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Helsinki 1992

Finnish National Road Administration
Overseas
Projects Office

Hannu Lehtikankare

SOIL STABILIZATION WITH AN ACIDIC CHEMICAL ON ZAMBIAN ROADS

FINNIDA
Finnish International Development Agency

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ABSTRACT

The Finnish National Road Administration is implementing road maintenance projects in Zambia, Tanzania and Ethiopia. A soil stabilizer whose trademark is ISS (Ionic Soil Stabilizer) was introduced in 1990 to the road maintenance project in Zambia. The stabilizer was promoted to be a cheap and lasting solution to problems on rural roads in developing countries. Before making larger investments on this product it was decided that further research would be done.

According to the supplier the ISS-chemical stabilizes soil electrochemically. In order to understand the effect of the stabilizer ion exchange and the structure of clay particles and adsorbed water is presented in this report. In an analysis ISS was found to be mainly lean sulphuric acid. The possible reactions taking place in the soil were not analyzed, but it is assumed that salt compounds could be produced. The only research reports available concerning ISS were received from the supplier, but reports from disinterested research institutes concerning another stabilizer with a similar composition (trademark RRP) were found. With one exception, none of the reports represented positive effects of RRP. The environmental impact of ISS was evaluated by using information from sulphuric acid studies.

Geotechnical properties were studied and unconfined compression tests, CBR tests and soaking tests were made with ISS-treated and untreated Zambian soil samples. The specimens cured in dry or moist air for 7 to 75 days. Parallel specimens were made with ISS, sulphuric acid, lime and water. Furthermore, a possibility to use ISS in dust binding was studied with Finnish gravels. Benkelman beam and the sand replacement methods were used in the field investigations on the test road in Zambia. To evaluate visually the result of the stabilization on the road a condition classification has been presented.

One of the investigated Zambian clays was more durable in the water soaking test when it had been treated with ISS or sulphuric acid and subsequently kept in moist air a minimum of 30 days. The specimens treated with lime were, however, considerably more durable. None of the other tests or soils (one exception) indicated any difference between the ISS-treated and untreated soils. The test road in Zambia began to deteriorate rapidly, and at least during this research the stabilization has not improved the quality of the road. It was not possible to show from these tests that ISS improved the properties of road materials so that this would have practical meaning. This stabilizer may work in some other soils or circumstances better but according to the tests in this research it is not a universally applicable solution for the road problems in developing countries.

FOREWORD

This research has been done in the Overseas Projects Office of the Finnish National Road Administration (FinnRA) as a part of a road maintenance project in Zambia implemented by FinnRA and funded by the Finnish International Development Agency (FINNIDA). The object of this research was to find out the possibilities of using an acidic, water soluble stabilizer (trademark Ionic Soil Stabilizer, ISS) especially for the improvement of African rural roads. Geotechnical laboratory tests have been carried out in the laboratories of FinnRA in Helsinki and the Zambian Roads Department in Lusaka. The stabilizer has been analyzed in the Finnish oil company Neste Ltd. The chemical and mineralogical composition of soils was analyzed by the Geological Survey of Finland. The stabilizer was tested on a road near Lusaka in Zambia.

The research is based on the results of laboratory tests with Zambian soils and on the experiences from a test road in Zambia. Furthermore, the physical and chemical foundation of the action of the stabilizer on the clay particles is dealt, and literature concerning the ISS-stabilizer has been studied together with literature concerning another, similar stabilizer trademarked RRP.

This report has been written by Hannu Lehtikankare, and this research has been accepted as his master's thesis by the Faculty of Civil Engineering and Surveying in the University of Technology in Helsinki, April 1992.

Helsinki, 14th of April, 1992

Overseas Projects Office
Finnish National Road Administration

CONTENTS

Appendix

SYMBOLS

E	modulus of deformation [MPa/m^2]
E	molecular weight [-]
K_w	ionic product of water [10^{-14} in 25°C]
LC50	concentration that within testing period kills 50% of the population [mg/l]
LD50	dose that kills 50% of the population [mg/kg]
LL	liquid limit [%]
$M_{e,(+m)}$	concentration of an exchangeable cation of valence m in the soil
$M_{0,(+m)}$	concentration of the exchangeable cations in the outside solution
P_k	load of a dual wheel [kN]
P_p	load of one tyre [kN]
PI	plasticity index [%]
T	temperature [K]
Å	Angstrom [10^{-7} mm]
a	quantity of an element [g]
c	distance from center to center between the tyres of a dual wheel [m]
e	elementary charge [1.6 x 10^{-19} C]
k	Boltzmann constant [1.38 x 10^{-23} JK^{-1}]
k_c	constant depending upon specific cation adsorption effects and upon the clay surface
meq	milliequivalent
n	concentration of ions [ions/cm^3]
n_o	concentration of ions at a large distance from a surface [ions/cm^3]
p_r	tyre pressure [kPa]

ppm	parts per million
q	contact pressure [kPa]
r	radius of a loading circle [m]
s	deflection [mm]
s_1	loading deflection [mm]
s_2	permanent deflection [mm]
v	valence of an ion [-]
x	distance from a surface [m]
ϵ	permittivity [$N^{-1}m^{-2}C^2$]
ϵ_o	vacuum permittivity [8.854×10^{-12} $N^{-1}m^{-2}C^2$]
ϵ_r	relative permittivity [-]
Ψ	potential [$JC^{-1} = V$]
ρ	density of elctric charge [Cm^{-3}]
μ	Poisson's ratio [-]

DEFINITIONS

CSIR	South African Council for Scientific and Industrial Research A disinterested research institute
earth road	constructed using the natural soil found on the route
FHWA	Federal Highway Administration, USA
FINNIDA	Finnish International Development Agency which plans and finances Finnish development co-operation within the Ministry for Foreign Affairs.
FinnRA	Finnish National Road Administration which is a national road authority subordinated to the Ministry of Communication. FinnRA is responsible for Finnish public roads, and it is actively involved in overseas projects within road, waterway and port sectors.
gravel road	surfaced with a layer of improved material which is stronger than the natural soil
ISS	Ionic Soil Stabilizer (Trade mark) An acidic chemical used for the stabilization of road surfacing. Researched in this study.

meq/100g	meq is milliequivalent meq = a/E, where a is quantity of an element [g] E is equivalent weight [-] E = (molecular weight)/(valence) Example of calcium: E of Ca^{2+} is 40.08/2 weight of sample is 100 g
NMR-analysis	Nuclear Mass Spectrometer analysis Used in the determination of the composition of matters
relative permittivity ϵ_r	$\epsilon_r = \epsilon/\epsilon_o$ ϵ $[N^{-1}m^{-2}C^2]$is permittivity which describes the influence of medium on the forces between charges. The bigger the permittivity the smaller the force. ϵ_o is vacuum permittivity $[8.854 \times 10^{-12} N^{-1}m^{-2}C^2]$,[2]
RRP	Reynold's Road Packer (Trade mark) A chemical which is very similar to the above mentioned ISS. Research reports concerning RRP are considered in this study together with writings concerning ISS.
van der Waals forces	all the forces between atoms that are not caused by ionic bond, covalent bond metal bond or hydrogen bond

1 Introduction

The Finnish National Road Administration (FinnRA[1]) is responsible for the implementation of a number of transport sector projects funded by the Finnish International Development Agency (FINNIDA[1]). The road infrastructure is a fundamental necessity of any developing country but the cost of establishing and maintaining it and a lack of expert knowledge impedes progress.

Especially in the tropical and subtropical developing countries the erosion and the loss of the bearing capacity due to the heavy rains and the poor road materials are severe problems for the roads, many of which are partly or totally impassable a long period of the year. To solve these problems with conventional road construction methods, i.e. use of good gravel or crushed material or soil stabilization with lime, cement or bitumen, is technically quite possible, but the costs are too high for a poor country, even if it is aided. The main roads can be in moderately good condition but most of the rural roads remain to be poorly passable earth roads. However, for the transportation of the agricultural products it is necessary to use these rural roads. Therefore, huge amounts of food become rotten in storage because it is not possible to supply them to the public.

Figure 1. *A rural road in a poor condition in Zambia. The place in the district road D154 near Lusaka where the red clay was taken for the laboratory tests (Chapter 4.).*

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[1] *See definitions!*

The existing road network which has once been satisfactory is rapidly deteriorating or is already ruined, due to neglect of maintenance. To turn this process around FinnRA is implementing road maintenance assistance projects in Zambia, Tanzania and Ethiopia (Figure 2.). The main tasks of the projects are repairing and improving the roads by providing technical assistance, equipment, machinery and spare parts to the local road authorities. Furthermore, the local staff is trained in the use of equipment, maintenance methods and management systems.

A chemical stabilizer (Trade mark ISS) was introduced to the Finnish project in Zambia in 1990. According to the litterature received from the supplier this chemical had been used in Latin America and in South Africa since early 1970's. The supplier assured that the stabilizer makes it possible to utilize poor materials that already exist along a route, and thus, the stabilized layer would replace imported base course, sub-base and sub-grade layers. In low-volume rural roads it could be used instead of regravelling and the roads would not need grading for some years. The action of the stabilizer is said to be based on ion exchange on the clay particles, and thus, the adsorbed water reduces permanently. Therefore, the soil could stay durable against wearing of traffic or water. The action of the chemical is explained and evaluated closer in Chapter 3, and for its background information the structure of clay minerals, soil water and ion exchange are considered in Chapter 2.

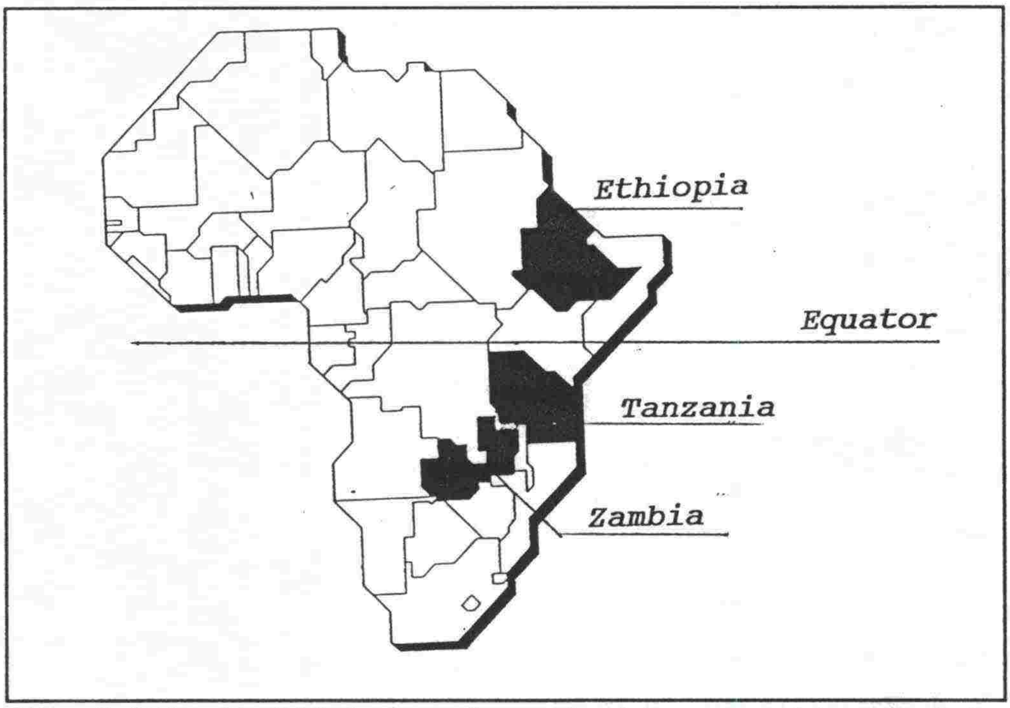

Figure 2. Africa. FinnRA is implementing road maintenance assistance projects in Zambia, Tanzania and Ethiopia.

This stabilization method costs less than the traditional alternatives. This method would be an ideal solution for the maintenance of rural roads if it worked on all fine grained soils, as declared by the supplier in Zambia. The chemical costs about 2500 USD per a 200 liter drum, and one drum should cover 1 km of a 7 m wide road.

Because the chemical is, however, considerably expensive, it was decided that before making an agreement for larger deliveries the properties and applicability of this stabilization technique are researched. The chemical was tested mostly with Zambian soils in laboratories in Zambia and in Finland, and two sections of gravel road in poor condition were stabilized in Zambia. The aim of the laboratory tests was to find out how the ISS-chemical affects the geotechnical properties, strength and water-resistance of the soils. A 15 cm thick surfacing layer of the test road was stabilized with the chemical in finding the suitable working methods of the stabilization and in proving the wear resistance of the stabilized surfacing.

The test road has been completed and most of the soil samples have been taken in the Lusaka Province of Zambia (Figure 3.). The test road was an old gravel road, district road number D177 north from Lusaka. Samples for the laboratory tests were taken from that road and from a rural earth road, district road number D154 southeast from Lusaka (Figure 27.). The geology in this part of Africa can differ from other parts of Africa and is at least totally different from the geology of Finland. Thus, the results of this research may be incongruous to soils from somewhere else.

Soil classifications of the tested soils as well as of the soils in referred articles have been made according to the internationally known American AASHO System and the Unified Classification System. This Unified Classification System is named in this text ASTM. It was originally developed by Casagrande, and is also known as the AC System. The both classifications - named here AASHO and ASTM - are presented in the ASTM standard book; the AASHO classification is standard D-3282 [7] and the ASTM classification standard D-2487 [6].

The unconfined compression tests, CBR-tests, compaction tests and water soaking tests were made and the plastic properties and the grain size distribution were determined before and after the stabilization in a laboratory to evaluate the influence of the chemical. The object of the tests was to find out what effects the stabilization has on the strength, compactability and water-resistance of soils. These tests followed AASHO, ASTM and British Standard and instructions of Finnish Road authorities where applicable, but due to the role of water and curing time, special tests had to be done.

Methods of executing the stabilization work were being learned

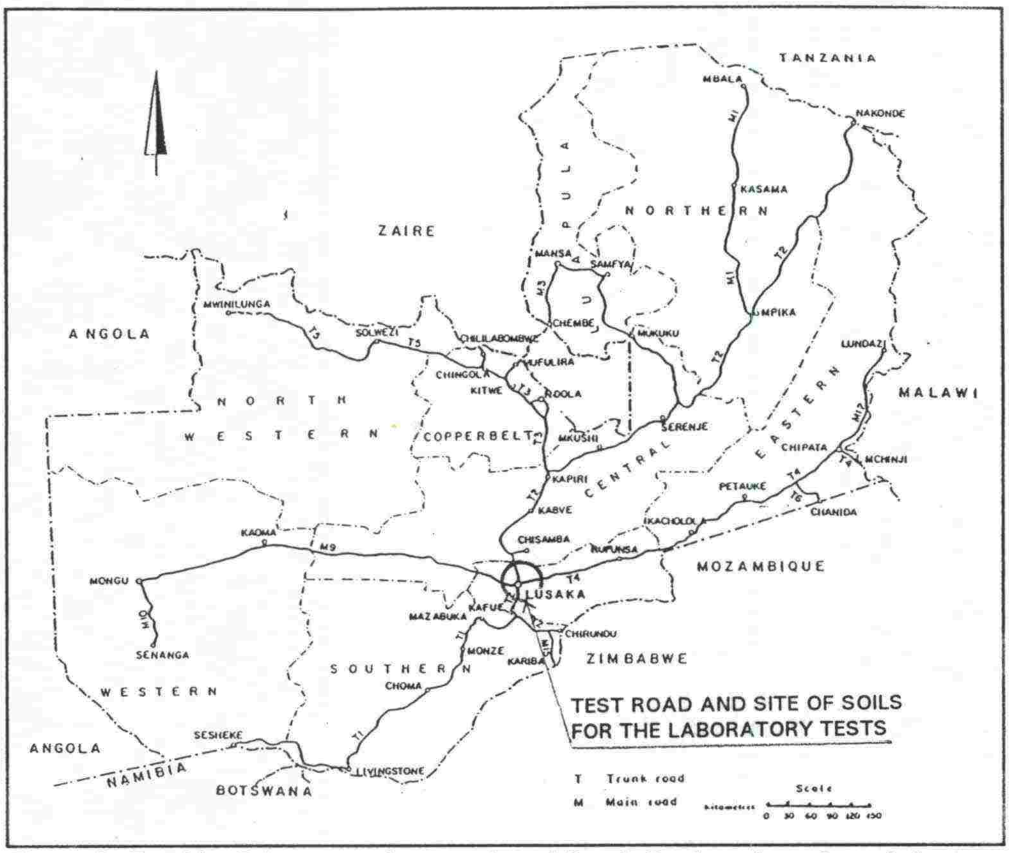

Figure 3. Zambia. Primary road network and Road districts. Location of the test road [12].

while working on the test roads and the work has been described in detail. The success of the stabilization has been evaluated with in-situ tests and visual examination. The in-situ field density and Benkelman beam tests on the roads were done with equipment from the Zambian Roads Department which in practice complies with British standards or instructions. A classification of stabilized roads is presented for visual examination.

2 Physical and chemical properties of clay particles

2.1 Clay minerals

2.1.1 Structure of the clay minerals

Mineralogy is the primary factor controlling the size, shape and physical and chemical properties of soil particles. The most of the solid phase consists of crystalline clay and nonclay minerals and it may contain various amounts of noncrystalline clay material, organic matter and precipitated salts. Although the amount of nonclay mineral is usually considerably greater than the proportion of clay minerals, the clay generally influence behaviour to an extent much greater than its relative abundance[31].

The term "clay" can mean the size fraction of soils with particles of less than 0.002 mm or certain minerals which are the result of chemical weathering of rocks and which are usually not present as larger particles.

A large number of different clay minerals has been identified but only few of them have practical significance in the soils commonly encountered in engineering purposes.

Clay minerals are alumino-silicates, i.e. oxides of aluminium and silicon with smaller amounts of metal ions substituted within the crystal. Substitution of ions of one kind by ions of another type, with the same or different valence but with retention of the same crystal structure, is termed **isomorphous substitution**.

The two basic units in clay mineral structures are the silica tetrahedron, with a silicon ion tetrahedrally coordinated with four oxygens and the aluminium or magnesium octahedron, wherein an aluminium or magnesium ion is octahedrally coordinated with six oxygens or hydroxyls. Usually the silica tetrahedra associate in a sheet structure in which three of the four oxygens are shared with the adjacent silicons. The bases of the tetrahedra are all in the same plane and the tips all point in the same direction. Because one silicon (Si^{4+}) has one oxygen (O^{2-}) of its own and shares three others, the unit has a negative charge of 1. When the top oxygen takes on a hydrogen with a positive valence of 1 to become hydroxyl ($O^{2-} \rightarrow OH^{-}$) the unit is neutral. The aluminium and magnesium octahedra associate in a sheet in which each oxygen or hydroxyl is shared by two aluminium (Al^{3+}) or magnesium (Mg^{2+}) or substituted ions. If the cation is trivalent, then only two-thirds the possible cationic places will be normally filled and the structure is called dioctahedral. If the cation is divalent, all possible cationic places will normally be filled and the structure is called trioctahedral. In the case of aluminium the composition is $Al_2(OH)_6$

and the mineral is called gibbsite while with magnesium the composition is $Mg_3(OH)_6$ and the mineral is called brucite [31],[50]. Diagrammatic sketches of the clay mineral structures are shown in the Figure 4.

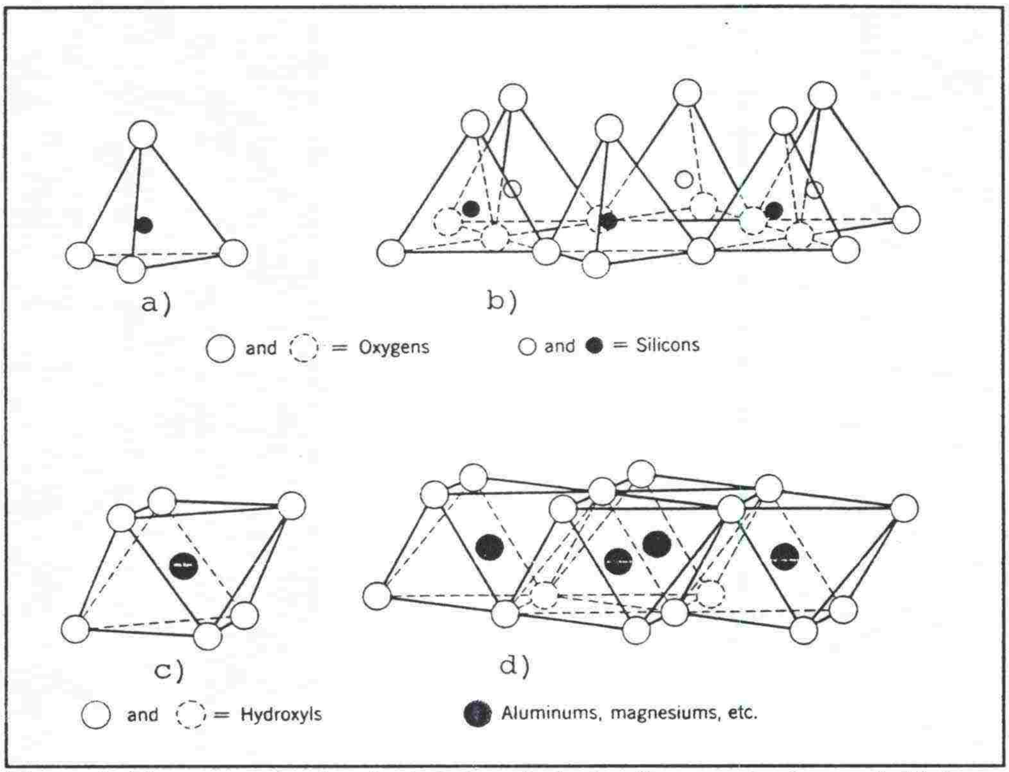

Figure 4. Diagrammatic sketch showing a) single silica tetrahedron unit b) the sheet structure of silica tetrahedra c) single octahedron unit and d) the sheet structure of the octahedra[15].

The different clay mineral groups are characterized by the stacking arrangements of sheets of these units and the interlayer bondings which hold two successive two- or three-sheet layers together. When a tetrahedron sheet is joined to a octahedron sheet, a crystal type is 1:1 while a octahedron sheet between two tetrahedron sheets is a type 2:1. A crystal type 2:2 is consisted of two tetrahedron and two octahedron sheets by turns (Figure 5.). The stacking in the basic clay mineral layer is such that a single plane of atoms is common to both the tetrahedral and octahedral sheets. Thus, bonding between these sheets is of the primary valence type and very strong [31].

Differences among minerals within clay mineral groups arise chiefly from differences in the type and amount of isomorphous substitution within crystal structure. Common examples of the substitution are aluminium in place of some silicon, magnesium instead of aluminium and ferrous iron(Fe^{2+}) for magnesium. The octahedral and tetrahedral cation distributions develop during initial formation of the mineral, not by later replacement. If an ion is substituted by an ion of lower valence (eg. Al^{3+} by Mg^{2+}), a clay particle will get a net negative charge, which is very typical.

To preserve electrical neutrality cations are attracted and held on the surfaces. These cations are termed **exchangeable cations** because in most instances cations of one type may be replaced by cations of another type. The quantity of exchangeable cations required to balance the charge deficiency of a clay is termed the cation exchange capacity and is usually expressed as milliequivalents per gram or per 100 gram[1] [31].

In the following, clay minerals common in soils are presented.

2.1.2 Kaolinite

Kaolinite is type 1:1 where crystal consists of repeating layers, each layer consisting of a silica sheet and an alumina sheet (Figure 6.a). The layers are held together by hydrogen bonding between hydroxyls from the alumina sheet on one face and oxygens from the silica sheet on the opposite face of the layer. The bonding can also be due to van der Waals forces[1] [31]. These layers are relatively strong, preventing hydration between layers and thus interlayer swelling and allowing particles up to 70-100 layers to build up [50].
Kaolinites are found in soils that have undergone considerable weathering in warm, moist climates, and so they are common in tropical and subtropical areas.

Halloysite is an exceptional member of the kaolinite subgroup because it can occur in hydrated form with a layer of water molecules between the layers of the kaolinite crystal [50].

Isomorphous substitution is not common in kaolinite [15].

2.1.3 Montmorillonite

Montmorillonite is type 2:1. It has repeating layers consisting of an aluminium sheet between two silica sheets(Figure 6.b). Bonding which occurs between successive layers is caused by van der Waals forces and by cations that may be present to balance charge deficiencies in the structure. Several layers of water molecules can easily be adsorbed between the mineral layers resulting in remarkable swelling to several times its dry volume [31].

Montmorillonite is mostly found in sediments of semiarid regions and it is the main mineral in bentonite rock. It is formed when volcanic ash weathers in marine water or under conditions of

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[1] *See Definitions!*

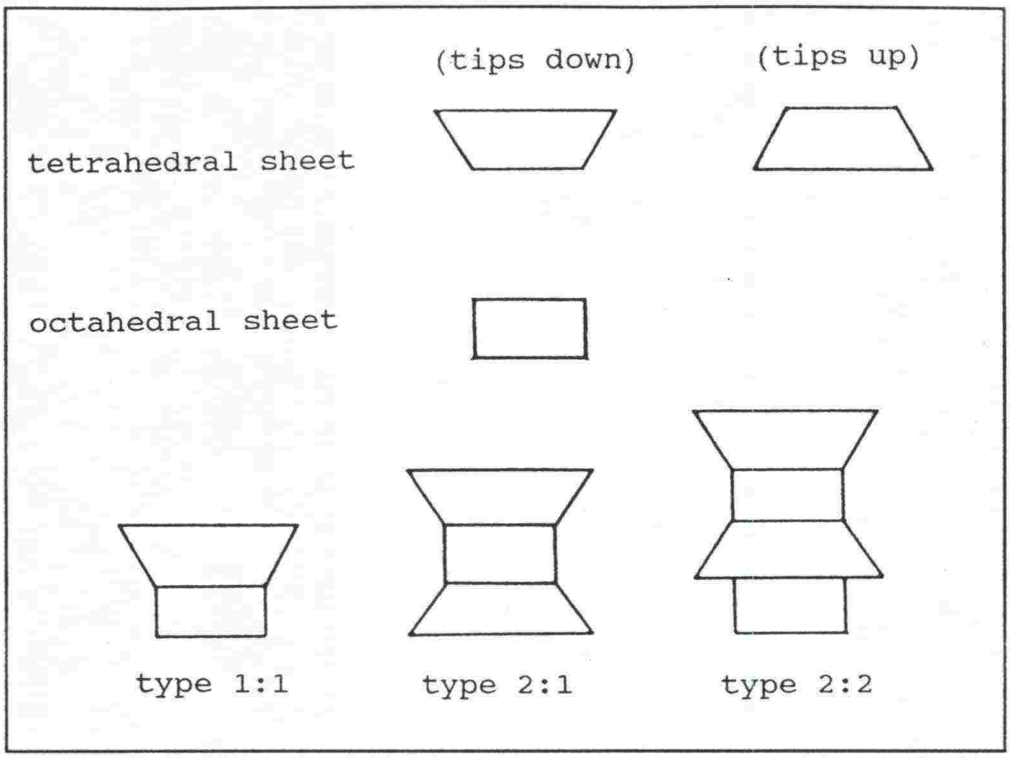

Figure 5. *Schematic representations of the clay mineral structural units [31,27].*

restricted drainage [50].

There are plenty of isomorphous substitutions in the montmorillonite. Most of them occur in the aluminium sheet, with magnesium or iron substituting for aluminium but aluminium may replace up to 15 per cent of the silicon ions in the tetrahedral sheet [31].

2.1.4 Illite (clay mica)

Illite is also type 2:1 when it has the same layer as the montmorillonite, however, the layers are bonded together by potassium ions (K^+) which are not exchangeable (Figure 6.c) [31].

Illite usually occurs as very small, flaky particles mixed with other clay and nonclay materials. It is also in soils derived from weathering of sedimentary rocks and it is the dominant mineral in slate and shale [50].

The isomorphous substitution in illite is extensive. The negative charge due to substitution of aluminium for silicon in the silica sheet is partly balanced by the potassium cations. Thus, the cation exchange capacity of illite is less than that of montmorillonite [31].

2.1.5 Vermiculite

Vermiculite is also type 2:1 when either it has one octahedral sheet between two silica sheets but in this case the adsorption of the water molecules is limited to two layers between mineral layers. In the vermiculite structure there are also hydrated exchangeable cations, usually magnesium and calcium, between the mineral layers (Figure 6.d). The organization of the water around the magnesium ions and the relatively large charge on the lattice as compared with montmorillonite appear to prevent the expansion of the mineral when treated with polar molecules [15]. However, the interlayer water is easily driven off by heating to temperatures higher than 100 °C, but the mineral quickly rehydrates and expands again when exposed to moist air at room temperature [31]. Commercially vermiculite is used for packing by rapidly heating it so that steam forces the layers apart and the clay expands [50].

Vermiculite is a weathering product of mica and occurs as small particles as an accessory mineral in many clay soils. It can also appear in nature as large crystalline masses [50].

An aluminium substitutes for a silicon in the silica sheet leaving a high net negative charge. Thus vermiculite has the highest cation exchange capacity of all the clay materials [50].

2.1.6 Chlorite

The structure of chlorite is similar to vermiculite except that an octahedral sheet replaces the double water molecule layer between the 2:1-layers (Figure 6.e). Thus, it is type 2:2. Various members of the chlorite group differ in the kind and amounts of substitution and in the stacking of successive layers, and there may be some hydration between the layers [31].

Chlorite is typically found in areas of metamorphic parent rock, and it is common in marine sediments and sedimentary rocks. It is not normally present in dominant proportions but in mixtures with other clay minerals [50].

Silicon may be substituted by aluminium in the tetrahedral sheet, and magnesium by aluminium or iron in the octahedral sheet [50].

