6. STABILIZED PAVEMENT MATERIALS

The term 'soil stabilisation' may be defined as the alteration of the properties of an existing soil either by blending (mixing) two or more materials and improving particle size distribution or by the use of stabilizing additives to meet the specified engineering properties. Quite often soils are stabilized for road construction in most parts of the world for the following one or more objectives:

- Improve the strength (stability and bearing capacity) for subgrade, subbase, base, and low-cost road surfaces,
- Improve the volume stability – undesirable properties such as swelling, shrinkage, high plasticity characteristics, and difficulty in compaction, etc. caused by change in moisture,
- Improve durability – increase the resistance to erosion, weathering or traffic, and
- Improve high permeability, poor workability, dust nuisance, frost susceptibility, etc.

Due to their mineralogical composition, soils may be rather complex materials. Stabilization is therefore not a straightforward application of a given stabilizing agent; a number of aspects should be taken into account in the selection of the proper stabilization technique. The factors that should be considered include physical and chemical composition of the soil to be stabilized, availability and economical feasibility of stabilising agents, ease of application, site constraints, climate, curing time, and safety. Such factors should be taken into account in order to select the proper type of stabilisation.

Basically four techniques of soil stabilization are commonly practiced in pavement construction. These are: -

- Mechanical stabilization,
- Cement stabilization,
- Lime stabilization, and
- Bitumen stabilization.

Mechanical stabilization is a method by which a soil or gravel is mixed with the original soil in order to improve the grading and mechanical characteristics of the soil. Other methods of stabilization use additives such as cement, lime and bitumen to improve strength, workability or waterproofing.

Portland cement has been used with great success to improve existing gravel roads, as well as to stabilize natural soils. It can be used for base courses and subbases of all types. It can be used in granular soils, silty soils, and lean clays, but it cannot be used in organic materials. Since soil cement shows strength gains over that of the natural material, it is very often used for base-course construction. Another cementing agent, which is often used, is lime. Lime increases soil strength primarily by pozzolanic action, which is the formation of cementatious silicates and aluminates. It is the most effective agent to stabilize clayey materials. Bituminous materials are used as stabilizers to retard or completely stop moisture absorption by coating soil or aggregate grains in the soil-aggregate mixture. Bituminous stabilization is best for semigranular soils. As will be seen in the coming sections, the suitability of these methods depends on site constraints, materials, climate, and economic feasibility.

The stabilizing process with admixture involves the addition of a stabilizing agent to the soil, mixing with sufficient water to achieve the optimum moisture content, compaction of the mixture, and final curing to ensure that the strength potential is developed.

6.1. Mechanical Stabilization

As has been mentioned before, mechanical stabilization is an improvement of an available material by blending it with one or more materials in order to improve the particle size distribution and plasticity characteristics. Typical materials used for mechanical stabilization include river deposited sand, natural gravel, silty sands, sand clays, silt clays, crushed run quarry products and waste quarry products, volcanic cinders and scoria, poorly graded laterites and beach sands, etc. Materials produced by blending have properties similar to conventional unbounded materials and can be evaluated by ordinary methods.

The principal properties affecting the stability of compacted base or sub-base materials are internal friction and cohesion. Internal friction is chiefly dependent on the characteristics of the coarser soil particles, i.e. gravel, sand and silt sizes. The cohesion, shrinkage, swelling and compressibility are mainly associated with the quantity and nature of the clay fraction as indicated by plastic properties.

Preliminary mix design of mechanical stabilization is based on particle size distribution and plastic properties. It is desirable also that strength tests (CBR, etc.) be carried out to verify that the required improvement has been achieved. When unconventional materials are used, more

detailed testing and investigation will often be needed and may include the modification of the accepted design or specification criteria.

Particle Size Distribution: While maximum frictional strength does not necessarily coincide with maximum density, the achievement of a high density will generally provide a high frictional strength. A particle size distribution that results maximum dry density, obtained with the closest packing and minimum voids, has been shown experimentally to follow Fuller's equation with the value of the exponent '*n*' usually 0.45 to 0.50 for most soils. However, with some materials, e.g. gravel-sand-clays, high densities can be achieved with '*n*' values as low as 0.33. For materials with a maximum size of 19 mm, the amount of fines passing the 75 μm sieve will be 6 and 8 percent for '*n*' values of 0.5 and 0.45 respectively. In certain cases higher percentages of material passing the 75 μm sieve may provide the best performance.

