CEMENT AND CEMENT-RICE HUSK ASH STABILIZATION OF SELECTED LOCAL ALLUVIAL SOILS

A Thesis by

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ABSTRACT

Two typical silty soils were stabilized using Portland cement and Portland cement and Rice Husk Ash blended admixture.

Stabilized samples were prepared at their maximum dry density and optimum moisture content obtained by the standard AASHTO test. They were cured and tested for evaluating durability, volume and moisture change characteristics, unconfined compressive strength and plasticity characteristics.

The results obtained show that cement-treated local silty soils satisfy the durability criteria recommended by the Portland Cement Association (PCA) at about 8 per cent cement content. But at the same cement content, they do not attain the specified minimum unconfined compressive strength. Silty soils stabilized with only 2 per cent cement content show considerable gain in unconfined compressive strength over untreated soil.

A blended admixture of Portland cement and Rice Husk Ash, proportioned in the ratio of cement to Rice Husk Ash, 3 to 1, met the durability criteria. However, slight decrease in unconfined compression of cement-treated soil was observed on addition of Rice Husk Ash.

Cement-treated silts tend to show a reduction in volume. Tolerable increase in volume of stabilized soils was noted due to addition of Rice Husk Ash along with cement on wetting. Cement reduces plasticity index of plastic silts, change being pronounced at higher cement contents.

Finally, it was observed that Rice Husk Ash like many other Pulverized Fuel Ash (PFA) has little cementitious property of its own and can only be used as an admixture with other cementitious materials.

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CHAPTER 1

INTRODUCTION

1.1 General

A soil exhibiting a marked and sustained resistance to deformation under repeated or continuing load application, whether in dry or wet state, is said to be a stable soil. When a less stable soil is treated to improve its strength and its resistance to change in volume and moisture content, it is said to be "stabilized". Thus stabilization infers improvement in both strength and durability. In its earlier usage, the term stabilization signified improvement in a qualitative sense only. More recently stabilization has become associated with quantitative values of strength and durability which are related to performance.

These quantitative values are expressed in terms of compressive strength, shearing strength or some measure of load bearing value. These in turn indicate the load bearing quality of the stabilized construction. Again the durability indicates its resistance to freezing and thawing and wetting and drying.

Soil stabilization always involves certain treatment of the soil which again always involves remixing the soil with other soil types or foreign matter and the compaction of the mixture. When applied to road construction, it produces new materials which resist traffic loading and weather effects if correctly used, and allow transport and communication in all weather conditions.

According to Winterkorn (1975) "Soil stabilization is a collective term for any physical, chemical or biological methods, employed to improve certain properties of a natural soil to make it serve adequately an intended engineering purpose".

Since early forties, the stabilization of soil with admixtures like cement, lime, bitumen, fly ash etc. have been successfully experimented and used extensively for the construction of road and airport foundations in the U.S.A., Europe, India, Africa and many other parts of the world (IRC, 1976).

1.2 Soil Stabilization Techniques

There are many methods of soil stabilization in use. The degree of improvement of in-situ soil may differ within a particular method and also between the other methods. The reason behind is that soils exist in a broad range of types and different soils react differently to a stabilizer.

The available important methods may be listed as below:

i) Mechanical stabilization

ii) Cement stabilization

iii) Lime treatment

iv) Bitumen treatment

v) Electro-osmosis

vi) Thermal treatment

vii) Chemical grout.

Fig. 1.1 shows the feasibility of different stabilization techniques related to soil type.

Mechanical stabilization is sometimes termed as granular stabilization. In this process, gradation of soil-aggregate mixture is the only factor which controls the stability of the resulting construction. The basic principles involved in mechanical stabilization are 'proportioning' and 'compaction'. Stability and strength of granular materials having negligible fines when mixed with clay and compacted, can be improved by this technique. Similarly, the stability of the clayey soil can be improved by mixing a proper proportion of granular materials in it.

Cement stabilization has been used successfully to stabilize granular soils, sands, silts and medium plastic clays. Details of cement stabilization will be discussed later.

Lime stabilization has been in use to stabilize clayey soils. Lime depends for its action on pozzolanic materials in the soils. These normally consist of clay minerals and amorphous compounds. Lack of these materials in pure sands and granular soil, makes lime stabilization ineffective for them. Addition of lime to a soil generally results in decreased soil density, changed plasticity properties and increased soil strength.

Bitumen when mixed with soil imparts binding property and makes it waterproof. Water proofing property imparted to the soil helps in retaining its strength even in the presence of water. In the case of fine grained soil, bituminous materials seal the voids between the small soil clods and keep soil away from coming in direct contact with water and thus inherent properties of the soil are retained. In the case of soils like sand and gravel, individual particles get coated with a very thin film of bituminous materials and thus impart binding property in the soil.

The electrical stabilization technique is also known as electro-osmosis. The process involves sending a direct electric current through a saturated soil. This flow of current results in movement of water towards the cathode end from where it is pumped out. Thus the soil is consolidated with decrease in volume. This consolidation increases the strength of the soil appreciably. The method is suitable for silty and clayey soil (Fig. 1.1).

By thermal treatment, soil can be stabilized for expediting construction facility. A reliable temporary expedient to facilitate construction of open and underground excavation is stabilizing the soil by freezing the pore water. When a clayey soil is heated, there is a progressive hardening.

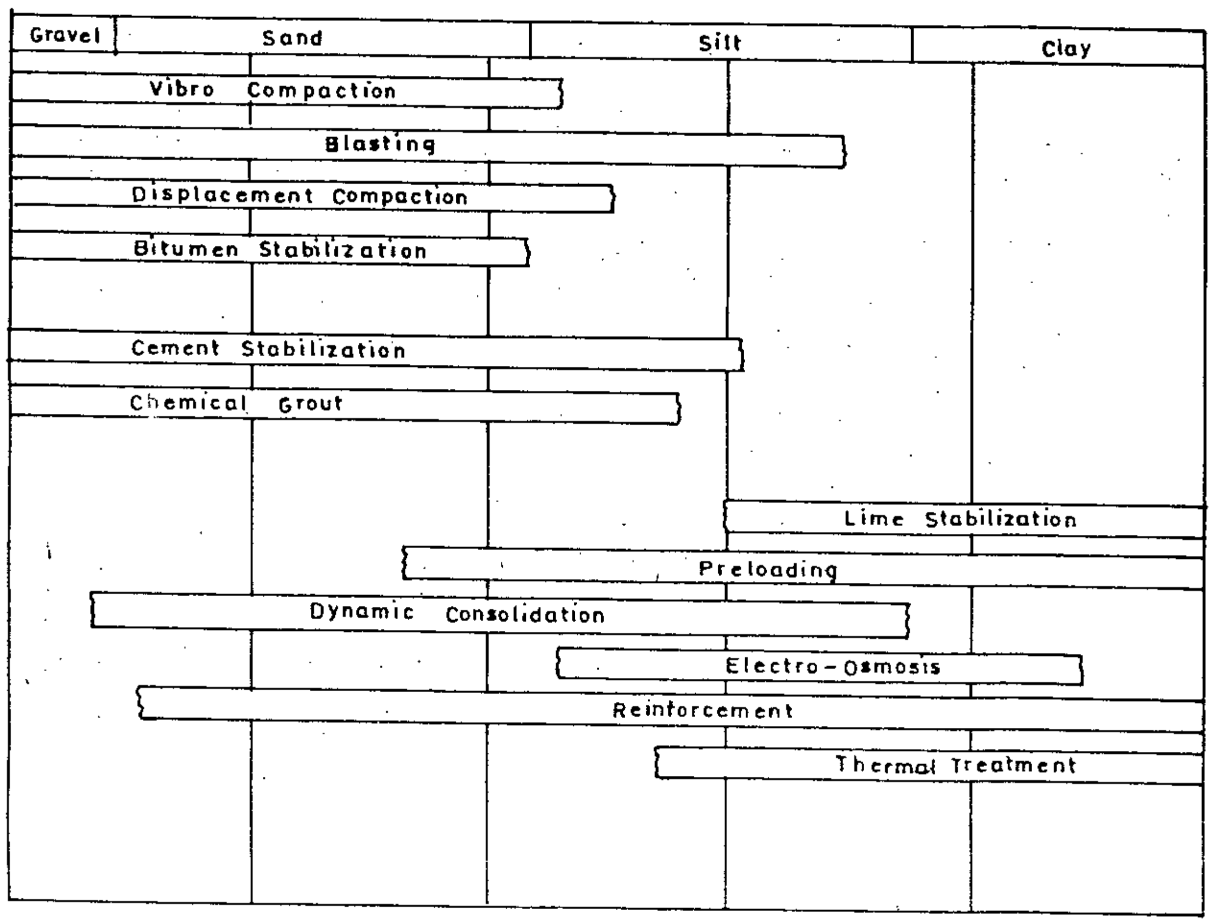


Fig. 1.1 Feasibility of stabilization techniques (after Mitchell, 1976).

The resultant effect is improvement of certain properties of soil like plasticity index, swelling properties, strength, compressibility and durability. The method is uneconomical for stabilizing in-situ soils.

By chemical grouting, it is possible to stabilize fine sands and silts. Grouts fill the pores of these soils resulting in stabilized material.

1.3 Soil-Cement Stabilization

Soil-cement stabilization is the process in which cement is used as an admixture. The strength of the soil is increased and it becomes resistant to softening by water. This improvement in the quality and bearing capacity of the soil at a reasonable cost make it more desirable and efficient in comparison to other methods of stabilization.

Though history of stabilization using admixture dates back to early civilizations of Mesopotamia and Babylon and more recent Roman civilization, in modern times, it was in South Carolina, USA in 1935, that a highway engineer innovated this method of stabilization. Since then 50 millions sq. yds. of soil-cement pavements including roads, runways, car parks and similar construction have been made in U.S.A. alone. Soil-cement construction in Britain exceeded 6,60,000 sq. yds. in 1950, half of which had been constructed since the Second World War. These include building blocks, foundation for houses, housing estate roads and sub-base of major roads (Road Research Laboratory, 1952).

Today soil-cement stabilization is used in many developed and developing countries in the tropical and arctic regions of the world (Kezdi, 1979).

1.4 Soils of Bangladesh

The surfacial geology of Bangladesh may be split into three formations as shown in Fig. 1.2. These are described separately below.

1. Tertiary and Pleistocene Hill Formations

The tertiary and pleistocene hill formations consist almost entirely of unconsolidated or poorly consolidated sand-stones, silt stones and shales. These hill formations run roughly north-south in the Chittagong Hill Tracts and South of Sylhet but east-west along the north-east border parallel to the Shillong Plateu.

2. Uplifted Alluvium Terraces

These terraces, commonly known as the Madhupur and Barind tracts, are both underlain by a relatively homogeneous clay known as Madhupur clay. This clay is believed to have been laid down in a stable marine or deltaic environment in the late Miocene. The clay is underlain by fine sand and the land systems are fault blocks which have since been uplifted and locally tilted.

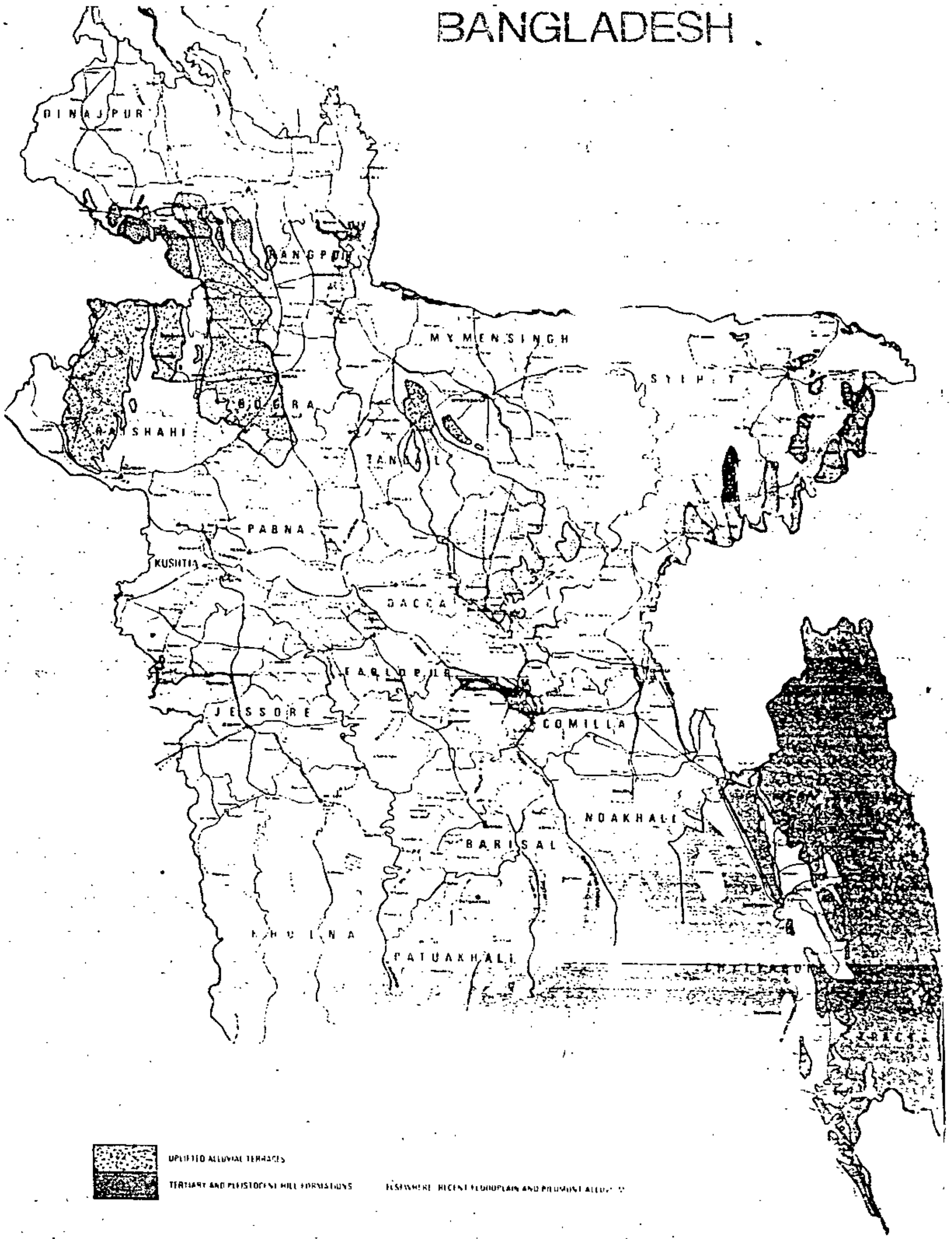


Fig. 1.2 Surfacial geology of Bangladesh (after Bangladesh Transport Survey, 1974).

3. Recent Floodplain and Piedomont Alluvium

This occupies roughly seventy percent of the total land area. The Quaternary flood plain sediments were mainly deposited by the Ganges, Brahmaputra, Teesta and Meghna rivers and their distributaries; sands frequently occupy large areas in the north-east and south-west of this zone. Generally elsewhere, however, silts and silty clays predominate. Piedomont deposits are usually found close to the existing hill areas and usually overlie older flood plain alluvium.

Each formation is divided into a number of land systems. Out of them, Recent Flood Plain and Piedommont Alluvium has the highest number (17) of land systems compared to 2 of Tertiary and Pleistocene Hill Formations and 2 of Uplifted Alluvial Terraces (Bangladesh Transport Survey, 1974).

In this research, soil samples have been collected from Jamuna land system which is a recent flood plain alluvium.

Most of the area is under water during the monsoon and the surface is covered with a large number of tributaries and distributaries of Jamuna, criss-crossing at many points. The river gradient is flat and is one of the causes for reduction of the velocity and deposition of fine eroded particles like silt and clay.

1.5 Need for Soil-Stabilization for Road Construction in Bangladesh

From the previous article, it is seen that the flood plain deposits are of recent origin. In these deposits, soils alternate in repeated layers of clays, silt and sands. Major portion of this deposit is inundated by seasonal flooding every year. As a result, the sub-soil becomes soft and has low density and shear strength. Presence of ground water table close to the surface in other times of the year except flood time also contributes to lower the density and bearing value of the sub-soil. Due to low topography, during road construction in most of the land surface, earth fillings become necessary. Filling soils are generally excavated from nearby borrow pits. These fill-soils have inadequate shear strength to support the traffic loads applied on them. Also, prolonged rainfall seriously impair the stability of these soils. In order to serve adequately, it is essential to improve their strength properties.

The conventional practice of constructing earth roads in rural areas is to dump the loose soil over the road formation and to render a nominal compaction. This road is subsequently exposed to rain and monsoon flood. This together with inadequate compaction seriously impair the durability of earth roads. The resultant effect is comparatively low subgrade strength and eventually higher pavement thickness in case of paved road construction.

In Bangladesh, since resources are limited, it is extremely difficult to mobilize resources for constructing paved roads covering the whole country. But for uplifting rural masses, communication is a must. If the rural masses are to join the mainstream of the more previleged urbanites, the most essential pre-requisite would be to provide an adequate network of roads. With limitations, it is essential that roads are to be constructed in stages. The way is to be found out to provide low cost roads in rural areas.

Bangladesh Transport Survey (1974) recommended the possibility of using cement stabilization for non-plastic alluvial soils of flood plains of Bangladesh for sub-base and base construction of roads.

Central Road Research Institute (CRRI), India has been advocating low cost soil stabilization techniques for rural roads in India, Swaminathan et al (1976).

1.6 Cement-Rice Husk Ash Stabilization

Since late sixties there has been a growing emphasis on the use of agricultural wastes for engineering purposes. Rice Husk then drew attention in all agricultural countries because it has a little traditional use values in country side as cattle fodder, fuels or as a source of manure. It is used to a large extent in Rice Mill Boilers and again, the ash produced creates a dumping problem.

In Bangladesh, annual rice production was about 135 lakh tons in 1982-83, Housing and Building Research Institute (HBRI) (1984). Twenty percent husk are produced during milling. This husk sample generally contains 42% cellulose, 21% lignin and 19% silica, HBRI (1984). On burning Rice Husk under a controlled condition, Rice Husk Ash (RHA) containing more than ninety percent silica is produced. This ash can be exploited as a construction material like Pulverized Fuel Ash (P.F.A) obtained from coal fired electricity generating plants.

Lazzaro and Moh (1970) indicated that lime-rice husk ash mixtures can be used to stabilize deltaic soils.

Ramaiah and Satyapriya (1982) successfully stabilized Black Cotton Soil in India with lime and rice husk ash.

SIRI, Malaysia (1979) found that RHA is a good source of material for making blended Portland-RHA cement by intergrinding. The resulting blended cement shows high early strength, good long term durability and better acid resistance than Portland cement.

The per capita consumption of cement in Bangladesh is about 14 kg only compared to 30 kg in India, 44 kg in Pakistan and 27 kg in Srilanka, HBRI (1984). As per the estimate made in the draft Second Five Year Plan (SFYP), Bangladesh needed 13.0 lakh tons of cement in 1982-83. Out of this requirement only about 3.07 lakh tons of cement are produced in the country.

Hence the major source remains the import. For self sufficiency in this field cement production is to be increased or any other cement like material is to be manufactured so that it can atleast partially replace portland cement in the construction sector. Keeping this view in mind, a blending of Portland cement with Rice Husk Ash in suitable proportion would be a possibility of producing a cement substitute.

Studies at HBRI (1984) have shown that Portland cement-RHA blend in the ratio, cement to RHA, 1 to 1, can be used for masonry work satisfying ASTM specification C-91 for masonry cement.

In this research, selected alluvial soils of Bangladesh have been stabilized with Portland cement and Portland cement-RHA mixture in various proportion and the durability, strength and plasticity characteristics have been studied with a view to examining the potentiality of using Portland-cement-RHA blend in the construction of rural roads.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The properties of the stabilized soils are influenced by a number of factors, such as quality and amount of admixtures, soil properties, compactive effort, condition following addition of admixture, curing period and many other. In this chapter, a brief review will be made about the mechanism of cement and cement-Rice Husk Ash stabilization, important aspects of properties of stabilized soil, factors influencing the mechanism of cement stabilization and probable effect of Rice Husk Ash on cement stabilization. A summary at the end of this chapter briefs the detailed discussion in this chapter.

2.2 Basic Principles of Soil-Cement Stabilization

Addition of inorganic stabilizers like cement and lime have two fold effect on soil — acceleration of flocculation and promotion of chemical bonding. Due to flocculation, the clay particles are electrically attracted and aggregated with each other. This results in an increase in the effective size of the clay aggregation (Jha, 1977).

Ingles (1968) asserted that such aggregation converts clay into the mechanical equivalent of a fine silt. Also, a strong chemical bonding force develops between the individual particles in such aggregation. The chemical bonding depends upon the type of stabilizer employed.

When water is added to neat cement the major hydration products are basic calcium silicate hydrates, calcium aluminate hydrates and hydrated lime. The first two of these products constitute the major cementitious compounds, while the lime is deposited as a seperate crystalline solid phase. They are also responsible for strength gain of soil-cement mix (O'Flaherty, 1974).

The interaction between cement and soil differs somewhat for the two principal types of soil, granular and cohesive.

In granular soils, the cementation effect is similar to that in concrete, the only difference being that the cement paste does not fill the voids of the additives, so that the latter is only cemented at contact points (Fig. 2.1).

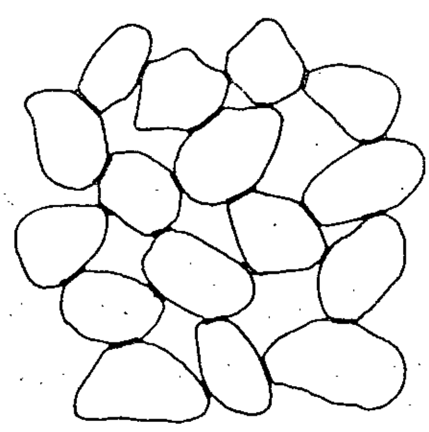


Fig. 2.1 Cementation effect around the contact points of the coarse grains (after Kezdi, 1979).

Thus no continuous matrix is formed and the fracture type depends on whether the interparticle bond or the natural strength of the particles themselves is stronger. The better graded the grain distribution of a soil, the smaller the voids and the greater the number and the larger the interparticle contact surfaces, the stronger the effect of cementation (Kezdi, 1979).

In fine grained silts and clays, the hydration of cement creates rather strong bonds between the various mineral substances and forms a matrix which efficiently encloses the non-bonded soil particles. This matrix develops a cellular structure on whose strength that of the entire construction depends. This happens due to the fact that the strength of the clay particles within the matrix is rather low. Since this matrix pins the particles, the cement reduces plasticity and increases shear strength. The chemical surface effect of the cement reduces the water affinity of the clay and in turn, the water-retention capacity of the clay. Together with a strength increase, this results in the enclosure of the larger unstabilized grain aggregates which, therefore, cannot expand and will have improved durability. The cement-clay interaction is significantly affected by the interaction of lime, produced during hydration of portland cement and the clay minerals. The interaction can be classified into two groups : rapid rate (ion exchange and flocculation) and slow processes (carbonatization, pozzolanic reaction and the production of new substances). The whole process can be divided into a primary and a secondary process.

The primary process includes hydrolysis and the hydration of the cement. In this process, hydration products appear and the pH value of the water increases. The calcium hydroxide produced in this period can react much more strongly than ordinary lime.

Clay is important in the secondary processes. The calcium ions produced during cement hydration transform the clay first into calcium clay, and increase the intensity of the flocculation that had been initiated by the increased total electrolyte content due to cement addition. Calcium hydroxide then attacks the clay particles and the amorphous compound parts. Then the silicates and aluminates dissolved in the pore water will mix with the calcium ions and additional cementing material is precipitated. The calcium hydroxide consumed during the course of the secondary processes is partly replaced by the lime produced by cement hydration.

During the secondary processes the cementation substances are formed over the surface of clay particles or in their immediate vicinity, causing the flocculated clay grains to be bonded at the contact points. Still stronger bonds may be created between the hydrating cement paste and the clay particles coating the cement grains.

The products of primary process harden into high-strength additives and differ from the normal cement hydrated in concrete or mortar only by their lower lime content. The secondary processes increase the strength and durability of the soil cement by producing an additional cementing substance to further enhance the bond strength between the particles (Kezdi, 1979).

2.3 Types of Cement-Treated Soil Mixtures

Four major variables control the degree of stabilization of soils with cement. They are (i) the nature of the soil, (ii) the proportion of the cement in the mix, (iii) the moisture content at the time of compaction and (iv) the degree of densification attained in compaction.

The possibility of controlling the properties of the mix to suit the construction and the degree of stabilization to satisfy the strength and durability requirements have resulted in the development of four principal types of soil-cement mixtures as follows:

1. Soil-Cement

This is the most general category and the mixtures used for the construction of stabilized soil roads are usually in this class. They have to meet predetermined strength, durability and frost resistance requirements and can be used for the construction of the load-bearing layers of roads, bank reinforcement, parking lots etc.

2. Cement-Modified Granular Soil Mixtures

Cement is used here principally to reduce plasticity and swell characteristics and thus to improve the bearing value of marginal or substandard granular materials to make them acceptable base or sub-base materials for both rigid and flexible pavements. The cement content may range from about 1 per cent by weight upward, but is always less than that required for soil-cement.

3. Cement-Modified Silt-Clay Soil Mixtures

In cement-modified mixtures, the cement is used to control the swell-shrink characteristics of the soil. This degree of stabilization may also be used to strengthen abnormally weak soils or wet-soil areas. This type always contains less cement than is required for soil-cement. It is often used for foundation-layer improvement.

4. Plastic Soil Cement

This is a soil-cement mixture that can be placed in a plastic state. But it ultimately hardens into a material that meets the strength and durability requirements set for soil-cement. It is usually made from lighter textured sandy soils. It can be used for lining ditches and irrigation channels and for their protection against erosion.

2.4 Characteristics and Composition of Admixtures

In this research, Portland Cement Type-I was selected as the major admixture. Possibility of substituting this admixture partially by Rice Husk Ash was studied.

2.4.1 Portland Cement Type-I

As per ASTM, cement is designated as Type-I, Type-II, Type-III, Type-IV, Type-V and other minor types like Type-IS, Type-IP etc.

Type-I is designated as Ordinary Portland Cement for use in general construction where the special properties for Types-II, III, IV and V are not required.

Composition of ordinary portland cement according to Mindess and Young (1981) is as follows:

Chemical Name	Chemical Formula	Weight percent
Tricalcium silicate	$3\,CaO, SiO_2$	50
Dicalcium silicate	$2\,CaO, SiO_2$	25
Tricalcium aluminate	$3\,CaO, Al_2O_3$	12
Tetracalcium-aluminoferrite	$4\,CaO, Al_2O_3, Fe_2O_3$	8
Calcium sulfate dihydrate (gypsum)	$CaSO_4, 2H_2O$	5

Calcium trisilicate sets fast and is responsible for immediate strength gain. Calcium disilicate is responsible for long term strength due to hydration reaction. Free lime, a product of hydration reaction, brings about base exchange capacity and changes the texture of the soil (Jha, 1977).

On hydration of the two calcium silicate types which constitute about 75 per cent of the Portland cement new compounds: lime and tobermorite gel are formed. Tobermorite gel i.e. calcium-silicate-hydrate plays the leading role as regards strength (Kezdi, 1979).

On an average 23 percent of water by weight of cement is required for chemical reaction. This water chemically combines with cement. A certain quantity of water is trapped within the pores of tobermorite gel. It has been estimated that about 15 per cent water by weight of cement is required to fill up the gel-pores. Therefore, a total 38 percent of water by weight of cement is required for the complete chemical reactions and occuping the space within gel pores (Shetty, 1982).

2.4.2 Rice Husk Ash

Rice Husk Ash (RHA) with pozzolanic property is obtained by burning Rice Husk under a controlled condition and temperature. Rice Husk Ash with a higher carbon percentage can be obtained as a by-product in rice mill boilers.

Research at Ceylon Institute of Scientific and Industrial Research (CISIR), Sri Lanka (1979) for making pozzolanic cement from Rice Husk Ash was based on rice husk ash obtained by first burning rice husk in boiler. Subsequently, the ash was further fired in a furnace at 650°C for reducing carbon percentage.

SIRI (Standards and Industrial Research Institute) of Malaysia (1979) studied the possibility of producing Rice Husk Ash and Portland cement blended cement by rice husk ash from rice mill boilers.

For large-scale industrialized burning, Pitt (1974) has designed a furnace which looks like an inverted cone into which rice husk is sucked due to negative pressure maintained by an exhaust fan. From the furnace, the hot gases containing ash are taken to a boiler and finally to a multicone seperator which removes the ash from the gases. Thus the heat produced by combustion of husk is usually recovered in the form of steam. A typical flow diagram of the process is shown in Fig. 2.2.

Composition of Rice Husk Ash reported by Dass and Rai (1979) is as in Table 2.1.

These results are similar to the composition after Chopra (1979) as in Table 2.2.

HBRI (1984) analyzed RHA and showed the components in Table 2.3.

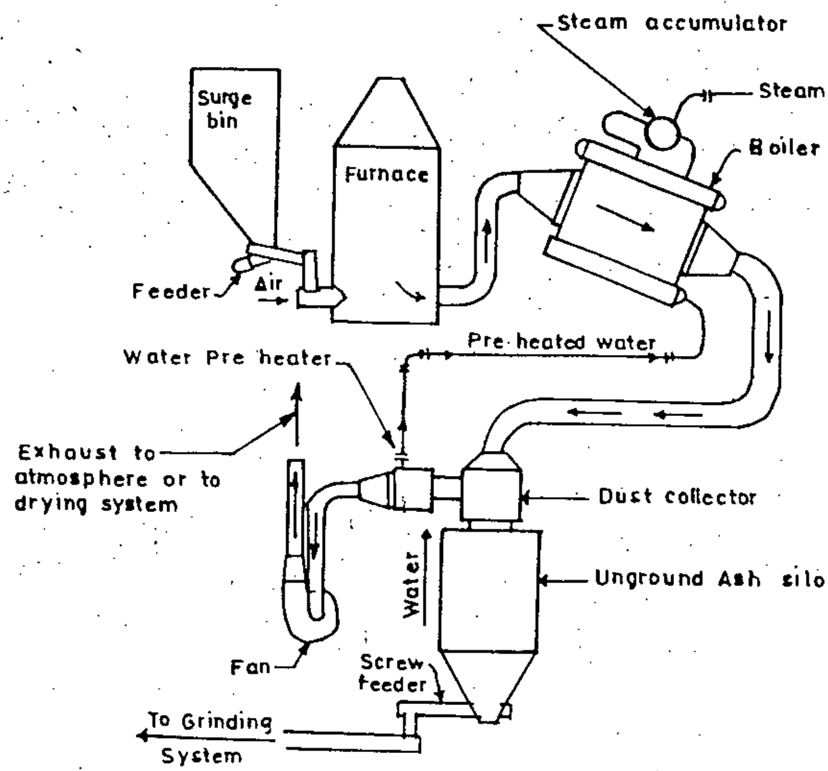


Fig. 2.2 Schematic flow diagram of plant for producing rice husk ash and steam (after Pitt, 1974).