2.2 Soil water

Water is one of the most important factor affecting the properties of soil. In coarse fractions the behaviour of water is simpler and also the influence of it is less harmful than in clays where change of water amount changes volume, plastic properties, strength,

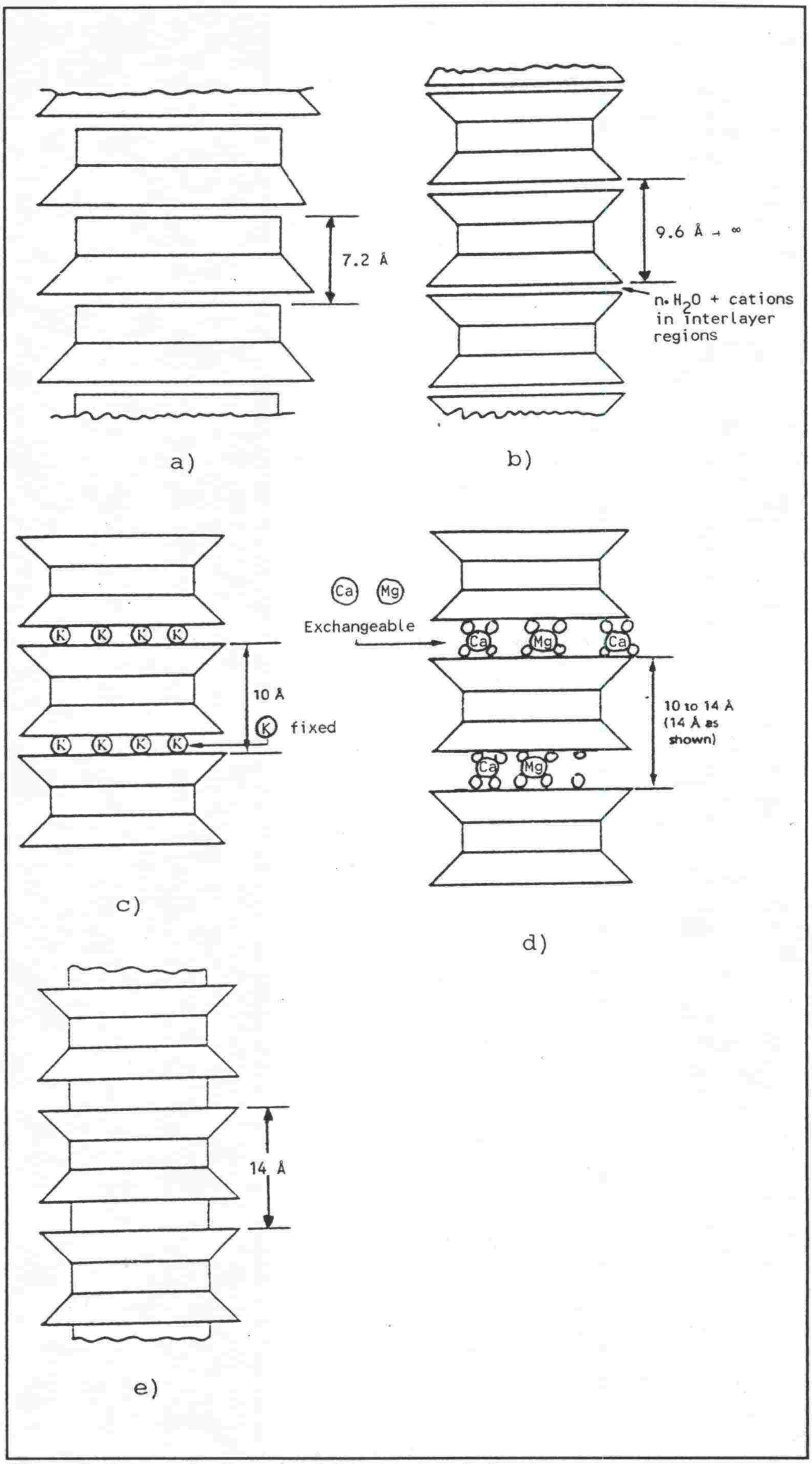

Figure 6. *Schematic diagram of the structures of a)kaolinite b)montmorillonite c)illite d)vermiculite e)chlorite [31].*

compressibility etc. Fine-grained soils can contain a greater volume of water than solids but in coarse-grained soils the water content is only few ten percent at the most, and water can move and drain easily. Usually an increase of the water content deteriorates the engineering properties, and prevention of water accumulation is one of the most important matters in soil stabilization.

Water is retained in the voids of a soil; a changing water content results from a changing proportion of water and air in the voids or from a changing volume of voids. The water in a soil can be divided to gravitational water, capillary water and adsorbed water. The gravitational water moves because of the gravitational forces and its meaning is more important in coarse-grained soils. Soils resist draining of water caused by gravitational forces or evaporation of water in drying. This water retention is due to capillary forces in the voids holding capillary water or due to surface forces bonding water molecules which constitute the adsorbed water. The capillary forces depend upon the size of voids and the surface forces upon the amount and nature of the surfaces of soil grains. Consequently, the finer the soil the more important the meaning of the capillary and adsorbed water. The behaviour of the adsorbed water is extremely important in clays because of their big surface area.

The water molecule (H_2O) is composed of a V-shaped arrangement of atomic nuclei, with an average H-O-H -angle of slightly less than 105°. This shape produces that the water molecule is a dipole which means that its other end is positive and the other negative. That is important in the behaviour of the water. Moreover, water in soil is hardly ever pure but ions - cations(+) and anions(-) - and perhaps some organic matters are dissolved in it [31].

As a result of the uneven charge distribution and dipolar character of water molecules, they are attracted to ions in solution, leading to ion hydration. Positive ions attract the negative corners of water molecules and vice versa. Not all ions hydrate, although cations common in soils do, but ions disrupt normal water structure, whether they hydrate or not [31]. A model for ion-water interaction is shown schematically in Figure 7.

Region A is a zone of immobilization. Water molecules are strongly oriented in the field of the ion and have little kinetic energy. In region B the water structure is broken down and more random than in normal water. Region C contains water with normal structure but which is polarized by the ionic field [31].

If a soil is not totally dry, clay particles will always be hydrated, i.e. surrounded by layers of water molecules (adsorbed water) [50]. These water molecules should be thought as part of the clay

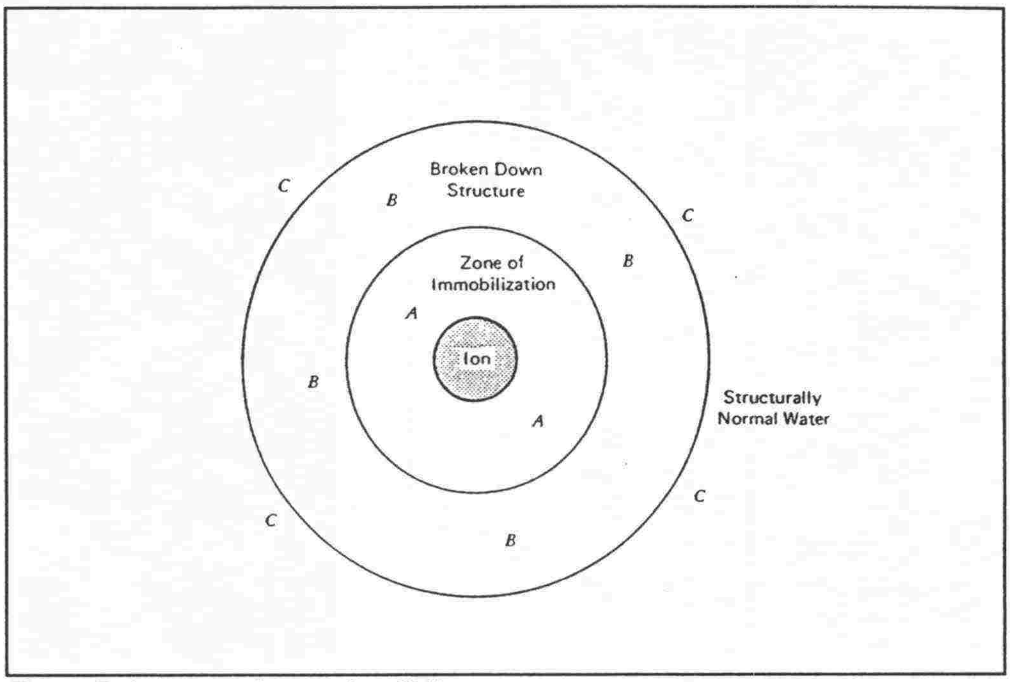

***Figure** 7. Ion-water interaction [31].*

surface when the behaviour of clay soils is considered. The properties of clays change as the thickness of this hydration shell changes. In this consideration the water, which is far enough not to be influenced by forces of the particles and ions, is called free water.

The surface of clay particles is usually negative charged because of the isomorphous substitution and broken bonds at the edges of the particles. The amount of the broken-bond charge per unit weight of clay increases with decrease in particle size, because the proportion of edge area to total area is increased.

The clay surface can be thought to be an electrode-electrolyte interface where the clay surface is a negative electrode and the soil water is an electrolyte. There will form in the interface of two phases a zone whose properties differ from those of the inner parts. This zone is called the **electric double layer** [40]. This layer describes the behaviour of the adsorbed water on a clay particle.

The electric double layer is divided into two main layers: the **Helmholtz layer** and the **diffuse double layer** [40]. Water molecules and some anions (-) adsorb in the Helmholtz layer by specific or contact adsorption. In the boundary of the Helmholtz and diffuse double layer the hydrated cations are adsorbed by electrostatic adsorption (Figure 8.).

In the diffuse double layer the electric force field caused by the negative clay surface attracts positive cations and repels negative anions. Because the concentration of the adsorbed cations is much higher near the surface of clay particle, there is a tendency for them to diffuse away in order to equalize concentrations throughout. The diffusion is, however, restricted by the electric

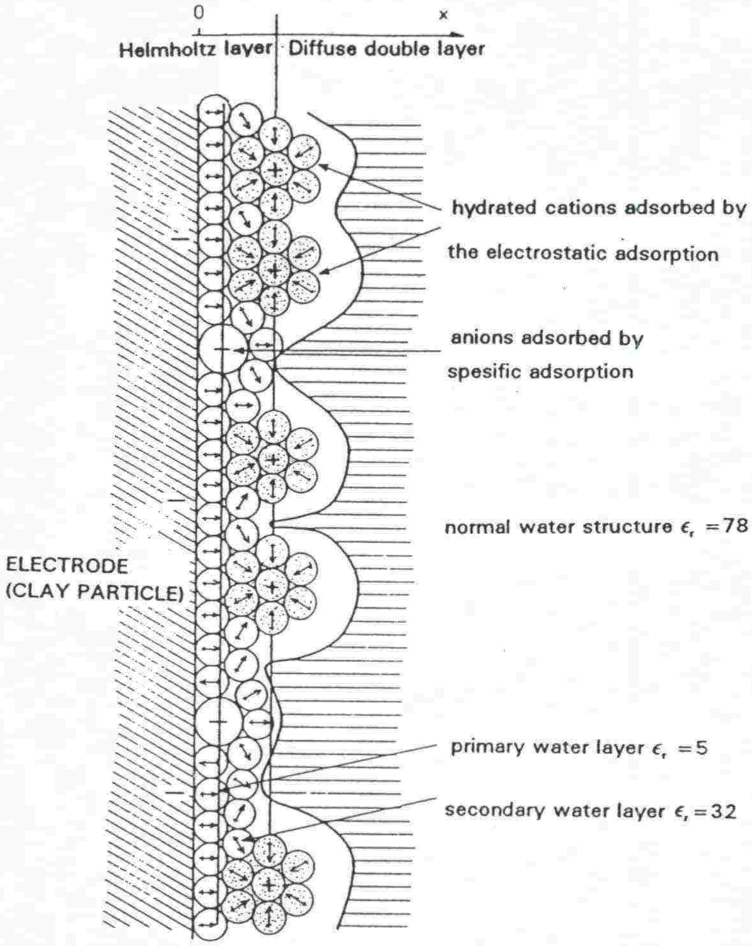

***Figure 8.** The structure model of the electrolyte side of the electric double layer. ϵ_r is relative permittivity of water layers,(See Definitions!).[40]*

field. The balance of the electrical attraction and the diffusion leads to a distribution of the cations [31].

The diffuse double layer is described mathematically with the **Gouy-Chapman** model.

In the case of the double layer there is an electric field produced by the negative clay particle but on the other hand the field is produced by many cations which can be thought to form a continuous charge distribution.

The potential (Ψ) varies with distance from a charged surface in the manner shown by Figure 10. In clays Ψ is negative because of the negative surface charge. At a large distance from the surface
$\Psi = 0$.

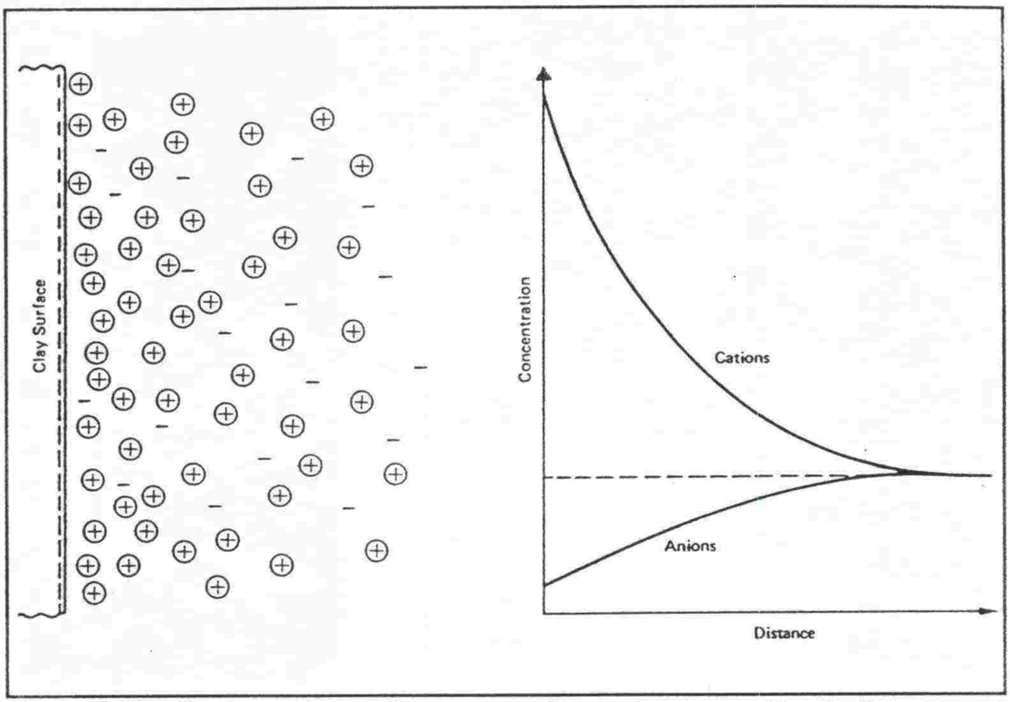

Figure 9.*Distribution of ions adjacent to a clay surface according to the concept of the diffuse double layer [31].*

The potential distribution in the diffuse double layer is given by the **Poisson equation** [40,31]

$$\frac{d^2\psi}{dx^2} = -\frac{\rho(x)}{\epsilon_0 \cdot \epsilon_r} \tag{1}$$

ψ *is*	*electric potential of an ion [$JC^{-1} = V$]*
x	*distance from the surface [m]*
ρ	*density of electric charge [Cm^{-3}]*
ϵ_0	*vacuum permittivity [$8.854 x 10^{-12}\ N^{-1}m^{-2}C^2$]*
ϵ_r	*relative permittivity [$N^{-1}m^{-2}C^2$]*

The concentration of ions in the electric field is given by the **Boltzmann equation** [31]

$$n = n_0 \cdot \exp\left(\frac{-v \cdot e \cdot \psi}{k \cdot T}\right) \tag{2}$$

n *is*	*concentration of ions [$ions/cm^3$]*
n_0	*concentration of ions at a large distance from the surface [$ions/cm^3$]*
k	*Boltzmann constant ($1.38 * 10^{-23}\ JK^{-1}$)*
T	*temperature [K]*
v	*valence of an ion [-]*
e	*elementary charge [$1.6 * 10^{-19}\ C$]*
Ψ	*electric potential of an ion [$JC^{-1} = V$]*

The equation (2) relates concentration to potential as illustrated by Figure 11. For cations the valence $v > 0$ and for anions $v < 0$. Therefore, in close proximity of negative charged clay particles is $n_{cations} > n_0$ and $n_{anions} < n_0$.

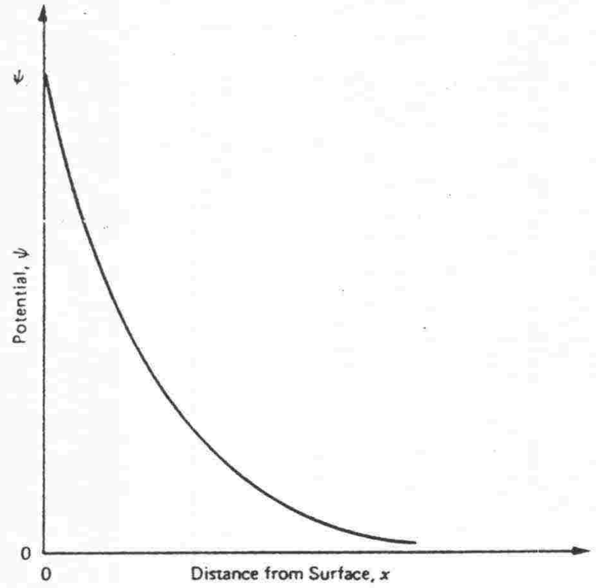

Figure 10. *Variation of electrical potential with distance from a charged surface [31].*

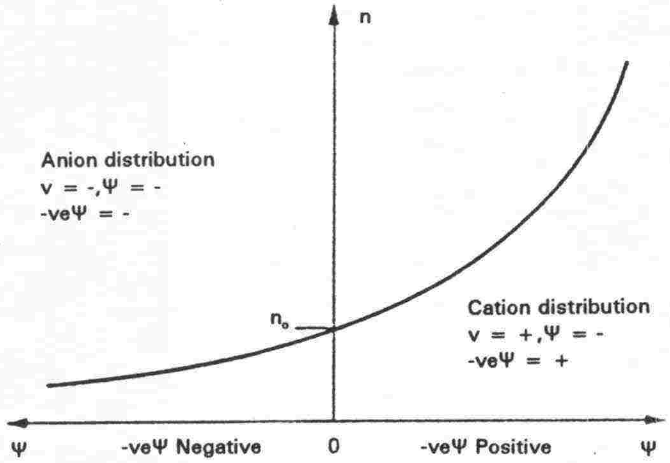

Figure 11. *Ionic concentration in a potential field according to the Boltzmann equation [31].*

Because the interactions between the particles, their distance and positions, are very complicate, the equations are not quantitatively applicable to most clay soils but they describe some of the principles of particle interaction and give the influence of factors such as ion valence, ion concentration and temperature.

A brochure of the supplier of the ISS-stabilizer [19] claims that "*the cations and anions are liberated from the diffuse double layer*" by the action of ISS. Because the cations are hydrated, their liberation might reduce the amount of water molecules, too.

There are no exact conclusions for the interpretations of the nature
of soil-water interaction. However, the following possible mechanisms of clay-water have been represented [31]. At least partly they are analogous to the electric double layer.

1) The main force bonding water to the surface is due to the hydrogen bond where a hydrogen atom of a water molecule bonds an oxygen in clay surface, or a hydrogen atom of a hydroxyl ion in clay surface bonds an oxygen of the negative end of a water molecule. This is a strong bond compared with other bonds between neutral molecules. The second layer of water molecules is held to the first, again by hydrogen bonding, but the force becomes weaker with distance as the orienting influence of the surface on the water molecules decreases. Each successive layer is held less strongly and the bonding quickly decreases to that of free water (Figure 12.a) [31,50].

2) Since cations are attracted to negatively charged clay surfaces, their water of hydration will also be attracted (Figure 12.b). This process would be most significant at low water contents.

3) The concentration of cations increases as negatively charged clay surfaces are approached. Because of this increased concentration and the restriction on diffusion of ions from the vicinity of the surface, as a result of electrostatic attraction, water molecules tend to diffuse towards the surface in an attempt to equalize concentrations (Figure 12.c).

4) Water dipoles could orient with their positive poles directed toward the negative clay surfaces. At the midplane between parallel surfaces there would be structural disorder, because negative poles would be adjacent to each other but the water could have removed counterions from the surface to the midplane between the parallel surfaces (Figure 12.d). The same type of arrangement could result from ion hydration. In a dry clay, adsorbed cations occupy positions in holes on the clay surfaces. On hydration they surround themselves with water and move to the central region between clay layers.

5) There could also be attraction of water by van der Waals

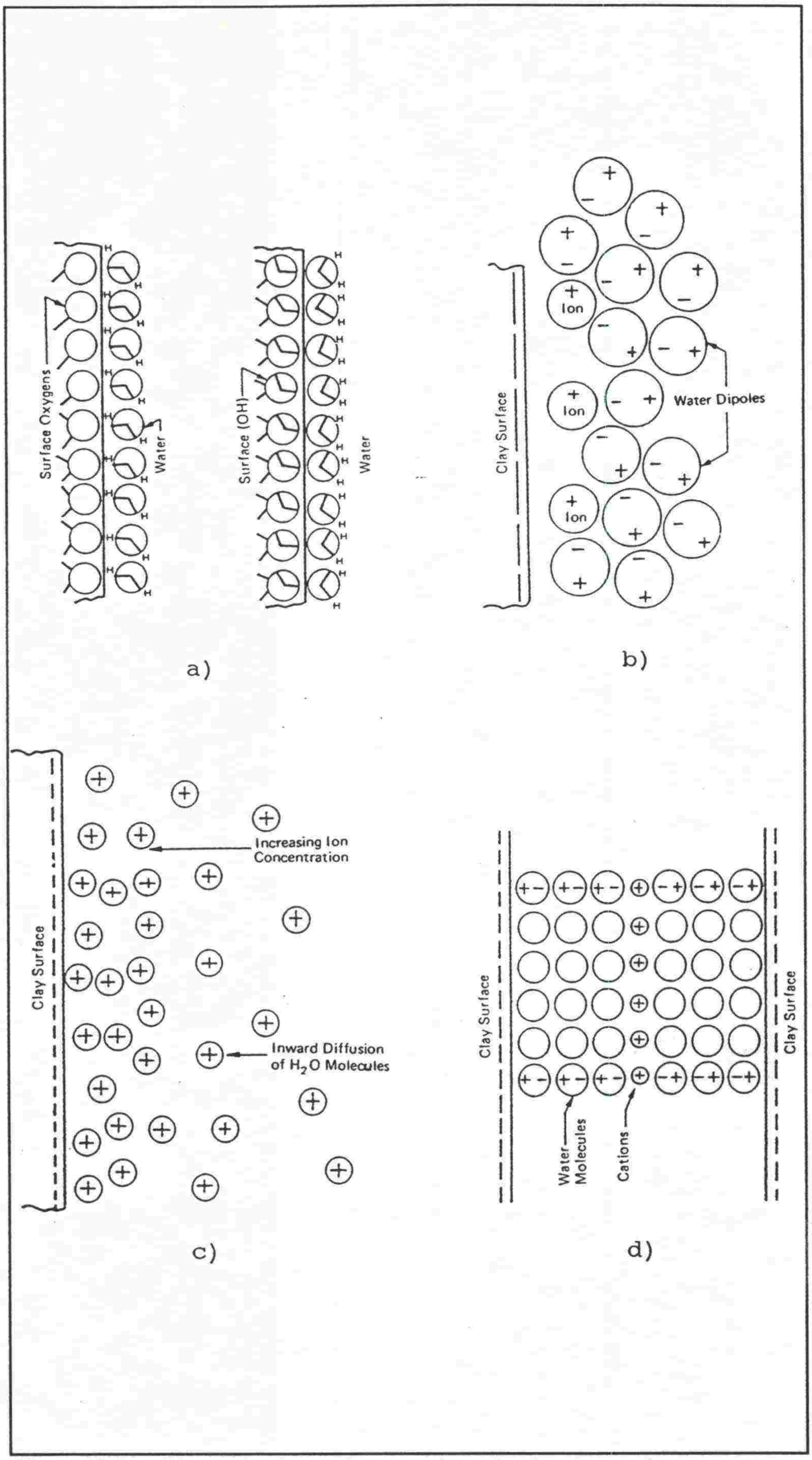

Figure 12. *Possible mechanisms of water adsorption by clay surfaces:*
a)Hydrogen bonding b)Ion hydration
c) Attraction by osmosis d) Dipole attraction [31].

forces[1]. Because such bonds would be nondirectional the water structure would be close packed and more fluid than the hydrogen-bonded structure.

The density and the viscosity of the adsorbed water differ from those of free water. Water molecules adsorbed on the clay mineral surfaces are relatively free to move in the two directions parallel to the clay surface but are restricted in their movements perpendicular to, or away from, the surface. Movement parallel to the surface is a transfer from one bonded position to another. The forces holding water decrease further away from the surface, so there is no sharp division between adsorbed water and free water. This rate of decrease is a function of exchangeable cations and of the surface. The first two or three layers of water molecules are thought to be strongly bonded to the surface, and that properties of adsorbed water differ from those of free water for several more water layers.

2.3 Ion exchange

Clay minerals have the property of adsorbing certain cations and anions and retaining these in an exchangeable state; i.e. these ions are exchangeable for other anions or cations by treatment with such ions in a water solution or sometimes in a nonaqueous environment. The exchange reaction is stoichiometric, and it does not affect the structure of clay particles themselves. More information is available regarding cation exchange than anion exchange. One cation can be replaced by another of equal valence, or by two one-half the valence of the original one. The kind and number of exchangeable cations have an important influence on the behaviour of soils like plasticity properties, strength, permeability and compression and swelling properties [16].

There are three causes of the cation-exchange capacity of the clay minerals [16]:

1. **Isomorphous substitution**. Substitutions within the lattice structure of Al^{3+} for Si^{4+} in the tetrahedral silica sheet, and of ions of lower valence, particularly Mg^{2+}, for Al^{3+} in the octahedral aluminium sheet result in unbalanced charges in the structural units of clay minerals, and the balance is achieved by the adsorbed cations. The exchangeable cations are to be found mostly on the basal cleavage surfaces of the layer clay minerals. This is the major source of exchange capacity, except possibly for the kaolin minerals. In montmorillonite and vermiculite, substitution within the lattice cause about 80 per cent of the total cation exchange capacity.

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[1] *See definitions!*

2. **Broken bonds** around the edges of the silica-alumina units would give rise to unsatisfied charges. The number of broken bonds and hence the exchange capacity due to this cause increase as the particle size decreases. The exchangeable cations are held around the edges of the flakes and elongate units. In the kaolinite and halloysite minerals broken bonds are the major cause of the exchange capacity, and also in the illite and chlorite minerals they are an important cause.

3. **The hydrogen of exposed hydroxyls** may be replaced by a cation which would be exchangeable. Some hydroxyl groups would be exposed around the broken edges of all the clay minerals, and cation exchange due to broken bonds would, in part at least, be replacement of the hydrogens of exposed hydroxyls. This cause of exchange capacity is important for kaolinite and halloysite because of the presence of the sheet of hydroxyls on one side of the basal cleavage plane.

There is no single cation-exchange capacity value that is characteristic of a certain clay mineral but a range of capacities must be shown for each mineral. However, the capacity of different clay minerals varies subsequently from each other. The capacities are shown in Table 1. Besides the above mentioned causes, clay concentration, the nature of the cation, lattice distortion, clogging of exchange positions, etc. may also affect the cation-exchange capacity.

Table 1. Cation-exchange capacity of clay minerals [15].

CLAY MINERAL	CATION-EXCHANGE CAPACITY [milliequivalents/100g]
Kaolinite	3-15
Chlorite	10-40
Montmorillonite	80-150
Vermiculite	100-150
Halloysite $2H_2O$	5-10
Halloysite $4H_2O$	40-50
Illite	10-40

The predominant exchangeable cations in soils are calcium and magnesium. Potassium and sodium are found in smaller amounts. Aluminium and hydrogen are the predominant exchangeable ions in acidic soils. Geological environment and subsequent leaching determine which ions will be present. Clays deposited in seawater will have predominantly magnesium and sodium while calcareous soils will contain mostly calcium [50].

Replaceability of the exchangeable cations is not same with various ions but different matters affect that. For example a small amount of calcium easily replaces exchangeable sodium, but the same amount of sodium does not replace much exchangeable calcium. The valence of the cation has the dominant influence on ease of replacement. The higher the valence the greater its replacing power, or the harder to replace if the cation of higher valence is at the surface. For ions of the same valence, increasing ion size gives greater replacing power.

The cations can be arranged in a series on the basis of their replacing power. While the position in this series will depend upon the kind of clay and upon the ion which is being replaced, the cations will appear approximately as follows, arranged in order of increasing replacing power [50]:

$$Li^+ < Na^+ < H^+ < K^+ < NH_4^+ << Mg^{2+} < Ca^{2+} << Al^{3+}$$

However, in general increased concentration of the replacing cation causes greater exchange by that cation. Thus it is possible to displace a cation of high replacing power such as Ca^{2+} by a cation of low replacing power such as H^+, by mass action, wherein the concentration of hydrogen is made very high relative to that of calcium.

The exchange will take place until at equilibrium a certain percentage of the exchangeable ions will still be the original cations and the remainder will be the replacing cations. The **Gapon equation** is useful for assessing the proportions of exchangeable cations, as the outside ion concentration varies [50]:

$$\frac{M_{e,(+m)}}{N_{e,(+n)}} = k_c \frac{\sqrt[m]{M_{0,(+m)}}}{\sqrt[n]{N_{0,(+n)}}} \tag{3}$$

$M_{e,(+m)}$ is	*concentration of an exchangeable cation of valence m in the soil*
$N_{e,(+n)}$	*concentration of an exchangeable cation of valence n in the soil*
k_c	*a constant depending upon specific cation adsorption effects and upon the clay surface, decreasing as the surface density of charge increases.*
$M_{0,(+m)}$ $N_{0,(+n)}$	*concentrations of the exchangeable cations in the outside solution*
$\sqrt[m]{\quad}$	*m^{th} root*

The knowledge of the anion exchange and its meaning is little. Possible explanations for the anion-exchange have been presented [15]:

1. The reaction may be due to the presence of broken bonds around the edges of the clay mineral particles. It would be expected that broken bonds would provide as many negative as positive positions around the edges of the clay mineral particles so that anion-exchange capacity due to that cause would equal the cation-exchange capacity.

2. The hydroxyls on the surface of the clay mineral particles apparently can enter into exchange reactions .

The literature received from the supplier of the ISS-chemical in Zambia explains a theory of how the chemical acts on the soil particles and stabilizes them. The stabilizer is defined to effect through ion exchange on the clay particles, which permanently reduces the thickness of the water layer adsorbed on the surface of the particles. In this procedure the chemical is expressed to make the water molecules break its electrochemical bonds with the clay particles and separate to become free water which can then drain by gravity, evaporation and compaction.