When the pavement design relies on a relatively low permeability in the pavement courses, the materials used should be of particle size distribution within the limits established by substituting values of 0.50 and 0.33 for '*n*' in the above equation. These limits are sufficiently wide to allow for variations that will inevitably occur in field mixing. However, if plant mixing is undertaken, more restrictive limits may be set. Where the value of the exponent '*n*' is less than 0.33, the fines content of the material may be excessive. A high fine content will result in reduced permeability, but may lead to the development of pore pressures and consequent instability during compaction or in service. Where '*n*' is greater than 0.5, the material tends to be harsh, and may be prone to segregation and ravelling and therefore more difficult to work.

Liquid Limit and Plasticity Index: The plasticity limits indicated in Chapter 5 for different layers of pavement structure can generally be used as satisfactory design criteria for mechanical stabilized materials. Moreover, Plastic Index and Linear Shrinkage of a material passing 0.425 mm are normally related to one another. The permissible values of shrinkage may be determined by test or estimated from the permissible values of PI. Typical values are 2 % for sealed and 3 % for unsealed pavements.

When the percentage of soil binder is low, as a rough rule, the Plasticity Modulus (PI x the percentage passing the 425 mm sieve relative to the whole material) should not exceed 200 for gravel to receive bituminous surface treatment. In arid climates, consideration could be given to relax the PM to about 400, provided road formations are well drained. Slightly wider limits of Plasticity Index may prove satisfactory with some ironstone gravels and limestone rubbles, if the

soil binder has some natural setting properties. This should not, however, be taken as a general rule - each case should be treated on its merits and caution should be exercised in dealing with new and unfamiliar materials. In the case of major works it is advisable to construct trial sections of pavement for evaluation at least two years before embarking upon their large-scale use.

