


Fig. 4.5 (b) Effect of mellowing time on unconfined compressive strength of soil 'C' (CL) stabilized with 7% lime

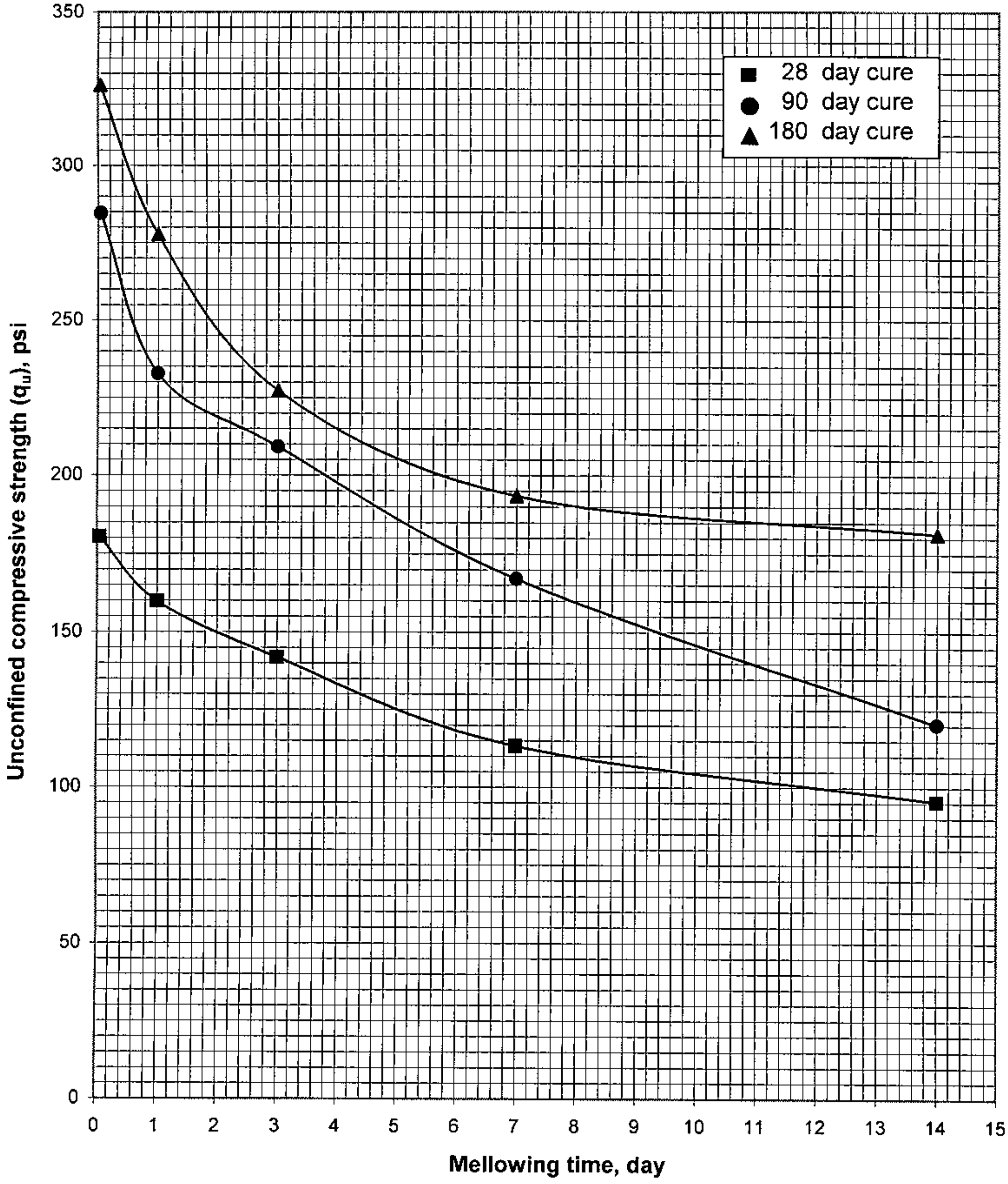


Fig. 4.5 (c) Effect of mellowing time on unconfined compressive strength of soil 'C' (CL) stabilized with 3% lime

Table: 4.5 Effect of compaction delay (mellowing time) on unconfined compressive strength of lime stabilized soils

Curing time, day	Compaction delay, hr.	Unconfined compressive strength, q_u, psi (kPa)			Decrease in strength		
		Soil 'A' (ML/CL) 7% lime	Soil 'C' (CL) 7% lime	Soil 'C' (CL) 3% lime	Soil 'A' (ML/CL) 7% lime	Soil 'C' (CL) 7% lime	Soil 'C' (CL) 3% lime
28	1	105.29 (725.87)	217.14 (1496.96)	180.44 (1243.95)	0 %	0 %	0 %
	24	78.56 (541.59)	162.42 (1119.72)	159.87 (1102.14)	25 %	25 %	11 %
	72	69.35 (478.10)	156.12 (1076.29)	142.00 (978.95)	34%	28 %	21 %
	168	51.14 (352.56)	146.56 (1010.38)	113.31 (781.16)	51 %	33 %	37 %
	336	—	138.32 (953.58)	95.45 (658.03)	–	36 %	47 %
90	1	228.09 (1572.45)	379.2 (2614.20)	284.58 (1961.89)	0 %	0 %	0 %
	24	182.22 (1256.22)	328.97 (2267.92)	232.78 (1604.79)	20 %	13 %	18 %
	72	162.27 (1118.69)	302.04 (2082.26)	209.16 (1441.95)	29 %	20 %	27 %
	168	125.61 (865.96)	225.58 (1555.15)	167.05 (1151.64)	45 %	41 %	41 %
	336	—	197.94 (1364.60)	120.37 (829.83)	–	48 %	58 %
180	1	292.26 (2014.84)	460.37 (3173.79)	326.16 (2248.55)	0 %	0 %	0 %
	24	242.47 (1671.59)	430.44 (2967.45)	277.56 (1913.50)	17 %	7 %	15 %
	72	205.44 (1416.30)	363.23 (2504.11)	227.33 (1567.21)	30 %	21 %	30 %
	168	146.10 (1007.21)	313.97 (2164.51)	193.41 (1333.37)	50 %	32 %	41 %
	336	—	244.46 (1685.31)	181.34 (1250.16)	–	47 %	44%

Note: Value in parentheses represents the value in SI unit

strength for delay in compaction after mixing might be due to the formation of coagulation between soil and lime particles.

4.4.4 Effect of Retempering or Reworking on Unconfined Compressive Strength

The soil-lime mixtures were first compacted with 25 (twenty-five) blows in each layer in the mold. They were then removed from the mold and kept in sealed containers for a period of 24 hours (1 day), 72 hours (3 days), 168 hours (7 days) and 336 (14 days) hours. After the desired period the tempered soils were broken down and sieved by # 4 sieve. They were then again compacted in the mold, to prepare specimen for unconfined compression test.

Unconfined compressive strengths of retempered lime stabilized soil are shown in Fig. 4.6(a), Fig. 4.6 (b) and Fig. 4.6 (c). The values are given in Table 4.6 and they were compared with the strength values of the sample prepared by no retempering.

From the test results it is observed that, for retempering after 24 hours (1 day), the strength of soil ‘A’ with 7% lime is reduced by 14%, soil ‘C’ with 7% lime is reduced by 11% and soil ‘C’ with 3% lime is reduced by 11%.

For retempering after 72 hours (3 days), the reduction of strength of soil ‘A’ with 7% lime is 38%, soil ‘C’ with 7% lime is 24% and soil ‘C’ with 3% lime is 15%.

For retempering after 336 hours (14 days) the strength of soil ‘C’ stabilized with 7% lime is decreased by 46% and with 3% lime it is decreased by 53%.