Table 2.1 Composition of Rice Husk Ash (After Dass and Rai, 1979)

Constituent	Percent by weight
SiO_2	93.2
Al_2O_3	0.59
Fe_2O_3	0.22
CaO	0.51
MgO	0.41
Na_2O	0.05
K_2O	2.93
Loss on Ignition	1.91

Table 2.2 Composition of Rice Husk Ash: Dry Basis (After Chopra, 1979)

Constituent	Percent by weight	
	Average composition	Batch composition
SiO_2	85-97	91.08
K_2O	0.5-3.0	2.08
Na_2O	2.0	0.18
CaO	2.0	0.58
MgO	2.0	0.75
Fe_2O_3	Traces -0.7	0.31
P_2O_5	0.2 - 3.0	-
SO_3	0.1 - 1.5	-
Cl	Traces -0.5	Traces

Table 2.3 Constituents of Rice Husk Ash (After HBRI,1984)

Constituents	Percentages present
SiO_2	89.6
CaO	1.22
MgO	1.40
Al_2O_3	0.58
Fe_2O_3	0.60
Loss on ignition	6.0

From the chemical analyses presented, it is clear that Rice Husk Ash contains a high amount of silica. Further study by Dass (1979), Chopra (1979),and HBRI (1984) revealed that this silica is reactive and makes the ash pozzolanic.

A pozzolana or pozzolanic material is a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but will, when in finely divided form and in the presence of moisture chemically react with lime at ordinary temperatures to form compounds possessing cementitious properties (O'Flaherty, 1974).

Mehta (1975) has shown that cement can be made burning rice husk in a controlled condition. Columna (1974) found out that the use of village burnt Rice Husk Ash as a pozzolanic additive to cement is possible.

As far as production is concerned, Rice Husk Ash is similar to Pulverized Fuel Ash (P.F.A.). Pulverized Fuel Ash has been defined as solid material extracted by electrical or mechanical means from the flue gases of boilers fired with pulverized coal (BS 3892: 1965). Regarding composition, primary ingredients of fly ash, silica and alumina, silica is common both in P.F.A. and RHA.

2.5 Role of Rice Husk Ash in Stabilization

A few works have been done in the field of stabilization technique employing Rice Husk Ash (RHA). These are outlined in the following discussion.

Chemical analysis of the RHA indicates the presence of silica as a primary constituent. At low combustion temperature, silica is essentially amorphous but beyond 500°C, it crystallizes in the form of tridymite and cristobalite (Houston, 1972). The other metallic oxides present constitute between 7 and 10 per cent by weight, the dominant metals being potassium, sodium, calcium and magnesium (Tables 2.1, 2.2 and 2.3).

Cook et al (1976) suggested that combination of amorphous silica in RHA with calcium hydroxide, either as slaked lime or as a by-product of hydrating cement results in a cementing agent like pozzolanic cement.

SIRI, Malaysia (1979) mentioned another effect of RHA addition to Portland cement. As found under electron microscope, the fine ash acted as a source of 'reinforcement' in between the cement setting work.

These signify the justification of using RHA as a potential additive or replacement for lime and Portland cement in stabilization.

2.6 Factor Governing Properties of Soil-Cement Mixtures

There are a number of factors e.g. soil type, cement content, degree of compaction,degree of pulverization of soil,mixing methods and environmental condition which have marked influence on the properties of cement admixed soil. A sound understanding of the behavior of the mixture is possible only by an extensive study of the nature and extent of these influences. A brief review of the important factors is presented in subsequent articles.

2.6.1 Soil Characteristics

The characteristics of soil which affect the properties of soil-cement mixtures are inherent nature of the soil, physical and chemical composition, grain size distribution and behavior on moisture addition. Interrelated and diversified effect are exerted by these factors. As a result, no one can be identified as playing the leading role in determining the behavior of soil-cement mixtures.

Hicks (1942) found out that soil of the similar parent materials with similar topography and exposed to similar climatic conditions have comparable influence on the properties of cement-treated soil mixtures.

Norling and Packard (1958) showed the effect of materials retaining on No. 4 sieve on the properties of soil-cement mixtures. They found that addition of such materials to fine aggregates in soil-cement mixtures increases the cement demand of the mix, and also increases the compressive strength. However, if the cement content by weight of the fine aggregates is held constant, the compressive strength is not affected by the proportion of coarse aggregates (larger than No. 4 sieve) provided that proportion is smaller than 50 per cent by weight of the total material (Fig. 2.3).

Handy et al (1955) showed the effect of clay content on soil-cement mixture by experimentation on four Iowa* loess soils of similar shape but with varied silt and clay content. They found that cement demand by the loess soils increased with the increase in clay content.

Diamond and Kinter (1958) determined surface area of soils by the glycerol-retention method. They correlated between the surface area and the cement contents required for soil-cement mixtures. They found that with the increase in surface area cement required by the soils increases as shown in Fig. 2.4.

Catton (1940) showed that the plasticity of a soil influences the properties of cement-treated soils. However,

* a state in the United States of America.

due to overlapping influence of other raw soil properties, well-defined relationships between the plasticity and nature of soil-cement mixes are not always clear. No relationship has yet been established between liquid limit (LL) and plasticity index (PI) and cement content for AASHO A-2 and A-3 grouped soils. But Catton (1940) showed that for soils of the AASHO A-4 group cement requirement increases appreciably with increase in liquid limit. There is further increase in cement requirement for the soils of AASHO A-6 and A-7 groups (Fig. 2.5). Indian Road Congress (1973) does not recommend cement stabilization for clay soils having PI greater than 22.

Redus (1958) illustrated the effect of aging over periods upto several years. He showed that plasticity index reduces for different proportions of cement admixtures in a soil after various periods of curing as shown in Fig. 2.6.

2.6.2 Chemical Properties of Soils

The presence of different substances in soil affect the degree of reaction of soil with the cement. The cat-ions carried by these substances are responsible for this. Soils having pH values ranging from 4 to 14 show satisfactory performance when treated with cement. However, Catton (1940) suggested that pH and organic matter content should be treated as seperate variables, because soils containing more than 5000 parts per million (ppm) organic matter turn out

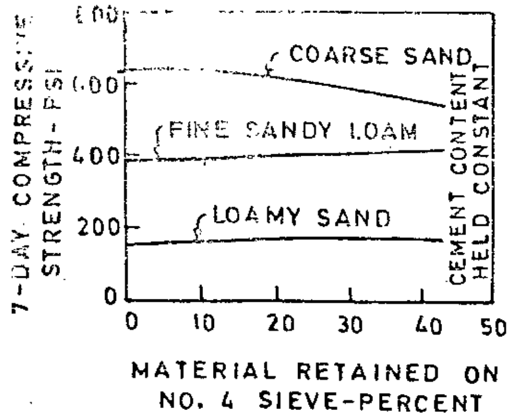


Fig. 2.3 Effect of material retained on no.4 sieve on the compressive strength of soil-cement (after Norling and Packard, 1958).

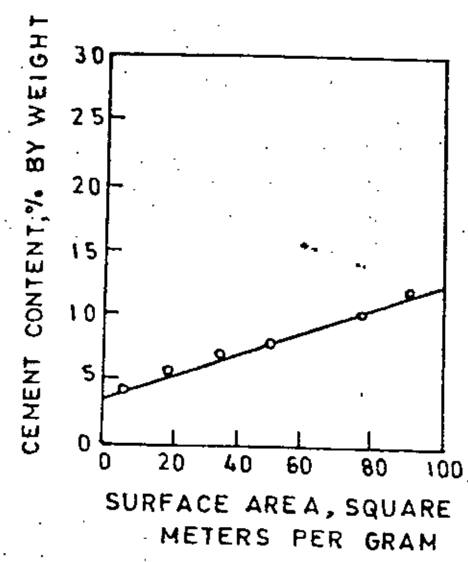


Fig. 2.4 Cement content satisfying freeze-thaw test vs. surface area (after Diamond and Kinter, 1958).

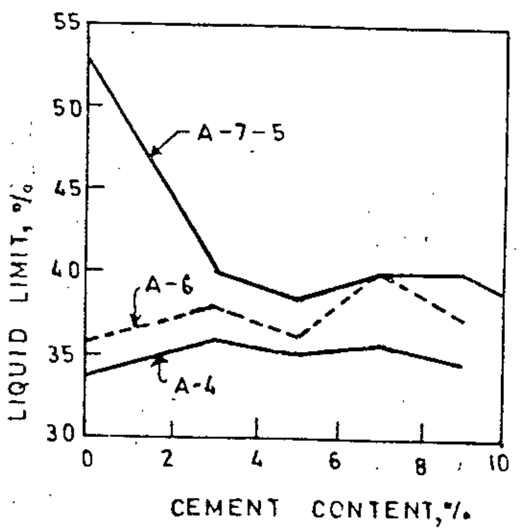


Fig. 2.5 The effect of cement addition on the liquid limit of three different soils (after Catton, 1940).

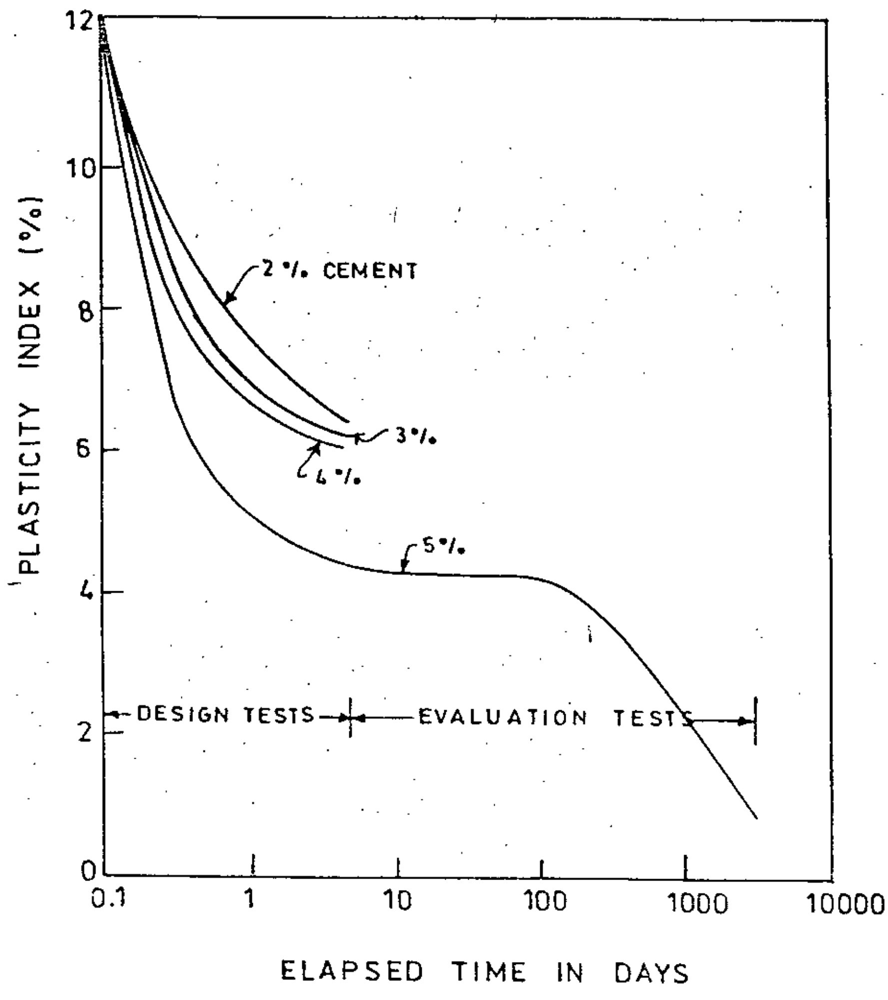


Fig. 2.6 Plasticity index versus time (cement-treated soil mixture from Hot Spring, Ark.) (after Redus, 1958).

to be acidic. Winterkorn et al (1942) found out that the nature of the cat-ion influences the properties of raw soil as well as the properties of soil-cement.

Catton (1940) asserted that the quantity of the organic matter in ppm is not indicative of its potential influence. Clare and Sherwood (1954) basing on their experimental work with several types of organic matter concluded that compounds with high molecular weight donot affect the strength of the soil-cement mix. But, those with lower molecular weight such as nucleic acid and dextrose retard hydration and reduce strength. However, they found that retardation of setting and strength reduction is related, not to the total organic matter content but to some active function of it. This activity depends on the capacity of surface soils to absorb calcium ions.

Ahmed (1984) showed for a silty soil of AASHO group A-4 having organic matter content of about 4% by weight that strength increase of the soil beyond 8% cement content is insignificant.

IRC (1973) does not recommend cement stabilization for road construction for soils having organic matter content greater than 2 per cent.

2.6.3 Soil State

The degree of pulverization defines the soil state during mixing and compaction of cement-treated soils. The degree of pulverization determines the degree of mixing and in effect, the quality of soil-cement mixtures. Felt (1955) showed that during the wet-dry and the freeze-thaw tests, the poorest durability is obtained when the clay lumps in the mixes were dry. Mixes having moist clay lumps showed less soil-cement loss in the wet-dry and the freeze-thaw tests.

Grimmer and Ross (1957) showed the effect of pulverization on compressive strength of the samples cured by immersion in water. They found that decrease in percentage of 3/16 inch size soil aggregates in soil-cement mix increases the unconfined compressive strength. They also found that cement treated silty and clayey soils are of best quality when 100 per cent of the soil is pulverized to pass through No. 4 sieve.

Felt (1955) illustrated the influence of moisture content on compressive strength test on specific soils. He showed the influence of moisture content by taking the optimum moisture content as a base line moisture content and varying moisture content above or below that line. Keeping the compactive effort constant, he showed that density varies with the variation of moisture content. He also showed that the compressive strength for sandy and silty soils increases to a maximum at slightly less than optimum while for clay soil the compressive strength increases at moisture content slightly greater than optimum moisture content. However, generally, the compressive strength values will exhibit a variation similar to the moisture-density curve obtained by Proctor test (Kezdi, 1979).

Felt and Abrams (1957) compared the results of unconfined compressive strengths of dry and moist specimens for a non-plastic sandy soil (AASHO soil group A-1-b) and a sandy clay soil (AASHO group A-6). Using 3 and 10 percent cement content, they showed that for the sandy soil, the dry strength averages 180 per cent of the strength of moist specimens and for the sandy clay, dry compressive strength averages 245 per cent of that of the moist specimens.

It can be stated that in dry cement-treated soils, strength is contributed both by the cohesion of the soil and the cementing action of the cement. In field, due to presence of ground water table nearer to the surface, the cement-treated soils in the form of base courses for highways exist in the moist state. So, if representative strength values are to obtained, strength tests must be made on moist specimens.

Density strongly influences the strength and durability of soil-cement mixtures. For some soils and cement content, relationship between strength and density approaches a straight line. Maclean et al (1952) showed that 5 per cent decrease in relative compaction may reduce strength by 10 to 15 per cent. Wood et al (1960) reported that increase in density reduces the soil-cement loss in the wet-dry test.

2.6.4 Cement Content and Type

If a soil normally reacts with cement, then the cement content will determine the type of cement-treated soil mixture.

Variation of cement content changes the plasticity and volume change characteristics the elastic properties, the durability of the soil-cement mix and other properties to different extent.

Catton (1940) tabulated the cement requirement by AASHO soil groups as shown in Table 2.4.

Table 2.4 Cement Requirement by AASHO Soil Groups (After Catton, 1940)

AASHO soil group	Usual range in cement requirements		Estimated cement content and that used in the moisture density test, % by wt.	Cement content for wet-dry and freeze-thaw tests, % by wt.
	% by-volume	% by weight		
A-1-a	5-7	3-5	5	3-5-7
A-1-b	7-9	5-8	6	4-6-8
A-2	7-10	5-9	7	5-7-9
A-3	8-12	7-11	9	7-9-11
A-4	8-12	7-12	10	8-10-12
A-5	8-12	8-13	10	8-10-12
A-6	10-14	9-15	12	10-12-14
A-7	10-14	10-16	13	10-13-15

Portland Cement Association (PCA) (1956) also gave a table showing average cement requirement for both sandy and fine grained soil. This is shown in Table 2.5.

Table 2.5 Average Cement Requirement (After PCA, 1956)

B and C horizon Sandy Soils

Material retained on No. 4 sive (%)	Material smaller than 0.005 mm (%)	Cement content (% by wt.)					
		Maximum density (pcf)					
		105 to 109	110 to 114	115 to 119	120 to 124	125 to 129	130 to or more
0-14	0-19	10	9	8	7	6	5
	20-39	9	8	7	7	5	5
	40-50	11	10	9	8	6	5
15-29	0-19	10	9	9	8	6	5
	20-39	9	8	7	6	6	5
	40-50	12	10	9	8	7	6
30-45	0-19	10	8	7	6	5	5
	20-39	11	9	8	7	6	5
	40-50	12	11	10	9	8	6

Contd...

Table 2.5 Contd..

B and C Horizon Silty and Clayey Soils.

AASHO group index	Material between 0.05 mm and 0.005 mm (%)	Cement content (% by wt.)						
		Maximum density (pcf)						
		90 to 94	95 to 99	100 to 104	105 to 109	110 to 114	115 to 119	120 or more
0-3	0-19	12	11	10	8	8	7	7
	20-39	12	11	10	9	8	8	7
	40-59	13	12	11	9	9	8	8
	60 or more	-	-	-	-	-	-	-
4-7	0-19	13	12	11	9	8	7	7
	20-39	13	12	11	10	10	9	8
	40-59	14	13	12	10	10	9	9
	60 or more	15	14	12	11	10	9	9
8-11	0-19	14	13	11	10	9	8	8
	20-39	15	14	11	10	9	9	9
	40-59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
12-15	0-19	15	14	13	12	11	9	9
	20-39	16	15	13	12	11	10	10
	40-59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
16-20	0-19	17	16	14	13	12	11	10
	20-39	18	17	15	14	13	11	11
	40-59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

Felt (1955) showed the influence of cement content on compressive strength of three soils - a sandy loam, a silty loam and a silty clay where only cement content was varied. Curing period was from 2 days to 1 year. The result showed that only the sandy loam has satisfactory compressive strength and for increasing cement content and curing period, strength increases. Medium and silty clay showed promising result upto certain cement content and after that no significant changes were observed.

It is to be noted that quantity of cement required for stabilization increases as soil-plasticity increases. For highly plastic soil as much as 15 to 20% cement by weight is required to bring about the hardening of the soil (Yoder, 1975).

The volume change of soil-cement mix also depends on the cement content. Since cement demand by various soils depends on the soil type, a specified maximum volume change on cement addition will define the suitability of the soil for cement stabilization regarding volume change. The Table 2.6 shows physical characteristics of soils suitable for soil-cement road construction purpose. This also includes permissible volume change of different soils.

From the Table 2.6, it is evident that coarse silty sands and silty sands, coarse silts and silts are most suitable for soil-cement road construction. Maximum permissible volume change in every case has been limited to 2%.

Table 2.6 Physical Characteristics of Soils Suitable for Soil-Cement Road Construction Purposes (After Kezdi, 1979)

Type	Soil	Weight,% dia < 0.1 (mm)	Weight,% dia < 0.005 (mm)	Plasticity index,%	Permissible maximum volume change,%	Note
1	Sand, fine sand	0	0	-	2	Excessive cement demand
2	Coarse silty sand	20-70	0	-	2	Favorable
3	Coarse silt	60-90	5-20	7	2	Favorable
4	Silts with coarse fraction and medium silts	90-100	30	7-15	2	Intensive pulvertization required
5	Lean clay	100	35	15-20	2	Sensitive to frost

Felt (1955) made experiments on three different types of soils to find out the effect of cement type on cement-treated soil mixtures. He compared the results of compaction test, compressive strength tests and the wet-dry and the freeze-thaw tests made on soils treated by normal Portland cement (Type-I) and air-entraining Portland cement (Type-IA). It was found that moisture-density relationships, compressive strengths and the soil-cement losses in the wet-dry and the freeze-thaw tests were almost the same. This indicates that these two types of cement can be used interchangeably in soil-cement construction.

It was further observed on experimentation with Type-III cement that the optimum moisture contents and maximum densities obtained are approximately the same for Type-I and Type-III cements.

Felt (1955) also found that, influence of Type-III cement on strength of different soils varies. For loamy sand, the 7 and 28-day strength for Type-III cement were about 2 and 1.4 times those for Type-I cement respectively. For a silty-clay loam, the strength for Type-III was only slightly higher than that for Type-I cement.

2.6.5 Mixing and Compaction

To ensure best results by cement stabilization, efficient mixing and compaction are essential pre-requisites.

These together with the equipment used and the time lag between mixing and compaction influence both the strength and durability characteristics of soil-cement mixtures. The degree of mixing using a particular equipment and following a specific procedure depends on the soil type as well as on its degree of pulverization and its moisture content.

In addition to the soil type and water content, the efficiency of mixing depends on the mixing time. An increased wet mixing time usually increases the optimum moisture content, reduces the compression strength and increases the weight losses during the wet-dry and freeze-thaw tests.

Studies on cement hardening and certain in-situ experiences gave rise to the idea that the compression strength of the soil-cement mix could be increased by waiting between wet mixing and compaction. In such cases, consolidation can even start during this rest period, while in the course of compaction cement cover under development would be torn off and prepared for further hydration. This results in an increased strength. Hungarian experience supported this assumption. But Marshall (1954) claimed that this waiting period would lead to strength reduction in case of several soils. Felt (1955) also showed that the compressive strength of cement-treated soil mixtures is reduced with the increasing period of mixing.

In Britain, the current specifications require that compaction be completed within 2 hours of mixing being initiated, Maclean and Lewis (1963).

2.6.t Curing Conditions

The environmental conditions under which curing takes place have a considerable effect on the extent to which a soil may be stabilized with cement. The strength of soil-cement increases with age. Soil-cement must be moist cured during the initial stages of its life so that moisture sufficient to meet the hydration needs of the cement can be maintained in the mixture. Curing in the laboratory moist room meets the requirements of humidity and temperature. But in field the fresh surface must be covered by a loose material such as straw, foliage, reed, earth etc. Another way is to cover the surface with a waterproof protective coating, usually bituminous, which then keeps the water in the pavement.

Temperature strongly influences the strength of cement-treated soil mixtures. Clare and Pollard (1953) showed that when the test-temperature is around 25^{o}C (or 77^{o}F), the 7-day compressive strength increases with the increase in temperature by 2 to $2\frac{1}{2}$ per cent per degree. They also found that taking the compressive strength as the sole-criterion of quality of cement-treated soil mixture, less cement is needed in warm weather than in cold weather.

Leadbrand (1956) showed the relationship of the compressive strength with time by testing two soils for a period of 5 years. He showed that soil-cement continues to increase in strength with age in a manner similar to concrete.

2.6.7 Additives

In order to improve the strength and other properties of soil-cement, small quantities of various chemicals have always been used. Very favorable effects were observed upon the addition of certain compounds of alkali metals (sodium , potassium, lithium), but experimentation also involved other substances. With many of them, it is a distinct advantage that the desired effect can be secured even by the addition of very small specific quantities. Lambe et al (1960) conducted detailed examinations with alkali metals and found that the addition of 1 to 4 per cent by weight of hydroxides and various salts would greatly increase the compressive strength. The efficiency of the additives depends on the amount of reactive silica in the soil. However the efficiency of the sodium compounds depends upon the soil type involved : the higher the plasticity index or the organic matter content, the lower the efficiency. The best results are obtained by the simultaneous addition of the compound and the cement to the soil. Compound addition increased the strength particularly at the beginning of hardening period. Other cement-soil additives include calcium chloride, bitumen and bitumen emulsions.

The addition of bitumen emulsion was experimented with in U.K. (Road Research Laboratory, 1952). The emulsion formulated specially for this purpose remained stable for a short while when admixed to a fine grain soil type, all owing the bitumen to be evenly distributed in the soil. According to the results collected about 5 to 7.5 percent emulsion and 3 to 5 per cent cement had to be added to achieve a favorable effect. The 'end product' was something between the cement and bitumen soils; slightly rigid and rather water impermeable.

Hungarian experience revealed a favorable effect upon liquid bitumen addition upto a maximum 6 per cent resulting in increased compressive strength. This confirms that cement hardening was not prevented by the bitumen addition (Kezdi, 1979).

The strength-increasing effect of the various additives is also quite significant from economic aspects, since the same specified strength can be achieved when using such additives with a much lower cement consumption. Numerical data of the economics are presented in the Table 2.7.

2.7 Properties of Stabilized Soil Mixtures

The properties of soil-cement mixtures vary with several factors as mentioned in the above articles. Again, when Rice Husk Ash is used as an additional admixture the

Table 2.7 Data on the Cost Reducing Effect of Strength-Increasing Additives (After Kezdi, 1979).

Soil	Cement (wt. %)	Additive	Additive quantity (wt. %)	Relative cement-additive cost	Savings ((%)
Silt	11.0	-	-	1.00	-
	7.5	NaOH	0.9	0.98	2
	6.5	Na_2CO_3	1.0	0.81	19
	5.0	Na_2SO_4	0.8	0.54	46
Silty sand	13.0	-	-	1.0	-
	7.0	Na_2SiO_3	1.0	0.96	4
	10.5	$CaCl_2$	0.6	0.89	11
	9.0	NaOH	0.5	0.86	14
	9.5	Na_2SO_4	0.5	0.81	19
Silty clay	18.5	-	-	1.0	-
	13.0	NaOH	1.0	0.81	19

situation becomes more complex since a few literature is available to account for probable action of RHA. Again ash has the variability in its own properties. Considering all these factors together, it is not possible to list specific values representative of the several properties. However, in the laboratory, it is possible to control the test conditions in accordance with the standard methods. Accordingly, the strength characteristics, durability, volume and moisture change characteristics, plasticity and moisture-density relationships of the treated soil will be discussed in a limited range in the following articles.

2.7.1 Compressive Strength

Evaluation of stabilized soil with admixture like cement is widely made with the help of compressive strength of stabilized mix. It serves as an indicator of the degree of reaction of the soil-cement-water mixture as well as an indicator of 'setting time' and 'rate of hardening'. For normally reacting granular soils, it serves as a criterion for determining cement requirements for the construction of soil-cement. In Britain, usual practice is to specify the desired stabilities of most soil-cement mix in terms of minimum unconfined compressive strengths. The most recent specification for soil-cement require a minimum 7-day value of 400 psi for moist-cured cylindrical specimens having a height/diameter ratio of 2:1 and 500 psi for cubical specimens (Ministry of Transport, 1969). Portland cement Association (1956) established the range of compressive strength of cement treated soils under three broad textural soils groups - sandy and gravelly soils, silty soils and clayey soils as shown in Table 2.8. The cement contents of the soil-cement mixtures for which strength values are given are those which will satisfy the accepted stability criteria for soil-cement.

Table 2.8 Range of Compressive Strength of Soil-Cement (PCA, 1956)

Soil type	Compressive strength, psi	
	7 days	28 days
Sandy and Gravelly soils: AASHO group A-1, A-2, A-3 Unified group GW, GC, GP, GM, SW, SC, SP, SM.	300-600	400-1000
Silty soils: AASHO group A-4, A-5 Unified group ML and CL	250-500	300-900
Clayey soils: AASHO group A-6, A-7 Unified groups MH, CH.	200-400	250-600

PCA (1959) requires that the stabilized material should be evaluated using the compressive strength criteria given in Figs. 2.7 and 2.8.

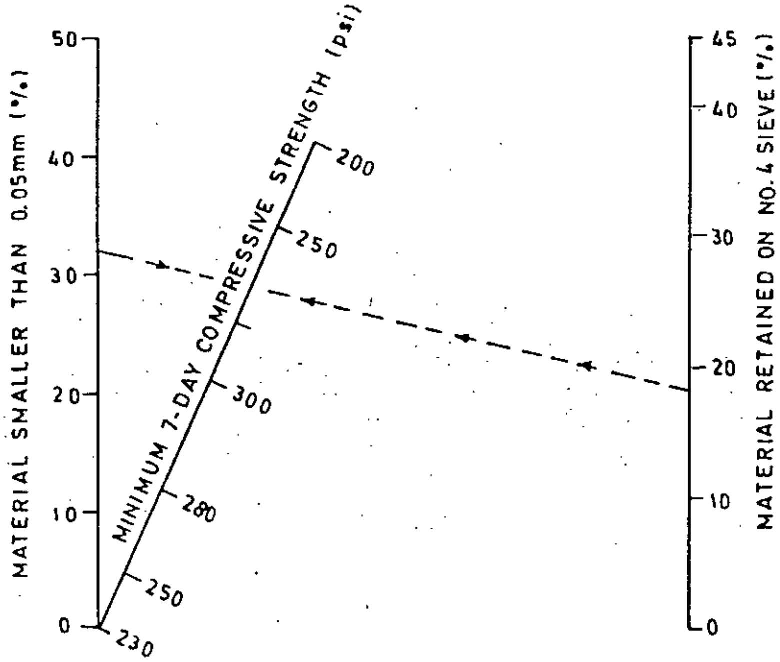


Fig. 2.7 Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No. 4 sieve (after PCA, 1959).

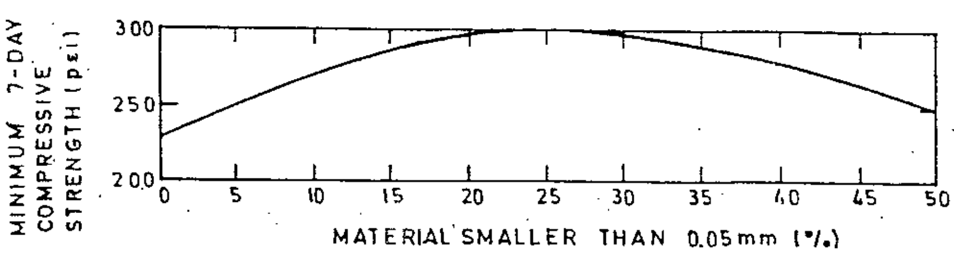


Fig. 2.8 Minimum 7-day compressive strength required for soil-cement mixtures not containing material on the No. 4 sieve (after PCA, 1959).