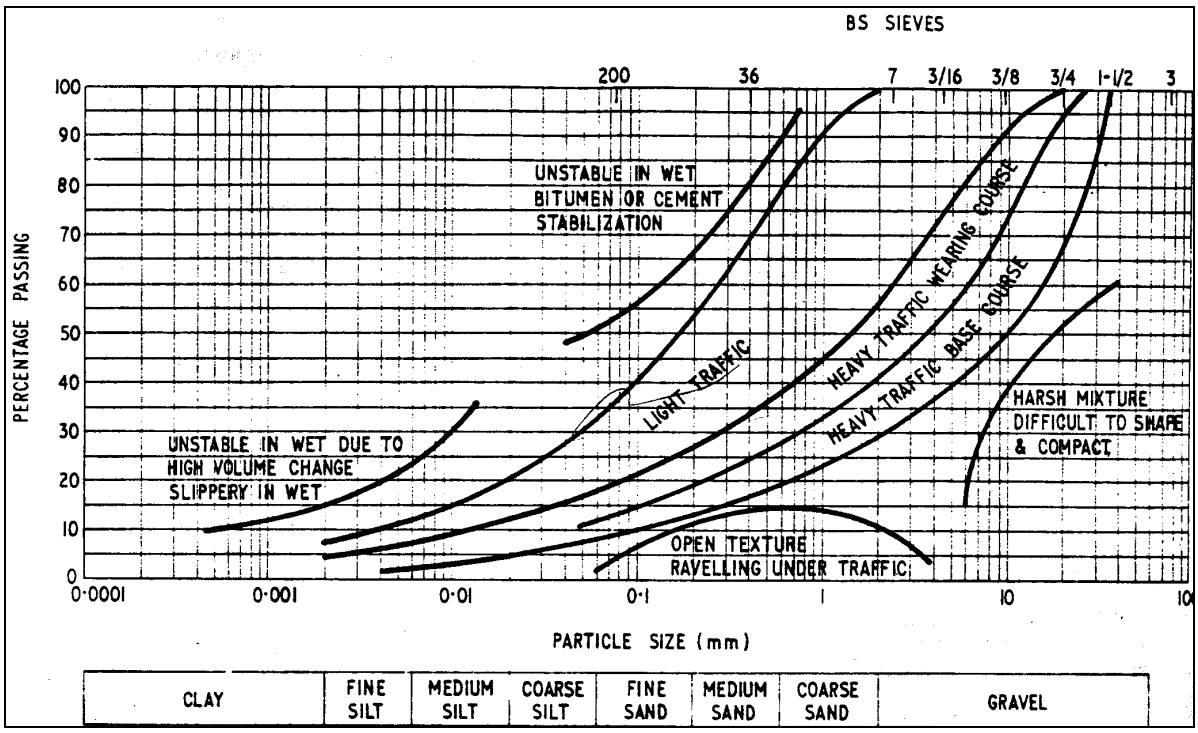

Figure 6-1: General properties of mechanically stabilised gradings

Strength Tests: Stabilized materials may be assessed by strength tests suitable for this purpose at the density and moisture conditions prevailing in the pavement during the service life. It is important, in the testing of a potential base material, to be able to predict its moisture condition. By this means, the failure envelopes at moisture conditions bracketing the equilibrium moisture conditions and at the required density anticipated in the proposed pavement may be derived. The equilibrium moisture conditions to be expected in a pavement may be obtained by examining existing roads constructed from materials similar to those being investigated and assembling such information for future use.

One of the most commonly used strength tests is the laboratory CBR test. The values given in Table **6-1** have generally been found to be applicable. A 4-day soaking of compacted specimens before testing is generally used. Conditions adopted for the test may be altered in respect of the degree of compaction and moisture content, to simulate the worst conditions expected in service.

In some circumstances, conditioning the specimens by soaking for 4 days might be too conservative, and in other cases a period longer than 4 days might be more appropriate for relatively impermeable materials. In this case the adoption of a minimum CBR value different to those tabulated above should be considered.

The selection of suitable criteria should take account of local experience, especially that related to the performance of local materials. Design of stabilised mixtures involves characterising the individual materials, proportioning them to fit the selected criteria, and making up a trial mixture to check that the preferred proportions do provide the desired qualities. In addition to adequate investigation and design, good construction and control testing techniques are essential if a satisfactory road pavement is to result. This involves careful proportioning and thorough mixing of the constituent materials to produce a uniform unsegregated final product which can be compacted and finished in accordance with the specification.

Table 6-1: California bearing ratio limits for mechanical stabilised base materials

Pavement	Minimum CBR values
High class, high traffic volume	100
Rural roads, wet areas	80
Rural roads, dry areas	60

6.2. Cement Stabilization

Cement is an effective stabilizing agent applicable to a wide range of soils and situations. It has two important effects on soil behaviours:

- Reduces the moisture susceptibility of soils — cement binds the particles greatly and reduces moisture induced volume change (shrinkage and swell) and it also improve strength stability under variable moisture, and
- Develop inter-particle bonds in granular materials — increased tensile strength and elastic modulus.

Soil properties progressively change with increasing cement contents. For practical reasons, two categories of cement stabilised materials have been identified.

Cement modified materials — cement is used to reduce plasticity, volume-change, etc, and the inter-particle bonds are not significantly developed. Such materials are evaluated in the same manner as conventional unbound flexible pavement materials.

Cement bound materials — cement is used to sufficiently enhance modulus and tensile strength. Cement bound materials have practical application in stiffening the pavement.

There are no established criteria to distinguish between modified and bound materials, but an arbitrary limit of indirect tensile strength of 80 kN or unconfined compressive strength of 800 kPa after seven days moist curing has been suggested.

A number of factors influence the quality of the cement-soil interactions. The most important factors can be categorized into four groups:

Nature and type of soil: This include: clay content (max 5 %), plasticity of the soil (max LL of 45) , gradation, content of organic materials (max 2 %), sulphate content (max 0.25 % for cohesive soils and 1 % for non-cohesive soils), and PH content. Soils with high clay content and high plasticity are difficult to mix and high additive contents are required for an appreciable change in properties. Pre-treatment with lime however is good method to allow the soil to be cement-stabilized later on. Basically well graded material requires less cement content than poorly graded one. The requirements with respect to the organic matter, PH, and sulphate contents are in fact the same as those which are used for concrete.

Cement content: The cement required to stabilize soils effectively vary with the nature and type of soils. The criteria used are the compressive strength (about 1.7 MPa) after seven days. The quantity required for gravely soils is generally much less than required for silty and clayey soils. Generally, a soil is regarded to be suited for cement-stabilised if, the soil has a maximum grain size less than 75 mm, percents passing and retained 0.075 mm sieve is less than 35 %, and greater than 55 % respectively, and liquid and plastic limits less than 50 and 25 respectively. Based on vast experiences on cement stabilization, the general guidelines shown in Table **6-2** have been provided regarding the amounts of cement that are needed to stabilize a soil.

