Evaluation of thermal resistivity of soils in Saudi Arabia

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Civil Engineering

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Evaluation of Thermal Resistivity of Soils in Saudi Arabia

by

Nasser Hassan Al-Asiri

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

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This thesis, written by **NASSER HASSAN AL-ASIRI** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**

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التخصص : هندسة مدنية

تاريخ الشهادة : يناير ١٩٩١م

في هذه الرسالة تم دراسة الخواص الحرارية لعينات مختلفة من تربة المنطقة الشرقية ومنطقة الرياض . وقد درست الخواص الحرارية لهذه العينات باستعمال طريقة المجس الحرارى في المعمل ، حيث تم تحديد ودراسة العوامل المؤثرة في المقاومة الحرارية للتربة بناءا على نتائج التجارب التي أجريت .

توضح نتائج هذه الدراسة أن المقاومة الحرارية عالية لمعظم العينات وخصوصا حينما تكون جافة تماما مما يتطلب البحث عن مواد أخرى لا ستعمالها في ردم خنادق الكوابل الارضية . ولهذا الغرض تم أيضا دراسة الخواص الحرارية لعدد من الردميات المصنعة في المعمل و تتكون من كميات صغيرة من الطين و غبار الحجر الجيرى و المارل والاسمنت مضافة الي المادة الاساس وهي الرمل المحلي . ومن النتائج يتضح أن خلط الطين مع الرمل وغبار الحجر الجيرى مع الرمل قد نتج عنه مقاومة حرارية منخفضة جدا تتناسب مع المواصفات المقترحة من قبل شركات الكهرباء .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

التاريخ : يناير ١٩٩١ م

<u>**THESIS ABSTRACT**</u>

FULL NAME OF STUDENT:		**AL-ASIRI, NASSER**
TITLE OF STUDY	**:**	**EVALUATION OF THERMAL RESISTIVITY OF SOILS IN SAUDI ARABIA**
MAJOR FIELD	**:**	**CIVIL ENGINEERING**
DATE OF DEGREE	**:**	**JANUARY, 1991**

The thermal behavior of a number of soils obtained from Eastern region and Riyadh area including those frequently used for high voltage cable backfills has been studied. Thermal resistivity tests using a thermal needle method were carried out in the Laboratory.

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CHAPTER 1

INTRODUCTION

1.1 Background

The transmission of power by means of underground cables is influenced significantly by the thermal characteristics of the soils that surround these cables. In simple terms, soils of low thermal resistivity enable heat to be dissipated rapidly and permit relatively high-power loads to be carried without the threat of cable burnout.

The thermal ohm, the unit of thermal resistivity , is defined as the number of degrees celsius of temperature drop that occurs when heat flows through a 1-cm cable at the rate of 1 watt. The thermal resistivity , often simply referred to as (ρ), is used in soil application while thermal conductivity (k), the inverse of thermal resistivity is used in some other applications. Common units for the thermal resistivity of a soil are degree centigrade-cemtimeter per watt (°C-cm/watt).

The temperature gradient around a buried cable, which is caused by the heat losses, may induce migration of moisture away from the immediate vicinity of the cable. Consequently, zones of low moisture content can develop resulting in considerable increase of soil thermal resistivity to well above that assumed in the design of the cable. The resulting increase in the temperature gradient will cause further drying of the soil and eventually the temperature of the cable may rise to a value far in excess of its safe operating level. In the range of loads and operating temperatures that are now being considered for underground transmission lines, an assessment of the thermal characteristics of the soils that surround these cables becomes critical in establishing an engineering procedure that will facilitate an economic design, yet avoid failure of the cables by overheating.

The power that can be delivered through a cable depends upon the current carrying capacity (ampacity) of the cable. The ampacity is limited by the maximum operating temperature of the insulation which in turn depends on the ability of the surrounding soil to dissipate the heat generated within the conductor. Thus, for a given cable design, the thermal resistivity of the soil immediately adjacent to the cable can limit its power transmission capacity.

In Saudi Arabia, due to a very ambitious industrialization and urbanization program, the electrical load experienced phenomenal growth, forcing the local electric companies to build large networks of overhead transmission and underground distribution systems in different parts of the country. Great reliance was made on international experience and standards. Backfill material was generally used by local electric companies to satisfy their design thermal resistivity which is (120°C-cm/watt). For actual economic evaluation of adopted procedures and to determine the degree of reliability, systematic investigations are needed to understand the soil characteristics prevailing in different parts of the country, and to study their heat transport properties.

1.2 Objectives

Understanding factors that affect thermal resistivity of a soil is a necessary requirement for predicting heat transfer capabilities of underground thermal systems. For the purpose of heat dissipation, the thermal resistivity of the soil immediately adjacent to the cable is the most influential factor. Therefore, in some cases, the use of a special backfill placed around the cable is needed to achieve low thermal resistivity .

The specific goals and objectives of this investigation of the thermal resistivity of soils are, therefore:

1. To employ the thermal probe method to obtain reliable thermal resistivity data for different local natural soils.

2. To experimentally identify the parameters involved in determining the thermal resistivity of soils.

3. To discuss the influence of the above parameters on thermal resistivity of soils in terms of a geotechnical approach.

4. To develop different backfills having low thermal resistivity using sand and different additives available locally.

CHAPTER 2

REVIEW OF SOIL THERMAL RESISTIVITY

2.1 Factors Affecting Thermal Resistivity

The thermal resistivity of a soil is primarily influenced by the following parameters :

a) Soil Type and Composition
b) Density
c) Moisture Content
d) Temperature of the Soil

The importance of these parameters is discussed below:

2.1.1 Soil Type and Composition

The influence of soil type and composition has been studied by many investigators (Brandon and Mitchell, 1989; Salomone, 1981; Mitchell, et al., 1977; Farouki, 1966; Fisher, et al., 1975; Sinclair et al., 1960). The literature reveals that fine grained or cohesive soils and peaty soils exhibit higher thermal resistivities than granular soils as shown in Figure 2.1. Because heat flowing through soil must flow through the solid mineral grains and the medium in which they are embedded, the thermal resistivity of a soil depends on the thermal resistivity of its component materials

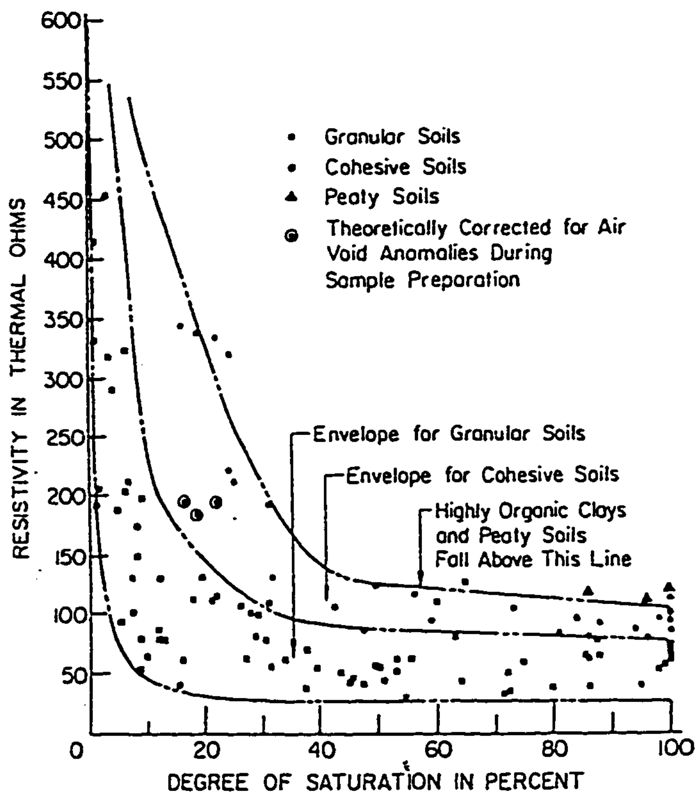

Fig. 2.1: Thermal Resistivity Data Showing the Effect of Soil Type and Moisture Content (Fisher, et al., 1975)

(Salomone, 1981). Sands, with quartz as the principal constituent, obviously have lower thermal resistivities because quartz is the best common natural solid material to give low value of thermal resistivity (Table 2.1). Brandon and Mitchell (1989) stated that the higher the percentage of the quartz fraction in a sand, the lower its thermal resistivity , all things being equal. Also, the type of clay minerals present, is a contributory factor of soil resistivity. Expansive clay mineral such as Montmorillonite, for example, would cause the soil particles to be forced apart during compaction by swelling action when moisture is added, thereby increasing the thermal resistivity of soil (Salomone, 1981).

2.1.2 Density

The density of a soil has an important influence on thermal resistivity of the soil. The presence of air, with its high thermal resistivity , greatly increases the overall thermal resistivity of the soil as compared with that of its solid components. It is evident that increasing density will reduce the thermal resistivity of the material, both by reducing the total void volume and by improving contact between the solid grains (Fisher, et al, 1975).

Some investigators have found a linear trend between the thermal resistivity of a soil and its dry density (e.g., Salomone and others, 1984; Farouki, 1981; Penner, 1962) and various correlations have been made. On the basis of numerous tests, Kensten (1949) found that at constant moisture content, the logarithm of the thermal resistivity decreased linearly with the dry density (Figure 2.2).

Table 2.1: Thermal Restivity for Some Soil Constituents (WinterKorn, 1960)

Material		Thermal Restivity (°C-cm/watt)
Quartz	..	11
Granite	..	25 - 58
Limestone	..	45
Sandstone	..	50
$CaCo_3$ (Calcite)	..	26
Marble	..	34 - 48
Dolomite	..	58
Slate	..	67
Shale	..	63
Water	..	165
Mica	..	170
Wet organic material	..	400
Dry organic material	..	700
Air	..	4,000

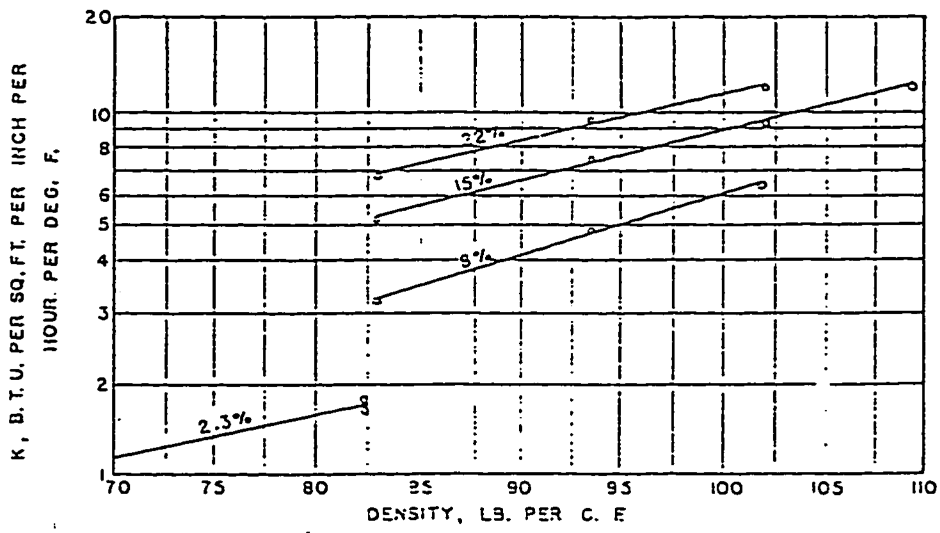

Fig. 2.2 : Variation of Thermal Conductivity with dry density of soil for different moisture contents (Kersten, 1949)

1 $BTU/ft^2/in/hr/^\circ F = 0.00144^\circ C/watt$

1 pcf = 0.016 g/cm^3

2.1.3 Moisture Content

The moisture content is the important factor affecting the thermal resistivity of a soil. When water is added to the soil, it tends to distribute itself in a thin film around solid grain of the soil. This water film provides a path for the flow of heat and hence bridges the air gaps between the solid particles. Additional water, over and above that required for film formation, serves to fill voids which were earlier occupied with air. Since the thermal resistivity of air is much higher than that of water, this additional water reduces the thermal resistivity further (Salomone, 1981).

When the moisture content in the soil approaches a wet condition, the effective contact area no longer increases with any further increase of moisture content and hence no significant decrease in thermal resistivity is evident when more moisture is added to fill the pore spaces (Salomone, 1981). The moisture content at which the thermal bridge mechanisms experience breakdown is referred to as the critical moisture content (Hartley and others, 1981). It has been reported that the greatest decrease in resistivity is found from dryness to about 10% of the voids saturated (degree of saturation. S = 10%) and there is very little change above S=30% (Fischer and others, 1975). The moisture content also has an indirect influence on thermal resistivity since higher density can be achieved by adding water to the soil.

2.1.4 Temperature of the Soil

The thermal resistivity of a soil may also be influenced by temperature , because each of the constituents has temperature - dependent thermal properties. The thermal resistivity of all crystalline minerals increase with increasing temperature, however, the thermal resistivity of water and gases exhibit the opposite effect (Brandon, 1985). Therefore, one might expect that the two factors tend to cancel each other. Not nearly as much research has been conducted concerning the temperature dependence of thermal resistivity of soils as compared to the influences of water content and dry density.

Mitchell et al. (1977) conducted laboratory thermal needle tests on a dry sand for temperatures ranging from 40 to 120°C, and found that thermal resistivity decreased with increasing temperature (Figure 2.3). As shown in this figure, the effect is very small compared to the wide range of temperature . Radhakrishna and Steinmanis (1981) measured the thermal resistivity of two saturated soils at 4, 20, and 45°C and found only a slight decrease of 6 to 11°C-cm/watt. Brandon and Mitchell (1989) investigated the temperature dependence of the thermal resistivity of a sand from moist to totally dry conditions of 20, 40, 60 and 80°C (Figure 2.4). This figure shows that thermal resistivity for moist sand decreased with increasing temperature and there was a tendency for the thermal resistivity of the sand to slightly increase with temperature .

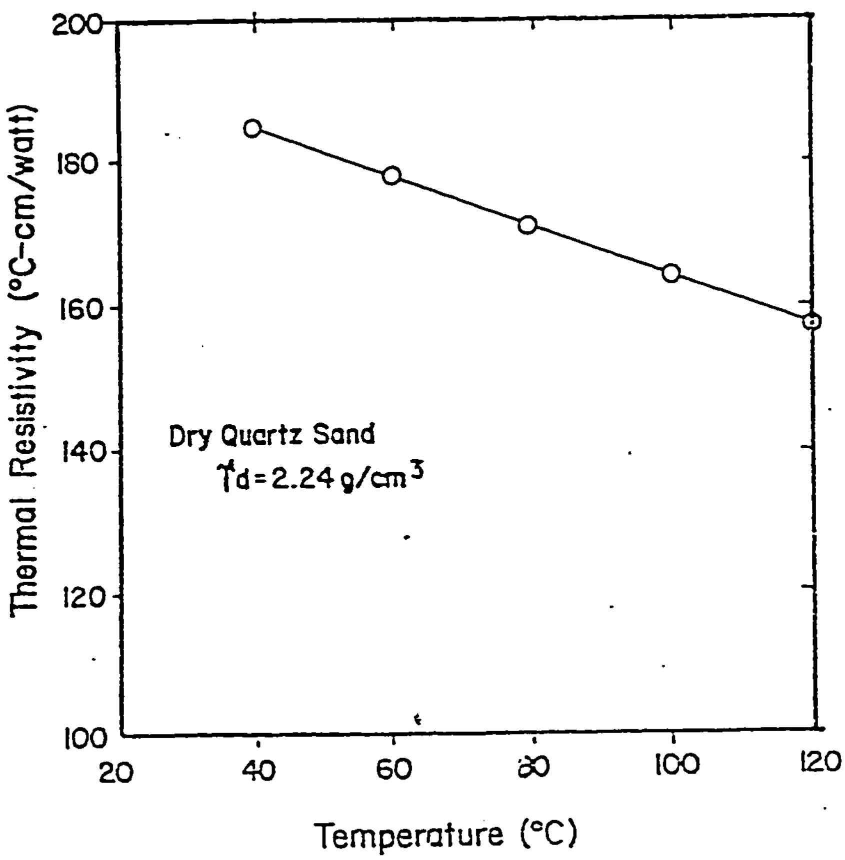

Fig. 2.3 : Thermal Resistivity of a dry Quartz Sand as a Function of Temperature (Mitchell et al., 1977)

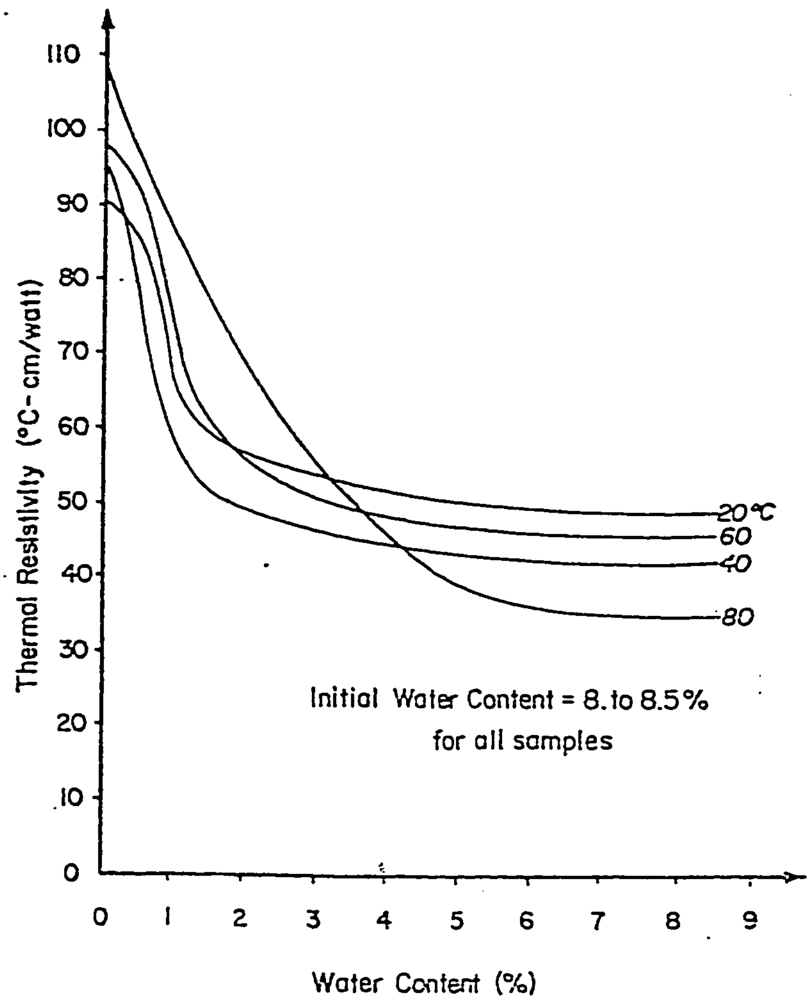

Fig. 2.4 : Thermal Resistivity-Moisture Content Relationship for Sand at Four Different Temperatures (Brandon, 1985)

2.2 Moisture Migration and Thermal Stability

It has been generally accepted that if thermal backfill materials are required, then sand is preferable under moist conditions (Jackson, 1980). However, extended operation of the cable at its maximum capacity can cause moisture migration and subsequent drying of the soil adjacent to the cable. Therefore, once drying begins, the dry sand next to the cable acts as thermal insulation and inhibits the transfer of heat from the cable. As a result, the temperature of the cable continues to rise and eventually thermal failure of the insulation occurs. The concept of a critical moisture content has been introduced to help explain how soil moisture content influences thermal stability, (Black, et al, 1982; Radhakrishna, et al, 1980). If the ambient soil moisture is above this critical moisture content, then moisture migration is not likely to occur when the soil is subjected to a temperature gradient. Conversely, if the ambient moisture content is below the critical moisture content, then under an applied temperature gradient, the soil moisture is likely to migrate from the high temperature source to the low temperature sink as is evident from Figure 2.5. Salomone and Kovacs (1983) studied the correlation between Atterberg limits and critical moisture content and found that the critical moisture content can be approximated by the plastic limit for fine grained soils with low natural density as shown in Figure 2.6. They also concluded that critical moisture content occurs as the optimum moisture content for most fine grained soils.

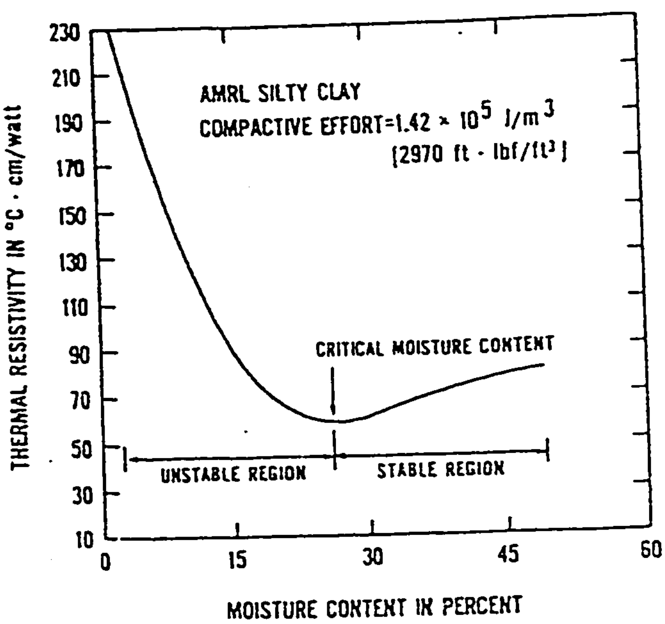

Fig. 2.5 : Variation of Thermal Resistivity with Moisture Content Illustrating the Concept of Critical Moisture Content (Salomone, 1984).

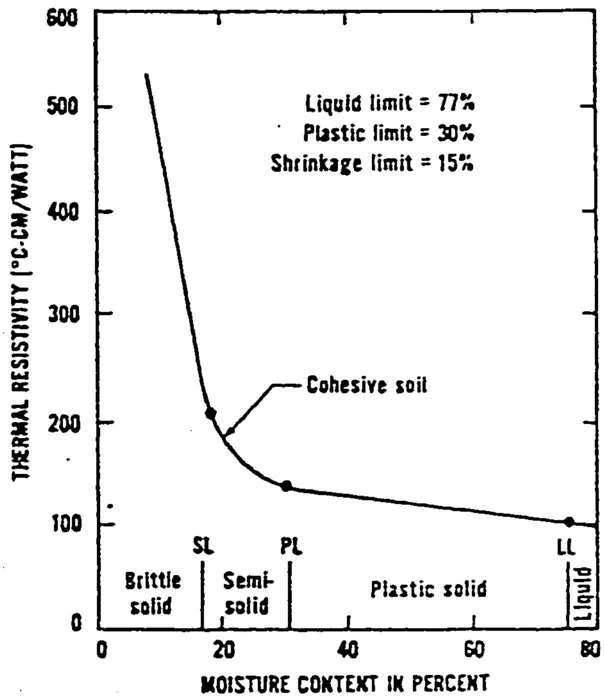

Fig. 2.6 : Correlation Between Atterberg Limits and Thermal Resistivity (Salomone and Covax, 1983)

Fink (1960) described the mechanism in which water through a very complex process changes its state between strata of capillary and hydroscopic water. When the temperature level is changed at one location, the equilibrium is upset and a redistribution of water takes place between the two states, and also between locations at different temperatures, with the moisture content at the cooler location exceeding that at the warmer. This redistribution is referred to as moisture migration under thermal gradients. Mickley (1950) attributed moisture movement under thermal gradient to variation in surface tension and concluded that vapor movement accounts for very little of the net moisture movement in the vicinity of heated sources. Farouki (1981) mentioned nine possible mechanisms of moisture movement among them is liquid film movement due to a greater affinity of the soil surfaces for the film at low temperature . He concluded that under given soil-water conditions and temperature distributions, transfer will take place by all possible mechanisms, although one may predominate.

2.3 Mechanism of Heat Flow Through Soils

The heat dissipation through a moist soil occurs in a number of complex forms, the predominant one being by conduction through the solid liquid matrix. Other less important modes of heat transfer are phase change from liquid to vapor [Radhakrishna, 1979]. The steady state heat flow equation from a buried line heat source can be written as :

$$H = \frac{1}{\rho} * 2 \pi r \frac{dT}{dr} \qquad (2.1)$$

Where:

H = Heat loss per unit of line source

ρ = Thermal resistivity

$\frac{dT}{dr}$ = Temperature gradient

r = The distance from heat source.

From this equation, it is evident that an increase in thermal resistivity will cause larger thermal gradients which will lead to higher source and cable temperature.

2.4 Thermal Resistivity Equations

With all these complex, independent, and interdependent variables, it is a complicated task to develop an equation that can be used to calculate the thermal resistivity of soil. However, some have developed such equations which may be classified into two categories :

1. Theoretical equations which are based on models, simplifying the actual soil structure to permit a mathematical analysis.
2. Empirical equations which are based on experimental results.

2.4.1 Theoretical Equations

Many equations have been presented in the literature. The difference between these equations lies in the differences of the models on which they are based. Mickley [1951] developed an equation to calculate thermal conductivity by using a model considering a unit cube of soil and assumed a certain monolithic arrangement of the solids. The equation for k, the equivalent conductivity of dry soil is :

$$k = k_a A^2 + k_s (1-A)^2 + \frac{k_s k_a (2A - 2A^2)}{k_s(A) + k_a (1-A)} \qquad (2.2)$$

for saturated soil k_a can be replaced by k_w

A can be calculated from the formula :

$$P_s = 1 - 3A^2 + 2A^3$$

Where:

P_s = Volume fraction of the solid material (percentage)

k = Conductivity of the soil

k_a = Conductivity of air

k_s = Conductivity of solid particles.

k_w = Conductivity of water.

Equation 2.2 was found to yield higher calculated values compared to the measured conductivities because the model did not account for the point contact between the angular soil particles (Sinclair and Buller, 1960). Kersten (1951) commented that Mickley's equation does not take soil type into account. Another equation proposed by Smith (Farouki, 1981) takes the form :

$$k = k_a P_a + k_o P_s \qquad (2.3)$$

Where:

$$k_o = \frac{1+\alpha}{1+k_s + \left(\frac{1}{k_a} - \frac{1}{k_s}\right)\frac{\alpha}{1+\alpha}} \qquad (2.4)$$

P_a = Total porosity

P_s = Partial volume of solid framework.

α = Thermal structure factor

Equations 2.3 and 2.4 were developed using a model which took into account the structure of the soil.

2.4.2 Empirical Formulae

1. Kersten's formula :

a. For soils composed of silt and clay (water content 7% or more)

$$k = \frac{1}{10}\ [\,1.3 \log (w) - 0.29]\ 10^{(0.6243\,\gamma - 3)} \qquad (2.5)$$

b. Sandy soils (water content 1% or more)

$$k = \frac{1}{10}\ [\,1.01 \log (w) + 0.58]\ 10^{(0.6243\,\gamma - 3)} \qquad (2.6)$$

Where k is in watt/C°-cm

w = water content percentage

γ = dry density in (g/cm^3).

Equations 2.5 and 2.6 which do not apply to dry soils can be represented graphically by Figure 2.7.

2. Van Rooyen Formula

$$K = 10^{n} + S_1 + S_2\gamma \tag{2.7}$$

Where:

$$n = a_1 - mb_1 + 5.5\, m\, \gamma - 0.44\, \gamma^2$$

$$m = \frac{1}{1 + P_a / 1.005\, \gamma\, w}$$

γ = Dry density (g/cm^3)

w = Moisture content percentage

S_1 = Soil type constant

S_2 = A constant equal to 47.5

$a_1 = 16r^{-0.9} + 3.4 \times 10^{-0.008c}$

r = Surface area constant.

c = Clay percentage.

$b_1 = 5.6 \times 10^{-0.04c} + 9.58$

P_a = Percent of air by volume.

Kersten formula is preferred by most cable engineers because of its relative simplicity, even though the Van Rooyen formula produced the best overall results [Hartley, 1977]. However, the application of Eq. 2.7 is complicated and the choice of the values for the parameters is uncertain.

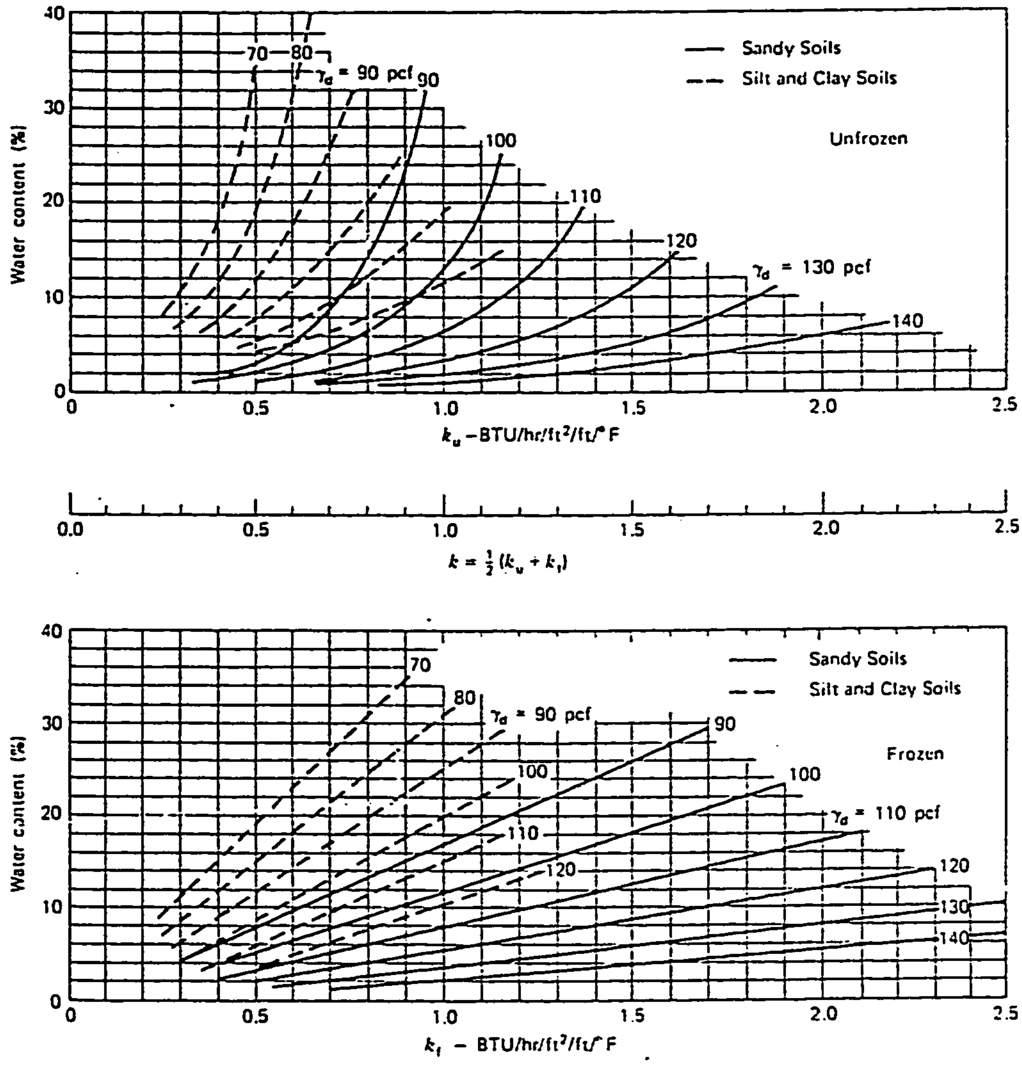

Fig. 2.7 : Thermal Conductivity of Soil-Kersen's Formula (Mitchell, 1976)

1 BTU/hr/ft/°F = 0.0173°C-cm/watt

1 pcf = 0.016 g/cm^3

2.5 Review of Backfill Materials

The main function of cable backfills is to efficiently dissipate the heat away from the power cables and thus maintain cable temperatures within the permissible limits. Backfills should also be able to resist moisture migration and thermal drying under extreme weather conditions. The term "thermal backfill" is used to refer to the material used instead of the original soil in situations where the original soil is not of good thermal quality (Sandiford, 1982).

Only a small amount of research has been conducted to investigate methods by which the thermal resistivity of soils can be decreased and little, well-documented data, are available to substantiate the efficiency of the proposed technique (Jackson, 1980).

Brookes and McGrath (1960) suggested the use of a high density quartz sand as a low resistivity backfill material if natural soils are to be used. Farouki (1981) reported that a small amount of clay colloidal particles added to a cohesionless granular material acts as a binder and improves the thermal conductivity. By using kaolinite as an additive, he found that 8% is the optimum, giving the lowest thermal resistivity. He stated that the improvement obtained is due to the improvement of interfacial conduction characteristics.

Cox, et al. (1975) investigated various stabilized backfills consisting of cement-bound sand, gravel/sand and bitumen-bound sand. The thermal resistivities of these backfills were reported to be less than 120 C°-cm/W.

Mochlinski (1976) tried stabilizers such as cement, lime and kaolinite. He observed that addition of 5% cement gives the best results and that using kaolinite and lime gave adequate thermal performance.

Mitchell et al. (1977) conducted an extensive investigation to evaluate the effects of various additives. Based on their results, the most effective inorganic additive tested was portland cement; however, it hardens the backfill, which would make further access to the cable difficult in practice. Mitchell also reported that among the additives tested, waxes seemed to be the most promising in terms of effectiveness in reducing thermal resistivity. Jackson (1980) noticed that for the backfill materials which used wax as a binder, the thermal resistivity increases three folds after heat aging and he attributed that to thermal degradation of wax after long term exposure to temperatures above the crystalline melt point of the wax which is 50°C. Since power cables frequently operate with interface temperatures of above 50°C, wax with low melting temperature should not be used in backfill materials if long-term thermal degradation is to be avoided.

Radhakrishna (1981) developed the concept of fluidized cable backfills in which the backfill is placed in a slurry form which after solidification, forms a low thermal resistance envelope. The fluidized backfills consist mainly of natural soil, cementitious material, and fluidizer or flow modifier to impart a homogeneous fluid consistency for use of placement. Fluidizers used in his study included fly ash, bentonite, polyox and emulsified wax. By using different sand gravel mixture with 2.5% cement and

7.5% fly ash and different fillers such as steel fibers, he measured low values of thermal resistivity such as 60 to 80°C-cm/Watt. However, he stated that these backfills are not cost effective compared to granular fills at the present time.

2.6 Review of Geotechnical Properties of Soils in Saudi Arabia

The main physical divisions of Saudi Arabia are the flat western and eastern coastal areas, the western mountain zone, and the central plateau which declines northward in elevation. The development of surface sediments is influenced by the arid and semi-arid hot climate in the Kingdom. From a geotechnical viewpoint, Saudi Arabia can be divided into four major zones (Oweis, 1981).

1. Zone A : Western coastal plain consisting of Zone A-1, generally covered by soft sabkha coastal deposits, and Zone A-2, covered by alluvial deposits from the coast to Arabian Shield.

2. Zone B : Arabian Shield extending north and east to the coastal plains of the Gulf.

3. Zone C : Sedimentary rocks from shield to coastal plains of the Gulf.

4. Zone D : Eastern Coastal plain.

Table 2.2 summarizes the main soil characteristics of each zone.

Table 2.2 : Soil Characteristics in Saudi Arabia (Owis, 1981).