Balmer (1958) and Christensen (1969) found that addition of cement increases both the angle of friction and the cohesion. At lower cement contents, the strength increase is mainly due to increase of angle of internal friction whereas the same at higher cement content is due to increase in cohesion. However, the rate of increase in cohesion and angle of internal friction depends on soil type and curing period.

Rajan et al (1982) found that Rice Husk Ash, to a certain extent contributes to the development of strength when used as a secondary additive along with lime and cement. They also indicated that RHA may be acting as pozzolana for the improvement of strength behavior of a highly organic soil, black cotton soil in India.

2.7.2 Durability

Durability of soil-cement mixture is its resistance to repeated drying and wetting or freezing and thawing.

In the United States, the desired cement content is normally selected to meet durability. Portland Cement Association (1956) gave a table for maximum soil-cement loss in the wet-dry or freeze-thaw test as shown in Table 2.9.

Kemahlioglu et al (1967) concluded that a minimum compressive strength requirement would not necessarily

Table 2.9 Soil-Cement Loss Criteria (After PCA, 1956)

AASHO soil groups:	Freeze-thaw and wet-dry losses (%)
A-1-a, A-1-b, A-3, A-2-4 and A-2-5	14
A-2-6, A-2-7, A-4 and A-5	10
A-6, A-7-5 and A-7-6	7

result in the most economical cement requirement due to the fact that different soil-cement mixtures exhibit different strengths at similar degree of durability. Another interesting conclusion by them was the minimum compressive strength required for various AASHO soil groups to meet PCA criteria when applied through wet-dry test (i.e satisfying maximum soil-cement loss criteria of PCA) is not a constant but probably varies as a function of other parameters (i.e physical, chemical properties etc.).

No information is available for effect of RHA addition on durability of soil-cement mix. However, Ghosh et al (1975) reported better performance of lime-fly ash stabilized alluvial soil with 40 percent sand content in wet-dry test. They found that a higher curing temperature than room temperature is especially helpful for the fly ash-lime stabilized alluvial soil to perform better.

2.7.3 Volu e and Moisture Change

The volume and moisture change of soil-cement mixtures are of particular importance with respect to pavement cracking. Crack formation is a natural characteristics of soil-cement mixes whose tendency to crack is related to strength, although this relation is not yet fully understood.

Apart from fractures due to loading, cracks are caused by volume changes which may be due to three effects : water content, temperature changes and freezing. If a cohesive soil is treated with cement, then the shrinkage due to water-content variation of the soil-cement thus obtained will certainly be less than that of the original soil. Shrinkage decreases with increased cement content, owing to the development of a soil-cement matrix (Willis, 1947 and Jones, 1958). With the increase in cement content, the soil-cement matrix assumes more stable configuration resulting in decreased shrinkage. If on the other hand, cement is added to a soil which is not liable to volume change by itself, the volume change of the product will be greater. This happens because of the shrinkage during the cement hydration (Kezdi, 1979).

The volume change of soil cement is determined by the usual wetting-drying test method through direct volume measurement or by linear measurement of height. Cement addition has been seen to reduce the specific volume variation up to 33 or even 50 percent. Fig. 2.9 illustrates the reduction of linear shrinkage in three different cohesive soil.

Another reason for the volume change of cement soils is temperature variation. According to measurements performed in India, the thermal expansion coefficient depends on the cement content and density (Kezdi, 1979).

If the water change in soil-cement mix is excessive, a pumping action results in the pavement. The water movement breaks down the intergranular cement bonds and the strength rapidly decreases.

2.7.4 Plasticity

If a plastic soil is treated with cement, its plasticity index decreases. This effect is reflected by the different types of failure encountered in such cases. The plastic limit and liquid limit are determined by Atterberg limit test on hardened soil-cement mixture. The test method usually consists of mixing the soil-cement, compacting it in the standard method, then storing the specimen for 7 days, drying and performing the Atterberg limit test with the pulverized stabilized soil.

Felt (1955) showed that plasticity index of the granular soil decreases when treated with cement (Fig. 2.10). He conducted experiments on a typical soil having the following grading:

		Percent
Gravel	(retained on No. 4 sieve)	15
Coarse sand	(No. 4 to 0.25 mm)	43
Fine sand	(0.25 mm to 0.05 mm)	8
Silt	(0.05 mm to 0.005 mm)	16
Clay	(less than 0.005 mm)	18

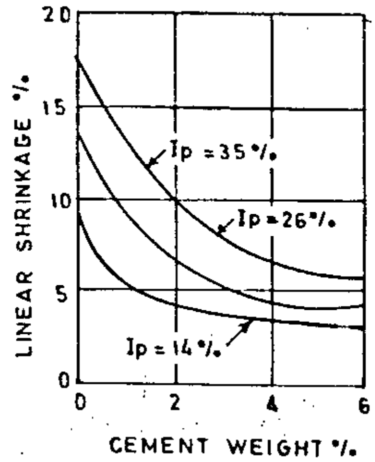


Fig. 2.9 Reduction of linear shrinkage upon the effect of cement addition (after Kezdi, 1979).

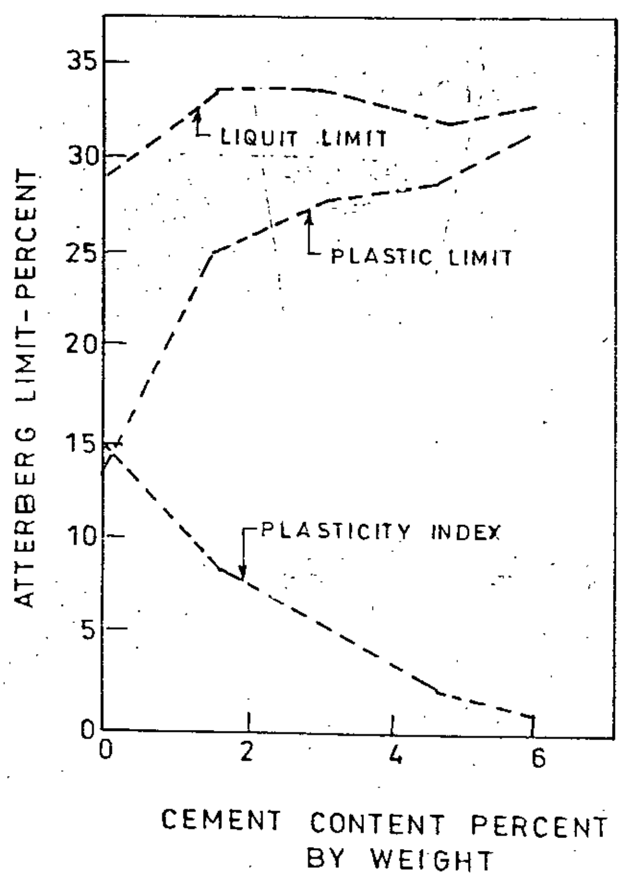


Fig. 2.10 Cement-plasticity relationships for a plastic gravelly sand (after Felt, 1955).

Atterberg limits determined after hydration period of 2 days. Maximum cement content for soil cement was 6 per cent by weight.

Generally, cement changes the plasticity of soils by increasing the plastic limit. As a result the range within which the soil is plastic is reduced. Willis (1947) showed that the cement admixture reduces slightly the liquid limit of mixtures made from soils having liquid limit greater than 40. He also showed that liquid limit increases for soils having liquid limits less than 40 when treated with cement.

No published information is yet available about the probable effect of RHA on plasticity characteristics of soil. However, information is available for fly ash. Ghosh et al (1975) reported that alluvial soil when treated by lime and fly-ash shows slight increase in plasticity.

2.7.5 Moisture-Density Relation

The optimum moisture content and maximum dry densities (found from standard proctor or standard AASHTO method T99) influence the compaction characteristics of cement-treated soils. Generally, for cement-treated soils, these two data can be said to vary only slightly from those obtained from untreated basic soils. However, there is exception of this behavior.

With the addition of cement, maximum dry density of sand increases. No change is observed for light to medium clays whereas it increases slightly for fat clays. For silts, density decreases on treatment with cement. Small changes can also be observed in the optimum moisture content. This can be best illustrated by Fig. 2.11.

Another consequence of cement addition to the soil is much more sensitivity to water effects, i.e. the two branches of the proctor curve run much closer to each other than in case of untreated soils and therefore, certain specified dry densities are attainable over a much narrower moisture content ranges.

2.8 Summary of the Literature Review

From the above literature review the important points may be summarized below:

i) Cement can be used successfully for stabilizing sands and silty soils whereas for increasing clay content in the soil excessive cement is warranted. Since Rice Husk Ash possesses the properties of a reactive pozzolanic material, it can be used as an additive to cement in soil-cement stabilization.

ii) Durability of soil cement mix is influenced by the soil state and the density. Different soil-cement mixtures at the similar degree of durability may exhibit different strength.

iii) For a specific compactive energy, and for sand, compressive strength increases with increasing

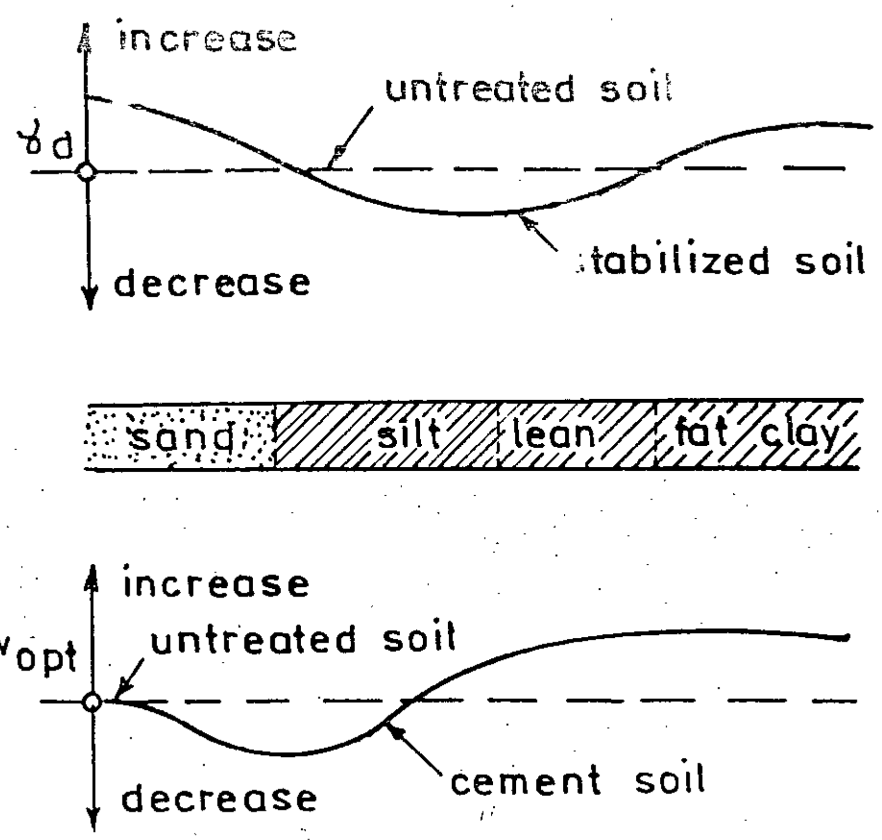


Fig. 2.11 The effect of cement-addition on the compaction characteristics of soils (after Kezdi, 1979).

cement content. For medium clay and silty clays result is promising upto certain cement content. The compressive strength decreases with increasing percentage of fines. The compressive strength is strongly influenced by density. Compressive strength of soil-cement mix can be increased by additives like compounds of alkali metals in small amount.

iv) Volume change of soil-cement mix depends on the soil type and cement content. Cement-treated clayey soil shows reduced shrinkage. But in the case of non-cohesive soil which has little or no shrinkage in untreated condition, the addition of cement results in an increase in shrinkage due to development of cohesion.

v) In cement-treated soil mixtures, the plasticity index reduces with increase in cement content. Cement increment increases the plastic limit thus reducing the range within which it is plastic.

vi) When compactive effort is held constant, density varies with the variation of moisture. Compressive strength increases to a maximum at slightly less than optimum moisture content for sandy and silty soil and greater than optimum for the clay soil.

vii) Degree of pulverization, organic matter content in soil and curing conditions also influence the strength and durability of soil-cement mix.

CHAPTER 3

THE RESEARCH SCHEME

3.1 Introduction

For efficient and economic application of stabilization technique it is essential to understand the basic mechanism of the process. The broad objective of this research is to experimentally review various aspects of soil-cement stabilization with Rice Husk Ash as an additional admixture and/or partial replacement of cement applied to some typical alluvial soils of this country.

3.2 Objective of the Research

Though soil-cement stabilization is widely used practice around the world, little published information is available about soils of Bangladesh. Rice Husk Ash (RHA) has been in use and experimented in neighboring countries of Bangladesh in stabilization of soils with lime and in masonry work in addition to cement or as an independent cementitious material but it is not familiar with the researchers of Bangladesh. This research work has been undertaken to achieve the following objectives:

i) To evaluate the potentiality of using reactive RHA with cement to stabilize alluvial soils in Bangladesh.

ii) To investigate the effect of cement and RHA admixtures on the durability of the stabilized mix.

iii) To investigate the effect of RHA addition on compressive strength of cement stabilized soil.

iv) To investigate the volume change characteristics of the stabilized soil on addition of cement and RHA.

v) To evaluate the effect of addition of RHA on the plasticity characteristics of cement stabilized soil.

vi) To investigate strength and plasticity characteristics of RHA stabilized soil.

3.3 The Test Program:

The whole research was divided into the following phases:

i) In the first phase, index properties of the soil samples were determined in order to classify them. The pH and organic matter content of the soils were also determined. From these tests the suitability of the soils for cement stabilization were ascertained following recommendation of Indian Road Congress.

ii) In the second phase, first the moisture-density relationships of the soils were established. Then durability, strength and plasticity characteristics of cement stabilized soil were evaluated by wetting-drying test, unconfined compressive strength test and Atterberg limit test respectively.

iii) In the third phase, Rice Husk Ash was produced in the laboratory from Rice Husk.

iv) In the final phase, the soils were stabilized by cement and RHA. The admixture content was.that satisfying the soil-cement loss criteria given by Portland Cement Association. Cement was replaced by ash in three definite proportion while keeping the total admixture content constant. The durability, strength and plasticity characteristics of cement-RHA stabilized soil were evaluated. Also attempt was made to stabilize soils by only RHA.

The experimental program followed is illustrated by flow chart shown in Fig. 3.1.

3.4 Methodology of Test Program

The soil samples were selected for research after concluding index properties test and the pH and organic matter content determination following the Indian Road Congress recommendation for soil-cement stabilization. They were subjected to compaction test to find optimum moisture content and maximum dry density. The samples were then tested for unconfined compression at maximum dry density. Next, the soils were stabilized with cement using cement contents of 2,4,6,8, and 10 percent by weight of air dried soil and subjected to wetting and drying test. The minimum cement content required to satisfy the soil-cement loss criteria

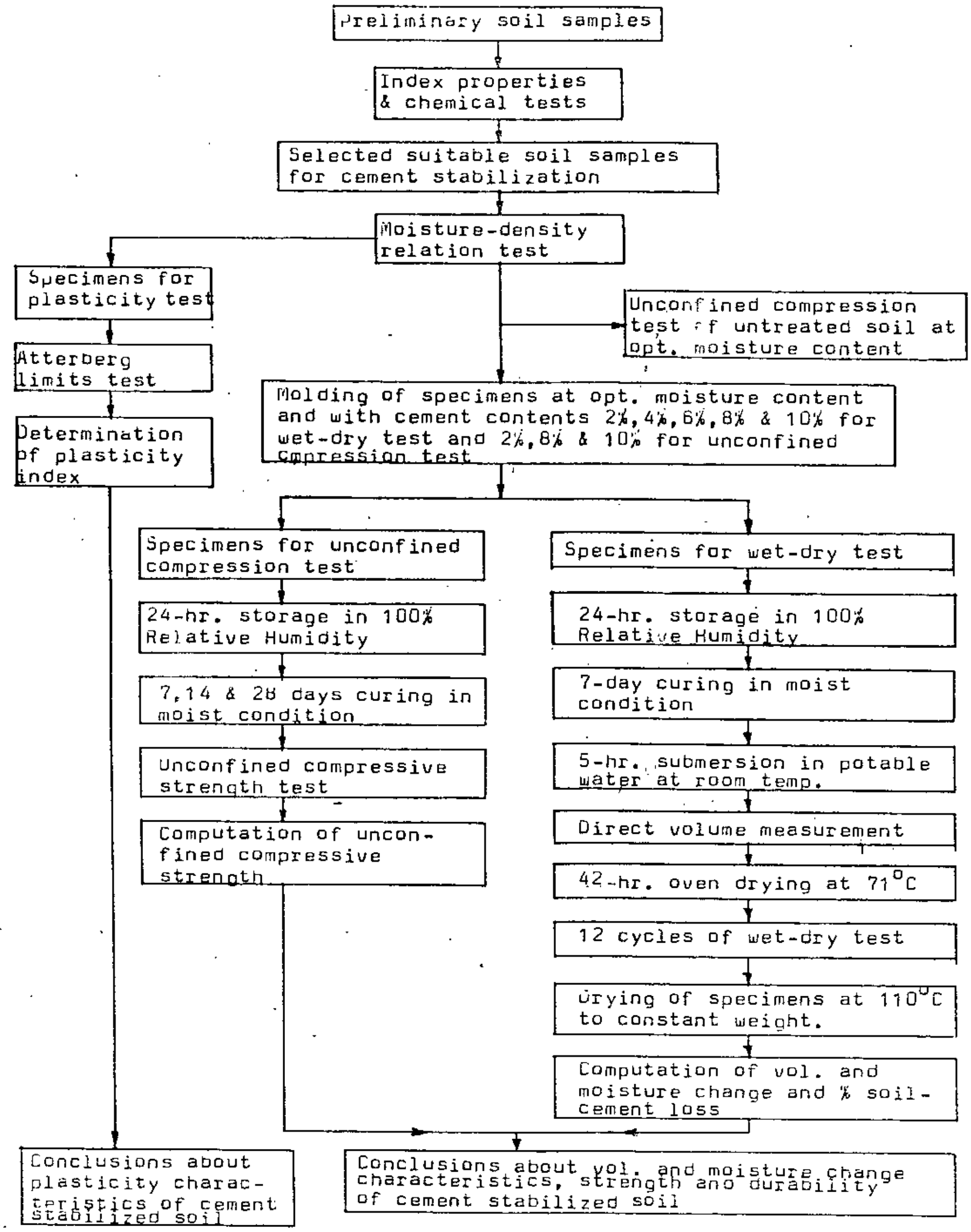
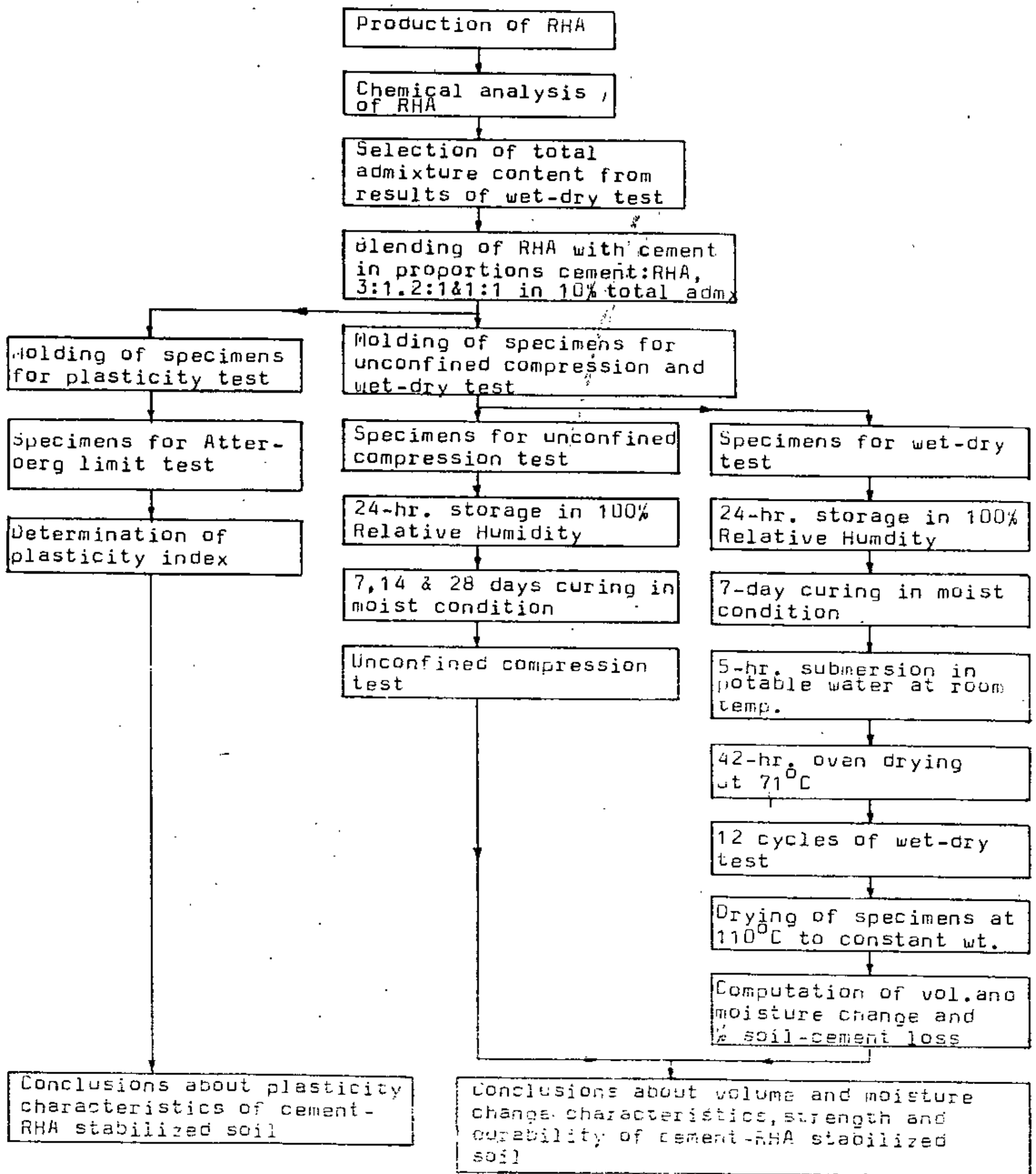


Fig. 3.1 Flow chart for experimental program (Contd...)

Fig. 3.1 (Contd..)


Production of RHA
Chemical analysis of RHA
Selection of total admixture content from results of wet-dry test
Blending of RHA with cement in proportions cement:RHA, 3:1.2:1&1:1 in 10% total admx
Molding of specimens for plasticity test
Molding of specimens for unconfined compression and wet-dry test
Specimens for Atterberg limit test
Specimens for unconfined compression test
Specimens for wet-dry test
Determination of plasticity index
24-hr. storage in 100% Relative Humidity
24-hr. storage in 100% Relative Humdity
7,14 & 28 days curing in moist condition
7-day curing in moist condition
Unconfined compression test
5-hr. submersion in potable water at room temp.
42-hr. oven drying at 71^{o}C
12 cycles of wet-dry test
Drying of specimens at 110^{o}C to constant wt.
Computation of vol.and moisture change and % soil-cement loss
Conclusions about plasticity characteristics of cement-RHA stabilized soil
Conclusions about volume and moisture change characteristics, strength and durability of cement-RHA stabilized soil

given by Portland Cement Association was found out to be 10% by weight of air - dried soil for both the soils. The stabilized samples with cement contents of 2,8 and 10 per cent by weight of air dried soil were tested for unconfined compressive strength. Rice Husk Ash (RHA) was produced in the laboratory from Rice Husk and analyzed chemically to determine its constituents. The soils were latter stabilized with admixtures of Portland Cement and RHA at optimum moisture content, keeping the total amount of admixture equal to the cement content found in wet-dry test. Cement was replaced in the total admixture content of 10% by wt. by RHA in the proportions of cement to RHA, 3 to 1, 2 to 1 and 1 to 1 by weight while keeping the total amount of admixture equal to 10% by weight of air dried soil. This cement-RHA stabilized samples were tested to evaluate plasticity characteristics, durability and unconfined compressive strength by Atterberg limits test, wetting and drying test and test for unconfined compression respectively. A total 102 number samples were prepared for unconfined compression test, 14 nos. for plasticity test and 32 nos. for durability test.

3.5 Soils Used

In this research, soil samples were collected basing on study of geology and soil formation of Bangladesh. As outlined in Chapter 1, soils from Jamuna land system were collected for this research.

Four soils with varying index properties were preliminarily selected for this research. Two of them were discarded after index properties test and the pH and organic matter content determination. They were found unsuitable for cement stabilization according to recommendation of Indian Road Congress (1973).

The rest two were selected for research following recommendation of Indian Road Congress. Out of the selected two, one was collected from Nayarhat in Dhaka District and another from Kaliakoir in Gazipur District. These two samples were collected from the borrow pits of two local unpaved roads connecting main highways with the interior growth centers. The soils were designated as follows:

Soil-A Collected from Nayarhat, Dhaka.

Soil-B Collected from Kaliakoir, Gazipur.

The properties of untreated soils are presented in Table 3.1 and grain size distribution curves are shown in Fig. 3.2.

Table 3.1 Properties of Untreated Soils

Soil property	Soil-A	Soil-B
Textural composition (MIT classification):		
Sand, % (2 mm - .06 mm)	14	6.5
Silt, % (.06 mm - .002 mm)	86	89.5
Clay, % (< .002 mm)	0	4.0
Percent passing # 200 sieve	95	98.0
Materials smaller than 0.05 mm, (%)	81	84.0
Atterberg limits and indices:		
i) Liquid limit, %	-	33.0
ii) Plastic limit, %	-	27.5
iii) Plasticity index, %	-	5.5
Natural moisture content, %	26	23.0
Specific gravity	2.63	2.68
Engineering properties:		
Optimum moisture content, % (Standard Proctor or AASHTO)	15	18
Maximum dry density, pcf	98.5	104.6
Unconfined compressive strength, psi	9.67	11.23
Chemical properties:		
pH	7.2	6.6
Organic matter content, %	0.71	0.62
Classifications:		
AASHTO/AASHO	A-4	A-4(0)
Unified/ASTM	ML	ML
General rating as subgrade:		
AASHTO/AASHO	Fair to poor	Fair to poor
Unified/ASTM	Not suitable	Not suitable

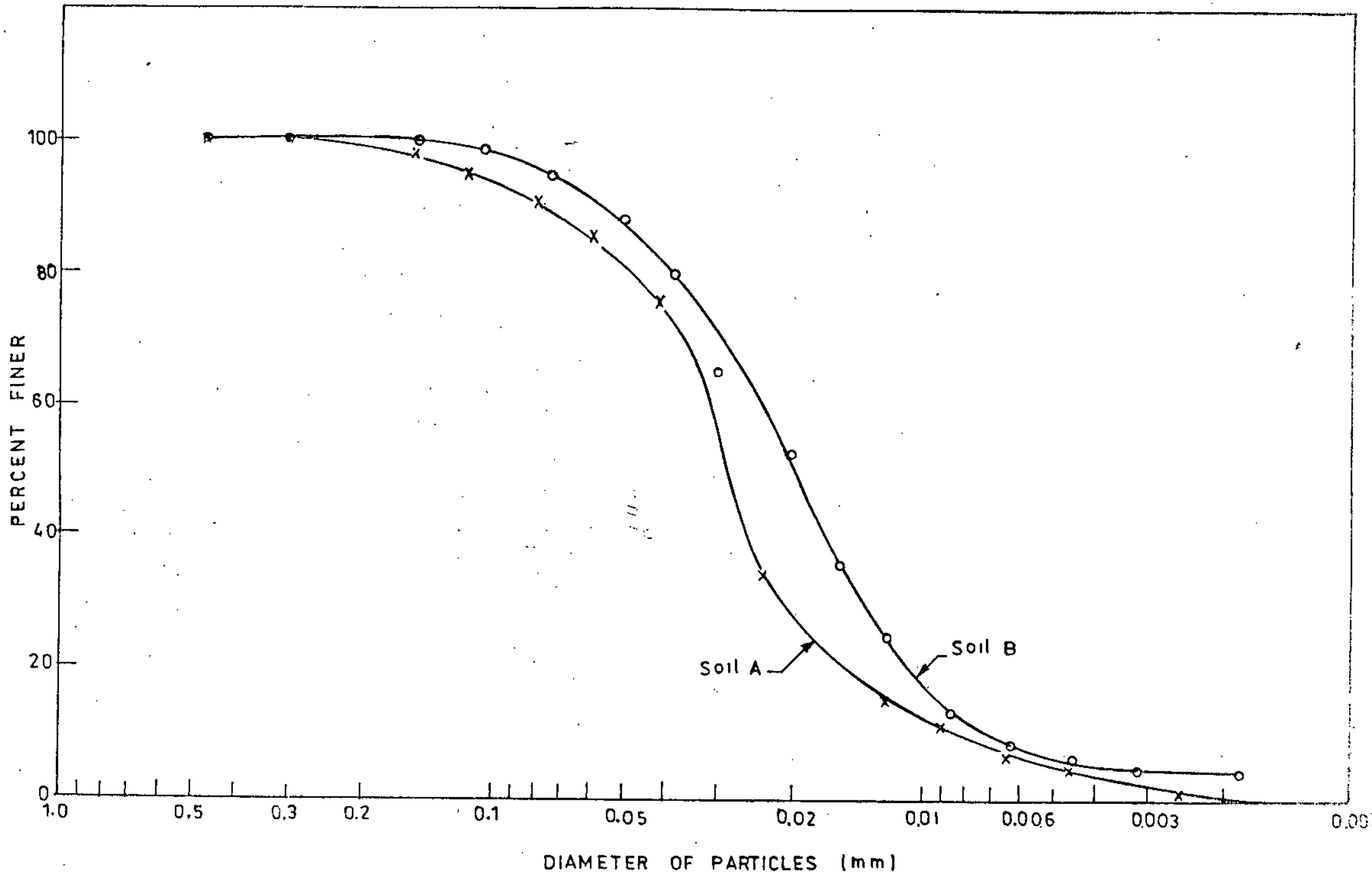


Fig. 3.2 Grain size distribution curves of the soils tested.