Table 6-2: General guidelines on cement requirement to stabilise soil

Soil type	Amount of cement (%)	
	By weight	By volume
A-1-a	3-5	5-7
A-1-b	5-8	7-9
A-2	5-9	7-10
A-3	7-11	8-12
A-4	7-12	8-13
A-5	8-13	8-13
A-6	9-15	10-14
A-7	10-16	10-14

Moisture content: Moisture is required for hydration of cement to take place, to improve the workability, and facilitate the compaction of the soil-cement mixture. The soil-cement mixture exhibit the same type of moisture-density relationship as an ordinary soil. Thus, for a given compaction effort, there is an optimum moisture content at which the maximum density is obtained. It is, however, seen that the highest compressive strength can be obtained with specimens compacted slightly below the optimum for maximum density.

Pulverization, mixing, compaction, and curing conditions: Many procedures of construction are available, but can be categorised into mixing in plant (in a travelling plant and stationary plant for dry mixing), and in place mixing. The methods are principally the same except mixing in the first is done in mixing plants and in the later is in-place. Regardless of the type of machine used, the procedure of mix-in-place construction involves initial preparation of the subgrade, pulverization of the soil, spreading of the soil, dry-mix the soil and the cement, adding water and wet mix, compact and finish, and protect and cure (place a curing membrane to keep moist).

The influence of the degree of mixing and compaction is self explaining. One should however be aware of the fact that any delay in compaction after mixing will have a negative effect. As with concrete, curing is an important factor influencing on the end result. The temperature

should be high enough and the stabilised material should be prevented from drying out in order to obtain the best result.

Since cement stabilized materials constitute in most cases the main structural part of pavements, much attention is given to their mechanical characteristics such as:

- Tensile and compressive strength,
- Deformation behaviour, and
- Fatigue characteristics

Tensile and compressive strengths: After rapid strength gains in the first one to two days, cement stabilised materials continue to gain strength, providing curing is sustained. The compressive strength based on the unconfined compressive test increases with the cement content in the mixture depending on the nature and types of soil as shown in Figure 6-2. It has been used to determine the strength of stabilized materials, but has little direct application to pavement design. CBR can be used to evaluate the strength of cement modified materials, but not for bound materials. Tensile strength is important in the design of cement bound materials. Density is also an important parameter which has a direct relationship with the UCS.

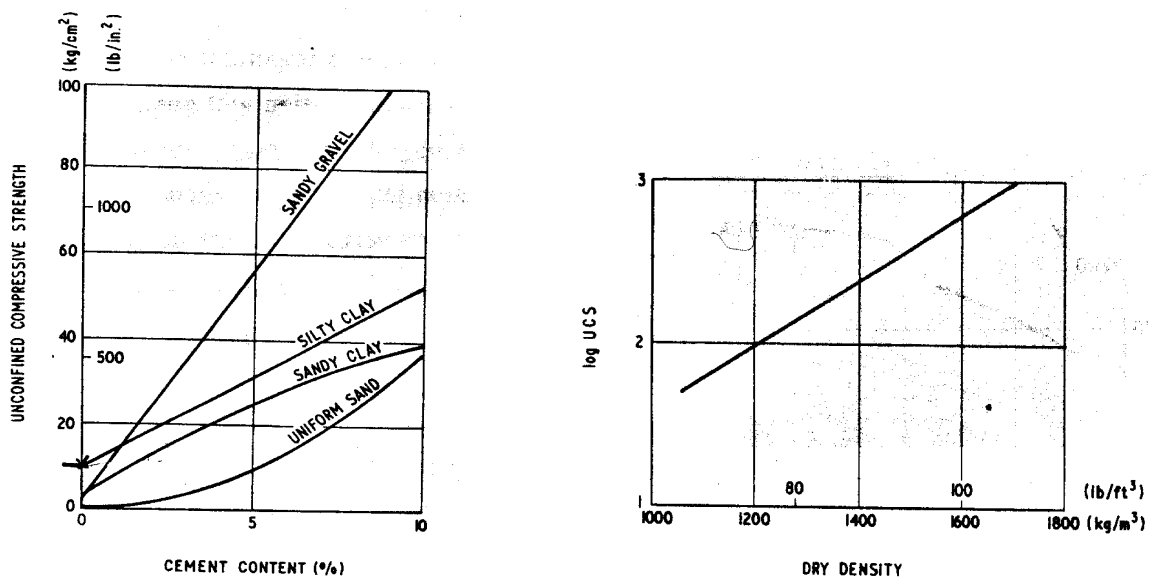

Figure 6-2: Effect of cement content on UCS and density of various stabilized soils