Zone	Location	Soil Characteristics
A-1	The western coastal plain along the Red Sea.	- Soft and loose surface sabkha deposits varying in classification from sand to clay and may be underlained by dense granular soils, limestone or loose sand and soft clay.
A-2	East of coastal plains extending to the Arabian shield.	- Dense alluvial fans and wadi deposits. - Generally dense sands and gravel or hard clays overlying limestones, shales sandstones and crystalline rocks.
B	Arabian shield.	- Shallow in-place weathered soils, or wind blown sands and silts over rock which is encountered within about 2 meters of the surface. - Dense sand and gravel or hard clay near the eastern border of the Arabian shield.
C	East of the shield extending to the Gulf.	Sedimentary rocks overlaid by a thin soil cover characterized by: - The presence of cavities in limestone bedrock, e.g. Riyadh, Buraydah. - The presence of gypsum bearing soils in poorly drained locations, e.g. Tabuk, Al-Kharj, Qaysoomah. - The presence of inland sabkhas, e.g. Wadi Sirhan.
D	The Eastern coastal plain along the Gulf.	- Salt bearing soils or sand dunes underlained by medium dense to dense sands.

2.7 Data of Soil Resistivity Measurements in the Eastern Region

The review of data of soil measurements carried out at 1-1.5 m. depth in the Eastern Region indicates that the thermal resistivity values varies from 40°C-cm/watt for moist dense soils to 350°C-cm/watt for dry loose soils. However, most of the values fell between 120 and 200°C-cm/watt. Table 2.3 summarizes thermal resistivity measurements for soils located at different proposed routes for buried cables in the Eastern Region of the Kingdom.

The design value of thermal resistivity adopted by Saudi Consolidated Electric Company of the Easatern Region (SCECO East) is 120°C-cm/watt. If a soil with higher thermal resistivity was used as a backfill and the design value was assumed to be 120°C-cm/watt, then the conductor would be subjected to overheating and consequently thermal failure of the cable when the soil becomes dry.

In Saudi Arabia, electric utilities use natural clean sand as a thermal backfill. A layer of clean sand is placed in the trench, the cables are laid, then another layer is placed above the cables. The selection of natural sand as a thermal backfill in Saudi Arabia is due to its easy availability everywhere in the Kingdom and its good thermal quality specially if well graded; however, long-term stability and high thermal resistivity at dry conditions are major factors when sand is used. Generally, Saudi soil conditions are such that in almost all cases, use of more effective backfill material becomes essential to acquire the design value of 120°C-cm/watt.

Table 2.3 : soil resistivity measurements at different proposed routes for buried cables in the Eastern Province

LOCATION	SOIL PROPERTIES	THERMAL RESISTIVITY °C.cm/W	REFERENCE
Safaniyah desalting facility buried cable	-Fine to coarse sand with various degree of cementation, contains shell fragments and gypsum crystals. - W is in the range of 3-6% - γ is in the range of 1.50-1.68 g/cm^3	- Generally <u>less than 100</u> - Some <u>higher values (>140)</u> were observed in locations contains shell or gypsum.	- Al-Hotai and Stanger (1979).
Dammam Industrial Estate	- Dense to very dense fine to medium sand overlaid by a covering of limestone and marl. - Soil is in dry nature of moisture content (W) less than 2%.	- In most locations <u>above 180</u> - <u>Some lower values (<150)</u> in <u>locations with higher w.</u>	- Al-Hoti and Stanger (1980).
Along 16 KMs of a proposed route for buried cable between Aziziyah and Al-Khobar	- Fine to medium sand - Silts are also evident in some locations - γ ranges from 1.50-1.67g/cm^3 - W is high in locations near the groundwater.	- <u>Larger than 150 at</u> higher elevations with low moisture. - <u>Less than 100</u> in areas near the coast where the soil is saturated.	- Al-Hoti and Stanger (1979).
69 KV Cable at K.F.I.A.	- Sandy soil with high density. γ ranges from 1.69-1.91. - W from 1.4-12.4%	- Generally <u>less than 100</u> with the lowest <u>value of 40</u> <u>for</u> γ = 1.70 and W = 3.9%.	- AARTCO (1981).
230 KV Cable in Aziziyah	- Sandy - silty sands. - γ = 1.64-1.94. W % = 1.1-12.3%.	- Generally <u>less than 100</u> <u>when</u> γ > 1.70 and w > 2.70% values are higher than 120 for w < 2%.	- CEO(1982).
Dammam Industrial Estate	- Fine to medium sand, medium dense. - W = 1-6%.	- Generally <u>above 150 with</u> values as <u>high</u> as <u>above 300</u>	- McClelland-Suhaimi (1980).

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 Background

Several methods have been used for evaluation of the thermal resistivity of soils, including spheres, line heat sources, i.e. probes, guarded hot plate, buried cylinders and heat flow meters. Details of these methods have been presented in the literature (Chaney et al., 1983; Salomone and Covax, 1984; Weedy, 1988; Boggs et al., 1981; Radhakrishnan et al., 1980). These methods can be divided into two categories : steady state and transient. Mitchell and Kao (1978) evaluated these methods and concluded that transient methods (i.e. thermal needle method) are most suitable for soils because of their relative simplicity and the short time required for measurements. By carefully controlling the test details, the thermal needle method gives consistent and reproducible results. It offers the added advantage that knowledge of the specific heat is not required for calculation of resistivity (Mitchell and Kao, 1978). Moreover, the transient method is preferable to steady state tests for determining the thermal resistivity of soil because moisture migration and subsequent change in thermal resistivity is not likely to occur if the test is conducted in relatively short time (Salomone and Covax, 1984).

3.1.1 Thermal Needle Method

The thermal needle method is based on the measurement of the rate of temperature rise along a line heat source within an infinite, homogeneous medium. A typical response of the needle is shown in Fig. 3.1. Because of the heat capacity of the thermal needle, the straight line response does not occur instantaneously as probe power is initiated. The heat capacity of the probe results in a delay of the straight line portion of the curve. The time needed to reach the straight line portion is called initial transient time (Figure 3.1.).

3.1.2 Thermal Needle Theory

The thermal needle method is based on the theory of the infinite line heat source (Carslow and Jaeger, 1959) which predicts the temperature as a function of time at a distance "r" from an infinite line heat source dissipating "q" power per unit length into a medium of thermal resistivity ρ. The basic equation governing heat flow in a cylindrical coordinate system can be expressed as :

$$\frac{1}{r^2}\frac{\delta^2 T}{\delta\varphi^2} + \frac{\delta^2 T}{\delta r^2} + \frac{1}{r}\frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta^2 z} = \frac{1}{\alpha}\frac{\delta T}{\delta t} \tag{3.1}$$

Where:

T = Temperature

r = The distance from line source

φ = Heat loss

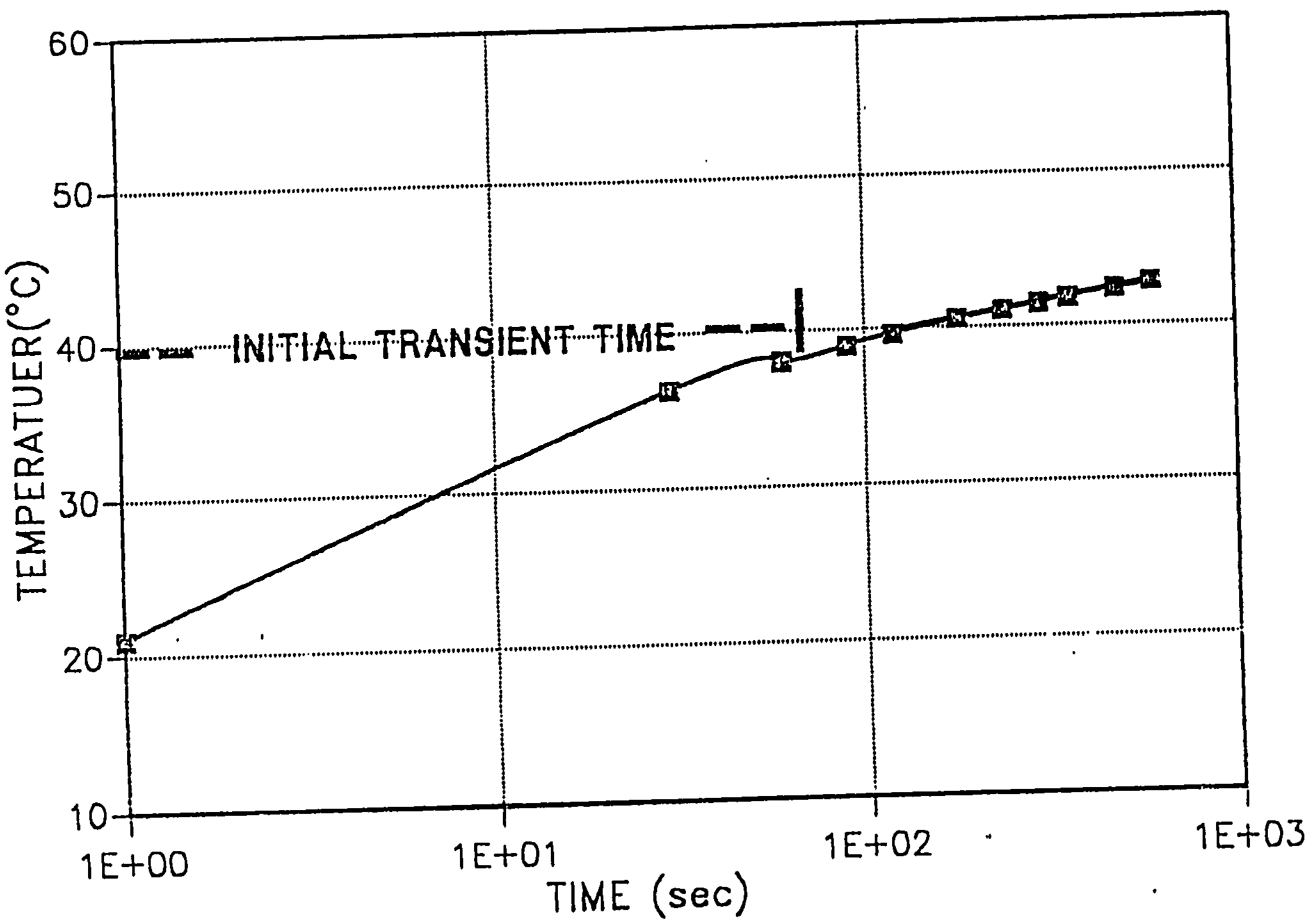

Fig. 3.1: Thermal Probe Response for Beach Sand Sample at 1.5% Moisture Content.

t = Time

The following assumptions are made to solve this equation (Steinmanis, 1981).

(i) The heat source is a line source (an infinitely long of vanishing diameter).

(ii) The line source is embedded in an infinite, homogenous, isotropic medium.

(iii) Perfect thermal contact exists between the heat source and the medium.

(iv) The heat source and the medium are initially at a uniform temperature

(v) The heat input is maintained constant.

Application of these five assumptions as well as a long time solution to the above equation leads to the following simple expression :

$$\rho = \frac{4\pi}{q} \frac{T_2 - T_1}{\ln (t_2 - t_1)} \qquad (3.2)$$

Where:

ρ = Thermal resistivity

q = Power input per unit length

T_1 = Final temperature at some final time (t_1)

T_2 = Initial temperature at some initial time (t_2)

Considering equation (3.2), thermal resistivity of a soil using the line source theory requires a knowledge only of the heat input and the resultant temperature response. Thus, if heat is applied at a known constant rate to line source embedded in the soil and the temperature of the line is measured as a function of time, a straight line relationship is expected between T and log t, with a slope proportional to the thermal resistivity, ρ.

For test results to agree with the above theoretical predictions, the experimental procedure should comply with the five assumptions made in the theory. In the following section, a discussion of these assumptions and their influences on the accuracy of measurements are provided.

3.1.3 Deviations From the Line Source Theory

3.1.3.1 Using Line Source as a Heat Source

This assumption requires a source of vanishing diameter and infinite length. In practice, the needle having finite dimensions is used. The finite length and diameter of the needle result in a finite needle heat capacity; therefore, thermal inertia will cause the needle response to lag the analytical prediction for the soil. The finite length of the needle will also result in axial heat flow due to both diverging isotherms in the medium and end losses, while the thermal conductivity of the needle material and the diameter will cause a radial temperature to exist (Drew, 1982). To approximate the assumption of an infinite line heat source (only radial heat flow), the length-to-diameter ratio of the thermal needle should be sufficiently large. Blackwell (1954) showed that a length-to-diameter ratio of 30 would reduce the relative axial flow error to below 0.05 percent.

3.1.3.2 The Line Source Embedded in an Infinite Medium:

Errors introduced due to a finite size of the medium (soil sample) may be significant only when the duration of the test is long enough to allow thermal front to reach the boundaries of the soil sample. Many investigators have tried to estimate the minimum soil sample diameter required for the test. Based on experimental and theoretical work, Mitchell and Kao (1978) showed that even for values of ρ as low as 23°C-cm/watt the needle temperature will be uninfluenced by the external boundary conditions for times up to 600 seconds assuming a 101.6 mm diameter mold containing the soil sample. Pratt (1969) showed that for test duration of 900 seconds, the sample radius should be at least 46 mm for dry soils and 76 mm for wet soils. Steinmanis (1981) stated that 76 mm diameter soil sample has proved to be sufficient for materials with thermal resistivities greater than 45°C-cm/watt. It can be concluded, therefore, that a soil sample of 80 mm is sufficient to prevent boundary conditions to affect test results for soils with low thermal resistivity , even smaller sizes could be used for materials with higher thermal resistivity .

3.1.3.3 Perfect Thermal Contact Between the Heat Source and the Medium

One of the largest sources of error is the contact resistance between the needle and the soil. To minimize the error caused by contact resistance, every effort must be made to ensure that the heater is embedded as firmly as possible; therefore, it can be said that contact conductance depends on the soil under test and the skill of the operator in installing the probe with minimum disturbance.

3.1.3.4 Constant Heat Input and Temperature Uniformity of the Heat Source and the Medium

These two assumptions are achieveable experimentally (see Section 3.2.3). In Section 3.2, a further discussion of various factors affecting the accuracy of the test and experimental precautions required to make the actual operation of the thermal probe simulates the line heat source is provided.

3.2 Thermal Resistivity Measurement

The thermal resistivity data for soils investigated in this study were derived from the transient thermal probe technique because this method, as mentioned earlier, requires relatively simple instrumentation and only a short time for the measurements. The probe technique is based upon the rate of temperature rise of an infinitely long line source of heat which is embedded in an infinite, homogeneous, isotropic medium. The probe is inserted into the soil sample and is supplied with a constant heat input per unit length of the probe. The temperature response of a thermocouple located adjacent to the heating element at the center of the probe is measured as a function of time. If the thermal probe approximates the line heat source, then the temperature rise, T, and time t, can be recorded at specified intervals and then a straight line relationship can be obtained by plotting T versus log t (Fig. 3.1). The thermal resistivity ρ is proportional to the slope of this line as shown by Eq.3.2.

3.2.1 *Description of Apparatus*

The system used for measuring thermal resistivity in the laboratory consists of an IBM PC AT compatible microcomputer, a thermal property analyzer-5000 (TPA-5000), thermal needle, a printer and a test container as shown in Plate (3.1). A description of the thermal needle, TPA-5000 and test container, as well as the procedure for thermal property measurement is given below.

3.2.1.1 *Thermal Probe*

The probe used in this study is a 100 mm long stainless steel cylinder with a diameter of 3 mm and a temperature sensor of type T thermocouple located at midpoint of heater length. The general design features of the thermal probes used in this study are shown in Fig. 3.2. The probes were designed and fabricated by Geotherm Inc. (Canada). The thermal probes could easily be inserted into and extracted from loose specimens; however, the direct extraction procedure was not feasible for most backfill specimen and cemented natural soils. For specimen which is difficult to extract the thermal probe from at the end of the test, the sample is rewetted to soften the material and make it possible to extract the probe. The length-to-diameter ratio of probes used are 33 which is enough to maintain the recommended length-to-diameter ratio to approximate the line heat source. In the previous section, it was shown that the effect of the finite length of the probe is negligible for relatively short duration experiments if length-to-diameter ratio is greater than 30 (see Section 3.1.3.1).

Plate 3.1 : Set up of Thermal Resistivity Measurements

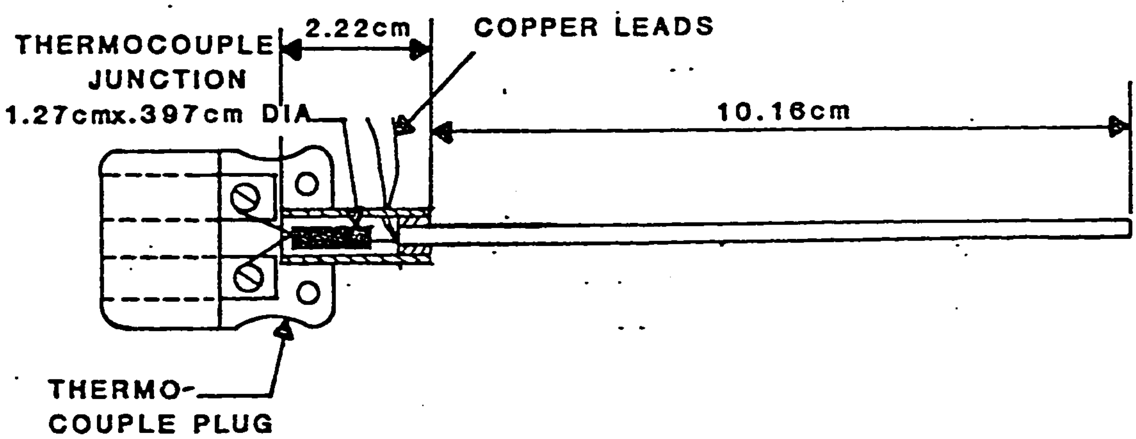

Fig. 3.2: Thermal Probe Construction Details.

3.2.1.2 TPA-5000

The TPA-5000 is an updated version of Electric Power Research Institute (EPRI) TPA developed by Ontario Hydro (Canada). It is a microprocessor-controlled portable system which can be used for thermal resistivity and thermal stability measurements. The unit consists of a programmable 10A, 60V power supply, a 12-channel data acquisition system and an IBM PC AT compatible microcomputer. The power supply is internally protected against excess voltage and current output. Either condition causes immediate shutdown. The thermal resistivity is calculated by a microprocessor from a least square fit of time - temperature data collected between 120 and 600 seconds. A special function keyboard is available so that all parameters such as probe power, time can be verified from the pre-set values stored in the microprocessor memory.

During the test, the time is continuously displayed along with the thermocouple temperature , current and thermal resistivity . As well, a coefficient of determination is calculated for the least square fit.

3.2.1.3 Test Container

The test container is a standard compaction mould which has an inside diameter of 10.16 cm and a height of 11.7 cm, (Figure 3.3). Minimum sample size required to minimize error in the thermal resistivity measurements due to the finite size of the medium were discussed in Section 3.1.3.2. The size of the mould used in this study is sufficient to prevent boundary from influencing test results for test durations of 600 sec-

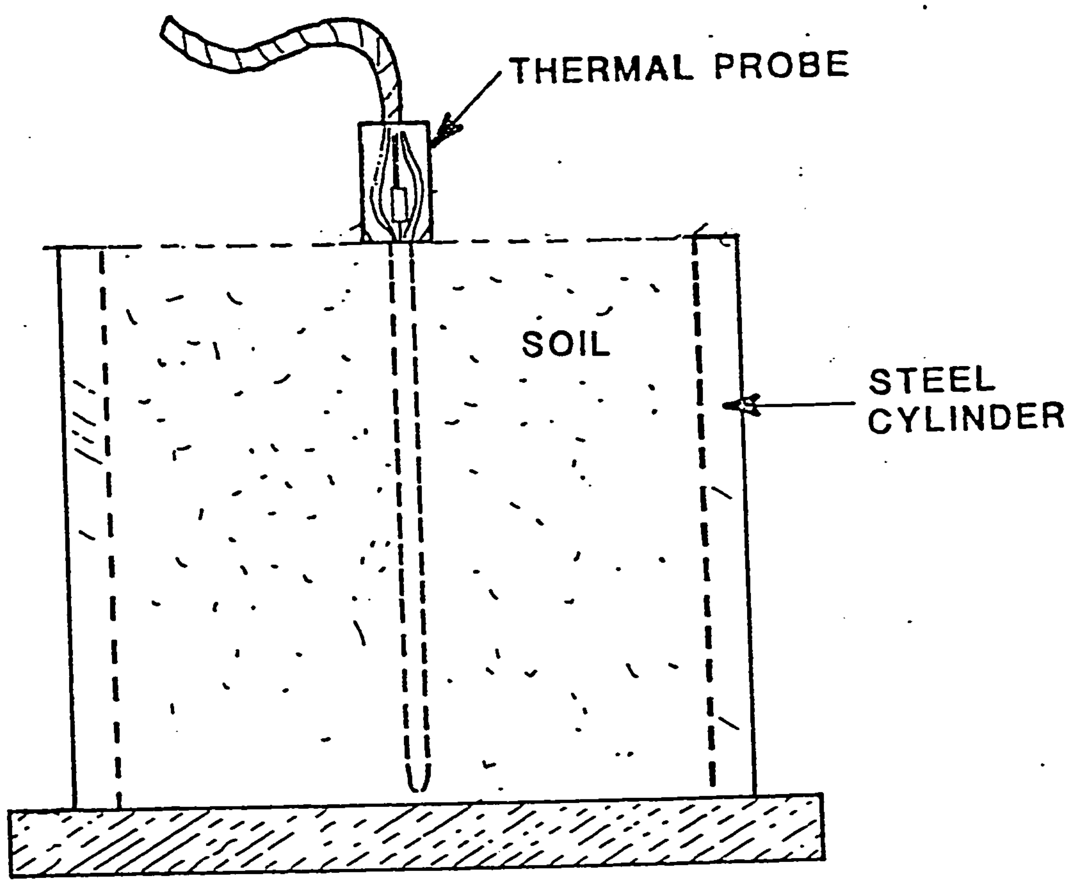

Fig. 3.3: Schematic Diagram of Laboratory Thermal Resistivity Test Arrangement.

onds.

3.2.2 Sample Preparation

Two methods have been used to determine the thermal resistivity versus moisture content curve. The first method involves stage drying reconstituted soil sample compacted wet to a dry density determined by the standard compaction test. The second method involves measuring the thermal resistivity of reconstituted soil samples at different moisture contents. The first method was applied in this study; however, the second method was used for some soils to study the effect of soil structure on thermal resistivity . The first method (stage drying) was chosen because it closely simulates drying in the field.

The soil to be tested was air-dried, and a specimen was taken to determine the initial moisture content of the air-dried soil. The initial moisture content was used to establish the quantity of water required to produce the molding water content. After the desired moisture content and density for a test had been selected, a quantity of air dried soil equivalent to 2500 g was thoroughly mixed with the necessary amount of water to achieve the molding moisture content. Then the soil is compacted to the desired density (Sec. 3.3.3). In the case of a clayey soil, the sample was stored in an airtight plastic bag for a minimum curing time of 24 hours before compaction.

3.2.3 Stage Drying Test

A step by step description of the stage drying test is given below.

(i) The thermal needle is inserted into the soil sample. Care is taken to insure that the needle is inserted in the center of the sample and to ensure good thermal contact between the needle and the soil. The insertion is done by pushing the needle by hands into the soil until the whole length of the probe is contained in the soil. In cases where it is difficult to insert the needle by hand, then a pilot hole of a diameter slightly less than the probe diameter is drilled and then the probe is inserted into the soil sample.

(ii) After inserting the needle, the total weight of the mold, the wet soil and the needle (W_{Ti}) is measured and recorded. The weight of the mold plus the weight of the needle alone (W_{M+N}) is subtracted from (W_{Ti}) to calculate weight of compacted wet soil at stage 1 (W_{si}). By knowing the weight of the soil, then the moisture content can be calculated using equation :

$$w = \left(\frac{W_{si} - W_d}{W_d} \right) x\ 100 \qquad (3.3)$$

Where:

w = Moisture content in percentage by weight

W_{si} = The wet weight of the sample at any stage (i) of the test

W_d = The oven dry weight of the sample.

(iii) Connections to the TPA are made and the sample is now ready for thermal resistivity measurements.

(iv) The thermal probe characteristics such as the probe resistance in Ω/cm, the probe active length in cm, and probe effective radius in cm, is entered through the set up file that is created before a test run can be executed.

(v) The probe is energized to the required power and the test starts. The test is run and stopped automatically as described earlier for 600 seconds. The amount of input power to the probe and hence to the soil must be carefully selected to ensure that conduction is the only mechanism of heat transfer. If high power is used, moisture migration will be induced and hence erroneous results will be obtained. Conversely, if low power is used, then small temperature rise will occur and there will not be a clear definition in the experimental curve. Therefore, the power selected should not be too high to induce moisture migration and should not be too low to give indefinite results. Steinmanis (1982) suggested the use of power level that will result in temperature rise of 6 to 10°C. In this study, power levels used fall in the range suggested by the TPA-5000 manufacturer (Table 3.1). It has been noted that applying the above power levels gives usually temperature rise of about 6 to 8°C. The power applied is kept constant throughout the test and no power is initiated until the needle and the soil are at uniform temperature which satisfy assumptions (iv) and (v) of the line source theory.

Table 3.1: **Selected Input Power for Stage Drying Test for Different Anticipated Values of Thermal Resistivity**

Anticipated °C-cm/watt	**Power Level (watt/cm)**
< 60	0.36
60-120	0.2
> 120	0.1

(vi) The thermal probe is left inserted and the sample is dried in stages to obtain the thermal resistivity as a function of moisture content. After each drying stage, the sample must be weighed, sealed using plastic wrap and allowed to cool.

(vii) The sample is left sealed in order to equilibrate with respect to ambient conditions. This step is very important for obtaining good results because of two reasons. First, when the sample is moved from a warmer environment (oven) to a cooler environment (room), there will be moisture distribution and consequently moisture may not be constant in the sample. Secondly, there will be also temperature gradient which will give erroneous results if the test is started immediately after moving the sample from the oven or even after equilibration for insufficient period. Equilibration periods used in this study were at least 6 to 8 hours for sandy soils and 24 hours for clayey soils.

(viii) After running the last stage of the thermal resistivity test, the needle is extracted and the dry soil weight is determined.

3.3 Geotechnical Properties

3.3.1 Introduction

In Chapter 2, it is shown that thermal resistivity is influenced by many factors such as density, moisture content, soil composition and grain size distribution; therefore, it is important to study the geotechnical properties that are related to thermal resistivity . One of the objectives of this study is to study relationships between geotechnical and thermal properties of different soil types. To achieve this objective, an experimental program was designed to investigate the geotechnical properties of soils selected for this study (natural soils and backfill materials).

3.3.2 Grain size Analysis

Grain size distribution was determined depending on the type of soil. For sandy soils, the sieve analysis is carried out according to (ASTM D-422. For silts, silty clay, etc., which have a measureable portion of their grains both coarse and finer than a No. 200 sieve, the combined analysis is used. The combined analysis employs both the sieve and hydrometer tests (ASTM D-422).

3.3.3 Moisture Density Relationships

The moisture density curves were developed using the standard compaction test (ASTM D-698). The apparatus includes the standard mold 117 mm high and 102 mm in diameter with a volume of 944 cm^3, removable mold collar 64 mm high and a 5.5 lb (2.5 kg) hammer. The soil is compacted in three approximately equal layers by letting the hammer fall from a standard height of 305 mm.

To prepare two samples from each soil at different densities, a typical compaction curve, as shown in Figure 3.4, is used. One sample is prepared by compacting the soil with the optimum moisture content to get the maximum dry density. The other sample can be chosen from any point on

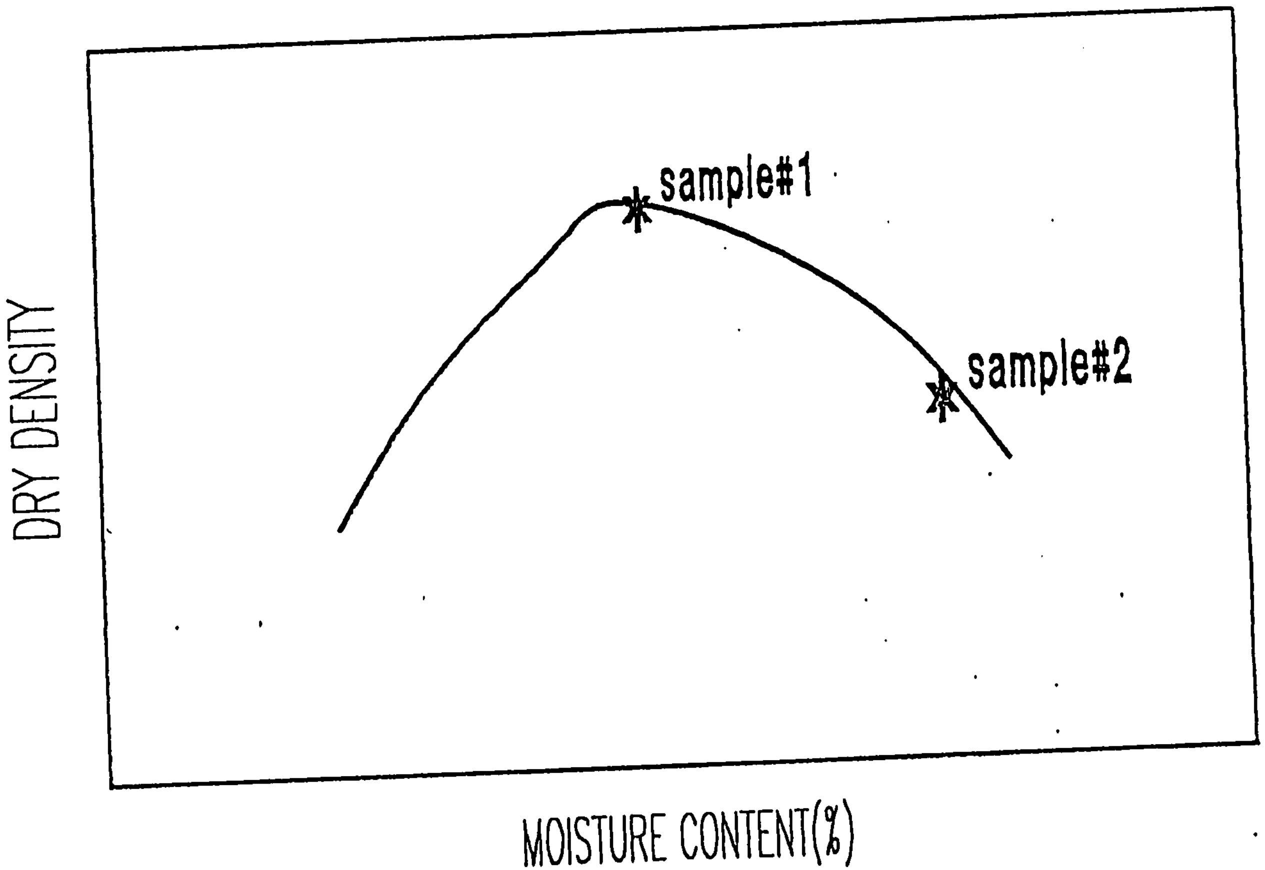

Fig. 3.4: Typical Compaction Curve Showing Two Samples Selected for Stage Drying Test.

the curve that will give a reasonably lower dry density. It is thought that selecting the second sample from the wet side of the curve will give more representative results since it contains a wide range of moisture contents when the sample is tested by stage drying. For sandy soils, compaction by tamping was used. The apparatus used for tamping compaction (Plate 3.2) was fabricated in the Mechanical Engineering Workshop.

3.3.4 Atterberg Limits

The Atterberg limits were carried out mainly for the purpose of soil classification. The procedure of determining liquid and plastic limits is the same as described by ASTM D-423.

3.3.5 Mineral Composition

The mineral composition of the soils were determined by means of X-ray flourescence (XRF) and X-Ray diffraction (XRD). The analyses were carried out in the Central Analytical and Materials Characterization Laboratories of the Research Institute, of King Fahd University of Petroleum and Minerals.

Plate 3.2 : Tamping Compaction Apparatus

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Geotechnical Properties of Selected Natural Soils

4.1.1 Introduction

In selecting soil samples for thermal resistivity tests, two criteria were kept in mind. First, it was desirable that as broad a grain size range as possible be covered. Secondly, it was desirable that the selected soils be of different types (e.g. sand, silt, clay) having a wide range of mineral composition. The properties and classification of the nine soil samples that were selected are shown in Tables 4.1a and 4.1b and the grain size distribution of them are shown in Figures 4.1 to 4.3. The coarser was the dune sand sample with all grains retained on No. 200 standard sieve and the finer sample is the expansive clay with more than 84% passing through No. 200 standard sieve. The other samples fall in the range of these two samples. The mineral composition of these samples are shown in Table 4.2.a while Table 4.2.b shows the chemical composition of these samples (see Appendix for x-ray diffraction and x-ray flourescence analysis results). The thermal needle method was used to investigate the thermal properties of these samples and the moisture content - thermal resistivity curves were obtained by stage-drying every sample as described in Chapter 3.