CHAPTER 4

LABORATORY INVESTIGATION

4.1 Introduction

The investigations in the laboratory were conducted in accordance with the program outlined in Art. 3.3. The details of the experimental procedure are discussed in this chapter.

4.2 Test Procedures for Classifying Soil and for Determination of Suitability for Cement-Stabilization

These tests were done to ascertain the classification of soils and to determine the pH value and amount of organic matter present in them. The results of these tests are combined to find out the suitability of the soils for cement stabilization following recommendation of IRC (1973).

The details of the tests are outlined in brief as follows:

4.2.1 Test for Index Properties

Test for Index Properties of the soils were determined according to procedures specified by the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing Materials (ASTM). The following table shows the standard methods followed:

Property of soil	AASHTO standard followed
Liquid limit	T89
Plastic limit and plasticity index	T90
Grain size distribution	T88
Amount of materials finer than no. 200 sieve	T11

In addition, ASTM D2216-71 and AASHTO T100 were followed for determination of natural moisture contents and specific gravities of the soils respectively.

The soils were then classified according to AASHTO M145-49 and ASTM D2487-69 (1975) standards. The test results along with their classification and grain size distribution are presented in Table 3.1. The grain size distribution curves have been shown in Fig. 3.2.

4.2.2 Test for Chemical Properties

The following chemical properties were evaluated:

i) pH value

ii) Organic matter content.

The pH value of the soils were determined by pH indicator paper by inserting a strip of indicator paper into the wet soil for one minute. The wet reverse side of the paper was then compared with the colour scale.

For determination of organic matter contents in the soils, Hydrogen Peroxide was used. Oxidized soil samples on addition of Hydrogen Peroxide solution was washed and the percentage loss of the sample after filtration was reported as organic matter content. The organic matter content of each soil was less than 1 per cent.

4.3 Moisture-Density Relation

Moisture-density relationships for the soils were determined according to AASHTO Method T99. For compaction of the soils, a cylindrical mold of 4 inch diameter and 4.6 inch height was used. The weight of the hammer was 5.5 lbs and the height of the drop was 12 inches. The mold was filled with soil in three approximately equal layers. Each layer was compacted by 25 blows of the hammer. Air-dried samples passing through No. 4 sieve were used for compaction. For cement-treated soils AASHO method T134-61 was followed.

The results are shown in Fig. 4.1. From the moisture-density curves of Fig. 4.1, optimum moisture contents and corresponding maximum dry densities for the soils were determined.

4.4 Properties of Cement Used for Stabilization

For this research, Ordinary Portland Cement Type-I was selected. ASTM Standards 1979(b), C187-79, C191-77, C190-77 and C109-77 were followed for determination of normal consistency, time of setting, tensile strength and compressive strength of the cement respectively.

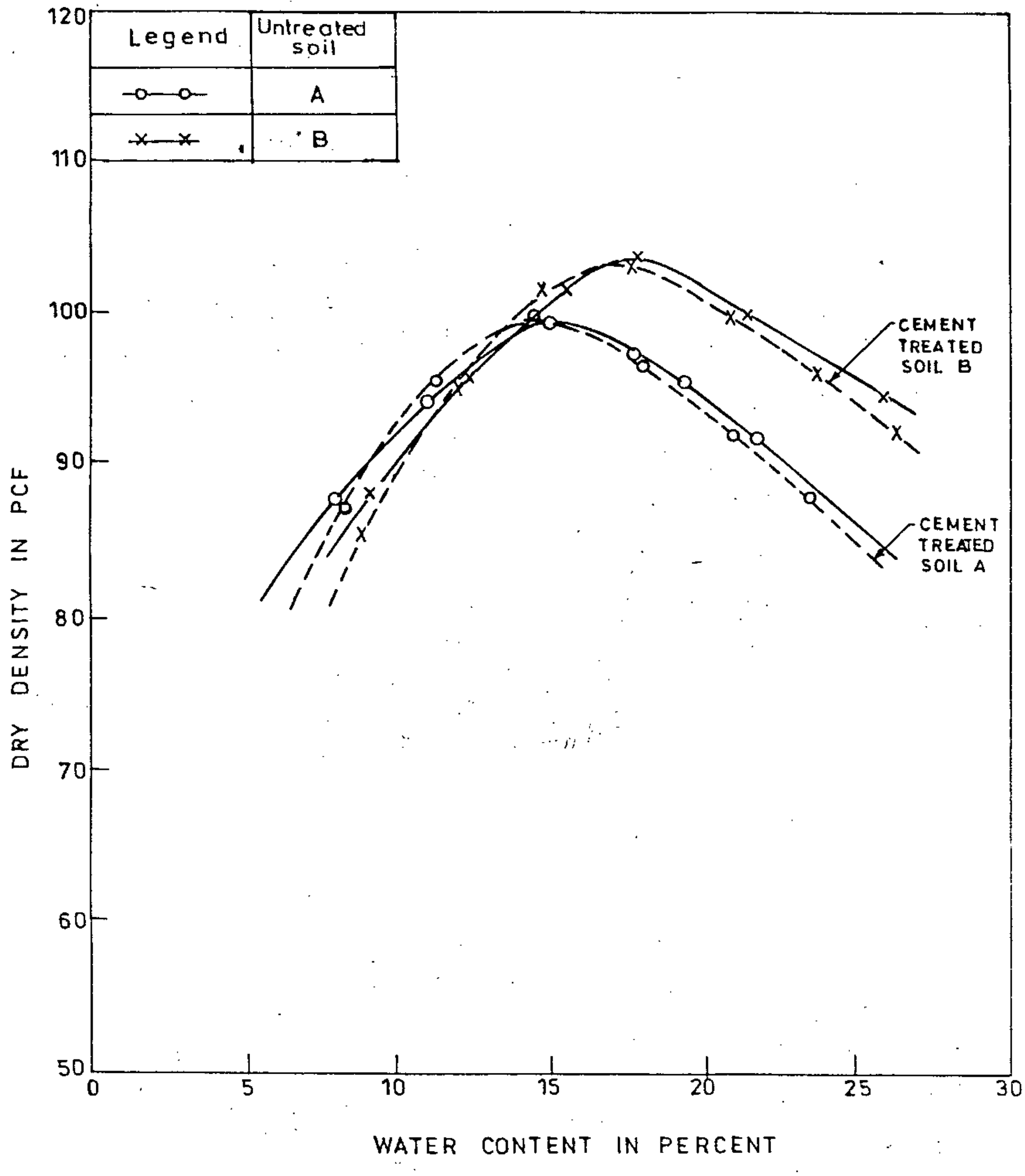


Fig. 4.1 Moisture-density relationships of the soils tested.

The results are presented below:

i) Normal consistency is 26%.

ii) Initial setting time is 2 hours 15 minutes.

iii) Final setting time is 3 hours 10 minutes.

iv) Tensile strength of standard briquettes are 250, 340 and 400 psi for 7, 14 and 28 days respectively.

v) Compressive strength of 2-inch, standard cube specimens are 2590, 4525 and 5255 psi for 7, 14 and 28 days respectively.

4.5 Production of Rice Husk Ash

Rice Husk, a by-product during production of rice from paddy, was procured from rice mill. The dry husk was taken in a cylinder made from steel plates with one end closed. The diameter of the cylinder was 1 ft and height 2 ft. In each batch, around 20 lbs husk was taken. The cylinder with husk filled in was placed in a gas-fired 'pit' furnace lined by refractory bricks with air blowing arrangements. There, the husk was burnt for 2 hours at 750^{0}-$800^{0}C$. The temperature within the furnace was measured by a thermo-couple arrangement. Temperature within the furnace was regulated by regulating both the gas burner and the air blower.

With this burning the husk was converted to ash with high carbon content. This was ascertained by visual identification of black ash. This ash was then transferred to a saucer-shaped container to provide a larger surface area of ash exposed to air and burnt in open-air by a controlled gas-burner. The temperature was time to time checked by thermo-couple arrangement. This operation was continued for 3 hours keeping temperature within the ash at $500^{o}C$-$525^{o}C$. It was noted that rice husk was a self-burning material. Burning was discontinued on visual identification of ash. i.e. when the black ash was converted to white ash.

It was then cooled and ground in ball-mill for half an hour. The ground ash from ball-mill was passed through No. 200 sieve. About 4 lbs of ash passing No. 200 sieve was produced.

The same process was continued for another batch.

The ash passing No. 200 sieve was chemically analyzed. The silica content of the ash was found to be quite high and it was mixed with ordinary Portland cement in threee definite proportions to produce RHA-Portland cement blended admixture for stabilization.

The whole process is shown in a flow-diagram in Fig. 4.2.

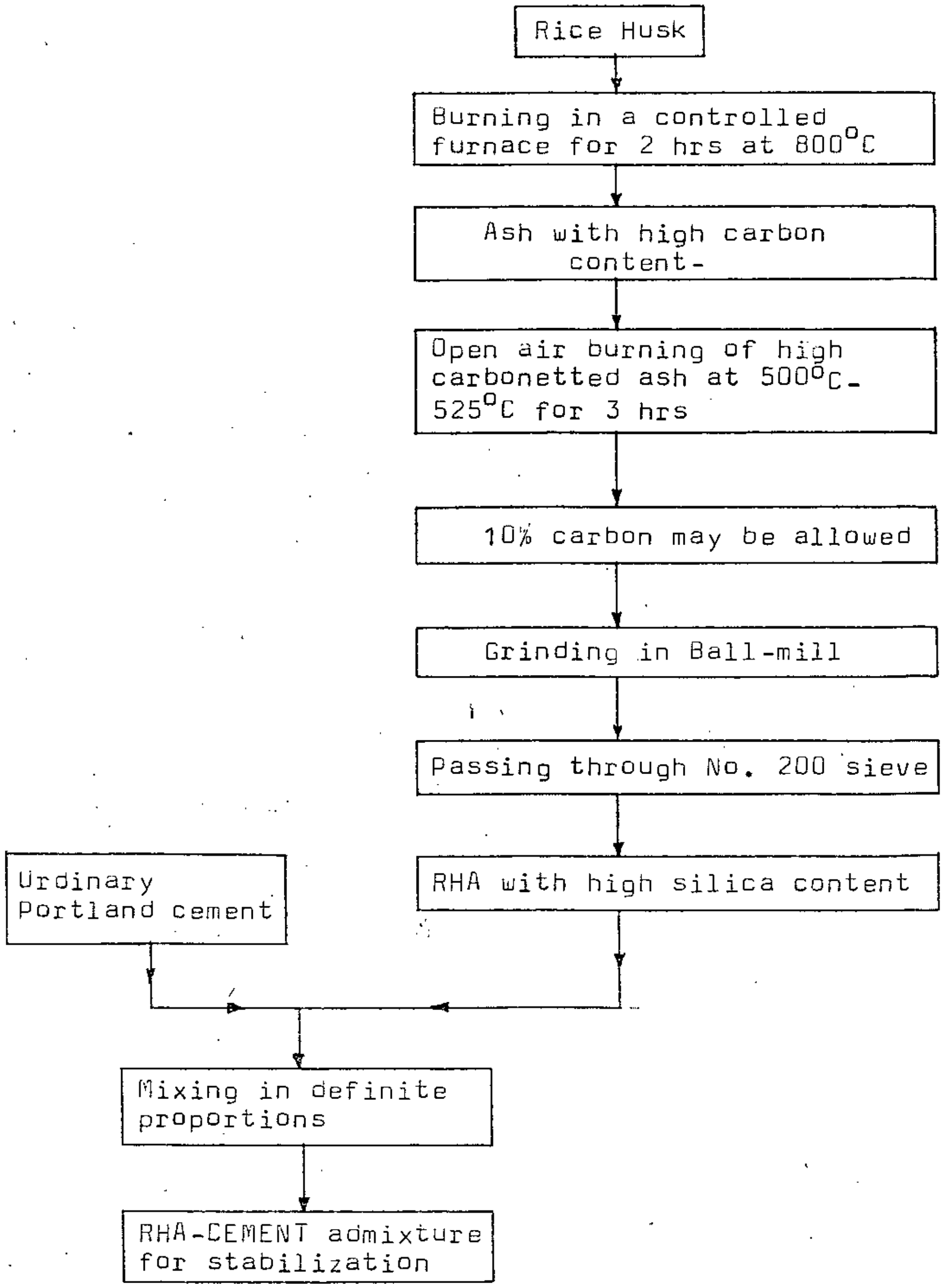


Fig. 4.2 Schematic diagram showing production of RHA and CEMENT-RHA admixture for soil-cement-RHA stabilization.

4.6 Constituents of Rice Husk Ash Used

Rice Husk burnt according to the procedure described in Art. 4.5 was chemically analyzed at the Housing and Building Research Institute. The results have been shown below and represent average of two determinations.

Constituent present	Percent by weight
SiO_2	91.08
Al_2O_3	0.56
Fe_2O_3	0.60
CaO	1.23
MgO	1.30
Loss on ignition	5.23

The results show that Rice Husk Ash produced contains a high amount of silica. From the literature survey, it is clear that silica produced at high temperature by burning Rice Husk is reactive and the ash as a whole acts as a good source of pozzolanic material. Accordingly, RHA produsec in this research would act as a pozzolanic addition to cement in cement-RHA stabilization of local silty soils.

4.7 Tests on Stabilized Soil

A biref description of the tests done to find the properties of the stabilized soil as mentioned in Research Scheme are outlined as below:

4.7.1 Wetting and Drying Test

This test is aimed at testing the reaction of the stabilized soil to the effect of repeated drying and wetting.

The samples were prepared by compaction following AASHO Method T99. Dimensions of the samples tested were identical to those of the standard proctor molds i.e. 4.0 inches in diameter and 4.6 inches height. The air dried soils were passed through No. 4 sieve. Air-dry moisture content was calculated. For cement stabilized samples, cement contents of percentages of 2,4,6,8 and 10 by weight of air dried soil were used. For cement-RHA stabilized soil, total admixture content was taken as 10% by weight of air dried soil. The optimum moisture contents for untreated soil and cement-treated soil vary slightly (Fig. 4.1). The moisture content taken was that corresponding to optimum moisture content calculated by AASHO Method T99.

In order to attain the required moisture content, the water required in addition to air dried state was calculated and for cement stabilized soil, an additional amount of water with previous amount for hydration were added to the soil and the admixture. For hydration of cement water required was 38 percent by weight of cement (Shetty, 1982).

For cement-RHA stabilized soil the additional water was assumed equal to that required for only cement (No literature is available describing the exact amount of water required for hydration of Rice Husk Ash). For each cement content or cement-RHA content, 8 lbs of soil sample was taken and the required amount of water and admixture were added. The mixture was compacted according to AASHO standard T99 except that the surface of each compacted layer was roughened prior to the application of the next by scratching a square grid lines 1/8 inch wide and 1/8 inch deep having approximately 1/4 inch spacing. During compaction the water content of a representative sample was determined. After compaction, the mold was weighed for determination of density. The compacted sample was then extracted from the mold by an extruder.

Each test required two samples: one for testing the volume and moisture changes. While the second was used for soil-cement loss determination. The ready-made samples were weighed and stored for 24 hours in humid sorrounding. Then the samples were cured for 7 days in desicator, keeping the samples over a filter paper just touching the water below. Weight and dimensions are checked in curing period. Following the 7-day treatment, the samples were submerged in tap water for 5 hours at room temperature, leaving a water layer of 1 inch above them. After removal the weight and dimensions of specimen No. 1 were checked, then both samples were placed into an oven at 71°C for 42 hours. This was followed by another weight check, then specimen No. 2 was brushed by standard ASTM brush by eighteen to twenty strokes on sides and four on each end. The force applied was 3 lbs and it was done on a consolidation-test-machine platform. Finally a third weighing was performed o determine the weight loss.

The operations enumerated represent a single durability or wetting-drying test cycle, 12 cycles for each sample performed.

Thereafter, volume and moisture change were calculated as a percentage of original volume and moisture content. The soil-cement loss was expressed as a percentage of the original oven dry weight.

The results of wet-dry test using cement stabilized samples were interpreted to calculate the minimum cement content i.e the minimum cement content satisfying the Portland Cement Association soil-cement loss criterion. This cement content was taken as the total admixture content in strength test and durability test using cement-RHA blended admixture.

The results of the wet-dry test for soil-cement and for soil-cement-RHA have been shown in Figs. 5.1 to 5.9 and tabulated in Appendix in Tables A.11 to A.14.

4.7.2 Unconfined Compressive Strength Test

This test was done to determine the unconfined compressive strength of the soils.

The soils were air dried first and then broken down to pass No. 4 sieve. Air dry moisture content was calculated. For cement stabilized soil, cement contents used were 2%, 8% and 10% by weight of air dried soil. For cement-RHA stabilized soil, total admixture content was taken as 10% by weight of air dried soil. Moisture content was the optimum moisture content calculated by AASHO method T99 for untreated soil. It may be noted that optimum moisture contents determined by compaction test (AASHO Method T134-61) on cement treated soil vary slightly than those of untreated soil (Fig. 4.1).

The molding moisture content for cement-treated soil was calculated summing the water required in addition to air-dried state and that-required for cement hydration. For hydration of cement, water required was 38 per cent by weight of cement used (Shetty, 1982). For cement-RHA stabilized soil, the additional water was assumed to that required for only cement, though this assumption requires verification. For each batch, 8 lbs of soil samples were taken and mixed manually with the required amount of moisture and admixture. Immediately after mixing, the mixture was compacted following AASHTO standard T99. After compaction, density was determined by weighing the mold with the compacted soil. This is the molding density. For molding moisture content determination, around 50 gms of sample from the mixture was taken. The compacted sample was then extracted from the mold by a jack.

From each compacted sample, 2 to 3 cylindrical samples of 1.4 inch diameter a d 2.8 inch height were trimmed off by a piano wire.

These samples were then transferred to a dessicator to store in moist environment for 24 hours and then cured for 7, 14 and 28 days. Curing was done by placing the samples on a filter paper placed on the porous plate in the dessicator. Water was added so that the filter paper became saturated and water level was always maintained just in touch with the filter paper. It was expected that the samples would draw water from the dessicator by capillary rise and got cured.

The unconfined compressive strengths for 7, 14, and 28 days were then determined following ASTM standard D2166-66 (1972). Failure moisture contents were also determined.

The results are presented in the next chapter in Fig. 5.11 to 5.20 and represent average of two test results. The details of the results are tabulated in Appendix in Tables A.1 to A.4. The variation of density with cement content has been presented in Fig.5.21 and the effect of RHA on density has been effect of RHA on density has been shown in Fig. 5.22. The corresponding results are tabulated in the Appendix in Tables A.7 to A.8.

4.7.3 Plasticity Index Test

Plasticity index of cement-treated and cement-RHA treated soils were evaluated by performing Atterberg limit tests on the air-dried pulverized samples. The treated soils were compacted following AASHTO Method T99. The compacted samples were cured in moist environment for 7 days and air-dried. The dried samples were pulverized to pass through No. 40 sieve. Liquid limit and plastic limit tests were performed on these pulverized soils following AASHTO Methods T89 and T90 respectively. The results are presented in the next chapter in Figs. 5.23 to 5.26 and are tabulated in Appendix in Tables A.9 and A.10.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

In this chapter, test results of the research are presented and discussed in details. These results would demonstrate the effect of admixture i.e. cement and rice husk ash on the durability, strength, volume and moisture change and plasticity characteristics of the stabilized soil.

5.2 Wetting and Drying Test

The results of the wetting and drying test are presented in the following articles:

5.2.1 Minimum Cement Content

Minimum cement content required for soil-cement mixture was ascertained from the results of the wet-dry test. Combining wet-dry test results with the results of the unconfined compressive strength test, cement content can also be estimated by Louisiana Slope Value Method, Kemahlioglu et al (1967) together with corresponding unconfined compressive strength.

Fig. 5.1 shows the relationships between soil-cement loss and cement content for Soil-A and Soil-B. It indicates that the higher the cement content, the lower the soil-cement

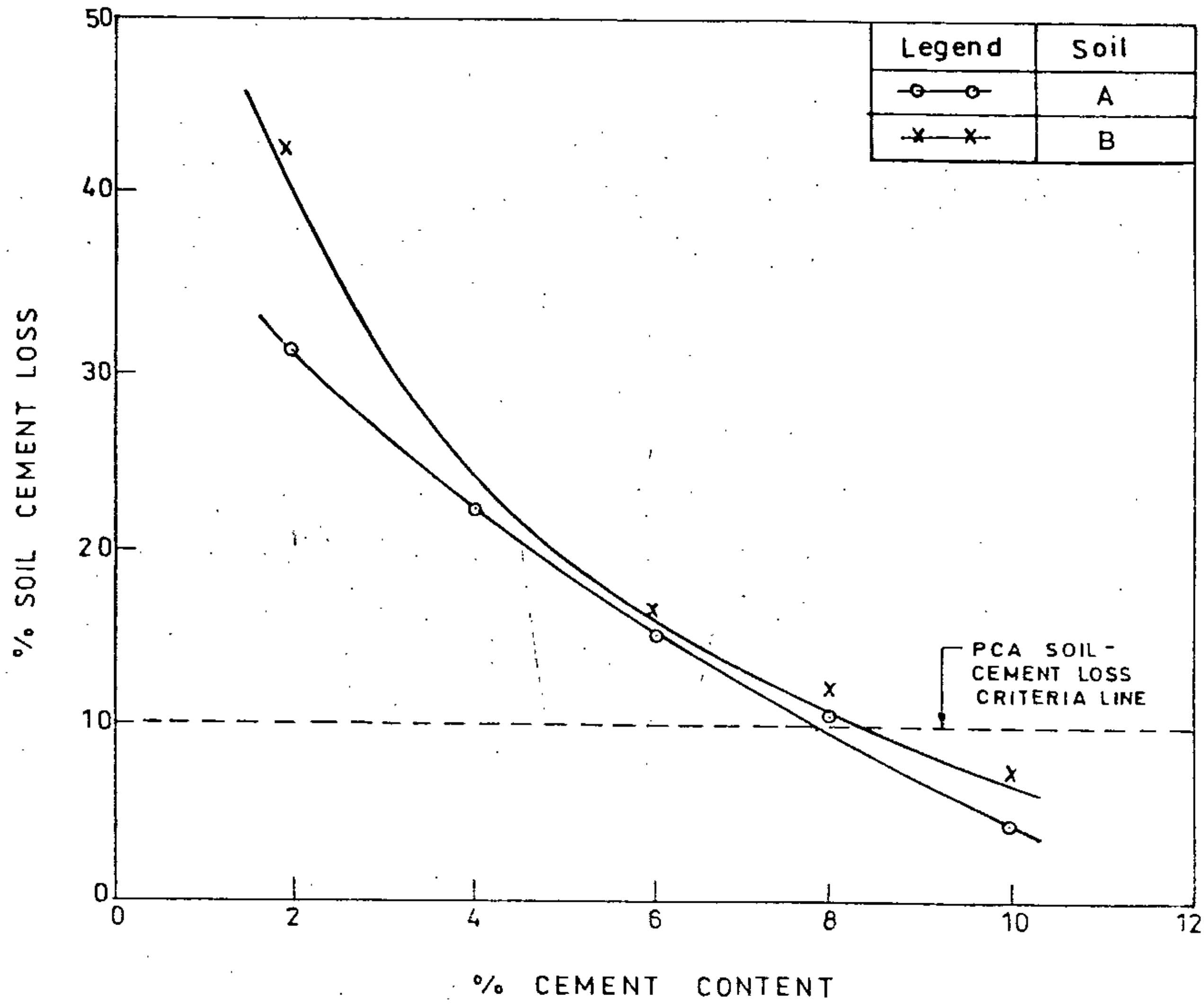


Fig. 5.1 Effect of admixture content on soil-cement loss of the soils in wet-dry test.

loss in wet-dry test. According to AASHO classification, Soil-A is a soil of group A-4. The Portland Cement Association (PCA, 1956) suggested that a maximum of 10 percent loss of soil-cement in the wet-dry test is allowable for this type of soil. Fig. 5.1 shows that addition of 7.9 percent cement in this soil would result in a durable soil-cement mixture satisfying PCA criteria. This result also supports the recommendation of Catton (1940) who tabulated that cement required by AASHO A-4 group-soil is within the range of 7-12 percent by weight for stabilization.

From AASHO classification, Soil-B is also a soil of A-4 group with a little plasticity. Cement requirement satisfying PCA (1956) soil-cement loss criteria in wet-dry test is 8.3 per cent which is within the range of cement content recommended by Catton (1940).

Hence it can be said that these two silty soils exhibit similar degree of durability at about the same cement content.

Again the results of wet-dry test for two silty alluvial soils of Bangladesh used in the present research confirm the validity of recommendation of PCA to be applied through the wet-dry test.

Fig. 5.2 shows the relationships between the soil-cement loss in wet-dry test and amount of rice husk ash in total admixture for soils A and B. The figure indicates the

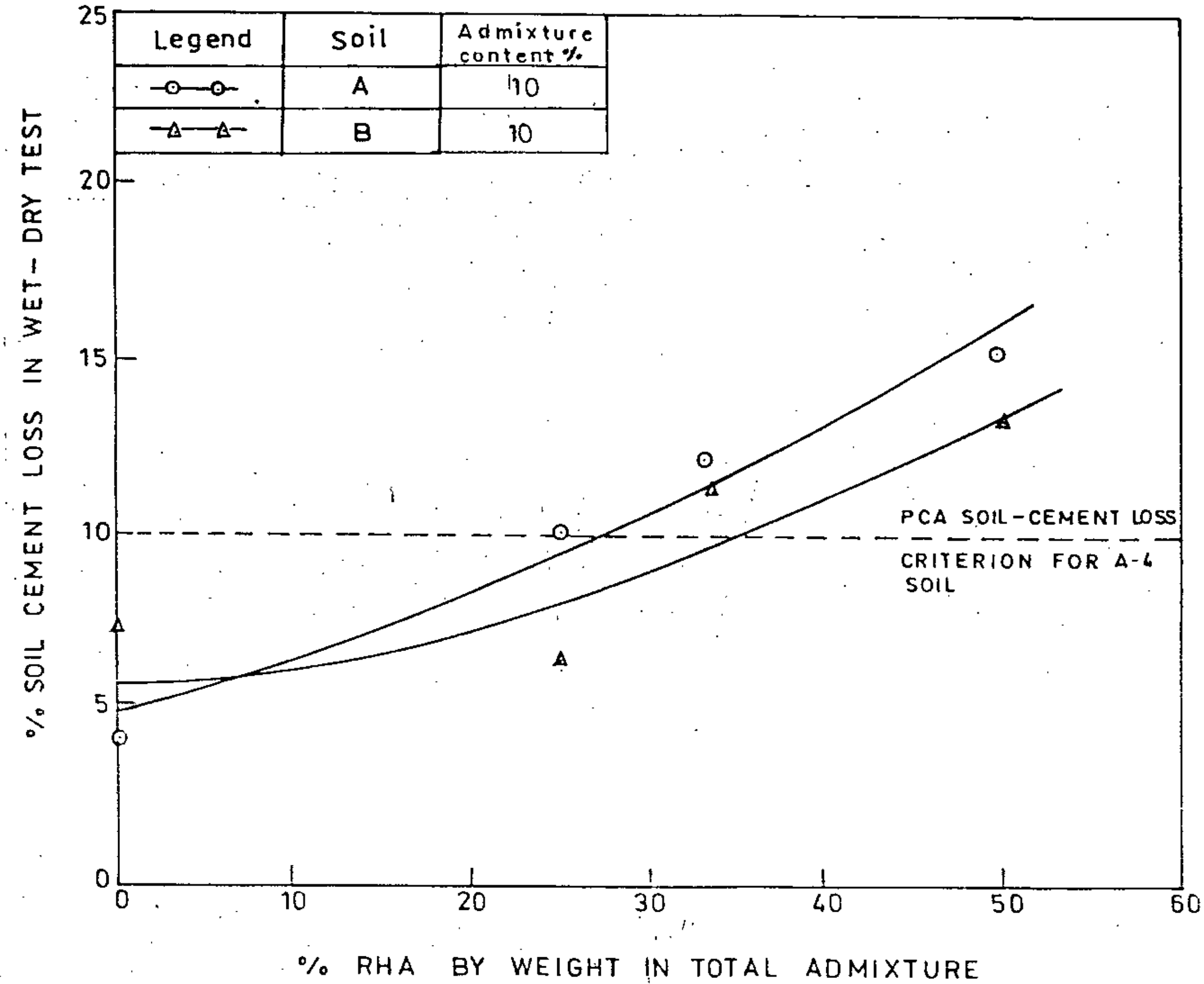


Fig. 5.2 Effect of replacement of cement by RHA in the total admixture on wet-dry loss of soils.

effect of replacement of cement by rice husk ash (RHA) in total admixture satisfying PCA criteria of soil-cement loss in wet-dry test for soils A and B. It is seen that soil-cement loss increases with increasing ash content in total admixture.

Taking the same criteria of loss as used in soil-cement mixtures, it is found that for Soil-A, 28 per cent cement by weight can be replaced by RHA. For Soil-B, 36 per cent by weight RHA can be incorporated in a blended admixture of cement and RHA for satisfying the same criteria.

Fig. 5.3 and 5.4 show the determination of minimum cement content required for satisfying PCA soil-cement loss criteria for Soil-A and Soil-B respectively by Louisiana Slope Value Method (Kemahlioglu et al, 1967). The cement content at which the loss line cuts the allowable PCA criteria line (as points a, a_1 in Figs. 5.3 and 5.4) is the minimum cement content. Corresponding unconfined compressive strengths can be found on strength line (as points b, b_1 in Figs. 5.3 and 5.4).

So as before, minimum cement contents by this method for Soil-A is 8.1 per cent by weight and for Soil-B is 8.5 per cent by weight. The corresponding 7-day unconfined compression are 86.9 psi for Soil-A and 112.25 psi for Soil-B.