Curing temperature and curing time, compaction, and degree of pulverization are important factors which affect the strength gained by cement stabilization. Curing time is meant the time during which evaporation of moisture is prevented. The method of compaction is also important

for clayey soils. High degree of pulverization achieved in a shorter period of time leads to more intensive reaction between soils and cement and results high strength.

Deformation behaviour: In order to make proper stress-strain analyses, information on the elastic modulus of the materials should be known. It is well known that clays, sands, and gravels show different elastic deformation behaviour under repetitive loading. The addition of cement on these materials changes the elastic deformation properties, but not completely. The parent material will have a great influence on the properties of the soil-cement mixture.

It has been shown that cemented clayey materials have a different behaviour in compression (about 1.5 times of modulus) than in tension. However, a more or less linear behaviour is observed up to 75 % of the failure load. Cemented clayey material also exhibits some degree of permanent deformation under repeated loading and a certain amount of creep under steady loads. Cemented sand and gravel exhibit a similar performance but permanent deformation and creep are less than in cemented clayey soils. The less fines are present in the soil mixture the more the cement-treated soil behave like concrete. Altogether, this means that the influence of the parent soil is still noticeable in the performance of the stabilized material.

Fatigue characteristics: Cement stabilized materials cracks either due to hydration and drying shrinkage and fatigue at the result of repeated tensile stresses (strains). Knowledge of fatigue characteristics of cement-treated materials is essential for design purposes. It has been apparent that the parent soil has a great influence on the fatigue characteristics of cement stabilized materials. Although there seems a great variation, there is indeed something like a threshold strain level under which no fatigue will occur.

Since durability and UCS are strongly related, the durability test is normally used in the soil-cement mix design procedure. However, UCS test is also used as an additional test to the durability test. Durability is defined as a loss in weight of a specimen after 12 freeze-thaw cycles or 12 wet-dry cycles. The material loss is generated by brushing the samples after each cycle.

6.3. Lime stabilization

Lime is a broad term which is used to describe calcium oxide (CaO) – quick lime; calcium hydroxide $Ca(OH)_2$ – hydrated lime, and calcium carbonate ($CaCO_3$) – carbonate of lime. Out of these, calcium oxide and calcium hydroxide react with soil and calcium carbonate is of no value for stabilization. In practice, various forms of quick lime and hydrated lime have been

successfully utilized as a soil stabilizing agent. The most commonly used products are hydrated calcitic lime (Ca (OH_2)), monohydrated dolomitic lime (Ca (OH_2) MgO), calcitic quick lime (CaO), dolomitic quick lime (CaO MgO). They are available as commercial and waste lime. Lime can be applied as dry hydrated lime, quick lime or slurry lime.

As has been indicated above, lime is an effective stabilizing agent for clayey materials to improve both workability and strength. Lime is not effective with cohesionless or low cohesion materials without the addition of secondary (pozzolanic-fine materials which react with lime to form cementitious compounds) additives. The cementitious products resulting from cement and lime stabilization are with comparable behaviour and may follow fairly similar evaluation, design, and construction considerations. The significant difference in the nature and rate of cementitious reactions, however, is a basis for the choice between cement and lime.

The reaction between soil and lime are complex and still not completely understood. Basically four different factors are involved in the soil-lime reaction which are: cation exchange, flocculation, pozzolanic reaction, and carbonation. Cation exchange is an immediate reaction and unlike pozzolanic reaction, it is not significantly dependent on temperature in which cations such as sodium and hydrogen are replaced by calcium ions for which the clay mineral has a greater affinity. It has been shown that the thickness of the water layer around the clay particles decrease substantially as the result of cation exchanges. This condition in turn promotes the development of flocculent structures. This means that plasticity, shrinkage and swelling and other normal clay – water interactions are distinctly inhibited. The effects of lime on the plasticity properties of soils are primarily due to cation exchange reactions. An immediate reduction in plasticity results in an immediate increase in shear strength. The effect of lime on clay minerals of high cation exchange capacity, such as montmorillonite clays, is therefore more apparent than it is on clay minerals of low cation exchange capacity such as koalinite clays.