Table 4.1.a Properties of Tested Samples

Sample	max γ (gm/cm^3)	min γ (gm/cm^3)	C_c	C_u	Fines (%) Passing # 200	Clay Content < 0.02 mm	Classi-fication USCS
1. Dune Sand	1.89	1.57	0.77	3.6	0	0	SP
2. Beach Sand	1.85	1.55	0.88	3.2	1	0	SP
3. SCECO Backfill	1.84	1.53	0.89	3.0	3	0	SP
4. Jubail Sand	1.79	1.50	0.81	4.0	4	0	SP-SM

Table 4.1.b Properties of Tested Samples

Sample	maxγ (gm/cm^3)	wop (%)	C_c	C_u	Fines (%)	Clay Content	Plastic Limit	Liquid Limit	Classification USCS
5. Riyadh Sand	1.88	9.50	1.19	3.4	7	0	-	-	SW-SM
6. Sabkha	1.80	11.5	1.38	3.4	13	0	-	-	SM
7. Marl	1.50	20.0			35	7	-	-	SM
8. Sandy Clay	1.81	13.0	-	-	38	20	12	32	SC
9. Highly Plastic Clay	1.22	37.0	-	-	85	73	35	142	CH

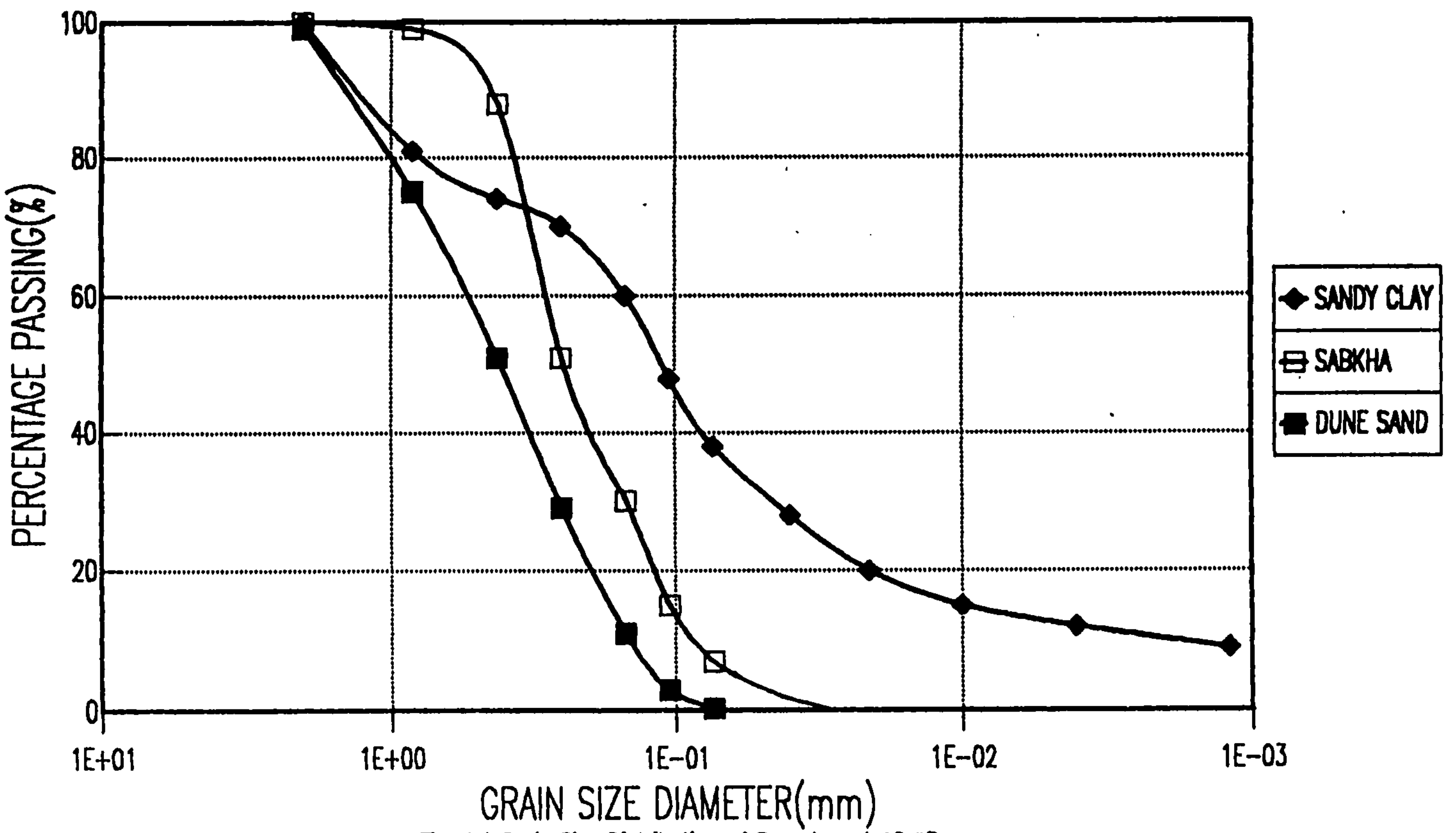

Fig. 4.1 Grain Size Distribution of Samples #1,#6,#8

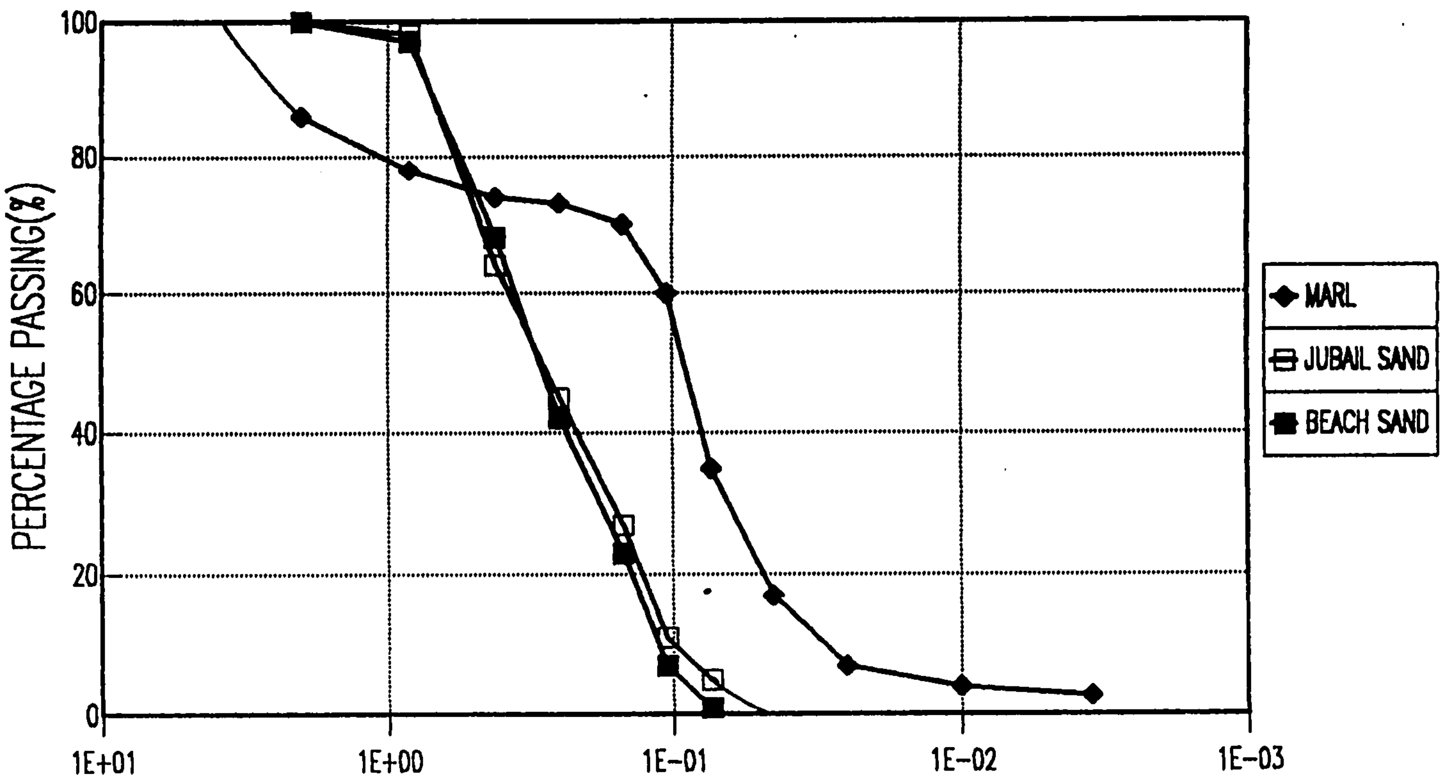

Fig. 4.2 Grain Size Distribution for Samples #2,#4,and#7

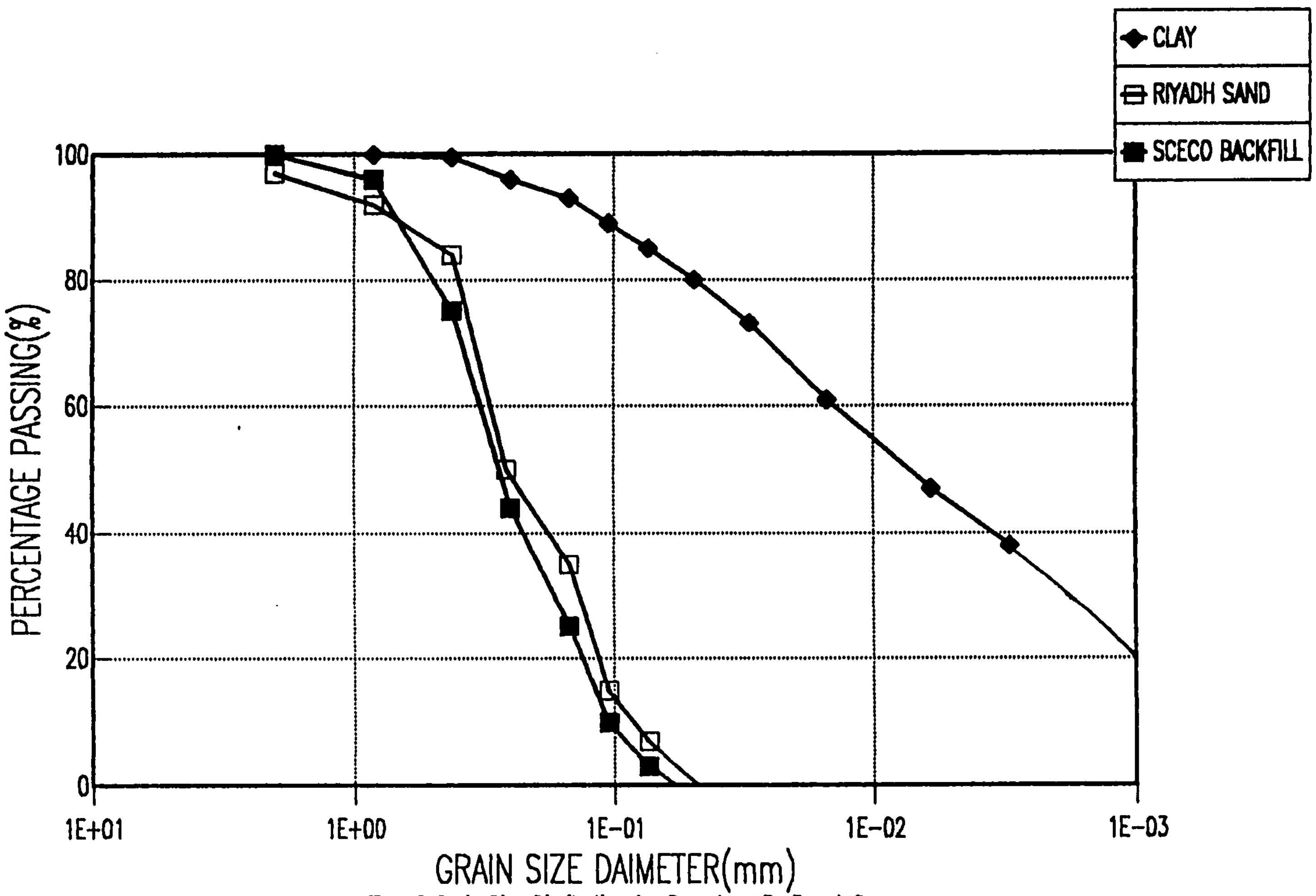

Fig.4.3 Grain Size Disribution for Samples #3,#5,and#9

Table 4.2.a Mineral Composition of Tested Samples

Sample	Mineral
1. Dune Sand	Quartz Calcite Dolomite
2. Beach Sand	Quartz Calcite Dolomite
3. SCECO Backfill	Quartz Calcite Dolomite Gypsum
4. Jubail Sand	Quartz Calcite
5. Riyadh Sand	Quartz Calcite
6. Sabkha	Quartz Halite Gypsum
7. Marl	Dolomite Calcite Quartz Gypsum
8. Sandy Clay	Quartz Calcite
9. Plastic Clay	Quartz Clay Minerals Gypsum

Table 4.2.b : Chemical Composition of Tested Samples

Sample #	AL Oxide	Si Oxide	S Oxide	K Oxide	Ca Oxide	Ti Oxide	Cr Oxide	Fe Oxide	Sr Oxide	Mn Oxide	CL Oxide
1	2.6	36.6	0.9	4.9	55.6	-	-	-	-	-	-
2	2.6	53.0	3.0	4.4	37.0	-	-	-	-	-	-
3	2.5	62.5	1.4	5.6	28.0	-	-	-	-	-	-
4	1.0	22.7	0.5	1.6	69.1	0.3	0.3	1.8	2.6	-	-
5	3.8	36.6	-	3.5	35.5	3.8	0.7	15.9	-	0.3	-
6	1.5	16.9	11.5	3.6	50.8	-	-	-	-	-	15.7
7	0.9	5.7	0.4	1.7	91.3	-	-	-	-	-	-
8	1.4	7.4	0.8	1.3	79.8	0.8	-	7.0	1.4	0.2	-
9	6.6	40.0	3.5	22.2	27.7	-	-	-	-	-	-

4.1.2 Description of Tested Samples

i) Dune sand (Sample #1) : The sample investigated in this study was obtained from a location near to Saudi Aramco-Half Moon Road. The grain size distribution of this sample is shown in Figure 4.1. It is a medium uniform sand with a coefficient of uniformity (Cu) of 3.6 and a coefficient of curvature (Cc) of 0.77. Its maximum and minimum density are 1.89 and 1.57 g/cm^3 respectively. It consists mostly of quartz (SiO_2) with small amounts of both Dolomite and Calcite. According to the Unified Soil Classification System (USCS), the soil is described as a poorly graded sand; its Unified Soil Classification is SP.

ii) Beach Sand (Sample #2) : This sample was collected from the KFUPM beach. The grain size distribution of this sample (Figure 4.2) is approximately the same as that of sample #1 with two differences. First, it is slightly finer as the material retained on No. 20 sieve (0.84 mm) is only about 3% compared to 25% in the case of sample #1. Secondly, the fine material (passing No. 200 sieve) is 2%, whereas there are no fines in sample #1. It is a poorly graded uniform sand with Cu and Cc coefficients of 3.2 and 0.88 respectively. Its maximum density is 1.85 g/cm^3 and its minimum density is 1.55 g/cm^3 and its Unified Soil Classification is SP also.

iii) SCECO Backfill (Sample #3) : This sample was obtained from

SCECO East. It is the material usually used by the company for the purpose of backfilling cable trenches. Examining figure 4.3 and the mineral composition of this sample, it is evident that this sample has almost similar properties as sample No. 2.

iv) Jubail Sand (Sample #4) : This sample was obtained from Jubail area. It is a uniform fine sand with Cu and Cc of 4.0 and 0.81 respectively and contains 5% of fines. The Unified Soil Classification of sample #4 is SP-SM.

v) Riyadh Sand (Sample #5) : This sample was obtained from Riyadh area. The sample is distinguished by its reddish color and its cementitious properties. Its cementitious behavior was mainly due to the presence of appreciable amount of calcite. The high maximum density achieved in this sample (Fig. 4.4) is probably due to the presence of Fe compound (Table 5 in the Appendix). Sample #5 is relatively well graded and its Unified Soil Classification is SW-SM.

vi) Sabkha Soil (Sample #6) : This sample was obtained from Ras Al-Ghar area, it is a relatively well graded sand with Cu of 3.4 and Cc of 1.38 and contains 13% of fines. It is a highly cementitious sand due to the presence of Halite (NaCl). The maximum dry density obtained from the Standard Proctor test (Figure 4.5) is 1.80 g/cm^3 at an optimum moisture content of 11%. Its Unified Soil Classification is SM.

vii) Marl (Sample #7) : This sample was obtained from Al-Khobar area. Its gradation curve is shown in Figure 4.2. It covers a wide range of grain sizes with appreciable amount of fines (35%) and 7% of clay size particles (0.02 mm). Dolomite ($CaMg(CO_3)_2$) is the predominant mineral in this sample and small amounts of quartz, Calcite and Gypsum are also present. The maximum density is relatively low (1.50 g/cm^3) as shown in Figure 4.6. The Unified Soil Classification of this sample is SM.

viii Sandy Clay (Sample # 8): This sample was obtained from Riyadh area. Its gradation curve is shown in Figure 4.3. About 38 percent of the sample is passing # 200 sieve and the clay size content is about 20%. It has a liquid limit of 32 and a plastic limit of 12 with a plasticity index of 20. The main components of this sample are calcite and quartz. Maximum dry density is 1.81 g/cm^3 at an optimum moisture content of 13%. The Unified Soil Classification of this sample is SC.

ix) Highly Plastic Clay (Sample #9): This sample was obtained from near Al-Qatif area. It is an expansive soil having a liquid limit of 142, a plastic limit of 35 and a plasticity index of 107. The gradation curve (Figure 4.3) shows that 85% of the soil is passing # 200 sieve and 60% of the grains have clay size particles (0.02 mm), consequently, it can be described as a very fine grained soil. The maximum density of this sample is 1.22 g/cm^3 at an optimum moisture content of 37% (Figure 4.8).

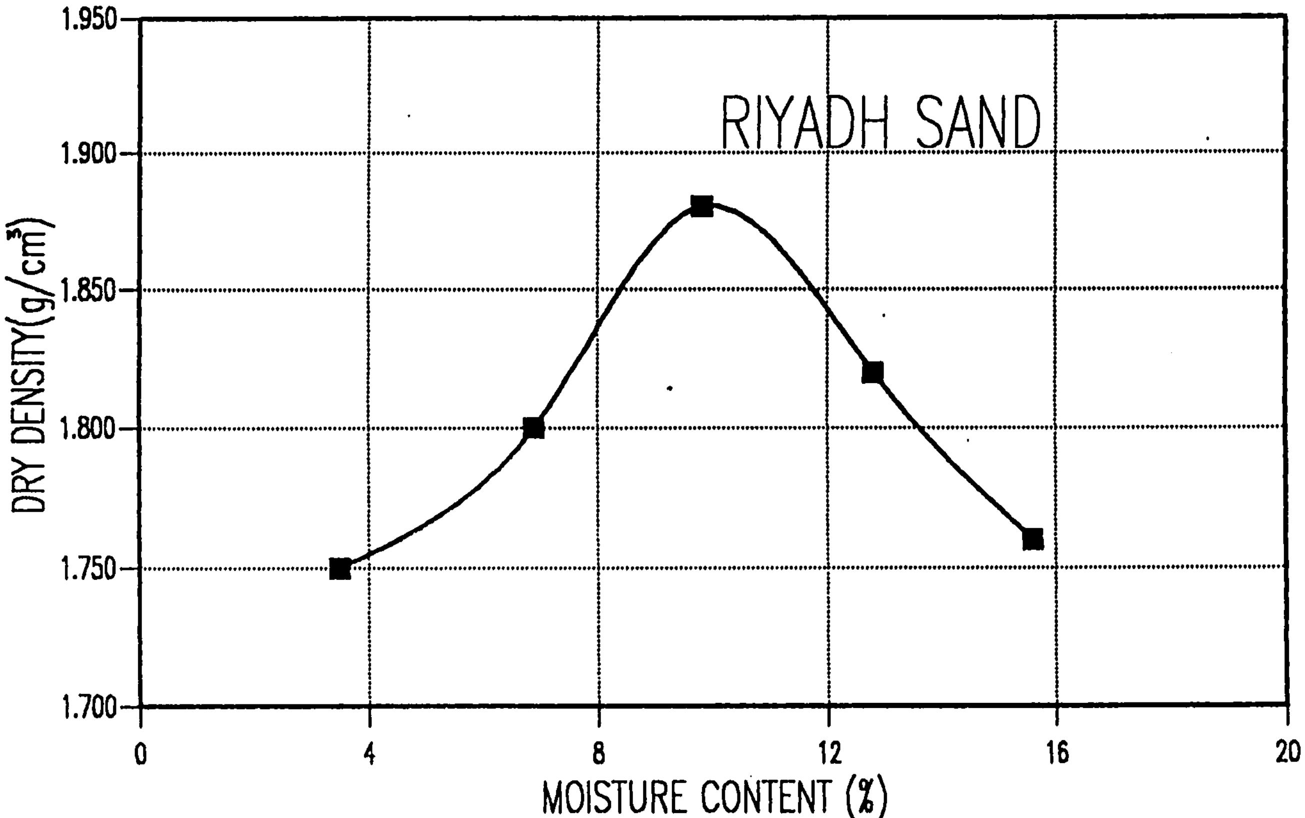

Fig.4.9 Standard Compaction Curve for Riyadh Sand(Sample#5)

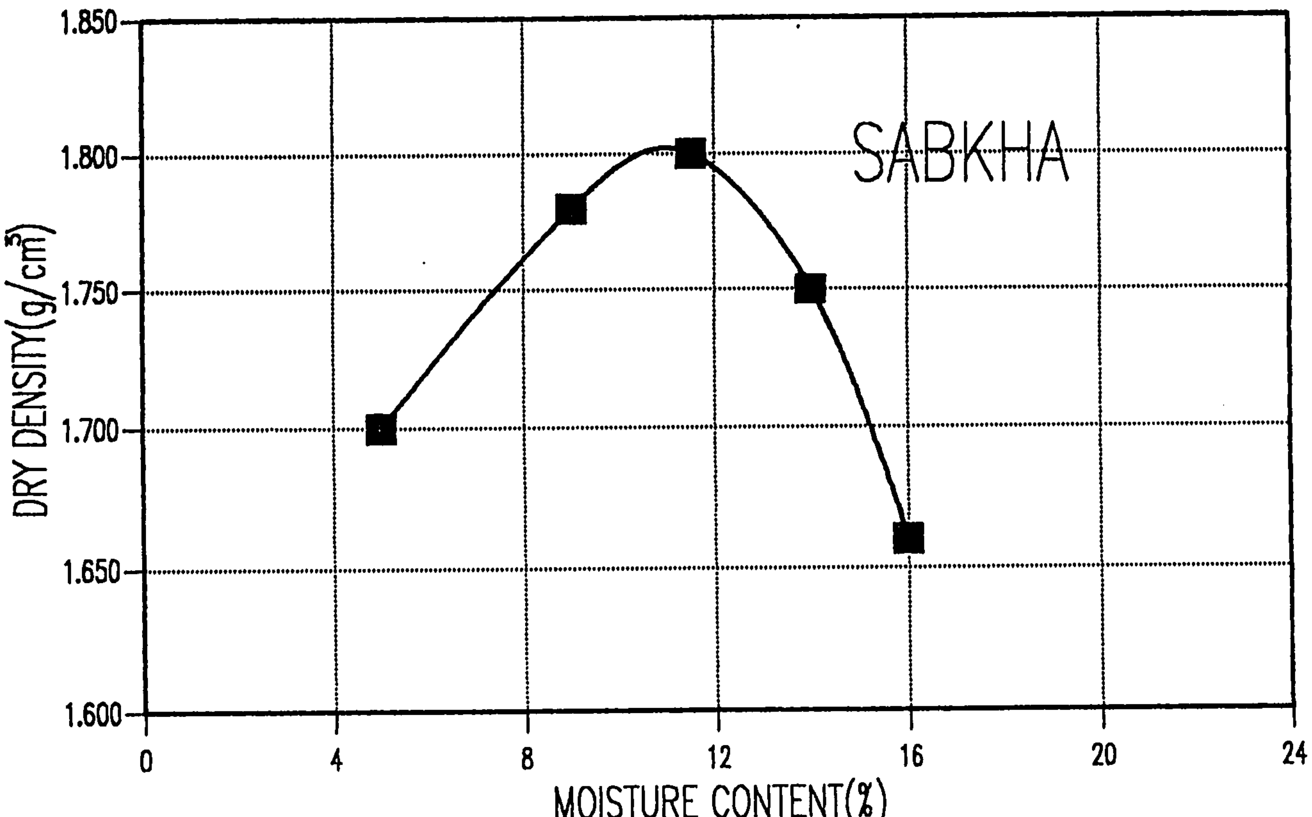

Fig. 4.5 Standard Compactin Curve for Sabkha(Sample#6)

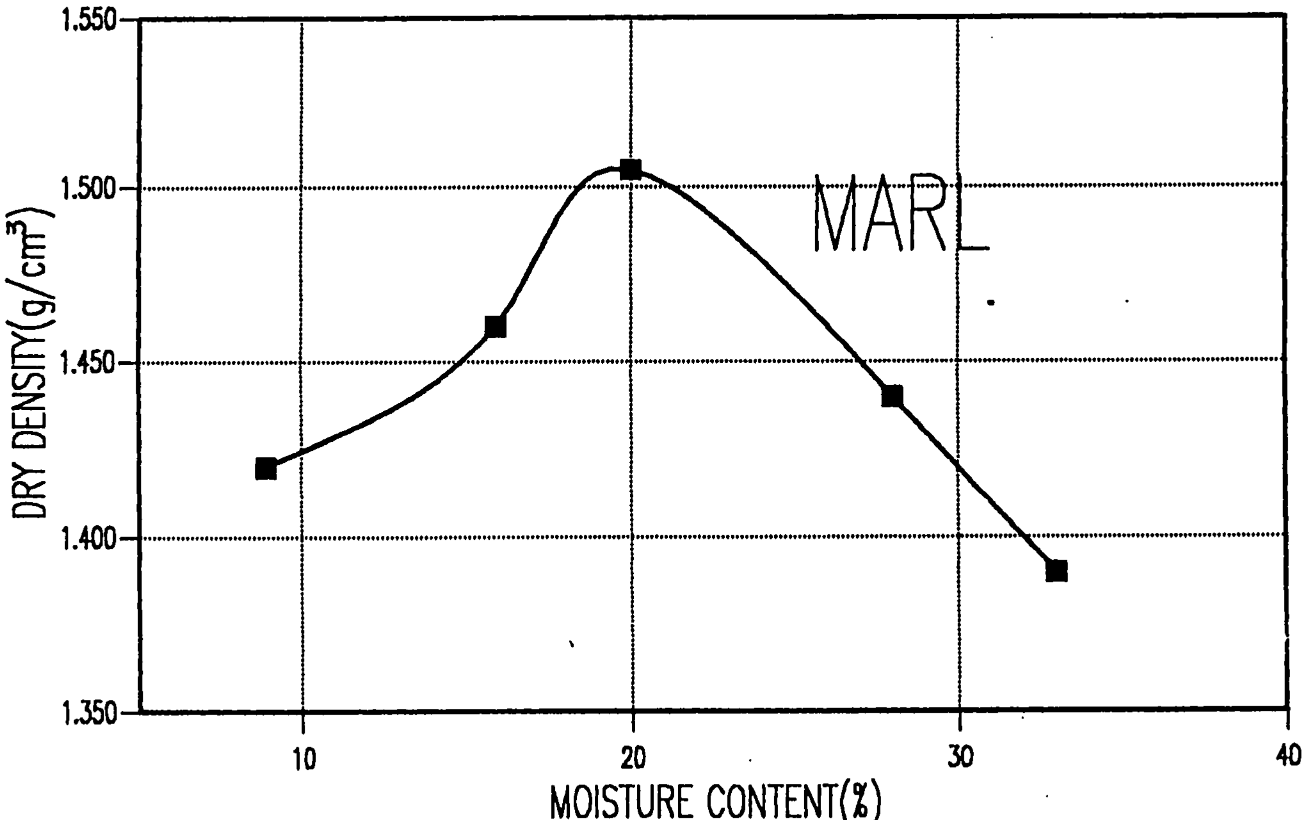

Fig. 4.6 Standard Compaction Curve for Marl(Sample#7)

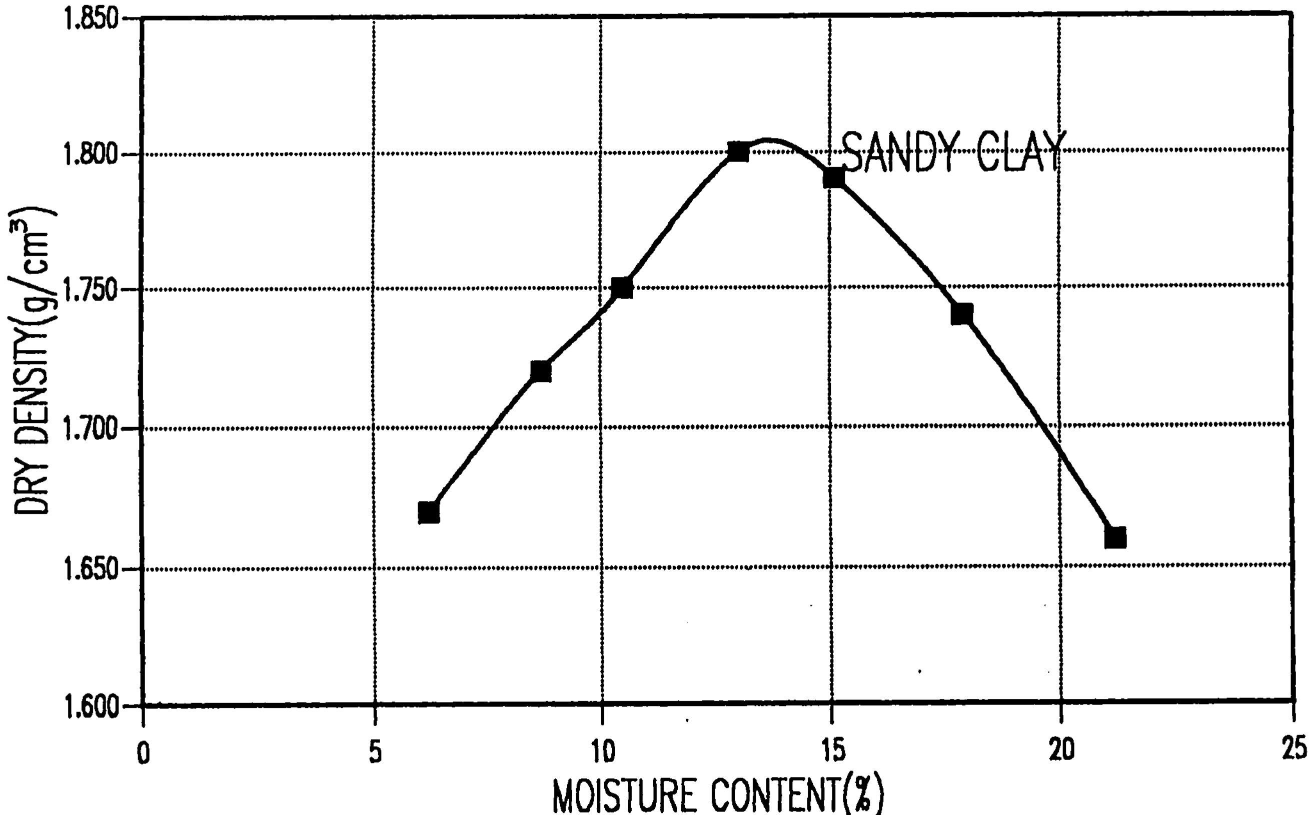

Fig.4.7 Standard Compaction Curve for Sandy Clay(Sample#B)

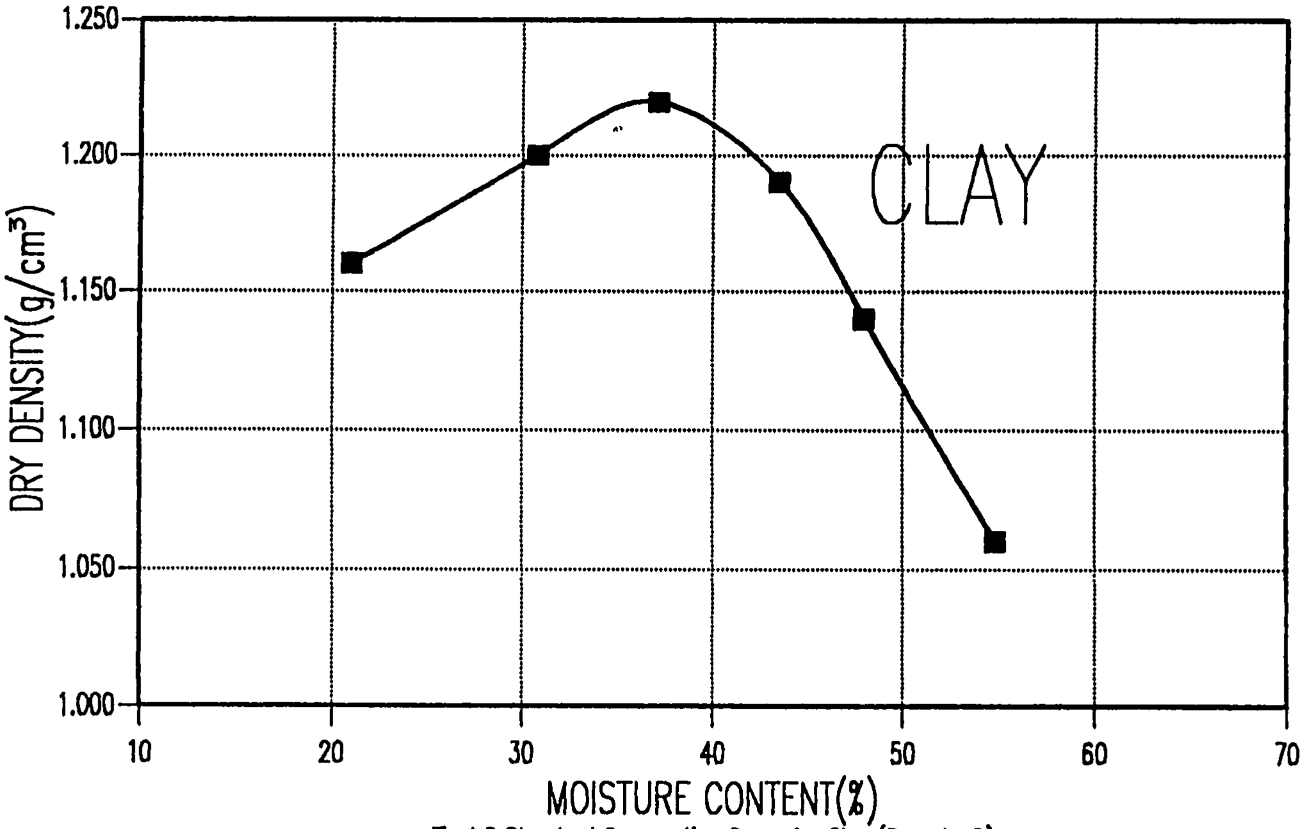

Fig.4.8 Standard Compaction Curve for Clay (Sample#9)

4.2 Thermal Resistivity of Tested Samples

4.2.1 General

The influence of moisture content and dry density on the thermal resistivity of the selected samples were investigated using the laboratory test program described in Chapter 3. Figures 4.9 through 4.17 show results of thermal resistivity versus moisture content for the nine samples. Two curves were plotted for each sample. Every one of these curves represents different dry density. All samples were compacted wet and then thermal resistivity were measured in stages as samples were gradually drying (stage drying technique). Factors influencing thermal resistivity based on stage drying tests are discussed in the following subsections.