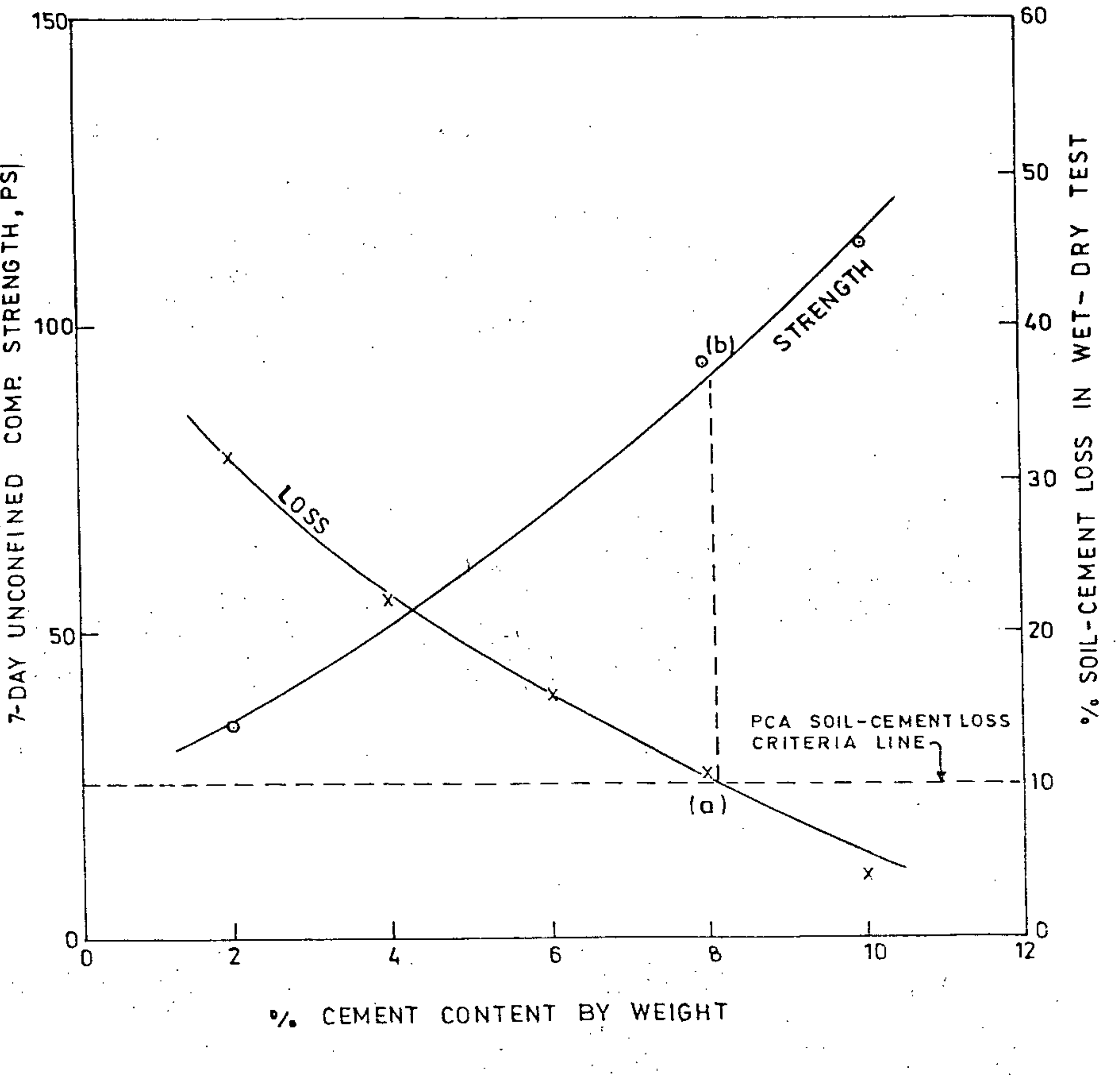


Fig. 5.3 Estimation of minimum cement content and corresponding unconfined compressive strength for soil-A.

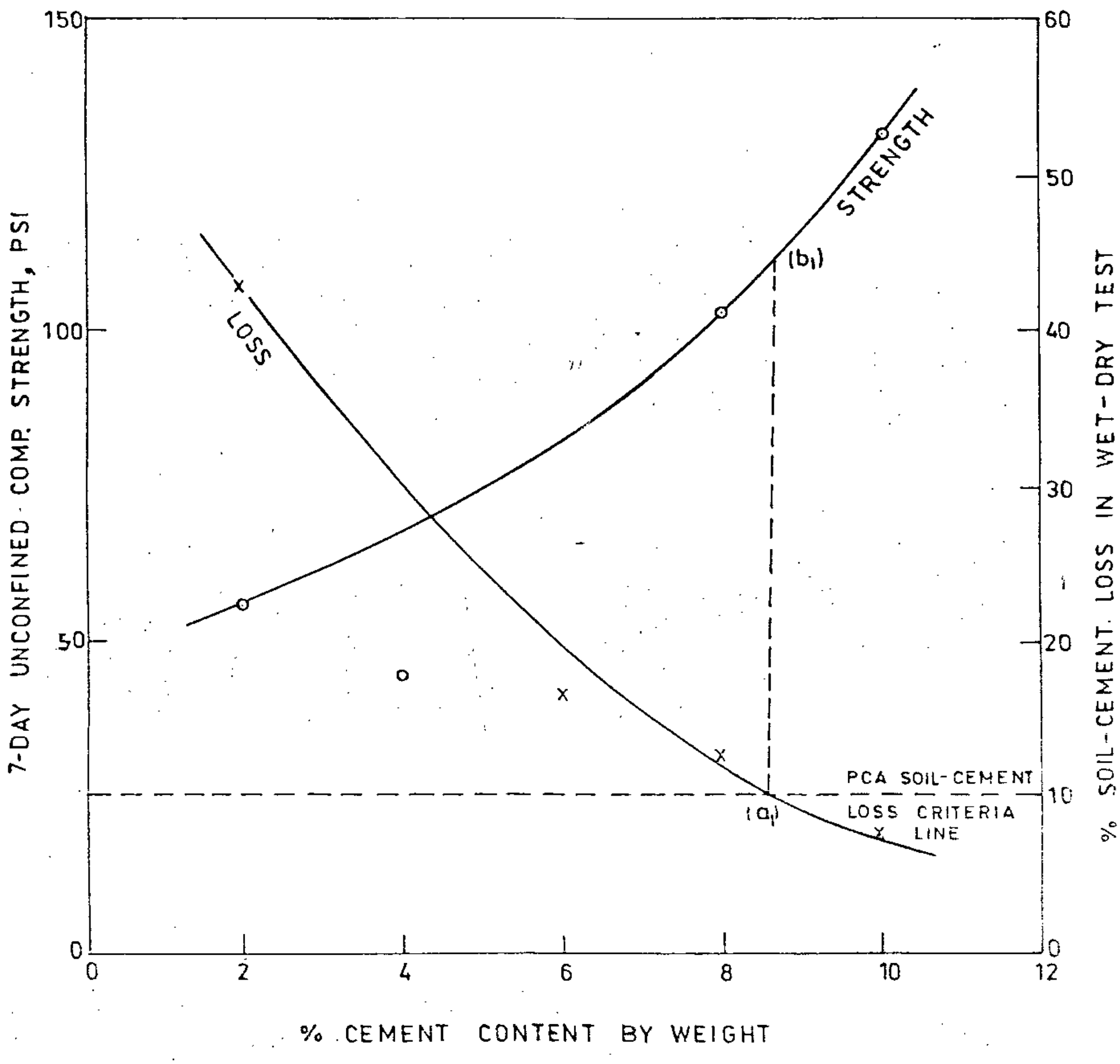


Fig. 5.4 Estimation of minimum cement content and corresponding unconfined compressive strength for soil-B.

Figures 5.5 and 5.6 illustrate the determination of amount of ash in a blended admixture of RHA and cement satisfying soil-cement loss criterion given by PCA using Louisiana Slope Value Method. As before, it is seen that 28 per cent cement for Soil-A and 36 per cent cement for Soil-B can be replaced by RHA satisfying the same criteria.

It is seen that Soil-A and Soil-B require almost same amount of cement for stabilization to satisfy durability criteria. From AASHO classification, it is found that they are both from AASHO soil group A-4. This confirms the reporting of Catton (1940) that different AASHO soil groups require different amount of cement and cement content required by soils of same group ranges within a tolerable limit.

Again, it is found that more cement can be replaced by ash for Soil-B than Soil-A. Since Soil-B contains four percent clay, ash may be more reactive to clay fraction.

5.2.2 Moisture Change

Maximum moisture content is the highest amount of water held up in the soil sample during its cycles of wetting in wet-dry test.

Fig. 5.7 shows the maximum moisture contents for Soil A and B against cement contents. It is seen that moisture content increases for higher cement contents. From Fig. 5.7 it is seen that for Soil-A maximum moisture content in wet-dry

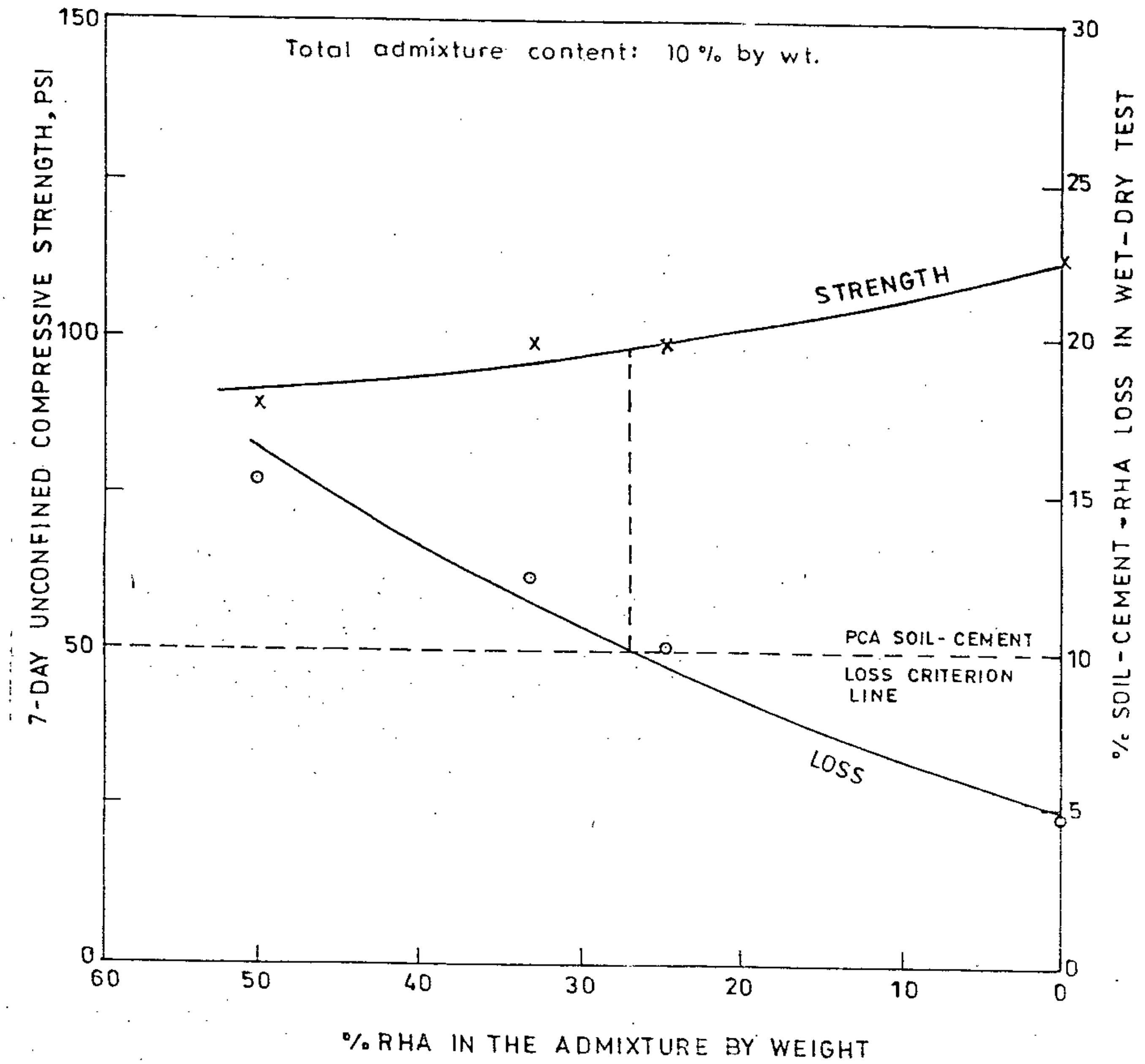


Fig. 5.5 Estimation of optimum ash content in cement-RHA blend and corresponding unconfined compressive strength for Soil-A.

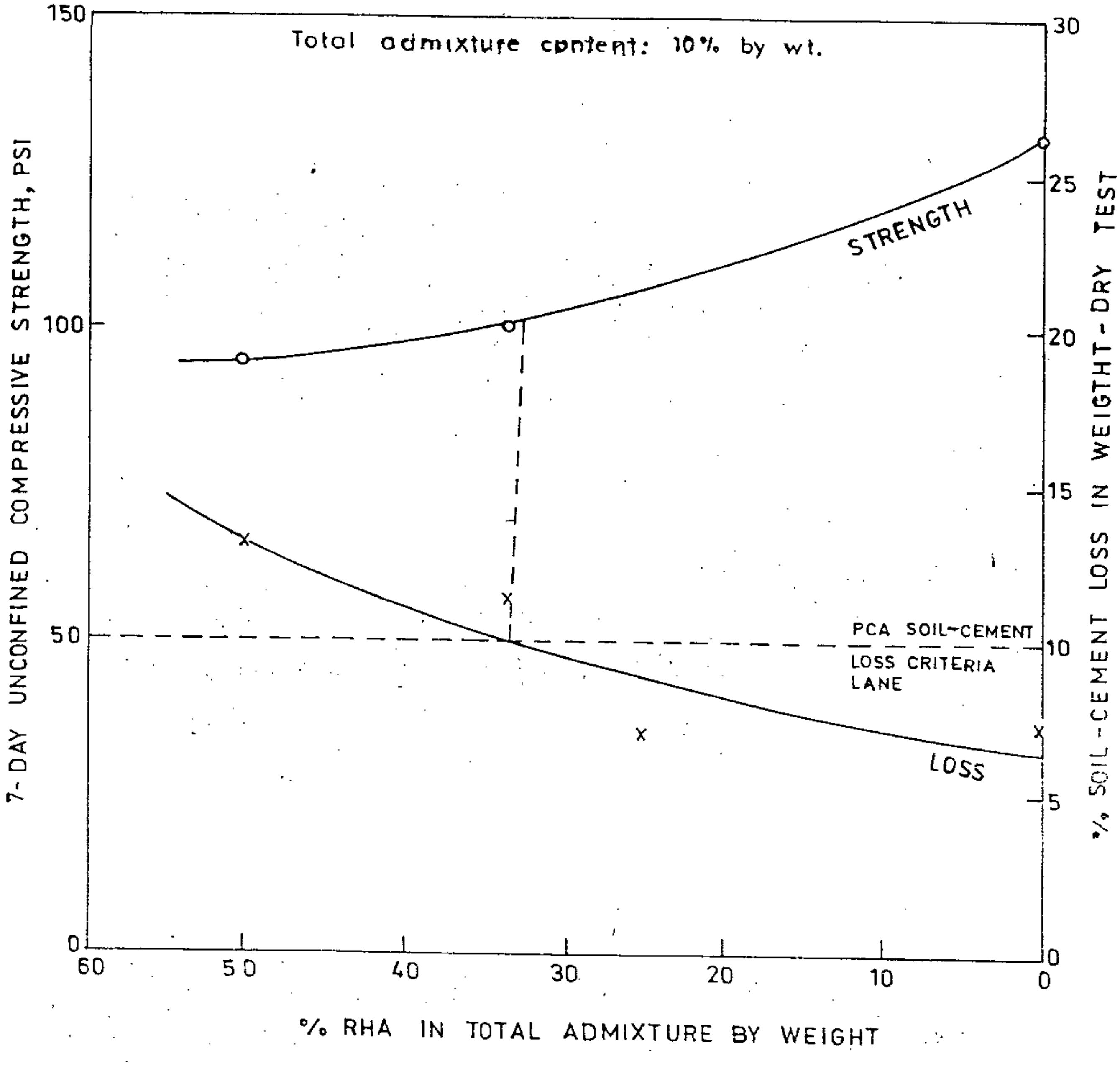


Fig. 5.6 Estimation of optimum ash content in cement-RHA blend and corresponding unconfined compressive strength for Soil-B.

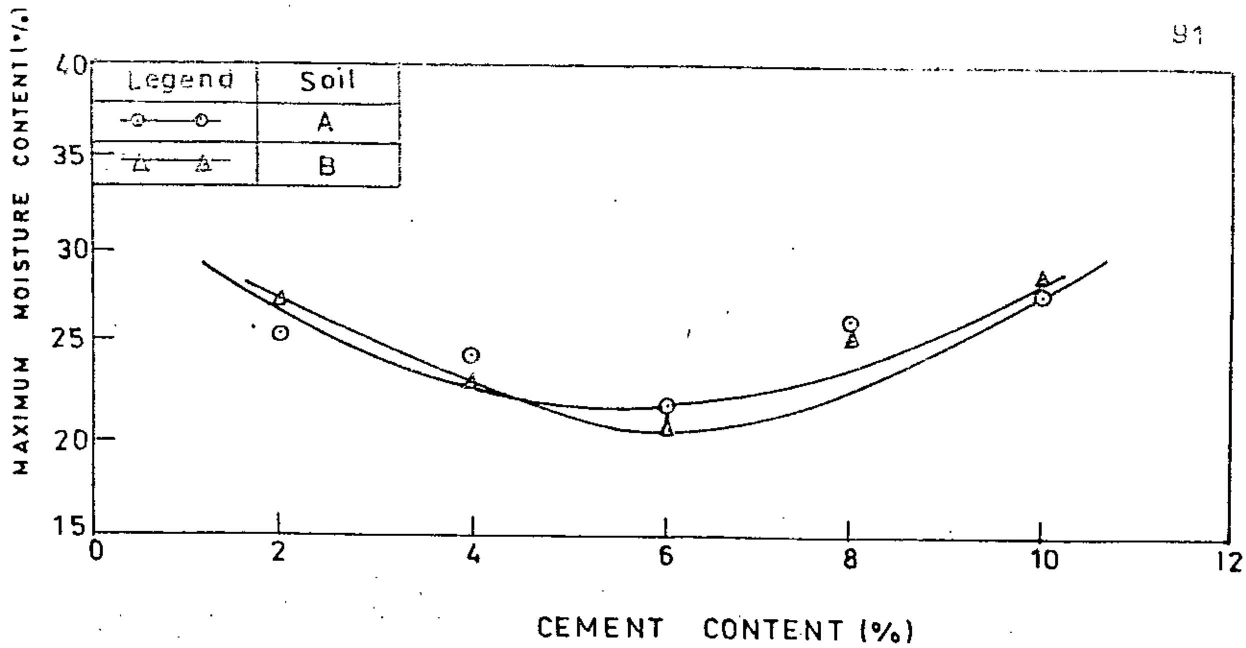


Fig. 5.7 Maximum moisture content in cement-stabilized soils during wet cycle of wet-dry test.

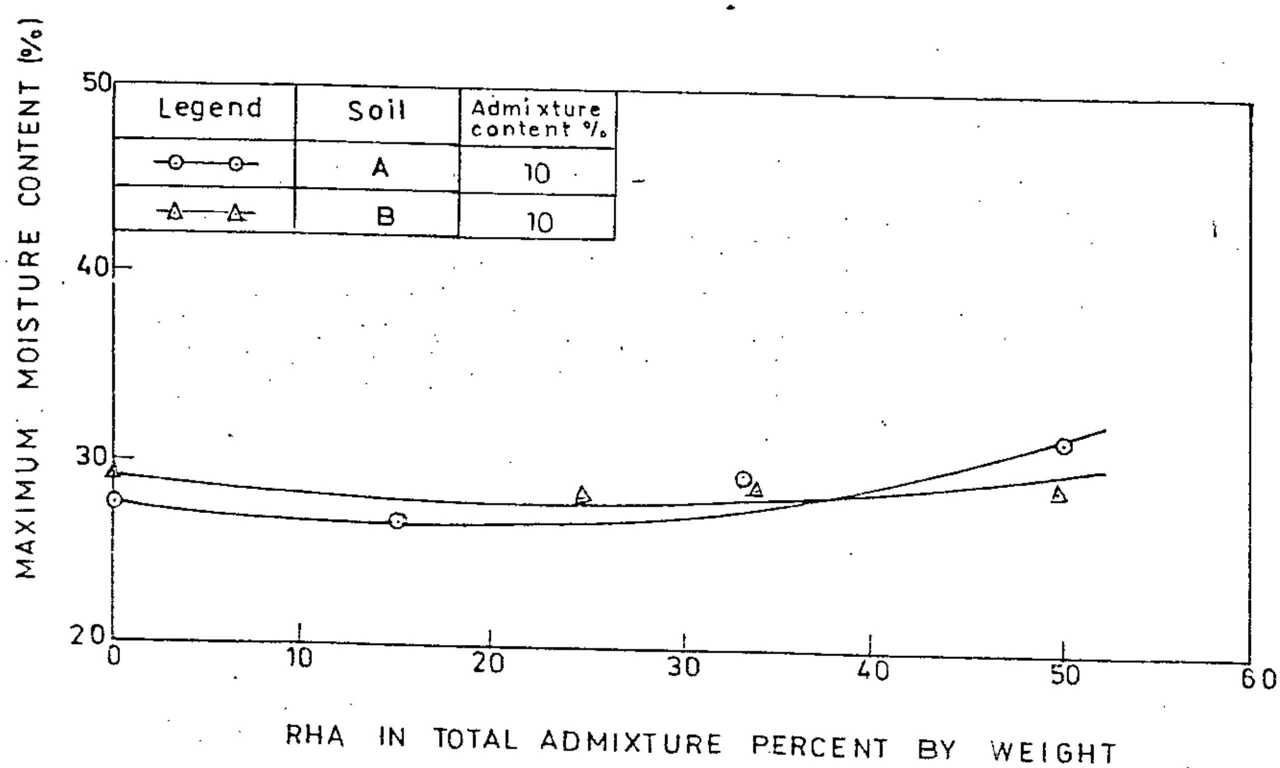


Fig. 5.8 Maximum moisture contents in cement-RHA stabilized soils during wet cycle of wet-dry test.

test occurs for 10 per cent cement content which is about 29.2 per cent. Failure moisture content of unconfined compression test samples of this soil after 28-day curing stands at 29.8 per cent (Table A.1). For Soil-B, maximum moisture content in wet-dry test is 28.70 per cent (Table A.5) and failure moisture content of unconfined compression test sample after 28-day curing is 29.46 per cent (Table A.3). So it is seen that failure moisture contents in unconfined compression test are well above the maximum moisture contents in wet-dry test. So strength test results are representative for a situation when road subgrade or sub-bases are completely submerged.

Fig. 5.8 shows the maximum moisture contents in Soil-A and B when stabilized with RHA and cement. It is seen that maximum moisture content in wet-dry test for Soil-A is 31.41 per cent (Ref. Table A.6) and failure moisture content in unconfined compression test is 33.09 per cent (Table A.2). For Soil-B, maximum moisture content is 28.9 per cent in wet-dry-test (Table A.6) and that in unconfined compression test is 30.33 per cent (Table A.4). So maximum water content in wet-dry test lies well below the failure moisture content in unconfined compressive strength test. So strength test results using cement-RHA admixture are also representative considering moisture change.

5.2.3 Volume Ch. ge

The relationships between volume change and per cent of cement content for Soil-A has been shown in Fig. 5.9. This figure also shows the same relationships for Soil-B. It is found that with the increase in cement content shrinkage occurs in both the soil. This occurs due to shrinkage during the cement hydration (Kezdi, 1979).

But on addition of RHA-cement blended admixture, shrinkage decreases and volume increases with increasing ash content (Ref. Fig. 5.10). The decreased shrinkage on addition of RHA to cement may be due to the fact that fine ash acts as a source of reinforcement in between the cement setting work (SIRI, 1979).

However, the volume change in both cases is well below 2 per cent reported as requirement by Kezdi (1979).

So rice husk ash addition decreases the shrinkage of soil-cement mix for alluvial silty soils.

5.3 Unconfined Compressive Strength Test

The relation between unconfined compressive strength and cement content cured for 7-days, 14 days and 28 days are presented in Fig. 5.11 for Soil-A and in Fig. 5.12 for Soil-B. Figs. 5.13 and 5.14 show the relation between unconfined compression and curing period for Soil-A and Soil-B respectively.

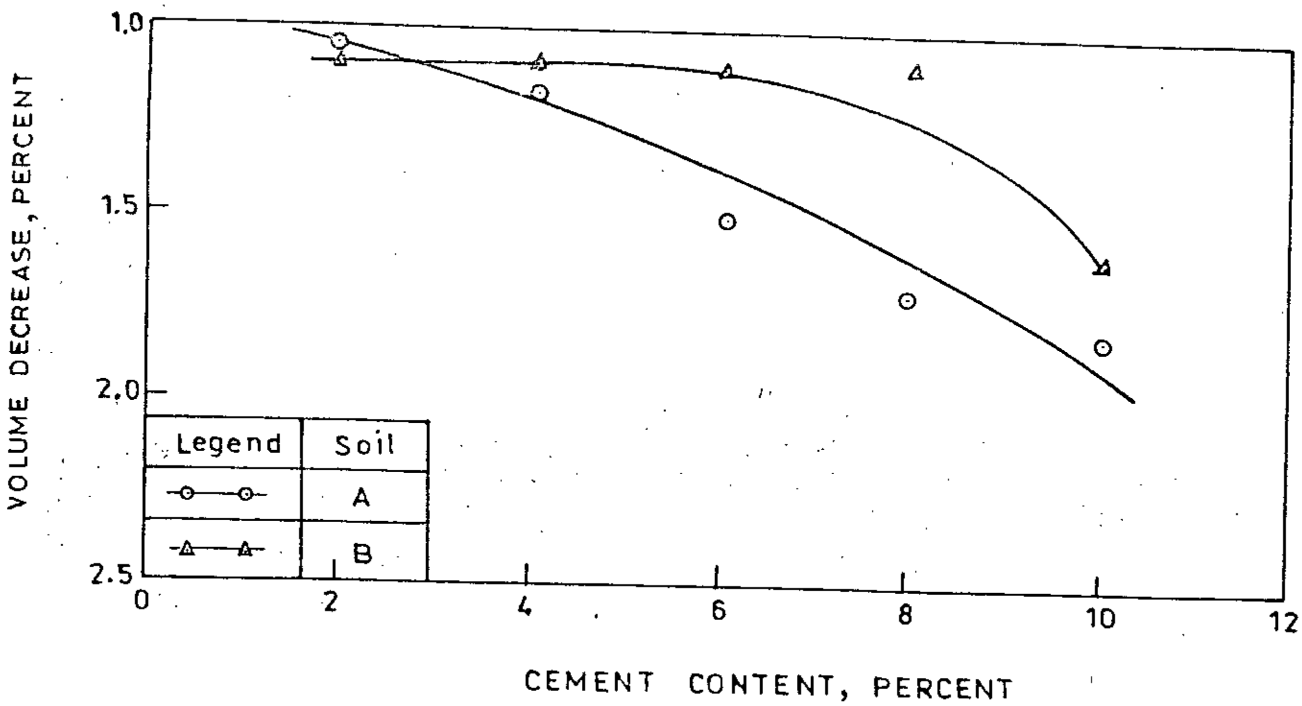


Fig. 5.9 Volume change of the cement-treated soils during dry cycle of wet-dry test.

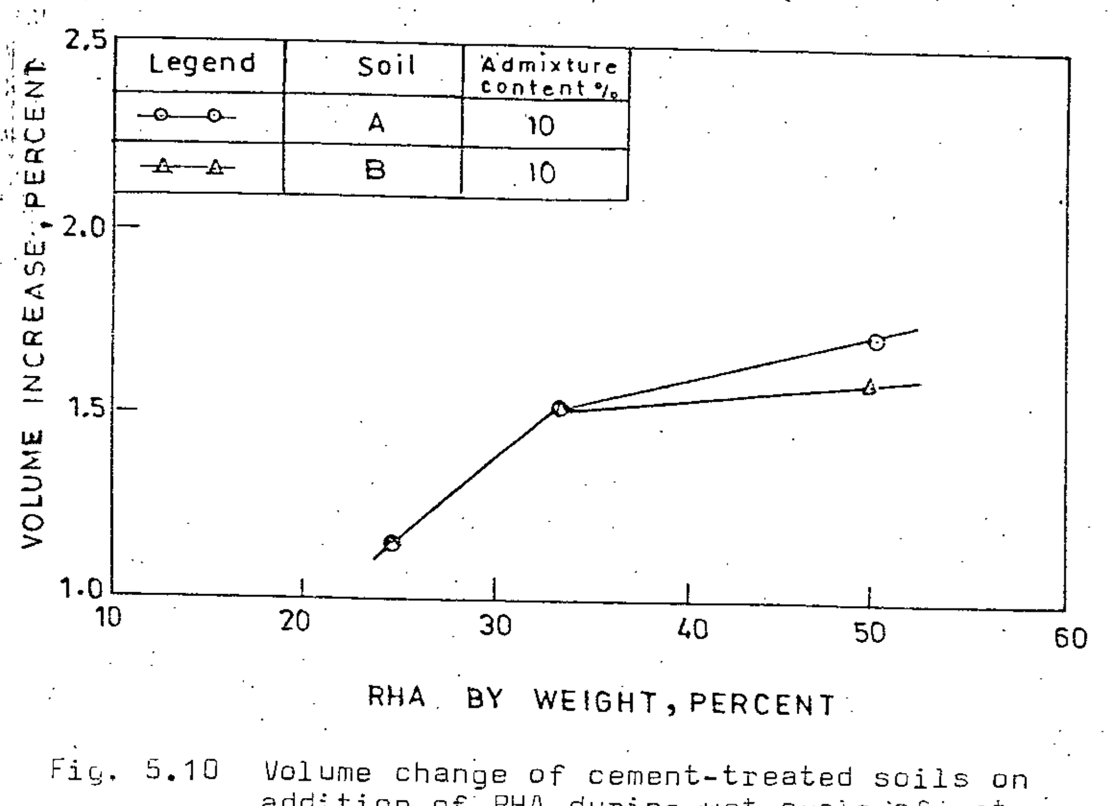


Fig. 5.10 Volume change of cement-treated soils on addition of RHA during wet cycle of wet-dry test.