It can be observed from the test results that the strength of the stabilized soil decreases due to retempering. The loss of strength is high for the sample retempered after a long period than the sample retempered after a short period.

NLA (1987) states that distressed sections can be reworked and recompacted into permanent, durable sections. They suggested adding 1% lime in reworking.

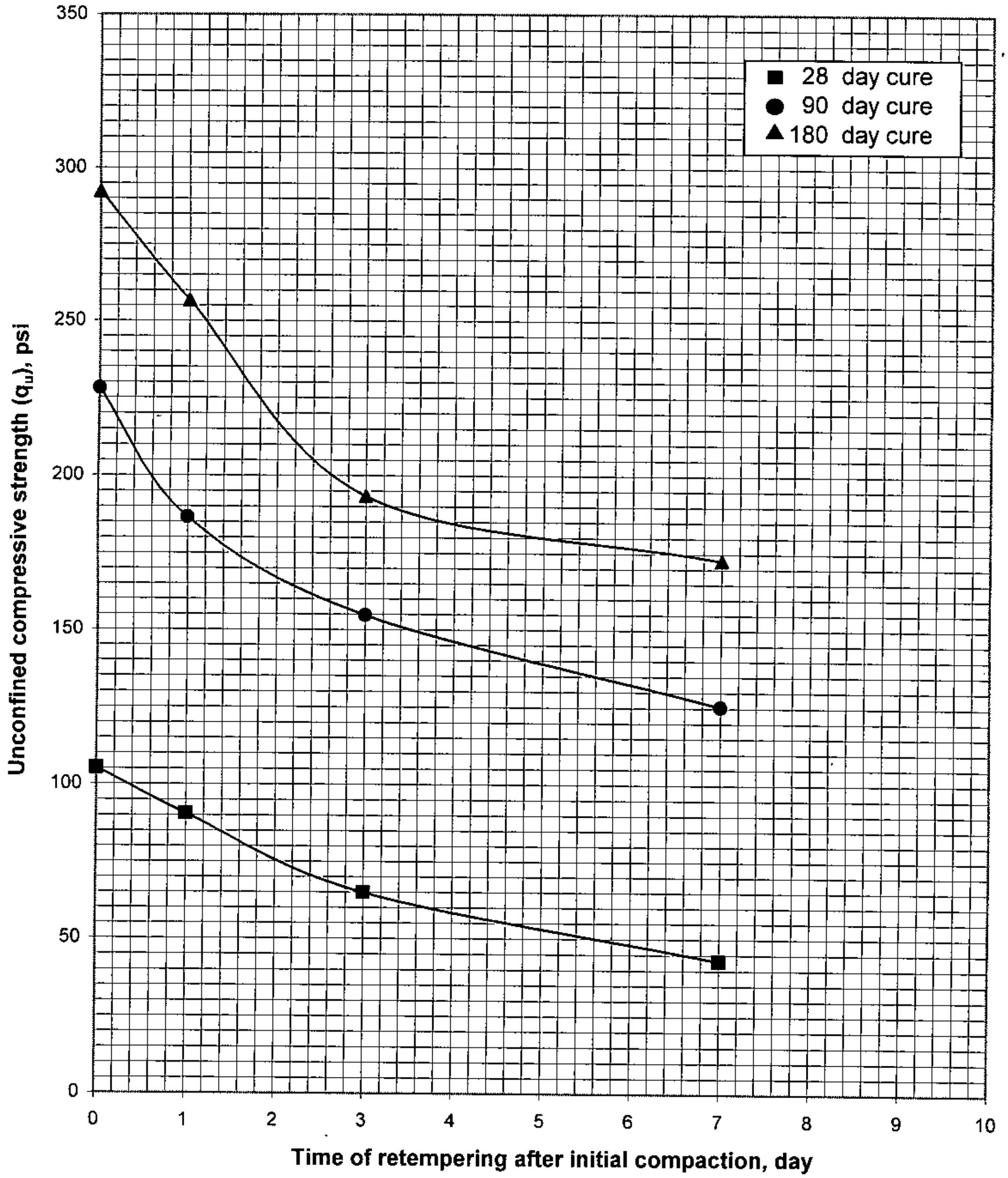


Fig. 4.6 (a) Effect of retempering on unconfined compressive strength of soil 'A' (ML/CL) stabilized with 7% lime

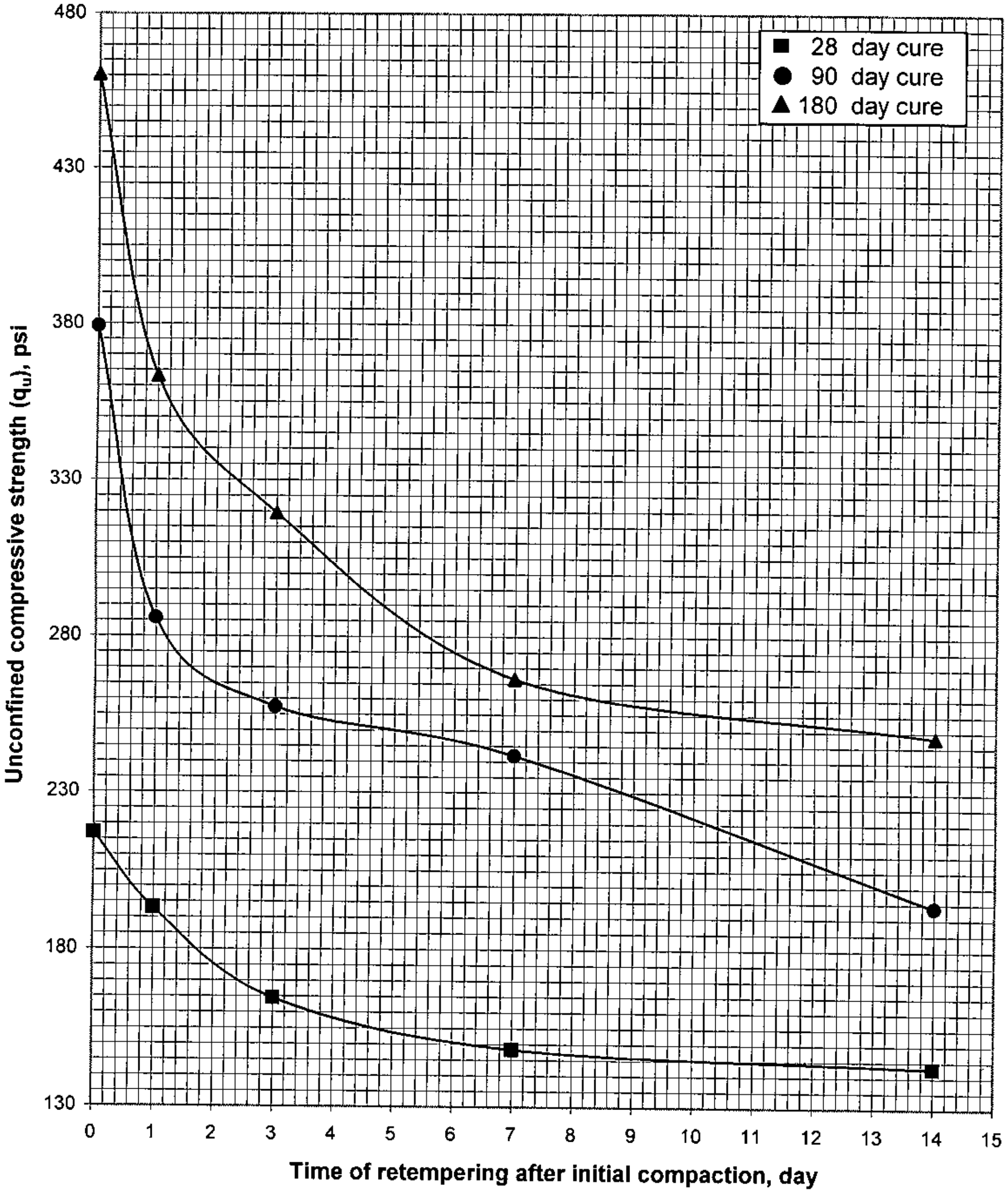


Fig. 4.6 (b) Effect of retempering on unconfined compressive strength of soil 'C' (CL) stabilized with 7% lime