To be able to estimate what the possible working mechanism of this type of chemical could be, it is important to understand the basic structure of clay minerals and how different matters influence the structure of the adsorbed water.

3 Soil stabilization with certain chemicals

3.1 Soil stabilization

The material available along a route of a road is seldom proper for construction. A basic decision must therefore be made, whether to

1. accept the site material as it is and design to standards sufficient to meet the restrictions imposed by its existing quality.

2. replace the site material with a superior material.

3. alter the properties of the existing soil so as to create a new site material capable of better meeting the requirements of the task in hand.

The latter choice, the alteration of soil properties to meet specific engineering requirements, is known as soil stabilization [23]. When the required bearing capacity is very high, it is usual, to even stabilize the good material that is replaced. When there is a question about soil stabilization, two different principles can be distinguished: deep stabilization in which vertical reinforced columns are made many meters into the ground, and stabilization of surface in which a layer of a few decimeters is improved. The properties which are usually desired to be improved in the surface stabilization are strength, water resistance, volume stability, durability, permeability and in cold regions frost susceptibility. The aim of the deep stabilization is a higher strength and less settlement. The used stabilizers and thus the reactions in the soil are very much the same. Economic calculations of the road quality, suitable for traffic, roads meaning, its lifetime etc., versus the costs are made for the basis of the decision. This study concentrates on the surface stabilization.

3.2 The composition of the ISS- and RRP-stabilizers

The purpose of this research is to find out the possibilities of using in soil stabilization an acidic chemical whose trademark is ISS (Ionic Soil Stabilizer). The literature received from the supplier informs us that the chemical is a sulphonated oil product [10] but its actual composition has not been revealed. According to a South African disinterested research institute CSIR[1] [14], ISS is one of three sulphonated petroleum products currently being used in various projects in southern Africa. They say that a stabilizer

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[1] *See Definitions!*

with the trademark RRP (Reynold's Road Packer), is the original sulphonated petroleum product. Also the manufacturer of RRP indicates that RRP is derived from sulphonated petroleum [13].

Analysis of ISS and literature shows that these two chemicals are very similar both by their composition and their action. They may be same substance only with different names.

ISS was analyzed in the laboratory of the Finnish oil company Neste Ltd, and RRP had been analyzed in a research of Hübner and Suß of the Technical University of Darmstadt [21]. These tests show that the main compound in these both stabilizers is sulphuric acid (H_2SO_4) (Table 2.).

***Table** 2. The chemical composition of the stabilizers ISS and RRP [13,21,32].*

ISS	RRP
Analyzed by Neste Ltd [32]	Analyzed in Hübner's et al. research[21] pH in Fohs's research [13]
95% water 5% sulphuric acid (H_2SO_4) (total sulphur 2.2%) Solid matter which is probably coke. pH 1.3	81% water 19% mixture of sulphuric acid (H_2SO_4) and organic matter pH 1.5
Analysis methods: gaschromatographic-mass spectrometer analysis infrared analysis nuclear mass spectrometer analysis (NMR) microscopical observation	

ISS-stabilizer is a dark, sharp smelling water-soluble liquid with a specific gravity of 1.1. It is an acid, and the tests have shown that its pH varies, which means that its sulphuric acid concentration varies. Its viscosity is near that of water and small black solid particles can be seen in it. In appearance it is not similar to weak sulphuric acid which is colourless and almost odourless.

The results of the NMR-analysis[1] prove that the ISS does not contain sulphonated naphthalenes at least not in such levels which can be measured by conventional analytical parameters. Thus, this liquid can not be derived from the naphthalene fraction of petroleum, and this fact is in contradiction with the supplier's information.

The mentioned CSIR[1] institute states that these sulphonated oil

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[1] *See Definitions!*

products consist of a molecule with a hydrophilic cation head which is exchangeable with the normal cations found in clays and a hydrophobic tail consisting of aliphatic and aromatic hydrocarbons. However, this research institute has carried out so little research of these products, that they do not recommend these products in use. They do not mention if they have analyzed the composition by themselves or if they rely on the information of a supplier.

3.3 Action of the stabilizers

The literature received from the supplier of ISS explains a theory of how sulphonated oil or ISS-stabilizer acts on the soil particles, and what the improvements in the stabilized soil are [10,19]. The information of the manufacturer about the action of RRP is very similar [13].

Escobar describes the action of sulfonated oil on soil particles [10]:

> "Sulfonated oil by its chemical composition, has an enormous potential of ionic exchange. When small quantities of the product are put in water, they activate the hydrogen (H^+) and hydroxyl (OH^-) ions, ionizing the water which then vigorously exchanges its electric charges with the soil particles, making the water adhered to the particles break its electrochemical bond and separate to become free water which can then drain by gravity, evaporation and compaction. This electrochemical reaction of ionic exchange is permanent."

Another article of Escobar et al.[36](not received from the ISS-supplier) explains the action in the next way:

> "Sulphonated, petroleum-based ion exchanger used in soil stabilization alters the fine grain fraction (clays and silts). Excess hydrogen ions (H^+) are provided by the sulphonated petroleum product. The hydrogen ions (H^+) from the sulphated petroleum are added to the compaction water in sufficient quantity to ionize the compaction water. The ionized compaction water interacts with the hydrogen-bonded water around individual clay particles. Polarization of individual clay particles and reduced cationic forces allow agglomeration of clay particles to occur. Excess water molecules "drain" as free water by gravity."

In the following citate from a brochure of the supplier [19] the process is explained:

> "During treatment with the chemical the voids in the soil must be filled with pore water derived from the static water. This way can ion exchange by higher valency cations take place and the dipole moment of the soil particles be reduced. As a result of a lowering of the dipole moment of the water molecule there occurs dissociation into a hydroxyl (OH^-) and a hydrogen (H^+) ion.The hydroxyl ion in turn dissociates into oxygen and hydrogen, while the hydrogen atom of the hydroxyl is transformed into a hydronium (H_3O^+) ion.

> The positive charges of the hydronium ion or of the negatively charged hydroxyl ion will normally combine with the positively charged metal ions in the water adhering to the surface of the particles. Because of the effect of the chemical in reducing the electric charge of the water molecule, there is sufficient negative charge to exert adequate pressure on the positively charged metal ions in the adsorbed water film. The cations and anions are liberated from the diffuse double layer.
>
> When this reaction occurs, the metal ions migrate into the free water which can be washed out or removed by evaporation. Thus the film of adsorbed water enveloping the particles is reduced."

As a result of the ion exchange and the reduced adsorbed water layer the soil particles are said to acquire a tendency to agglomerate and have less surface area. The compactability and the shearing strength of the soil is improved and the swelling capacity is reduced.

There are several points in the previous explanations in common with the theory of the structure of clay minerals and the adsorbed water represented in Chapter 2. However, especially the explanations of the behaviour of the water molecule (H_2O), hydrogen (H^+) and hydroxyl (OH^-) ions are partly confused. Generally, the quantities of hydrogen (H^+) and hydroxyl (OH^-) in a water solution depend on each other according to the ionic product of water (K_w) which is a constant in a constant temperature (Equation (4)). When an acid (like ISS) is added into a water solution, the hydrogen (H^+) concentration increases and respectively the hydroxyl (OH^-) concentration decreases. A hydrogen (H^+) ion joins always to a water molecule to form a hydronium or oxonium ion (H_3O^+) [26].

$$[H^+][OH^-]=K_w \qquad \textbf{(4)}$$

$[H^+]$ is	concentration of hydrogen ions [mol/l]
$[OH^-]$	concentration of hydroxyl ions [mol/l]
K_w	ionic product of water, 10^{-14} in 25 °C

All the three explanations say that ion exchange occurs, but it is not said which ions exchange. Their reason for this may be to conceal a business secret, but one cannot help but feel that market personnel have tried to create very theoretical sounding claims of their product based on a mixture of true and untrue scientific facts. If they presented the process more precisely, it would convince the clients much better.

The laboratory tests in this research have mainly concentrated on geotechnical behaviour of stabilized samples. Analyses have been carried out on the composition of ISS and also on the mineral contents or some other factors of the soils, but because this is not a research of chemistry, the reactions which take place in the soil with the treatment by the stabilizers were not examined in a laboratory; the possible influences on the engineering properties of the soils were the main interest. The studying of different sources and the use of the stabilizer have, however, created a mental picture of the action taking place in this stabilization.

Sulphuric acid in the stabilizer dissociates in the water to hydrogen (H^+) and sulphate (SO_4^{2-}) ions. The hydrogen ion in turn adheres to a water molecule (H_2O) to form an oxonium (hydronium) ion (H_3O^+). This dissociation is explained in equation (5).

$$\begin{aligned} H_2SO_4 + H_2O &\rightarrow H_3O^+ + HSO_4^- \\ HSO_4^- + H_2O &\rightleftharpoons H_3O^+ + SO_4^{2-} \end{aligned} \tag{5}$$

Thus, it can be said that water is ionized. It could be very possible that some salts would precipitate in reactions between the acid and metal compounds. Gypsum would be a product of neutralization reactions between sulphuric acid and calcium hydroxide ($Ca(OH)_2$). First calcium oxide (CaO) reacts with water according to the Equation and the product is calcium hydroxide ($Ca(OH)_2$).

$$\begin{aligned} CaO + H_2O &\rightarrow Ca(OH)_2 \\ Ca(OH)_2 + 2H_3O^+ &\rightarrow Ca^{2+} + 4H_2O \end{aligned} \tag{6}$$

The net reaction of the gypsum generation is

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 \cdot 2H_2O \tag{7}$$

Gypsum may be produced also in the next reaction between sulphuric acid and calcite

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2 \tag{8}$$

The salts have a good ability in binding water, which could improve the properties of the soil. The structure of the adsorbed water layer was presented in Chapter 2. It shows that the metal cations have a significant meaning in the water layer (Figure 12.). According to the previous citates from ISS-brochures ion exchange takes place on the soil particles. This would be the exchanging of metal cations by the hydrogen ions.

It is obvious that if this stabilizer works, it will produce chemical modifications over the surface of the soil particles. The intention is to modify the interactions between water and soil by surface reactions in such a manner that the disastrous effects of water in the soil can be avoided. It follows that the stabilized soil must have a large specific surface; so the reactions can take place mainly in clays. It is highly probable that the adsorbed water and its restriction are the main things in this stabilization. The analyses indicate that both ISS and RRP contain some organic matter. Many surface-active agents are organic, and they could cause a restriction of the adsorbed water.

The amount of the stabilizer diluted into the soil is very small. The supplier advised to use 200 liters of stabilizer diluted in 40 000 liters of water on 7000 m^2 road. When 95% of the stabilizer is water, the amount of the pure chemical is only few grams per road-m^2. To reach the optimum moisture content more solution has to be used. If the strength of the solution is kept unchanged, the quantity of the chemical will also be greater. The moisture to be added depends of course on the natural moisture content of the soil during the stabilization work. Content of the conventional stabilizers, i.e. cement, lime, bitumen,is many times greater varying usually between 0.5-10% of the dry weight of the soil. The conventional stabilizers form a skeleton in the soil, and the soil particles are bound together. Because of the tiny amount and the chemical nature, the ISS-stabilizer itself can not bind the particles together.

Table 3. *The quantity of the 0.5% ISS-water solution, pure ISS and the including sulphuric acid in the stabilization. The expected depth of the stabilized layer is 0.15 m and its dry weight 290 kg.*

Sprayed 0.5% ISS-solution on a road	0.5% ISS-solution content per dry soil weight	Pure ISS content per road-m^2	Pure ISS content per dry soil weight	Sulphuric acid content per road-m^2	Sulphuric acid content per dry soil weight
6 l/m^2	2 %	0.03 l/m^2	0.01 %	1.7 g/m^2	0.6×10^{-3} %
30 l/m^2	10 %	0.15 l/m^2	0.05 %	8.2 g/m^2	0.003 %

In the preceding reaction (Equation (7)) 1000 grams of sulphuric acid produces 1755 grams gypsum. The gypsum also binds water molecules as a water of crystallization. The stabilized road surface would contain only few grams of gypsum. The gypsum has been used as a stabilizer before but its amount has been much greater: several per cent of the dry weight of the soil. When it is used with lime in clay, they form ettringite which strengthens the soil [28,29].

Ingles [22] has researched mechanisms of clay stabilization with some inorganic acids and alkalis. He used hydrofluoric acid (HF) and phosphoric acid (H_3PO_4) in the stabilization of kaolinite and montmorillonite clays.

It is evident from Ingles's results [22] that water-resistance and increased strength are obtained if, and only if, a water-insoluble product appears as a result of degradation of the clay. On the other hand, degradation of the clay to form water-soluble products leads to a diminution of strength at a given level of compaction. This latter qualification is important, since reduced strength is often accompanied by enhanced compactability (i.e. greater compaction density achieved for the same compaction effort), and increased strengths are often accompanied by greater resistance to compaction. Nevertheless, not all systems which deposit water-insoluble reaction products lead to equivalent strength gains. In the case of HF treated kaolinite insoluble products are formed, but the increased strength is compensated by simultaneous formation of soluble (weakening) phases from the aluminous layers of the clay lattice. The interlayer attractive and repulsive forces (See Chapter 2.2), which change in the chemical treatment, may lead to greatly reduced strengths or water instability. If the soil possibly can be stabilized, the pH of the acid treated soil should be below 2 for a successful stabilization [22].

Ingles [22] continues that displacements of ions on the clay exchange complex is extremely rapid and an important reason for immediate strength gains. However, even clays with a high exchange capacity do not contain sufficient exchange sites to render this an important source of stabilized strength. Since the exchange ions are incapable of reinforcing the large surface areas involved in any significant mechanical sense, such reinforcement can come only from the conversion of the chief clay components, silicon and aluminium, to suitable insoluble forms - or by providing the deposition of a third phase in the pores as is done, for instance, by grouting procedures. Since silica is the only constituent common (in major quantity) to all clay minerals (See Chapter 2.1), the formation of insoluble silicon compounds will be the mark of those stabilizers with widest applicability for soils. This explains the widespread utility of lime and cement as soil stabilizers.

3.4 ISS in literature (received from the supplier)

3.4.1 Escobar, Venezuela

Escobar writes about experiences in the use of the sulphonated oil in rural roads in Venezuela and in Colombia [10]. Between the years 1976 and 1986 550 km of roads had been stabilized with this system. After three years of service with a minimum of maintenance, many of the treated roads had preserved a good condition of trafficability.

The road embankments had been injected, and the existing gravel or sand had been recycled. The moisture of soils treated with sulfonated oil was reduced between 30% to 90%, with respect to the optimum moisture, and their density was increased up to 15% compared to the maximum dry density, as a result of which their permeability was also reduced. The required time for this reaction is minimum 60 days, but the process continues longer. Escobar presents microscopic photographs of treated and untreated clays, where the treated soil seems to be more densely packed. There was also a notable increasing in the bearing according to CBR tests. However, Escobar does not explain more closely, what kind of conditions had prevailed during the construction and the curing time or what the properties of the stabilized soil were.

In the closing of the paper it is said that the sulphonated oil will work with A-4 to A-7 soils. The mixture of gravel and fines should contain finer than 0.075 mm at least 20% per volume. Respectively, mixing of sand and fines should contain 30% to 40% fines.

3.4.2 Herron Testing Laboratories Inc, Ohio, USA

An abridged and a little contradictory report describes laboratory tests, which had been made in order to determine the probable effectiveness of ISS on some soils [18]. The testing company says the studies are more or less cursory.

A total of four soils were studied: two non-plastic fine sands and two clays with a plasticity index of about 10. However, the results of the stabilization effects, presented in that report, have been taken from some other soil.

In their test procedure the soil materials were air-dried and placed in cylindrical containers in loose state. The area of the soil surface (of the container) was 0.017 m^2. The soil was sprinkled with 0.12 liter of 1/1000 part diluted aqueous solution of the chemical. It means 0.007 l/m^2 of undiluted chemical. During a period of seven days, shear strength of the soil was determined daily with the standard penetration resistance test according to the standard ASTM D-1558-63 [4]. Subsequent to this test, daily as well, the surface was compacted with ten blows of a hammer. During the entire period, the specimens were sprinkled three times daily with either water or, in the case of granular material, with a 1/4000 part aqueous solution of the chemical. After the compaction the specimens cured additional periods of steady state soaking conditions, but the length of those periods has not been told.

According to one table in the report considering some soil which has not been determined closer, the treatment with the chemical has changed the plastic properties so that liquid limit has decreased from 49% to 45% and plastic limit from 28% to 20%. Respectively, the plasticity index has increased from 20% to 25%. (The properties became poorer?!)

As a conclusion of the study the report [18] states: *"On the basis of the resent relatively cursory test results, it is considered obvious that ISS significantly improves the strength characteristics of both cohesive and granular soil materials when such materials have been subjected to physical compaction."*

3.4.3 National Institute for Road Research, South Africa

Reynolds [38] has studied the use of the ISS-chemical as a stabilizing agent in road works in South Africa in 1973. The stabilized road area was 3500 m^2, and two other sections on the same road, one stabilized with 4% lime and the other natural soil compacted, were as control.

The soils vary slightly from section to section, the test section being slightly more granular than the other two. The amount of the fines (< 0.075 mm) varied from 24% to 30% while the plasticity index being 12 and the optimum moisture content 13.5%. According to AASHO classification the soil belonged to class A-2-4 [7].

The soil surface was ripped to a depth of 20 cm and mixed to obtain more or less uniform texture. Water was applied until the moisture content was approximately 10%. The chemical solution was added in four lots with intervals of 24 hours except the fourth application was sprayed two days after the third one.

The applications were:
1st application: 20 l ISS/5000 l of water/1000 m^2 of road
2nd application: 15 l/5000 l
3rd application: 2 l/5000 l
4th application: 4 l/5000 l

Thus, the total amount of undiluted chemical was 0.04 l/m^2 of road.

After the first application of the chemical the road surface was graded and compacted with a grid roller and a flat vibratory roller. Before all the next applications, the road surface was scarified, shaped and watered, and after the chemical applications the road was rolled with the flat roller. The road was opened to traffic on the 8th day after thorough watering, and the watering was continued twice a day during a week after opening for traffic. The two control sections were also processed and compacted and watered at the same time as the test section.

watered at the same time as the test section.

The writing [38] describes that a noticeable hardening in the test section to a depth of 2cm to 3cm was evident within the first week after opening to traffic while the control sections were considerably softer. The rains started soon after the opening to traffic and continued for the following five months. In that time the test section became harder to a depth of about 50 cm, and the surface was not slippery like in the control sections. The test section remained dust-free during the dry periods while the control sections were very dusty. Some potholes had developed on the test section. The lime stabilized section showed very little rutting, but the unstabilized section became unpassable at some rainy periods.

3.5 RRP in literature

3.5.1 Federal Highway Administration (FHWA), USA

Fohs has researched RRP as a compaction aid and a soil stabilizer in laboratory for Federal Highway Administration of USA [13]. Evaluation of the chemical was based on the results of tests to determine its effects on four soils.

The soils in the test are fine-grained soils which are named Keyport clay loam, Cecil clay, Readington silt loam and Mattapex silt loam. The first two are quite plastic and the other two less plastic. The grain size curves are presented in Figure 13. and data on the physical, chemical and mineralogical properties are presented in Table 4.

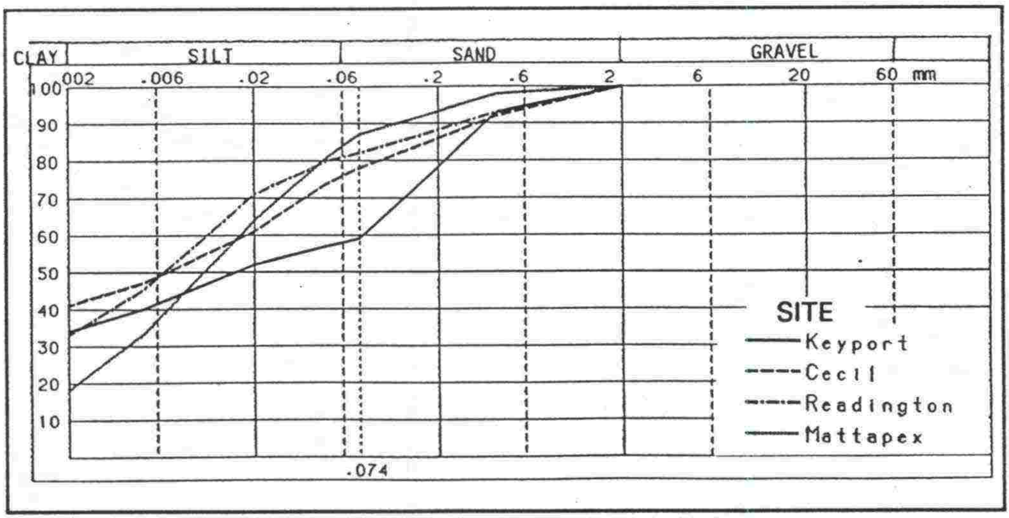

Figure 13. Grain size distribution in the test of FHWA [13].

The soils were prepared for the tests according to the next procedure [13]:

55 kg of each of the air dry soils were mixed with sufficient pure water so as to bring the soils to a moisture content equal to about one-half their optimum moisture content. The moist soil was then transferred to a truncated 220 liters steel drum to a depth of about 0.25 meters loose. The steel drum had a diameter of 0.53 m and a number of little holes were drilled in the bottom of the drum to permit drainage.

Table 4. *Properties of the soils in the tests of FHWA [13].*

PROPERTY OF THE SOILS	SITE AND SOIL			
	Keyport clay loam	Cecil clay	Readington silt loam	Mattapex silt loam
Liquid limit [%]	46	56	29	32
Plasticity Index [%]	24	26	9	11
Max. dry density [kg/m^3]	1762	1586	1826	1794
Optimum moisture content [%]	16	24	16	17
Cation exchange capacity [meq/100g]	21.5	6.0		
Calcium content [%] [meq/100g]	0.15 4.0	0.01 0.3		
pH	3.9	3.9	4.1	4.2
Major clay mineral	Montmorillonite	Kaolinite	Vermiculite	Vermiculite
Classification AASHO	A-7-6	A-7-5	A-4	A-6
Classification ASTM	CL sandy lean clay	MH elastic silt with sand	CL lean clay with sand	CL lean clay

Two liters of 5/1000 RRP-solution was sprinkled on the surface of the soil. After this the soil was covered with damp burlap, to minimize evaporation but not to make it air-tight, and the treated soil permitted to cure for at least 24 hours. During the following several days the soil in the drum was repeatedly sprinkled with a 1/1000 RRP-solution until a total volume of 8 liters of 1/1000 solution had been applied. Thus, the total amount of unthinned chemical was about 0.036% of the air dry soil.

The soil was sprinkled with an additional 2 liters of pure water after completing the application of the chemical to cause free drainage from the bottom of the stabilized soil layer suggested by the manufacturer of RRP [13].

Each of the soils was retained in the steel drum for several days, after which it was removed and placed in an oven of 60°C for simulated air drying. After drying, the soil was pulverized for testing.

The above soil preparation procedure was again performed on each of the four soils by replacing the chemical by pure water.

To evaluate the effectiveness of RRP in soil improvement following soil tests were done: Atterbergs limits and moisture-density relationship determination, unconfined and triaxial strength tests and CBR-test.

Results [13] show that this chemical had no significant effect on the plastic properties or the maximum dry density or the optimum moisture content of the four soils. The chemical had some significant effect on the unconfined compressive strength, but three out of six cases, where differences occurred, the strength of the treated soil specimens was lower than for specimens of the untreated soil. The strength of the Mattapex soil seems to improve 15-29% in two different densities, but the conclusion of the writer is that results are inconclusive. Furthermore, the magnitude of the strength increase is deemed too small to be of any practical utility. Triaxial test results do not show any effect of the chemical. CBR results indicate that the chemical effectively increased the CBR value for the Keyport and Readington soils when effectively compacted, but for the Cecil and Mattapex soils significant decreases were observed at the same density, although Mattapex soil strength improved in the compression test. However, these effects were eliminated by soaking, indicating that RRP affords no protection against the detrimental effects of moisture.

Finally the writer [13] mentions about a hypothesis that acidic compaction aids like RRP (or ISS) might not be effective with acidic soils.

3.5.2 Technical University of Munich, Germany

Heitzer, Soos and Jelinek have researched the action and application of RRP as a soil stabilizer in the University of Technology in Munich for the German road authorities [17]. Test sections were built on a bad forest road in Germany, and the behaviour of the stabilization was followed three years from 1973 to 1976.

Before the stabilization the draining of the road was rehabilitated and the surface was formed to the right shape. The road was an earth road whose soil was fine-grained. The grain size curves of three samples from the road are in Figure 14. and the plastic properties and the classifications are in Table 5. The soils differ from moderate plasticity to high plasticity.

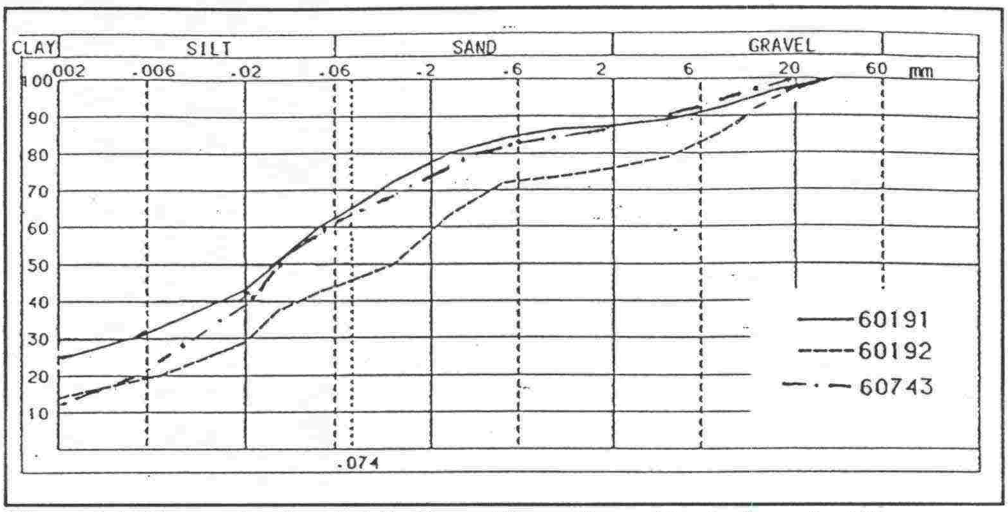

Figure 14. *The grain size distribution of the soils on the test road of the Technical University of Munich, Germany [17].*

Table 5. *The properties of the soils in the test road of the University of Technology in Munich, Germany [17].*

PROPERTY	Sample 60191	Sample 60192	Sample 60743
Liquid limit [%]	54.6	35.0	33.6
Plasticity Index [%]	29.9	12.8	10.6
Max. dry density[kg/m^3]	1770	1910	1790
Optimum moisture content [%]	15.0	12.2	15.2
Classification ASTM	CH Sandy fat clay	CL Sandy lean clay with gravel	CL Sandy lean clay
Classification AASHO	A-7-6	A-6	A-4

The test section of 240 meters was divided to three parts. The middle part was a reference section sprayed with pure water only, and the surrounding parts were stabilized with the chemical. The road was already quite wet in the beginning.

When the surface had been scarified with a rotavator to a depth of 5-10 cm, the solution was sprayed in six lots during six days on the surface. The first two lots were diluted 1/32 RRP with water, and the their combined volume was 0,029 liters RRP/m^2. In the number 3. and 4. lots the mixing ratio was 1/47 with a combined volume of 0.019 liters RRP/m^2. In the number 5. and 6. lots the mixing ratio was 1/100 and the amount together 0.010 liters RRP/m^2. In the six lots the total volume of sprayed solution was 3.84 l/m^2 containing 0.067 l RRP/m^2. The reference section was sprayed with same amount of pure water.

The weather was rainy three weeks after the treatment, but after the dry fourth week the other stabilized section and half of the reference section were compacted. The rest of the road stayed too wet for compacting.

A gravel wearing surface was laid on the compacted sections after two months, but just the same the treated as well as the untreated subgrade bore the lorries very poorly.

Next summer, 7 months after the stabilization, the bearing of the road was investigated with in-situ plate load tests. The results were better on the stabilized section, but even those did not attain half of the requirement for the bearing of of a road subgrade in Germany. The opinion of the research team is that the difference between the bearings is caused by the uneven compaction.

As a conclusion the writers of the report state [17]:

The building of the test road and the investigations carried out there show unambiguous that the treatment of subsoil with RRP-chemical does not improve bearing, water resistance or other properties. During the construction work or in the course of several months they did not notice any differences between the treated and untreated sections.

3.5.3 Technical University of Darmstadt, Germany

Hübner and Süß have researched use of RRP-chemical in soil stabilization with laboratory tests in the Technical University of Darmstadt in Germany [21].

The tests were made with one semi-plastic fine-grained soil whose grain size curve is in Figure 15. and other properties in Table 6.

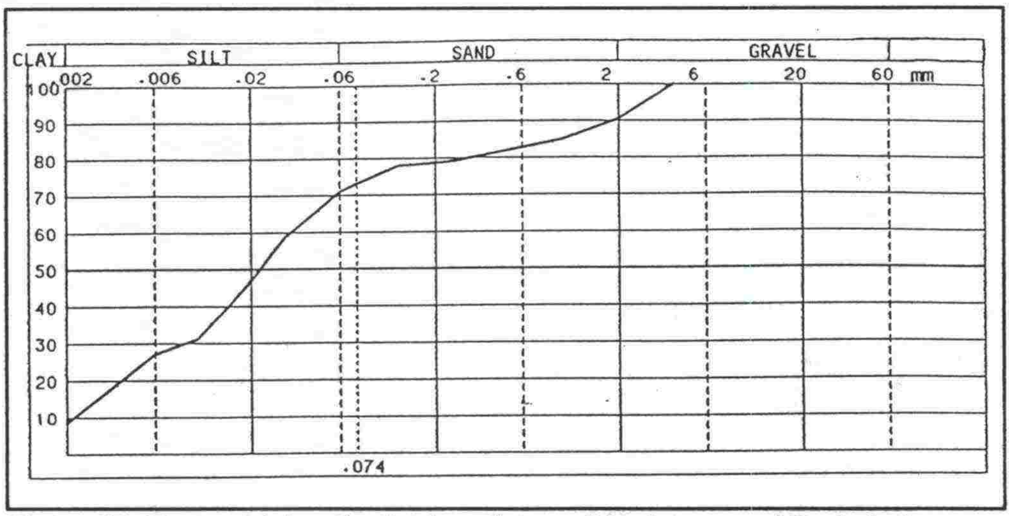

Figure 15. The grain size distribution of the soil in the tests of Technical University of Darmstadt, Germany [21].