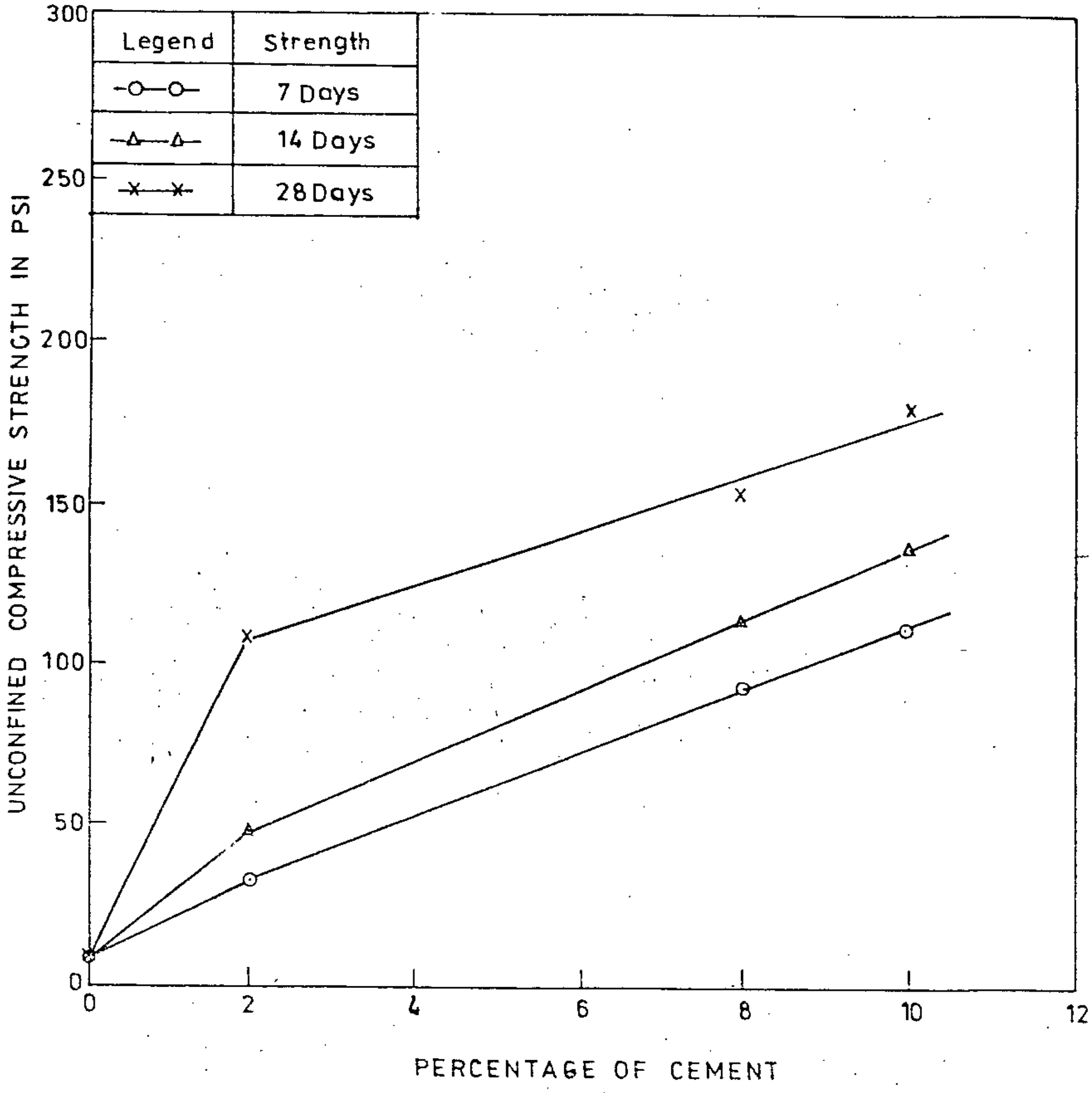


Fig. 5.11 Effect of admixture content on compressive strength of soil-A.

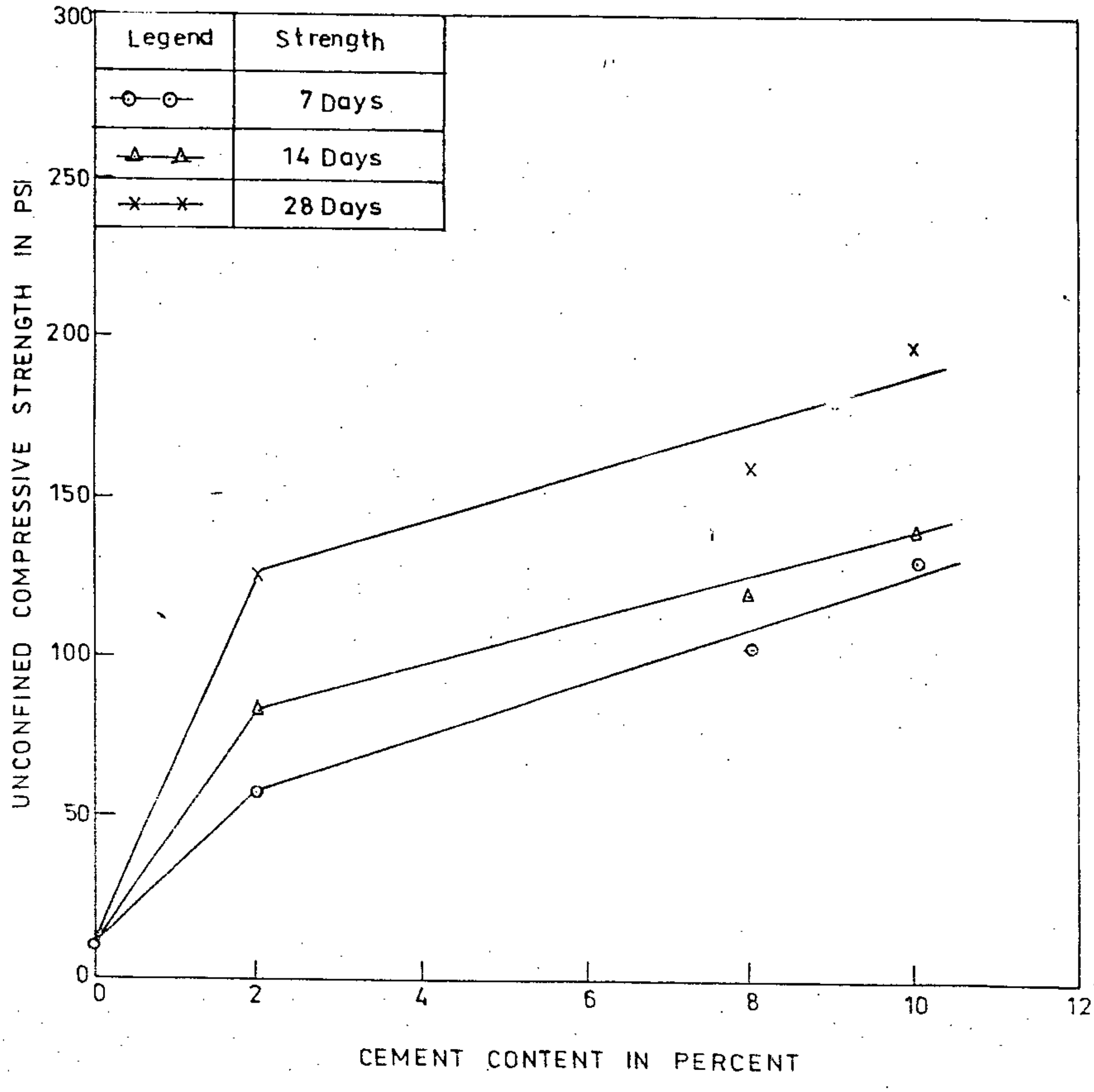


Fig. 5.12 Effect of admixture content on compressive strength of soil-B.

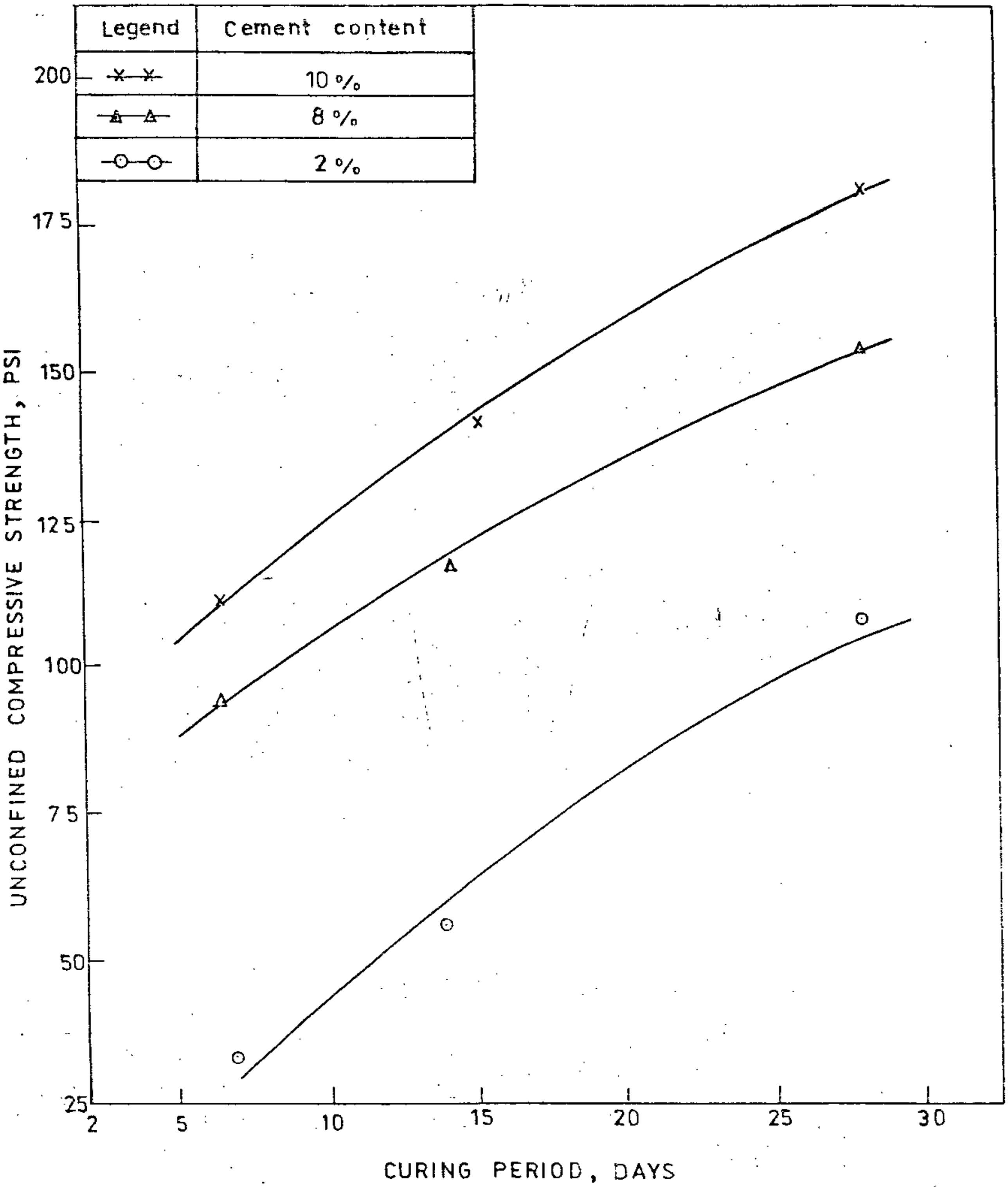


Fig. 5.13 Effect of curing period on compressive strength of cement-treated soil-A.

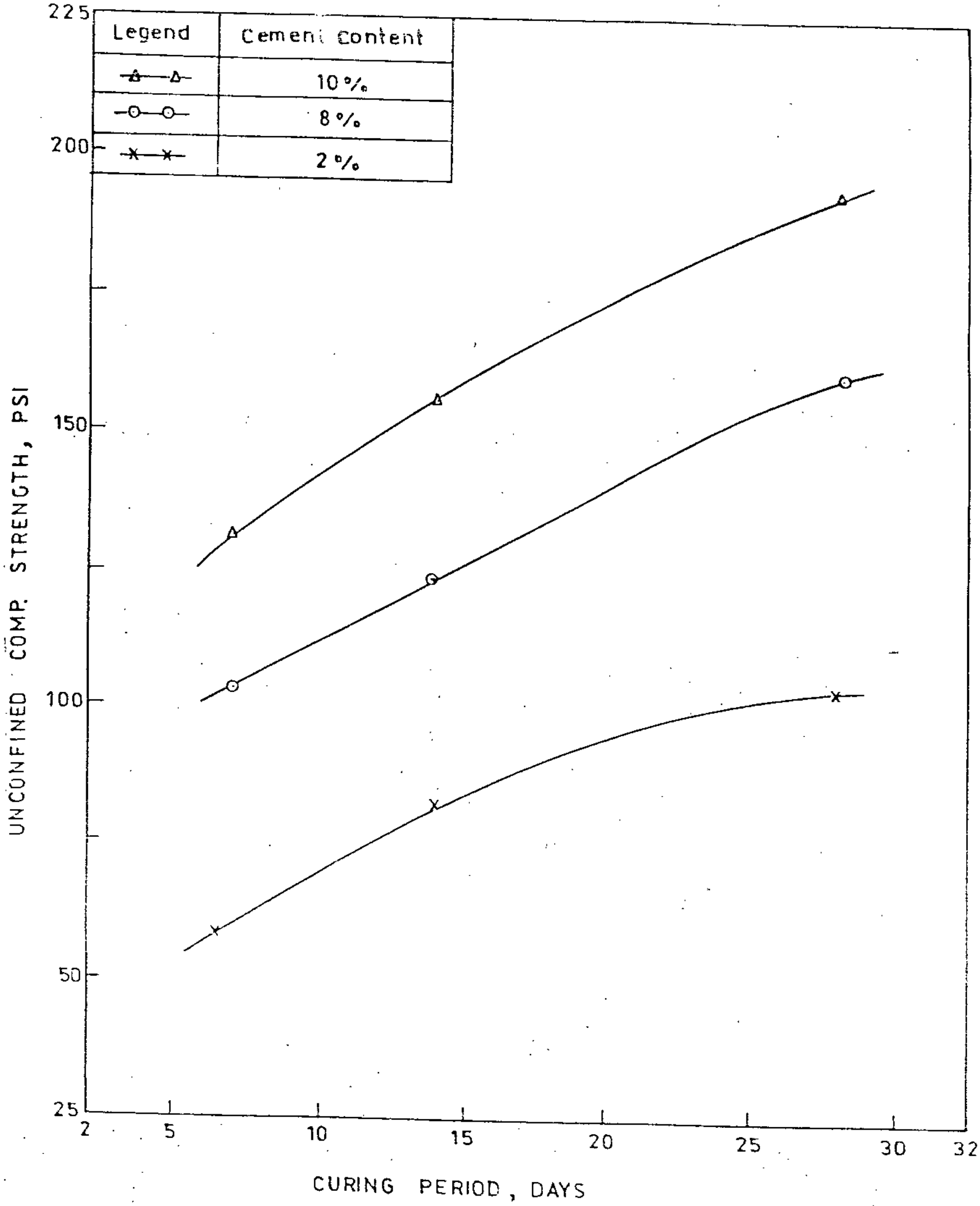


Fig. 5.14 Effect of curing period on compressive strength of cement-treated soil-B.

Here it is seen that with increasing cement content and curing period, the compressive strength increases. The results confirm the experimental findings of Leadbrand (1955) where he showed that the soil-cement continues to increase in strength with age. Ramaswamy et al (1984) showed for silty soils in Singapore that with increasing cement content and curing period, cement stabilized soil continues to increase in strength with age. Ahmed (1984) showed for a silty sand of Bangladesh that addition of cement in increments and with increasing curing period, the soil-cement continues to increase in strength. However, a silty clay showed decrease in unconfined compression due to addition of 1/2% cement by weight. But strength increased appreciably on cement addition of 2% and upto 15% by weight.

Both for Soil-A and for Soil-B, it is also seen that at 8% and 10% cement content strength gain rates are similar while for 2% cement content this rate is smaller for similar curing periods. This was also observed by Ahmed (1984) for a sandy silt and silty clay in Bangladesh. This may happen due to formation of stronger soil-cement matrix at higher cement contents.

Table 5.1 shows the ratio of unconfined compressive strength of cement stabilized (UC_c) Soil-A and Soil-B at 7, 14, and 28 days to that of untreated soils (UC) respectively. Figs. 5.15 and 5.16 illustrate the results.

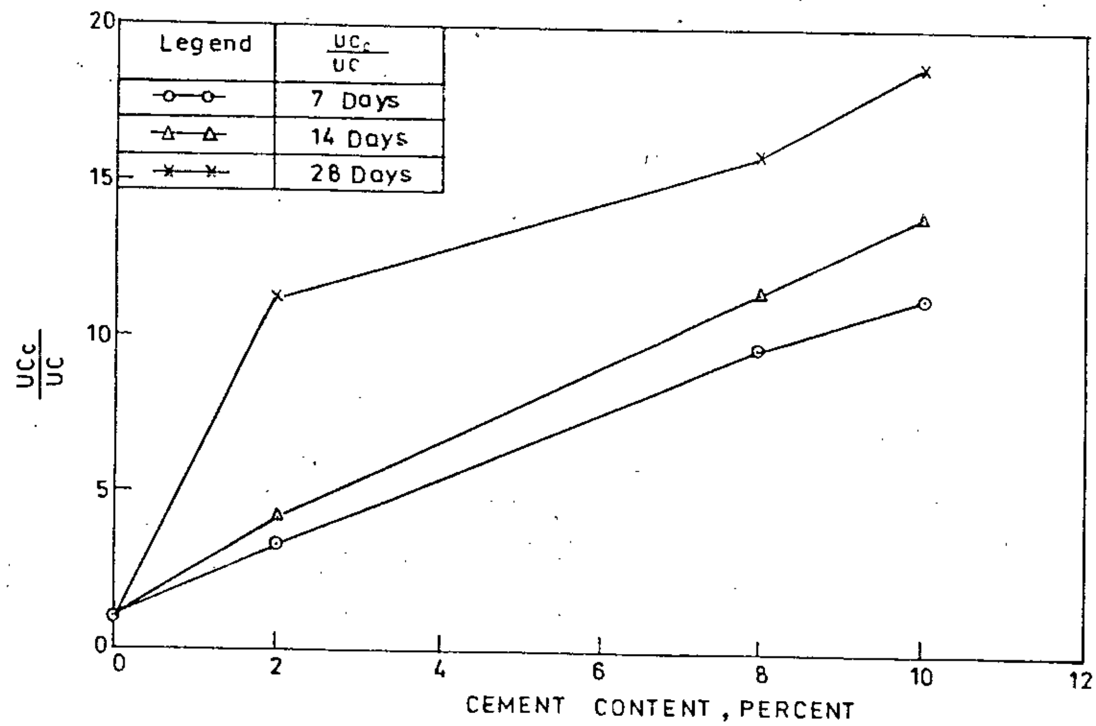


Fig. 5.15 Strength gain of cement treated soil-A over untreated soil.

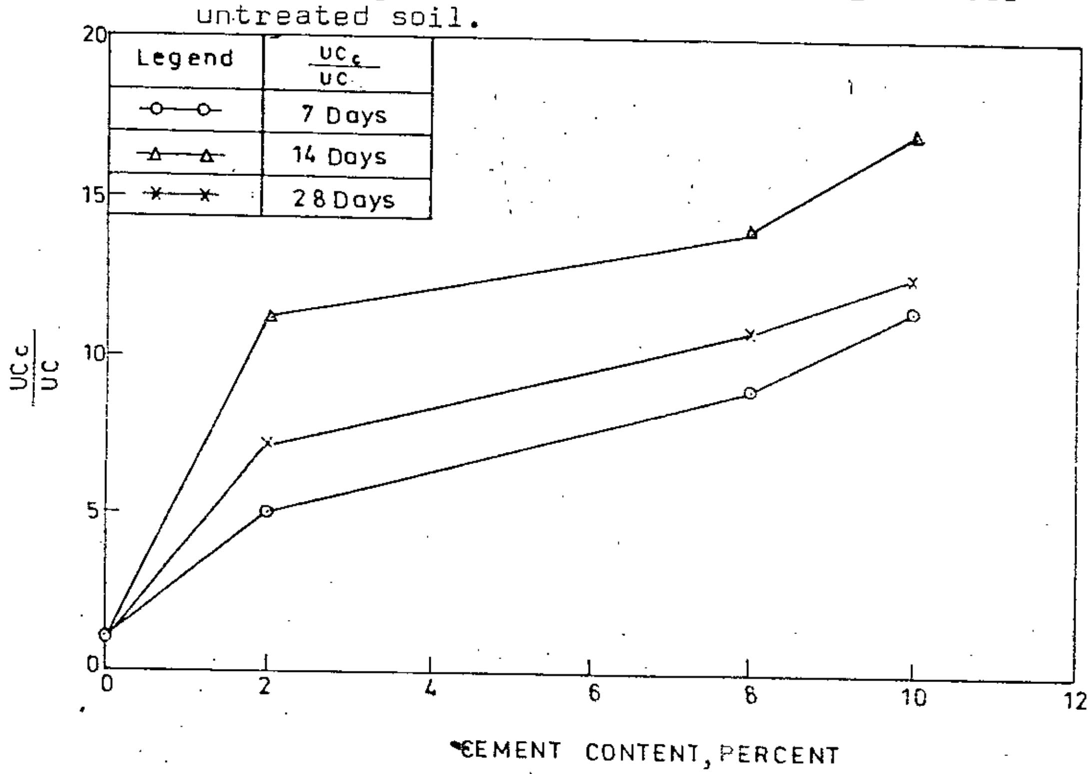


Fig. 5.16 Strength gain of cement-treated soil-B over untreated soil.

Table 5.1 Strength Gain of Cement Stabilized Soil Over Untreated Soil

Soil sample	Cement content(%)	UC_c/UC		
		7 days	14 days	28 days
A	2	3.42	4.92	11.14
	8	9.71	11.73	[illegible]
	10	11.48	14.10	18.65
B	2	5.16	7.32	11.43
	8	9.14	10.93	14.28
	10	11.75	12.70	17.13

For Soil-A, it is seen that with the addition of a small amount of cement (i.e. 2%) this strength ratio is 3.42 for 7-day curing period and 11.14 for 28-day curing period. For 10 per cent cement content, this ratio is 11.48 for 7-day curing and 18.65 with 28-day curing. So it is clear that for this soil, increasing cement content 5 times does not produce that much increase in strength for higher curing period.

For Soil-B, the strength ratio at 2 per cent cement content is 5.16 for 7 day curing period and 11.43 for 28 day curing period. For 10 per cent cement content this ratio is 11.75 for 7-day curing and 17.13 for 28 day curing. Hence, for this soil also, increase in cement content 5 times does not produce that much strength gain for higher curing period.

However, for both the soils, appreciable increase in strength can be achieved by mixing a small amount of cement (i.e 2%) and allowing it to cure for higher periods.

For the Soils-A and B, it is observed that for Soil-B strength values are greater than those for Soil-A at similar cement contents and curing periods. From textural composition, it is seen that Soil-A contains 14% fine sand and 86% silt, and Soil-B contains 6.5% fine sand, 89.5% silt and 4% clay. Presence of 4% clay in Soil-B may contribute to its higher strength development compared to Soil-A. However, more tests should be done to establish this fact.

This finding is similar to the observation by Ahmed (1984) for two local silty soils. He found that between two local A-4 soils, one with 62% fine sand and 38% silt and the other with 8% fine sand, 87% silt and 5% clay, the soil with lower fine sand content and with certain clay fraction showed more strength at similar cement content and curing condition.

As mentioned in literature review, excluding the durability criteria, soil-cement mix is characterized by unconfined compression values. PCA (1956) recommended that a stabilized soil attain a range of strength as shown in Table 2.8. From the test results, it is seen that none of the two soils in the present research satisfy the strength criteria by PCA though they satisfy the durability criteria. PCA (1959) differentiate the strength criteria for soil-cement mix into one as shown in Fig. 2.7 for soil-cement mix containing material retained on the No. 4 sieve and the other as shown in Fig. 2.8 for soil-cement mix not containing material retained on the No. 4 sieve. PCA (1959) required that a minimum 7-day unconfined compression value of 250 psi is to be attained for soil-cement mixtures not containing material on the No. 4 sieve and 50% of which are smaller than 0.05 mm. No specification is available for soils containing materials more than 50 per cent of which are smaller than 0.05 mm. In this study, both Soil-A and Soil-B have more than 50 per cent materials smaller than 0.05 mm (Table 3.1).

Fig. 5.3 shows that the 7-day unconfined compressive strength of Soil-A for 8.1% cement content at which the PCA criteria of soil-cement loss is satisfied is only 86.9 psi. From Fig. 5.4 for Soil-B, that unconfined compression strength is 112.25 psi for 8.5% cement content. Thus for both the alluvial soils the unconfined compressive strengths are much below the range of strength mentioned in Table 2.8 by PCA. The relationships between the unconfined compressive strength and the cement content (Figs. 5.11 and 5.12) for Soil-A and Soil-B indicate that a very high percentage of cement would be required to satisfy the strength criteria as specified by the PCA resulting in uneconomy.

In the United States, the desired cement content is normally selected to meet durability i.e. the implied assumption is that strength needs will automatically be met (O'Flaherty, 1974). But this is not true for the alluvial silty soils of Bangladesh like those used in this research. Though the Soil-A and B meet the durability criteria set by PCA, they failed to achieve the specified strength at the same cement content.

The results obtained confirm the findings of Ahmed (1984) who for two locally selected soil of types A-4 and A-4(12) AASHO group showed that the A-4 soil gained the specified strength value of PCA (1956) at 13.90% cement content and the other would require much higher cement content. However, the A-4(12) soil contained about 4% organic matter. This may be responsible for lower strength of the soil-cement mix of this soil.

These findings also confirm the assertion of Kemahlioglu et al (1967) that a minimum compressive strength requirement would not necessarily result in the most economical cement requirement due to the fact that different soil-cement mixtures exhibit different strengths at similar degree of durability.

5.3.1 Effect of Addition of Rice Husk Ash on Strength of Cement-Stabilized Soil

The effect of replacement of cement by Rice Husk Ash in a blended admixture of cement and Rice Husk Ash on unconfined compressive strength of Soil-A is shown in Fig. 5.17. Fig. 5.18 shows the same result for Soil-B. It is seen that

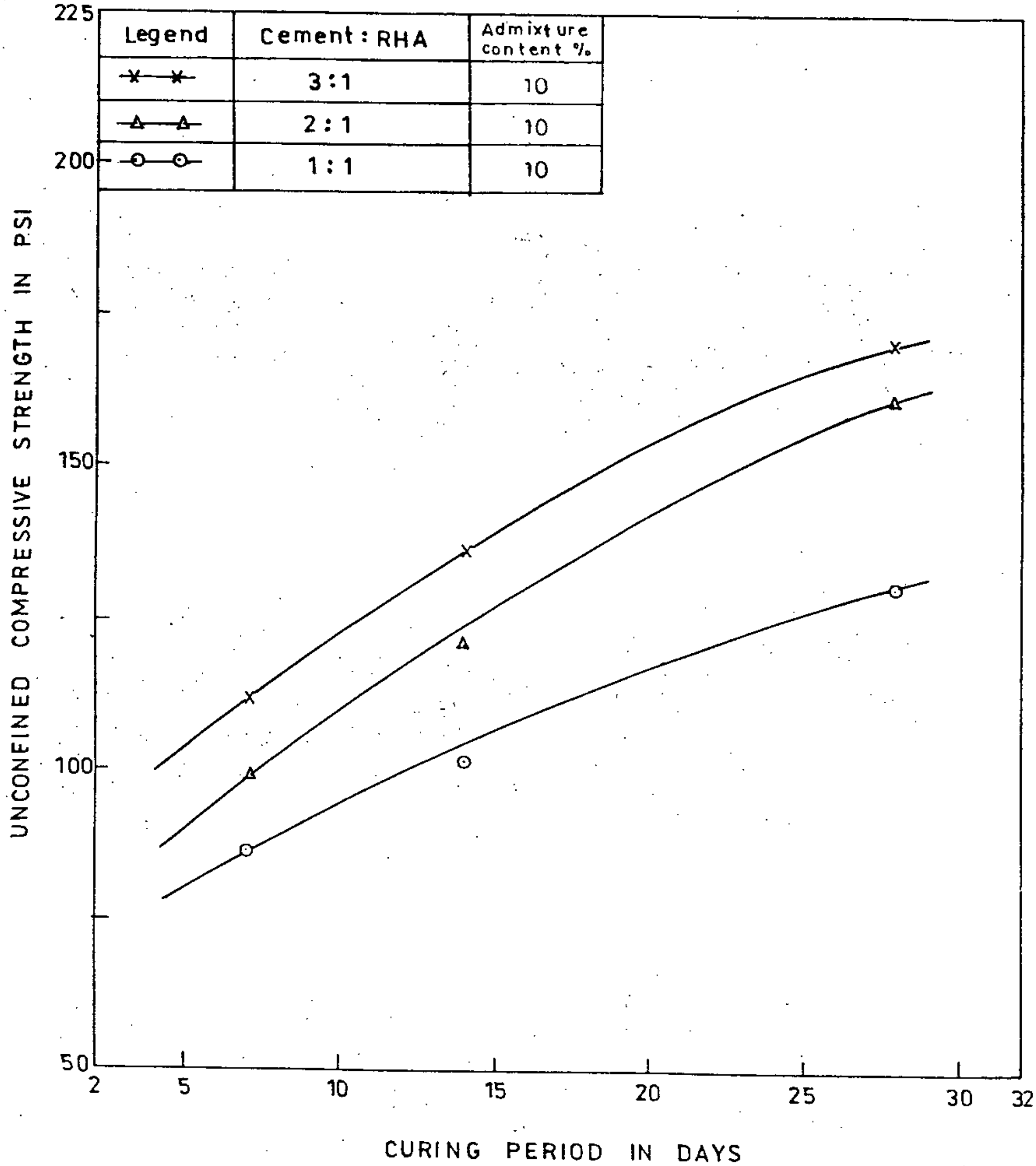


Fig. 5.17 Effect of curing period on unconfined compressive strength of cement-RHA treated Soil-A.