4.2.2 Influence of Moisture Content

The importance of soil moisture is illustrated in Figures 4.9 through 4.17. These figures generally show that the thermal resistivity decreases as moisture content increases. Also, these data demonstrate that three distinct stages exist in the thermal resistivity - moisture content relationship. These stages are shown schematically in Figure 4.18 and can be classified as follows :

Stage I exists from zero moisture content up to a moisture content which is just below the critical moisture content (see section 2.2). By considering that heat flow will occur through the region which has the least thermal resistance which in this case is the solid to solid contact, most of the heat will flow through the particle contacts. The actual contact area

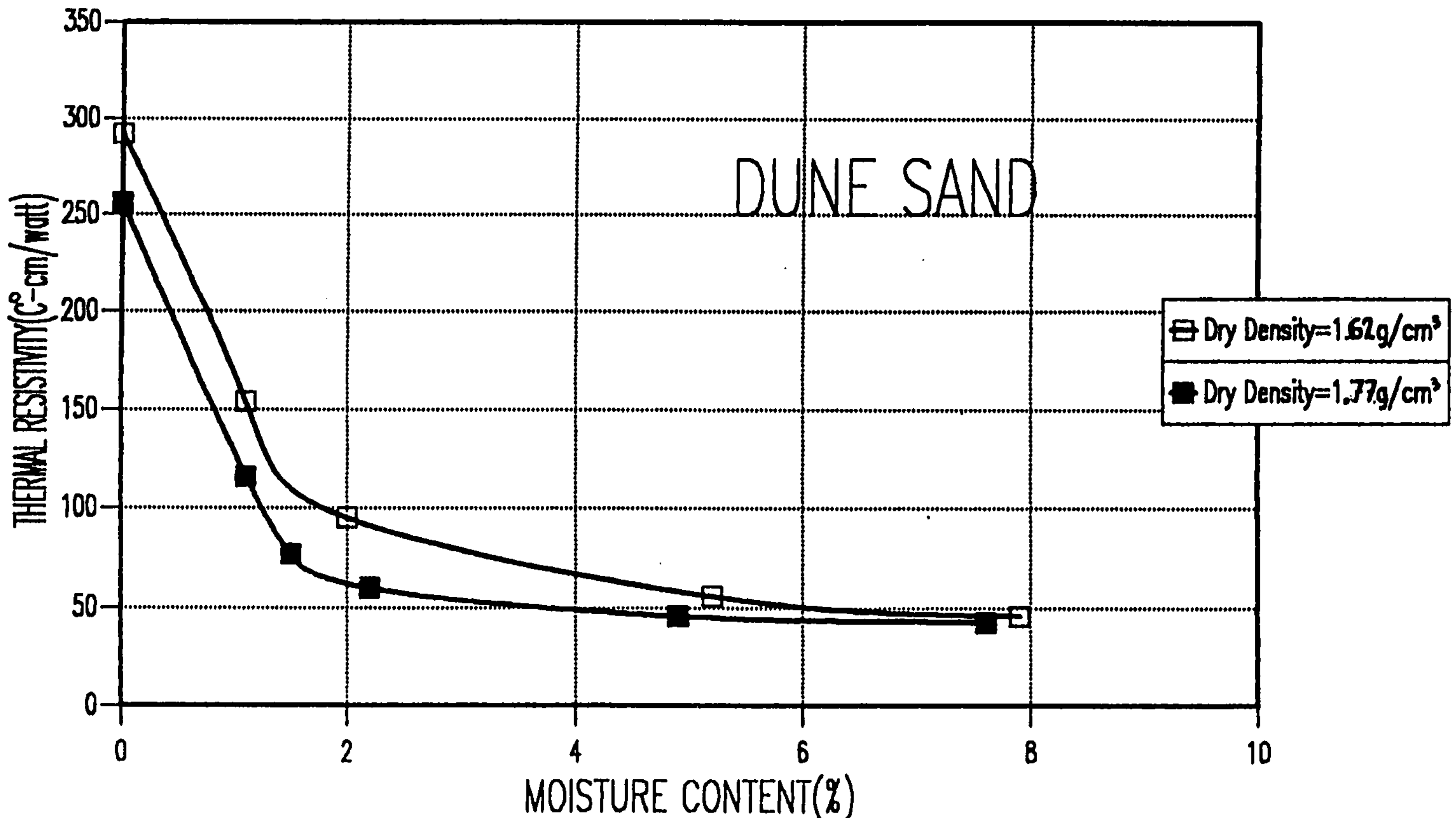

Fig.4.9. Thermal Resistivity vs Moisture Content for Sample#1

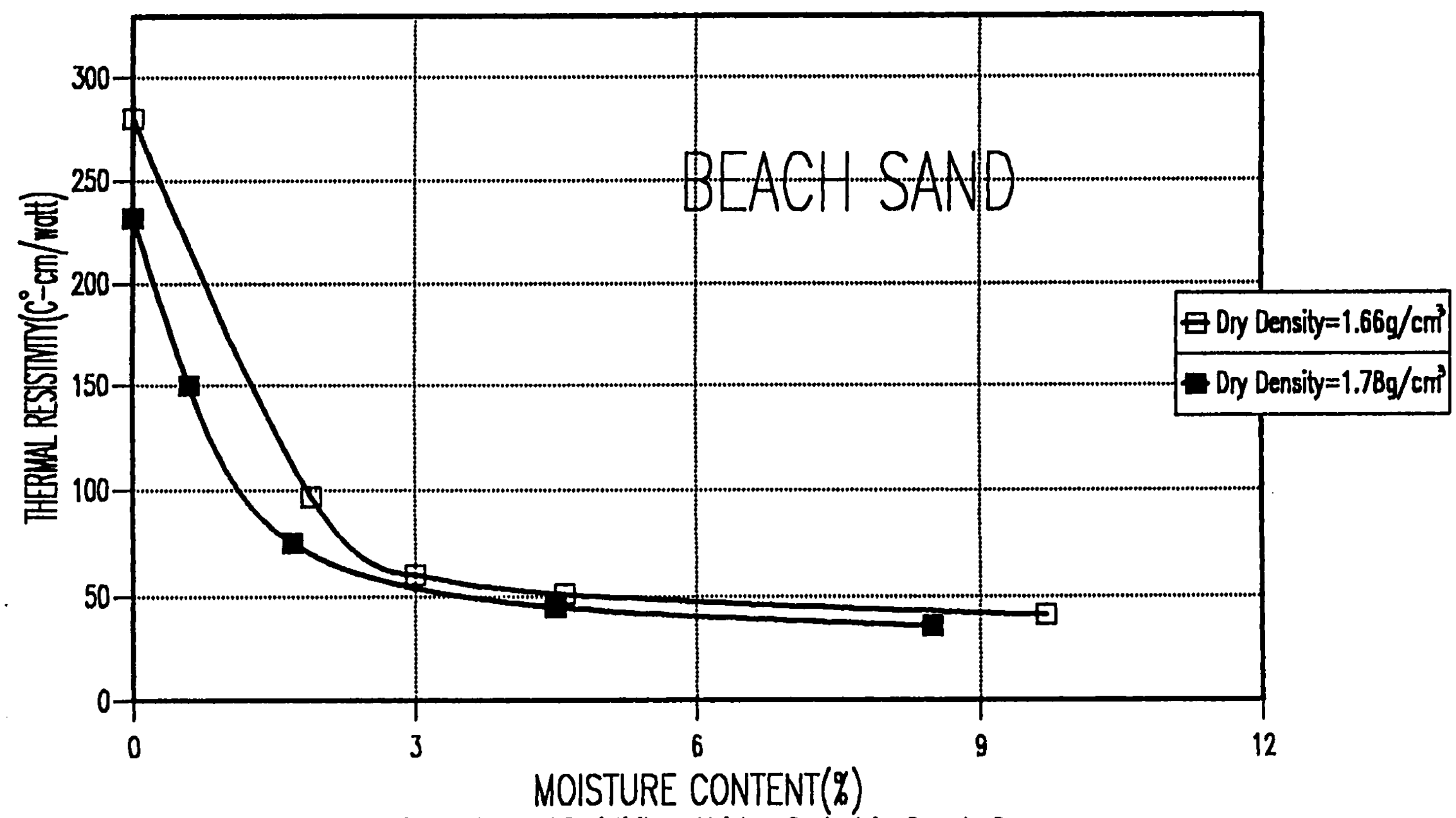

Fig.4.10 Thermal Resistivity vs Moisture Content for Sample#2

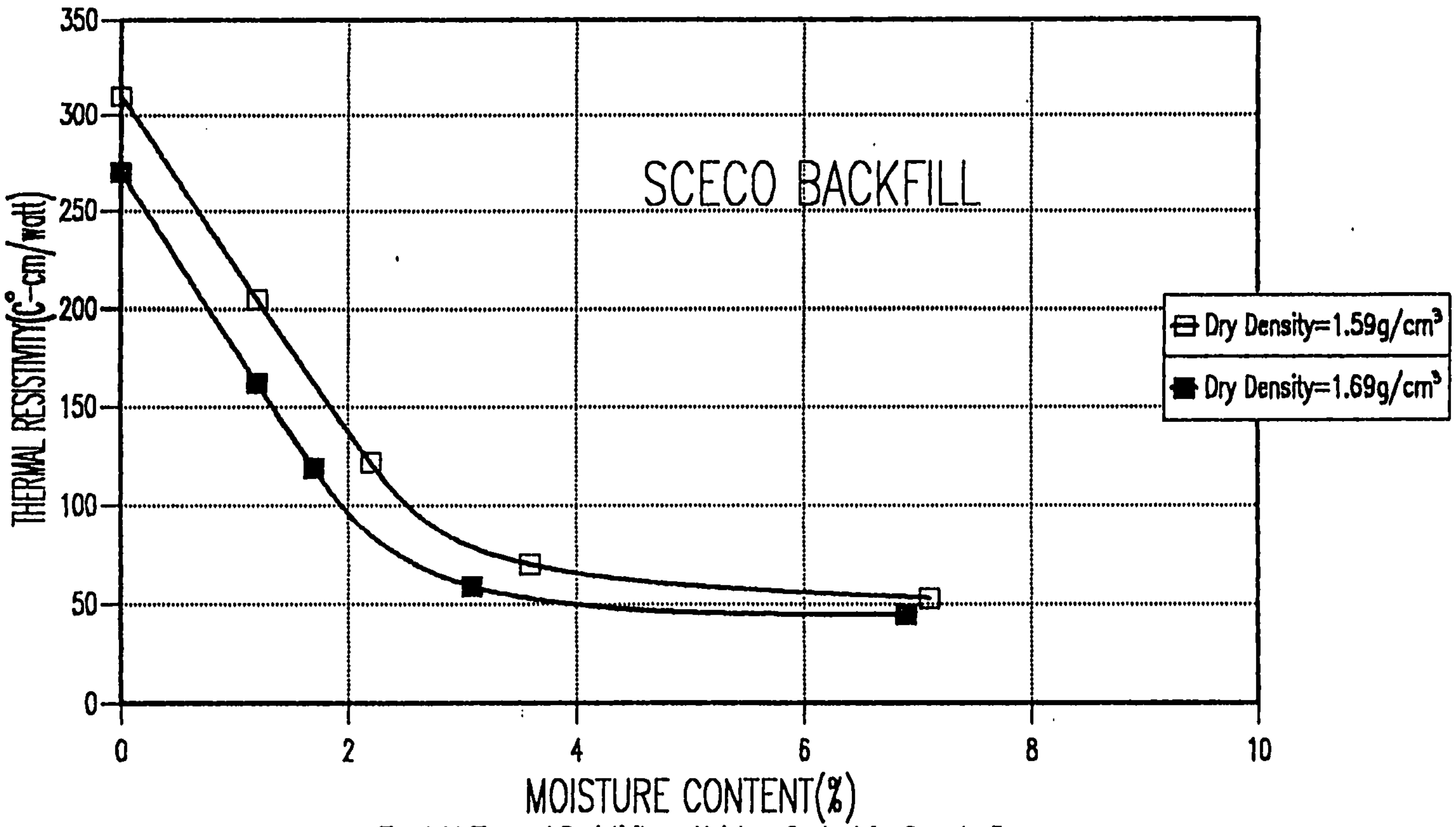

Fig. 4.11 Thermal Resistivity vs Moisture Content for Sample#3

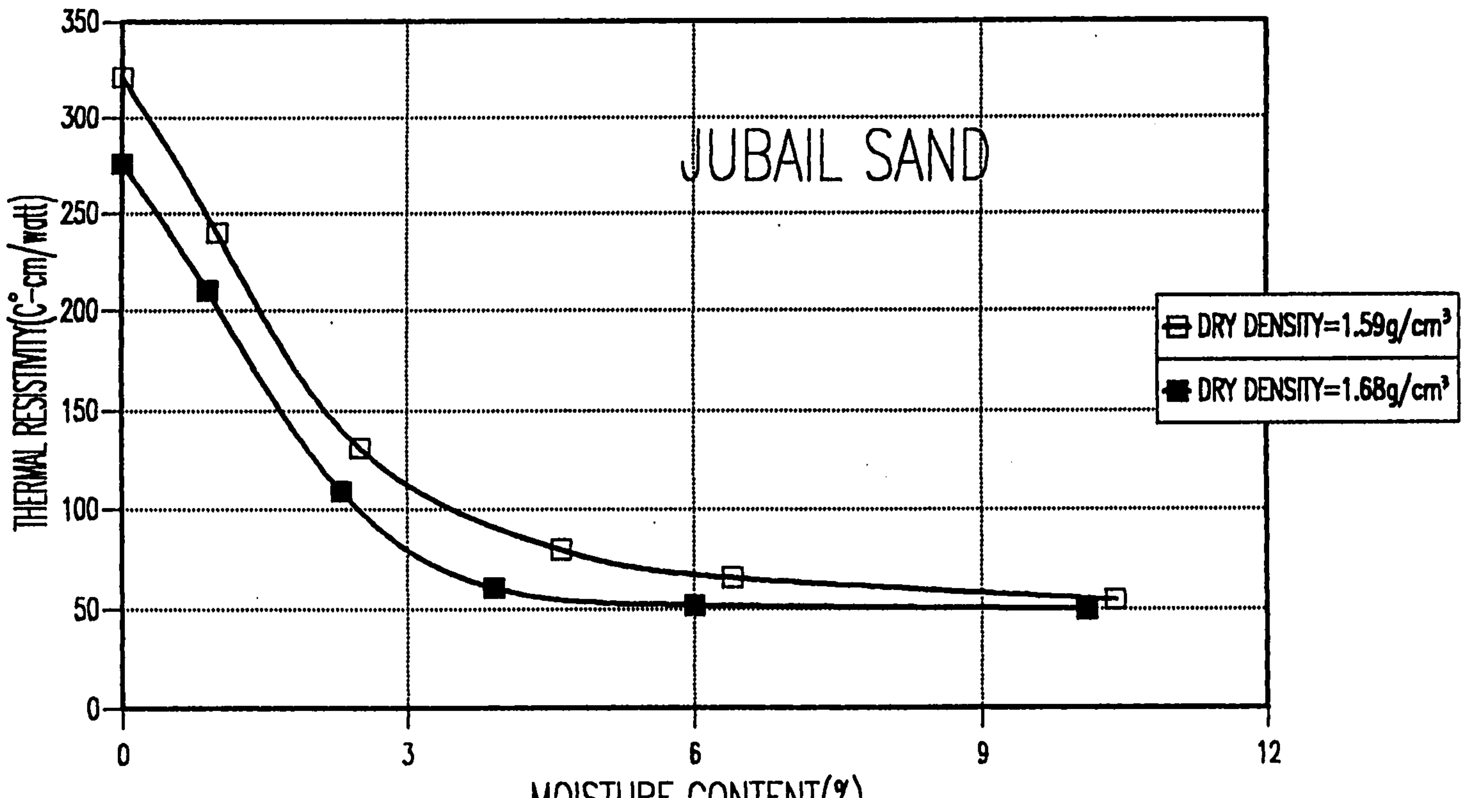

Fig.4.12 Thermal Resistivity vs Moisture Content for Sample#4

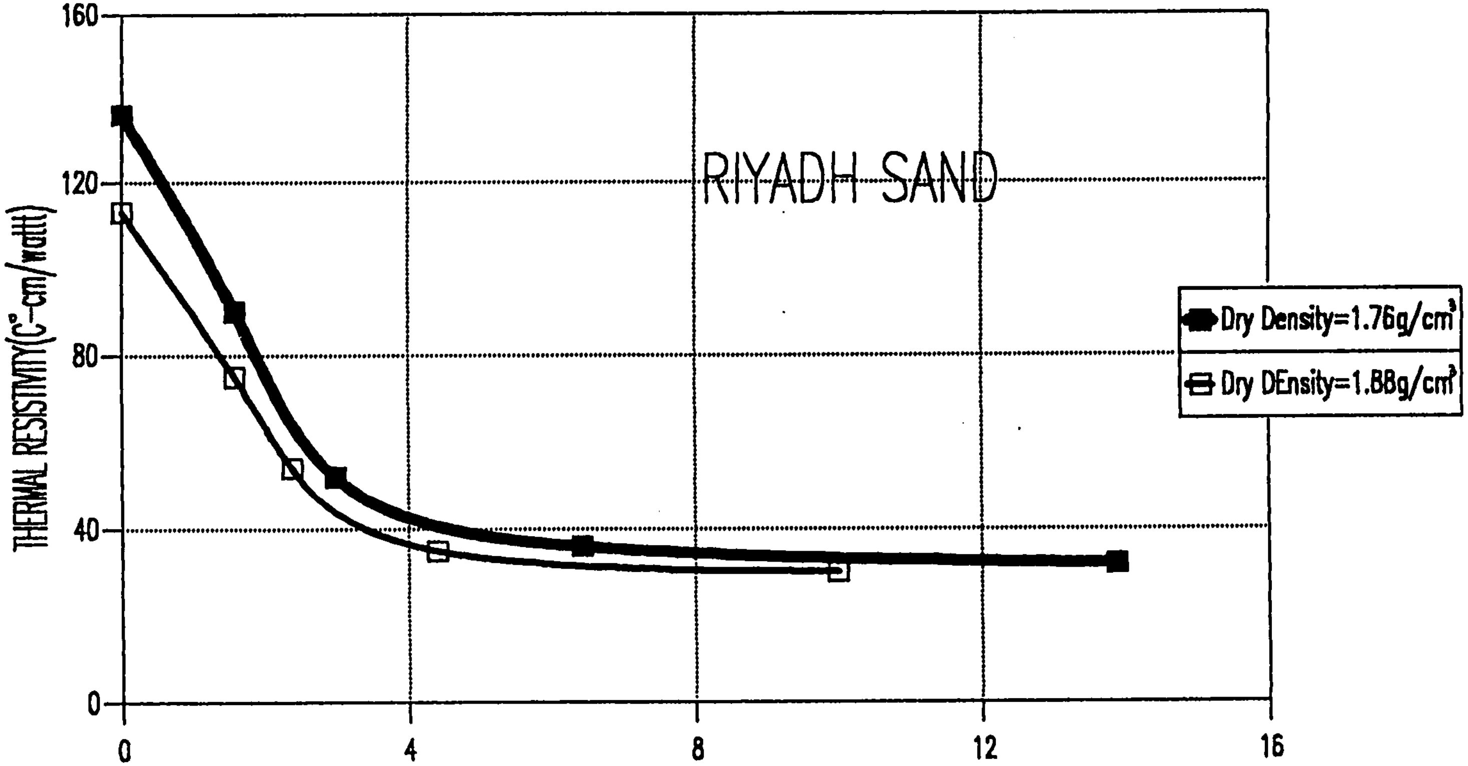

Fig. 4.13 ThermalResistivity vs Moisture Content for Sample#5

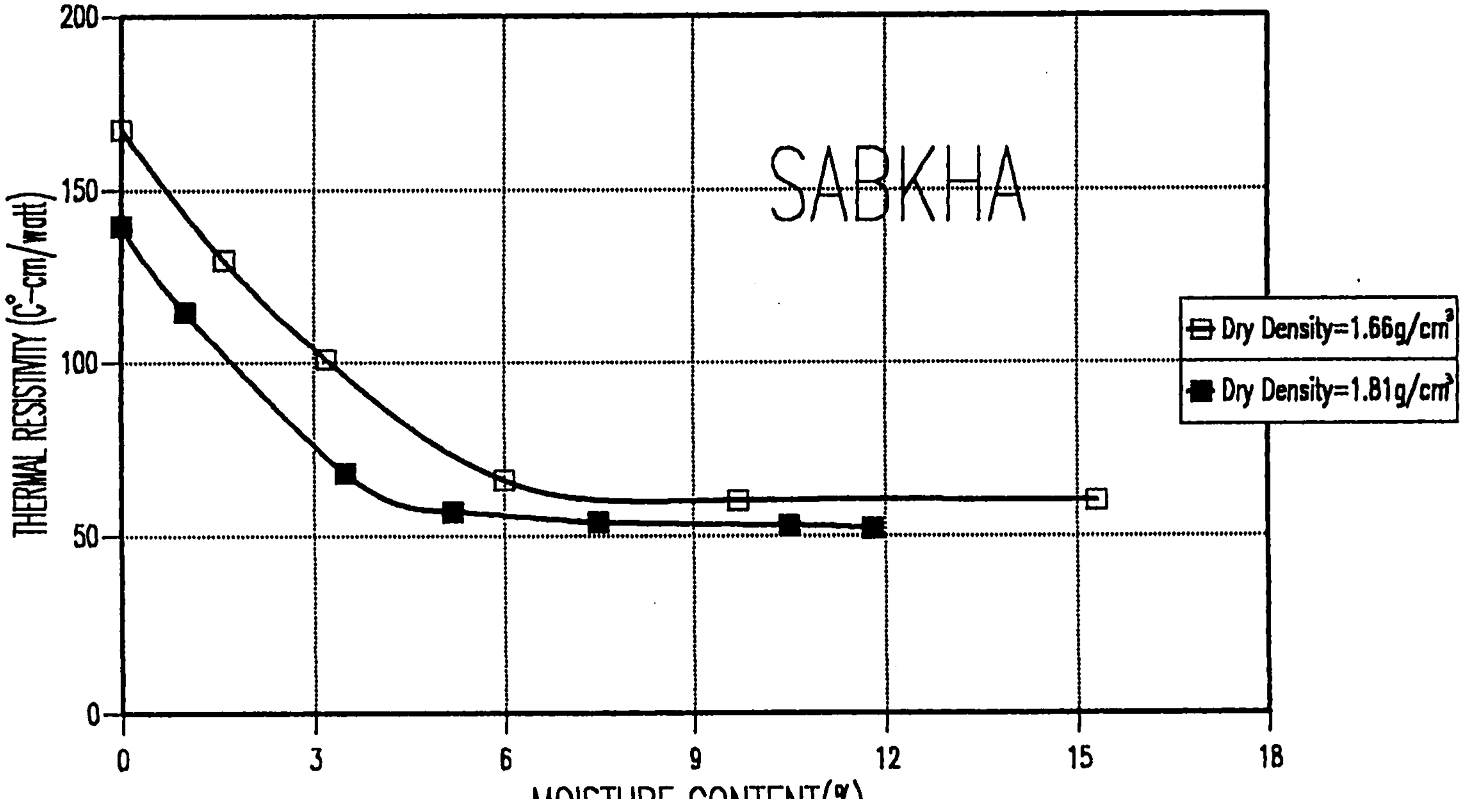

Fig.4.14 Thermal Resistivity vs Moisture Content for Sample#6

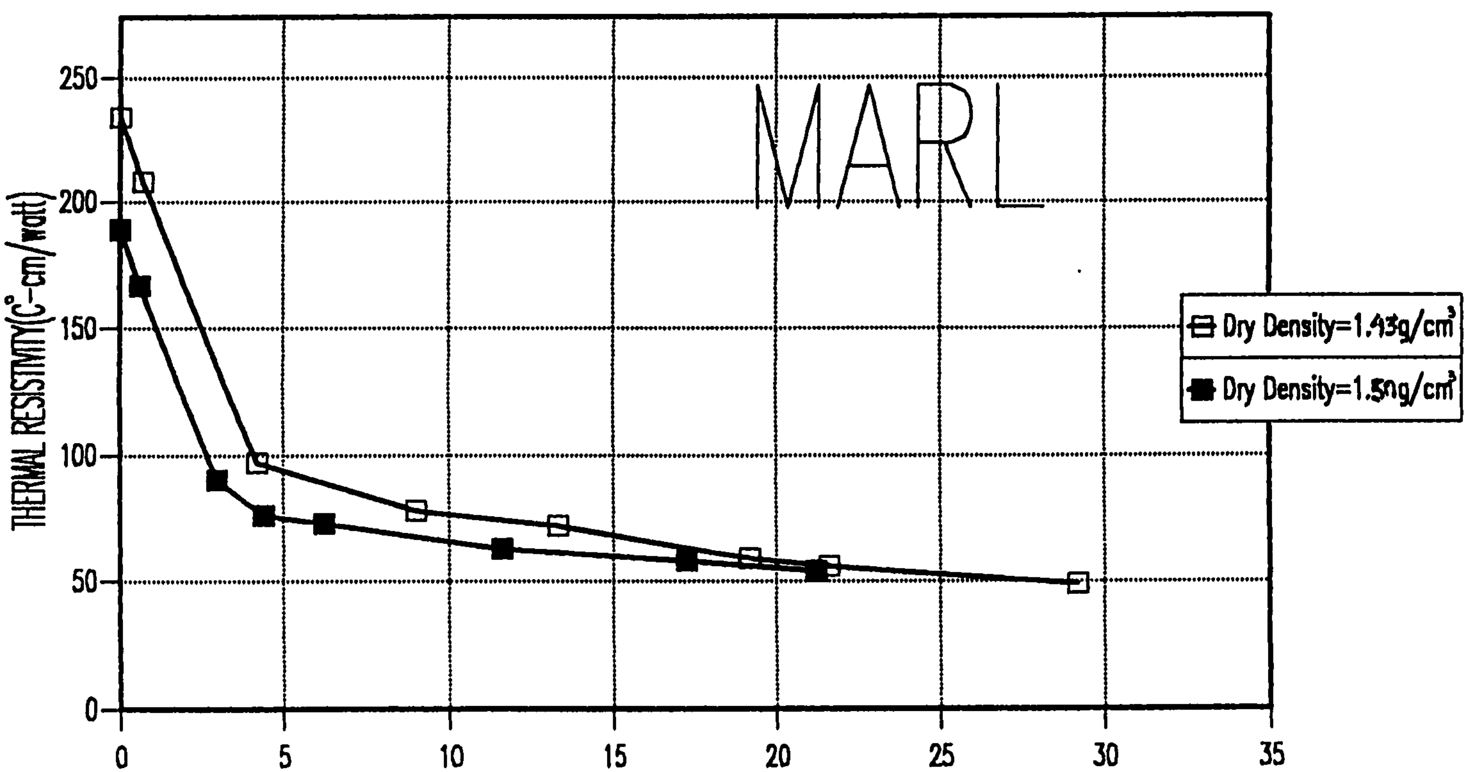

Fig.4.15 Thermal Resistivity vs Moisture Content for Sample#7

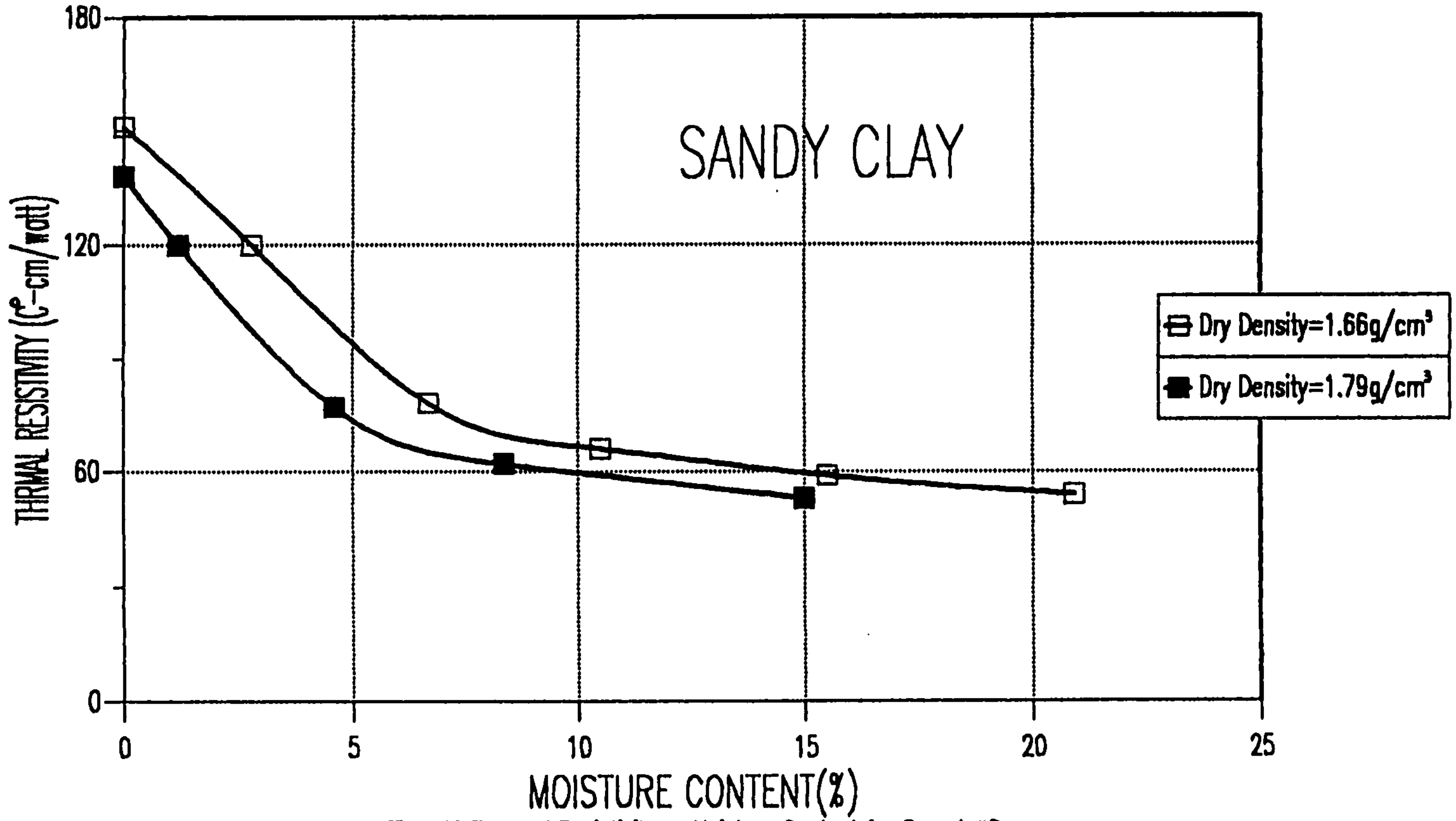

Fig.4.16 Thermal Resistivity vs Moisture Content for Sample#8

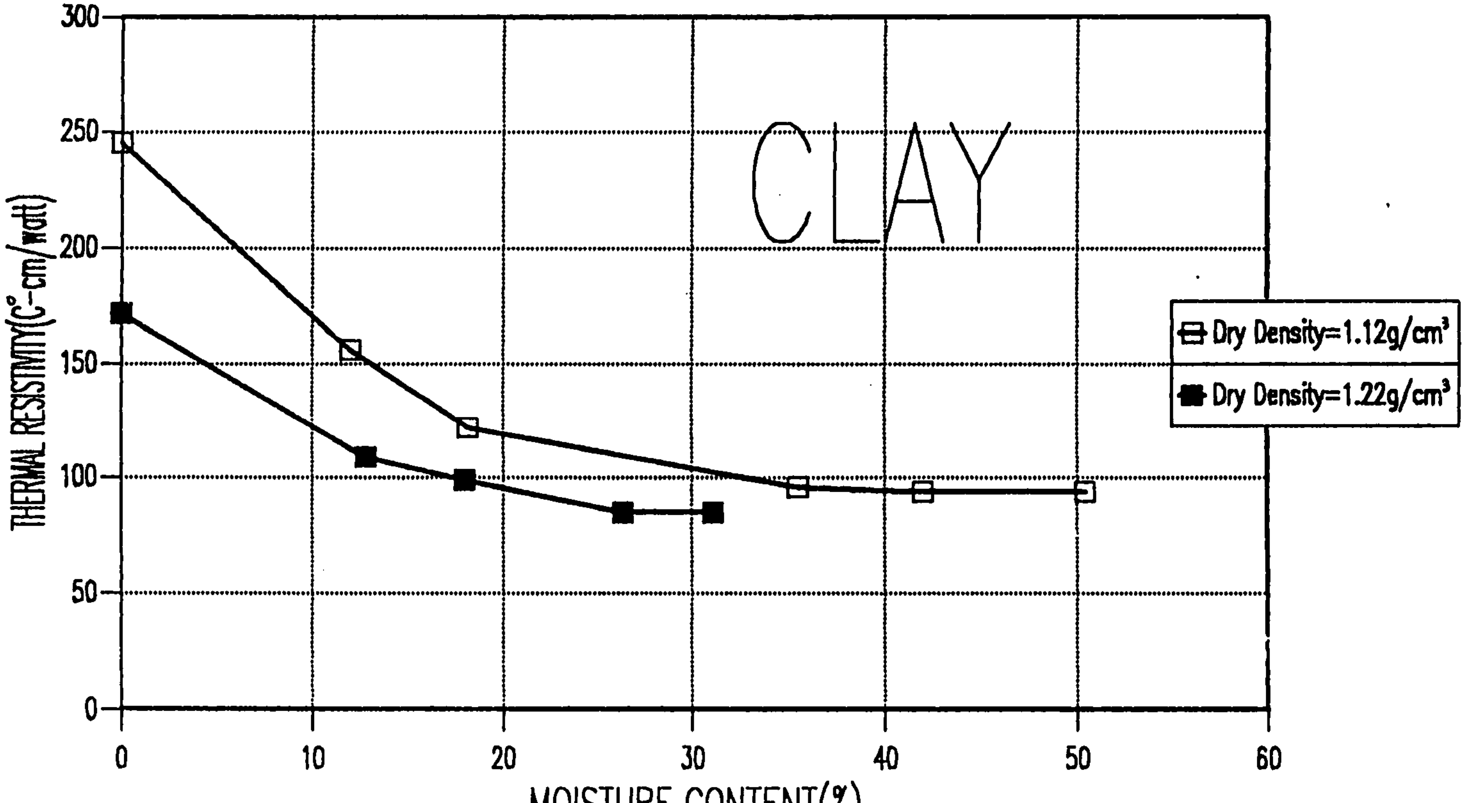

Fig.4.17 Thermal Resistivity vs Moisture Content for Sample#9

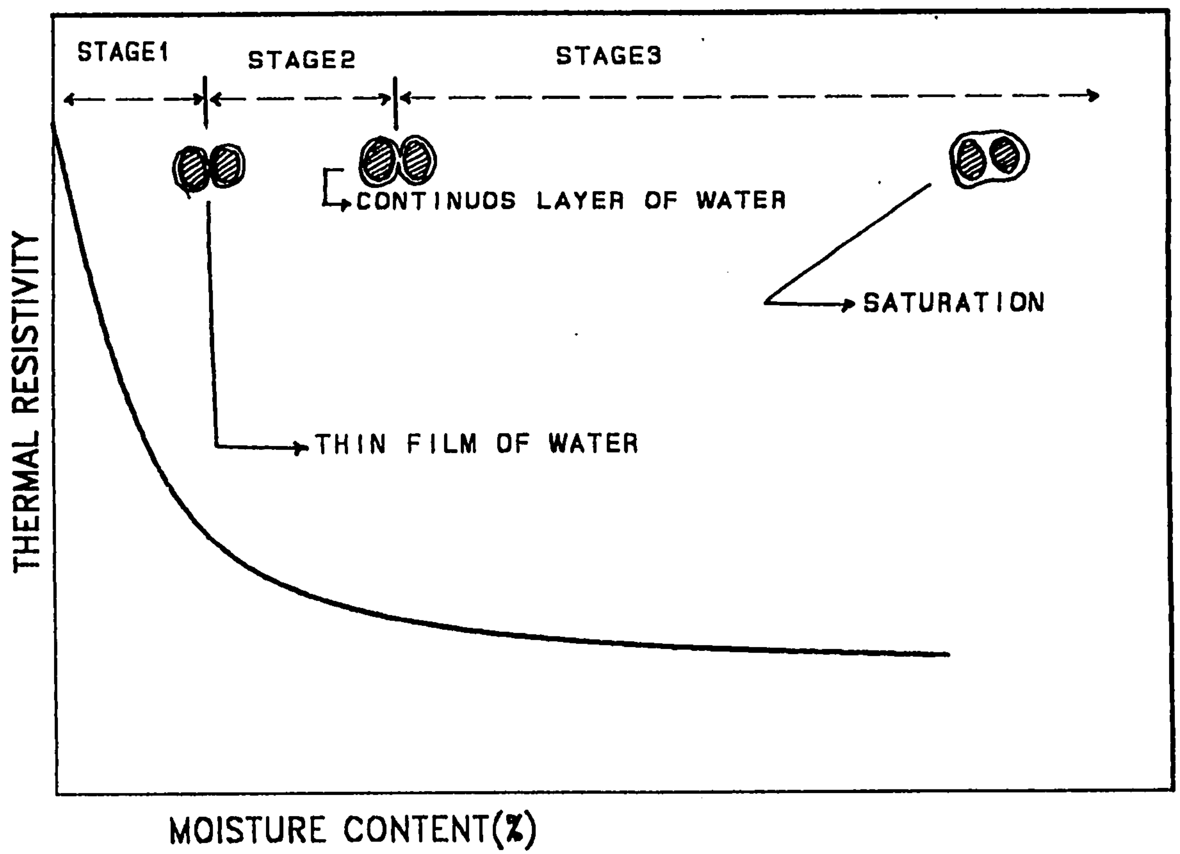

FIG.4.18 TYPICAL THERMAL RESISTIVTY_MOISTURE CONTENT CURVE SHOWING THE IMPORTANCE of MOISTURE on HEAT PATH

between any two adjacent particles is extremely small and hence a high thermal resistivity is expected for dry soils.