Test specimens were made with 0.015%, 0.1% and 0.18% RRP content of the dry soil. As reference specimens soil which was treated with pure water was used. All the specimens were compressed in the optimum moisture content to the maximum density. Thereafter, the specimens were coated with a paraffine film to prevent them from drying. Before testing the specimens were cured without drying either 5 or 26 days.

After 5 and 26 days of curing the specimens, they were placed in 1 cm deep water to see how the capillarity changes in the stabilization and how the water affects the compression strength. However, the treated and untreated specimens had been resolved considerably after 30 minutes in the water. With this test it was shown that the chemical had no better influence on the capillarity of this soil.

After the previous soaking the specimens were placed fully under water. The difference in the durability was, that the treated specimens resolved totally in three hours while the untreated lasted only five minutes.

Unconfined compression tests were done after 7 and 28 days curing without soaking. These results do not indicate any improvement in strength; on the contrary, the strength of the specimens with a bigger chemical content seem to decrease.

Table 6. *The properties of the soil in the tests of the Technical University Darmstadt, Germany [21].*

PROPERTIES OF THE TEST SOILS	
Liquid Limit [%]	27.2
Plasticity Index [%]	6.4
Max. dry density [kg/m^3]	1860
Optimum moisture content [%]	16
pH	5.7
Minerals	Quartz 70% Mica 10% Feldspar 2% Chlorite with other clay minerals 8% Others 10 %
Classification AASHO	A-4
Classification ASTM	CL-ML Silty clay with sand

The plastic properties were also studied and the test pieces were subjected to several freezing cycles, but differences were not noticed.

The writers [21] assume that arrangement of soil particles may be better in the treated soil. Furthermore, soil type and especially the quantity and type of the clay mineral may affect the function of the chemical.

As a conclusion the writers [21] state, that although the chemical slightly improved the durability against water, it had no practical meaning. Thus, according to these tests they concluded that this soil could not be stabilized by RRP-chemical. However, the possibility that the chemical could work in some other soils can not be excluded.

3.5.4 Technical University of Budapest, Hungary

Kézdi writes about soil treatment with RRP [25]. According to him RRP does not produce binding forces between the particles; so, it does not stabilize the soil. Instead it alters, through ion exchange, the water absorptive capacity of the fine soil particles. The hydrated shell will be thinner, therefore, the soil can be more easily compacted,moreover, the volume change, capillarity, frost susceptibility and water sensitivity decreases and the bearing capacity increases.

The treatment starts with scarifying the soil in a depth of 5 cm. If necessary, a granular wearing course material is spread over the surface. Before treatment, the moisture content of the upper soil layer should be somewhat below the optimum. The chemical will added in two doses:

a) 2-6 kg RRP/200 l water
b) 1 kg RRP/400-500 l water.

(Kézdi does not mention, what size of an area this amount is sprayed on.)
The treated soil remains in a loose state at least two weeks. Mixing is not required. When the upper soil layer is nearly around the optimum moisture, the soil is compacted.

According to Kézdi, since 1968 several low-traffic roads were treated with this chemical in Germany. They were covered by a thin granular wearing course or an asphaltic layer [25].

Kézdi refers to investigations in the Hungarian Road Research Institute by Gáspár. Those investigations have suggested to judge the suitability of the soil to chemical treatment on the basis of the following requirements [25]:

1) The application of a small amount of chemical is sufficient to cause a major drop of the liquid limit.

2) Due to the treatment, the maximum dry density and the optimum moisture content are increased.

3) CBR value of treated samples exposed to capillary action for 4 days is at minimum 15 to 20%, and the accompanying

swelling is not more than 2 to 3 mm.

4) The value of pH is not more than 7.5.

Advantages of the chemical soil treatment according to Kézdi:

1) It requires the use of very small amount of chemical (30 to 70 g/m^2)

2) The application is simple, no complete pulverisation and mixing is needed.

3) There is no definite setting time; water will not elutriate the material; consequences of eventual bad weather can be eliminated by appropriate organization.

4) In regions where granular soils are scarce the treatment can substitute the base course.

5) Simply adding a thin granular wearing course will permit low traffic to be carried.

The disadvantages are:

1) Not all cohesive soils can be successfully treated.

2) 2 to 3 weeks waiting time cannot always be ensured.

3) Effective compaction of the treated and moistened soil is a prerequisite for successful application.

3.6 Evaluation of the effect of the stabilization according to various literature

The similarity between the stabilizers ISS and RRP was shown in Chapter 3.2. Contrary to ISS, RRP has been studied in disinterested scientific research reports [13,17,21,25]. Therefore, the RRP references are dealt with here together with the reports and brochures received from the ISS-supplier in Zambia. The references concerning ISS [10,18,38] are in one chapter and the others concerning RRP [13,17,21,25] in another chapter. References received from a supplier must always be treated with caution.

All three writings concerning ISS state that the soil properties have improved, but the matter is handled rather generally. The conditions, soils, test methods or working methods are not described precisely if at all.

Escobar [10] (Chapter 3.4.1) does not explain more definitely how the stabilization has been done or how much stabilizer has been used. Neither does he explain neither the conditions prevailing during the construction and the curing time or what the properties of the stabilized soil were. His text is an overall survey of the positive effects of ISS.

The test report of the Herron Testing Laboratories [18] (Chapter 3.4.2) is so contradictory and confuse that its results do not prove anything to a reader, although its conclusion is positive for ISS.

The third reference of ISS is from the National Institute for Road Research [38]. This institute may be a part of the disinterested South African CSIR-institute which is mentioned in chapter 3.2. but the connections of this article to CSIR have not become clear. This text describes clearly how the construction was done and what the chemical quantities and the circumstances were. The measurements and the results are presented only quite generally.

The texts considering RRP [13,17,21,25] can be taken more seriously because they are published by worldwide known, disinterested institutes or writers. The two German [17,21] and one American [13] reports describe tests, treated soils and results clearly (Chapters 3.5.1-3). The fourth source, Kézdi [25], is not a research report but it shortly tells generally of the action, working methods, advantages and disadvantages of RRP (Chapter 3.5.4).

Fohs's [13] test (Chapter 3.5.1) tried to imitate the circumstances of road stabilization in a laboratory. They had obeyed the orders of the manufacturer, but RRP did not afford any protection against detrimental effects of water. The length of curing time does not appear in the text, although it is an important factor.

Fohs mentions a hypothesis that acidic compaction aids might not be effective with acidic soils. On the other hand Ingles [22](Chapter 3.3) writes that the soil should be acidic.

Heitzer et al. [17] (Chapter 3.5.2) researched a test road for several years, but they did not notice any differences between chemical treated and untreated sections. The weather conditions on the road were very poor during the period, which may have disturbed the action of the chemical.

Hübner and Suß [21] (Chapter 3.5.3) made simple laboratory tests which indicate improvements with the conventional lime and cement stabilizers. They state that although the chemical improved a little the durability against water, it had no practical meaning.

There is quite clear black and white division: ISS-writings [10,18,38] praise and RRP-reports [13,17,21,25] blame. Soils in the RRP-tests have been silts or clays, and so they should be suitable. However, Kézdi [25] (Chapter 3.5.4) writing about RRP mentions also advantages of the chemical soil treatment. It may be that the chemical stabilization works with exactly certain types of soil only. For instance a soil in Africa differs very much from a soil in Germany or USA.

4 The effect of the stabilizer on Zambian soils in laboratory tests

4.1 Test program

To evaluate the action of the ISS-chemical and its applicability to soil stabilization, geotechnical laboratory tests were carried out with three different soils from Zambia. Furthermore, two Finnish soil samples were used in tests to study the possibilities of using the chemical in dust binding of gravel roads.

Most of the geotechnical tests were done in the laboratory of Finnish National Road Administration (FinnRA[1]) but some of them were carried out in the laboratory of Roads Department of Zambia.

The grain size distribution and the plastic properties were determined according to instructions of FinnRA [44]. The wet sieving procedure and the determination of the liquid limit and the plastic limit are very similar to the ones in British Standard (BS 1377) [8]. The hydrometer analysis procedure is much the same as in the ASTM (D-422) [3].

Soil compaction tests were done dynamically with the modified AASHO tests and statically with a hydraulic press. In Zambia the optimum moisture content and the maximum dry density were determined dynamically with the modified AASHO test [1], and in Finland they were determined with the modified Proctor test according to the instructions of FinnRA [44]. In the static compaction tests the same quantity of work was applied to every specimen with a hydraulic press but this test did not follow any certain standard.

An effect of excess accumulations of outside water was studied in soaking tests which did not follow any certain standards but tests of similar type had been used in other researches of stabilization by Hübner and Suß [21] and Lehtinen [30].

The unconfined compression tests were used to find out if the stabilization improves the strength of soils. They were carried out according to the ASTM D-2166 [5] but this standard does not mention curing time or curing conditions. They were set suitable for this stabilization.

Two CBR tests were carried out to see the effect of the stabilizer on strength after soaking. The tests followed British Standard BS-1377 [8].

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[1] *See Definitions!*

Few simple tests were carried out for an evaluation to see if the stabilizer can bind dust on Finnish gravel roads. These tests did not follow any standard, they were developed for this purpose.

In addition to the geotechnical tests, a closer mineralogical and chemical investigation was made into two Zambian soils which were most studied in the geotechnical tests also. These tests were ordered from the Geological Survey of Finland. As mentioned in Chapter 3.2 the composition of the ISS-stabilizer was analyzed in the laboratory of the Finnish oil company Neste Ltd.

Parallel specimens were treated with the ISS-chemical and pure water. Because the chemical analysis indicated, that ISS contains sulphuric acid, the test program includes also parallel specimens treated with sulphuric acid. Some tests were made with parallel specimens treated with lime also.

4.2 Samples

The researched soils were sampled from the top layer of the road surface with a shovel and pick. Because of the dry season in Zambia the soils were rather dry when they were taken. The soils are named here as Soil 1, Soil 2 and Soil 3. The sites where the samples were taken are typical rural roads for Zambia. Thus, the samples are quite representative from the roads which could be stabilized with the ISS-chemical.

Soil 1, fine sand, was taken from the same district road D177 where the stabilization was tested in-situ (Chapter 5). The two other soils, red and gray clays, were taken from a poor quality district road D154 near Lusaka in points located 500 m from each other. The samples were dug from the surface layer of the roads. See Figure 27.

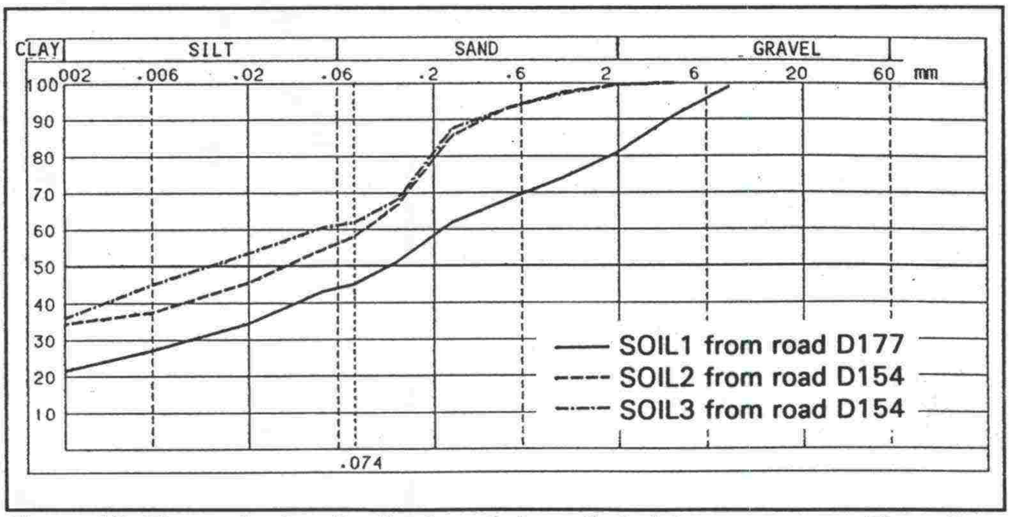

Figure 16. *The grain size distribution of the soils in laboratory tests. The soils are from the district roads D177 and D154 near Lusaka, Zambia.*

Soil 1 is a red, low plastic silty, clayey sand which is probably a mixture of the original, natural soil and a material hauled to the site in the past for gravel wearing course. It contains 21% clay fractions (<0.002mm) and the total amount of fine aggregates is 45%. Liquid limit is 22.5%, plastic limit 17.5% and thus plasticity index 5%. According to the ASTM classification [6] it is SC-SM (silty, clayey sand with gravel) and the AASHO class [7] is A-4 (See Appendix). A closer mineralogical or chemical investigation into Soil 1 was not made like that done for the two other soils.

Soil 2 and Soil 3 are sandy lean clay with medium plasticity. The road where they were sampled is an old, deteriorated gravel road, and therefore, there can also be some coarser fractions of the old wearing course. Grain size distributions and plastic properties are very similar between these two soils. Soil 2 contains 35% clay fractions and Soil 36%, the total amount of fine aggregates being 58% with Soil 2 and 62% with Soil 3. Liquid limit is 31.6%, plastic limit 20.0% and plasticity index 11.6% with Soil 2; with Soil 3 respectively, 32.8%, 22.5% and 10.3%.The ASTM class of both soils is CL (sandy lean clay),and the AASHO class is A-6. The grain size curves are presented in Figure 16. and the other properties in Table 7.

Table 7. *Properties of the soils in the laboratory tests. The soils are from the district roads D177 and D154 near Lusaka, Zambia .*

PROPERTY	SOIL 1 from the road D177	SOIL 2, road D154	SOIL 3, road D154
Liquid limit [%]	23	33	36
Plastic limit [%]	18	20	20
Plasticity Index [%]	5	13	16
pH	-	5.4	6.5
Cation exchange capacity[meq/100 g]	-	8.1	7.7
Major clay mineral	-	Kaolinite	Clay mica Kaolinite
Colour	red	red	brownish grey
Classification AASHO	A-4	A-6	A-6
Classification ASTM	SC-SM silty, clayey sand	CL sandy lean clay	CL sandy lean clay

Table 8. *Proportions of the chemical main components in the clay fraction of the clay soils Soil 2 and Soil 3,[%]. The soils are from the district road D154 near Lusaka, Zambia.*

SOIL	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	CO_2
SOIL 2	71.45	14.55	4.75	0.55	0.24	1.36	0.71	2.46
SOIL 3	70.38	14.74	4.90	0.46	0.24	0.20	2.28	2.57

Despite the similarity in the plasticity and grain size distribution there are differences in some other properties. Soil 2 is red as typical for laterites in Africa but Soil 3 is brownish grey. Usually the red colour in a soil is caused by rich ferro-oxide content.

Because these samples contain almost the same amounts of ferro-oxides (Fe_2O_3 of Soil 2 4.75%, of Soil 3 4.90%), the ferro obviously appears in different forms. The proportions of the other chemical main components are also very similar between the samples.

Table 9. *Content of the exchangeable ions in the clay fraction of the clay soils Soil 2 and Soil 3, [ppm[1]]. The soils are from the district road D154 near Lusaka, Zambia.*

SOIL	Al	Ba	Ca	Fe	K	Mg	Na	P	S	Si
SOIL 2	162	48	1274	12	123	275	27	2	16	47
SOIL 3	104	43	1701	7	109	47	17	<1.5	15	66

The mineral composition of the fine fractions samples differs so that kaolinite is the main mineral in Soil 2, and in addition it contains quartz and a little dioctahedric mica and chlorite. Soil 3 has dioctahedric mica and kaolinite as the main minerals and a little plagioclase and quartz. Neither of the soils has any minerals from the smectite group (montmorillonite) or the vermiculite group as well as calcite.

The ion exchange capacity of these soils is insignificantly small (Table 7.,Table 9.). As an important matter, there is a notable difference between the pH of the samples. The pH of Soil 2 is 5.42 while the one of Soil 3 is 6.49 meaning tenfold amount of hydronium ions (H_3O^+) in the former, because the pH scale is logarithmic.

A brochure of the ISS-chemical received from the supplier in Zambia informs that the chemical will work in soil types: A-4, A-5, A-6 and A-7. In addition, the soil should have a plasticity index of 30% or less and 10-80% of soil particles must pass through

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[1] *See definitions!*

30% or less and 10-80% of soil particles must pass through 0.075 mm sieve [42]. Thus, the soils in these laboratory investigations should be very suitable for soil improvement according to the instructions of the supplier. (By the way, the soils in classes A-4...A-7 must contain at least 36% fines passing through 0.075 mm sieve.)

4.3 Preparation of the specimens

The samples were already quite dry when they were taken from the roads, but they dried further by air in the laboratory. Thus, the moisture content was about 1-2% in the air-dried samples. Clumps of the soils were broken so that a soil was even enough for the specimens.

The optimum moisture content and the maximum dry density were determined with untreated soils (pure water added). In Zambia Soil 1, Soil 2 and Soil 3 were compacted with the modified AASHO test [1] and in Finland the compaction of Soil 2 and Soil 3 were checked with the modified Proctor test [44]. The results were same. Thereafter, all the specimens were compacted in the optimum moisture to the maximum density.

Parallel specimens were treated with the ISS-chemical and pure water. Because the chemical analysis indicated, that ISS contains sulphuric acid, the test program includes also parallel specimens treated with sulphuric acid, and some tests were made with parallel specimens treated with lime also. As mentioned in Chapter 3.2 concentration of ISS varies, but the aim was to use as strong sulphuric acid dilution as the ISS dilution is. The chemicals were added so, that the dry soils were moistened to the optimum moisture content with a liquid, which was a mixture of water and the chemical in question. When this text says that a soil has been treated with 0.5% of a chemical, it means that the added liquid contains 0.5% of this chemical. It is only 0.06% of the dry weight of the soil, when the added moisture to the soil is 12% (0.12*0.5% = 0.06%). However, when this text says, that 3% lime has been added to a soil, it means 3% of the dry weight of the soil.

The supplier of ISS adviced to use a dilution of 200 liters of the chemical with 40 000 liters of water in the road stabilization, which is 0.5%. Therefore, the basic dilution in these tests is 0.5% chemical in water and respectively, sulphuric acid of 0.05% strength. Also stronger and leaner mixtures were used.

The added moisture in the laboratory tests with Soil 2 and Soil 3 was about 12 % to reach the optimum moisture content. Thus, the amount of pure ISS was 0.06% of the dry weight of the soil.

The dilution of 200/40000 l was meant to cover an area of 7000 m^2. If the stabilized layer is 15 cm thick, its dry weight will be 290 kg/m^2, and the amount of ISS will be 0.01% of the dry weight of the soil.(See Table 10.) The concentration used in the laboratory tests is considerably stronger, but on the other hand, the soil should be compacted in the optimum moisture content, and the amount of the solution, that should be added, depends considerably on the moisture content in the road surface. Moreover, the thickness of the stabilized layer varies also. The other way would have been to keep the chemical proportion constant and to add water only, which would probably be the right way on the road.

In Zambia the test specimens for the unconfined compression test were compacted dynamically by hand. The mould size was ∅10 x 20 cm^3 and the soil was compacted in five layers each layer being given 62 blows from a 4.5 kg rammer dropped from a height of 450 mm above the soil.

Table 10.

The quantity of the 0.5% ISS-water solution, pure ISS and the including sulphuric acid in the stabilization. The expected depth of the stabilized layer of a road is 0.15 m and its dry weight 290 kg/m^2.

Sprayed 0.5% ISS-solution on a road	0.5% ISS-solution content per dry soil weight	Pure ISS content per road-m^2	Pure ISS content per dry soil weight	Sulphuric acid content per road-m^2	Sulphuric acid content per dry soil weight
6 l/m^2	2 %	0.03 l/m^2	0.01 %	1.7 g/m^2	0.6×10^{-3} %
36 l/m^2	12 %	0.18 l/m^2	0.06 %	9.9 g/m^2	0.003 %

In Finland the test specimens for the unconfined compression test as well as for the soaking tests were compacted statically with a hydraulic press. The soil was put into a steel cylinder of a diameter of ∅55 mm. Two steel pistons compressed a moist soil mass of 280 g until a load of 1000 kg was reached. Thus, the height of the specimen was about 55 mm, and the soil was at the maximum density. These specimens were used in the soaking test, but for the compression test another similar mass was added on the top of the 55 mm high compacted mass, and the whole sample of soil was compressed again with a 1000 kg load. Then the specimen was pushed out from the cylinder with a long piston. This way the same quantity of work was applied to every specimen. (See Figure 17.)

The specimens were cured in room air (dry curing) or in a container where it had a relative humidity of 100% (moist curing). The curing times varied from 7 days to almost 90 days.

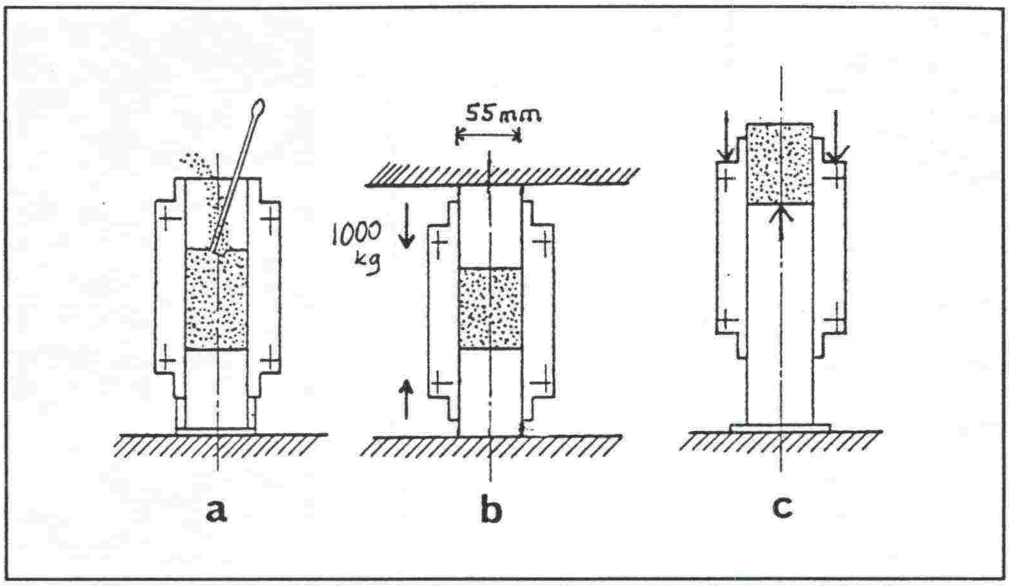

Figure 17. Preparation of the specimens for the soaking tests and for the unconfined compression tests [30].

4.4 The effect of the stabilizer on the geotechnical properties

Proctor tests or soil compaction tests were made to determine the dry density/moisture content relationship of the chemically treated and untreated soils. Immediately after the moistening with the chemical or pure water Soil 1 was subjected to dynamic compaction in the modified AASHO test (Method D) where the soil was put in a mould (size ∅15.3 x 11.6 cm^3) in five layers each layer being given 56 blows from a 4.5 kg rammer dropped from a height of 450 mm above the soil.

Soils 2 and 3 were subjected to static compaction in the hydraulic press which is mentioned in Chapter 4.3. Dry soil masses of 270 g were moistened to get different moisture contents. These samples were compressed until the load of 1000 kg was reached. The soils were compacted immediately after treatment without any curing time. This test did not follow any certain standard. The results are presented in Table 11.

Table 11. The optimum moisture content and the maximum dry density of treated and untreated soils. The soils are from the district roads D177 and D154 near Lusaka, Zambia.

SOIL	Optimum moisture content [%]			Maximum dry density [kg/m^3]		
	Un-treated	Treated with 0.5% ISS	Treated with 5% ISS	Un-treated	Treated with 0.5% ISS	Treated with 5% ISS
SOIL 1	10.5	9.7	--	2090	2140	--
SOIL 2	13.4	13.4	--	1900	1910	--
SOIL 3	14.0	14.0	14.2	1880	1880	1900

After moist curing over 60 days the plastic properties of Soil 2 and Soil 3 were determined. The specimens had been treated with 0.5% of ISS and 0.05% of sulphuric acid. The untreated samples had been cured similarly, and all the specimens had been compacted to the maximum density in the beginning of the curing time. To determine the plastic limit and the liquid limit the specimens were moistened with pure water (such as would happen in nature). The results are in Table 12.

The grain size distribution of the similar samples in the plasticity tests was determined with hydrometer analysis and wet sieve analysis. The treatment of the chemicals did not affect on the grain size curves, but they remained as they are in Figure 16.

Table 12. *Plastic properties of the treated and untreated soils. The soils are from the district roads D177 and D154 near Lusaka, Zambia.*

	SOIL 2			SOIL 3		
	Untreated	Treated 0.5% ISS	Treated 0.05% sulphuric acid	Untreated	Treated 0.5% ISS	Treated 0.05% sulphuric acid
Liquid limit [%]	33	32	32	36	36	37
Plastic limit [%]	20	18	17	20	19	20
Plasticity Index [%]	13	14	15	16	17	17

The maximum dry density of Soil 1 has increased 2.4%, but this tiny improvement has no meaning. Also, the test was made only once, and so the reason could be due such as a difference in compaction, sample etc. The density of Soils 2 & 3 stayed same despite the treatments. The chemicals did not improve the density of the soils when the soils were compacted immediately after the application. However, this test does not indicate what the behaviour would have been if the soils were compacted after a curing time.

The chemical treatments did not change the plastic properties or the grain size distributions of the clays, Soils 2 & 3. If the small clay particles flocculated and agglomerated, they would produce larger-sized aggregates, which is caused by ion exchange on the clay particles [15]. This happens in lime stabilization. The larger aggregates would decrease the plasticity index, and the fine end of the grain size curve would fall lower. Thus, the engineering properties of the soils would improve. These tests indicate, that despite a long curing time (over 60 days) the chemicals did not cause flocculation or agglomeration, and so they did not improve these engineering properties of Soil 2 or Soil 3. The ion exchange capacities of these soils are very low, so it could explain, why these flocculations or agglomerations do not arise. However, neither the soils with a high cation exchange capacity could have been stabilized by RRP in the American tests (See Chapter 3.5.1). Thus, the cation exchange capacity is hardly the only factor in the stabilization.

4.5 Soaking tests

The effect of adding of excess outside water was studied using soaking tests with the Zambian soils, red clay, Soil 2, and gray clay, Soil 3. The preparation of the specimens has been described in Chapter 4.3. They were laid on a #6 mm sieve which was placed in a vessel so that the specimens were immersed into 1 cm water. They were kept there until they broke or after a few days the specimens, which did not break during this soaking, were fully submerged. Before the soaking the specimens had been in dry curing or in moist curing either 7, 30 or 75 days. Some moist specimens were dried in the air before soaking.

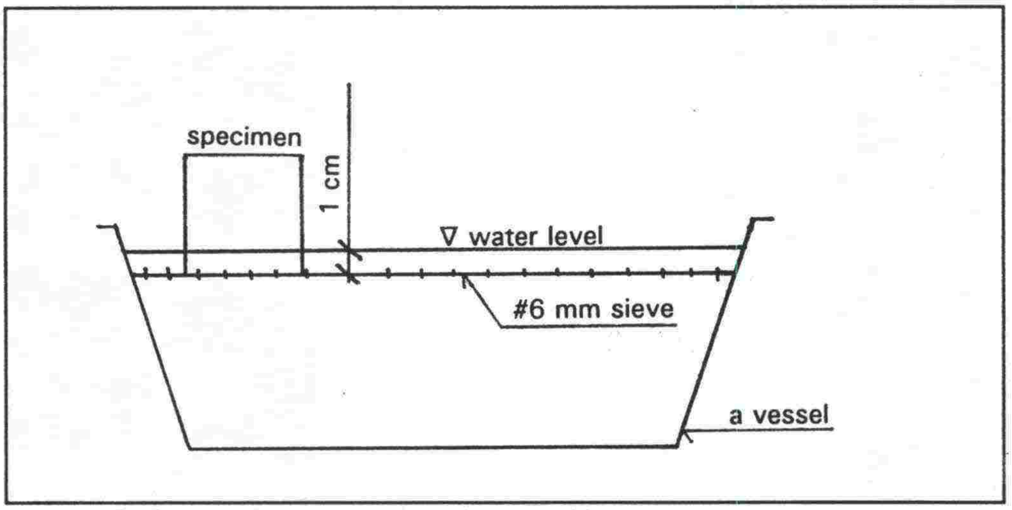

Figure 18. *Schematic presentation of the soaking test.*

On the dry specimens the capillary rise of water could be easily seen. They also started to crumble immediately after being set in the water, and many of them totally broke into the water after a time from 10 minutes to a few hours. The rest of the dry specimens fell to pieces more or less - some of them sustained their shape quite well - but after the capillar water reached the top of a specimen they became waterlogged, swelled and lost their strength completely in a period of less than 24 hours. (However, the soils were not swelling clays.) The red clay, Soil 2, withstood better than the gray clay, Soil 3, but there was no difference between chemical treated and untreated soils or between the curing times with these dry specimens. The only exception were the soils mixed with 2-3% of lime (CaO) which only softened a little in the bottom. The lime was used in the test program as a comparison to see, how a conventional stabilizer works with these African soils.