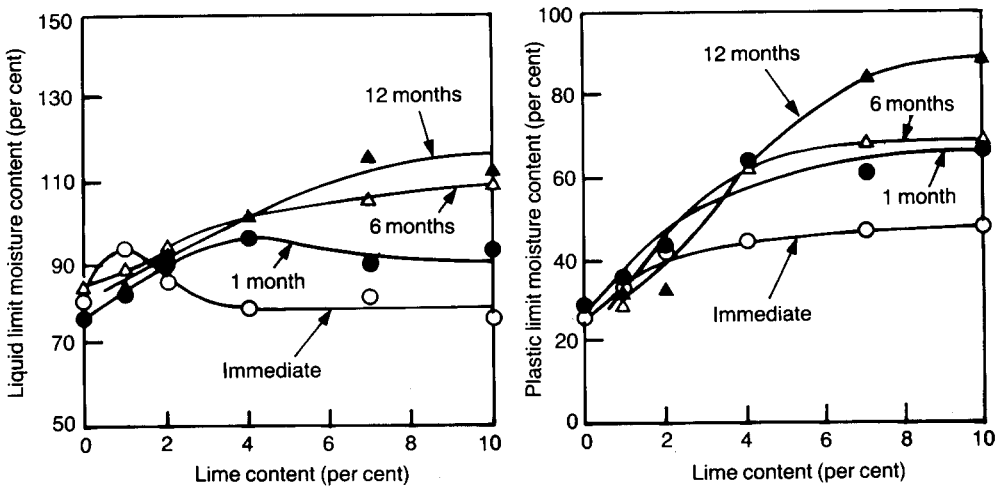

Figure 6-3: Effect of time on the plasticity of lime stabilized clays

Chemically equivalent amounts of quick lime and hydrated lime have the same effect on plasticity. However, quick lime has an additional drying effect since, the chemical reaction between the lime and the water in the soil removes free water from the sol and the heat produced by the reaction assists in drying.

The change in plasticity is accompanied by an immediate change in the strength of the soil as measured by the CBR. Figure **6-4** shows how the effect of lime on the CBR value increases with time as the pozzolanic reactions take effect. Siliceous and aluminous materials in the soil react with lime to produce a gel of calcium silicates and aluminates. This gel cements the soil particles together in a manner that is similar to that of hydrated cement. Minerals in the soil that react with lime to produce a cementing compound are known as pozzolans. Lime-cementing action in a soil is usually a slow process; depending on the type of pozzolans, it takes considerably more time than required for hydration of Portland cement. This long term effect on strength, causing continuing strength improvements with time, often called pozzolanic reactions. The cementing action also depends on climatic conditions and a thorough compaction of the mixture. High curing temperatures have a positive effect on the pozzolanic reactions. Temperatures lower than 13 and 16°C retard the reaction; from this point of view it is obvious that lime stabilization is especially popular in tropical countries.

Carbonation occurs when the hydrated lime reacts with the CO2 from the air. Carbonates (CaCO3) add some strength but the carbonation reaction “eats” the lime and will therefore deter pozzolanic reactions.