Addition of small amount of water to the dry soil (say 1 to 2% in the case of sand) results in the formation of a thin film of water on the surface of the particles and the formation of meniscus water at the points of contact between particles. These water molecules are oriented and attracted to the surfaces where they are held very tightly. The formation of meniscus water produces a dramatic decrease in the thermal resistivity of the soil because of the increase of heat flow through the soil water interfaces. As an example of this dramatic change associated with stage I, the thermal resistivity of the dune sand of dry density 1.77 g/cm^3 at zero moisture content is 256°C-cm/watt. By adding 2 percent moisture, which is approximately the critical moisture content for this sample, the thermal resistivity is reduced to about 60°C-cm/watt which is less than one fourth of that at zero moisture content. This large reduction in thermal resistivity is evident for all other samples. Figures 4.9 to 4.17 indicate that the reduction in thermal resistivity associated with stage I is higher for granular sands (samples 1,2,3 and 4) than for the other samples which reflects the sensitivity of these samples to small changes in moisture content.

Stage II is the transition between stages I and III and exists near the critical moisture content. During this stage, the thermal resistivity decreases rather slowly compared to stage I. In this stage, a continuous water layer is provided and all the soil grains are coupled with water. Two points can be observed about the critical moisture content. The first is that the amount of water required to achieve the mechanism described above is a function of the grain size as shown in Table 4.3. The critical moisture content for the dune sand sample which contains no fines is only 2% whereas it needs 25% of water by weight to achieve the critical moisture content for the highly plastic clay which contains 85% of fines. The other samples fall within these two extremes; and generally the critical moisture content increases as percentage of fines increases (Radhakrishna, et al, 1980). This can be explained by noticing that the specific area (ratio of total particle surface area to total mass) increases as particle size decreases and hence more and more water is needed to form a thin film of water around soil particles as particle size gets smaller (Mitchell, 1976).

The second point to be observed is that for every soil tested, it is clear that increasing the dry density decreases the critical moisture content slightly. A closer packing of the soil reduces the pore voids and brings the grains nearer to each other with consequent decrease of the critical moisture content, as the development of a continuous water film would then require less moisture. By considering the soil moisture characteristics, it seems that other factors could also affect the critical moisture content such as the shape of the particles whether they are rounded, irregular or plate like as in the case of clays.

The results of the two fine grained soils (samples #8 and #9) indicate that the range of critical moisture content falls just below the plastic limit for the two soils as shown in Table 4.4. Considering that the

Table 4.3. Relation Between Percentage of Fines (Passing NO. 200 Sieve) and Critical Moisture Content

Sample	% of Fines (Passing #200 Sieve)	Critical Moisture Range (%)
1. Dune Sand	0	2-3
2. Beach Sand	1	2-3
3. SCECO Backfill	3	2.5-3
4. Jubail Sand	4	3-4
5. Riyadh Sand	7	3-4
6. Sabkha	13	4-6
7. Marl	35	4.5-6
8. Sandy Clay	38	8-11
9. Highly Plastic Clay	85	25-35

Table 4.4. Correlation of Critical Moisture Content and Plastic Limit for Samples No.8 and No.9

Sample	Critical Moisture Content (%)	Plastic Limit (%)
Sandy Clay	8-11	12
Highly Plastic Clay	25-35	35

upper range of critical moisture content shown in Column 2 of Table 4.4 is associated with the lower dry density samples; this agrees with what was stated by Salomone and Kovacs (1983) that the critical moisture content can be defined by the plastic limit for soils that have low dry densities.

Stage III is the wet stage where thermal resistivity shows no or little decrease in thermal resistivity and exists up to near saturation. The addition of water in this stage serves to fill the pore voids filled originally by air and the contribution of heat transfer through water tends to decrease thermal resistivity by a small factor since thermal resistivity of water although better than the replaced air, still high compared to solid particles.

Out of those three stages, stages I and III are the most important. The maximum thermal resistivity occurs at stage I. For design of cables where soil is expected to be nearly dry, usually dry thermal resistivity is considered. In stage II, although the thermal resistivity is very much lower than the dry thermal resistivity , however, the soil in this stage is susceptible to moisture migration. As mentioned in Chapter 1, the soil can be considered thermally stable if moisture content is above critical moisture content (stage III) for any realistic power input. If the soil moisture content is expected to be in the critical moisture content range for relatively long periods of time, then the thermal resistivity corresponding to critical moisture content cannot be taken as the design value without the consideration of the heat input. It is well known that moisture migration away from a cable dissipating heat associated with the critical moisture content can result in an increase in thermal resistivity of the soil and hence thermal stability measurements should be carried out for such soils. The initial drying time can be measured with a thermal probe in-situ or on a recompacted soil sample in the laboratory for different heat inputs. If the measured drying time is long compared to the time that the cable is expected to be energized at that level in the field, then the soil is thermally stable and consequently the value of thermal resistivity corresponding to the critical moisture content can be used for design. If the time is relatively short, then the soil can be expected to be thermally unstable and dry thermal resistivity should be used in design (Hartley, et al, 1981).

Soil moisture in most regions of Saudi Arabia varies on a seasonal basis. Generally, precipitation inputs exceed soil water use during the cooler months, while moisture deficiency and soil drying is experienced during the hotter months. Because of the relationships between moisture content and soil thermal resistivity (Figs. 4.9 to 4.17), variation of thermal resistivity with season and climatic factors is expected. The approach to this problem is to perform a statistical analysis on the basis of historical weather records. By applying these data, the variability of extreme values of soil moisture content can be established and used as a basis for predicting maximum likely thermal resistivity values for underground cable design.

4.2.3 Influence of Density

From Figures 4.9 through 4.17, it is clear that increasing density results in lower thermal resistivity for the same moisture content. A sample with higher density has more solid matter per unit soil volume, less pore air per unit volume and hence better heat transfer across the contacts. It can also be noted by examining these figures that the effect of density is generally more pronounced as water content decreases. This can be explained by noticing that thermal resistance between the grains is higher in the dry side since the pores are filled completely with air consequently a slight reduction in the density causes higher effect on thermal resistivity compared to wet soil. Marl soil (Figure 4.15) is a good example, where by increasing density by 5%, the thermal resistivity tends to be approximately equal for the two densities for moisture content above 18%, while the density-dependent change in thermal resistivity is about 25% at 0% water content.

4.2.4 Influence of Soil Type and Mineral Composition

Type of soil and mineral composition cannot be separated from each other since mineral composition is the main factor by which a given soil can be identified. The data shown in Table 1.1 indicate that quartz is the best mineral in terms of its ability to transmit heat. Table 4.5 summarizes the results of the nine samples. Column 4 of this table shows the thermal resistivity of each sample at the wet state while column 5 shows the thermal resistivity of the samples when they are dry (0% moisture content). The term wet used here is relative because every sample has its own capacity to hold water molecules on particle surfaces and through the pores. The capacity to hold water molecules is a function of many parameters such as grain size distribution, void ratio of the sample, density

Table 4.5. Summary of Thermal Resistivity Results for Tested Samples

Sample	Average Dry Density (g/cm^3)	Average Wet Thermal Resistivity (°C-cm/watt)	Average Dry Thermal Resistivity (°C/cm-watt)
Dune Sand	1.70	47	274
Beach Sand	1.72	41	257
SCECO Backfill	1.64	50	289
Jubail Sand	1.73	52	299
Riyadh Sand	1.82	33	126
Sabkha	1.74	56	155
Marl	1.47	56	210
Sandy Clay	1.73	53	146
Clay	1.17	90	209

and other factors. Generally speaking, the wet thermal resistivity refers here to the thermal resistivity at moisture contents high enough that addition of more water results in no or very little decrease in thermal resistivity .

The data shown in Table 4.6 indicate that the first five samples which are rich in quartz resulted in wet thermal resistivities of about 50°C-cm/watt or less. These low values reflect the significance of quartz in reducing wet thermal resistivity . Quartz which as a solid mineral has a thermal resistivity of 11°C-cm/watt (Table 2.1) is the best common natural solid mineral to give low value of thermal resistivity . Sample #5 (Riyadh Sand) gives lower wet thermal resistivity in comparison to samples 1, 2, 3 and 4. The mineral composition for this sample indicates that it has lower quartz content than the previous four samples. However, it appears that its lower wet thermal resistivity is related to the higher density achieved by this sample.

Samples 6, 7 and 8 resulted generally in higher wet thermal resistivity compared to the first five sandy soils. This might be attributed to the presence of NaCl in sample #6, Dolomite in sample #7 and Calcite in sample #8. All of these minerals have higher thermal resistivity than quartz (Table 2.1).

The wet thermal resistivity of sample #9 (highly plastic clay) is almost double that of other samples which reflect the poor quality of a clay mineral to transmit heat. It is to be noted that this sample is expansive. Cracks were introduced in the sample and widened further, as sample got

Table 4.6. Effect of Soil Type and Mineral Composites on Wet Thermal Resistivity

Sample	Soil Type	Main Mineral Components	Wet Thermal Resistivity (°C-cm/watt)
Dune Sand	Sandy	Quartz	47
Beach Sand	Sandy	Quartz	41
SCECO Backfill	Sandy	Quartz	50
Jubail Sand	Sandy	Quartz	52
Riyadh Sand	Sandy	Quartz	33
Sabkha	Salty Sand	Quartz + NaCl	56
Marl	Silty	Dolomite	56
Sandy Clay	Sandy Clay	Calcite	53
Clay	Clay	Quartz + Clay Mineral	90

dry due to contraction of the sample. The results of this sample are questionable in the dry side considering that the line source theory assumes that conduction is the only mechanism in which heat can flow through the soil. The existence of a continuous gap of air would result in heat flowing by convection and hence lower values of thermal resistivity could be obtained in the dry region. Brandon and Mitchell (1989) stated that for convective heat transfer to take place, the pores of the soil must be several millimeters across. If the size of the cracks were smaller than that required for convective heat transfer, then these cracks would result in higher thermal resistivity at the dry region because of the fact that air has very high thermal resistivity . Since it was not possible to determine the size of cracks inside the sample and especially near the needle, no conclusion can be made about the results of this sample at the dry region.

As can be noted from the previous discussion that the relation between type of soil and wet thermal resistivity is that sandy soils generally exhibit lower wet thermal resistivity compared to silty and clayey soils. The presence of quartz tends to lower wet thermal resistivity whereas presence of clay minerals causes a reverse effect. It is also to be noted that consideration is taken only for wet thermal resistivity when considering the influence of mineral composition. Referring again to Table 4.5, it is clear that the same argument does not apply for dry thermal resistivity . As an example, the wet thermal resistivity of the plastic clay is more than double that of the beach sand whereas the dry thermal resistivity of the plastic clay is considerably less than that of the beach sand. This can also be seen from Table 4.5 for Riyadh sand, Sabkha, Marl and Sandy clay. Since this phenomenon has definitely nothing to do with mineral composition, it could be that during the process of drying the structure of these soils have gone through change of different magnitudes which might be responsible for this phenomenon.

4.2.5 Influence of Initial Moisture Content and Soil Structure

The significance of initial compacting moisture content on dry thermal resistivity is readily seen from the data shown in Figures 4.19 to 4.22. These samples were compacted at different moisture contents; however, the density effect was eliminated by compacting the samples at approximately the same density. For the dune sand sample (Figure 4.19), the effect of initial moisture content on dry thermal resistivity is very small. However, the results of the other three samples, namely Riyadh sand, marl and sandy clay (Figures 4.20 to 4.22) indicate that as the initial moisture content increases, the obtained dry thermal resistivity decreases, but this does not continue for ever. For example, the marl sample results indicate that the dry thermal resistivity decreases with increasing initial compacting moisture content, but compacting this sample at an initial moisture content above 12% gives no further decrease of dry thermal resistivity . In other words, there seems to be an optimum initial moisture content beyond which no further decrease in dry thermal resistivity can be achieved. This optimum moisture content seems to be the moisture content at which all grains are surrounded with a continuous layer of water in which all fine grains are in suspension. Any excess water to that required to make all fines in suspension will not contribute to the reduction

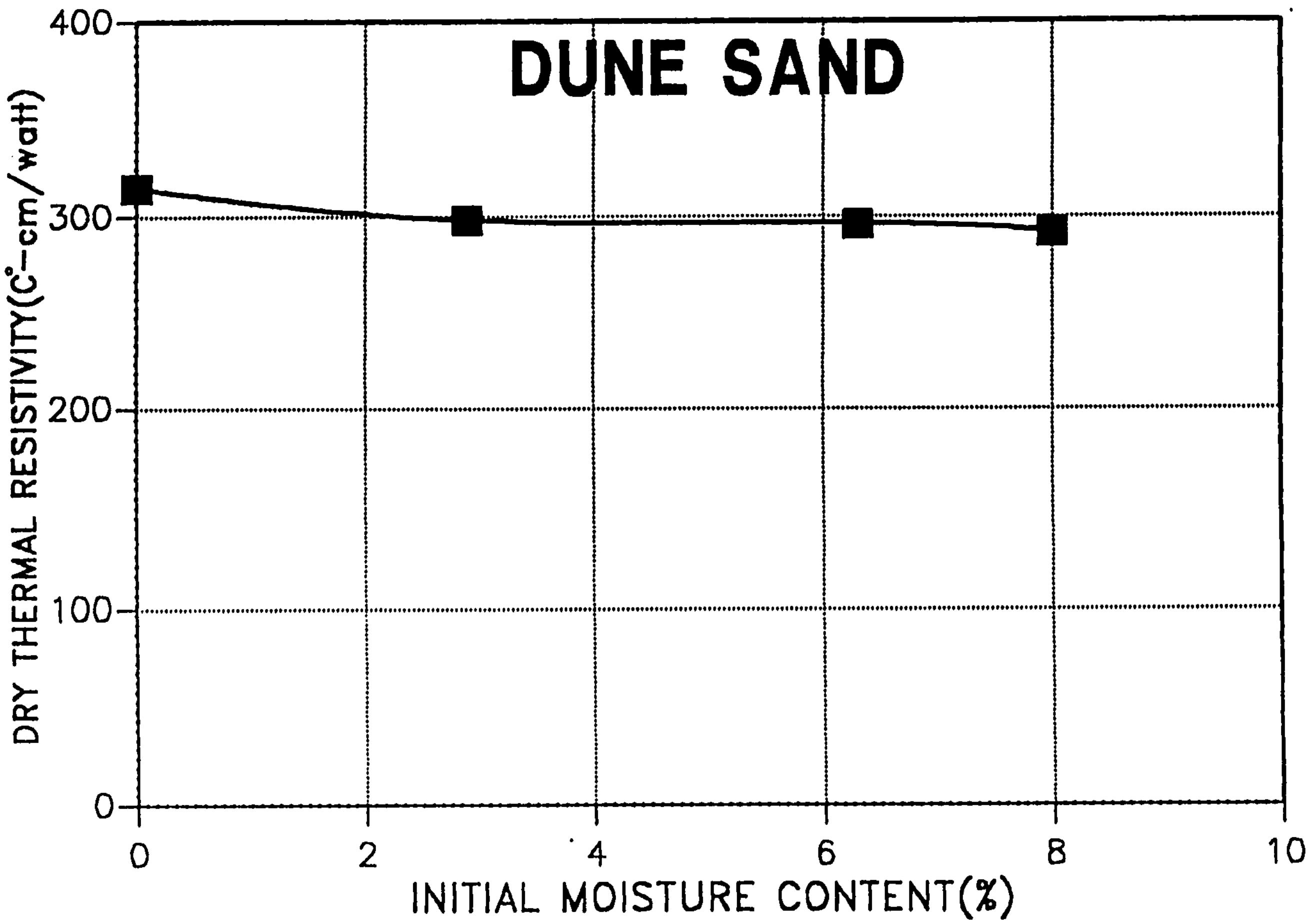

Fig.4.19. Effect of Initial Moisture Content on Dry Thermal Resistivity

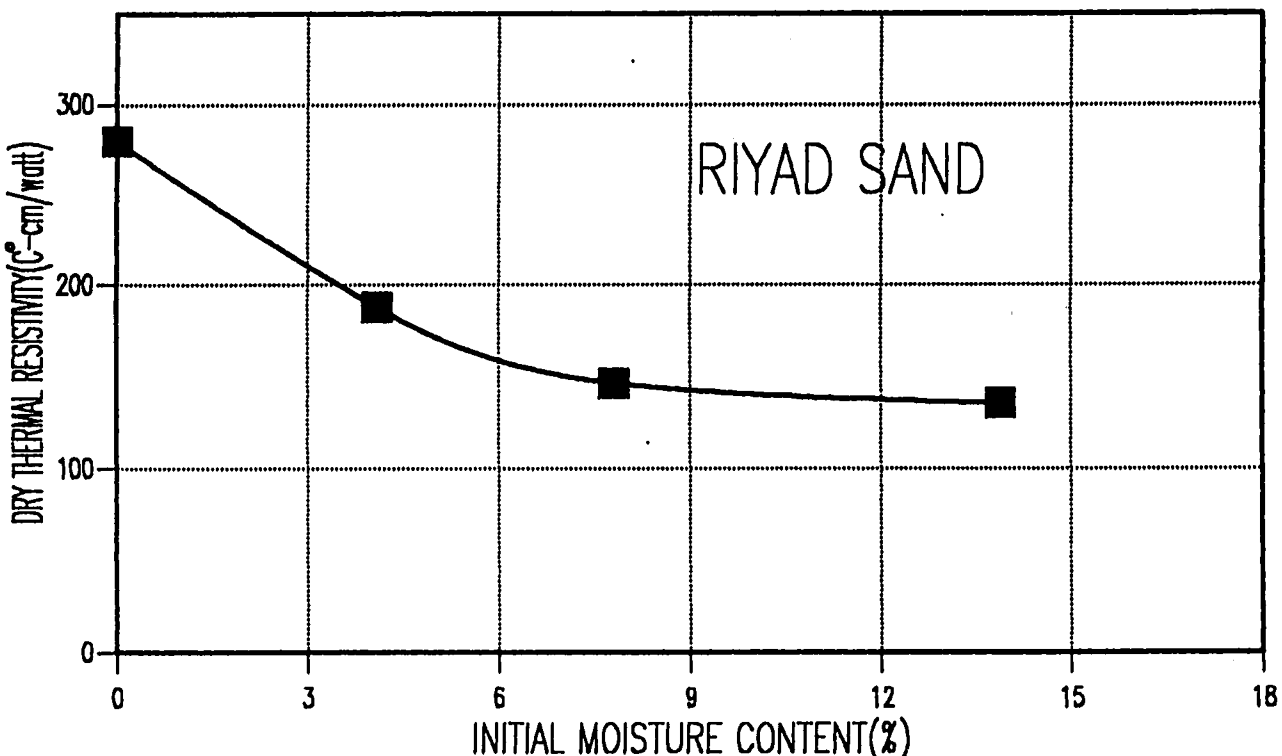

Fig.4.20 Effect of Initial Moisture Content on Dry Thermal Resistivity for Riyadh sand

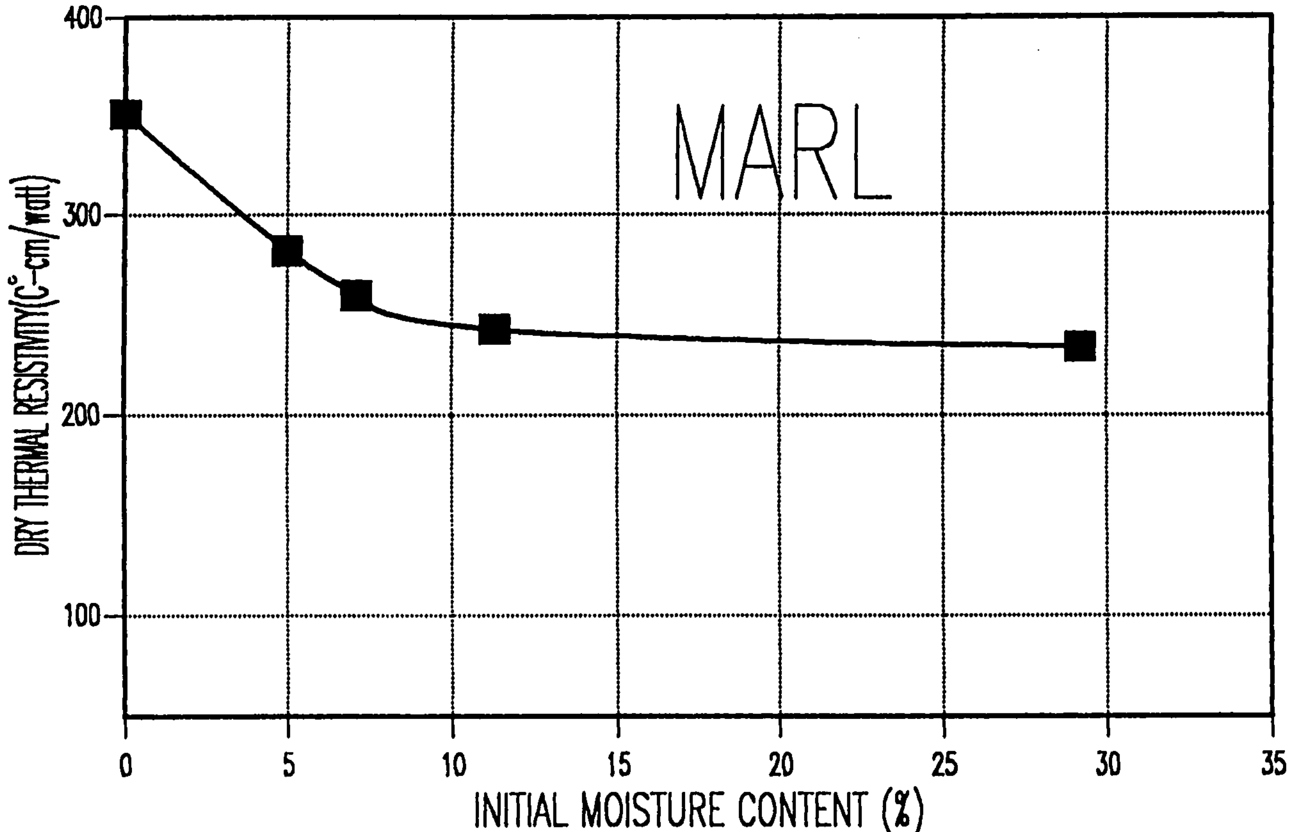

Fig.4.21 Effect of Initial Moisture Content on Dry Thermal Resistivity for Marl

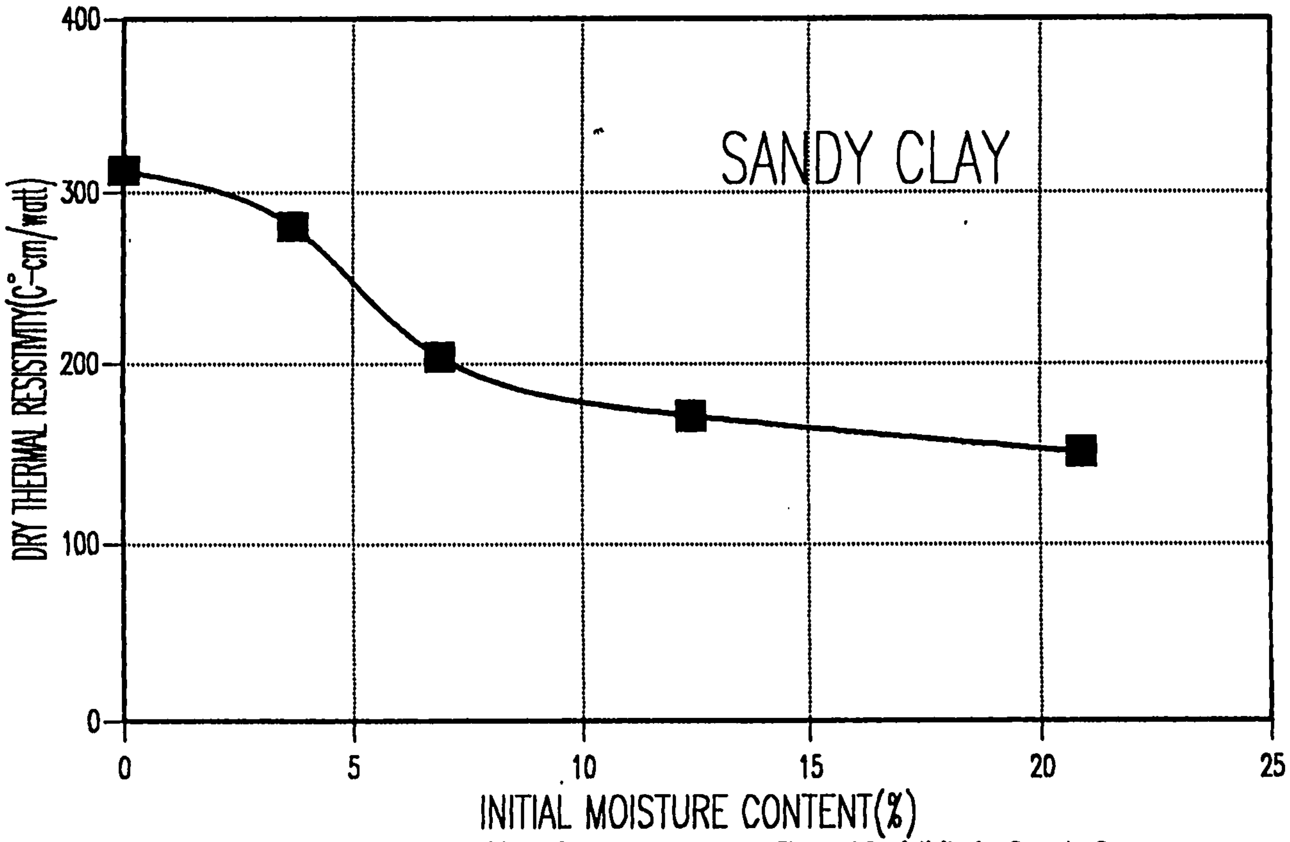

Fig.4.22 Effect of Initial Moisture Content on Dry Thermal Resistivity for Sample#8

of dry thermal resistivity . Referring to Table 4.7, the value of the initial optimum moisture content required to achieve the minimum thermal resistivity is shown to be above the critical moisture content and lower than the optimum moisture content required to achieve maximum dry density.

The influence of initial moisture content may explain the low dry thermal resistivities which were obtained for cementitious sands (Samples 5 and 6), marl, sandy clay and clay. For a further study of the initial moisture content effect, two series of tests were conducted. In the first series of tests, three specimens of each soil were compacted at zero percent moisture content (compacted dry) to different densities and then thermal resistivities were measured for every sample. These dry thermal resistivities obtained by compacting these samples dry were then compared to dry thermal resistivities obtained earlier by stage drying tests in which specimens were compacted wet. The results are shown in Figures 4.23 to 4.31 and are also summarized in Table 4.8. The difference appears to be greater for samples having lower contents of quartz. The first four samples which are rich in quartz show a slight different compared to other samples. Therefore, it is evident that the dry thermal resistivity depends on whether the soil sample was compacted wet or dry. Generally speaking, the dry thermal resistivity of a sample compacted wet and then dried is lower than that of the same sample compacted dry. This phenomenon is thought to be attributed to change of the soil structure.

In the second series of tests, three soils were selected for structure

Table 4.7: Correlation Between Optimum Initial Moisture Content, Critical Moisture Content and Optimum Moisture Content

Sample	Initial Optimum Mois-Content Required to Achieve Minimum Dry Thermal Resistivity (%)	Optimum Moisture Content Required to Achieve Maximum Dry Density (%)	Critical Moisture Content (%)
Marl	12	20	4.5-6
Sandy Clay	12	14	8-11
Riyadh Sand	8	10	3-4