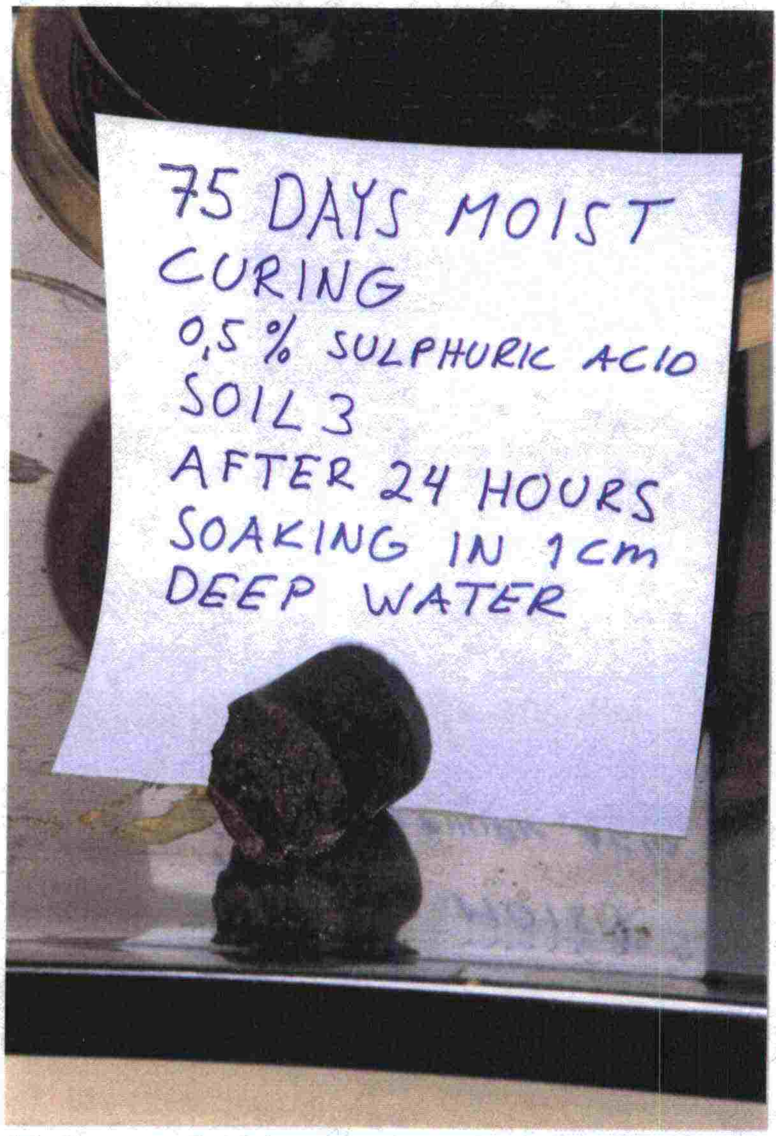

Figure 19. *Gray clay Soil 3 from the district road D154 near Lusaka, Zambia treated with 0.5% sulphuric acid. 75 days moist curing and soaking 24 hours.*

There were more differences in the testing of moist specimens. After 7 days of moist curing none of the specimens withstood the water for a long time (except for the lime treated specimens which were very good), and as well after 30 and 75 days of moist curing the untreated Soil 2 (red clay) and all but one of the specimens of Soil 3 (gray clay) were not durable in water. Above water part of a Soil 3 specimen treated with 0.5% sulphuric acid remained hard and did not become waterlogged, but that part that was under water crumbled from the corners and softened (Figure 19.). After 30 days and 75 days of moist curing Soil 2 treated with 0.5% ISS and 0.05% sulphuric acid behaved like the above mentioned Soil 3 treated with 0.5% sulphuric acid. In the test, after 75 days of moist curing there was also a specimen of Soil 2 treated with 5%

ISS, but it did not endure like the other chemical treated specimens but it was better than the specimen treated with pure water only. (Note, that the acid concentration of 0.5% ISS is near that of 0.05% sulphuric acid.) The chemical treated specimens which resisted any water effects in 1 cm deep water were set fully under water. In few hours they crumbled totally. The lime treated specimens kept their shape and strength under water still after 7 days moist curing; after 7 days dry curing the durability was a little poorer but they also kept their shape and strength (Figure 20.).

Figure 20. Red clay Soil 2 and gray clay Soil 3 with different treatments dried after 75 days moist curing, soaking 6 hours. The soils are from the district roads D177 and D154 near Lusaka, Zambia.

Specimens of Soil 2 and Soil 3, which had been in moist curing 30 or 75 days, were dried in air, and then they were set in water. The untreated and the chemical treated specimens of the gray clay, Soil 3, were broken in water in two hours. The untreated specimen of the red clay, Soil 2, withstood a few hours. Neither the chemical treated specimens withstood more than 1 or 2 days before they had become totally waterlogged and lost their strength. These chemical treated specimens did not resist water like the moist ones, but they broke into the water less than the dry ones.

The tests which were made and their influence on the soils are presented in Table 13. The behaviour of Soil 2 and Soil 3 when they were laid in the soaking test after 75 days of moist curing and air-drying is presented in Figure 21.

These soaking tests showed that some improvements can arise in a soil stabilized with these chemicals. The red clay, Soil 2, was more durable against water from outside when it had been treated with the chemicals. However, even these promising results were modest comparing to the lime treated soils.

Because all the specimens deteriorated when they were laid in water after dry curing, it is clear, that the chemical will not work, if a soil dries soon after the treatment.

The good results of Soil 2 appear to be questionable, because the 30 and 75 days moist cured specimens, which were laid in water after air-drying were broken in the water or became waterlogged in one or two days. The drying-getting wet cycle is happening in nature all the time: soil dries and gets wet, dries and gets wet etc. A stabilized soil should endure that.

The specimens of Soil 2 which were treated with ISS and sulphuric acid behaved in these tests very similarly. Thus, it is obvious that the component of ISS, which alters the properties of soil, is expressly sulphuric acid.

Although the grain distribution and plastic properties of the red clay, Soil 2, and the gray clay, Soil 3, are very similar, the effect of the chemicals on them is different. Soil 2 was improved with every chemical treatment with a minimum moist curing of 30 days, while Soil 3 needed a very strong dilution. The chemical main components and their proportions in these soils are almost the same, but Soil 3 has mica and kaolinite as main clay minerals while Soil 2 has mostly kaolinite. Another explanation in addition to different mineralogy is, that the better influence of the chemicals on Soil 2 could rise from the matter that it is more acidic (Soil 2 pH 5.4, Soil 3 pH 6.5). This is supported by the research of Ingles (See Chapter 3.3), [22].

Certainly the soils which can be improved by these chemicals have to contain a certain amount of fine aggregates, but this does not guarantee the working of the chemicals. The possible improvement depends on chemical properties of a soil, and they can not be predicted by the usual soil classification tests.

This soaking test is a simple test which does not require special equipment. However, it clearly shows the different behaviour of different specimens in excess outside water, and particularly water is the main problem in poor rural roads. Soils treated with the conventional stabilizers e.g. cement, lime or bitumen withstand water in this test very well.

Table 13. *The influence of different treatments and curing times on Soil 2 (red clay) and Soil 3 (gray clay) in the soaking test. The soils are from the district road D154 near Lusaka, Zambia.*

Note that 0.5% ISS is equivalent with 0.05% sulphuric acid.

	Treatment	7 days curing		30 days curing			75 days curing		
		dry	moist	dry	moist	air-drying after moist curing	dry	moist	air-drying after moist curing
SOIL 2	Pure water	0	0	0	0	0	0	0	0
	0.5% ISS	0	0	0	2	1	0	2	1
	5% ISS	--	--	0	--	--	0	1	--
	0.05% sulphuric acid	--	--	0	2	1	0	2	1
	0.5% sulphuric acid	--	--	--	--	--	--	--	--
	Lime 3%	3	3+	--	--	--	--	--	--
SOIL 3	Pure water	0	0	0	0	0	0	0	0
	0.25% ISS	--	--	--	--	--	0	0	--
	0.5% ISS	0	0	0	0	0	0	0	0
	5% ISS	--	--	0	0	--	0	0	--
	0.05% sulphuric acid	--	--	0	0	0	0	0	0
	0.5% sulphuric acid	--	--	--	--	--	0	2	--
	Lime 2%	3	3+	--	--	--	--	--	--
	Lime 3%	3	3+	--	--	--	--	3+	--

0 = no improvement
1 = a little improvement
2 = clear improvement
3 = well improved
3+ = excellently improved
-- = not tested

Thus, this test shows if a stabilizer makes soil more durable against the detrimental effect of water. Of course, this test does not satisfy higher demands, because numerical values can not be measured, but it can be recommended as a basic test in the stabilization investigations.

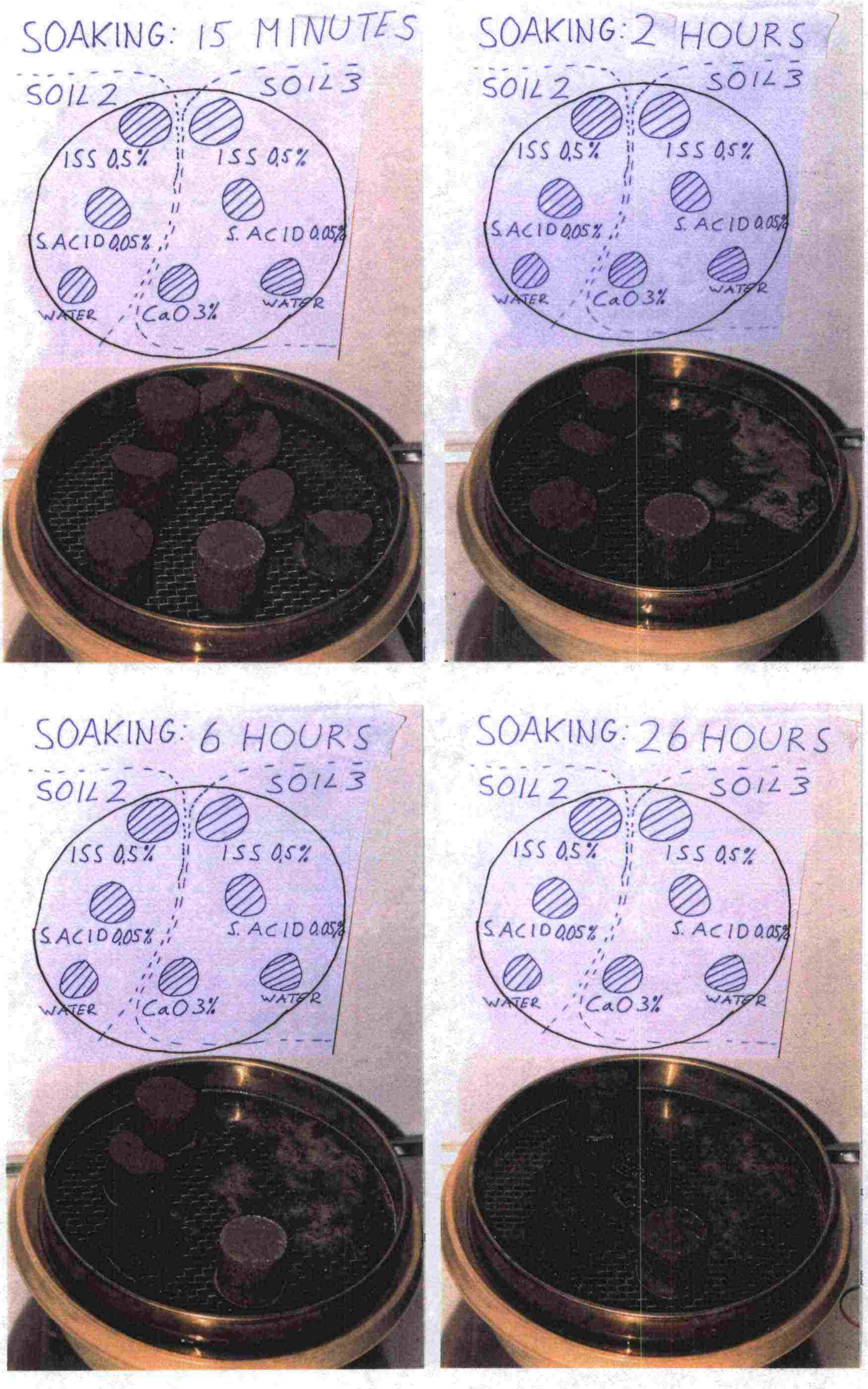

Figure 21. *Behaviour of the specimens of the Zambian clays in the soaking test when they were air-dried after 75 days of moist curing. The soils are from the district road D154 near Lusaka.*

4.6 Unconfined compression tests

The Zambian soils 1, 2 & 3 were studied in the unconfined compression test in order to see the possible increase in strength caused by the treatment with the chemicals. Specimens of Soil 1 (clayey sand) which had been treated with ISS were compressed after 7 days of dry curing. Soil 2 (red clay) and Soil 3 (gray clay) were treated also with sulphuric acid and lime (CaO). In addition to 7 days of dry curing these specimens of Soil 2 and Soil 3 were stored 30 or 75 days in moist and dry air. All the combinations had parallel specimens which were treated with pure water only. The making of the specimens has been explained in Chapter 4.3.

The size of the specimens cured 7 days in dry air was ∅10 x 20 cm^3 and they were compressed in a electromechanical press with a speed about 1.25 mm/minute. The rest of the specimens were in size ∅5.5 x 11 cm^3 and the compression maschine was much the same. The speed was about 1 mm/minute. The test apparatue is presented in Figure 25.

The soaking tests showed that the chemicals do not react in a dry soil. Thus, it might have been useless to test the soils after dry curing. However, these compression tests were done simultaneously with the soaking tests, and their results are also presented here. These soils are very hard and their strength is well sufficient for the roads, when they are dry, although they have not been stabilized. If a road is stabilized, moistened and compacted, the surface will be hard and perhaps good a long time during dry season especially when the soil is fine-grained. However, the rains should be experienced, before it can be said, whether the chemicals have affected the soil or not.

The tests with the gray clay, Soil 3, after moist curing are the only ones that show some better results with the specimens treated with chemicals. After 30 days moist curing the mean value of the strength of ISS-treated is 17% better than strength of untreated soil. The strength has decreased considerably during the curing from 30 days to 75 days. The increase compared to the untreated soil is so small, that it does not have any practical meaning. Moreover, the population in this test was so small, that these values are included in the deviation of the results caused by differences in compaction work, grain distribution, evenness of the specimen surface etc. Although the strength increase would be real, the work on a road is so rough and the results are so uneven, that the increase could not be produced through the road.

The moist specimens were weighed before and after the curing, and the moisture content had decreased only 0.5%. The untreated and chemical treated specimens had lost their weights equally.

The strength of the lime treated specimens was considerably better than the strength of the others, when the specimens had been in moist curing. It can be seen, that already a lime amount of 2% of the dry weight of the soil is enough to improve notably the properties of these soils (at least Soil 3). Often a larger amount of lime up to 10% is used, which increases the strength considerably more. The smaller strength of the lime treated soils after dry curing is caused by the smaller density of the specimens, and the development of the bindings has been interrupted by the lack of moisture. Lime changes the properties of a soil soon after mixing so that its maximum dry density decreases and the optimum moisture content increases [41,43].

The unconfined compression tests did not indicate any improvement in the strength of the chemical treated soils. Because the clayey sand, Soil 1, was tested only after a 7 days of dry curing, it can not be declared for sure, that it will not strengthen. If the strength arose in the clays, Soils 2 and 3, it should be seen in the tests already after 75 days.

4.7 CBR tests

Because the soaking tests indicated an improvement of the chemical treated Soil 2, one CBR (California Bearing Ratio) test was carried out both with ISS-treated and untreated Soil 2. The test followed the BS 1377 [8].

The samples were compacted at the optimum moisture content in five layers with 62 blows of the 4.5 kg rammer being dropped from a height of 450 mm. The mould size was ∅152 x 127 mm^3 and it was provided with a perforated plate which permitted the sample to be exposed by outside water from both bottom and top during soaking.

When the compacted specimens had cured in moist air 40 days, they were placed in water for one day with the water level kept just below the top of collar. The permeability of the specimens was to be studied, but the water level did not reach the top of the specimen in 24 hours. Thereafter, the specimens were kept in water for three days before the testing. During the soaking the swelling of the specimens was measured, but it was only 0.1 mm. Thus, the soils did not have swelling properties. The moisture content of the untreated specimen increased during the soaking 1.0% while the moisture content of the ISS-treated increased 1.2%. Thus, the treatment did not change the absorption properties of the soil.

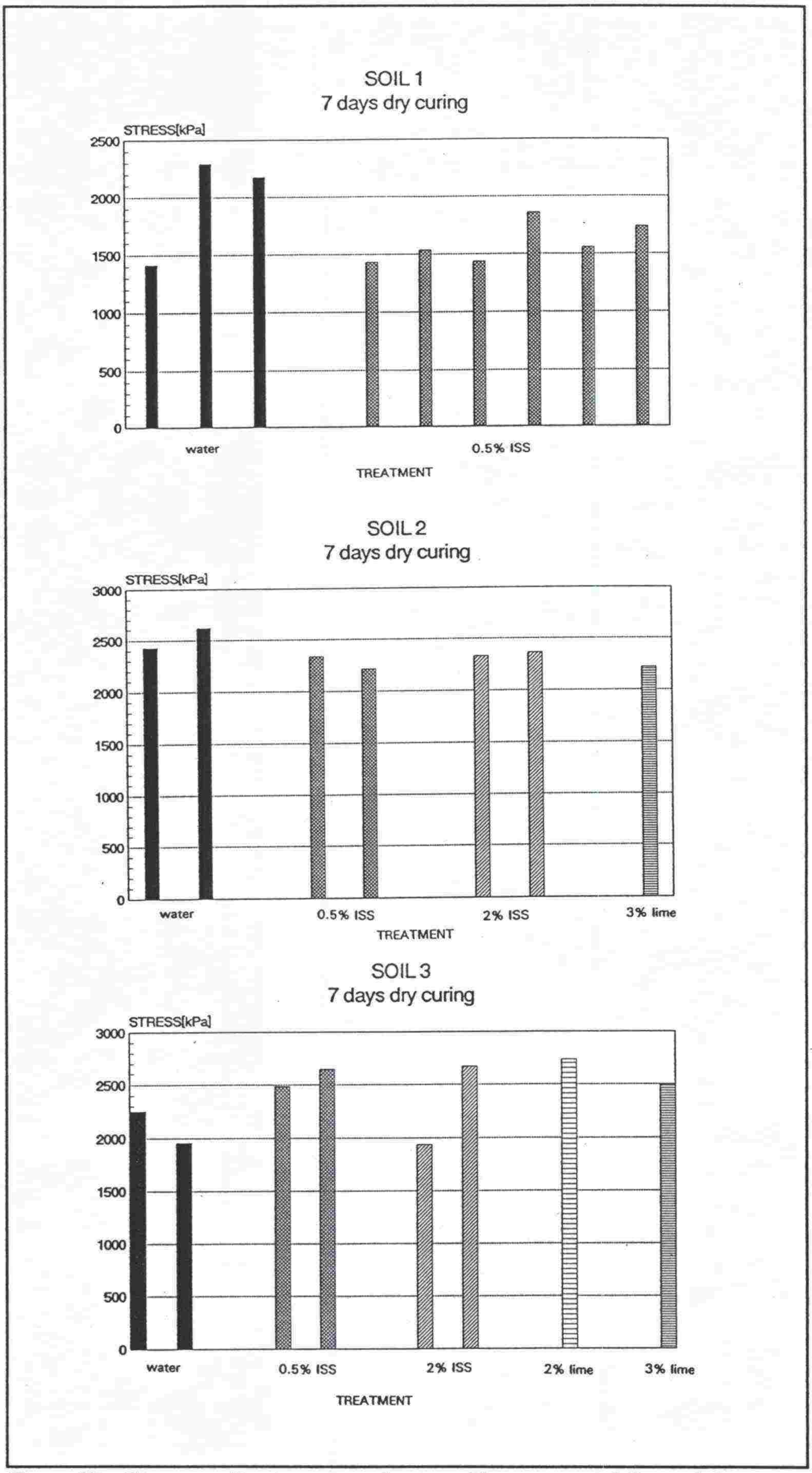

Figure 22. *The unconfined compression test. The stress at failure of the specimens after 7 days curing in room air.*
The soils are from the district roads D154 and D177 near Lusaka, Zambia.

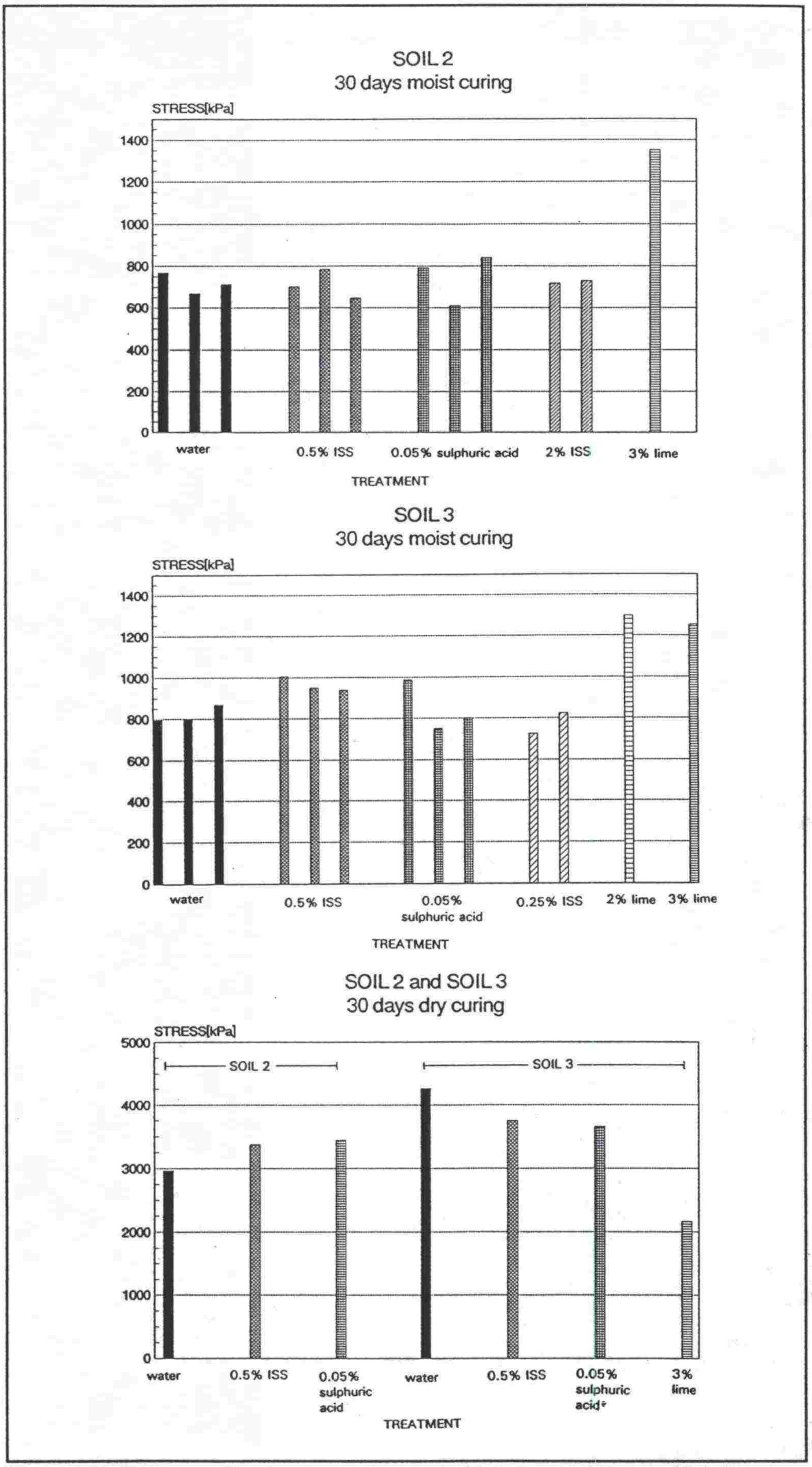

Figure 23. The unconfined compression test. The stress at failure of the specimens after 30 days curing.
The soils are from the district road D154 near Lusaka, Zambia.

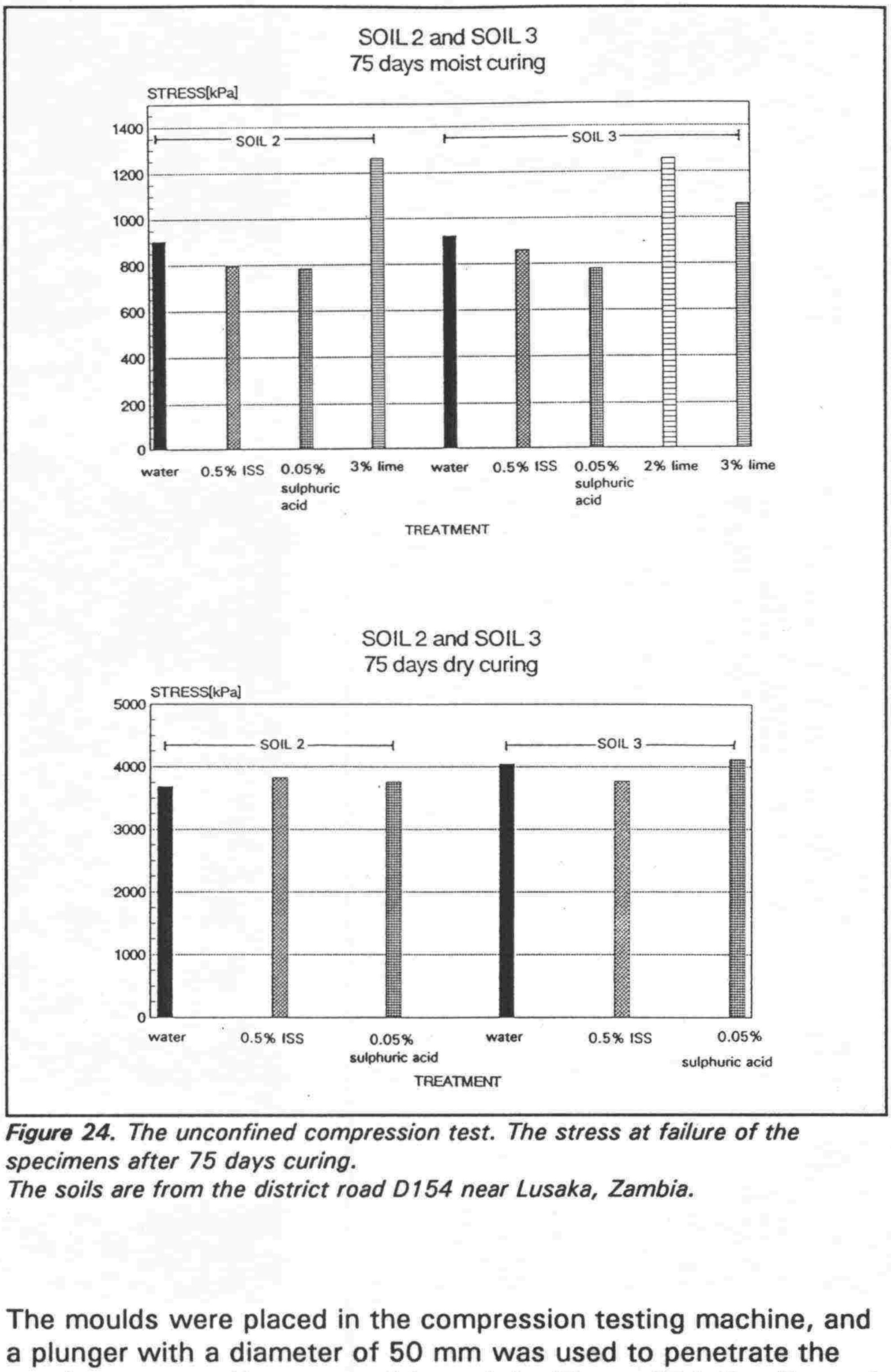

Figure 24. *The unconfined compression test. The stress at failure of the specimens after 75 days curing.*
The soils are from the district road D154 near Lusaka, Zambia.

The moulds were placed in the compression testing machine, and a plunger with a diameter of 50 mm was used to penetrate the specimen at a uniform rate of 1 mm/min (Figure 25.). Readings of the force were taken at intervals of penetration of 0.25 mm to a total penetration of 7.5 mm. These readings have been compared to the standard force penetration curve, and the CBR value [%] is higher of the ratios of force in this test compared to the standard force at penetrations of 2.5 mm or 5 mm (See Appendix). The standard force penetration curve has been obtained by testing a high-quality crushed-stone material [49].

After the CBR value was tested on the top of the specimen, the mould was inverted, and test was repeated on the other end of the specimen. The results are in Table 14.

Table 14. *The results of the CBR test with the Zambian red clay, Soil 2, from the district road D154 near Lusaka.*

Treatment	The end of the specimen	Bearing value [%] at penetration of		CBR value [%]
		2.5 mm	5.0 mm	
Untreated	top	9	10	10
	bottom	8	9	9
0.5% ISS	top	9	9	9
	bottom	6	6	6

The results of the CBR test do not indicate any improvement in the strength of the chemically treated Soil 2. The small decrease of the strength in the treated samples is probably only due to a deviation in the test. It is interesting to see, that although the durability against the detrimental effects of moisture improved in the soaking test in Chapter 4.5, the improvement cannot be found in this CBR test after soaking.

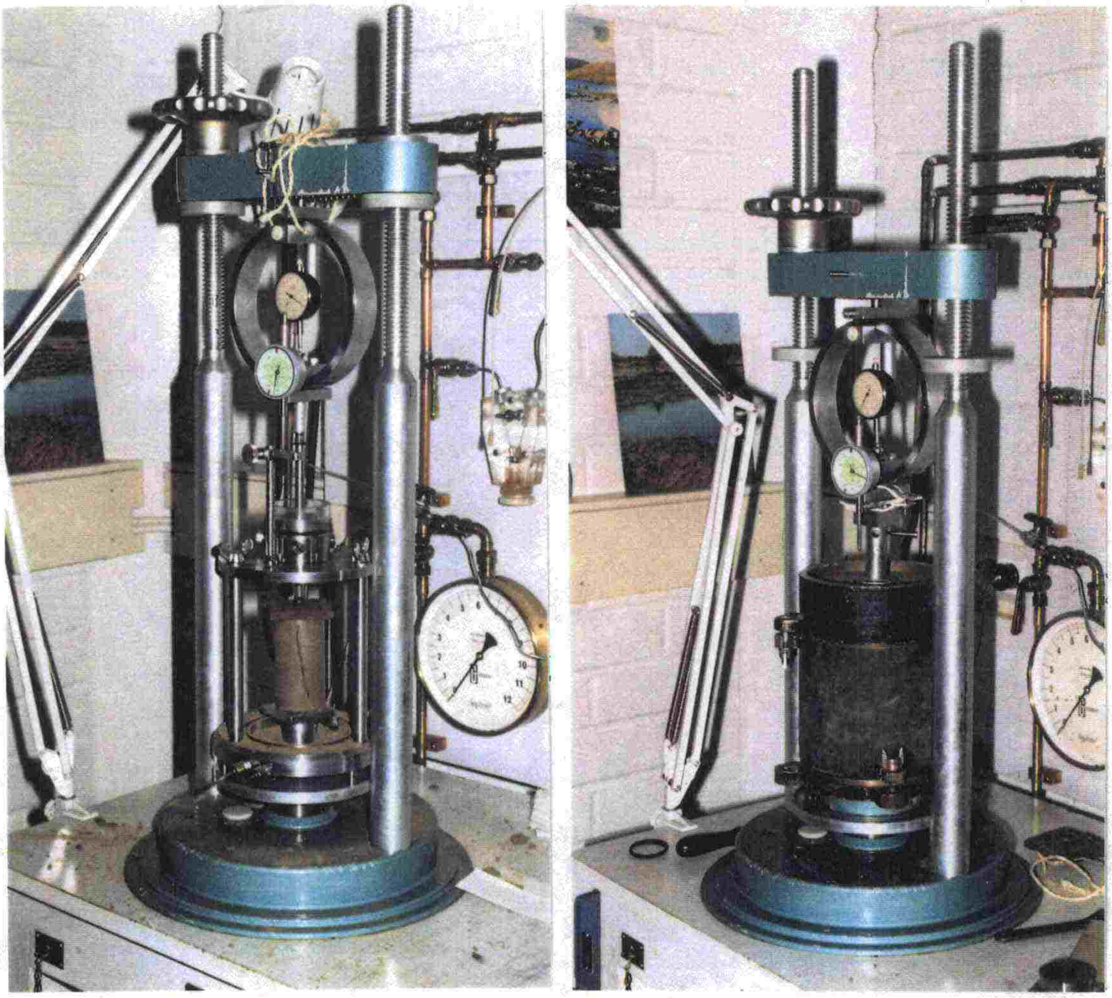

Figure 25. *a) The Unconfined Compression Test b) The CBR Test*

4.8 Dust binding tests with Finnish soils

A few simple tests were carried out with two Finnish wearing course gravels for an evaluation to see, if these chemicals could be used instead of calcium chloride ($CaCl_2$) in dust binding of gravel roads. The soils had been taken from the Vaasa road district. The other (Soil A) is crushed till (or crushed moraine) and the other (Soil B) crushed rock. The grain size curves and the classification of the soils are presented in Figure 26.