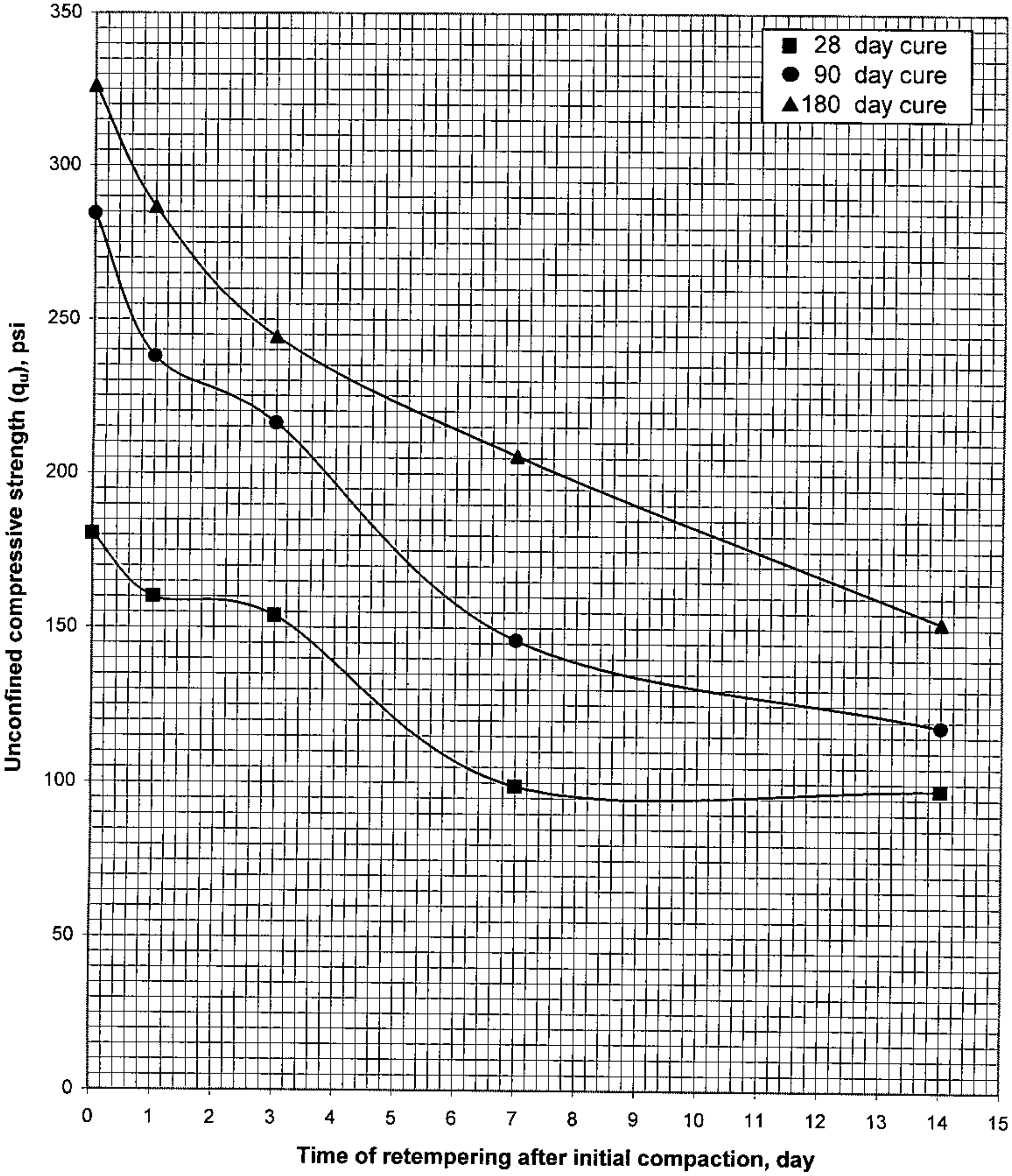


Fig. 4.6 (c) Effect of retempering on unconfined compressive strength of soil 'C' (CL) stabilized with 3% lime

Table: 4.6 Effect of retempering (reworking) on unconfined compressive strength of limestabilized soils

Curing time, day	Time of retempering after initial compaction, day	Unconfined compressive strength, q_u, psi (kPa)			Decrease in strength		
		Soil 'A' (ML/CL) 7% lime	Soil 'C' (CL) 7% lime	Soil 'C' (CL) 3% lime	Soil 'A' (ML/CL) 7% lime	Soil 'C' (CL) 7% lime	Soil 'C' (CL) 3% lime
28	Without retempering	105.29 (725.87)	217.14 (1496.96)	180.44 (1243.95)	0 %	0 %	0 %
	1	90.63 (624.80)	193.03 (1330.75)	160.06 (1103.45)	14%	11%	11%
	3	64.97 (447.90)	164.559 (1134.47)	153.91 (1061.06)	38%	24%	15%
	7	42.97 (296.24)	148.3 (1022.38)	98.88 (681.68)	59%	32%	45%
	14	—	142.87 (984.95)	97.79 (674.16)	–	34%	46%
90	Without retempering	228.09 (1572.45)	379.2 (2614.20)	284.58 (1961.89)	0 %	0 %	0 %
	1	186.57 (1286.21)	285.91 (1971.06)	237.9 (1640.08)	18%	25%	16%
	3	154.78 (1067.05)	257.47 (1775.00)	216.3 (1491.17)	32%	32%	24%
	7	125.31 (863.89)	241.93 (1667.87)	145.99 (1006.46)	45%	36%	49%
	14	—	193.77 (1335.85)	118.38 (816.11)	–	49%	58%
180	Without retempering	292.26 (2014.84)	460.37 (3173.79)	326.16 (2248.55)	0 %	0 %	0 %
	1	256.73 (1769.90)	363.23 (2504.11)	286.69 (1976.44)	12%	21%	12%
	3	193.34 (1332.89)	319.50 (2202.63)	244.29 (1684.14)	34%	31%	25%
	7	172.81 (1191.35)	266.55 (1837.60)	205.8 (1418.79)	41%	42%	37%
	14	—	248.14 (1710.68)	151.99 (1047.82)	–	46%	53%

Note: Value in parentheses represents the value in SI unit

4.4.5 Effect of Compaction Energy

In order to observe the effect of the application of lower compaction energy on the unconfined compressive strength of lime stabilized soils, sample were prepared with 15 blows and 8 blows per layer. The other variables such as, height of fall, weight of hammer and number of layers etc remained unchanged.

The optimum moisture content and maximum dry density of the soil lime mix with 15 blows and 8 blows per layer were also determined. These optimum moisture contents were used to prepare the test sample.

Moisture-density relationships for lime stabilized soil at different compaction energy are shown in Fig. 4.7 (a) and Fig. 4.7 (b). It can be seen from the figure that the optimum moisture content increases and the maximum dry density decreases with the decrease of compaction energy.

Unconfined compressive strengths of soil-lime mix compacted with different compaction energy are shown in Fig. 4.8 (a) and Fig. 4.8 (b) and the test results are shown in Table 4.7.

It is evident from the table that the effect of compaction energy on unconfined compressive strength of stabilized soil depends on lime content. As the lime content increases the effect of compaction energy reduces. Molla (1997) found similar results working with CL and ML type soil.