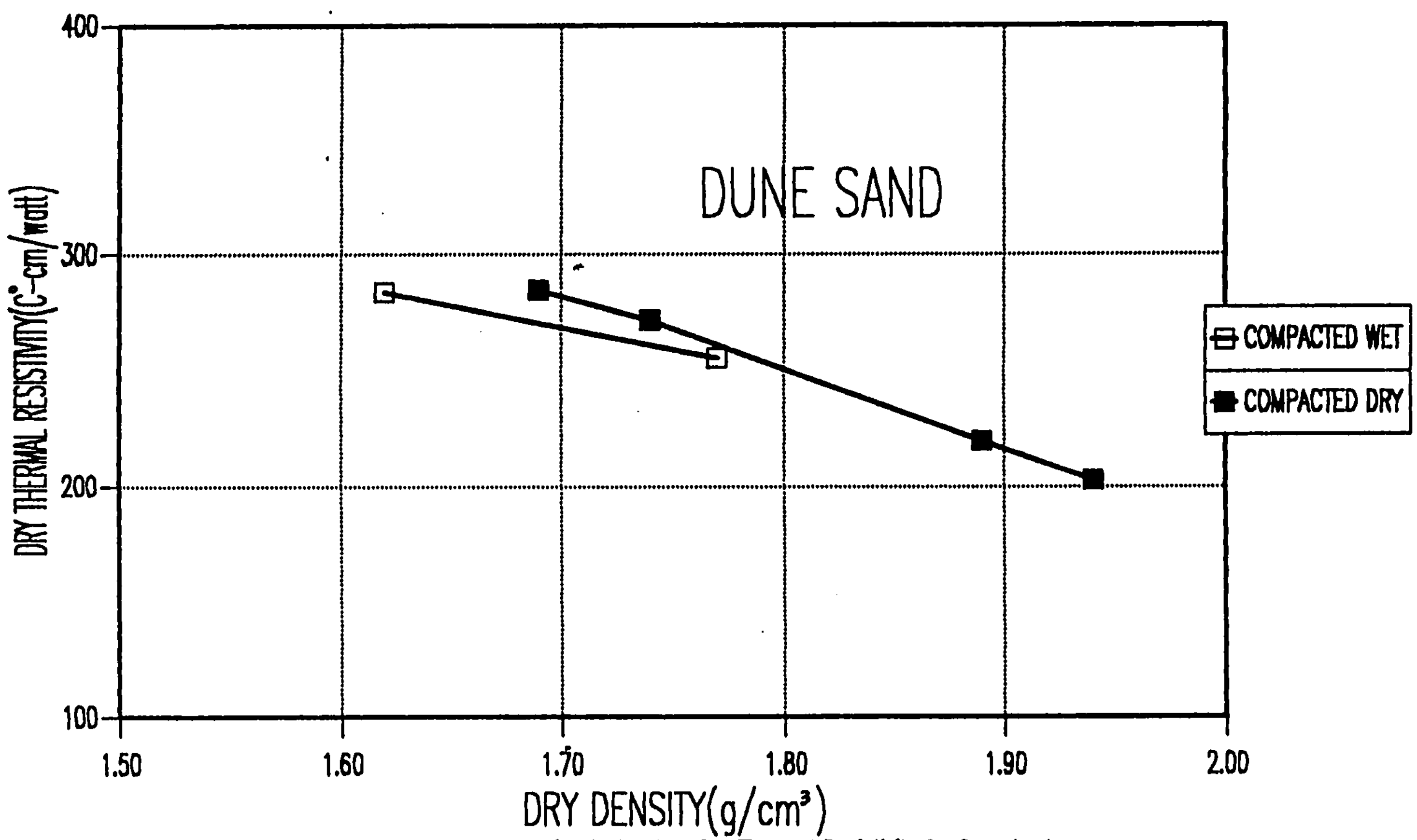

Fig.4.23 Effect of Compaction Method on Dry Thermal Resistivity for Sample#1

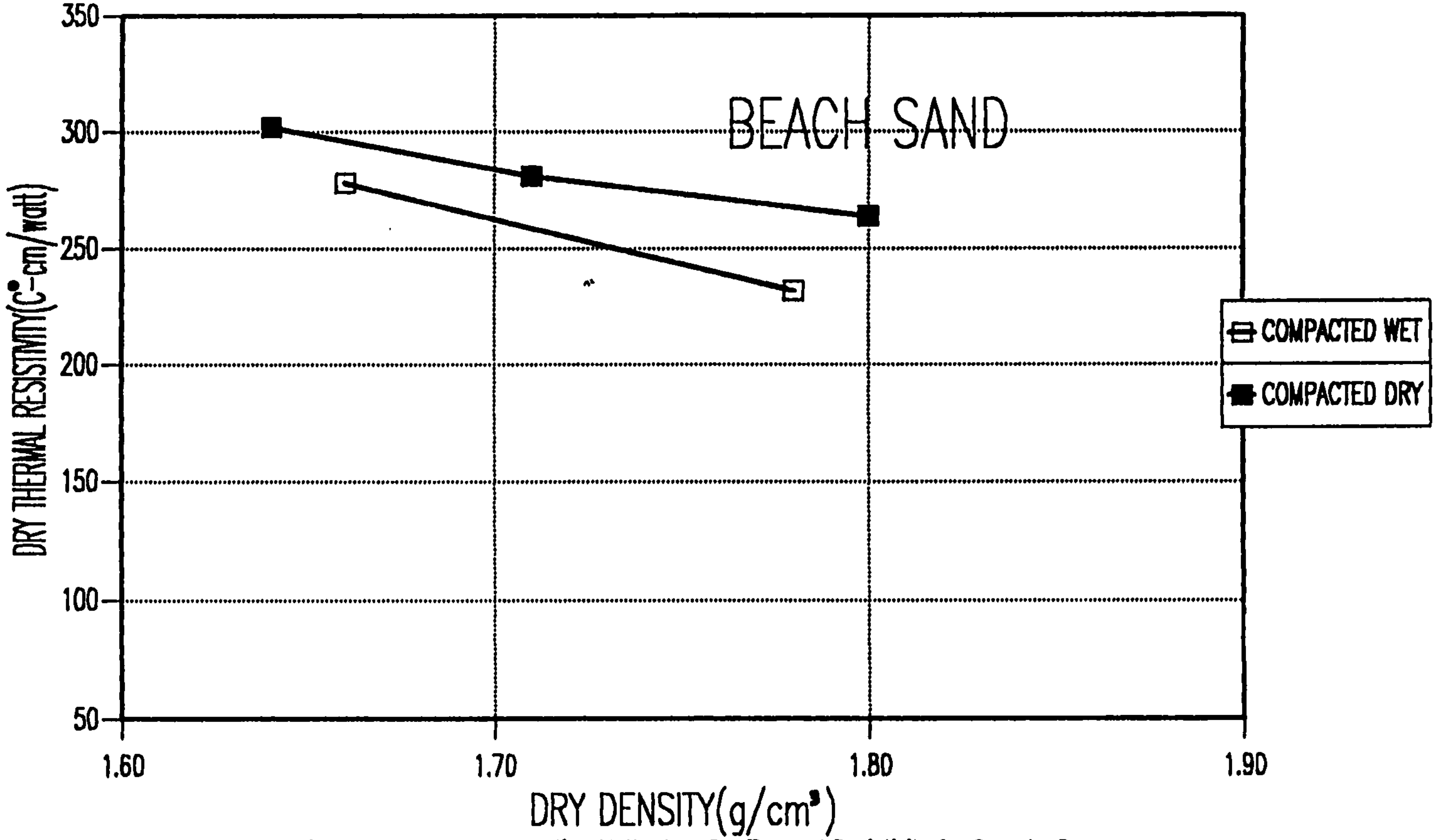

Fig.4.24 Effect of Compaction Method on Dry Thermal Resistivity for Sample#2

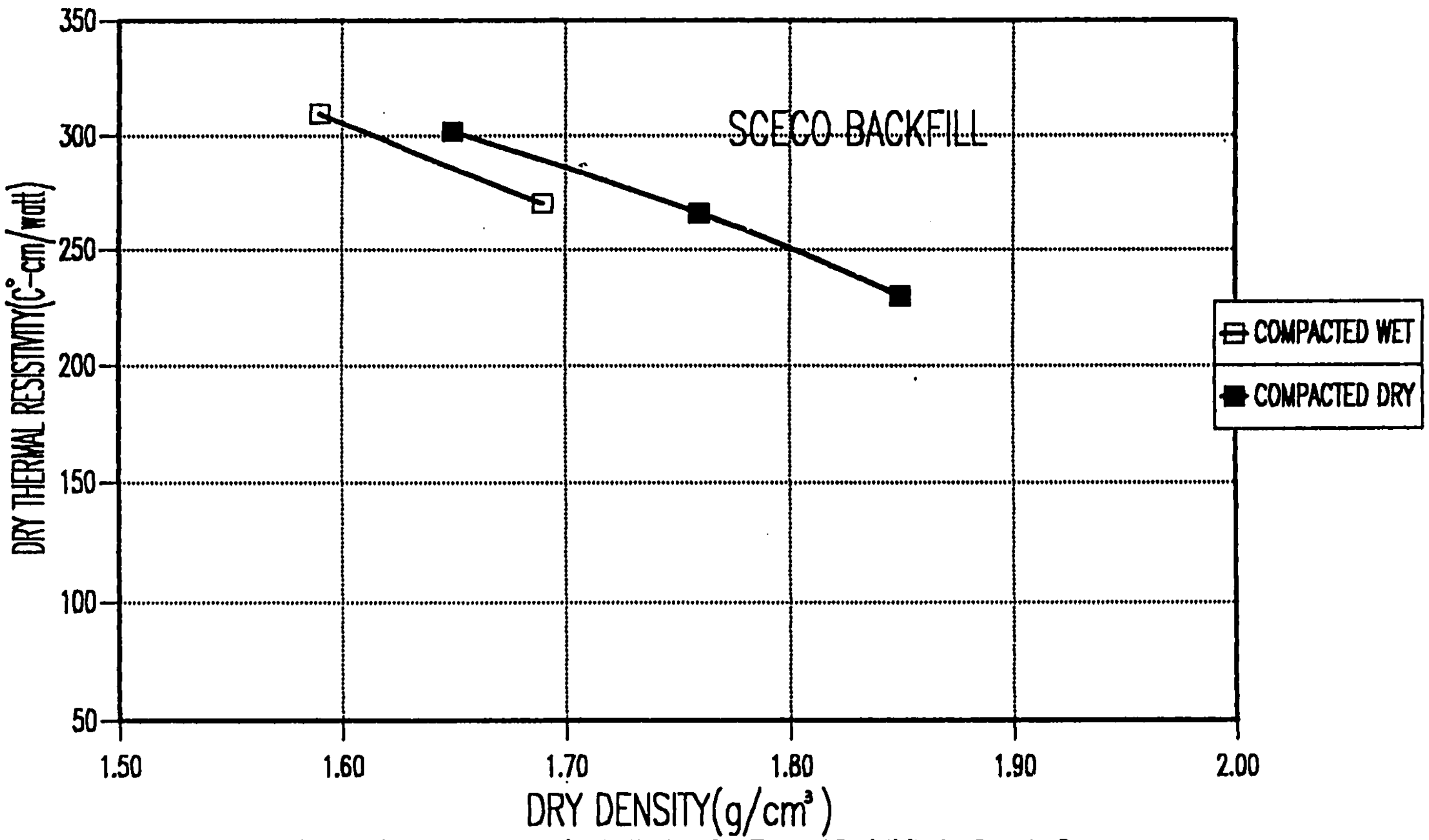

Fig. 4..25 Effect of Compaction Method on Dry Thermal Resistivity for Sample#3

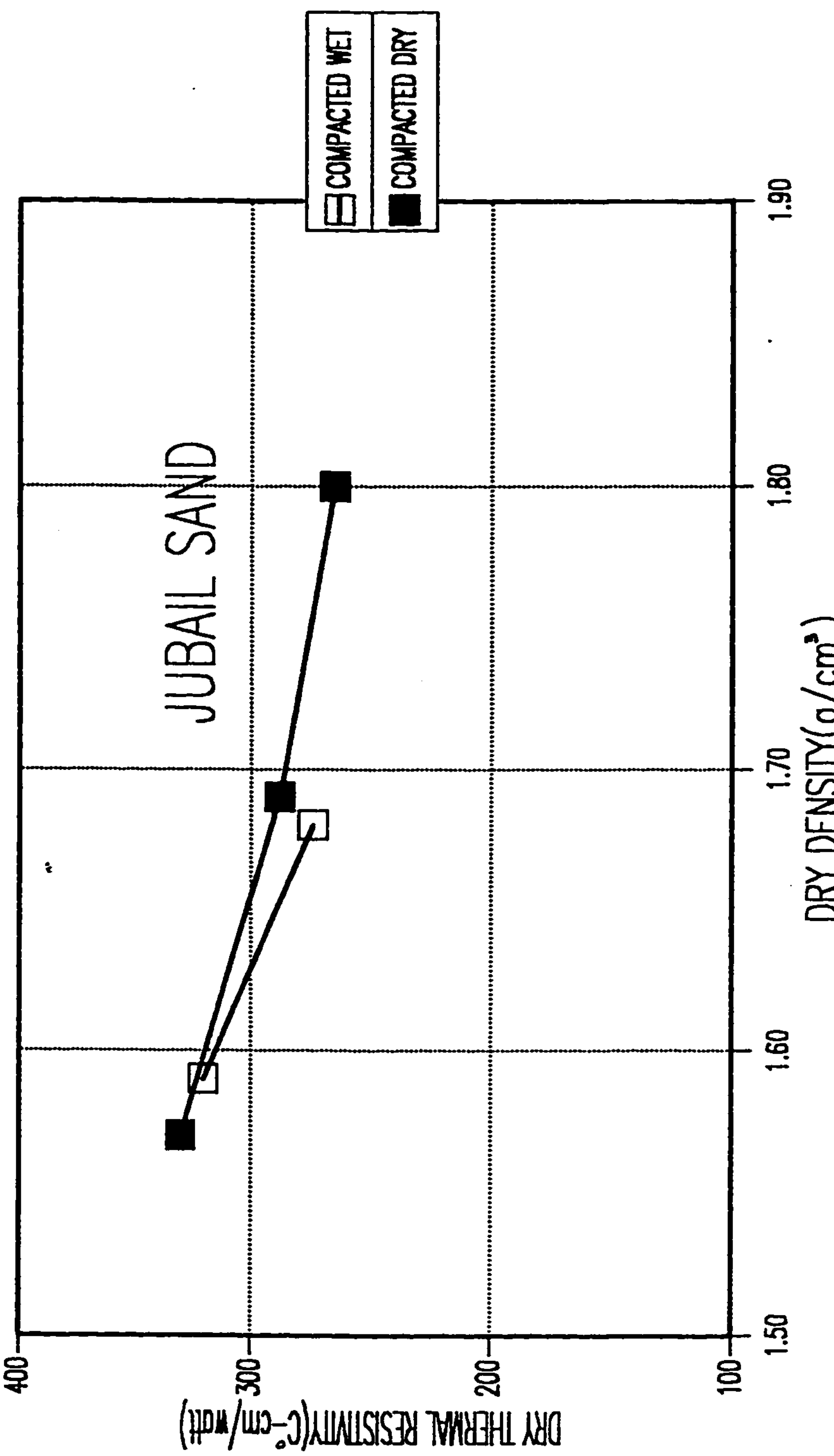

Fig.4.26 Effect of Compaction Method on Dry Thermal Resistivity for Sample#4

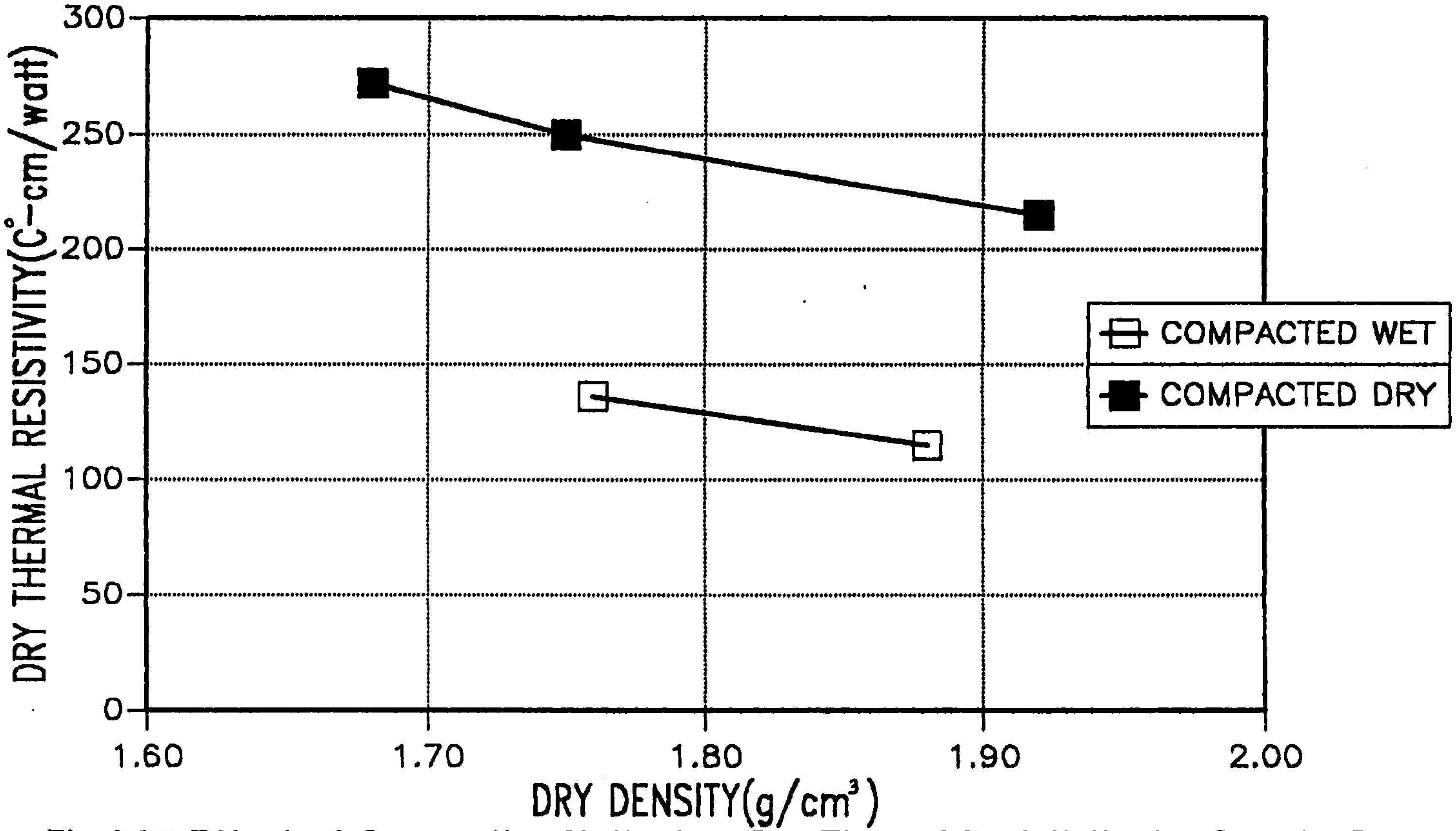

Fig.4.27 Effect of Compaction Method on Dry Thermal Resistivity for Sample#5

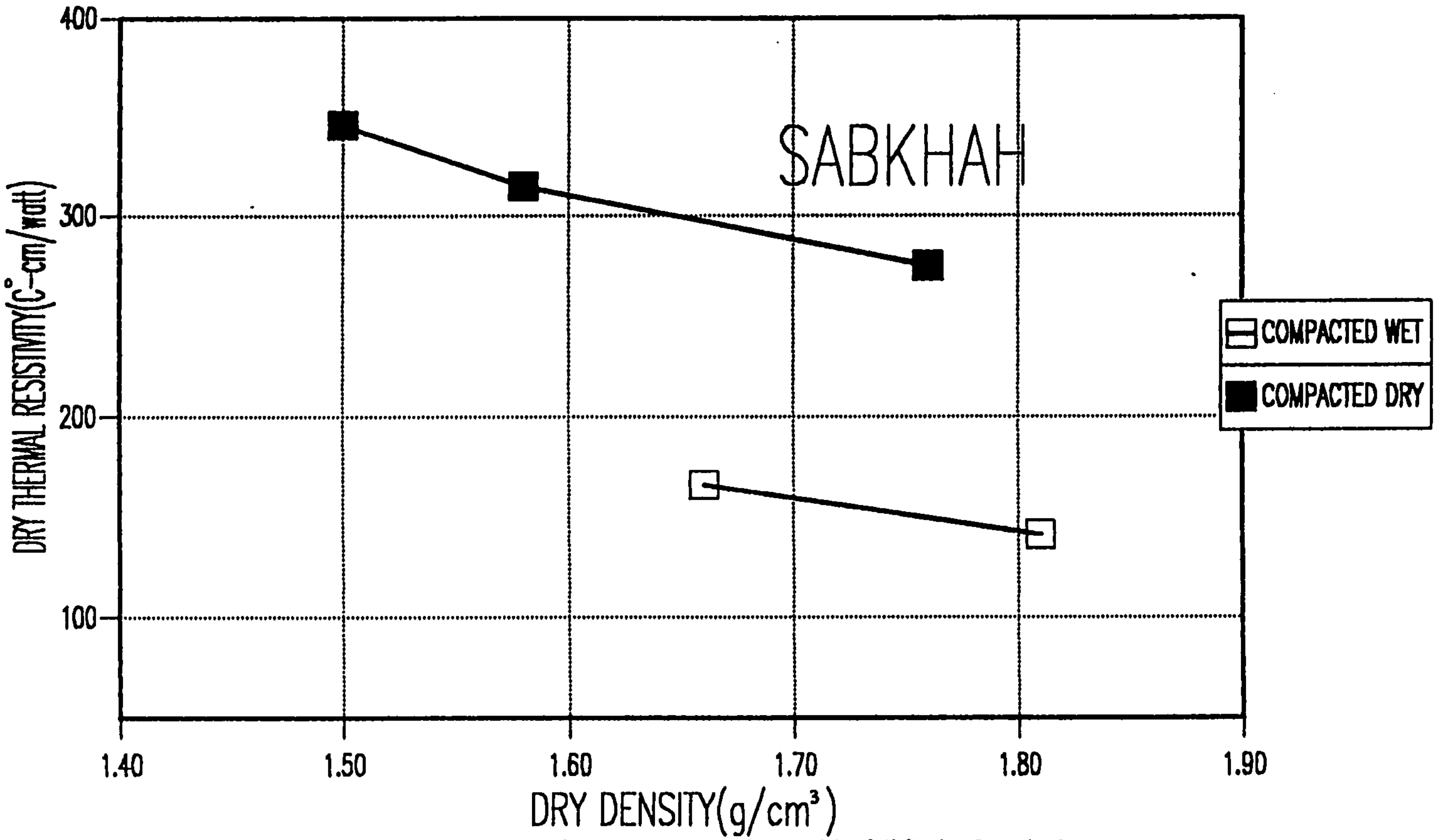

Fig.4.28 Effect of Compaction Method on Dry Thermal Resistivity for Sample#6

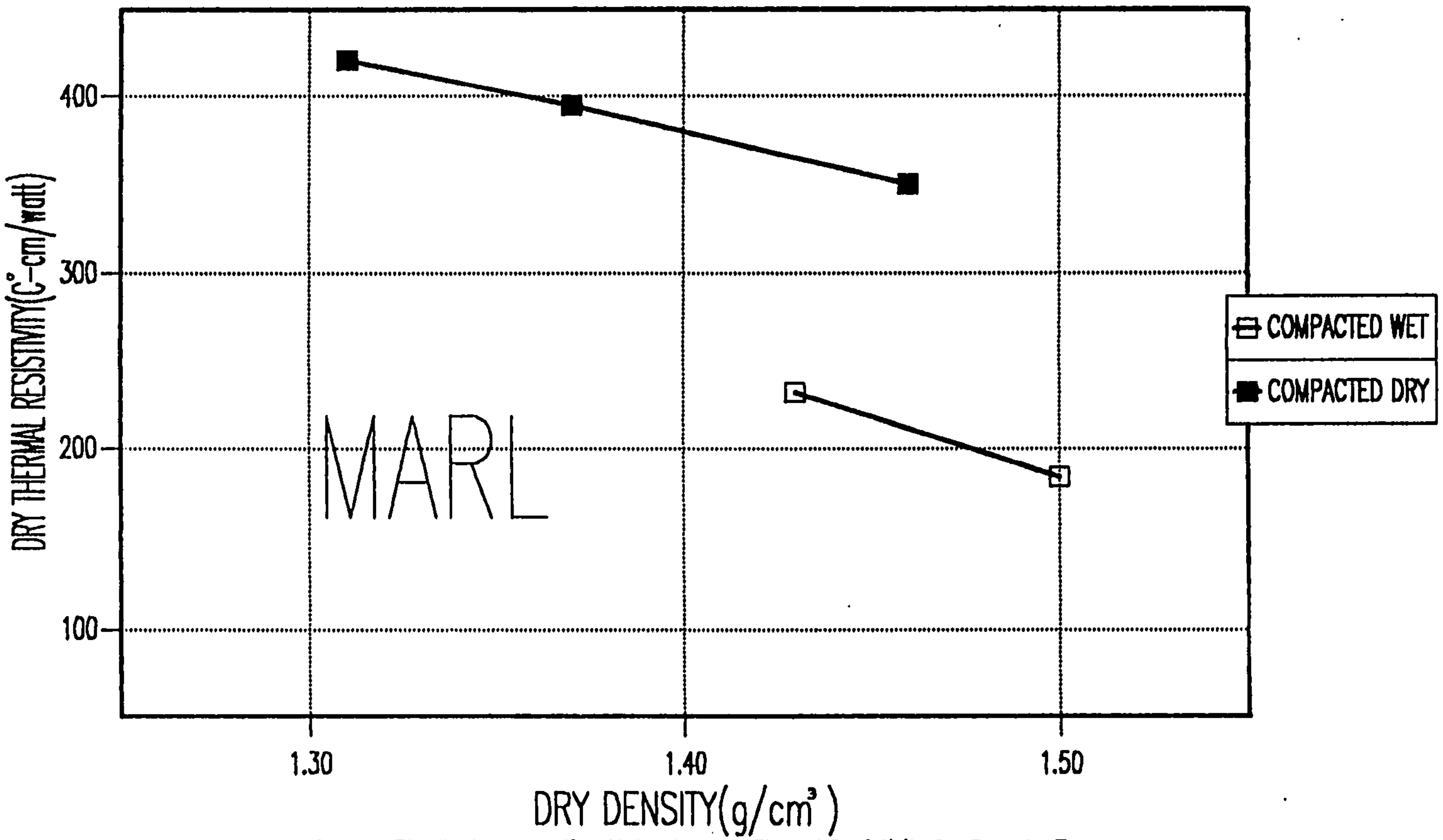

Fig.4.29 Effect of Compaction Method on Dry Thrmal Resistivity for Sample#7

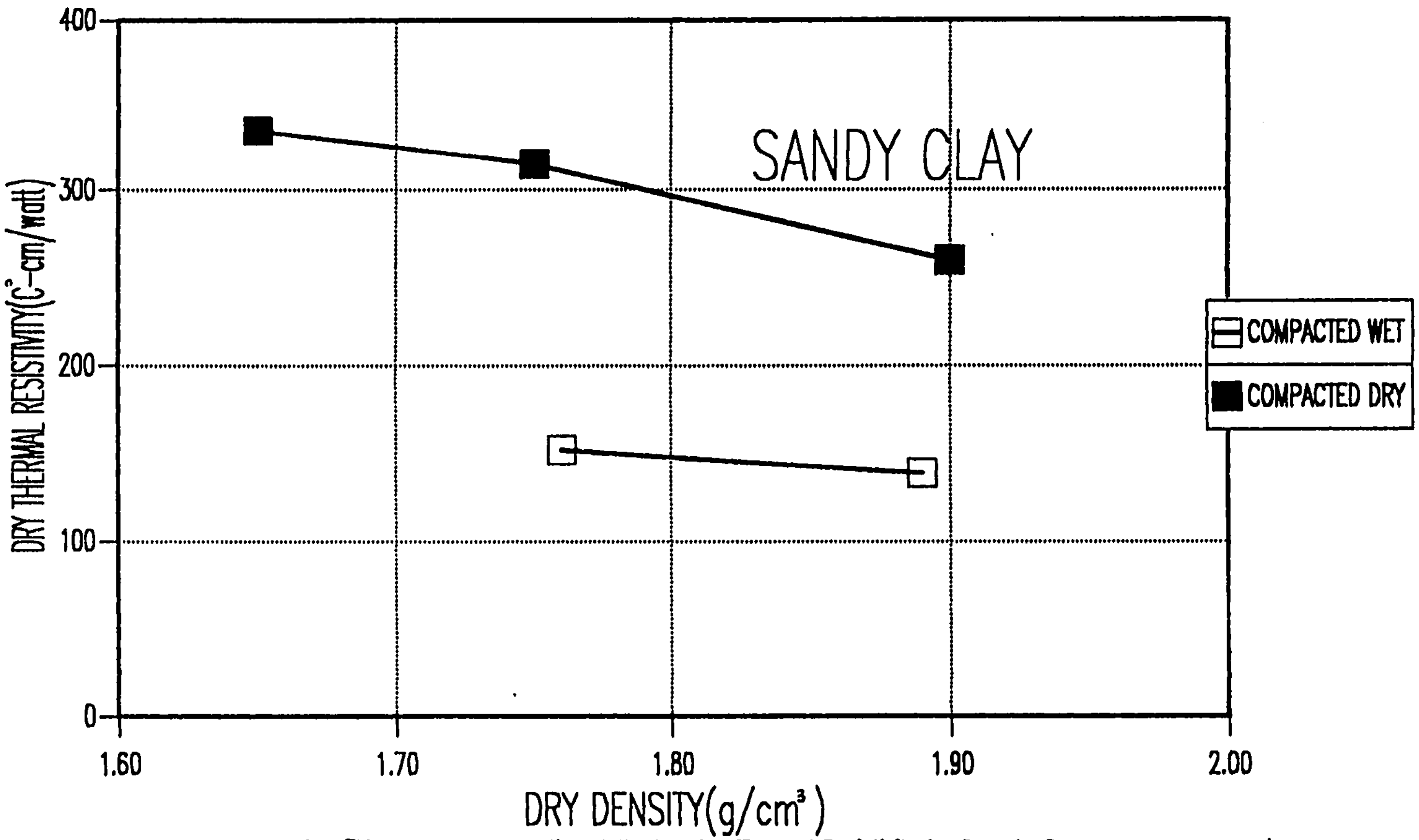

Fig.4.30 Effect of Compaction Method on Dry Thermal Resistivity for Sample#8

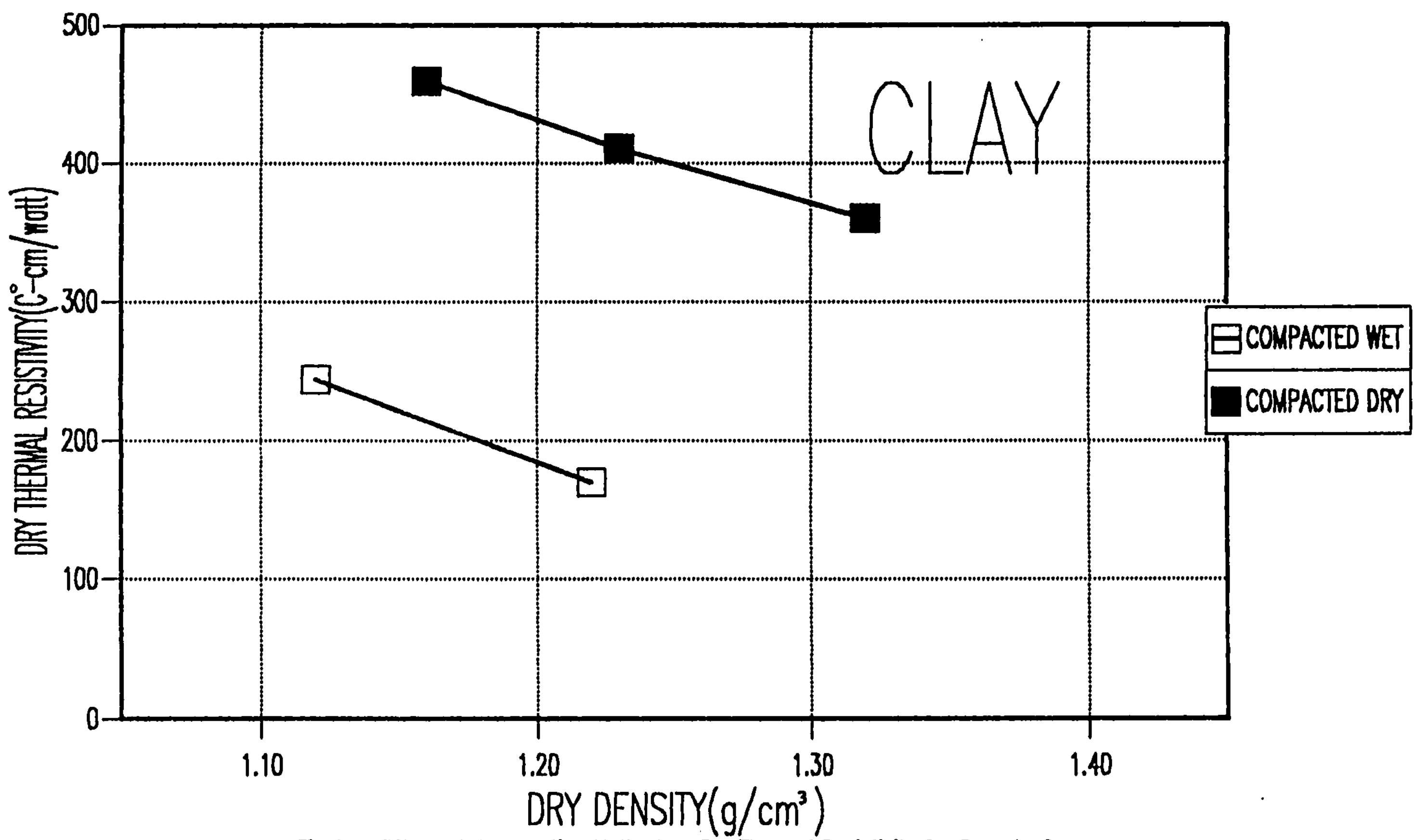

Fig.4.31 Effect of Compaction Method on Dry Thermal Resistivity for Sample#9

Table 4.8: **Dry Thermal Resistivity of the Tested Samples Obtained by Compacting the Samples Dry and Compacting Them Wet and Allowed to Dry**

Sample	Dry Density	Dry Thermal Resistivity (Compacted Dry)	Dry Thermal Resistivity (Compacted Wet)	ρ_d/ρ_w
1	2	3	4	5
Dune Sand	1.70	283	270	1.04
Beach Sand	1.70	285	263	1.08
SCECO Backfill	1.66	300	283	1.06
Jubail Sand	1.63	311	300	1.04
Riyadh Sand	1.80	241	131	1.84
Sabkha	1.70	289	161	1.80
Marl	1.45	356	218	1.63
Sandy Clay	1.80	327	148	2.21
Plastic Clay	1.20	433	185	2.34

investigation, namely Riyadh sand, marl and sandy clay. Two samples of each soil were prepared for scanning electron microscopic examination (SEM). The first sample was compacted at high moisture content (wet of optimum) and then dried to zero moisture content. The second sample was compacted at the same dry density but at a low moisture content (dry of optimum) and then dried to zero moisture content. The SEM analysis was then carried out for each sample. The microphotograph of each sample is shown in plates 4.1 to 4.6.

The difference in structure is clear for all samples. It can also be noted that the sandy clay sample exhibited the greatest change of structure out of the three tested samples which agrees with the high ratio shown in column 5 of Table 4.8 for the sample. The structures developed by compacting the samples at low moisture contents are uncemented structures in which smaller particles occupy pore spaces between larger particles. In the other case, the photomicrographs show cemented structures. When a given soil compacted at high moisture content, all grains are bounded with a continuous layer of water in which all fine grains are in suspension. During the process of drying, these fines floating in the water suspension are forced to the particle contacts due to surface tension of the water. Ultimately, they are attracted to the surfaces of larger grains at contact points acting as connectors between them as shown in microphotographs (Plates 4.1 to 4.6) of the samples which are compacted at the higher moisture contents. Consequently, these connectors reduce greatly interface resistance (solid-air resistance) at grain contacts which result in reduced thermal resistivity of the soil system. It is

Plate 4.1: Photomicrograph of Riyadh Sand Showing Uncemented Structure. This sample was Compacted at 4% Water Content and Allowed to Dry.

Plate 4.2: Photomicrograph of Riyadh Sand Showing Cemented Structure in which Fine Grains act as connectors between large grains. This sample was compacted at 15% water content and allowed to dry.

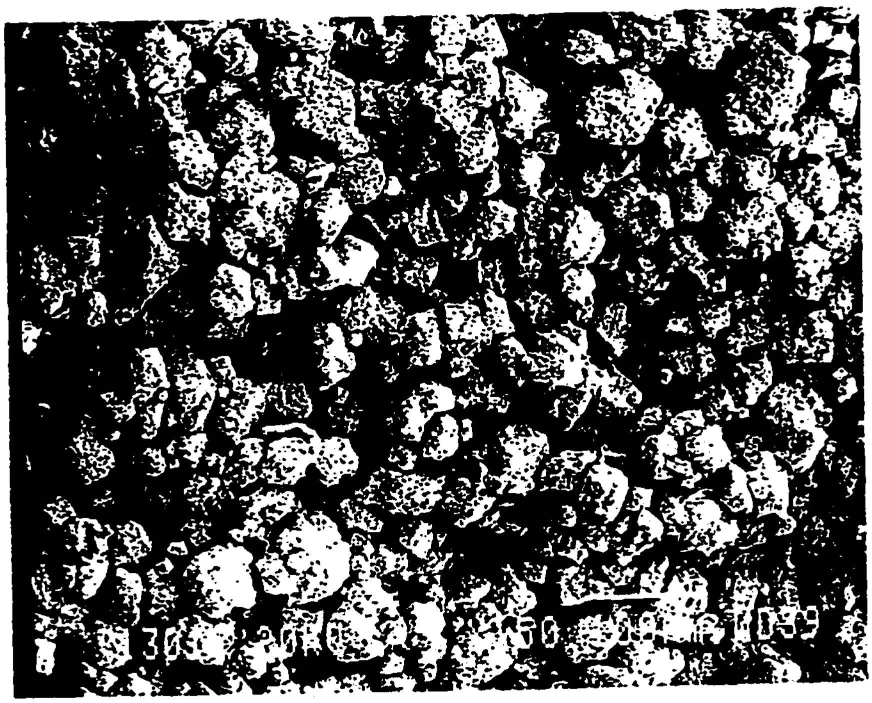

Plate 4.3: Photomicrograph of Marl Showing Uncemented Structure. This sample was compacted at 7% Water Content and Allowed to Dry.

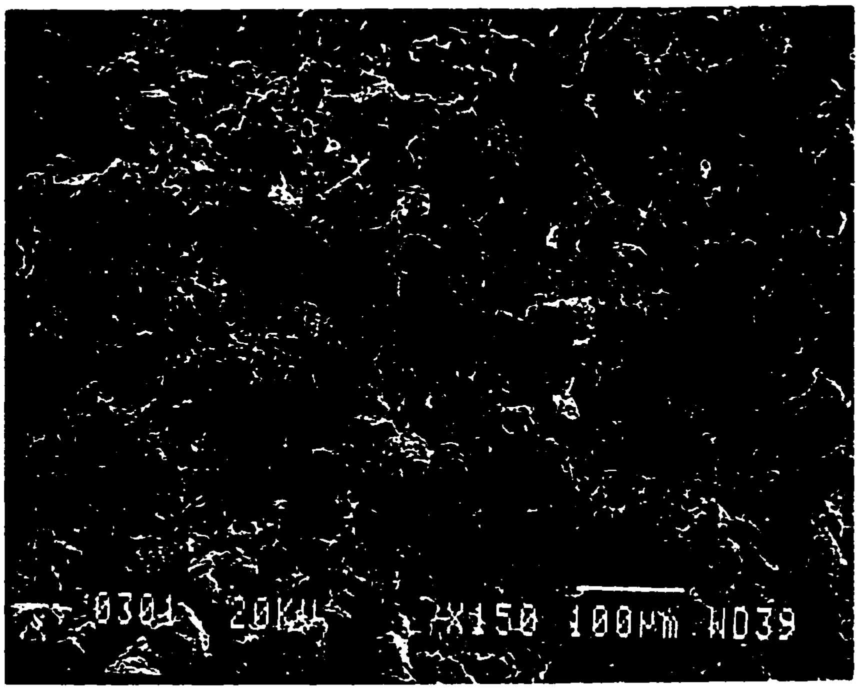

Plate 4.4: Photomicrograph of Marl Showing Cemented Structure in which Fine Grains act as Connectors between larger grains. This sample was compacted at 28% Water Content and Allowed to Dry.

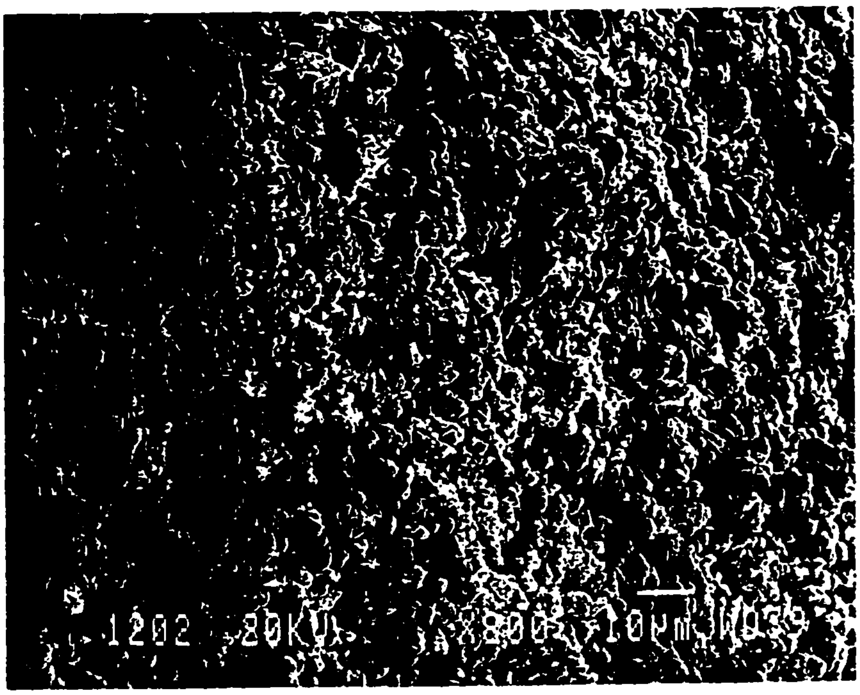

Plate 4.5: Photomicrograph of Sandy Clay Showing Relatively Cemented Structure. This sample was compacted at 7% Water Content and Allowed to Dry.