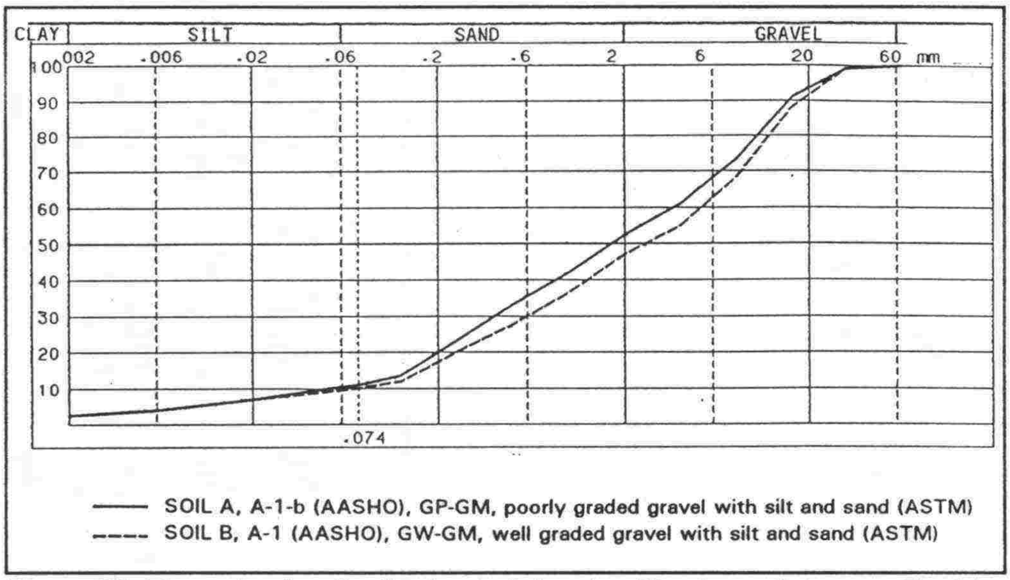

Figure 26. The grain size distribution and the classifications of the two Finnish wearing course gravels in the dust binding tests. The gravels are from the zone of Oravainen in Vaasa road district.

The soils were sieved for the tests through a #4 mm sieve, because the specimens size were as small as in the soaking tests. Before the compaction the soils were treated with 0.5% ISS and the parallel samples with 10% $CaCl_2$ or pure water. The specimens were stored in room air.

Later, the air-dried specimens were crushed, and their dusting was observed visually. The $CaCl_2$- treated specimens raised very little dust, while the others treated with ISS or pure water raised remarkably more dust.

These tests showed, that ISS does not prevent a road from dusting, at least not when the road surface will dry soon after the spraying. Moreover, it is difficult to believe, that this chemical is able of working in such coarse grained soils.

5 Use of the stabilizer on a test road in Zambia

5.1 Description of the test road

In Zambia five drums of the ISS-stabilizer were tested on two sections of district road D177 which leads east from trunk road T2 north from Lusaka (Figure 28.). D177 is an old gravel road which had been heavy graded (i.e. to restore the cross-section by returning material from the sides and shoulders towards the center of the road, by grading the camber[1] and by compacting [48]) some time ago and the surfacing is a mixture of previously hauled gravel and finer natural soil. The gravel is no longer evenly distributed and the amount is not sufficient. Therefore, despite the heavy grading, it could not withstand traffic or rains for long periods of time, the surface was full of corrugations, potholes and loose places and during rainy season it has been almost impassable.

Earlier the traffic volume had been low but after the heavy grading, regravelling and especially the stabilization after which the whole road began to be in quite good condition, traffic volume has risen considerably to about 50-100 vehicles per day, most of which is heavy.

Test section 1 began 2.2 km before road T2 and ended at the junction of T2 and D177. Section 2 began 7.0 km before T2 and its length was 1.0 km (Figure 28.).

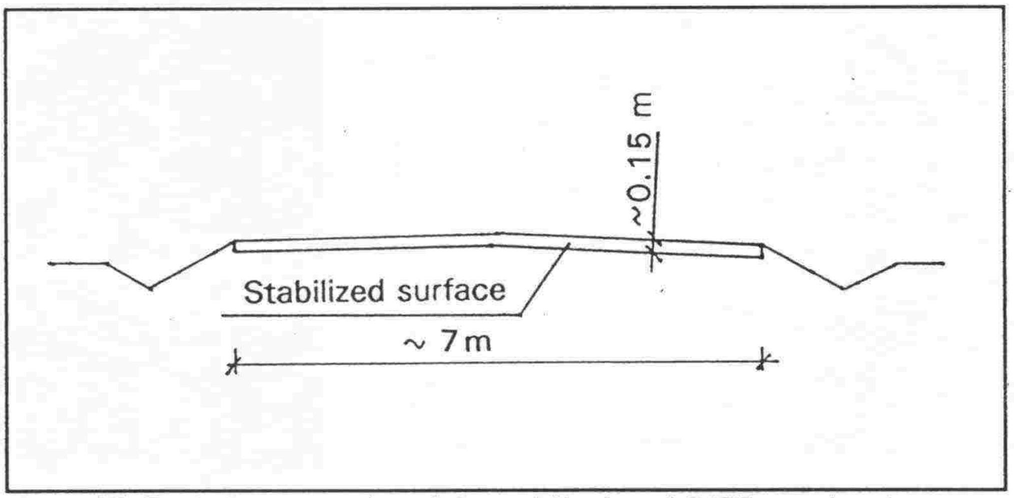

Figure 27. Typical cross-section of the stabilized road D177 near Lusaka, Zambia.

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[1] The arched geometric shape of the cross section of a straight section of a carriageway

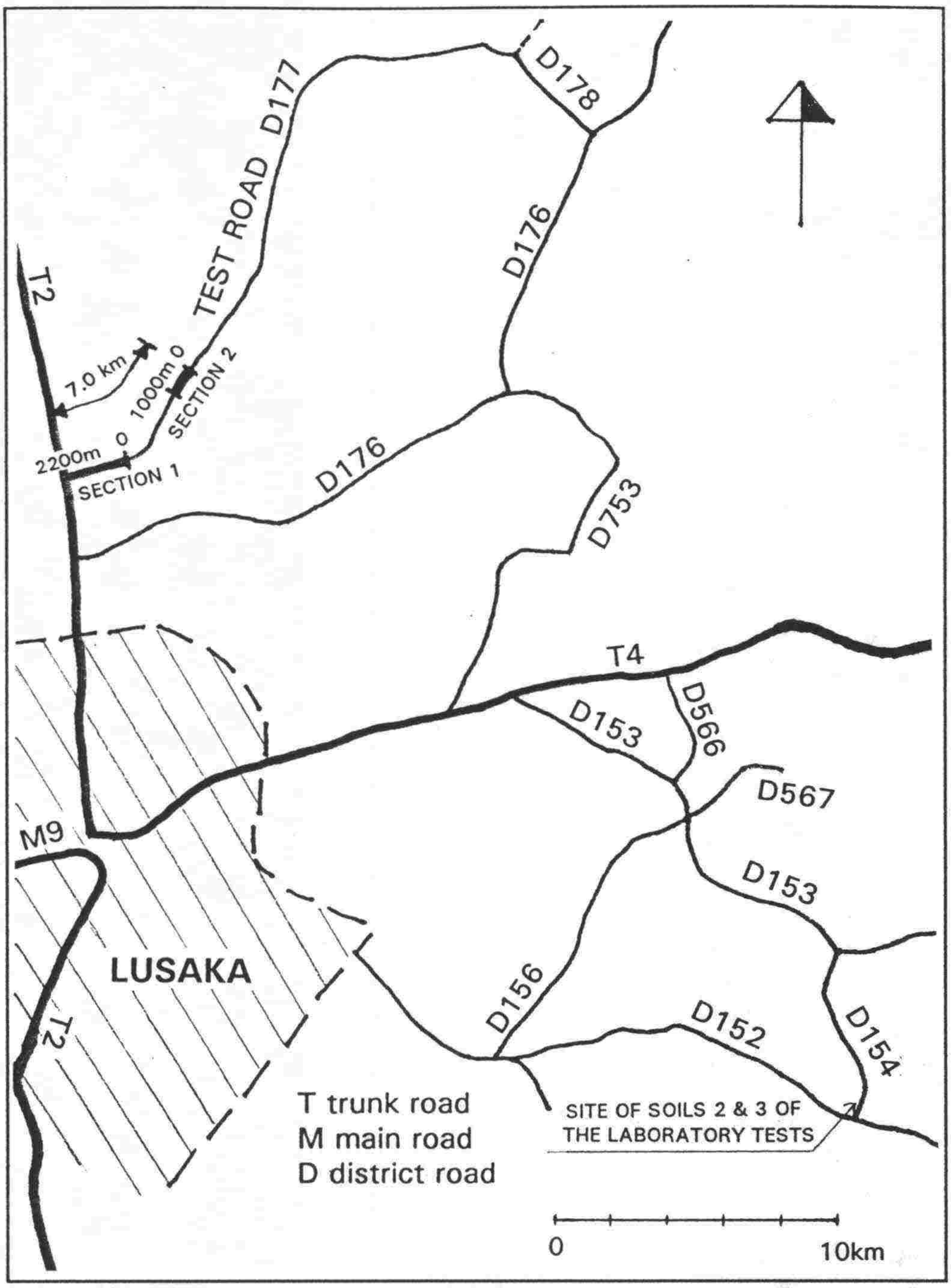


Figure 28. Location of the test road and the road where the samples for the laboratory tests were taken near Lusaka, Zambia.

5.2 Soil composition of the surfacing

Soil samples are at intervals of at least every 200 m in section 1 and every 100 m in section 2. The samples were taken using a shovel from the surface after it had been ripped with a bulldozer or mixed with a rotavator while dry.

Grain size distribution and the Atterberg's limits i.e. liquid limit, plastic limit and plasticity index were determined in laboratory tests. The grain size distributions can be found in the Appendix and the other results of the section 1 are presented in Table 15., the results of the section 2 in Table 16.

As typical in southern Africa soil is mostly red, lateritic soil which means that it is rich in ferro-oxides.

The soil in the sections 1 and 2 is quite similar. It is mainly clayey or poorly graded sand and it belongs to classes SC, SP-SC or SP (ASTM) and A-2-4 or A-2-6 (AASHO) (See Appendix). The liquid limit varies between 20.7-28.0 % and plasticity index between 4.4-17.5 % . The soil is mainly moderately plastic. The smallest amount of fine aggregates which pass the 0.075 mm sieve is 1.6 % and the biggest 39.0 %.

Table 15. *Liquid limit (LL), Plasticity index (PI), amount of fine aggregates and soil classifications of the soil samples from the surface of the section 1 of the test road D177 near Lusaka, Zambia.*

CHAINAGE SECTION 1	LL[%] PI[%]	FINES < 0.075mm [%]	CLASS AASHO	CLASS ASTM
100	21.5 11.7	10.2	A-2-6	SP-SC Poorly graded sand with clay
300	23.2 10.9	15.7	A-2-4	SC Clayey sand
500	23.0 13.4	1.6	A-2-6	SP Poorly graded sand
700	22.2 15.5			
900	22.3 15.5	8.7	A-2-6	SP-SC Poorly graded sand with clay
1100	23.4 11.7	12.7	A-2-6	SC Clayey sand
1300	22.4 10.1	11.2	A-2-4	SP-SC Poorly graded sand with clay and gravel
1500	23.1 15.9	8.8	A-2-6	SP-SC Poorly graded sand with clay
1700	24.2 12.8	10.6	A-2-6	SP-SC Poorly graded sand with clay
1900	24.3 17.5	3.8	A-2-6	SP Poorly graded sand
2100	21.6 14.0	8.6	A-2-6	SP-SC Poorly graded sand with clay
2150		39.0	A-4 to A-7	

There is an obvious contradiction between the plastic properties and the fine end of the grain size distribution. Therefore, and on the basis of some parallel findings, there is doubt whether or not the grain distribution has been determined with wet sieving (except section 1, 2150). Thus, the soils may be finer than expressed.

A brochure of the supplier [19] says that ISS will work in soil types A-4 to A-7, and in addition the soil should have a plasticity index of 30 or less and contain 10-80 % fines (0.075mm). (According to AASHO classification soil types A-4 to A-7 contain at least 36% fines!) (See Appendix!)

Thus, the soil in the test sections was not very suitable for the ISS-stabilization, probably more samples than just chain 2150 of section 1 would have belonged to classes A-4 to A-7, if they had been sieved wet. However, the surface at chain 2150 of section 1 deteriorated very rapidly.

Table 16*. Liquid limit (LL), Plasticity Index (PI), amount of fine aggregates and soil classifications of the soil samples from the surface of the section 2 of the test road D177 near Lusaka, Zambia.*

CHAINAGE SECTION 2	LL [%] PI [%]	FINES < 0.075 mm [%]	CLASS AASHO	CLASS ASTM
20	20.7 4.4	10.5	A-2-4	SP-SC Poorly graded sand with silty clay
300	23.5 10.7	17.0	A-2-4	SC Clayey sand
400	23.4 5.8	13.0	A-2-4	SP-SC Poorly graded sand with clay
500	21.4 8.9	18.0	A-2-4	SC Clayey sand
600	28.0 12.8	16.1	A-2-6	SC Clayey sand
700	22.8 12.0	12.3	A-2-6	SC Clayey sand
800	22.9 9.9	12.9	A-2-4	SC Clayey sand
900	24.0 13.9	10.9	A-2-6	SC Clayey sand with gravel

5.3 Condition classification of stabilized roads

To evaluate the result of the stabilization a condition classification was created by adapting the one used for Finnish gravel roads [45]. In the classification the quality of the road surface is estimated visually taking into the consideration shape, evenness, solidity and dusting (Table 17.). The shape means to have the desired cross-section geometry of the road in which the camber crown or superelevation permit good drainage. Evenness takes into account all the corrugations, potholes, loose places etc. A road is solid when the surface seems plastic and there is no loose material. During dry season dusting is a result of a nonsolid surface which has not been treated with calcium chloride or other suitable chemicals.

The road is divided into sections of about 100 or 200 meters whose average condition is evaluated. If the condition of the road apparently changes, the next section will begin from that point. This evaluation can be a little subjective view and not an absolute value, but the method is cheap and simple as well as being accurate enough for these purposes.

After expensive road construction like stabilization, a road should stay in a good condition (classes 4 or 5) for a long time. This long time depends on economic calculations in which different alternatives like regravelling and ISS-stabilization are compared.

Table 17. *Condition classes of ISS-stabilized roads.*

CLASS	DESCRIPTION OF ROAD
5	The shape of the road is good and the surface is even and solid. No dust.
4	The shape of the road is good and the surface is even. Wheel lines or most of the surface are solid. A little dust. There are only few corrugations, ruts or potholes.
3	The shape of the road is quite good and the surface of the road is quite even. About half of the surface is solid. There are some corrugations, ruts or potholes. Dusty.
2	The shape of the road may have changed. There are quite many corrugations, ruts or potholes and most of the surface is not solid. Very dusty.
1	The shape of the road may have changed. There are many corrugations, ruts or potholes. The surface is not solid and there may be very soft places. Very dusty.

5.4 Stabilization work

Stabilization work at the sections 1 and 2 was done during the period 6.6.-18.6. 1991. Because the rainy season had been from December to March, the surface of the road was very dry.

Equipment consisted of

- a bulldozer
- a rotavator pulled by a four wheel drive tractor
- two graders (the other is not essential)
- a water bowser
- a pneumatic roller.

Before starting -to get the right distribution of the stabilizer- chainage was marked on the road sides with lime, so, unlike using sticks the marks had no possibility to be adjusted. Proper working methods were not known and this meant that different ways of working were used in different segments of the test road.

Most of the road was so tough before stabilization that it had to be ripped by the bulldozer.The general procedure after ripping the soil was to mix it with the rotavator when dry and then the mixture of stabilizer and water was sprayed onto the top with the water bowser and the soil was mixed again while wet. Next the surface was graded and compacted.

Some problems disturbed the work. The tractor pulling the rotavator broke-down in section 1 from 400 to the end and also in section 2 from 600 to 800, so it was difficult to mix the soil with graders only. Moreover, the design of spray pipe in the water bowser was not perfect and left a wide dry gap between watering lines and the shoulders. Thus it was difficult to get the surface evenly saturated.

The stabilization was done in 200, 300 or 400 m long stretches and usual work achieved around 400 m per day. If the hauling distance of water is long and only one water bowser is in use, it would not be wise to stabilize a section longer than 200 m because having to wait for the water bowser slows the work. The road was passable for vehicles the whole time except small cars which had some difficulties during the work.

The stabilization work and the condition after one and half month at the sections 1 and 2 are described in detail in the Appendix.

Figure 29. Stabilization work on district road D177 near Lusaka in Zambia in June 1991. a)Ripping with a bulldozer, b) A tractor pulled rotavator, c)Spraying with a water bowser.(See the next Figure!)

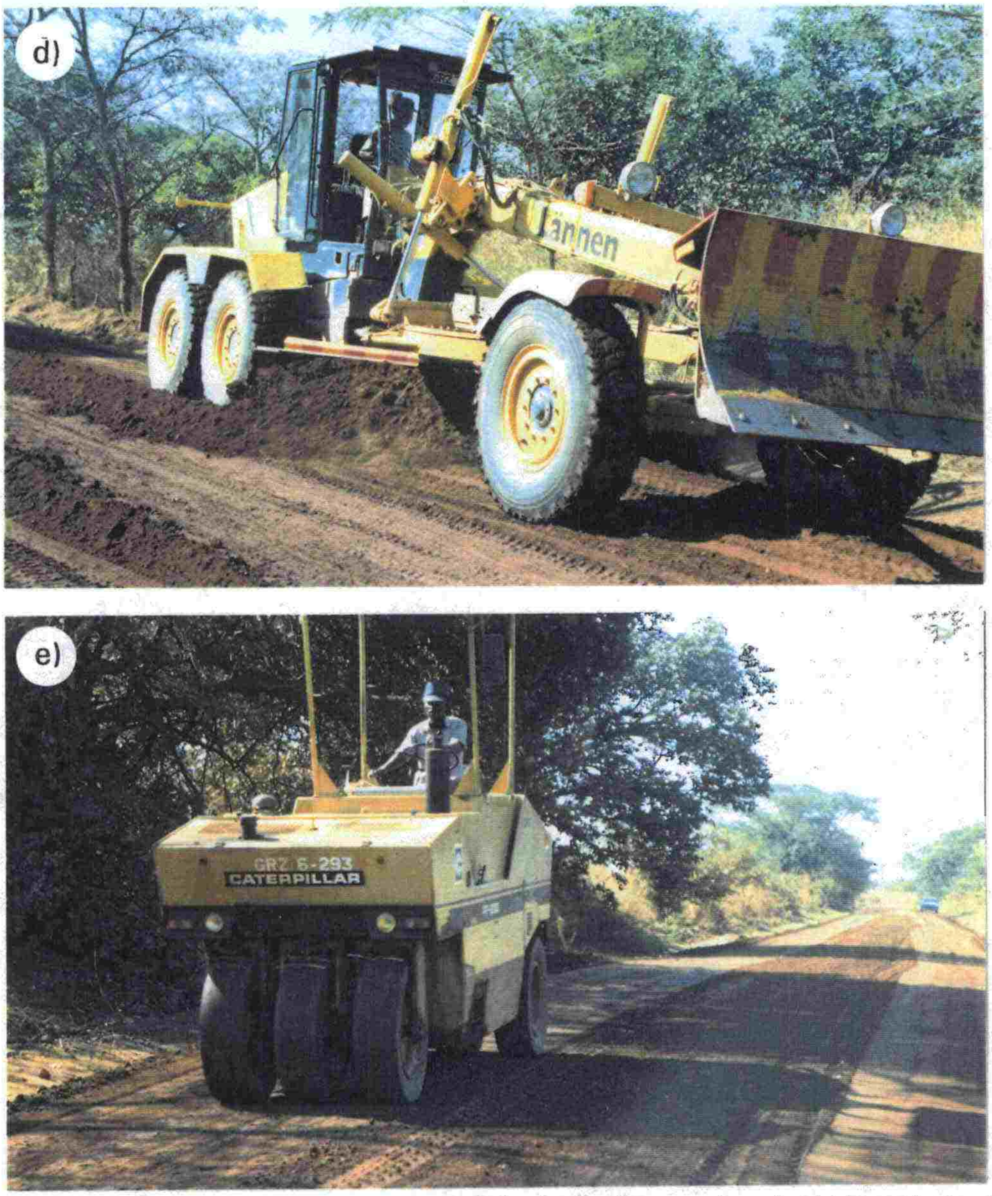


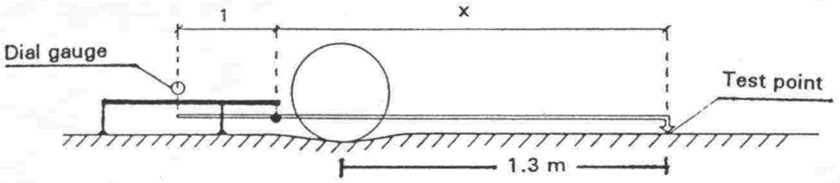
Figure 30. Stabilization work on district road D177 near Lusaka in Zambia in June 1991. d)Mixing and/or grading with a grader, e) Compaction with a pneumatic roller. (See the previous Figure!)

5.5 Field investigations

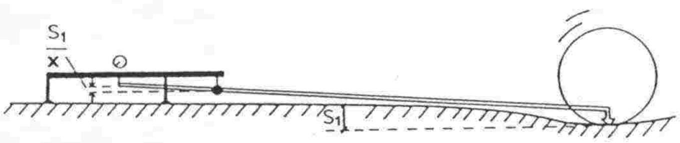
At section 2 in four stations, chainage 700, 800, 900 and 1000m, field bearing tests and density tests were done before and three and half weeks after the ISS-stabilization. The measuring places were chosen in areas where the surface was not loose before the stabilization because the tests would not have given sensible results on a loose surface. At this time after the stabilization the whole surface was still in quite good condition.

The bearing was tested with Benkelman beam measuring pavement deflections under a loaded lorry. That transient deflection test was carried out according to instructions by Transport and Road Research Laboratory (TRRL) [39] except for the vehicle that was used was different.

In the test procedure the test point is 1,3 m front of the rear wheel of a loaded lorry which moves forward until the test point is 5 m behind it.Deflection of the test point is measured by a dial gauge on the Benkelman beam. Records are kept of the initial, maximum and final dial gauge readings.(Figure 31.)



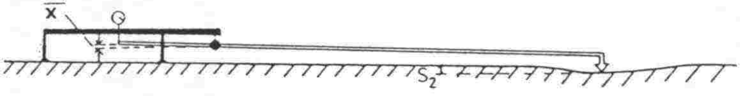
a) Test point before the loading



b) Test point under the loading of the wheel
The deflection is the dial gauge reading multiplied by x

S_1 is Transient loading deflection

S_1 - S_2 is Transient recovery deflection



c) Test point after the loading

Figure 31. *Diagrammatic presentation of the transient deflection test with the Benkelman beam [35].*

The difference between the initial and maximum readings is proportional to the transient loading deflection, and the difference between the maximum and final readings is proportional to the transient recovery deflection. These deflections are used in calculating the modulus of deformation E in the equation (11). (This test type is called the dynamic test in some sources.) The transient recovery deflection is elastic and the difference between the transient loading and recovery deflections is plastic deformation (permanent deflection) (Figure 33.). TRRL [39] advises that the result of the test - the transient deflection - is the mean of the loading and recovery deflections, but that report does not mention anything about moduli, but the aim is a deflection curve of a road for evaluating of the pavement condition.

The distribution of the pressure in the contact area of a tyre is very complicated. Usually, however, the contact area is assumed to be a circle. A dual wheel is expressed as an equivalent single wheel which has a similar effect on the road surface (Figure 32.).

The radius of a loading circle r equivalent to the loading area of a dual wheel is [35]

$$r = 0.4 \sqrt{\frac{P_p}{p_r} + 1.8\, c \sqrt{\frac{P_p}{p_r}}} \tag{9}$$

r	*is*	*radius of a loading circle [m]*
P_p		*load of one tyre [19.1 kN]*
p_r		*tyre pressure [550 kPa]*
c		*distance from center to center between the tyres of a dual wheel [0.4 m]*

Contact pressure q against the road can be expressed as

$$q = \frac{P_k}{\pi\, r^2} \tag{10}$$

q	*is*	*contact pressure [kPa]*
P_k		*load of a dual wheel [38.2 kN]*
r		*radius of a loading circle [m]*

Derived from the Boussinesq's theory the modulus of deformation E of the pavement is obtained [49,35]

$$E = 2\,(1-\mu^2)\,\frac{q\,r}{s} = 1.5\,\frac{q\,r}{s} \tag{11}$$

E	*is*	*modulus of deformation [MN/m^2]*
s		*transient recovery or loading deflection from the Benkelman beam test [mm]*
μ		*Poisson's ratio [0.5]*

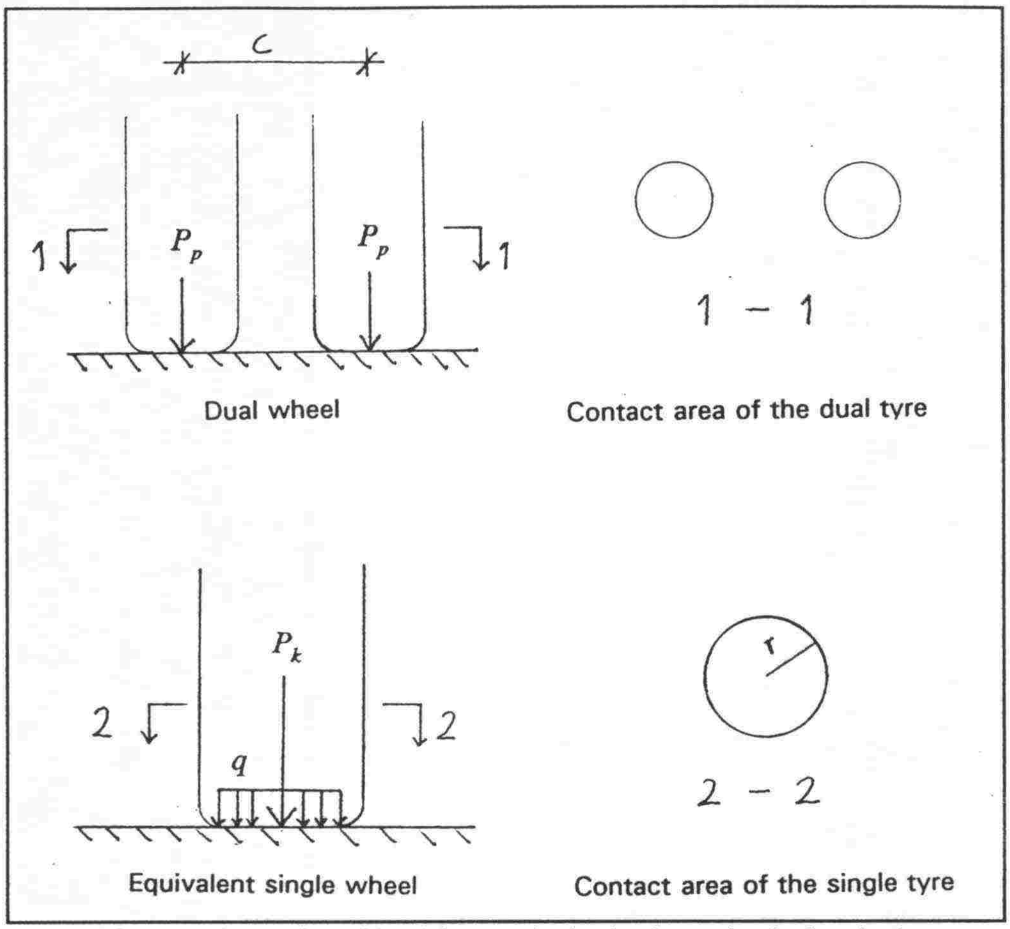


***Figure** 32. Transformation of load from a dual wheel to a load of a single wheel.*

In the equation (11) the assumptions are that the deflection is at the center of a flexible circular plate and the Poisson's ratio is 0.5. In reality the Poisson's ratio should be smaller because some volume change obviously appears during deformation.

Field densities were determined with sand replacement method of British Standard BS-1377 [8] and the maximum dry densities were determined with the modified AASHO test (AASHO T-180) [1].

Results of the field bearing and density tests in the section 2 are presented in Figure 34., Figure 35. and Figure 36.