It can be also observed from Table 4.7 that $q_{u,\ 8\ blows} / q_{u,\ 25\ blows}$ (the ratio of unconfined compressive strength of the soil samples prepared with 8 blows to 25 blows) or $q_{u,\ 15\ blows} / q_{u,\ 25\ blows}$ is smaller at 28 days curing period than that of the 90 days and 180 days curing period.

Serajuddin and Azmal (1991) observed the effect of reduced compaction energy by reducing the no. of blows per layer in the standard proctor test method. They observed lower strength of the stabilized soil at lower compaction energy. Molla (1997) found similar results working with CL and ML type soil.

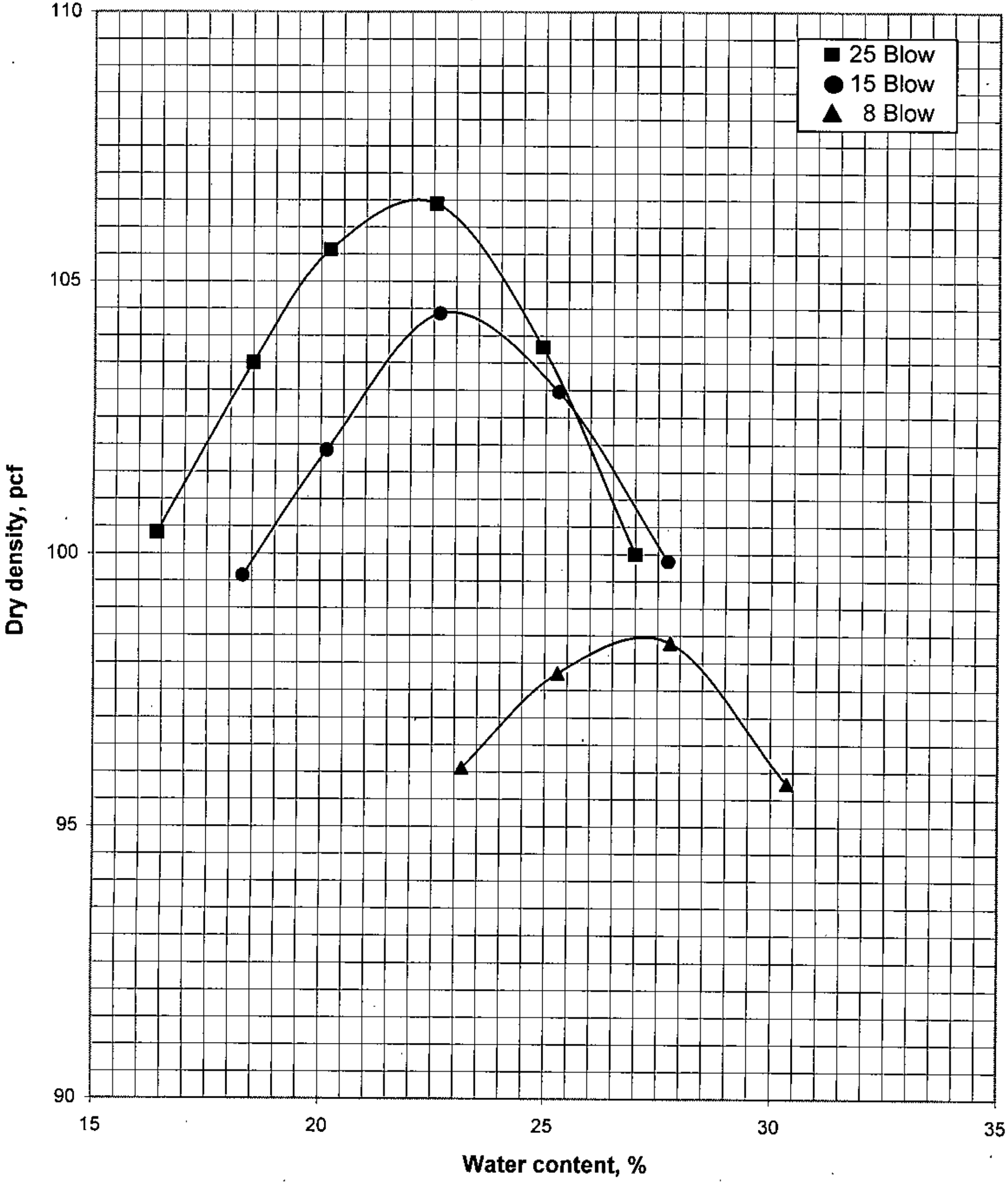


Fig. 4.7 (a) Moisture-density relationship at different compaction energy of soil 'C' (CL) stabilized with 3% lime

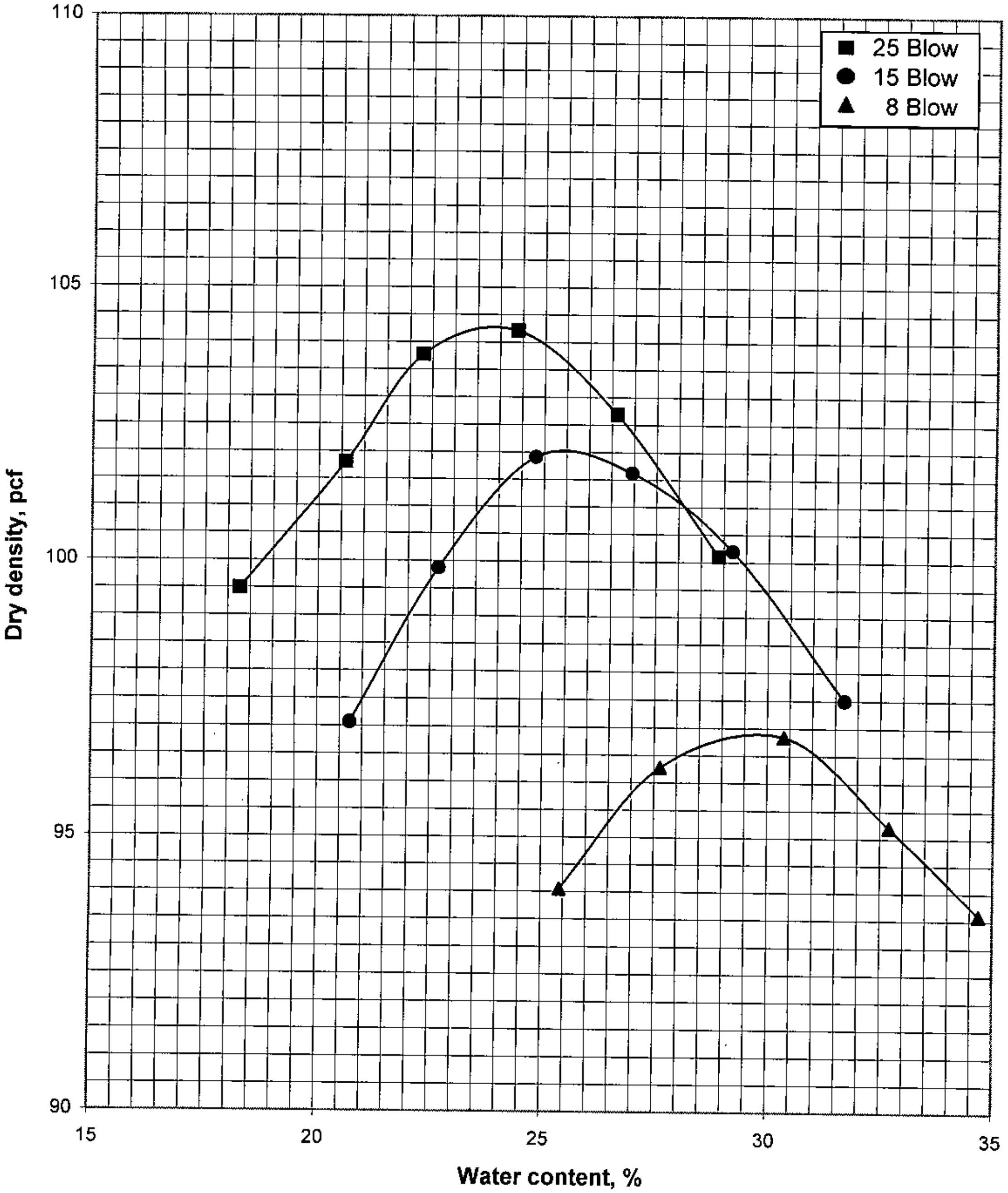


Fig. 4.7 (b) Moisture-density relationship at different compaction energy of soil 'C' (CL) stabilized with 7% lime