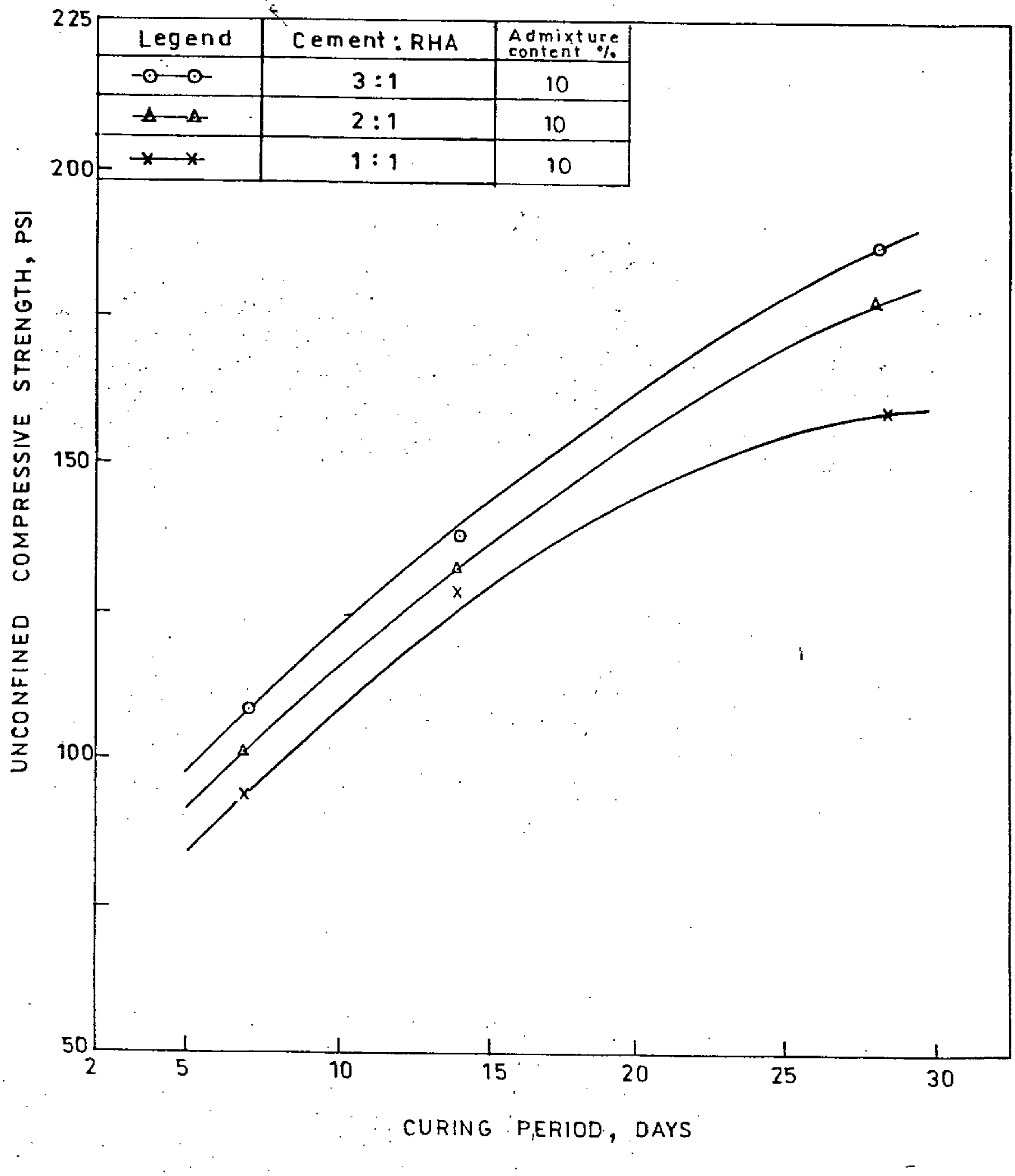


Fig. 5.18 Effect of curing period on unconfined compressive-strength of cement-RHA treated Soil-B.

strength development is comparable with that in cement stabilized soil. But with increasing ash content, strength decreases and for lower curing period, no appreciable change is observed.

Table 5.2 Strength Gain of Cement-RHA Blend Stabilized Soil Over Cement Stabilized Soil

Soil sample	Total admix. content(%)	Cement: RHA	UC_{RHA-c}/UC_c		
			7 days	14 days	28 days
A	10	3:1	0.945	1.0	0.948
		2:1	0.89	0.853	0.897
		1:1	0.789	0.746	0.73
B	10	3:1	0.82	0.96	0.973
		2:1	0.77	0.927	0.897
		1:1	0.72	0.904	0.823

Table 5.2 shows the ratio of unconfined compression (UC_{RHA-c}) of stabilized Soils A and B using RHA and cement blended admixture to that (UC_c) of cement admixed soil. Figs. 5.19 and 5.20 show those ratio in a graphical form. It is seen that for Soil-A, 25 per cent by weight of cement can be replaced by RHA with only 5.5 percent decrease in 7-day unconfined compressive strength, and for 14-day unconfined compressive strength, no change occurs. The test results show that change is pronounced for ash contents higher than 25 per cent and curing periods longer than 14 days.

For Soil-B, compared to Soil-A, lower 7-day compressive strength is obtained on addition of Rice Husk Ash. However,

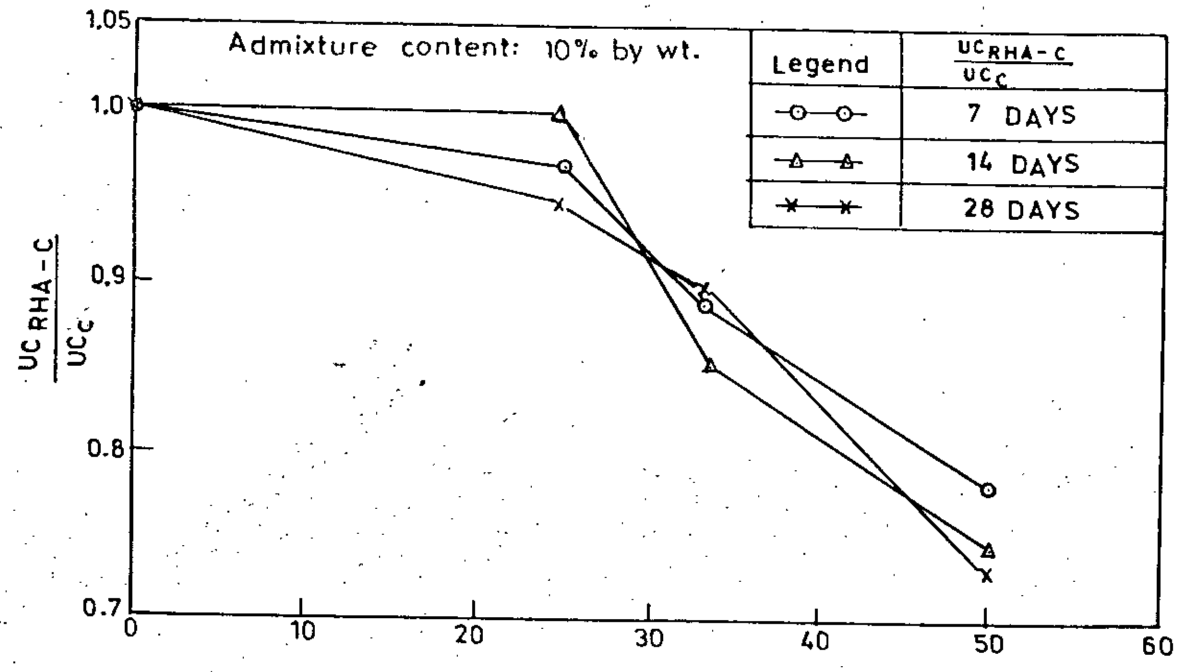


Fig. 5.19 Strength ratio of RHA-cement treated soil to cement-treated vs. RHA content in total admixture for soil-A.

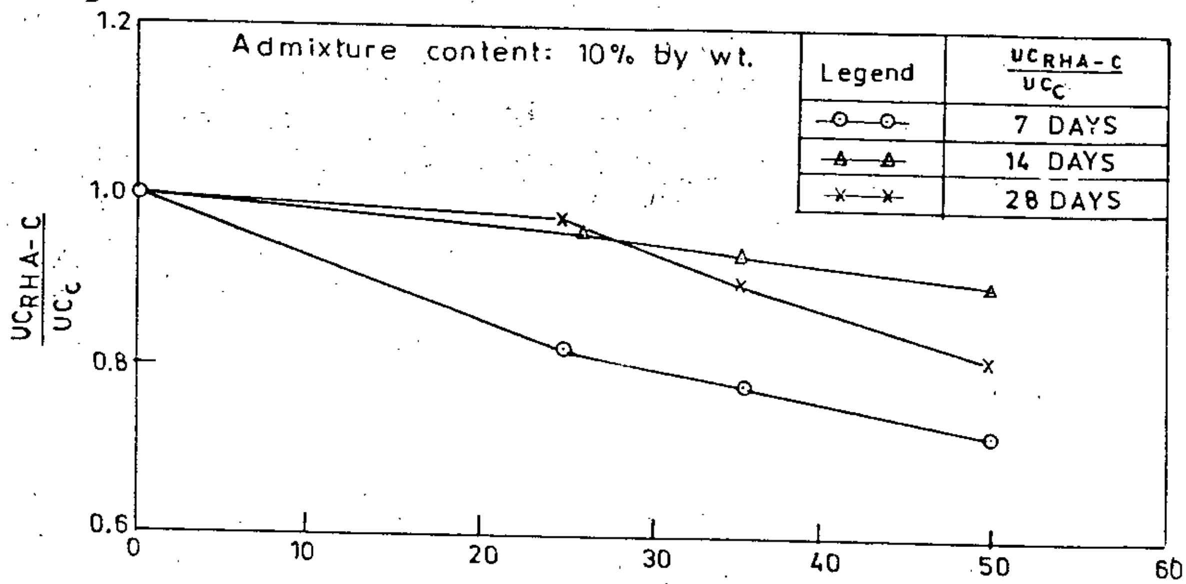


Fig. 5.20 Strength ratio of RHA-cement treated soil to cement-treated vs. RHA content in total admixture for soil-B.

for longer curing period and at 25% ash content, the results are similar (Table 5.2). So it can be said that for alluvial silty soils of A-4 group, 25% ash content in a blended admixture of cement and RHA for 14-day curing period produce strength almost the same as that produced by cement.

5.4 Change of Maximum Dry Density of Stabilized Soil

The relationships between the maximum dry density (obtained from compaction following standard AASHTO Method T99) and cement contents are presented in Fig. 5.21. It may be observed that for Soil-B, density decreases with increasing cement content. This may be due to the fact that flocculation of soil particles on addition of cement turns the soil-cement matrix in to a honeycomb structure. This results in an increase in volume and in effect, decreased density (Kezdi, 1979). This result confirms the finding of Ahmed (1984) who showed that for an A-4(12) local soil, there had been decrease in density with the increase in cement content from 1/2% upto 10% by weight.

For Soil-A, density decreases upto 4% cement content and after that, almost no changes occur. This may be due to the fact that cement addition upto 4% results in flocculation which is responsible for decreased density. But additional cement content does not result in any flocculation. So density does not decrease further.

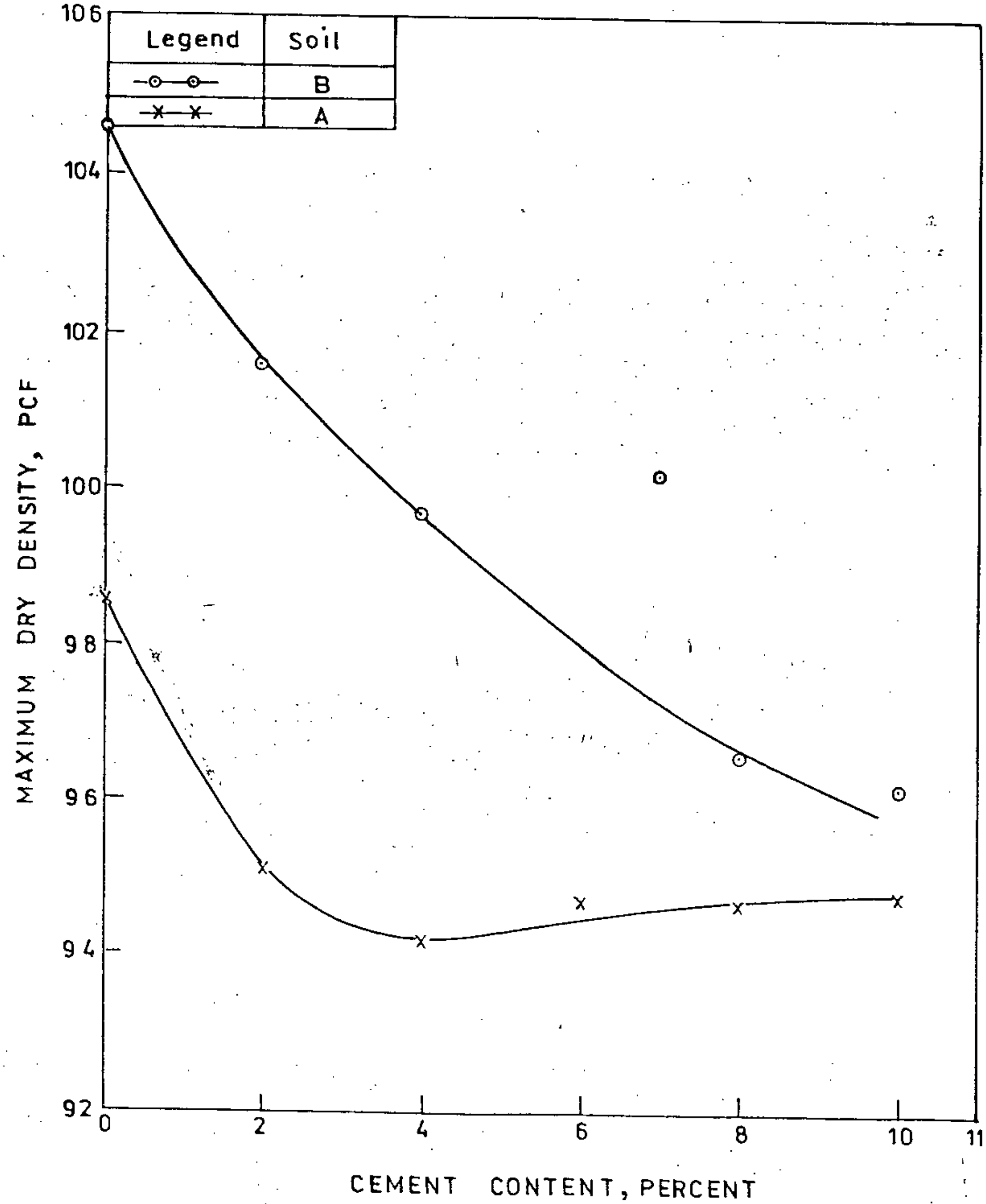


Fig. 5.21 Effect of cement addition on dry densities of soil A & B.

Fig. 5.22 shows the effect of addition of RHA on maximum dry densities of soil-cement mix for Soil-A and Soil-B. It may be observed that for both soil, the density decreases with increasing ash content in the blended admixture of cement and RHA. It may be noted that RHA has unit weight less than cement. So presence of RHA in soil-cement mix further reduces the density.

These results confirm the reporting of Williams and Sukpatrapinomore (1971). They used Rice Husk Ash as a stabilizer on an embankment of a proposed highway. It was found that low dry density was obtained on addition of RHA.

5.5 Plasticity Indices

The variation of the Atterberg limits and the plasticity index with the increments of cement contents is shown in Figs. 5.23 and 5.24 for Soil-B. For cement stabilized soil, it is seen that the plastic limit and liquid limit increase with increasing cement content. But increase in plastic limit is appreciable resulting in decrease in plasticity index at higher cement content. Felt (1955) found for a soil with 18 per cent clay that the plastic limit and the liquid limit increases and the plasticity index reduces considerably (Fig.2.10). Redus (1958) also showed that with increase in cement content and for longer curing period, plasticity index reduces. Ahmed (1984) showed that for sandy silt and silty clay plastic limit increases on addition of cement.

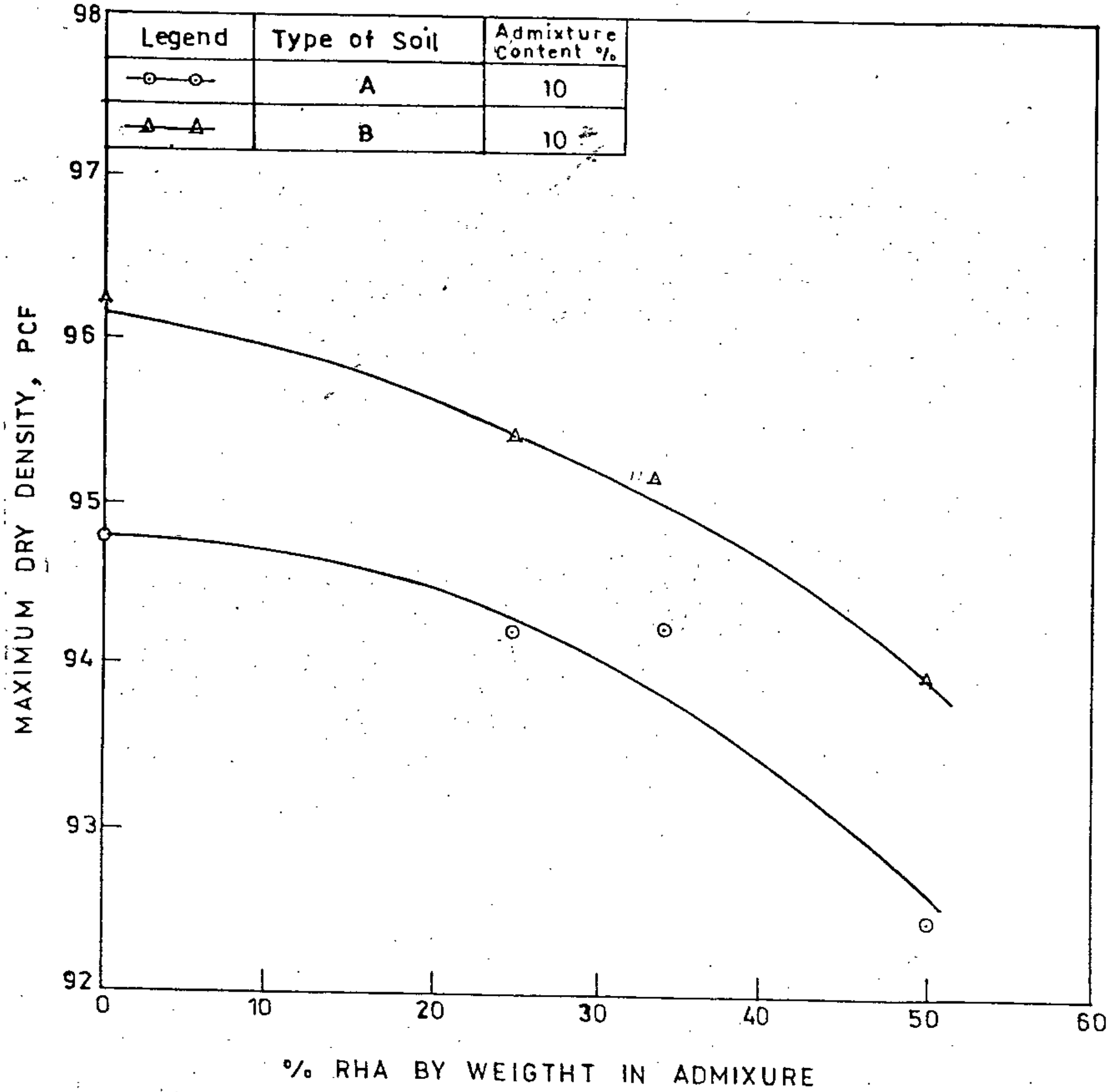


Fig. 5.22 Eeffect of addition of RHA on dry densities of cement-treated soil A & B.

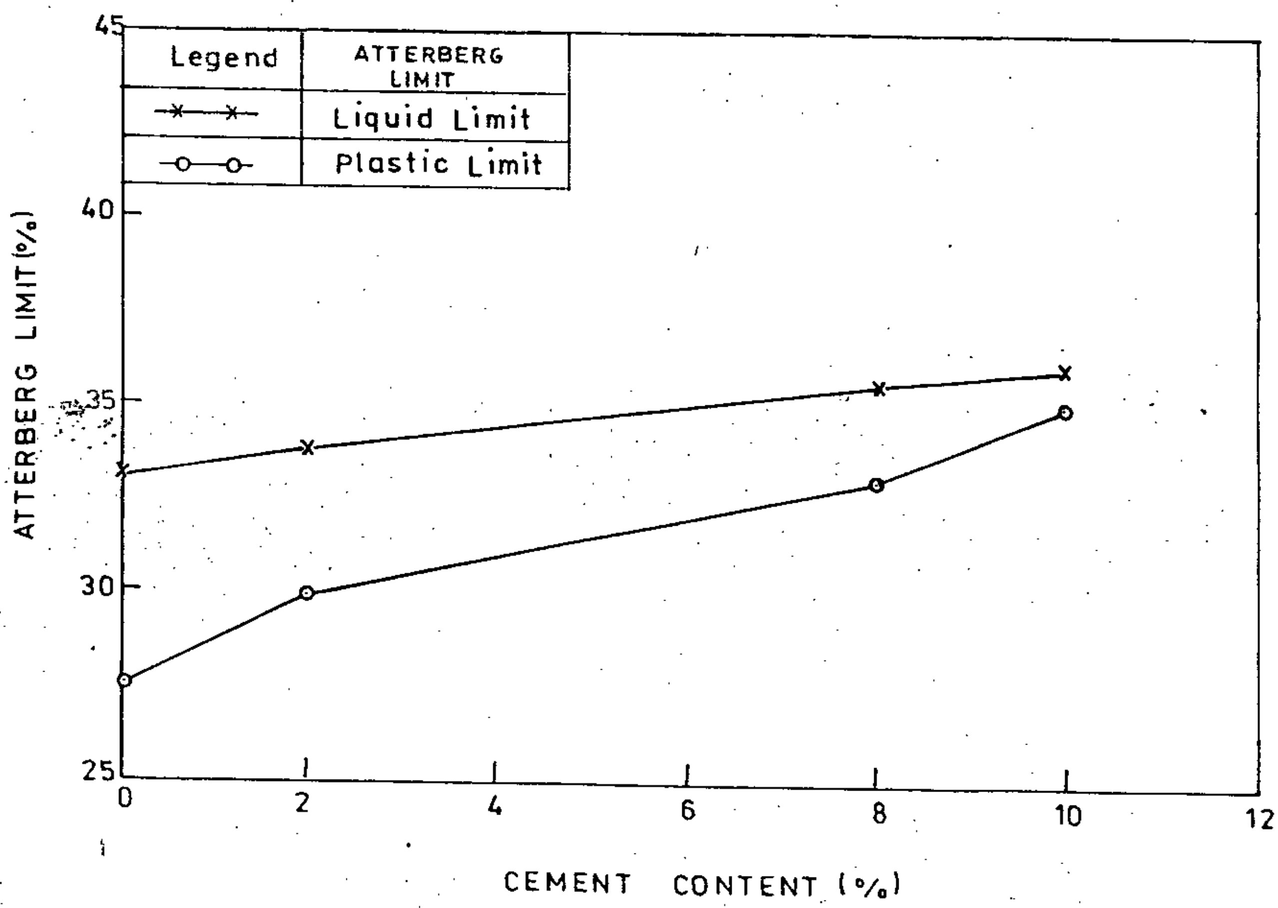


Fig. 5.23 Effect of cement addition on Atterberg limits of soil-B.

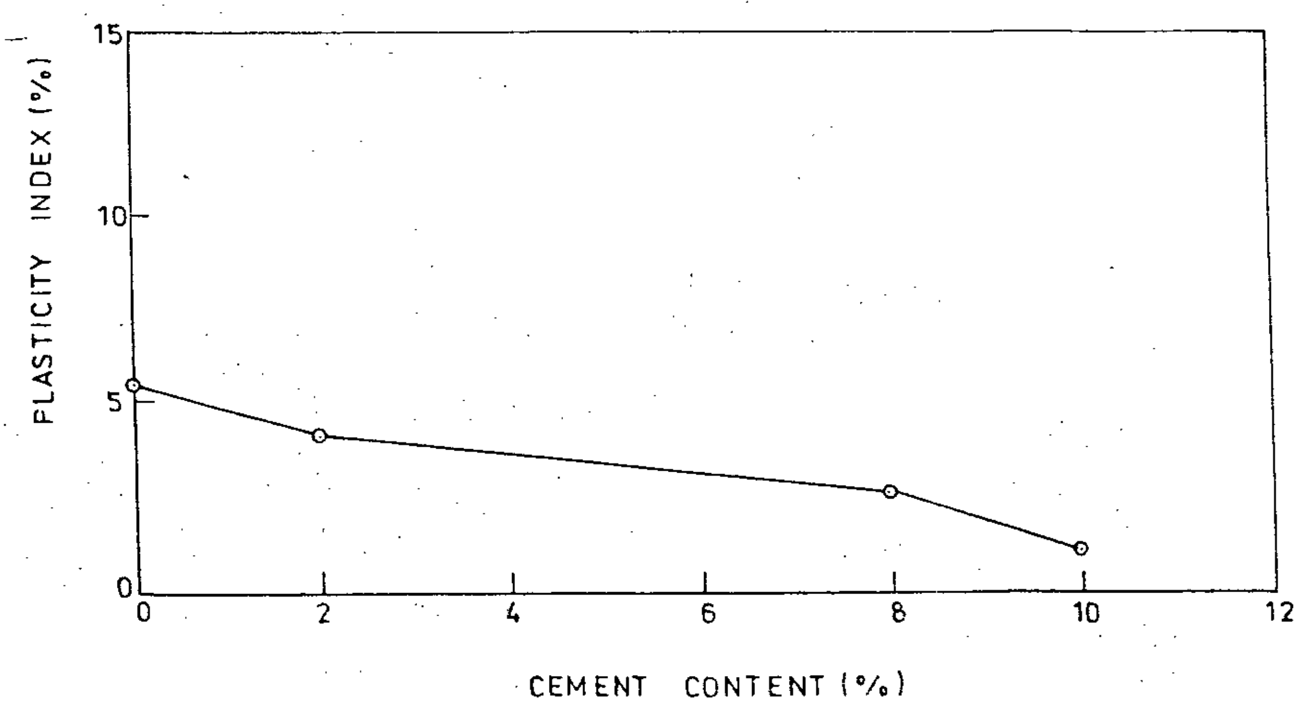


Fig. 5.24 Effect of cement addition on plasticity index of soil-B.

Fig. 5.25 shows that addition of rice husk ash initially decreases the liquid limit and plastic limit of cement-RHA stabilized soil but at ash content greater than $33\frac{1}{3}\%$ both increases, change being appreciable for liquid limit. This results in an increase of plasticity index (Fig.5.26).

5.6 Modification of Soil with Cement

From discussion in previous articles, it is clear that for local alluvial silty soils, strength attainment to meet PCA criteria for soil-cement mixture requires very high amount of cement. Since stabilization is initiated to achieve 'some economy', the technique fails to achieve its goal with involvement of such huge amount of admixture. So alternative is to be searched for other techniques within cement stabilization approach. Cement-modified soil may be thought as an alternative.

As defined earlier, cement-modified soil is an unhardened or semi-hardened mixture of soil and cement at a relatively small quantity of Portland Cement.

In this research, two alluvial silty soils were treated with 2% cement content. In the previous discussions, it has been found that on addition of 2 per cent cement, strength increase of treated soil over untreated one is appreciable. For Soil-A, it is found that at 2% cement content,ratio of unconfined compressive strength of treated

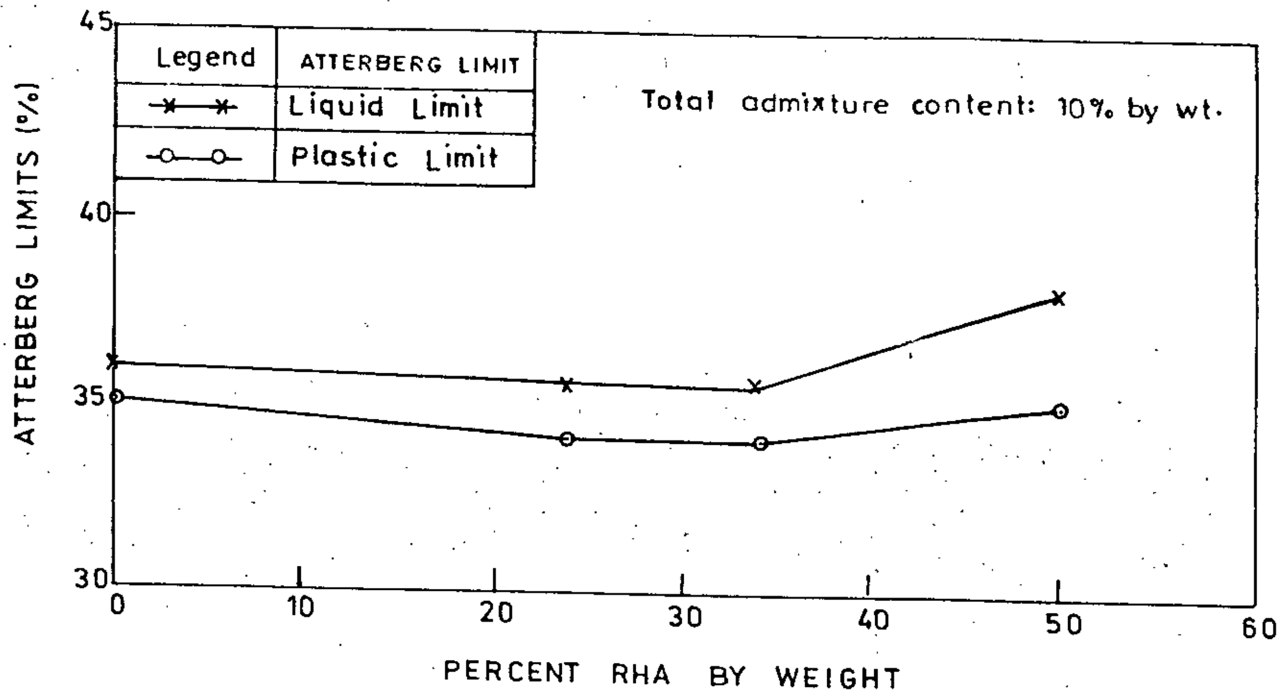


Fig. 5.25 Effect of addition of RHA on Atterberg limits of cement-treated soil-B.