Because the measurements were done during the dry season, the bearing values (moduli of deformation) and the densities were good. The moduli from the recovery deflection are in most cases considerably bigger than the moduli from the loading deflection, which means that the proportion of the plastic deformation is rather big. However, the surface was well compacted, which can be seen from the good densities. The deviation of the results is rather considerable, and any differences between the stabilized and unstabilized road can hardly be noticed. An exception is station 800m which was loose before the stabilization. It became denser after the stabilization, but this is obviously because of the compaction - not because of the chemical.

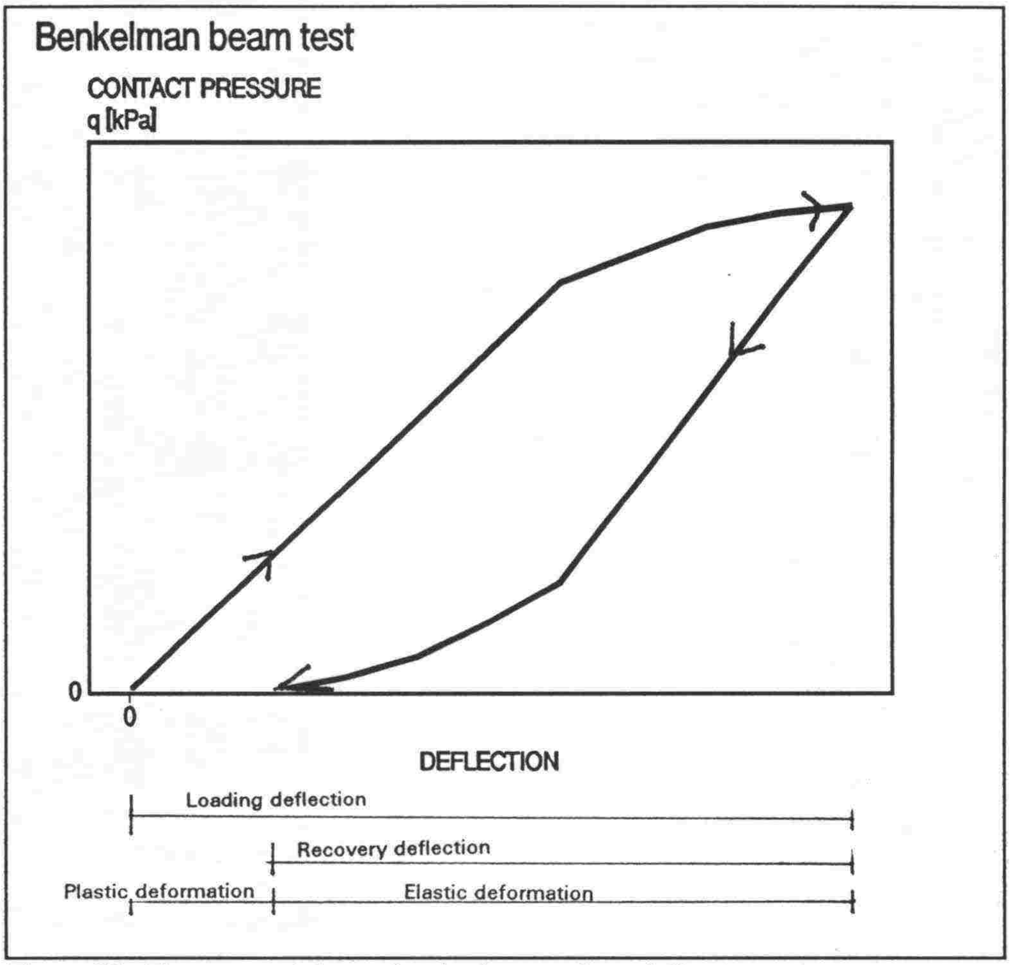


Figure 33. The stress-deformation in the transient deflection test.

5.6 Evaluation of the success of the stabilization

Because the road work crew was unexperienced in the stabilization work beginning in test sections 1 &2, quality of work was not possible in all places. The quality of work and the low plasticity of the soil were two reasons why the surface of the road was not solid in all places even immediately after the stabilization. However, even those segments which were perfect in the beginning have begun to deteriorate rapidly. As can be seen from the classification one and half month after the stabilization in Table 18., there are only few segments which were still comparatively good(class 4). After few months even those good segments had considerably more deterioration, and the road was as bad as it had been before the stabilization.

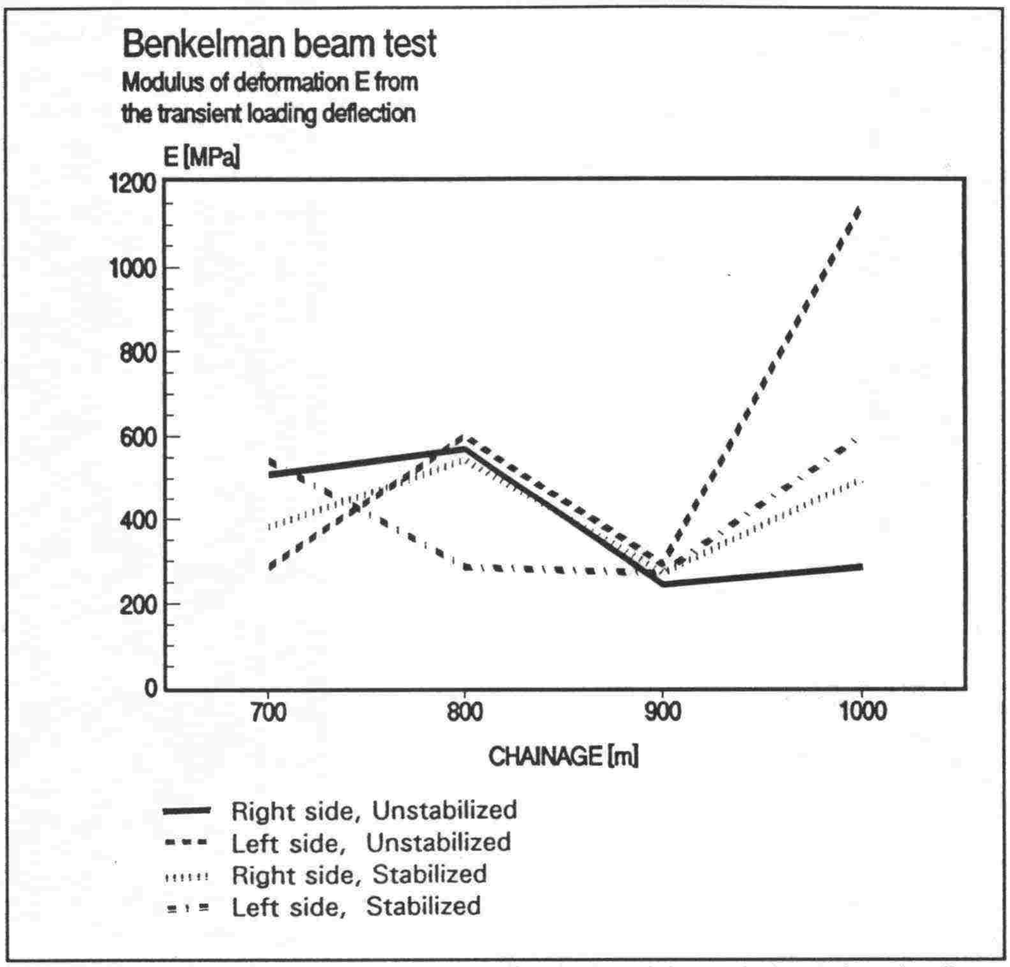


Figure 34. The modulus of deformation E calculated from the transient loading deflection. Measured before the stabilization and three and half weeks after it. Section 2 of the test road D177 near Lusaka, Zambia.

The Benkelman beam tests or the Field density tests did not indicate any improvement in the soil properties following the stabilization. The moduli of deformation varies, in some points the modulus of the unstabilized road was better and in some points vice versa. The bearing and density of the road were rather good but the measurements were done during the dry season. The results might have shown some differences if the measurements had been taken during or just after the rainy season when the bearing of the road is a problem. However, it is impossible to do Benkelman beam test on a very bad road.

According to Escobar[10] the minimum time required by the electrochemical action in the ISS-stabilization is 60 days. Thus it may be that the Benkelman beam and the field density tests as well as laboratory tests may not verify any progress in a short period, but if a road deteriorates considerably in this 60 days, it is hard to believe that the stabilization will work. This research followed the development of the test road only a few months during the dry season. Thus, it cannot be said how the stabilized road will behave after a longer period, but because the road began

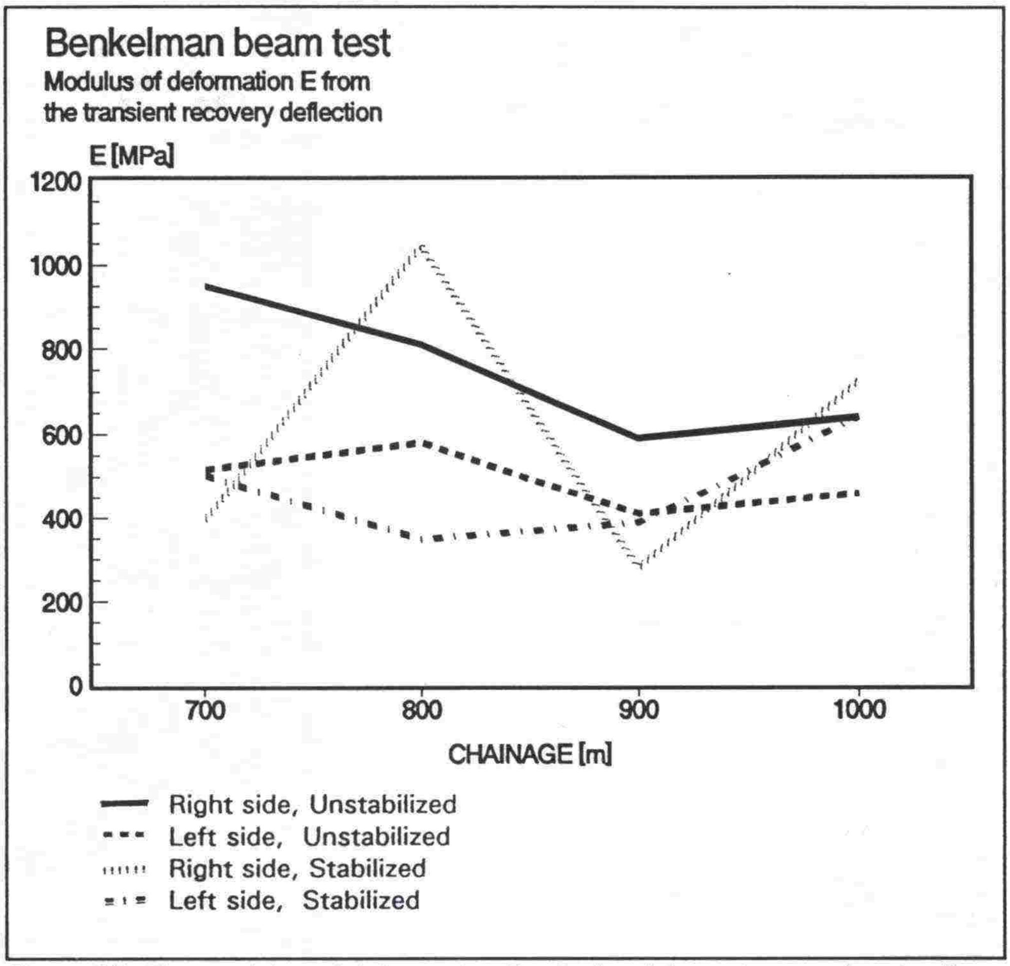


Figure 35. The modulus of deformation E calculated from the transient loading deflection. Measured before the ISS-stabilization and three and half weeks after it. Section 2 of the test road D177 near Lusaka, Zambia.

to deteriorate rapidly, it seems that ISS could not stabilize this road.

The soil in the test roads was probably too coarse in at least some parts of the sections. The evaluation of the test road sections 1 & 2 and the field tests have shown that ISS-stabilizer has not produced any alteration in soil properties. Therefore, it seems that at least old gravel roads or earth roads whose soil is clayey sand or coarser (class A-2/ SC) cannot be stabilized by ISS. This conclusion is not in contradiction with Escobar [10] or the supplier [19] who says that the sulfonated oil works with A-4 to A-7 soils.

The overly coarse material can be one reason for the failure of the stabilization, but the plastic properties of some samples show that there were also rather fine materials in the sections, and the stabilization did not work there either. The laboratory tests showed that if the stabilizer affects the soil, the soil will have to be moist. The surface of this stabilized road started to dry immediately after the stabilization. Thus, the reaction which might have taken place in the soil, has not been possible.

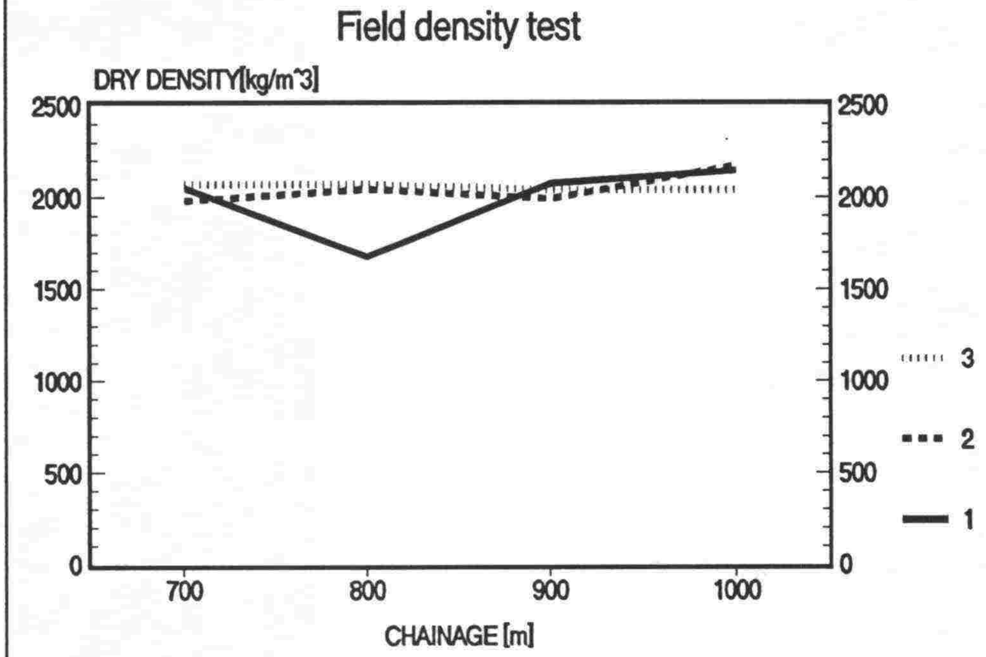


Figure 36. Field densities before and three and half weeks after the ISS-stabilization at the section 2 of the test road D177 near Lusaka, Zambia. 1) Untreated. 2) Treated. 3) Maximum dry density.

Table 18. Condition class one and half month after the stabilization at the sections 1 and 2 of the test road D177 near Lusaka, Zambia.

SECTION 1		SECTION 2	
Chainage	Condition class	Chainage	Condition class
0-400	4	0-400	3
400-700	1	400-600	4
700-1200	2	600-800	3
1200-1400	4	800-900	4
1400-1600	2	900-1000	2
1600-1800	3		
1800-2100	2		
2100-2150	3		
2150-2200	1		

6 Effects of the stabilizer on nature and human health

6.1 Environmental impact

In response to the concern for the environment in countries receiving Finnish development cooperation, FINNIDA's policy is to integrate environmental considerations into each stage of identification, preparation, implementation and evaluation of every project [11]. This Environmental Impact Assessment (EIA) considerates, if a project could cause significant environmental impacts under the prevailing ecological, physical and social conditions. Especially in transportation projects the adverse impacts may be air, water and soil pollution, land erosion and disruption of the natural surface water flows. They also can include less technical matters like destruction of valuable habitat areas, landscapes or historical sites, disruption of animal migration patterns and uncontrolled resettlement, isolation of neighbourhoods or disturbing people used to a silent countryside living. These facts concern more a construction of a new road but they have to be taken into the consideration also in road maintenance.

Because the stabilization chemicals studied in this research were dilute sulphuric acid, this consideration of their environmental impact is based on the information of the behaviour of the sulphuric acid in the ground.

Sulphuric acid (H_2SO_4) is not a poisonous agent in itself, but its toxicity is based on the acidity. The toxicity has been tested with animals. The values of lethal concentration (LC50) and dose (LD50) are presented in Table 19. If the LD50 value is >2000 the acute toxicity of the chemical is so little that the chemical is not any more determined as "hazardous to health when swallowed" [46].

Generally speaking, the acidification of soil and groundwater is adverse. It disturbs ecosystems, and plants grow less or may totally die. An acidic soil water proceeds solubility of many metals from the soil particles [24,9], and in addition to the acidity itself the metals make the groundwater quality worse also for humans. Furthermore, acidic water corrodes waterpipes.

Table 19. *The toxicity of sulphuric acid. Lethal concentrations and doses to calcareous, fishes and rats [46,33].*

Value	Concentration/dose	Duration of exposure	Animals
LC50	60-70 mg/l in swimming water	48 hours	Calcareous (Crangon Crangon, brown shrimp)
LC50	100-330 mg/l in swimming water	48 hours	Fishes (Platichthys flesus, flounder)
LD50	2140 mg/kg by mouth		Rats

LC50 is concentration that within testing period kills 50% of the population
LD50 is dose that kills 50% of the population

When the diluted stabilizer is sprayed on the road, the strength of the including sulphuric acid is 0.05% , which means 500 mg/l and pH is 2.1. Thus, in that state the solution is toxic. It probably would kill plants, if it were sprayed on a field. However, a road surface is not expected to grow anything, and it would be good for the shouldelrs if the bushes did not grow there.

When a road is stabilized, the soil in a road surface should be moistened to the optimum moisture content with the chemical solution. In that case the solution will not flow to the ditches and neither forward. It is unlikely that sulphuric acid shall drift horizontally to the neighbouring fields for instance, but it might settle downwards. When the rainwater seeps through the soil down to the groundwater, it changes its chemical composition. In the case of the stabilized road rainwater may dissolve hydrogen (H^+) and sulphate (SO_4^{2-}) ions and carry them down to the groundwater. The seeping water would be very acidic. However, the cation exchange capacity of the soils allows the soil to act as a filter or buffer for many undesirable elements e.g. acids or wastes [34,37]. Clay soils have the biggest cation exchange capacity (See Chapter 2.3), and their water permeability is low. Moreover, there are clay soils at the areas where these stabilizers might work, and usually the important groundwater areas are neither at the clay soils. Thus, the conditions are good for the prevention the seepage of the acid to the groundwater.

The quantity of the sulphuric acid affecting the nature is important. All over the world acid rains bring considerable amounts of sulphuric acid, nitric acid and other adverse compounds on the earth's surface. Of course it depends on the vicinity of the sources, but the pollutants are driven with the wind thousands of kilometres. In southern Finland the average deposition of acidic sulphur compounds expressed as total sulphur was about 1 g/m^2/year and in the cleanest northern Finland 0.2-0.7 g/m^2/year in 1987 [24]. In Central Europe and in large areas of the USA the deposition is over 2g/m^2/year being over 10 g/m^2/year in the worst areas [24,9].

In this road stabilization the amount of sulphuric acid expressed as total sulphur is 1-5 g/m^2. This sulphur would be sprayed on the road with a minimum interval of two to three years with the treated area being only the road, but acid rain covers every square meter on the land. Thus, the quantity of the acid in the stabilization is so little that it hardly has any adverse impact on the environment. Often repeated treatments could perhaps pollute the groundwater.

However, it must be seen that the chemical solution will not flow toward any well or field. If the acid gets to a place where it can be harmful, it should be neutralized with lime. The drums of the stabilizer have to be checked to see that they do not leak, and they should be stored so that possible leaking is noticed and it does not cause damage.

Table 20. *Quantities of acidic sulphur compounds on the earth's surface expressed as total sulphur [24,9].*

Area	Deposition or treatment
Southern Finland	1 g/m^2/year
Northern Finland	0.2-0.7 g/m^2/year
In large areas of middle Europe and the USA	2 g/m^2/year
Areas near very polluting industry	10 g/m^2/year
Road stabilized with the acidic chemical	1-5 g/road-m^2/ one stabilization

6.2 Work safety

When the concentration of the sulphuric acid is 5-15%, it is classified as an irritant according to Finnish authorities [46]. Its toxicity was explained in the previous chapter. Furthermore, if the concentration is over 15%, it will be classified corrosive [46]. The concentration of the sulphuric acid in the ISS-stabilizer has been 5-10%, an acid stronger than 15% should be used.

A splash of the lean acid (<15%) on the skin is not so dangerous, but a long-run or repeating contact causes eruption. Therefore splash should be avoided. Holes can come into clothing if the stabilizer splashes on them. Even the lean acid may cause damage to the eyes [47].

Instructions:

1) Eyes should be protected with safety glasses during the handling the undiluted stabilizer.

2) If the undiluted stabilizer splashes to the eyes, they must be rinsed with plenty of water at least 15 minutes. A doctor should take care of the patient.

3) A contact with the stabilizer should be avoided (rubber gloves) and splash on the skin should be rinsed away.

4) Containers must not leak and the undiluted stabilizer should be handled with care.

7 Summary and conclusions

The Finnish National Road Administration (FinnRA) is implementing a road maintenance project in Zambia funded by the Finnish International Development Agency (FINNIDA). A chemical stabilizer (trademark ISS) was introduced to the road maintenance project as a cheap and durable solution for the problems of rural roads. Poor materials along a route could be stabilized and thus be utilized as a base course of a road. The aim of this report was to find out through laboratory tests and investigations of a test road how the stabilizer improves the properties of soils for road construction.

The chemical was represented to act through ion exchange so that the adsorbed water on the clay particles is permanently reduced. This would make a better compaction possible. As a background for the above-mentioned action theory the structure of the most important clay minerals and the adsorbed water layer is expressed in this report.

Clay minerals are alumino-silicates, i.e. oxides of aluminium and silicon with smaller amounts of metal ions substituted within the crystal by isomorphous substitution. The two basic units in clay mineral are the silica tetrahedron and the aluminium or magnesium octahedron where the silicon, aluminium or magnesium are coordinated with oxygens or hydroxyls. Tetrahedron and octahedron sheets are formed, and the different clay mineral groups are characterized by the stacking arrangements of the sheets and the interlayer bondings which hold two successive two- or three-sheet layers together [31].

If an ion of a clay mineral is substituted by an ion of lower valence (eg. Al^{3+} by Mg^{2+}), a clay particle will get a net negative charge, which is very typical. To preserve electrical neutrality cations are attracted and held on the clay surfaces. These cations are termed exchangeable cations because in most cases cations of one type may be replaced by cations of another type. Clay minerals common in soils are for instance kaolinite, montmorillonite, illite (clay mica), vermiculite and chlorite [31,50].

Water molecule (H_2O) is a dipole which means that its other end is positive and the other negative. Water in soil is hardly ever pure but cations (+) and anions (-) are dissolved in it. Water molecules are attracted to ions in solution, leading to ion hydration. Clay particles are almost always surrounded by layers of water molecules and hydrated cations (adsorbed water). Because a clay particle is negative and forms an electric field, the structure of the adsorbed water can be expressed by the theory of the electric double layer [31,40]. The first layers of water molecules are held to the clay surface due to the hydrogen bond and the bonding forces decrease when the distance increases. The properties of clays change as the thickness of the adsorbed water layer changes.

Certain ions on the clay particles are exchangeable for other anions or cations by treatment with such ions in a water solution. The kind and number of exchangeable cations have an important influence on the behaviour of soils like plasticity properties, strength, permeability and compression and swelling properties [16]. The ion exchange capacity is different for different clay minerals, and cations can be arranged in order of increasing replacing power.

The composition of the ISS-chemical was not revealed closer by the supplier but it was represented to be sulphonated oil. The analysis made in the laboratory of the Finnish oil company Neste Ltd [32] showed that the main compound in the chemical is sulphuric acid (5% sulphuric acid, 95% water and some organic matter). The analysis proves that the ISS-chemical can not be derived from the naphthalene fraction of petroleum, and this fact is in contradiction with the supplier's information. The composition of another chemical stabilizer (trade mark RRP, Reynold's Road Packer) is very similar to ISS [21].

The literature received from the supplier of ISS explains a theory of how sulphonated oil or ISS-stabilizer acts on the soil particles, and what the improvements in the stabilized soil are. The theories are a little confused, and it is strange that ion exchange is portrayed to happen, but it is not which ions are the ones that exchange. The reason for this may be to conceal a business secret, however, it raises doubts to the theory.

This report is not a research of chemistry, and the reaction results have not been analyzed. It is however possible that salt precipitation could be present in reactions between the acid and metal compounds of soil. Gypsum would be a product of neutralization reactions between sulphuric acid and calcium hydroxide.

The only available literature [10,18,38] concerning the ISS-stabilizer was received from its supplier, but publications from disinterested research institutes concerning the RRP-stabilizer were available [13,21,17,25]. Therefore, the writings of these two chemicals are compared in this report.

The ISS-writings were only of positive nature, but all but one of the RRP-writings did not find any improvement in the properties of the stabilized soils. Kézdi [25] writing about RRP mentions also advantages of the chemical soil treatment.

The geotechnical laboratory tests represented in this report were carried out in laboratories of FinnRA[1] and the Zambian Roads Department. The mineralogical and chemical composition of two investigated soils were determined in the laboratory of the Geological Survey of Finland. Most of the tests were made with two Zambian soils taken from a district road D154 near Lusaka; a red clay and a brownish gray clay both with medium plasticity. Their grain size distribution and their chemical composition were similar. The main mineral in the red clay is kaolinite and in the gray clay mica and kaolinite. The red clay is more acidic (pH 5.4) than the gray clay (pH 6.5). Some tests were also made with a red, low plastic silty, clayey sand from Zambia. All the samples were taken from the top layer of a road.

Parallel specimens were treated with ISS-chemical, pure water and sulphuric acid. The strength of the sulphuric acid was equivalent to the strength of ISS. 1 part of ISS was diluted with 200 parts of water (0.5% ISS) and the equivalent strength of sulphuric acid was (0.05%). The solutions were added so that the dry soils were moistened to the optimum moisture content. Some parallel specimens were made with 2-3% lime.

Soil compaction tests (modified AASHO [1], static compaction with a hydraulic press) were made to determine the dry density/moisture content relationship of the chemical treated and untreated soils. These tests were made immediately after the treating of the soils. After a curing in a moist state over 60 days the plastic properties and the grain size distribution of the soils were determined.

An effect of excess outside water was studied in soaking tests with the Zambian clays. The specimens (∅55x55 mm^3) were compacted at the optimum moisture content to the maximum dry density, and they cured in a moist or dry state from 7 to 75 days. Thereafter, the specimens were laid on a #6 mm sieve which was in a vessel so that they were immersed in a 1 cm depth of water. Their structural breakdown was observed.

The strength of the treated and untreated specimens was studied in the unconfined compression test. The compacted specimens had cured in a moist or dry state from 7 to 75 days before the compression.

CBR (California Bearing Ratio) test was carried out with ISS-treated and untreated red clay. The samples were compacted at the optimum moisture content. Then they cured in a moist state 40 days. Before the testing they were totally submerged in water for four days.

The chemicals did not improve the density of the soils when the

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[1] *See definitions!*

soils were compacted immediately after the application. However, this test does not indicate what the behaviour would be if the soils were compacted after a curing time.

The chemicals did not change the plastic properties or the grain size distribution of the soils. Despite a long curing time (over 60 days) the chemicals did not cause flocculation or agglomeration of the clay particles, and so they did not improve these engineering properties.

The soaking tests were the only tests that showed some positive effect of the chemicals on the soils. The red clay was more durable against water from outside when it had been treated with the chemicals - both ISS and sulphuric acid, but only after curing in a moist state, minimum 30 days. The gray clay became more durable against water only with a rather strong acid treatment. The both soils treated with lime were, however, much more durable. Because all the specimens deteriorated when they were laid in water after curing in a dry state, the chemicals obviously will not wor, if a soil dries soon after the treatment. An explanation for the different behaviour of the red and gray soils is hard to give on the basis of this research but the different pH readings of the soils could be one. The improvements acquired with the chemicals (except lime) are, however, so modest that they do not have any practical meaning.

The soaking tests indicated, that sulphuric acid has the same positive influence as ISS. Consequently, although ISS is sharp smelling and a dark liquid unlike sulphuric acid, the most important component in the function of ISS is sulphuric acid.This was expected after the chemical analysis which indicated that sulphuric acid is the main compound in ISS.

The unconfined compression tests or the CBR tests did not indicate improvement in the strength of the chemical treated soils. Usually, a stabilizer is expected to increase the strength of a soil. On the other hand, the strength of the compacted soil would be sufficient in a low volume road, if it sufficiently were able to resist the deleterious effect of water.

A few simple tests were carried out with two Finnish wearing course gravel for an evaluation to see if the ISS-chemical could be used instead of calcium chloride in dust binding of gravel roads. The tests showed that ISS does not prevent a road from dusting, at least not when the road surface will dry soon after the spraying.

The ISS-chemical was used in a district road D177 near Lusaka in Zambia. The road is an old road whose pavement is a mixture of previously hauled gravel and finer natural soil. The road had to be graded very often to be kept in good condition. The soil is mainly clayey or poorly graded sand which perhaps is partly too coarse for this chemical stabilization.

Proper working methods were not known and therefore, different ways of working were used in the stabilization. Most of the road was so tough before the stabilization that it had to be ripped by a bulldozer. After ripping the soil was mixed by a rotavator while dry and the mixture of stabilizer and water was then sprayed on the top by a water bowser and the soil was mixed again when wet. The last step was to grade and compact the surface.

The condition of the surface after the stabilization was evaluated according to a classification which was created adapting the one used for Finnish gravel roads [45]. Bearing and density in four stations on the test road were investigated with Benkelman beam and sand replacement tests. The calculation of the modulus of deformation in the Benkelman test is expressed closer in this report.

Some sections of the test road were still in good condition, solid and undusty surface a few weeks after the stabilization but after few months the stabilized road section was as poor as the unstabilized. The bearing and the density were not improved by the stabilization but the bearing was not a problem during the dry season when these tests were done.