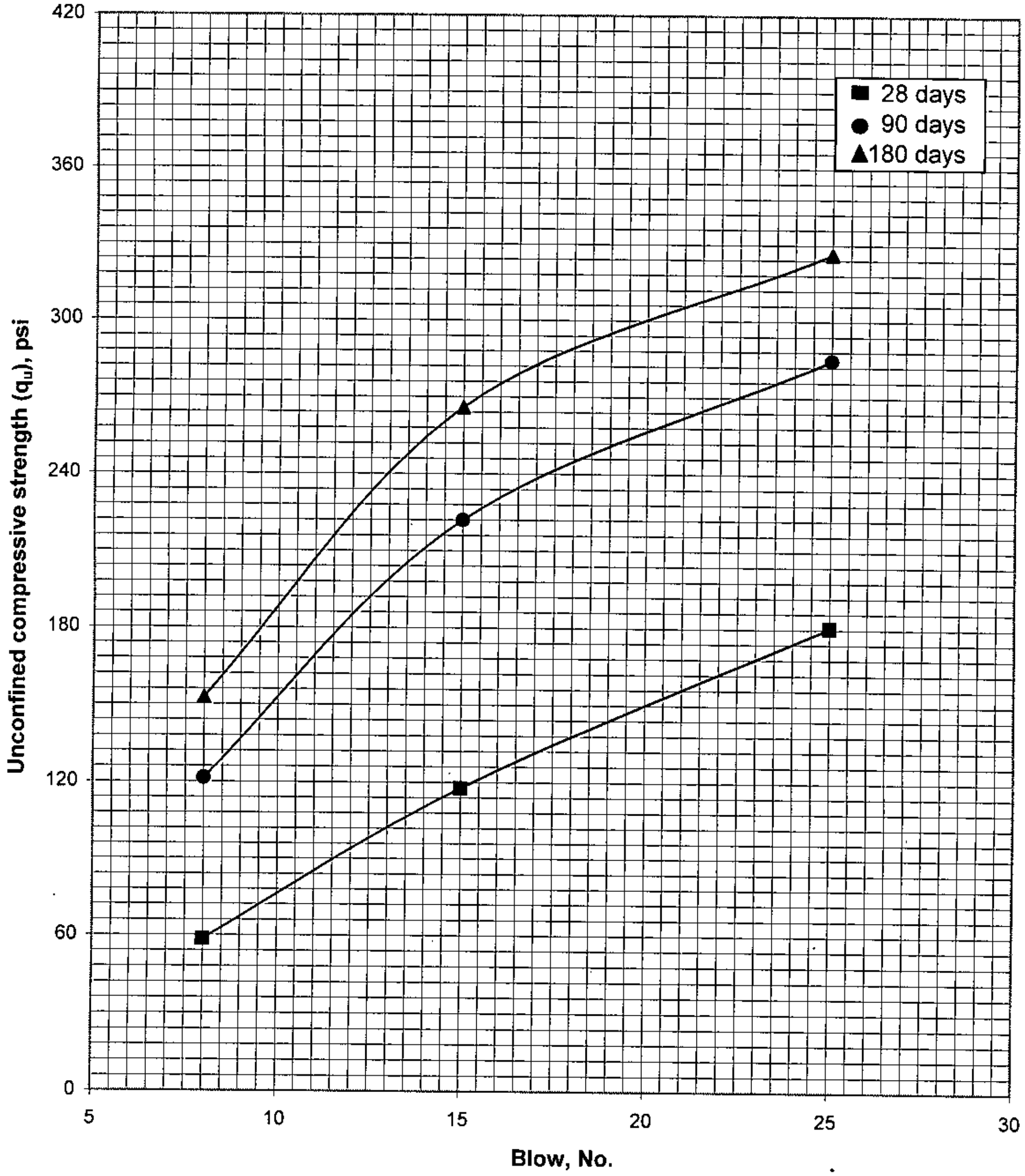


Fig. 4.8 (a) Variation of unconfined compressive strength with compaction energy for soil 'C' (CL) stabilized with 3% lime at different curing period

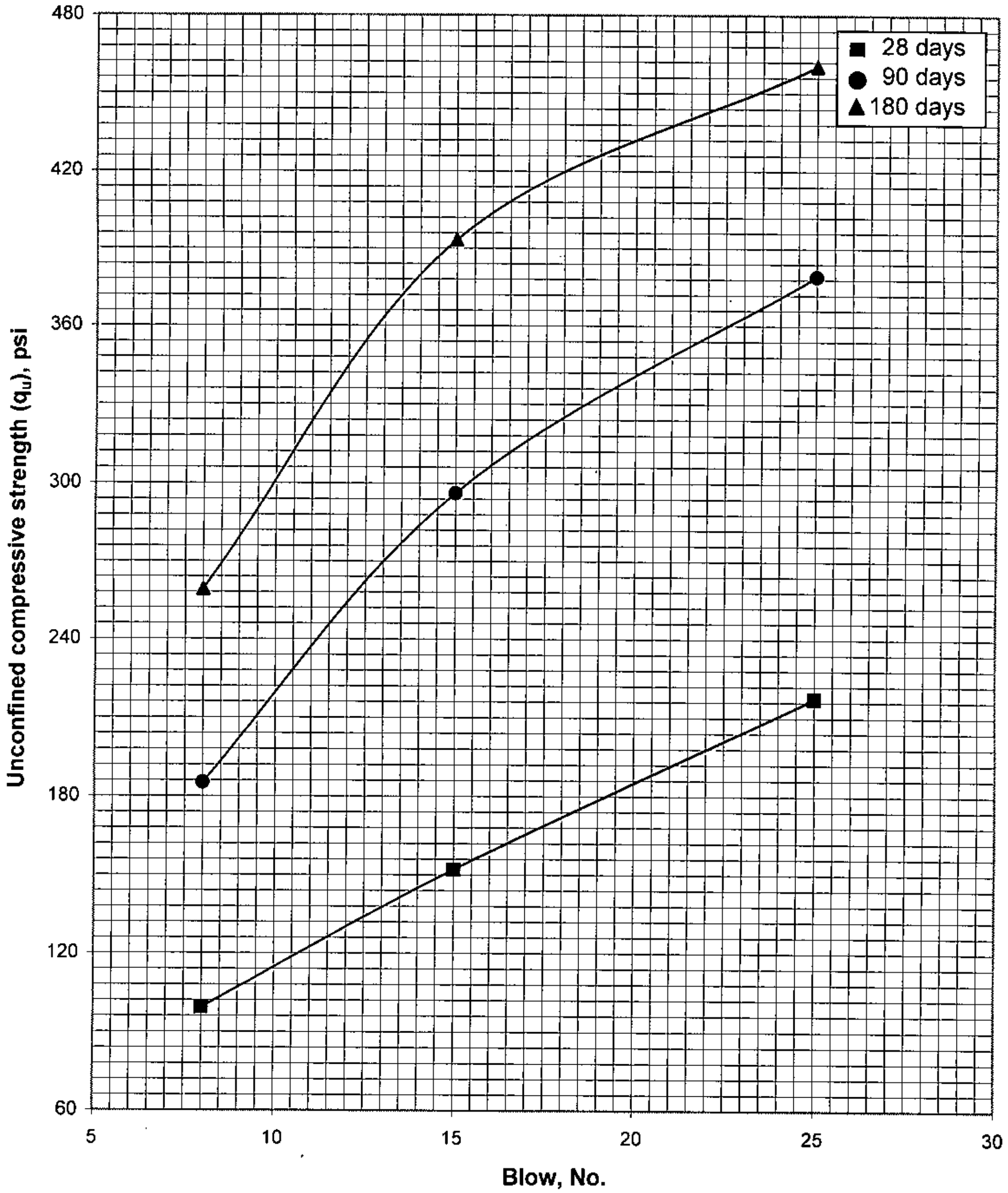


Fig. 4.8 (b) Variation of unconfined compressive strength with compaction energy for soil 'C' (CL) stabilized with 7% lime at different curing period