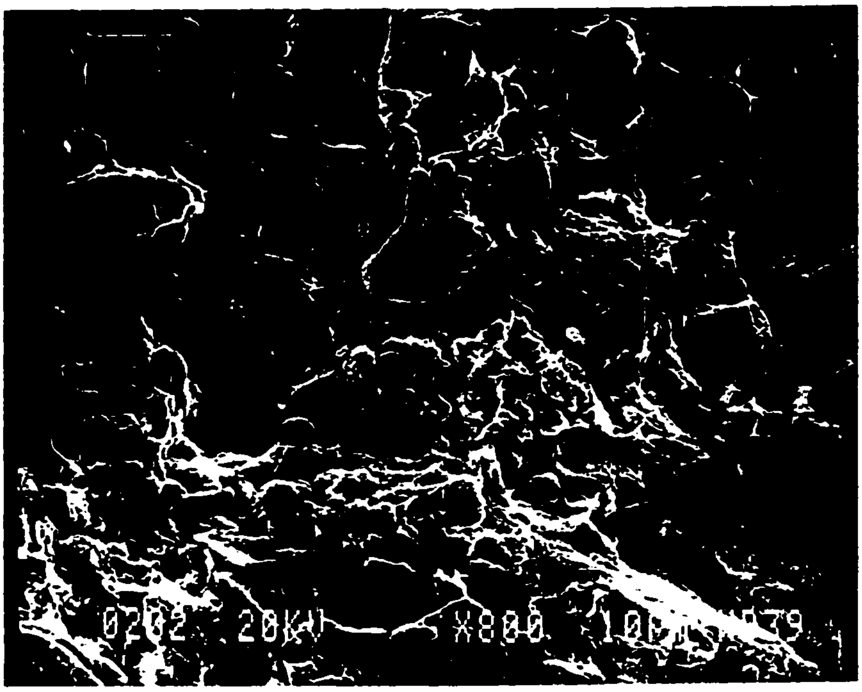

Plate 4.6: Photomicrograph of Sandy Clay Showing Clay Matrix Surrounding Aggregations of Larger Grains. This Sample was compacted at 20% Water Content and allowed to dry.

clear that this mechanism does not occur in soils which contain low amount of fines as in the case of dune sand, beach sand, SCECO backfill and Jubail sand. For these samples, dry thermal resistivities are approximately the same regardless of compaction process (Table 4.8).

The practical consequence of these findings is that moist compaction should be used in the field to provide the minimum dry thermal resistivity in case the backfill subsequently dries. The optimum moisture content derived from the compaction curve could be used as a conservative approximation of the optimum initial moisture content required to achieve minimum dry thermal resistivity (Table 4.7).

4.2.6 Influence of Method of Testing

It has been shown in the previous sections that the thermal resistivity of a soil at a certain moisture content is dependent on how it arrived at that moisture content. Comparison between two methods of testing, which are stage drying and the reverse method which may be called wetting process, are shown by data in Figures 4.32 to 4.34 for Riyadh sand, marl and sandy clay samples. The two methods give a reasonably similar values at the wet region, but as the moisture content decreases, the divergence of the curves in the two cases increases. Again, this can be explained by the soil structures difference resulted from the two methods. Considering that specifications for backfills used in cable trenches require that backfill should be compacted wet and that stage drying simulate drying process in the field, stage drying technique appears to be more efficient and accurate than the wetting process in determination

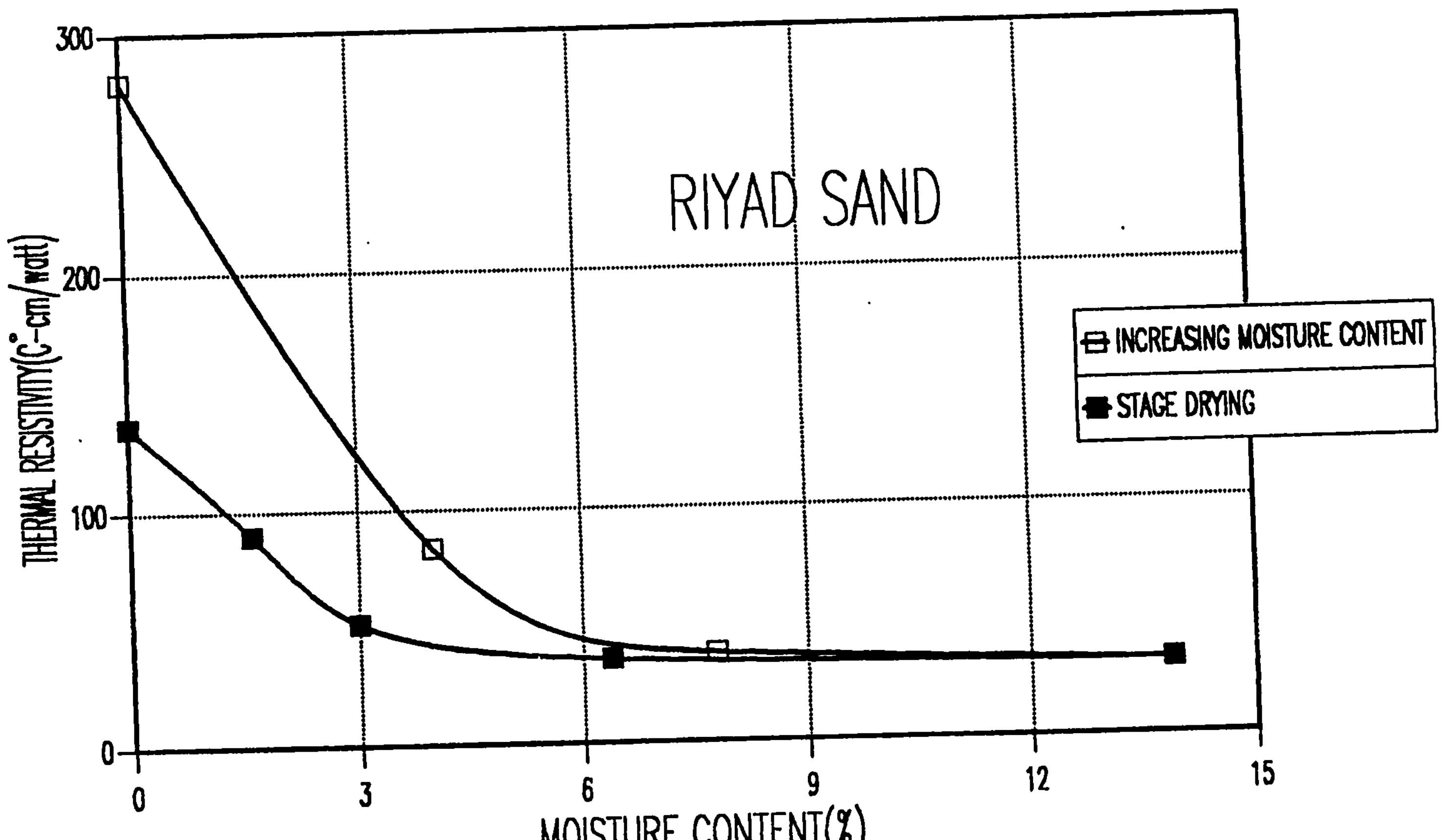

Fig.4.32 Effect of METHOD of Testing on Thermal Resistivity for Sample#5

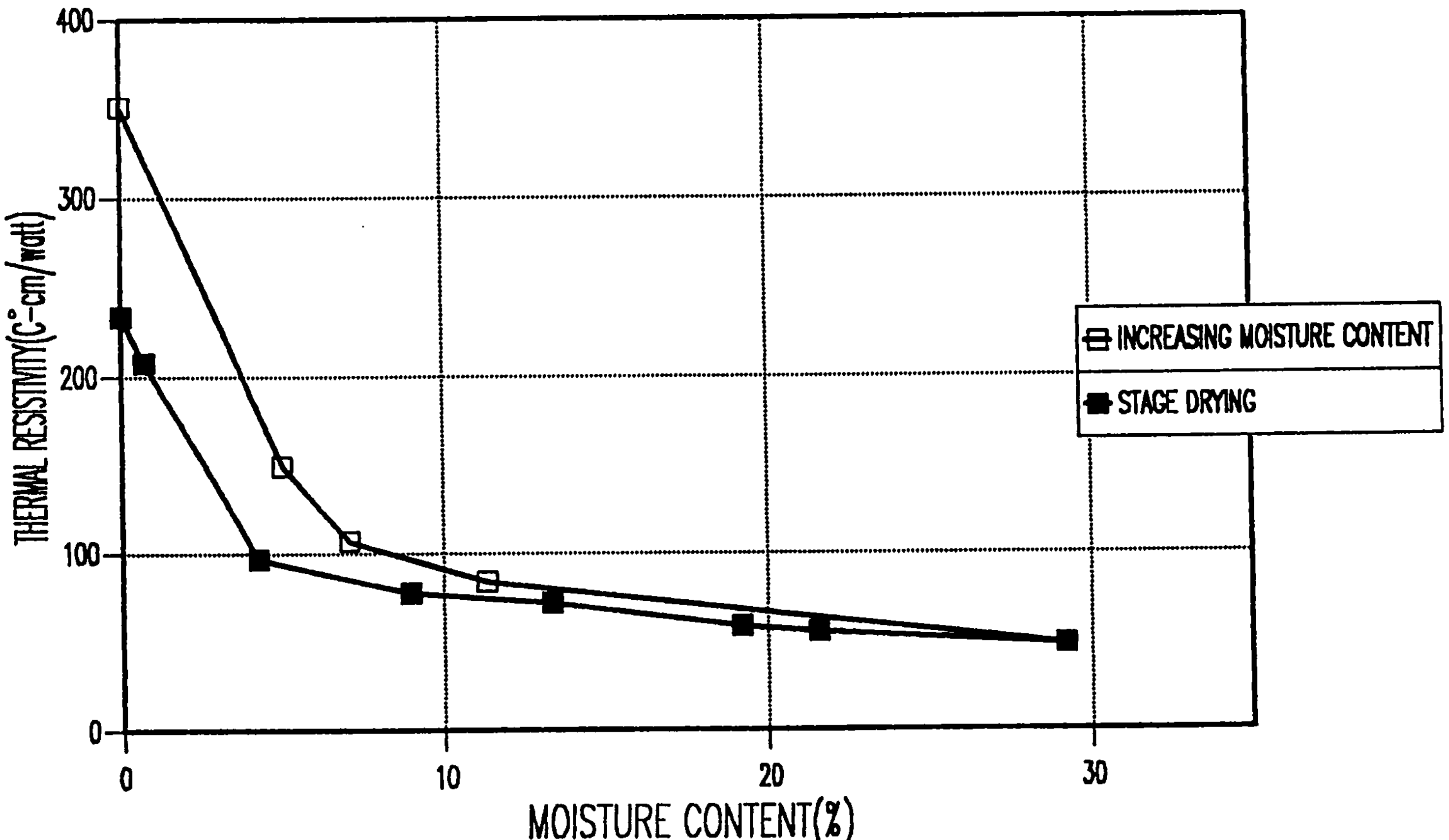

Fig.4.33 Effect of Method of Testing on Thermal Resistivity for Marl (Sample#7)

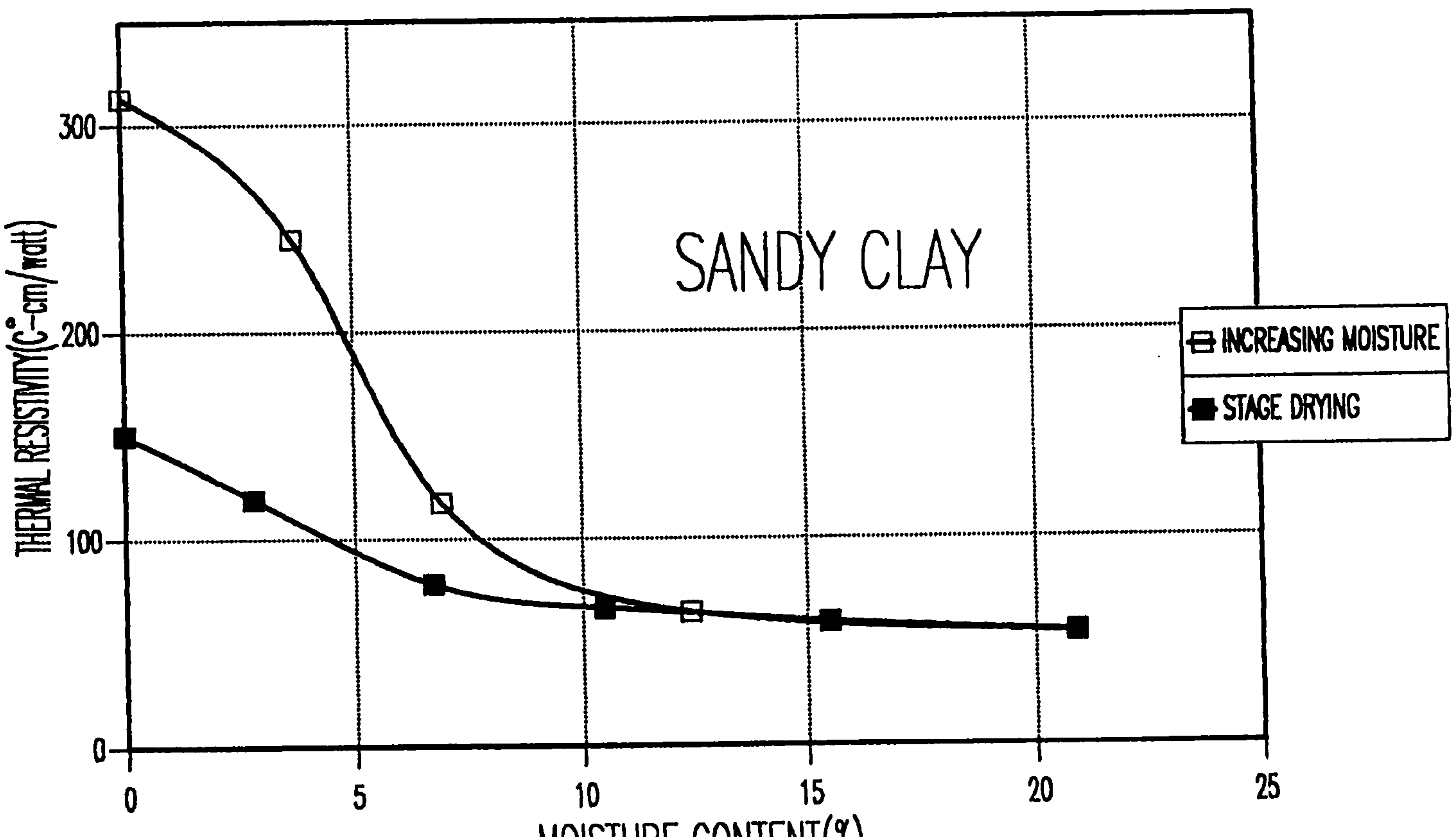

Fig.4.34 Effect of Method of Testing on on Thermal Resistivity for Sample#8

of soil thermal resistivity .

4.2.7 Influence of Gradation

The gradation influence is shown in Figure 4.35. The well graded sand was constituted in the laboratory by mixing different grain sizes of the natural dune sand. Grain size distribution of the two samples is shown in Figure 4.36. The two materials have identical mineral composition, tested for the same range of moisture content and tested through the stage drying test. As indicated in Figure 4.35, the well graded dune sand has a lower thermal resistivity for all moisture contents. The reduction in dry thermal resistivity is about 25%. This reduction is clearly due to higher density associated with better grading. As heat transfers mostly through the contact points between soil particles, better grading increases the contact points per unit volume and hence serves to reduce the thermal resistivity .

The gradation influence can be seen also from the results of the nine natural soils shown previously. Marl, sandy clay, and Riyadh sand samples which are well graded soils and cover a wide range of grain sizes have resulted in lower dry thermal resistivities compared to poorly graded sands (e.g. beach sand and dune sand). The well graded soil contains more fines which fill the voids between larger grains making it possible to compact the soil to higher densities than those for uniformly graded soils. Furthermore, these fines when accumulated at the contact points of the larger grains, increases the contact area between these grains. Consequently, lower thermal resistivity is accomplished with better

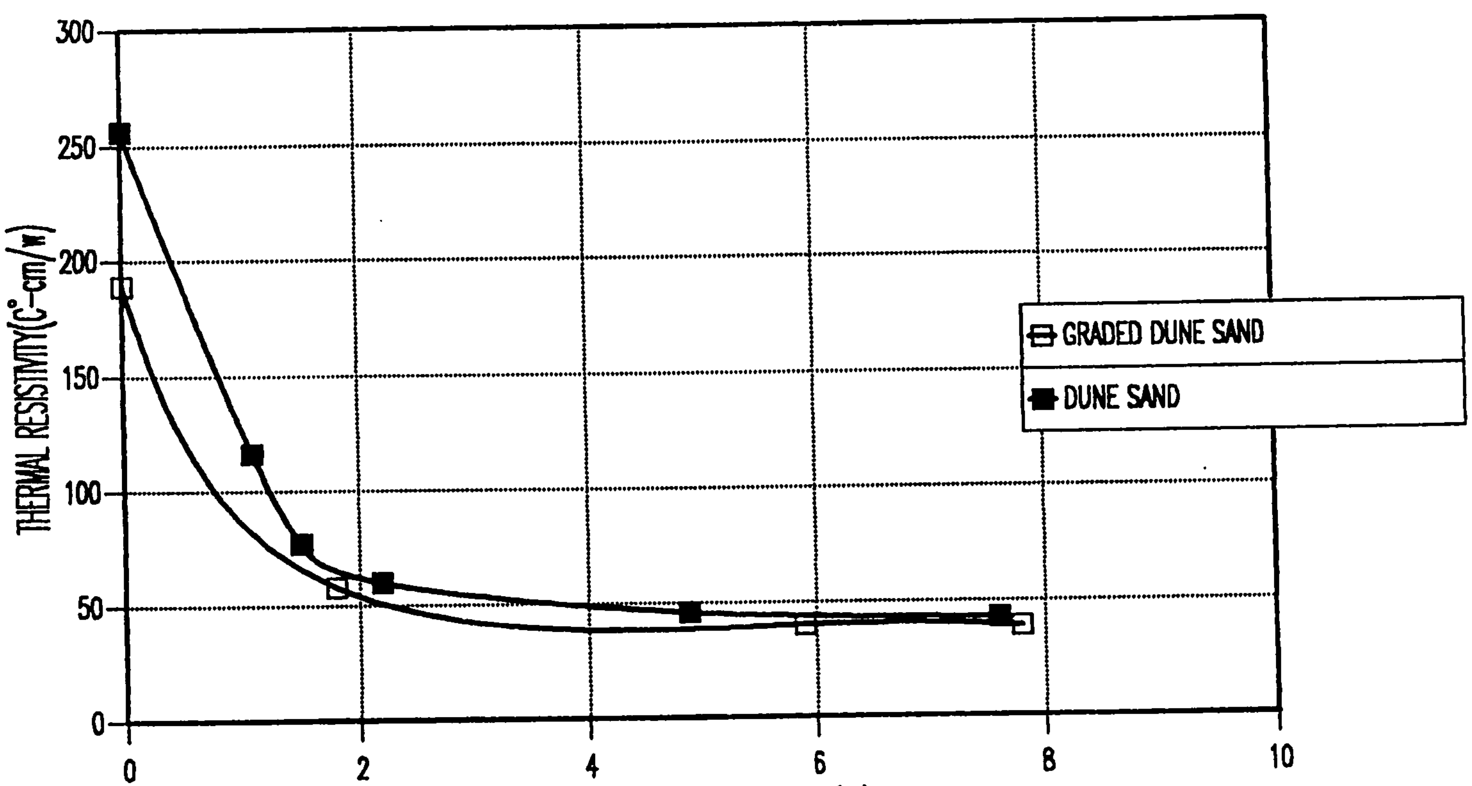

Fig.4.35 Effect of Gradation on Thermal Resistivity

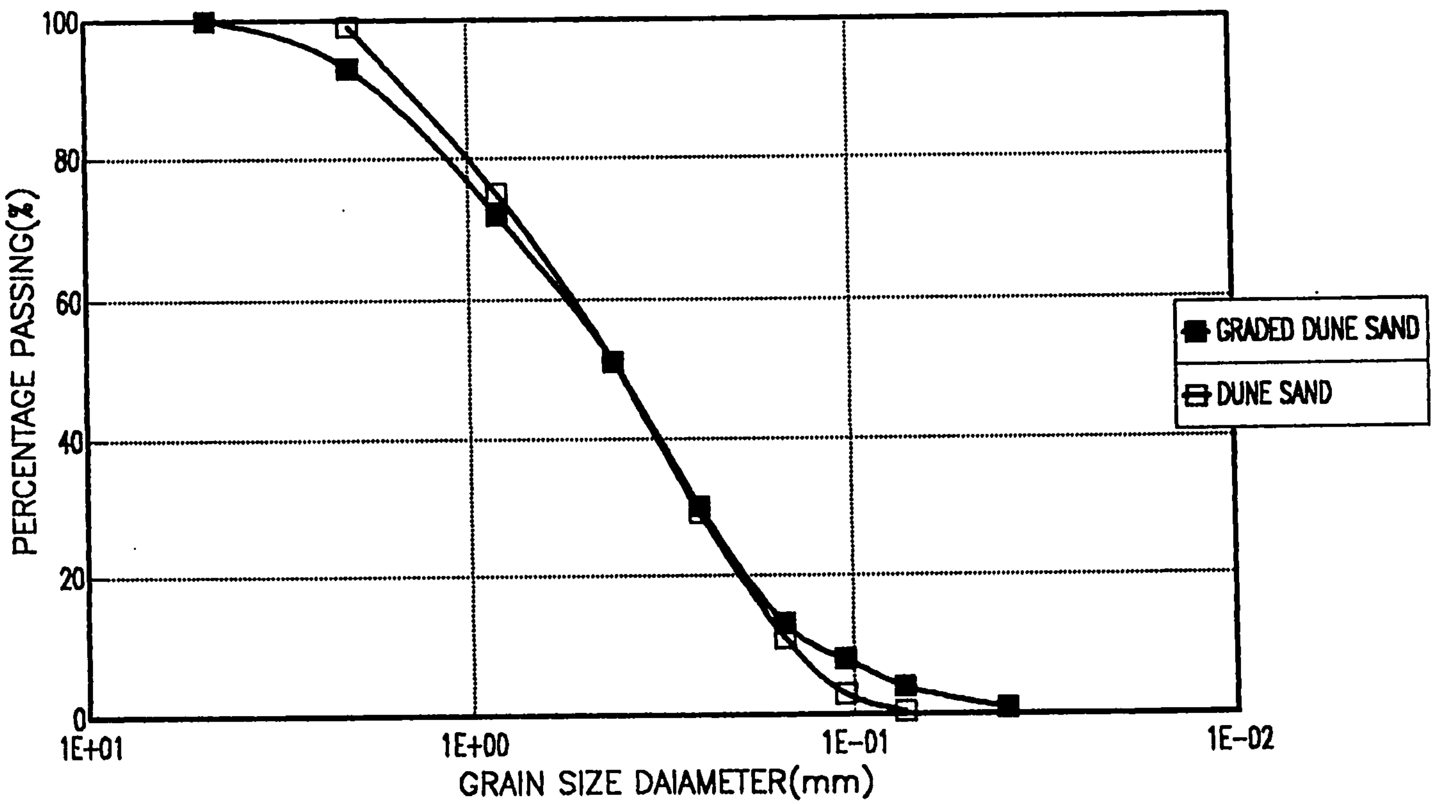

Fig.4.36 Grain Size Distribution for Both Well Graded and Poorly Graded Dune Sands

grading.

4.3 Backfill Treatments

4.3.1 Introduction

Results presented in the previous section suggest that natural soils can have very wide range of variations in terms of their thermal resistivity values. Specifications of backfill require that backfills should have a thermal resistivity of less than 120°C-cm/watt when they are dry (Boggs, et al, 1982). However, only Riyadh sand compacted at an optimum moisture content satisfies these specifications. Its dry thermal resistivity is found to be 115°C-cm/watt, just below the value suggested by the specifications. The other samples give values above this limit. The SCECO backfill is of special interest since it is the soil specified by SCECO East as a backfill. This sample shows a high dry thermal resistivity of 268°C-cm/watt which is very high compared to the specifications. If this soil is used as a backfill for the design value of 120°C-cm/watt, then the cable would be subjected to local overheating and consequently thermal failure of the insulation surrounding the cable when the soil becomes dry. To avoid this problem, the power engineer has the option of installing a second circuit, force cooling the cable along the portion of the route where overheating may occur, or replacing this backfill with a lower thermal resistivity backfill material.

For the purpose of heat dissipation, the thermal resistivity of the soil immediately adjacent to the cable is most influential. In some cases, the use of thermal backfill materials might be the most economical design option specially in congested areas such as power stations and substations where heavily loaded circuits must be routed through foundations and other underground utilities. Even in the case where thermal failure of the insulation is not a problem, the use of a low thermal resistivity backfill for a fixed applied current results in a lower temperature of the cable and hence a lower electrical resistance of the cable. The reduction of the electrical resistance of the cable reduces the I^2R losses and hence increases the power output (Jackson, 1980).

The foregoing discussion indicates a need for backfill materials whose thermal resistivity are low, even while subjected to higher temperatures for prolonged periods. The maximum operating temperature of the cable would then become independent of the surrounding backfill and soil conditions. The accompanying benefits would include a substantial increase in allowable cable loading and reduced maintenance.

4.3.2 Properties of Soil Additives

Additives used in this study are Type I Portland Cement, limestone dust, marl and clay. These additives were added in different proportions to dune sand. Selection of dune sand as a base material was made because of its general availability, its low cost and because of the low thermal resistivity of the quartzitic particles which constitutes most of the dune sand sample.

The grain size distribution of the four additives is shown in Figure

4.37. As indicated in this figure, the finest additive is the clay with 85% passing No. 200 sieve and 72% clay size content. 79% of cement passes through No. 200 sieve compared to 47% and 28% for the marl and limestone dust additives which indicates that cement is finer than the other two additives. However, the minimum size of those three additives is approximately the same (0.001 mm). The limestone dust was felt to be relatively coarse, as indicated by the grain size distribution of this additive, so the finer portion of this additive passing No. 100 sieve was also investigated and its grain size distribution is also shown in Figure 4.37.

Compaction curves of soil mixtures made up using these additives are shown in Figures 4.38 to 4.41. These figures show that optimum moisture content falls in the range 9-12% for all proportions of additives with the bottom of the range representing mixtures with low percentage of additives and the upper of the range representing mixtures with higher percentage of additives. It is apparent that increasing the amount of additives which contains appreciable amount of fines tends to increase the fines of the whole mixture and hence increases the amount of water required to achieve the maximum dry density. The maximum dry density generally increases with increasing percentage of additives with one exception. In the case of clay as an additive (Figure 4.40), addition of 7.5% clay was found to result in higher maximum density than that achieved using 10% of clay.

It is to be noted that the maximum percentage of cement and clay used is 10% whereas up to 20% of limestone dust and marl was tried. It