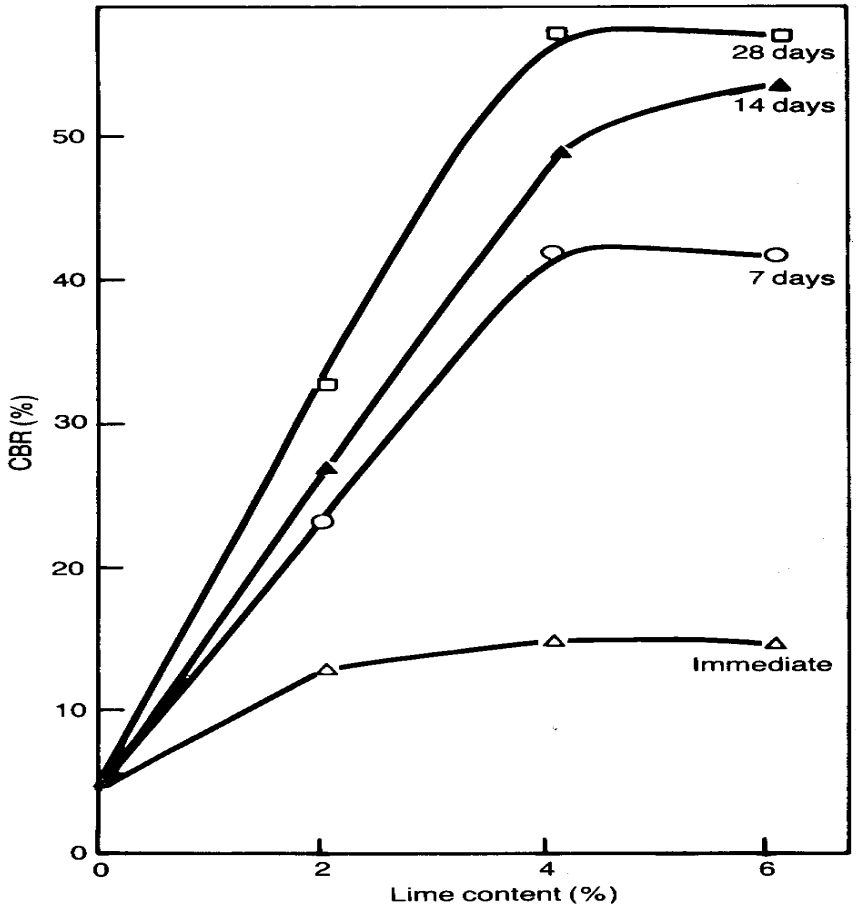

Figure 6-4: Effect of lime content and time on the CBR values of lime stabilised soil

Other factors that are of influence on the soil-lime reaction are:

- The presence of excessive quantities of organic carbon retards the lime-soil reaction,
- Moderately weathered and unweathered soils with high pH display good reactivity,
- Poorly drained soils exhibit a higher degree of lime-reactivity than better drained soils,
- All calcareous soils react satisfactorily with lime, and
- A minimum amount of clay approximately 15 % is required to insure an adequate source of silica and/or alumina for the lime-soil pozzolanic reaction.

The strength of lime stabilized materials is dependent on the amount of lime, the curing time, curing temperature and compaction. In addition, the quality of water, type of stabilizing lime, and uniformity of mixing are important factors affecting the quality of production as they are in cement stabilization. Although lime modifies or bonds soil as in cement stabilization, the tendency to form bound products is less with lime than it is with cement. Lime has more tendencies to produce granular materials and consequently its major applications are in the modification of clays, plastic sands, and plastic gravels.

Mix design procedures for lime stabilisation are the determination of the maximum amount of lime that can be taken by the soil before free lime occurs (the lime content above which further increases do not produce significant additional strength) or the lime requirement to attain a specific strength levels. Characteristics related design procedures are related to the conditions for which they have been developed. The usually used minimum strength requirements for mix design are 0.69 MPa for subbase and 1.03 MPa for base courses. These minimum strengths are related to the AASHTO coefficients of relative strength of 0.12 for subbase materials and 0.11 for base-course materials. When lime is used for subgrade improvements, the design lime content may be designated as the lime content above which no further appreciable reduction in PI occurs or a minimum lime content which produces an acceptable PI reduction. For field construction, the lime content is increased 0.5 to 1.0 % to offset the effect of field variability.

6.4. Bituminous Stabilization

Bituminous stabilization is used with non-cohesive granular materials — where the bitumen adds cohesive strength; and with cohesive materials — where the bitumen “waterproofs” the soil thus reducing loss of strength with increase in moisture content. Both effects take place partly from the formation of bitumen film around the soil particles which bonds them together and prevents the absorption of water, and partly from simple blocking of the pores, preventing water from entering the soil mass. Because more care is necessary in bituminous stabilization to achieve satisfactory mixing, its use has not been as widespread as cement and lime stabilizations.

Bituminous materials. The bituminous materials that are used for stabilization works are mostly penetration grade bitumen and cutback bitumen and bitumen emulsion. The characteristics of cutbacks depended on the particle size distribution of the soil, the temperature of application, and the type of mix plant. The more viscous binders are normally used soils having only a small

proportion of material passing the 0.075 mm sieve and for plat mixes, while the lighter binders are used for mix-in-place methods and with soils containing a larger proportion of fines. Emulsions are generally suitable fro soil stabilization in climate where rapid drying conditions occur, since this is equivalent to adding water to the soil as well as bituminous binder. I the tropics, where the temperature is high the use of emulsions may be an advantage since it helps to provide part of the optimum moisture content for compaction, thereby reducing the amount of water necessary for this purpose.