Table: 4.7 Unconfined compressive strength of lime stabilized soil 'C' (CL) at different compaction energy

Curing time, day	Lime content, %	No. of blows	Unconfined compressive strength, q_u, psi (kPa)	$\frac{q_u}{q_u\text{, 25 blow}}$
28	3	25	180.44 (1243.95)	1.00
		15	117.64 (811.01)	0.65
		8	58.46 (403.02)	0.32
	7	25	217.14 (1496.96)	1.00
		15	151.97 (1047.68)	0.70
		8	99.23 (684.09)	0.46
90	3	25	284.58 (1961.89)	1.00
		15	221.97 (1530.26)	0.78
		8	121.51 (837.69)	0.43
	7	25	379.20 (2614.20)	1.00
		15	296.15 (2041.66)	0.78
		8	185.23 (1276.98)	0.49
180	3	25	326.16 (2248.55)	1.00
		15	265.82 (1832.56)	0.82
		8	152.64 (1052.30)	0.47
	7	25	460.37 (3173.79)	1.00
		15	393.24 (2711.00)	0.85
		8	259.18 (1786.79)	0.56

Note: Value in parentheses represents the value in SI unit

4.4.6 Effect of Soaking

To study the effect of soaking on unconfined compressive strength of stabilized soil TRL (1993) recommends 7 days of soaking after 21 days of moist curing. In this study 21-day, 83-day and 173-day cure test samples were soaked for a period of 7 days before compressive strength test.

Unconfined compressive strengths of lime stabilized soaked samples cured for different periods are shown in Fig. 4.9 (a), Fig. 4.9 (b) and Fig. 4.9 (c). It is seen that the curve of soaked strength runs nearly parallel to that of unsoaked one.

The ratios of soaked to unsoaked compressive strength results are presented in Table 4.8. It is seen from the table that the variation in strength ratios (q_u soaked/q_u unsoaked) at different curing days are not so pronounced. The ratio also does not change considerably with lime content. The ratio of soaked to unsoaked compressive strength of lime stabilized soil varies between 76% to 82% with 3% lime, 71% to 77% with 5% lime and 75% to 85% with 7% lime when tested at different curing days.

This work reveals that the compressive strength of lime stabilized soils do not reduced greatly when they submerged in water. TRL (1993) found that a substantial proportion of strength is retained when the lime stabilized soil becomes saturated with water.

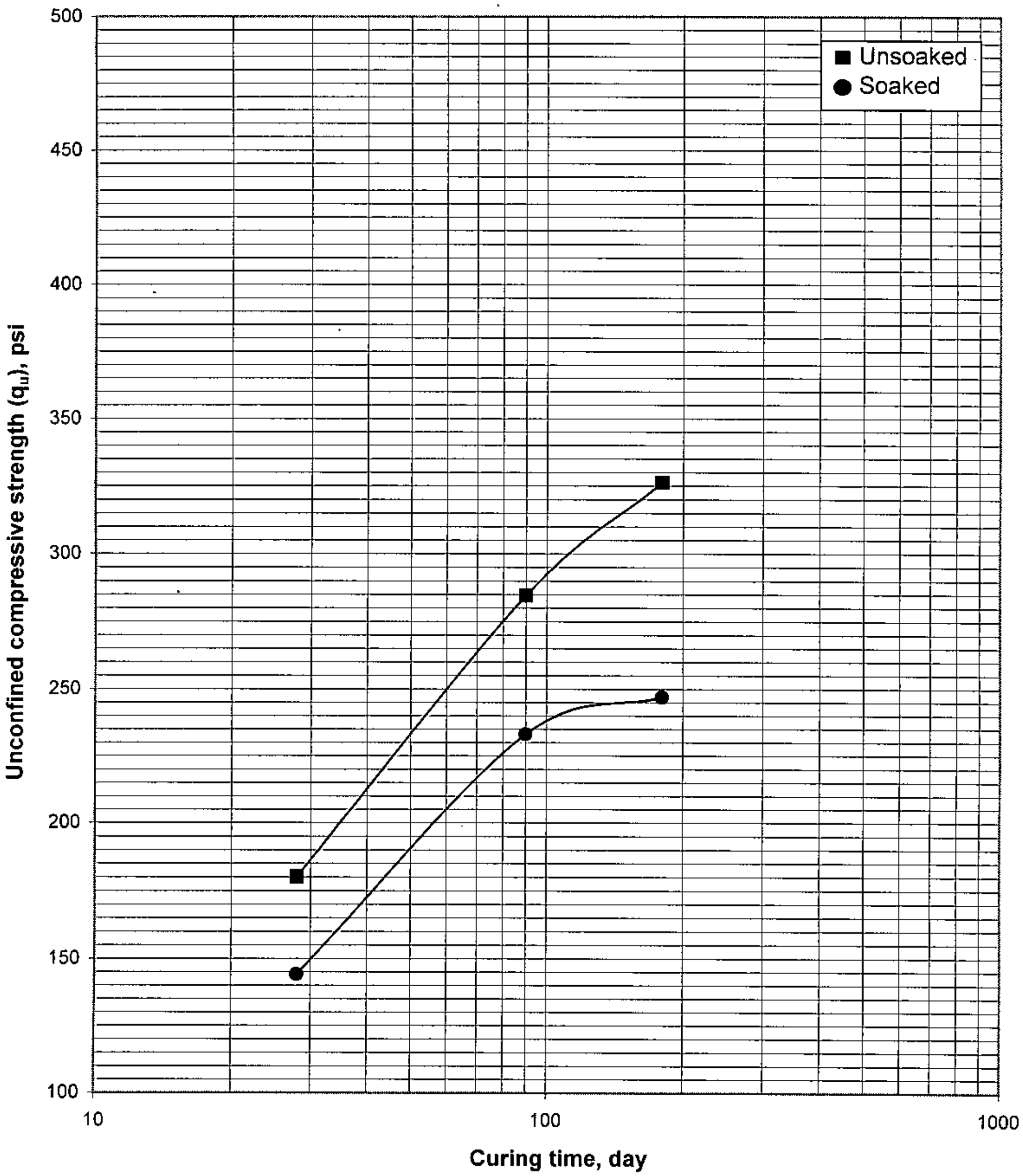


Fig. 4.9. (a) Unconfined compressive strength at different curing days of soaked sample and unsoaked sample of soil 'C' (CL) stabilized with 3% lime