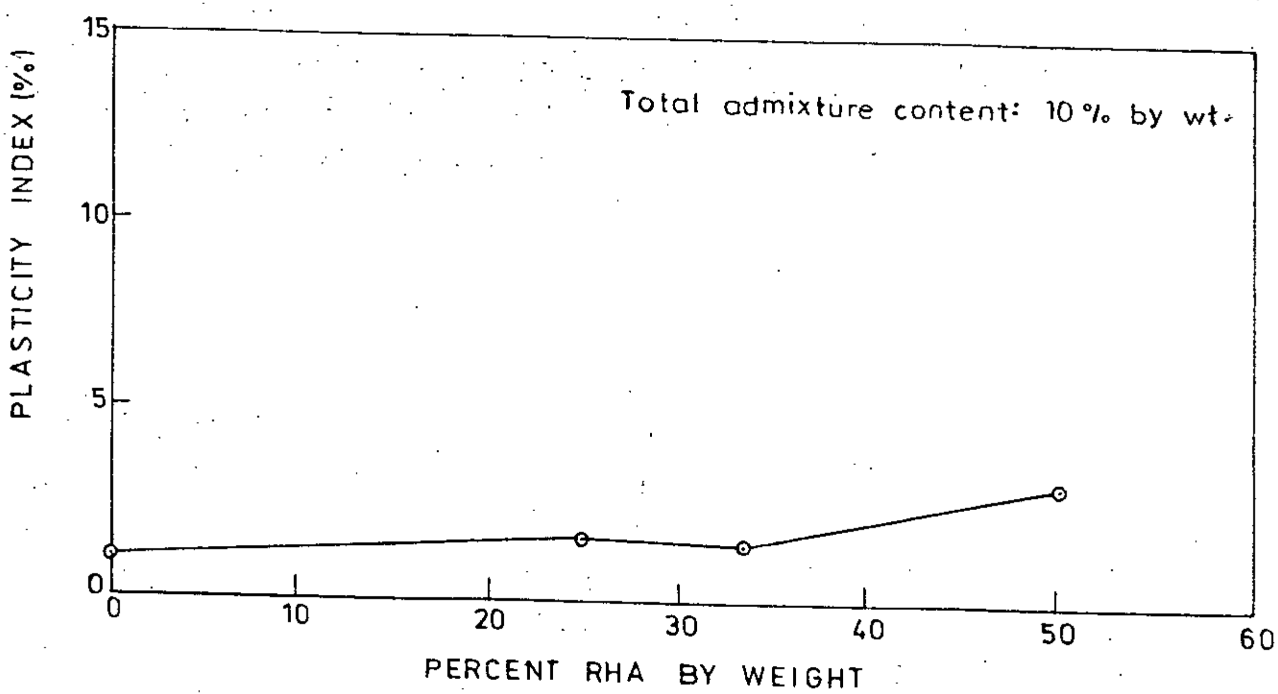


Fig. 5.26 Effect of addition of RHA on plasticity index of cement-treated soil-B.

soil to that of untreated soil stands at 3.42, 4.92 and 11.14 for 7, 14 and 28 days curing period respectively. The corresponding ratio for Soil-B are 5.16, 7.32 and 11.43 respectively. From the results, it is clear that higher strength gain is achieved for higher curing period. However, if the newly constructed cement stabilized road is to be opened to traffic earlier, 7-day curing is essential. Considering all these, cement-stabilized local silty soil with 2% cement content and 7-day curing may be thought as improved subgrade or sub-base material to be adopted in 'stage construction' of highways. Similar study at Singapore revealed that silty soils with only 2% cement addition can successfully be employed for good sub-base or subgrade construction satisfying requirement of Road Research Laboratory, England (1970), Ramaswamy et al (1984). However, more study and field performance observation are required to conclude definitely on this point for silty soils in Bangladesh.

5.7 Properties of RHA-Stabilized Soil

An attempt was made to study the properties of only RHA-stabilized soils. Samples prepared by mixing different percentage of RHA to soil for plasticity and unconfined compression test collapsed during curing. Only 10 hours were required for these to collapse.

So it can be said that like many P.F.As, RHA has no cementation value of its own.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATION FOR FUTURE RESEARCH

6.1 Conclusions

The important findings and conclusions drawn on the various aspects of this research may be summarized with this limited study as follows:

1. The local silty soils satisfy the durability criteria recommended by the Portland Cement Association (PCA) at about 8 per cent cement content. This is within the range suggested by Catton (1940) for similar soils.

2. The silty soils fail to satisfy the minimum unconfined compressive strength criteria of PCA for cement content at which the durability criteria is satisfied. Thus the results do not support the implied assumption that the strength needs will automatically be met if the durability needs are satisfied. For the type of soils used, much higher cement content would be required to satisfy the strength criteria. However, the soils showed appreciable strength gain over untreated soil with addition of only 2% cement by weight.

3. Rice Husk Ash can be blended with cement to stabilize silty soils. The results suggest that a partial replacement of cement by as much as twenty-five

percent of ash is possible without impairing the durability and appreciable decrease in strength of such mixtures in comparison to those where only cement is used.

4. Slight difference is observed in the volumetric changes of soil mixtures where Rice Husk Ash is used. It is found that a reduction in volume takes place during drying cycle of wet-dry test with higher proportion of cement whereas the addition of RHA results in an increase in volume on wetting. Silts show decrease in maximum dry density when treated with cement. Cement-RHA treated silty soils show further decrease in dry density.

5. Curing period and proportion of cement significantly influence the strength characteristics of soil-cement mixtures. The plasticity index value decreases with an increase in cement content.

6. RHA like many other pulverized fuel ash (PFA) has little cementitious property of its own and can only be used as an admixture with other cementitious materials.

6.2 Recommendation for Further Study

New studies are required for investigating various aspects of soil-cement stabilization and soil-cement-RHA stabilization which cannot be covered fully in this research. These may be listed as below:

1. In this research, RHA burnt in laboratory has been used. Recommendation is being made to study the RHAs available from village burnt and rice mill boiler burnt ash and the possibility of using in stabilization. Also various properties of ash e.g., effect of fineness, water required for hydration, actual mechanism of action with cement and soil are required to be studied.

2. Only two silty soil samples were used in this study. So conclusions based on relatively little data need more study to be confirmed. Also, other types of soil must be investigated on treatment with cement and RHA. Lime can also be tried with RHA for stabilization of heavy clay.

3. In the present study, compressive strength of stabilized soil obtained does not satisfy strength criteria set by agencies like PCA, Ministry of Transport, U.K. Field tests and field performances must be studied to set a separate strength criteria for these types of fine grained local silty soils.

4. In this research, silty soils with only 2% cement addition showed appreciable increase in compressive

strength. Further study is being recommended for these cement-modified soils for use as a sub-base or improved subgrade material for road construction.

4. Permeability characteristics, consolidation characteristics and erosion resistance of cement and cement-RHA stabilized mix need to be evaluated to get a thorough knowledge of moisture change, volume change and durability of stabilized construction.

5. Finally, cost of production of RHA and cost-benefit ratio of cement-RHA blend should be evaluated.

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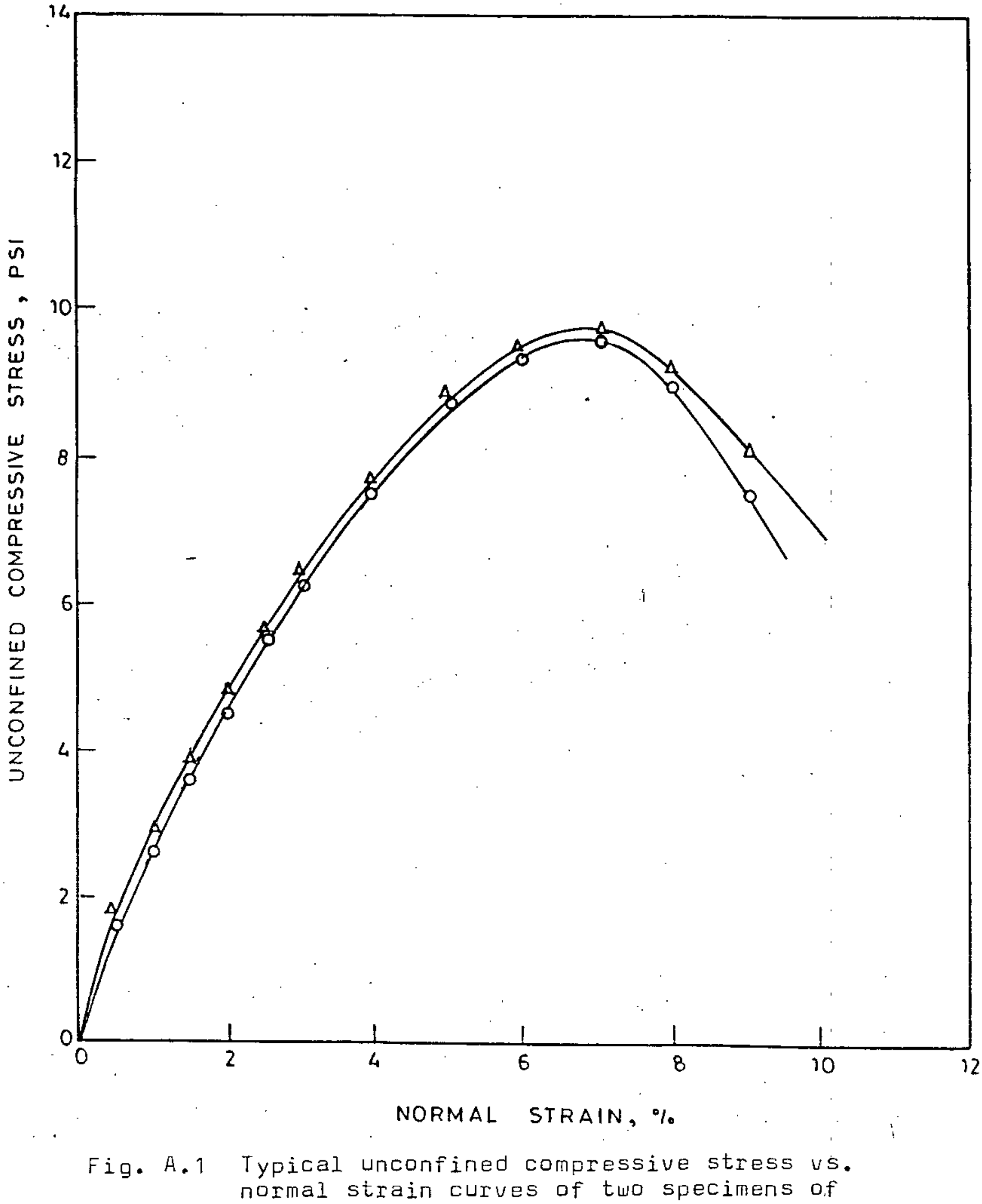

Fig. A.1 Typical unconfined compressive stress vs. normal strain curves of two specimens of untreated Soil-A.

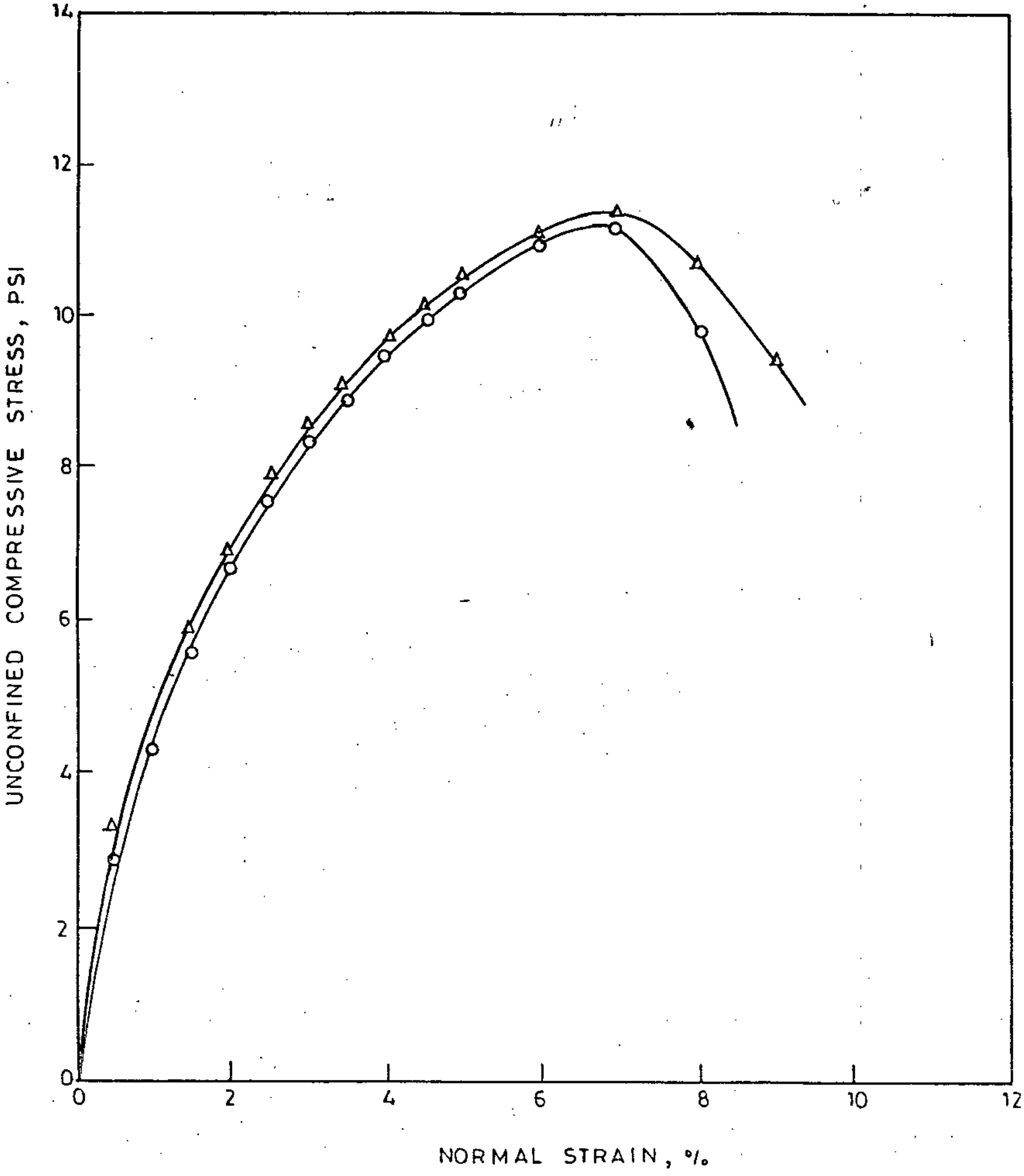

Fig. A.2 Typical unconfined compressive stress vs. normal strain curves of two specimens of untreated Soil-B.

Table A.1 Unconfined compressive strength test results for cement treated Soil-A.

Cement content (% by wt.)	7 days				14 days				28 days			
	Design m.c. (%)	Unconfined compressive strength, psi UC_c	Failure strain (%)	Failure m.c. (%)	Design m.c. (%)	UC_c (psi)	Failure strain (%)	Failure m.c. (%)	Design strain (%)	UC_c (Psi)	Failure strain (%)	Failure mc. (%)
2	15.50	33.10	1.75	27.37	15.50	47.6	2.0	28.83	15.50	107.68	1.50	29.68
8	16.31	93.81	1.25	28.09	16.31	113.32	1.5	29.09	16.31	153.6	1.75	30.01
10	15.81	110.96	1.5	27.82	15.81	136.2	1.25	28.02	15.81	180.31	1.5	29.80

Table A.2 Unconfined compressive strength test results for cement and RHA blend treated Soil-A

Cement:RHA in total admixture	7 days				14 days				28 days			
	Design m.c. (%)	Unconfined compressive strength, psi UC_{RHA-c}	Failure strain (%)	Failure m.c. (%)	Design m.c. (%)	UC_{RHA-c} (psi)	Failure strain (%)	Failure m.c. (%)	Design m.c. (%)	UC_{RHA-c} (psi)	Failure strain (%)	Failure m.c. (%)
3:1	15.1	104.86	1.50	29.22	15.10	136.38	1.50	29.72	15.10	170.94	1.25	33.10
2:1	15.2	99.02	1.25	30.05	15.20	116.21	1.50	29.96	15.20	161.76	1.25	30.25
1:1	14.8	86.95	1.75	31.00	14.8	101.60	1.25	29.72	14.80	131.55	1.50	33.09

Table A.3 Unconfined Compressive strength test results for cement tested Soil-B

Cement content (% by wt.)	7 days				14 days				28 days			
	Design m.c. (%)	Unconfined compressive strength, psi UC_c	Failure strain (%)	Failure m.c. (%)	Design m.c. (%)	UC_c (psi)	Failure strain (%)	Failure m.c. (%)	Design m.c. (%)	UC_c (psi)	Failure strain (%)	Failure m.c. (%)
2	19.3	57.95	3.0	24.97	19.3	82.16	1.75	25.03	19.3	128.33	2.0	25.22
8	19.2	102.64	1.25	25.03	19.2	122.69	1.25	29.16	19.2	160.31	1.25	28.48
10	19.8	131.96	1.5	24.86	19.8	142.68	1.0	29.94	19.8	192.42	1.25	29.46

Table A.4 Unconfined compressive strength test results for cement and RHA blend treated Soil-B

Cement: RHA in total admixture	7 days				14 days				28 days			
	Design m.c. (%)	Unconfined compressive strength psi UC_{RHA-c}	Failure strain (%)	Failure m.c. (%)	Design m.c (%)	UC_{RHA-c} (psi)	Failure strain (%)	Failure m.c. (%)	Design m.c. (%)	UC_{RHA-c} (psi)	Failure strain (%)	Failure m.c. (%)
3:1	19.8	107.92	1.0	27.8	19.8	137.7	1.25	29.7	19.8	187.21	1.25	30.10
2:1	18.4	101.82	1.25	28.21	18.4	132.3	1.25	30.26	18.4	172.58	1.25	30.33
1:1	19.1	95.45	1.25	28.37	19.1	128.96	1.50	29.77	19.1	158.35	1.50	29.82

Table A.5 Maximum volume change and maximum moisture content during wet-dry test of cement stabilized soils

Soil	Cement content, %	Maximum volume change, %		Maximum moisture content, %
		Increase	Decrease	
A	2		1.075	25.71
	4		1.075	24.92
	6		1.08	24.92
	8		1.08	26.42
	10		1.56	27.72
B	2		1.05	27.84
	4		1.15	23.71
	6		1.51	20.89
	8		1.69	25.78
	10		1.82	28.70

Table A.6 Maximum volume change and maximum moisture content during wet-dry test of RHA and cement blend stabilized soils

Soil	Cement:RHA in admixture	Admixture content (%)	Maximum volume change, %		Maximum moisture content, %
			Increase	Decrease	
A	3:1	10	1.15		26.73
	2:1		1.51		29.09
	1:1		1.62		31.41
B	3:1	10	1.15		28.25
	2:1		1.51		28.60
	1:1		1.71		28.90

Table A.7 Effect of addition of cement on maximum dry density of soils

Cement content	Maximum dry density obtained (pcf)	
	Soil-A	Soil-B
0	98.5	104.6
2	95.06	101.27
4	94.10	99.76
6	94.65	100.17
8	94.6	96.67
10	94.6	96.22

Table A.8 Effect of replacement of cement by RHA on maximum dry density of cement stabilized soils

Cement:RHA in admixture	Admixture content (%)	Maximum dry density obtained (pcf)	
		Soil-A	Soil-B
1:0	10	94.6	96.22
3:1		94.21	95.4
2:1		94.27	95.13
1:1		92:48	93.95

Table A.9 Effect of addition of cement on plasticity index of Soil-B

Cement content (%)	Atterberg limits		Plasticity index (%)
	Liquid limit (%)	Plastic limit (%)	
0	33.0	27.5	5.5
2	34.0	30.0	4.0
8	35.5	33.0	2.5
10	36.0	35.0	1.0

Table A.10 Effect of addition of RHA and cement on plasticity index of Soil-B

RHA in admixture (%)	Admixture content (%)	Atterberg limits		Plasticity index (%)
		Liquid limit (%)	Plastic limit (%)	
0	10	36.0	35.0	1.0
25		35.5	34.0	1.5
$33\frac{1}{3}$		35.5	34.0	1.5
50		38.0	35.0	3.0

Table A.11 Results of wetting and drying test of cement-treated Soil-A

a) Volume and moisture content (m.c.) change

Cement content (%)	Sample No.	Cycle No.	Moisture content (m.c.) change (%)			Volume change(%)	
			Moisture content as molded (%)	Subsequent m.c. on wetting (%)	Subsequent m.c. on drying	On wetting	On drying
1	2	3	4	5	6	7	8
2	2(1)	1	15.5	25.71	2.46	0	1.075
		2		Discontd.	Discontd.	Discontd.	Discontd.
		3		-	-	-	-
		4		-	-	-	-
		5		-	-	-	-
		6		-	-	-	-
		7		-	-	-	-
		8		-	-	-	-
		9		-	-	-	-
		10		-	-	-	-
		11		-	-	-	-
		12		-	-	-	-
4	4(1)	1	16.03	24.92	0.82	0	1.075
		2		24.10	0.85	"	"
		3		23.82	0.79	"	"
		4		24.73	0.82	"	"
		5		24.73	0.82	"	"
		6		24.10	0.78	"	"
		7		24.10	0.79	"	"
		8		23.93	0.81	"	"
		9		23.89	0.79	"	"
		10		22.92	0.81	"	"
		11		22.71	0.79	"	"
		12		22.82	0.79	"	"

Table A.11 Contd...

1	2	3	4	5	6	7	8
6	6(1)	1	16.2	21.92	3.36	0	1.08
		2		19.68	3.36	"	"
		3		18.72	3.36	"	"
		4		18.40	2.72	"	"
		5		19.04	3.28	"	"
		6		19.36	3.20	"	"
		7		19.04	3.33	"	"
		8		10.04	2.87	"	"
		9		19.04	2.97	"	"
		10		19.04	3.11	"	"
		11		19.04	2.85	"	"
		12		19.04	2.87	"	"
8	8(1)	1	16.31	26.42	1.79	0	1.08
		2		24.78	1.03	"	"
		3		24.71	1.03	"	"
		4		25.10	2.10	"	"
		5		25.10	1.79	"	"
		6		24.78	1.03	"	"
		7		25.12	1.82	"	"
		8		26.20	1.97	"	"
		9		26.10	1.32	"	"
		10		24.78	1.73	"	"
		11		25.12	1.73	"	"
		12		24.20	1.71	"	"
10	10(1)	1	15.81	27.72	2.27	0	1.56
		2		22.72	2.27	"	"
		3		25.0	2.27	"	"
		4		25.45	3.63	"	"
		5		25.45	2.98	"	"
		6		25.54	3.12	"	"
		7		25.91	2.72	"	"
		8		25.64	3.26	"	"
		9		25.00	3.11	"	"
		10		25.00	3.31	"	"
		11		25.45	3.45	"	"
		12		23.18	3.50	"	"

Table A.11 Contd..

b) Soil-Cement Loss:

Cement content (%)	Avg. water retained after drying at 110°C (%)	Soil-cement loss (%)
2	0.18	31.38
4	0.24	22.16
6	0.27	15.44
8	1.10	10.59
10	0.51	4.18

Table A.12 Results of wetting and drying test of cement-treated Soil-B

a) Volume and moisture content (m.c.) change

Cement content (%)	Sample No.	Cycle No.	Moisture content (m.c.) change (%)			Volume change (%)	
			Moisture content as molded (%)	Subsequent m.c. on wetting (%)	Subsequent m.c. on drying (%)	On wetting	On drying
1	2	3	4	5	6	7	8
2	2(1)	1	19.04	27.84	2.1	0	1.05
		2		21.56	1.6	"	"
		3		16.16	1.4	"	"
		4		discontd.	discontd.	dis-contd.	discontd.
		5					
		6					
		7					
		8					
		9					
		10					
		11					
		12					
4	4(1)	1	19.20	23.71	1.92	0	1.15
		2		23.10	1.82	"	"
		3		23.10	1.74	"	"
		4		22.80	1.69	"	"
		5		22.80	1.71	"	"
		6		23.10	1.71	"	"
		7		23.40	1.69	"	"
		8		22.80	1.72	"	"
		9		23.10	1.72	"	"
		10		22.80	1.81	"	"
		11		22.50	1.81	"	"
		12		22.50	1.81	"	"

Table A.12 Contd..

1	2	3	4	5	6	7	8
		1		20.89	2.69	0	1.51
		2		20.60	2.89	"	"
		3		20.30	3.28	"	"
		4		20.00	2.68	"	"
		5		20.60	2.68	"	"
6	6(1)	6	19.20	20.00	2.68	"	"
		7		20.60	2.68	"	"
		8		20.00	2.10	"	"
		9		20.30	2.68	"	"
		10		20.00	2.68	"	"
		11		20.00	2.98	"	"
		12		20.00	3.28	"	"
		1		25.78	0.93	0	1.69
		2		23.91	0.62	"	"
		3		23.60	0.93	"	"
		4		23.60	0.93	"	"
		5		23.91	0.73	"	"
8	8(1)	6	19.8	23.60	0.42	"	"
		7		23.60	0.66	"	"
		8		23.60	0.31	"	"
		9		23.60	0.38	"	"
		10		23.29	0.89	"	"
		11		22.98	0.38	"	"
		12		23.29	1.41	"	"
		1		28.70	3.47	0	1.82
		2		26.50	3.47	"	"
		3		26.50	3.47	"	"
		4		26.50	3.78	"	"
		5		26.81	3.69	"	"
10	10(1)	6	18.8	26.50	3.97	"	"
		7		26.50	3.76	"	"
		8		26.50	3.90	"	"
		9		26.81	1.18	"	"
		10		25.86	2.58	"	"
		11		25.86	1.18	"	"
		12		26.18	2.71	"	"

Table A.12 Contd..

b) Soil-cement loss:

Cement content (%)	Avg. water retained after drying at 110°C (%)	Soil-cement loss (%)
2	3.0	42.72
4	3.0	18.26
6	2.28	16.80
8	1.41	12.42
10	2.71	7.32

Table A.13 Results of wetting and drying test of cement-RHA treated Soil-A

a) Volume and moisture content (m.c.) change:

Cement: RHA	Sample No.	Cycle No.	Moisture content (m.c.) change (%)			Volume change %	
			Moisture content as molded (%)	Subsequent m.c. on wetting	Subsequent m.c. on drying	On wetting	On drying
1	2	3	4	5	6	7	8
3:1	3:1(1)	1	15.1	26.73	1.58	1.62	0
		2		24.44	0.61	"	"
		3		24.88	0.67	"	"
		4		25.21	0.28	"	"
		5		25.23	0.35	"	"
		6		26.10	0.30	"	"
		7		24.90	0.14	"	"
		8		24.92	0.10	"	"
		9		24.58	0.05	"	"
		10		24.97	0.07	"	"
		11		24.56	0.10	"	"
		12		24.56	0.29	"	"
2:1	2:1(1)	1	15.2	29.09	0.43	1.51	0
		2		23.14	0.74	"	"
		3		23.62	0.05	"	"
		4		23.57	0.44	"	"
		5		24.55	0.37	"	"
		6		23.67	0.14	"	"
		7		23.54	0.14	"	"
		8		23.31	0.81	"	"
		9		23.87	0.84	"	"
		10		24.10	0.10	"	"
		11		22.74	0.17	"	"
		12		22.97	0.12	"	"

Table A.13 Contd..

1	2	3	4	5	6	7	8
		1		31.41	4.35	1.15	0
		2		24.65	0.60	"	"
		3		27.44	0.15	"	"
		4		26.74	0.41	"	"
		5		27.48	0.24	"	"
1:1	1:1(1)	6	14.8	26.65	0.48	"	"
		7		27.20	0.21	"	"
		8		26.81	0.10	"	"
		9		26.46	0.18	"	"
		10		27.06	0.11	"	"
		11		27.56	0.05	"	"
		12		26.13	0.05	"	"

b)-Soil-cement loss:

Cement:RHA in total admixture	Avg. water retained after drying at 110°C (%)	Soil-cement loss (%)
3:1	0.18	10.03
2:1	0.39	12.26
1:1	0.16	15.43

Table A.14 Results of wetting and drying test of cement-RHA treated Soil-B

a) Volume and moisture content (m.c.) change:

Cement: RHA(%)	Sample No.	Cycle No.	Moisture content (m.c) change (%)			Volume change (%)	
			Moisture content asmolded (%)	Subsequent m.c on wetting	Subsequent m.c. on drying	On wetting	On drying
1	2	3	4	5	6	7	8
3:1	3:1(1)	1	19.8	28.25	0.63	1.15	0
		2		24.76	0.95	"	"
		3		24.13	0.75	"	"
		4		24.24	0.75	"	"
		5		24.69	0.75	"	"
		6		24.48	0.42	"	"
		7		24.20	0.69	"	"
		8		25.00	0.56	"	"
		9		24.08	0.14	"	"
		10		24.50	0.10	"	"
		11		24.25	0.35	"	"
		12		24.28	0.35	"	"
2:1	2:1(1)	1	19.2	28.60	1.93	1.511	0
		2		25.40	0.63	"	"
		3		25.07	0.53	"	"
		4		25.47	0.42	"	"
		5		27.36	0.42	"	"
		6		27.40	0.42	"	"
		7		26.29	1.32	"	"
		8		27.83	0.39	"	"
		9		27.13	0.31	"	"
		10		26.86	0.10	"	"
		11		26.36	0.10	"	"
		12		27.30	0.08	"	"

Table A.14 Contd.

1	2	3	4	5	6	7	8
		1		28.90	0.66	1.71	0
		2		26.91	0.66	"	"
		3		26.58	0.10	"	"
		4		27.72	1.00	"	"
		5		27.20	0.71	"	"
1:1	1:1(1)	6	19.1	24.50	0.61	"	"
		7		26.21	0.71	"	"
		8		26.92	0.81	"	"
		9		27.41	1.12	"	"
		10		27.72	1.40	"	"
		11		26.20	0.80	"	"
		12		26.40	0.71	"	"

b) Soil-cement loss:

Cement:RHA in total admixture	Avg. water retained after drying at 110°C (%)	Soil-cement loss (%)
3:1	0.41	6.41
2:1	0.24	11.25
1:1	0.30	13.28