Soil requirements. Bituminous materials are used for the stabilization of both cohesive and non-cohesive granular soils. Sols which can readily pulverized by construction equipment are satisfactory for bituminous stabilization. Cohesive soils usually have satisfactory bearing capacity at low moisture content. The purpose of using bitumen as a stabilizer in such soils is to waterproof them as a means to maintain them at low moisture contents and high bearing capacities. In the non-cohesive granular materials, bitumen serves as a bonding or cementing agent between particles. Depending on the particle size distribution and physical properties of the available soil materials and the function of the stabilising bitumen, there are four types of soil-bitumen mixtures in highway engineering:

1. ***Soil-bitumen***: this is a mixture of cohesive soil and bitumen for waterproofing purposes. The maximum grain size should preferably not greater than one-third of the compacted layer. The best result has been obtained with soils that fall within the grain size limits shown in Table **6-3**. The bitumen requirements commonly range from 4-7% of the dry weight of the soil.
2. ***Sand bitumen***: sands such as beach, river, pit, or existing roadway sand may be stabilized with bitumen if they are substantially free from vegetable matter, lumps or balls of clay or adherent films of clay. Some times it may require admixture of filler material to meet mechanical stability requirements. It is recommended that the sand contain less than 12 % of 0.075 mm. however, in the case of windblown sands up to 25 % finer than 0.075 mm may be allowed provided that the portion of the sand passing the No. 40 sieve has a field moisture less than 20 % and linear shrinkage less than 5 %. The required amount of bitumen content ranges from 4-10 %, the optimum should be determined by compaction, strength, and water resistance testing and should not exceed the pore space of the compacted mineral mix.

3. ***Waterproofed granular stabilization***. This is a system in which a soil material possessing good gradation of constituent particles from coarse to fine, and having high potential density is waterproofed by uniform distribution of small amount (1-2 %) of bitumen. Recommended gradations of the soil aggregate materials are shown in Table **6-3**.
4. ***Oiled earth***. This is a soil surface, consisting of silt-clay material made water and abrasion resistant by slow or medium curing bitumen cutbacks or emulsions.

Table 6-3: Characteristics of soils empirically found suitable for bitumen stabilization

Sieve size	Percent passing				
			Waterproofed granular stabilization		
	Soil-bitumen	Sand-bitumen	A	B	C
1.5 inch			100		
1 inch			80-100	100	
0.75 inch			65-85	80-100	100
No.4	> 50	100	40-65	50-75	80-100
No.10			25-50	40-60	60-80
No.40	35-100		15-30	20-35	30-50
No.100			10-20	13-23	20-35
No.200	10-50	<12;<25[1]	8-12	10-16	13-30
Plasticity characteristics					
LL	<40				
PI	<18		<10;<15	<10;<15	<10;<15[2]
Field moisture		<20[1]			
Linear shrinkage		<5[1]			

[1] lower value for wide and higher values for narrow gradation band sand

[2] values between 10 and 15 permitted in certain cases

The mechanism of stabilization with bituminous materials consists of adding cohesive strength and reducing the percolation of water; no chemical interaction is taking place. Waterproofing occur by coating the surface of particles or aggregated lumps of particles or by blocking the pores of the soil mass, and a strength comes from the presence of a continuous film of bitumen, giving cohesion. There are two opposing effects – the thinner the film of bitumen the stronger the material; however, thick films or filled pores are the most effective in preventing ingress of

water. Too much bitumen, however, causes loss of strength by lubricating the particles and preventing interlock.

The mix design procedure for bituminous treatments of soils may be considered under four headings: mix design for stability in non-cohesive material; mix design for waterproofing in non-cohesive or cohesive materials; mix design for sand-bitumen mixes, and mix design for oiled earth roads. For the first three types of mix, a series of tests should be made with varying bitumen contents and grades using hot bitumen, cutback and emulsion, and the appropriate mix is selected giving due weight to the need for stability or water resistance as required. Compaction, compressive, and water absorption test are normally used to select the optimum amount of bitumen content.

Many difficulties in construction and poor pavement performance may be attributed to a lack of appreciation of this additive effect.