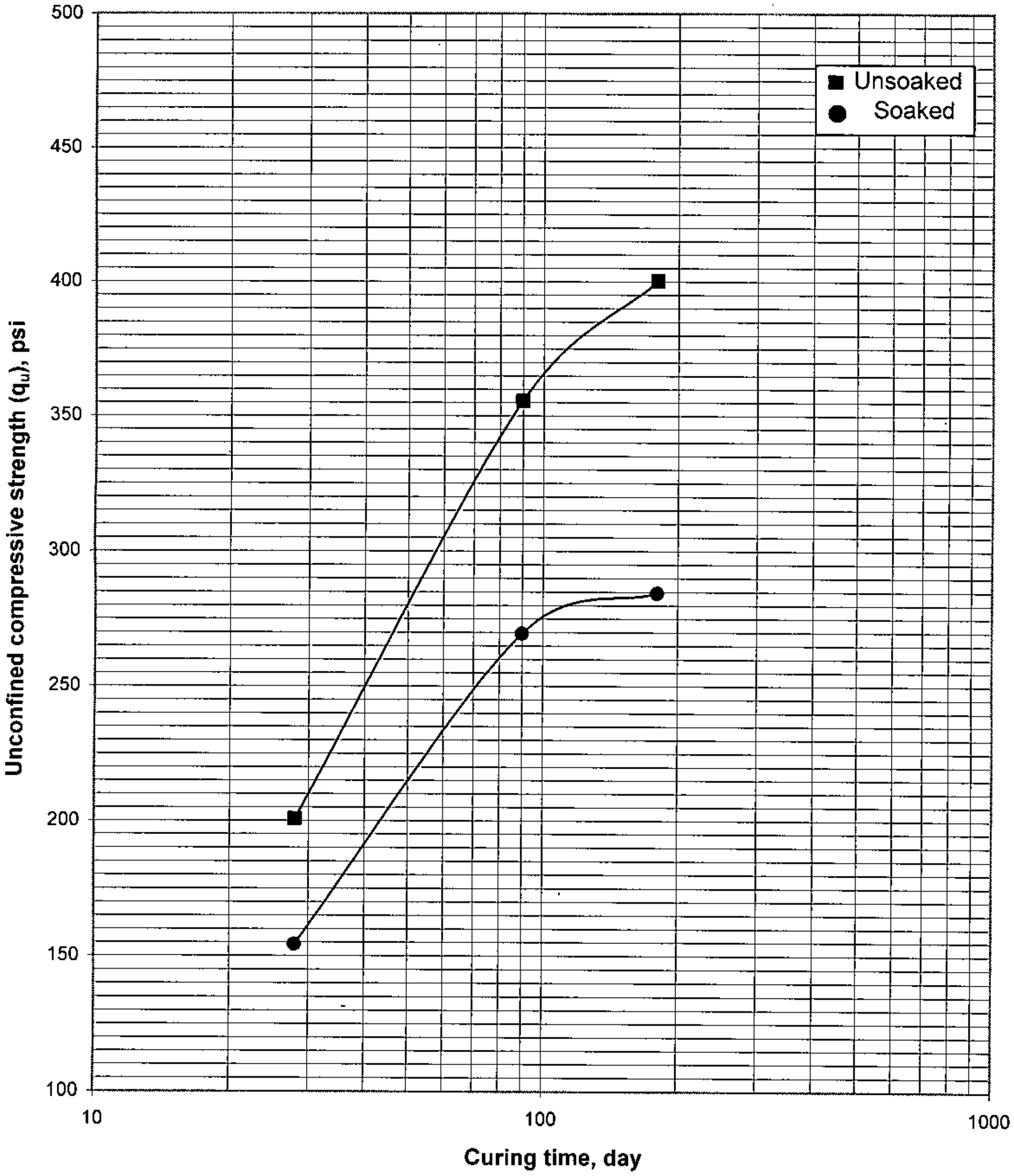


Fig. 4.9. (b) Unconfined compressive strength at different curing days of soaked sample and unsoaked sample of soil 'C' (CL) stabilized with 5% lime

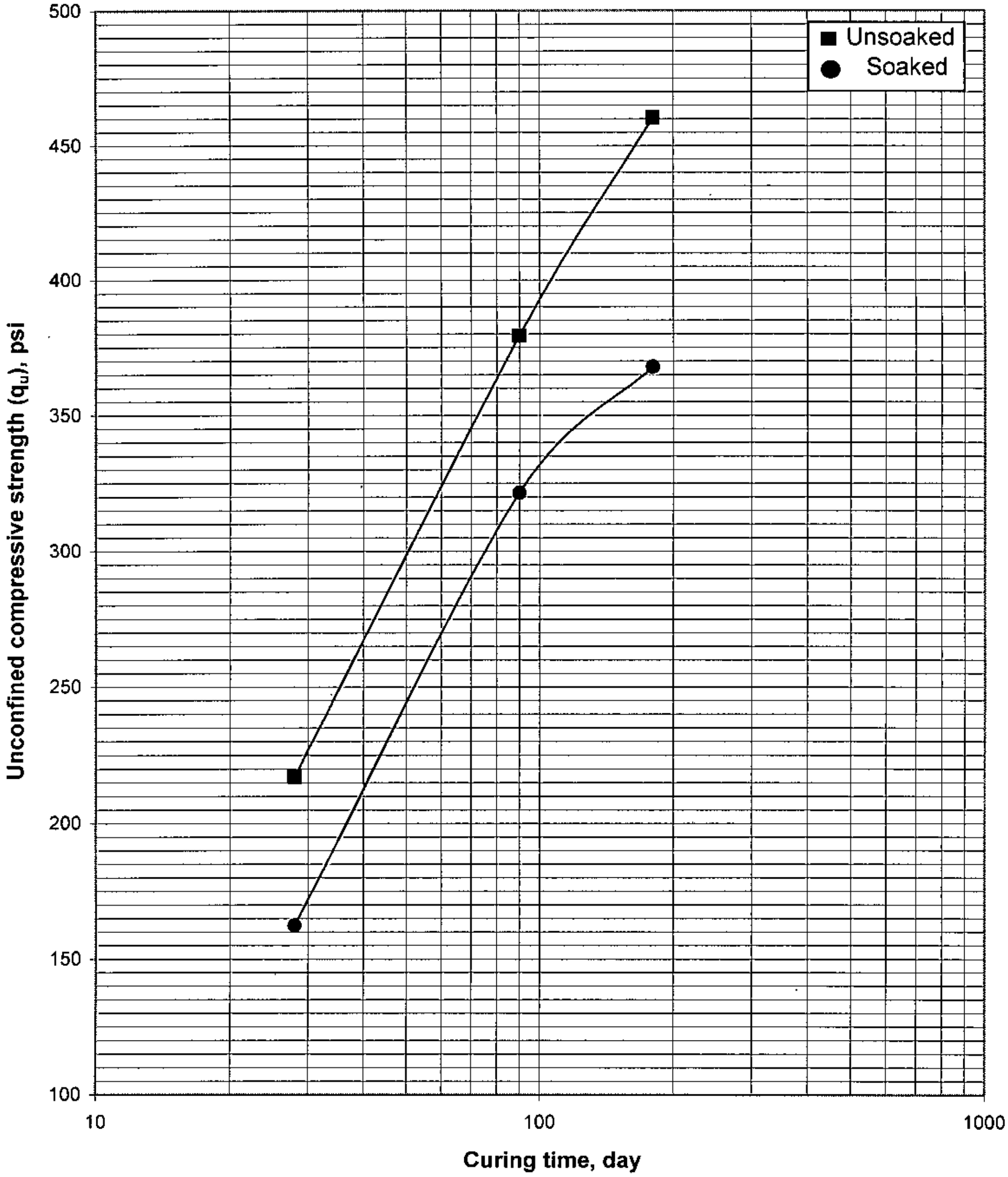


Fig. 4.9. (c) Unconfined compressive strength at different curing days of soaked sample and unsoaked sample of soil 'C' (CL) stabilized with 7% lime

Table: 4.8 Ratio of soaked to unsoaked compressive strength of lime stabilized soil 'C' (CL) at different curing time and with different lime contents