The stabilization of the test road has not produced any alteration in the quality of the road surface at least not during the period of a few months that the road was followed in this research. The soil may have been too coarse, and the surface was not kept moist after the stabilization. The soil in old gravel roads may often be too coarse for this type of chemical stabilization. Therefore, it seems that at least old gravel roads, whose soil is rather coarse,can not be stabilized by the ISS-chemical. It is hard to say if the stabilized road after a longer period will be better than the unstabilized road, the quality of a stabilized road should be rather good all the time.

The stabilization on the road demands many machines. A section of 400 m can be done in a day. Because the stabilization work is also quite expensive, the stabilized road should stay in good condition for several years.

Because the ISS-chemical is dilute sulphuric acid, the environmental impact assessment is based on the information of the behaviour of the sulphuric acid in the ground [9,24,33,37,46,47]. The quantity of the sulphur in the stabilization has been compared with quantities of the depositions by the acid rain. The quantity of the acid in the stabilization is so little that it has hardly any adverse impact to the environment. Repeated treatments might pollute the groundwater, and steps must be taken to see that the chemical solution will not flow to any well or field.

When the chemical is handled, work safety should be also remembered. Although the ISS-chemical is only 5-10% sulphuric acid, it can be very harmful especially for the eyes which should be protected.

The performance of the commercial ISS-stabilizer has been viewed with skepticism from the beginning. The representatives of the supplier in Zambia have not been able to present the working methods. If they had been sure about their product, they would have guaranteed the result by giving the first drum of the chemical free of charge and by supervising the work themselves.

The simple laboratory tests made in this research indicate indirectly the properties of the soils, and they do not express the straight parameters of the soils. Therefore, it can be questioned that some other tests may have brought out more favourable results for this chemical stabilization. The parallel specimens treated with lime have, however, indicated that the strength properties are improved with the addition of lime in these tests. One main thing is that the stabilized soil should be durable against the detrimental effect of water, but these ISS-treated soils were not sufficiently durable.

The final result of this research is that although the chemicals slightly improved the durability of the soil against water, it has no practical meaning. Therefore, these laboratory tests or the test road did not indicate any improvements of the soils treated with either ISS or sulphuric acid. Because the reaction is chiefly dependent on some chemical properties of soils, the possibility that the chemical could work on some other soils, cannot be excluded. However, it is certain that ISS is not a universally applicable solution for road problems in developing countries or anywhere else.

On the basis of this research some of the points to be considered when conducting experimentation with the ISS-stabilizer are:

1) The soil should contain moderately clay fraction
at least 5% < 0.002 mm

2) Laboratory tests should be made before the stabilization on the road. The soaking tests are easy and suitable for this, but the curing period must be at least 30 days in moist air (paraffin or plastic bag coated or in a container with water on the bottom so that the specimens are not immersed). Parallel specimens should be made with ISS, sulphuric acid and water. The pH of ISS should be measured to know the equivalent strength of sulphuric acid. A strong acid may be dangerous. Therefore, the sufficient concentration of sulphuric acid is <15%.

3) Sulphuric acid is much cheaper than ISS. If it works as well as ISS, it shall be used.

4) The optimum moisture content of the soil on the road should be determined in a laboratory, and the road must be compacted in that moisture. The mixing ratio of the chemical to the soil in a laboratory should be the same as on the road.

5) The road surface should be ripped, ground and mixed carefully.

6) The road should be kept moist long enough for curing (one month). Daily spraying of pure water on the surface may be the most suitable way to do this.

7) The road may need a further compaction after the curing time.

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APPENDIX

BS 1377 : 1975

Form S *(continued)*

California Bearing Ratio test

ISS 0,5% / pure water

Date 20. 12. 1991 Location Site No.

Soil type SOIL 2
water ISS

Dry density 1,87 1.88

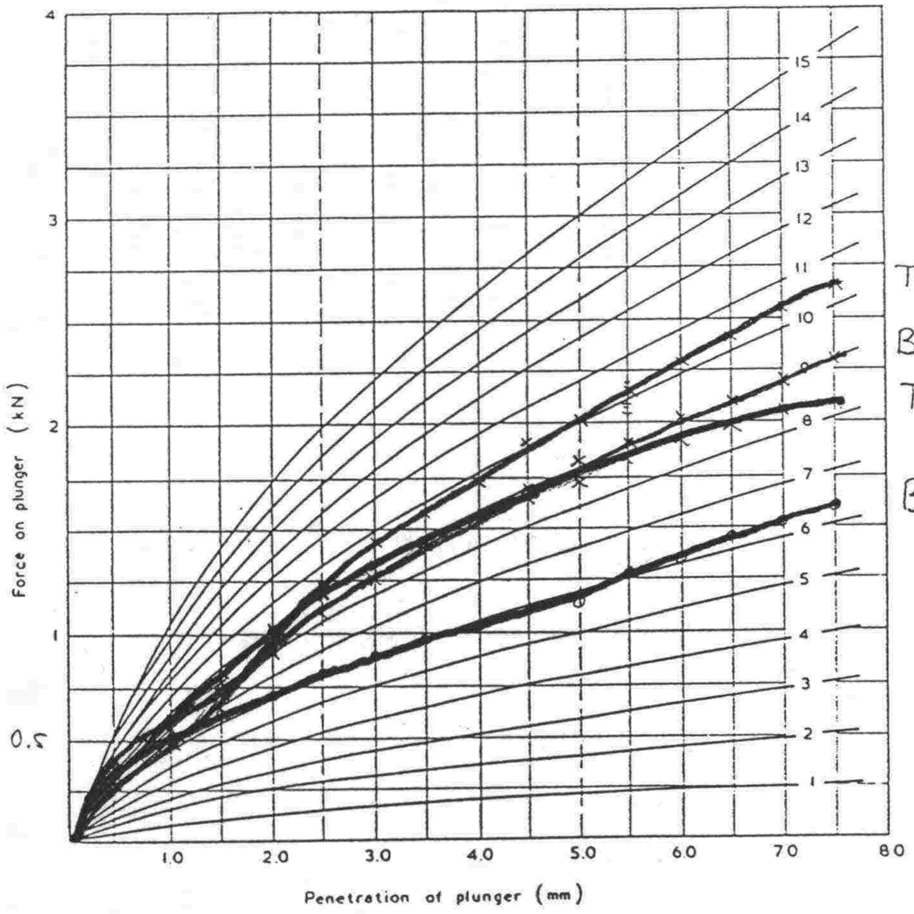
Moisture content

Tin No.	Moisture content	Mean moisture content
ISS	15.0 %	—
water	14.6 %	

Bearing value at

	2.5 mm		5.0 mm		
	water	ISS	water	ISS	
Top	9	9	10	9	%
Bottom	8	6	9	6	%

Penetration of plunger	Force on plunger		Penetration of plunger	Force on plunger		Penetration of plunger	Force on plunger	
mm	Top kN	Bottom kN	mm	Top kN	Bottom kN	mm	Top kN	Bottom kN
0.25			2.75			5.25		
0.50			3.00			5.50		
0.75			3.25			5.75		
1.00			3.50			6.00		
1.25			3.75			6.25		
1.50			4.00			6.50		
1.75			4.25			6.75		
2.00			4.50			7.00		
2.25			4.75			7.25		
2.50			5.00			7.50		



TOP, WATER

BOTTOM, WATER

TOP, ISS 0,5%

BOTTOM, ISS 0,5%

Figure. *Form for the CBR test of soils with a CBR value lower than 15%, [8]. These results are of the red clay taken from district road D154 near Lusaka in Zambia. Tests are presented in Chapter 4.7.*

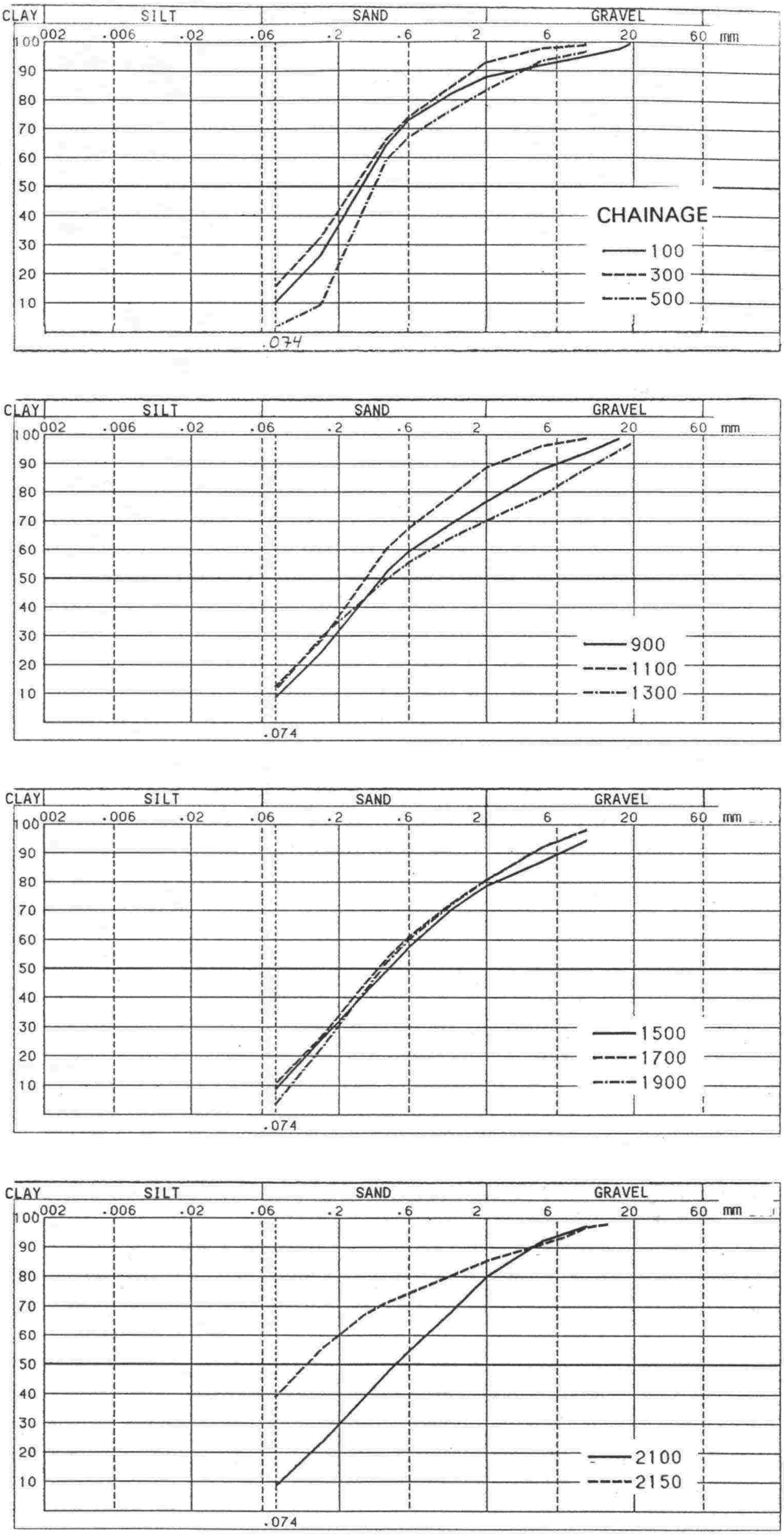


***Figure.** Grain size distributions of the soils in the test section 1 of the district road D177 near Lusaka in Zambia.*

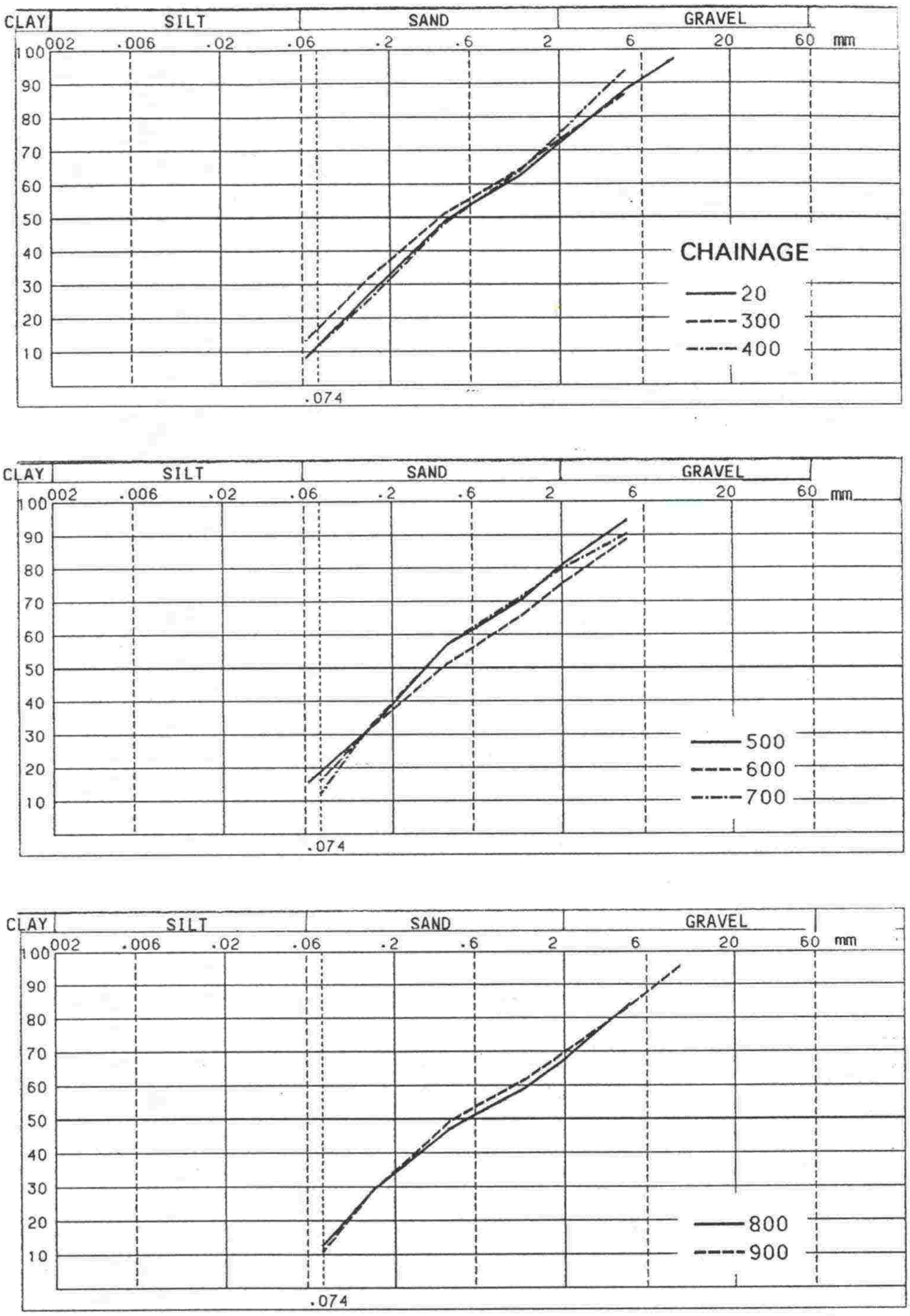


Figure. Grain size distributions of the soils in the test section 2 of the district road D177 near Lusaka in Zambia.

ANNEX 3 (1/3)

Table. *Description of the ISS-stabilization work and the condition class one and half month later on the test section 1 of the district road D177 near Lusaka in Zambia.*

CHAINAGE DATE OF STABILIZATION	DESCRIPTION OF THE STABILIZATION WORK	CONDITION CLASS 25.7. 1991
0-200 11.6.1991	*ripping 0-20 cm *mixing with rotavator when dry *30/7000 l ISS-water spraying *mixing with rotavator *1/3 of 20/7000 l ISS-water spraying *mixing with rotavator *1/3 of 20/7000 l ISS-water spraying *mixing with rotavator *mixing by grading the sides towards the center *1/3 of 20/7000 l ISS-water spraying on the shoulders *mixing by grading the windrow from the center towards the shoulders *grading the camber *10/2500 l ISS-water spraying on the shoulders *compacting *next day compacting In some points the soil became too wet and it was impossible to compact it although the surface was not slippery. Together per 200m:60/16500 l ISS-water	4
200-400 11.6.1991	*ripping 0-20 cm *mixing with rotavator when dry *grading the camber when dry *20/5000 l ISS-water spraying *mixing with rotavator *mixing by grading the sides towards the center *10/3500 l ISS-water spraying on the sides *mixing by grading the windrow from the center towards the shoulders *grading the top *compacting *10/3500 l ISS-water spraying Next day: *dragging with grader *20/3500 l ISS-water spraying on the sides *compacting Together per 200m :60/15500 l ISS-water + next day spraying	4

Continues...

CHAINAGE DATE OF STABILIZATION	DESCRIPTION OF THE STABILIZATION WORK	CONDITION CLASS 25.7. 1991
400-800 12.6.1991	*ripping 0-20 cm *mixing with rotavator when dry *mixing by grading the sides towards the center *20/3500 l ISS-water spraying on the sides *mixing by grading the windrow from the center towards the shoulders in 3 layers; 40/7000 l ISS-water spraying between the layers *grading the camber *20/7000 l ISS-water spraying on the surface *compacting after one hour waiting that the surface was not too wet *next day ISS-water spraying on the surface Together per 200m:40/8750 l ISS-water + next day spraying	400-700 1 700-800 2
800-1200 13.6.1991	*ripping 0-20 cm *mixing by grading the sides towards the center *40/7000 l ISS-water spraying on the sides *mixing by grading the windrow from the center towards the shoulders in 3 layers; 30/7000 l ISS-water spraying between the layers *mixing by grading the sides towards the center again and spraying between the layers until the soil seemed to be evenly wet *grading the camber *compacting *dragging with grader *20/7000 l ISS-water spraying on the surface *compacting after one hour waiting *next day dragging, ISS-water spraying and compacting Together per 200m:45/10500 l ISS-water + next day spraying	2
1200-1600 14.6.1991	Working method similar to the previous part. Together per 200m:35/10500 l ISS-water + next day spraying	1200-1400 4 1400-1600 2

Continues...

ANNEX 3 (3/3)

CHAINAGE DATE OF STABILIZATION	DESCRIPTION OF THE STABILIZATION WORK	CONDITION CLASS 25.7. 1991
1600-1900 17.6.1991	Working method similar to the previous part except the last 30/7000 l was sprayed on the compacted surface which was not compacted after that. Next day: *dragging with grader *compacting *dragging *20/7000 l ISS-water spraying *compacting after one hour waiting Together per 200m: 60/14000 l ISS-water + next day spraying	1600-1800 3 1800-1900 2
1900-2200 18.6.1991	Working method similar to the part 1200-1600. Next day: *dragging with grader *ISS-water spraying *compacting Together per 200m:40/10500 l ISS-water + next day spraying	1900-2100 2 2100-2150 3 2150-2200 1

***Table.** Description of the ISS-stabilization work and the condition class one and half month later on the test section 2 of the district road D177 near Lusaka in Zambia.*

CHAINAGE DATE OF STABILIZATION	DESCRIPTION OF THE STABILIZATION WORK	CONDITION CLASS 25.7. 1991
0-200 6.6.1991	This 200m-part had been ISS-stabilized one month earlier without success, but the reason it failed was thought to be in the working method. Now: *ripping 0-20 cm *mixing with rotavator when dry *40l ISS/7000l water spraying *mixing with rotavator when wet *grading *compacting The surface stayed too dry and therefore the next day 15/3500 l ISS-water fluid was sprayed and the road was dragged with grader and compacted again. Together per 200m:40/7000 l ISS-water + next day spraying	3
200-400 6.6.1991	*ripping 0-20cm *mixing with rotavator when dry *40/7000 l ISS-water spraying *mixing with rotavator when wet *grading *compacting *spraying pure water on the near ready surface The surface stayed too dry and therefore the next day 15/3500 l ISS-water was sprayed and the road was dragged with grader and compacted again. Together per 200m: 40/7000 l ISS-water + next day spraying	3

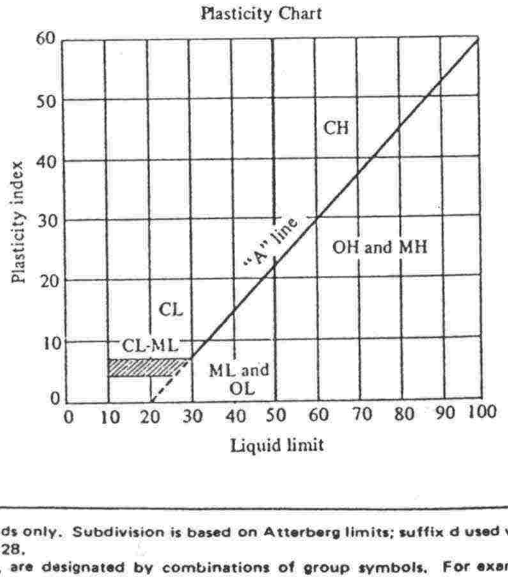
Continues...

CHAINAGE DATE OF STABILIZATION	DESCRIPTION OF THE STABILIZATION WORK	CONDITION CLASS 25.7. 1991
400-600 7.6.1991	*ripping 0-20 cm *mixing with rotavator twice when dry *30/7000 l ISS-water spraying *mixing with rotavator when wet *grading the sides towards the center *10/3500 l ISS-water spraying on the sides *grading the windrow from the center towards the shoulders *compacting Three days later 5/3500 l ISS-water was sprayed on the 400-800 m section and then was dragged with grader and compacted. Together per 200m:40/10500 l ISS-water + the later spraying	4
600-800 7.6.1991	*ripping 0-20 cm *mixing with graders only *30/7000 + 10/3500 l ISS-water spraying *grading *compacting Three days later 5/3500 l ISS-water was sprayed on the 400-800 m and that section was dragged with grader and compacted. Together per 200m: 40/10500 l ISS-water + the later spraying	3
800-1000 10.6. 1991	*ripping 0-20 cm *mixing with rotavator when dry *45/7000 l ISS-water spraying *mixing with rotavator when wet *grading the sides towards the center *5/3500 l ISS-water spraying on the sides *grading the windrow from the center towards the shoulders *compacting *dragging with grader *compacting *5/3500 l ISS-water spraying on the surface *compacting *next day compacting After the last spraying the surface became a slippery mud, but after two days drying it was very even and solid. Together per 200m: 55/14000 l ISS-water	800-900m 4 900-1000m 2

ANNEX 5

***Table.** ASTM Soil Classification (ASTM D-2487) [6,20]*

UNIFIED SOIL CLASSIFICATION SYSTEM (ASTM D-2487) [After USAWES (1967)[30a]]

Major Divisions			*Group Symbols*		*Typical Names*	*Laboratory Classification Criteria*		
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	Clean gravels (Little or no fines)	GW		Well-graded gravels, gravel-sand mixtures, little or no fines	Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows: Less than 5 per cent GW, GP, SW, SP More than 12 per cent GM, GC, SM, SC 5 to 12 per cent *Borderline* cases requiring dual symbols[b]	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			GP		Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW	
		Gravels with fines (Appreciable amount of fines)	GM[a]	d	Silty gravels, gravel-sand-silt mixtures		Atterberg limits below "A" line or P.I. less than 4	Above "A" line with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols
				u				
			GC		Clayey gravels, gravel-sand-clay mixtures		Atterberg limits below "A" line with P.I. greater than 7	
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SW		Well-graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			SP		Poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW	
		Sands with fines (Appreciable amount of fines)	SM[a]	d	Silty sands, sand-silt mixtures		Atterberg limits above "A" line or P.I. less than 4	Limits plotting in hatched zone with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols.
				u				
			SC		Clayey sands, sand-clay mixtures		Atterberg limits above "A" line with P.I. greater than 7	
Fine-grained soils (More than half material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50)		ML		Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity			
			CL		Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			OL		Organic silts and organic silty clays of low plasticity			
	Silts and clays (Liquid limit greater than 50)		MH		Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
			CH		Inorganic clays of high plasticity, fat clays			
			OH		Organic clays of medium to high plasticity, organic silts			
	Highly organic soils		Pt		Peat and other highly organic soils			

[a] Division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is based on Atterberg limits; suffix d used when L.L. is 28 or less and the P.I. is 6 or less; the suffix u used when L.L. is greater than 28.

[b] Borderline classifications, used for soils possessing characteristics of two groups, are designated by combinations of group symbols. For example: GW-GC, well-graded gravel-sand mixture with clay binder.

Sieve n:o		
4 is	#4.75	mm
10	#2.00	mm
40	#0.425	mm
200	#0.075	mm

ANNEX 6

***Table.** AASHO Soil Classification (also in ASTM D-3282) [7,20]*

AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS CLASSIFICATION OF SOILS AND SOIL-AGGREGATE MIXTURES AASHO DESIGNATION M-145

General classification*	**Granular materials (35% or less passing no. 200)**							**Silt-clay materials (more than 35% passing no. 200)**			
Group classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5, A-7-6
Sieve analysis, percent passing:											
No. 10	50 max										
No. 40	30 max	50 max	51 min								
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing no. 40:											
Liquid limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity index	6 max		NP†	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituent materials	Stone fragments—gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade	Excellent to good							Fair to poor			

*Classification procedure: With required test data in mind, proceed from left to right in chart; correct group will be found by process of elimination. The first group from the left consistent with the test data is the correct classification. The A-7 group is subdivided into A-7-5 or A-7-6 depending on the plastic limit. For $w_p < 30$, the classification is A-7-6; for $w_p > 30$, A-7-5.

†NP denotes nonplastic.

Sieve n:o		
	4 is	#4.75 mm
	10	#2.00 mm
	40	#0.425 mm
	200	#0.075 mm

Condition classification of stabilized roads

Figure. Class 1. *The shape of the road may have changed. There are many corrugations, ruts or potholes. The surface is not solid and there may be very soft places. Very dusty.*

Figure. Class 2. *The shape of the road may have changed. There are many corrugations, ruts or potholes and most of the surface is not solid. Very dusty.*

Figure. Class 3. *The shape of the road is quite good and the surface of the road is quite even. About half of the surface is solid. There are some corrugations, ruts or potholes. Dusty.*

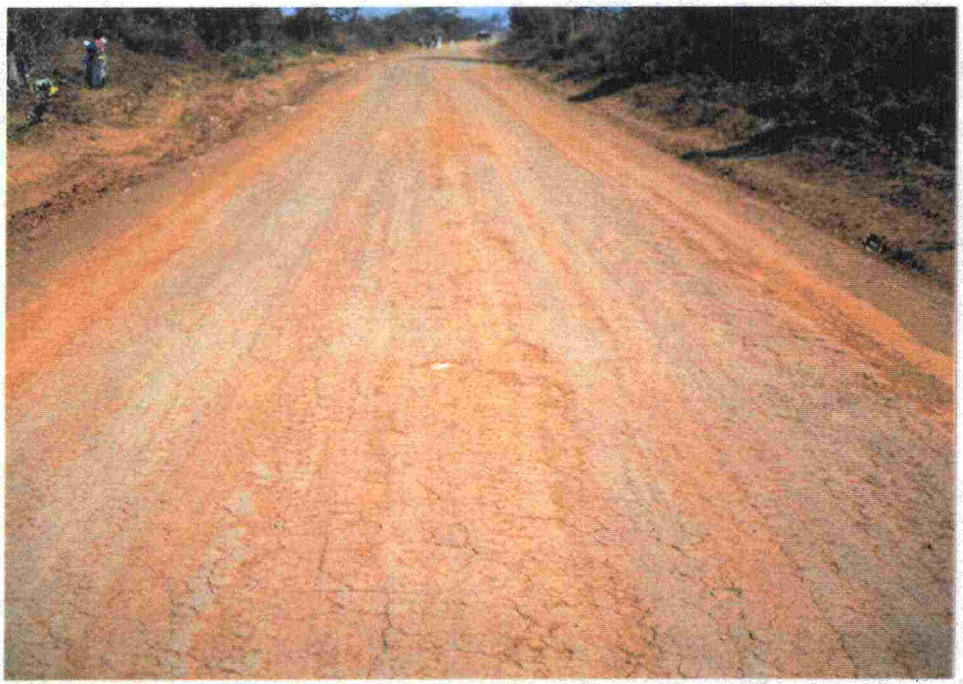


Figure. Class 4. *The shape of the road is good and the surface is even. Wheel lines or most of the surface are solid. A little dust. There are only few corrugations, ruts or potholes.*

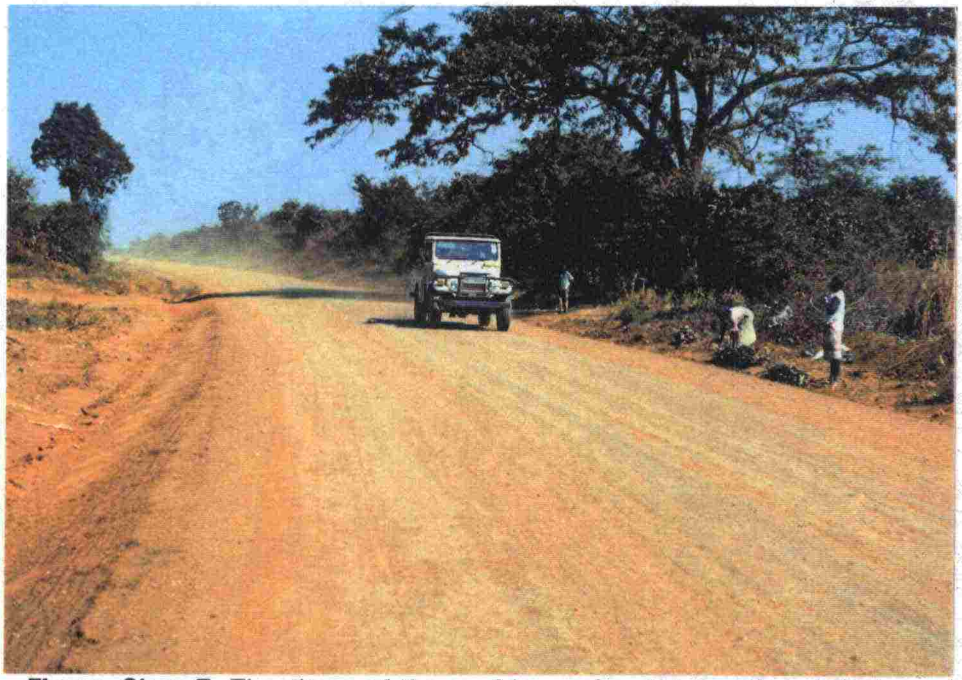


Figure. Class 5. *The shape of the road is good and the surface is even and solid. No dust.*

RWA
ROADS AND WATERWAYS ADMINISTRATIONS
OF FINLAND

Finnish National
Road Administration

National Board
of Navigation

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