Lime content, percent	Curing time, day	q_u, unsoaked psi (kPa)	q_u, soaked psi (kPa)	$\frac{q_u\text{, soaked}}{q_u\text{, unsoaked}}$
3	28	180.44 (1243.95)	144.18 (993.98)	0.80
	90	284.58 (1961.89)	233.07 (1606.78)	0.82
	180	326.16 (2248.55)	246.9 (1702.13)	0.76
5	28	200.69 (1383.56)	154.33 (1063.95)	0.77
	90	355.73 (2452.40)	269.64 (1858.90)	0.76
	180	400.18 (2758.84)	284.52 (1961.48)	0.71
7	28	217.14 (1496.96)	162.42 (1119.72)	0.75
	90	379.2 (2614.20)	321.56 (2216.83)	0.85
	180	460.37 (3173.79)	367.83 (2535.82)	0.80

Note: Value in parentheses represents the value in SI unit

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Long term strength development of lime stabilized soils has been investigated in this research work. Unconfined compressive strength tests were carried out on stabilized samples after 7, 28, 90, 180 and 360 days of curing using different type of soils with various lime contents. Strength test were also conducted on samples after 7 (seven) days of soaking in water. From the test results, presented in this study, the following conclusions are drawn:

i) The optimum moisture content increases with the increase of lime content, while the maximum dry density decreases. The shape of moisture- density curve becomes flat due to the addition of lime. For field control of lime stabilized soil, strength test should be performed. In situ density test should not be the criteria for field control as the dry density decreases with the addition of lime.

ii) The unconfined compressive strength of soil increases when it is stabilized with lime. The gain in strength depends on different factors, such as lime content, soil type, curing time, mellowing time, compaction energy etc.

iii) For a particular curing period soil stabilized with higher percentages of lime has higher compressive strength; however the increase in strength is not proportional to the lime content. The unconfined compressive strengths of CL type soil, at 28 days are 4.1, 4.9 and 6.8 times of that of base soil when stabilized with 3%, 5% and 7% lime content respectively. For ML/CL type soils the 28-day strengths are 1.5, 2.7 and 3.0 times of that of base soil for 3%, 5% and 7% lime content respectively.

iv) The CL type soil is more suitable for lime stabilization. It attains reasonably high strength with small quantity of lime. The unconfined compressive strength of lime treated CL type soil is higher than ML/CL type soil for a given lime content and curing period. Soil containing organic matter (about 2%) requires higher percentage of lime and longer curing period for stabilization.

v) The strength of lime stabilized soil continues to increase with curing period. Initially the rate of gain of strength is high, after that the rate decreases. The soils stabilized with lower amount of lime (3%) do not show increase of strength after 180 days of curing period. But with higher amount of lime (5%, 7%) the strength increases beyond 180 days.

vi) The 360-day strength of the lime stabilized soil is appreciably higher than 28-day strength. This is more pronounced when stabilized with higher percentages of lime. For CL type soil, the strength gain at 360 days is 2.4 times of 28-day strength when stabilized with 7% lime and about 1.6 times when stabilized with 3% lime. The strength gain of lime stabilized soil at longer curing period may be considered in design, where appropriate. The long term strength gain property is more pronounced in lime stabilized soil when compacted at reduced energy.

vii) The decrease of strength due to compaction delay depends on soil type and lime content. The decrease of strength is less in CL type soil than in ML/CL type soil. 24 hours (1 day) delay in compaction causes nearly 15% reduction in strength, whereas for 336 hours (14 days) delay in compaction the reduction in strength is approximately 50% when CL soil is stabilized with 3% lime. The decrease in strength due to retempering is similar to that of compaction delay.

viii) There is a small loss of strength of lime stabilized soil when they are immersed in water for 7 days. The ratio of soaked to unsoaked compressive strength varies between 0.71 to 0.85 for lime stabilized soil stabilized with different lime content and at different curing days (28 days, 90 days and 180 days).

5.2 Recommendations for Future Research

The present study investigates the effect of long term curing period on unconfined compressive strength of lime stabilized soil. Several aspects of lime stabilization require further study. It is recommended to extend the research in the following field.

i) As the soil type is one of the important parameter for lime stabilization, investigation using different types of soil can be performed. Investigation may be carried out on organic soil with high lime content.

ii) Other methods of compaction such as kneading compaction can be used in preparing the sample.

iii) In addition to unconfined compressive strength, CBR or triaxial shear strength may be used to evaluate the strength of lime stabilized soil.

iv) Investigation may be carried out to study the effect of use of extra lime and water in retempered sample and in samples prepared after longer mellowing time.

v) The permeability characteristics of lime stabilized soil can be investigated considering longer curing period.

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APPENDIX - A

MEASUREMENT OF pH

Determination of soil pH :

Soil pH was determined by using pH meter with glass electrode (Metrohm 691) from extraction of soil: water 1:2.5. In this process, 10 g of soil was mixed with 25 ml of water in a small beaker and it was stirred frequently for 50 minutes. After that the mixture was left for 10 minutes without stirring. Then the pH meter electrode was placed in the suspension and waited until the reading become steady. The pH meter was calibrated by three buffer solutions (pH 4.01, pH 6.87 and pH 9.18).

APPENDIX - B

DETERMINATION OF TOTAL ORGANIC CARBON

Determination of total carbon :

Total carbon was determined by dry combustion method "using LECO C-2000 Analyzer. In this method soil sample was taken in a ceramic crucible and iron and copper were added as accelerator. This crucible was placed in the combustion chamber of the machine. When the combination was completed the result (% carbon) was appeared on the display.

Determination of organic matter :

The organic matter of soil is determined by multiplying the content of organic carbon with a factor 1.724 (Van Bemmelen factor).

APPENDIX - C

DETERMINATION OF MINERAL CONTENT

Preparation of clay samples:

10g of air dry soil was treated with 30% H_2O_2 heated for about 2 hours to decompose organic matter. Excess H_2O_2 was removed by centrifugation by washing 3 times with water. 3M NaCl was added each time to prevent deflocculation of clay particles and the supernatant was discarded by decanation. The pH of the soil suspension was adjusted to 10 by addition of 1N NaOH. Soil suspension was then transferred in to a sedimentation cylinder and water was added up to mark. Time and temperature were recorded. After standing for an appropriate time, the <2 μ m clay fraction was siphoned out into a plastic bottle in which 0.1M NaCl solution was added to flocculate the clay particles. The sedimentation – siphoning process was repeated until the clay fraction was separated completely.

Mineralogical analysis:

Identification and estimation of mineralogical composition were carried out by X-ray diffraction (XRD). The separated clay fraction was treated by 1M KCl and 0.5 N $MgCl_2$ respectively to make K + and Mg+ saturated clay and wash them with ethanol to remove excess salts. Suitable amount (0.4 ml) of solution was dropped on a glass slide covering two third of its area, air dried, and X-rayed (parallel powder mount). In addition to the air-dried sample, the Mg saturated clay was X-rayed after saturation with glycerol: and K-saturated clay after heating at 300^0 C and 550^0 C for 2 hour.

The XRD pattern were obtain using shimadzu XRD 6000 diffractometer with Ni-filtered CuKα radiation at 40kV and 30mA and at a scanning speed of 2.0 ^{0}/min over a range of $3\text{-}35^0 2\theta$.

Approximate mineral contents of clay fraction estimated on the basis of the relative peak intensities in the XRD patterns of random powder mount. The intensities ratio of two components P and Q in a multi-component mixture can be related to their weight ratio as follows (Islam and Lotsc, 1986):

$$Ip / Iq = Kp.q.Wp/Wq$$

Where Ip and Iq are the intensities of the P and Q components in XRD, Wp and Wq are the weight proportion of P and Q components and Kp.q, a constant value, is the intensity –weight coefficient of and P and Q components.