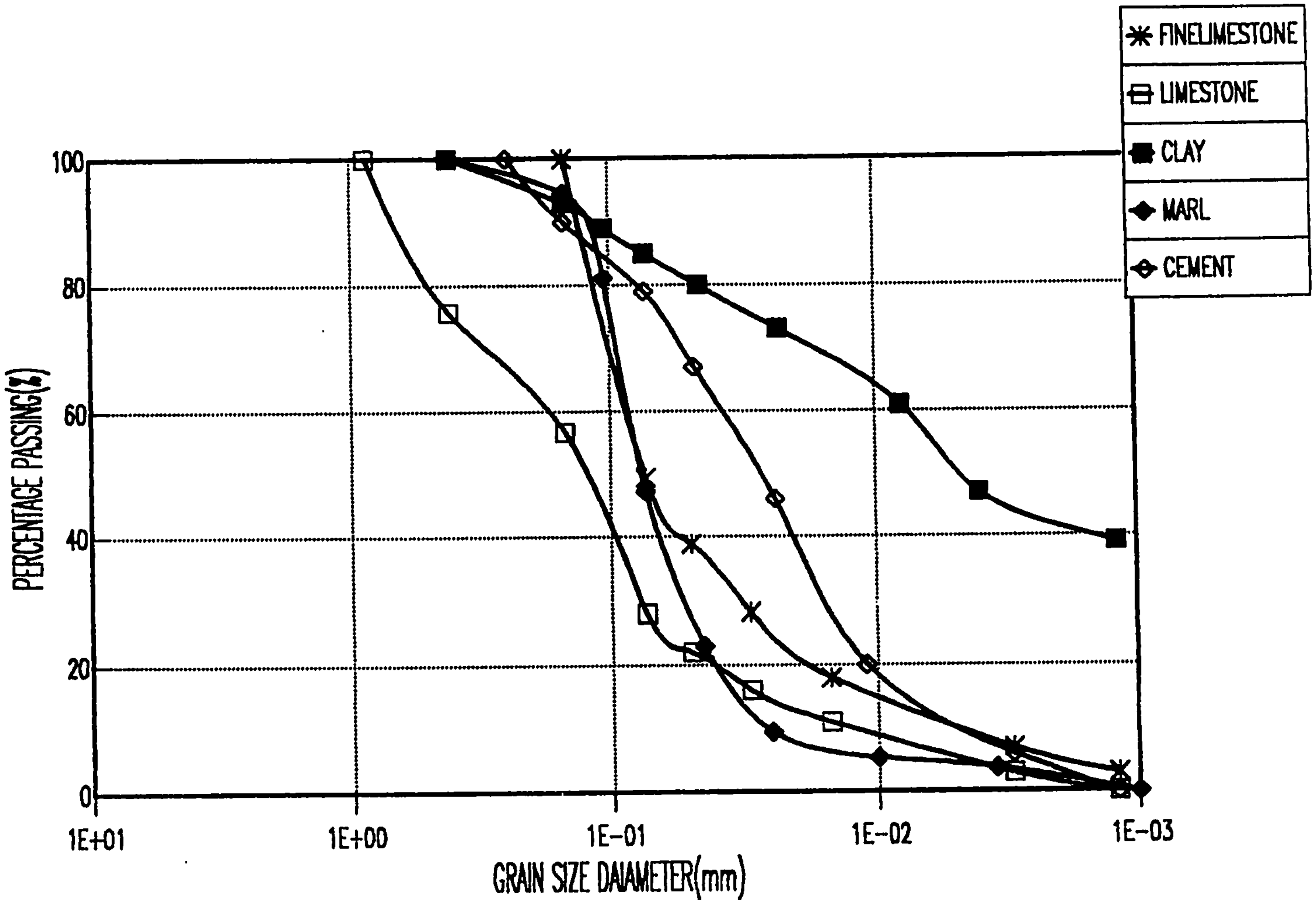

Fig.4.37 Grain Size Distribution for Additives

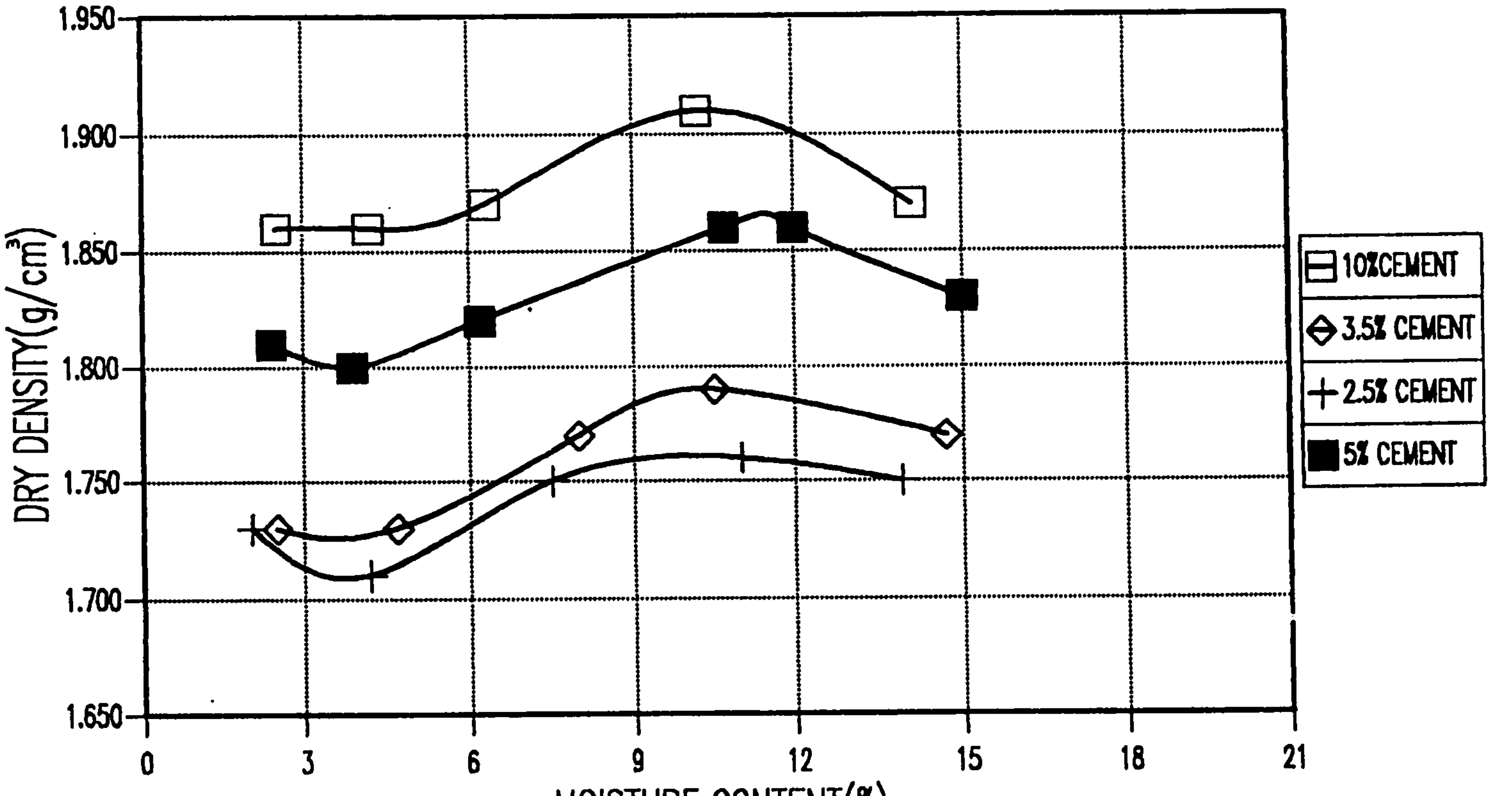

Fig. 4.38 Standard Compaction Curves for Sand–Cement Backfills

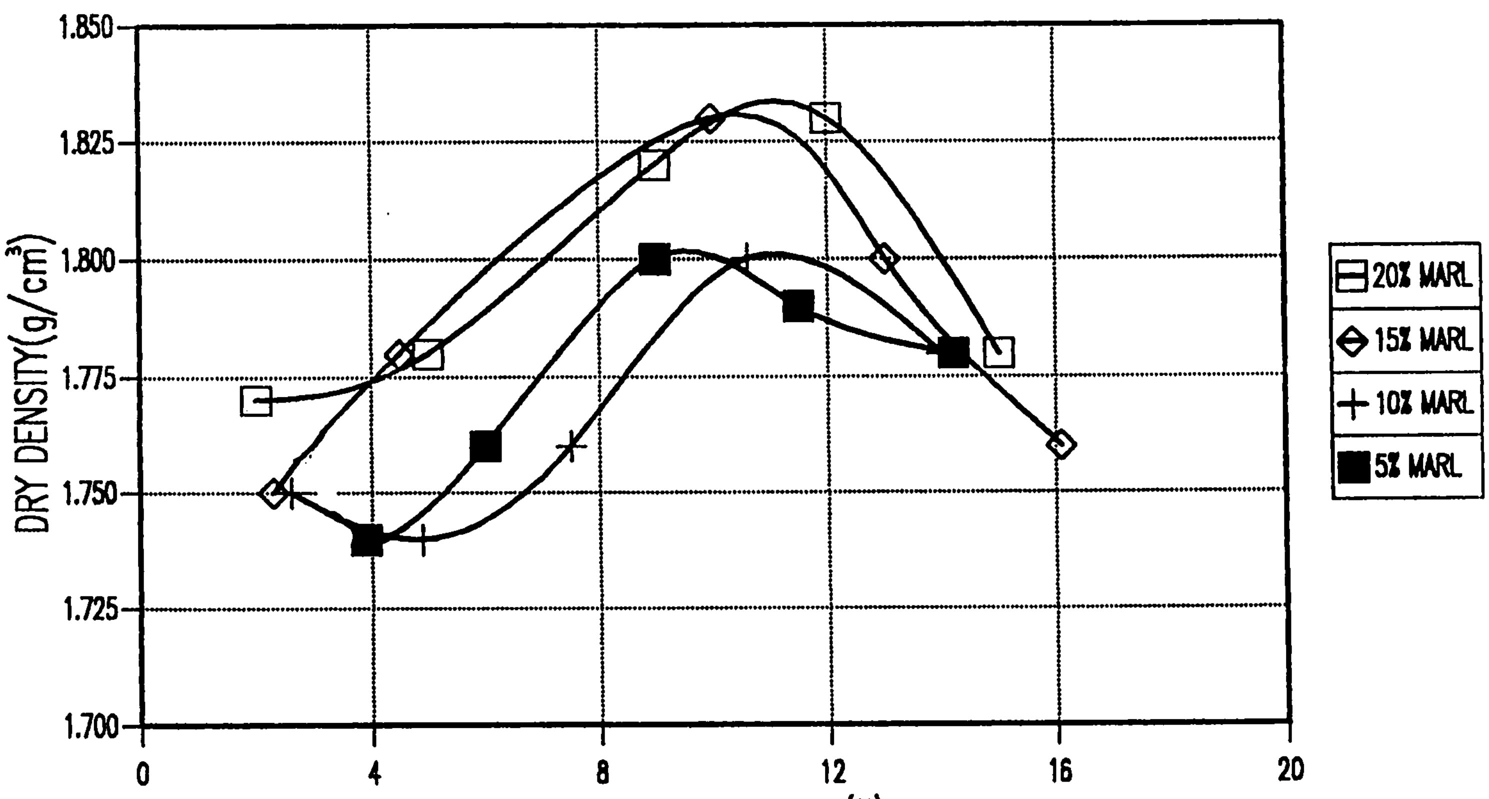

Fig.4.39 Standard Compaction Curves for Sand-Marl Backfills

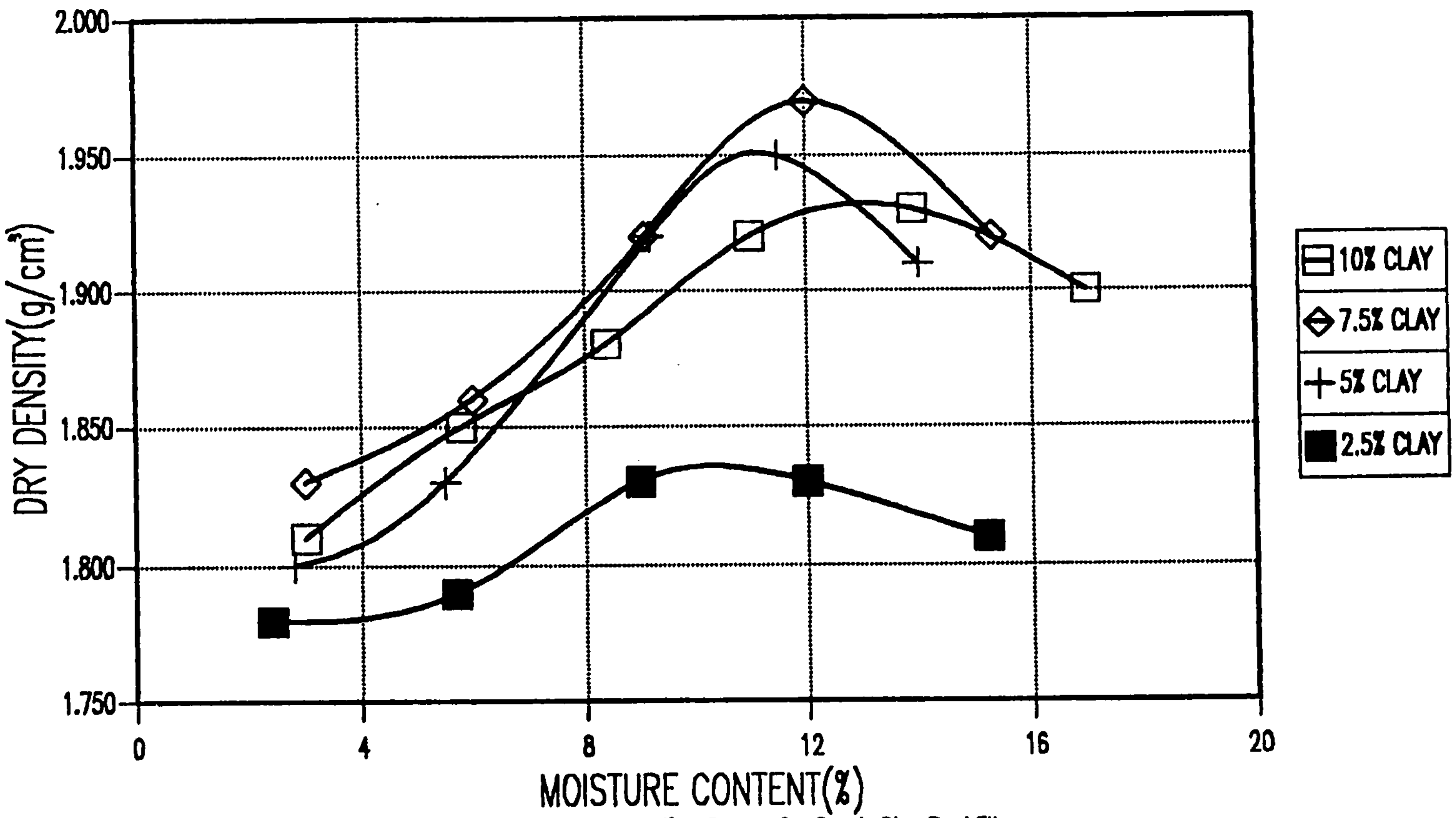

Fig. 4.40 Standard Compaction Curves for Sand-Clay Backfills

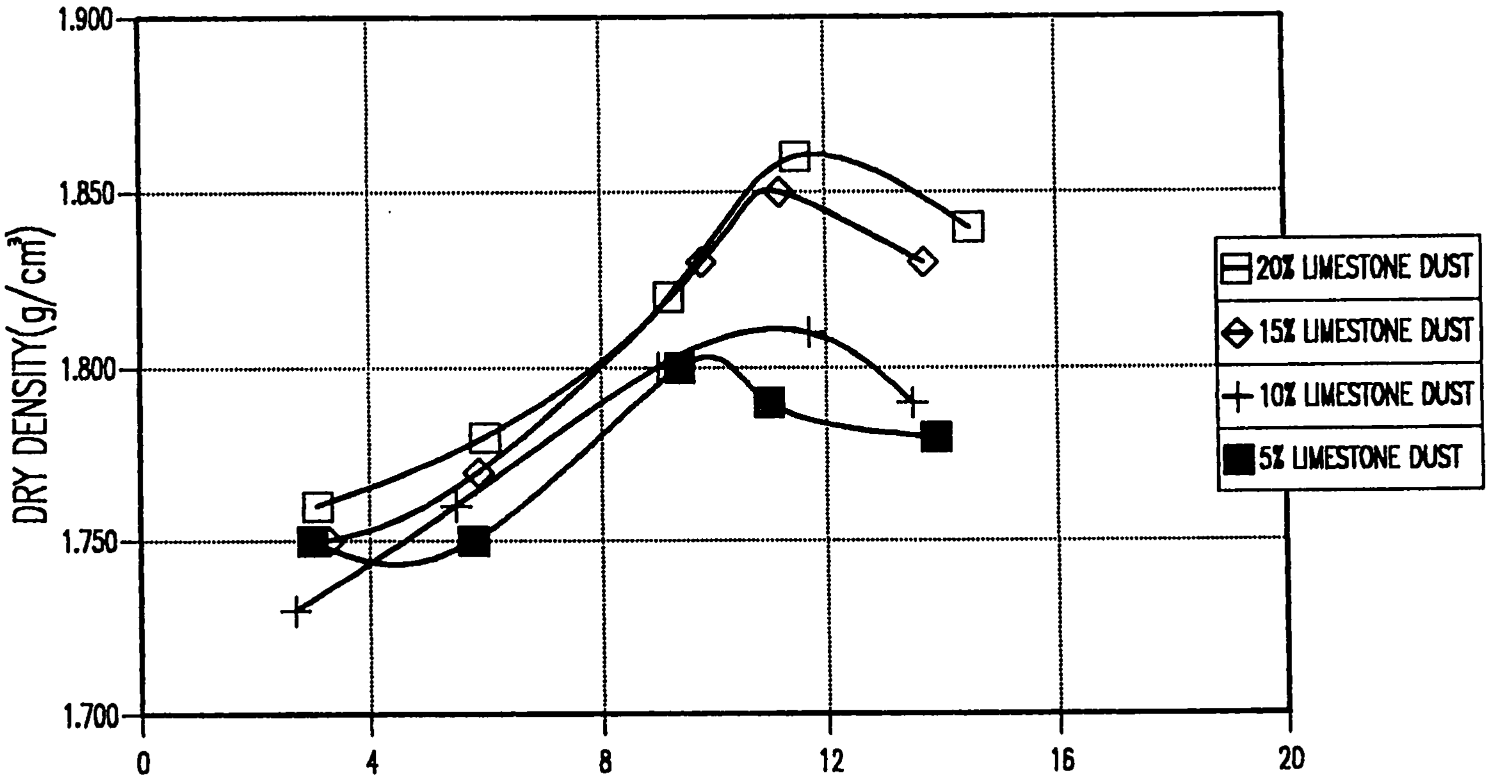

Fig. 4.41 Standard Compaction Curves for Sand–Limestone Backfills

was found that addition of 10% of cement produced a hard backfill which would make further access to the cable difficult in practice. Also, the upper limit used in the case of clay was 10% to reduce the undesirable effects related to higher amounts of clay considering that the clay used in this study is an expansive one.

4.4 Thermal Resistivity of Backfills

4.4.1 Sand-Cement Additives

Four backfills were investigated using Type I portland cement as an additive with 2%, 3.5%, 5% and 10% cement by weight of the dune sand. The stag drying test for every mixture is shown in Figure 4.42. These data show clearly that increasing the amount of cement reduces the thermal resistivity both at the wet and dry side; however, more reduction is evident in the dry region. All samples were compacted at the optimum moisture content and then tested for thermal resistivity using the stage drying technique. These results are summarized in Table 4.9 which show the reduction in dry thermal resistivity for every backfill compared with the dry thermal resistivity of the base material. A reduction of 12%, 28%, 45% and 61% was achieved by the addition of 2.0%, 3.5%, 5% and 10% of cement respectively. It is interesting to note that wet thermal resistivity for 2% and 3.5% cement backfills is higher than the wet thermal resistivity for the base material. This supports what has been concluded in Section 4.2.4 that mineral composition influences the wet thermal resistivity . Cement by itself has higher thermal resistivity than the quartzite sand, consequently, the addition of small amount of cement causes an increase in

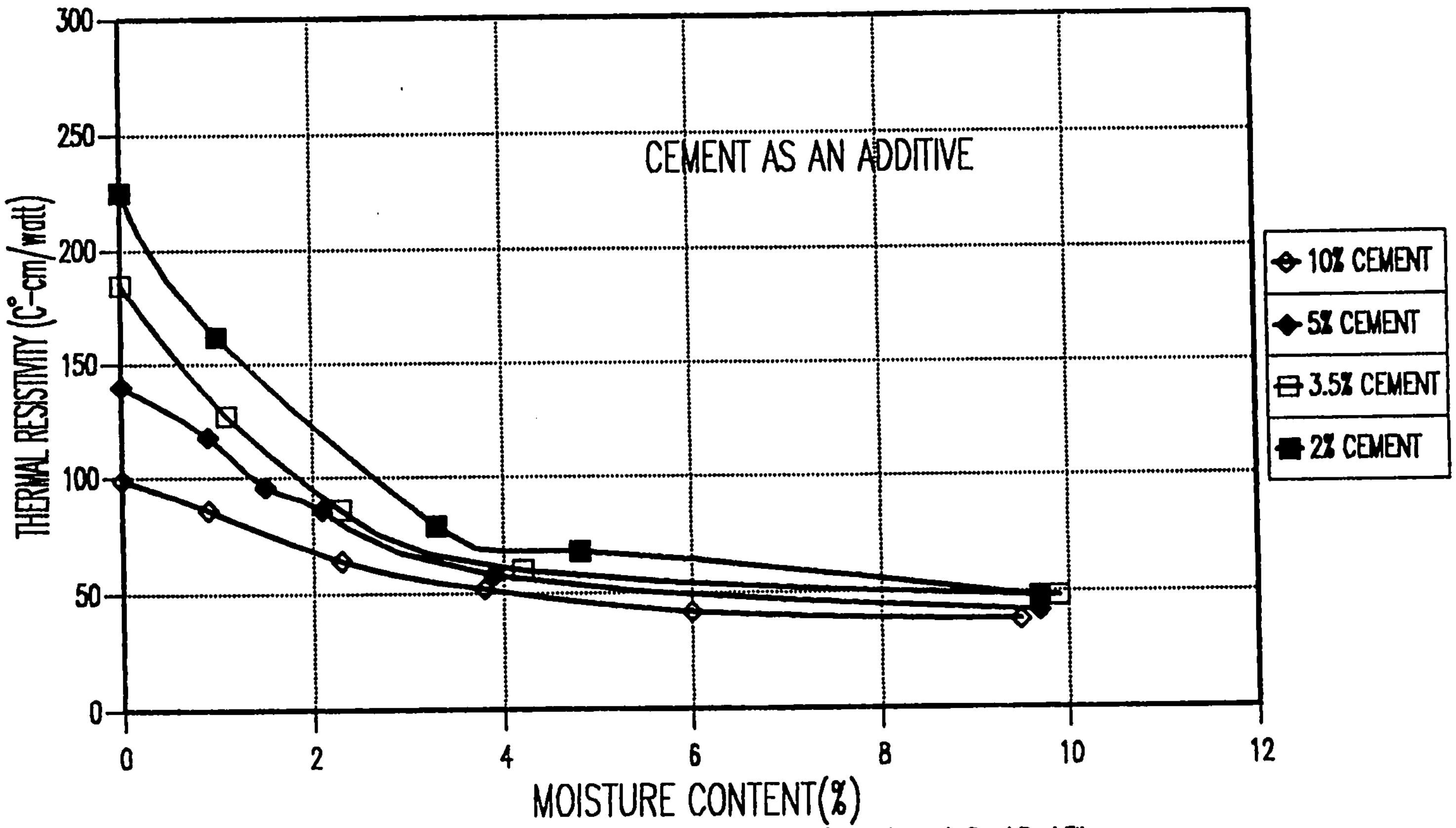

Fig.4.42 Thermal Resistivity -Moisture Content Relationship for Cement-Sand Backfills

Table 4.9. Thermal Resistivities of Sand-Cement Backfills

Backfill	γ_d (g/cm^3)	Wet ρ °C-cm/watt	Dry ρ °C-cm/watt	Percentage Reduction in Dry ρ
Base Material (Dune Sand)	1.77	42	256	-
Sand + 2% Cement	1.76	48	225	12%
Sand + 3.5% Cement	1.78	48	185	28%
Sand + 5% Cement	1.82	42	140	45%
Sand + 10% Cement	1.90	38	99	61%

wet thermal resistivity ; however, if more cement is used, lower wet thermal resistivity maybe obtained as shown in the case of adding 5% and 10% cement because the increase of wet thermal resistivity now is offseted by the reduction caused by increase in dry density associated with 5% and 10% cement backfills as shown in Table 4.9.

Figure 4.43 shows the dry thermal resistivity as a function of percentage of cement added. This figure indicates no optimum cement content at which minimum dry thermal resistivity occurs as noted with other additives. This is because the investigation was limited to addition of 10% cement. As mentioned earlier that 10% cement produced a very hard rock-like mixture which cannot be used as a backfill and addition of more cement will produce a harder backfill.

4.4.2 Sand-Marl Backfills

Results of the stage drying tests for backfills made up by adding 5%, 10%, 15% and 20% of marl to the dune sand are shown in Figure 4.44. The wet thermal resistivity for these backfills ranged between 39 and 42°C-cm/watt as indicated in Table 4.10. This slight decrease compared to the base material can be attributed to the increase of dry density of the backfills. On the other hand, the dry thermal resistivity for these backfills are 178, 166, 150 and 148°C-cm/watt for 5, 10, 15 and 20% of marl added which means a reduction of 30, 35, 41 and 42% respectively compared with dry thermal resistivity of dune sand. The reverse effect of additive on wet thermal resistivity noticed earlier with cement is also shown here. Addition of only 5% marl gives lower thermal resistivity on the wet side as

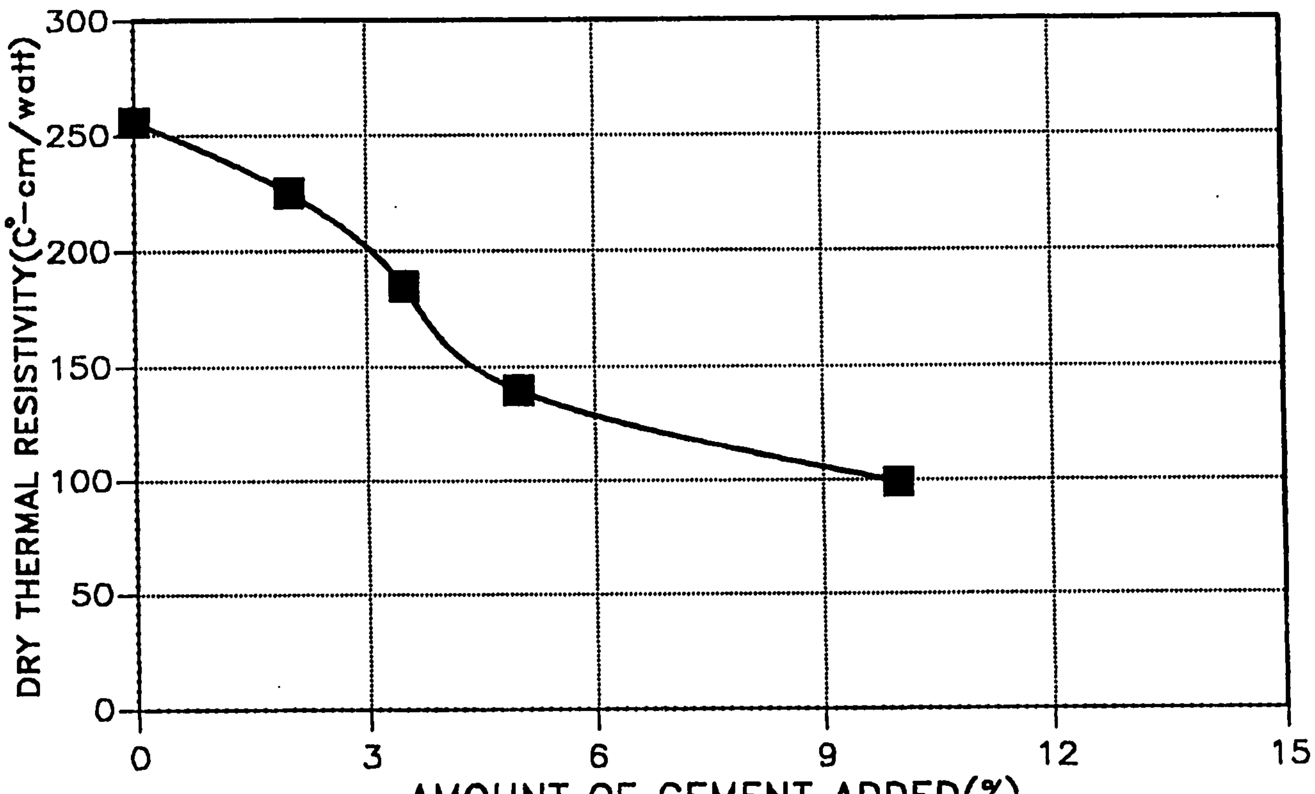

Fig.4.43 Effect of Amount of Cement on Dry Thermal Resistivity

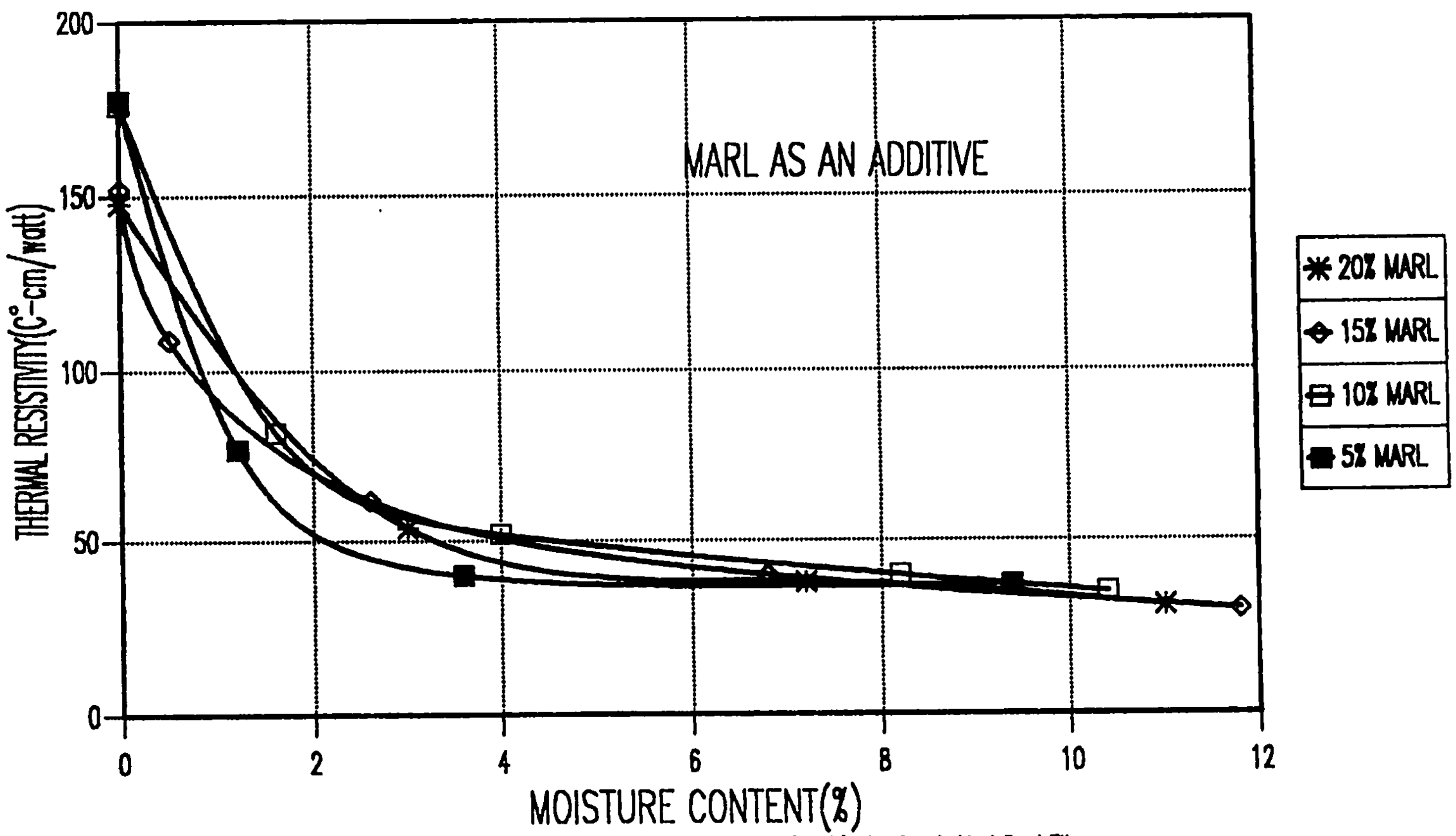

Fig.4.44 Thermal Resistivity–Moisture Content Relationship for Sand–Marl Backfills

Table 4.10 Thermal Resistivities of Sand-Marl Backfills

Backfill	γ_d (g/cm^3)	Wet ρ °C-cm/watt	Dry ρ °C-cm/watt	Percentage Reduction in Dry ρ
Base Material (Dune Sand)	1.77	42	256	-
Sand + 5% Marl	1.79	42	178	30%
Sand + 10% Marl	1.80	40	166	35%
Sand + 15% Marl	1.82	40	150	41%
Sand + 20% Marl	1.84	39	148	42%

indicated by stage drying curve for the 5% marl which plots lower than the other curves except near the dry region.

The dry thermal resistivity as a function of marl added is shown in Figure 4.45. As the amount of marl added increases, the dry thermal resistivity decreases with an optimum value of 15% marl. Addition of more than 15% marl shows no further decrease in thermal resistivity . The reduction of 41% associated with addition of optimum amount of marl which is 15%, is not comparable to the cement additives which results in higher reduction even with 5% cement content. However, marl-sand backfills are less harder than cement backfills even with addition of 20% marl.

4.4.3 Sand-Clay Backfills

For the clay backfills, Figure 4.46 shows stage drying results for the four proportions 2.5, 5, 7.5 and 10%. The four backfills indicate small variation among them with the backfill of 2.5% clay having larger dry thermal resistivity . From the summarized results listed in Table 4.11, the wet thermal resistivity reduced by more than 20% for all proportions which is mainly resulted from the substantial increase in maximum dry density at which samples were tested. The clay backfills are the most effective when considering dry thermal resistivity . The reduction in dry thermal resistivity ranged from 54% for 2.5% clay to 65% for the 5% clay. It is also interesting to note that all sand-clay backfills result in dry thermal resistivity which is lower than 120°C-cm/watt even with addition of 2.5% clay only.

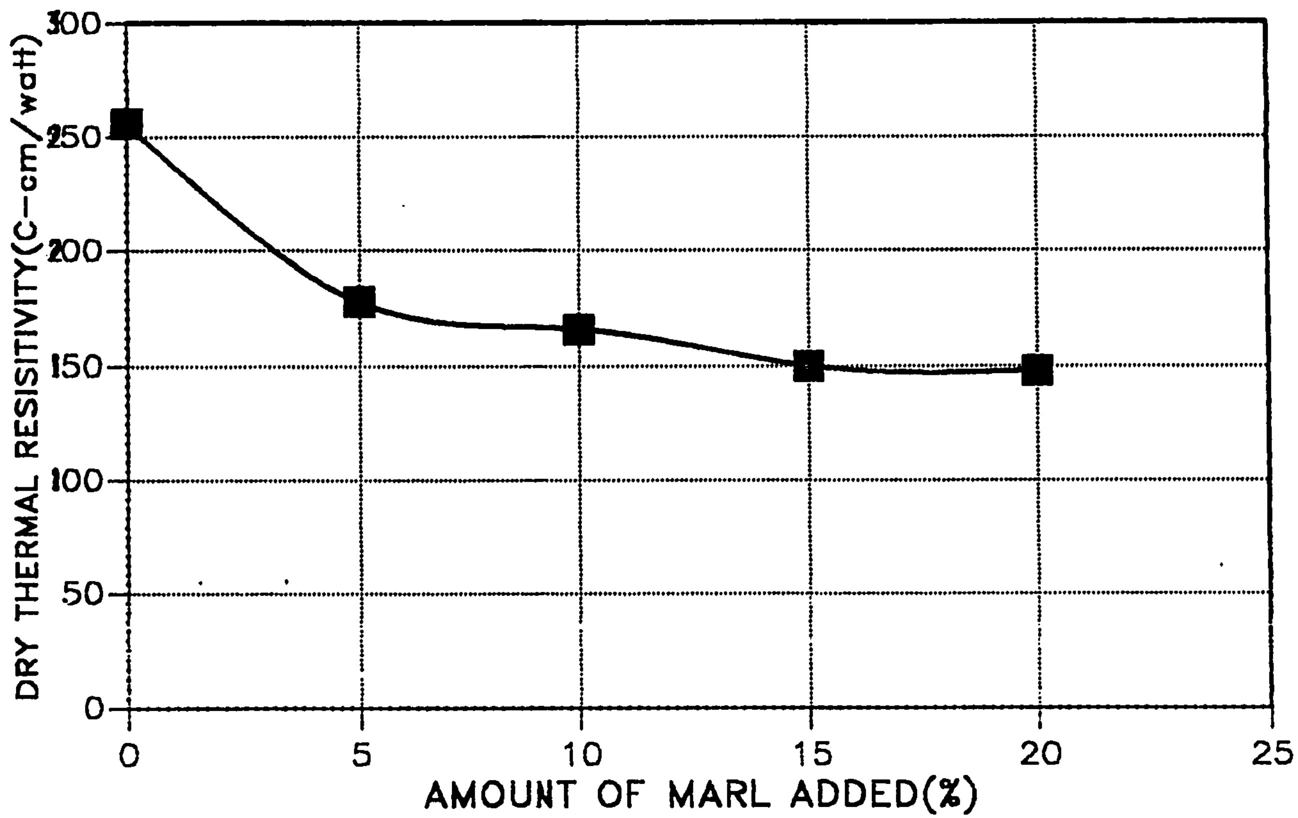

Fig.4.45 Effect of Amount of Marl on Dry Thermal Resistivity

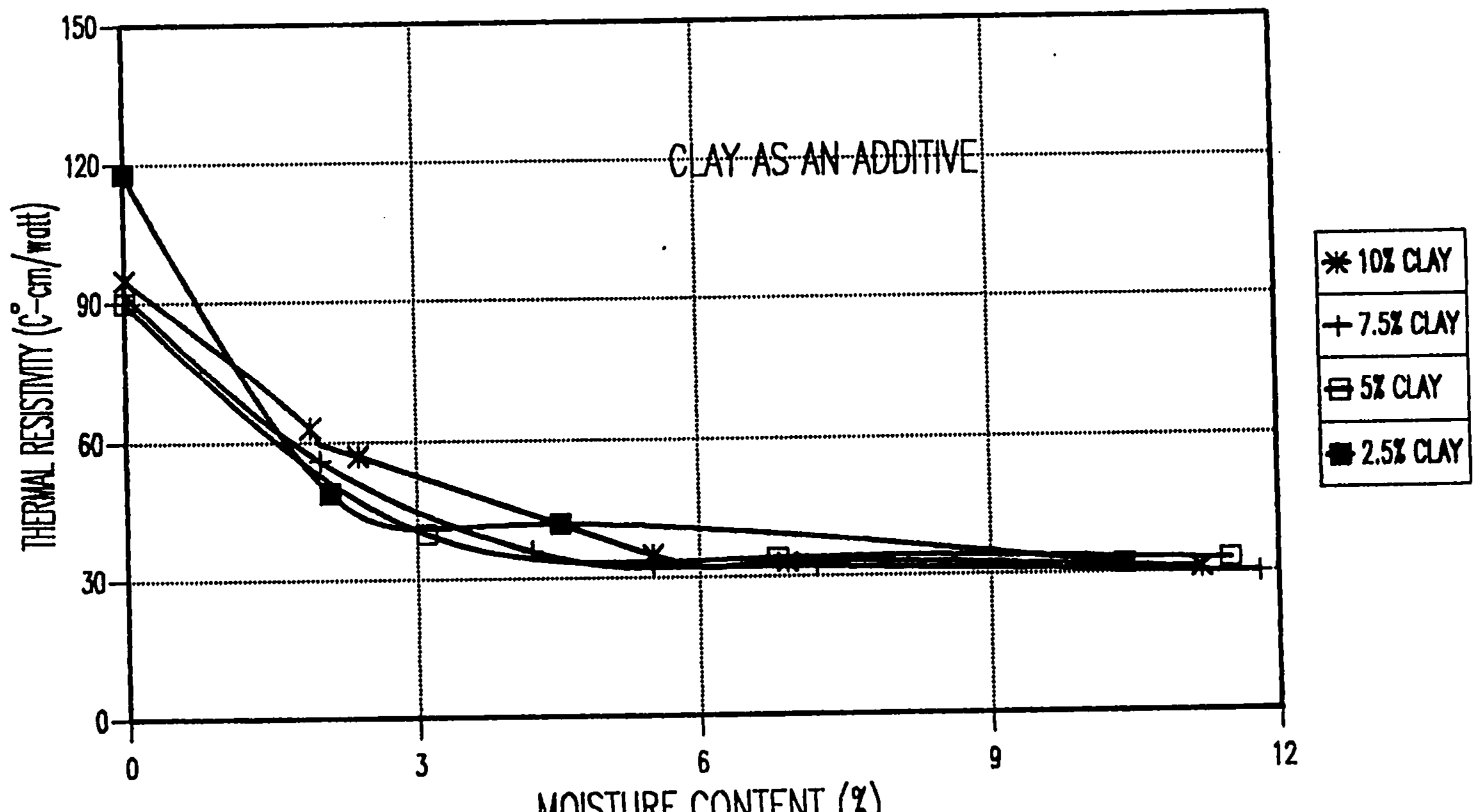

Fig.4.46 Thermal Resistivity–Moisture Content Relationship for Sand–Clay Backfills

Table 4.11 Thermal Resistivities of Sand-Clay Backfills

Backfill	γ_d (g/cm^3)	Wet ρ °C-cm/watt	Dry ρ °C-cm/watt	Percentage Reduction in Dry ρ
Base Material	1.77	42	256	-
2.5% Clay	1.86	32	118	54%
5.0% Clay	1.94	32	90	65
7.5% Clay	1.98	30	92	64
10% Clay	1.92	31	95	63

The optimum clay content is 5% at which a dry thermal resistivity of 90°C-cm/watt was achieved as shown in Figure 4.47. The slight increase in dry thermal resistivity after that can be explained by referring to the compaction curves shown earlier in Figure 4.40. The 5% and 7.5% clay backfills give approximately the same maximum dry density which is higher than that obtained from 2.5% clay backfill; however, the maximum dry density decreased when a 10% clay backfill is compacted.

4.4.4 Limestone - Sand Backfills

Stage drying results for the limestone-sand backfills are shown in Figure 4.48 and summarized in Table 4.12. These results indicate a reduction of dry thermal resistivity with increasing the amount of limestone dust with no apparent reduction of the wet thermal resistivity . The reduction of the dry thermal resistivity is 34, 41, 49 and 51% for 5%, 10%, 15% and 20% of limestone dust respectively. The optimum amount of limestone dust is about 15% as indicated by Figure 4.49. The material of limestone dust passing No. 100 standard sieve was also investigated and the results are shown in Figure 4.50 and Table 4.13. The fine limestone dust was proved to be more effective in reducing both the dry thermal resistivity and optimum amount of additive. Adding 10% or more of the fine limestone dust to the sand resulted in dry thermal resistivity values of less than 120°C-cm/watt which represents a reduction of more than 55% compared with untreated dune sand.

4.5 Evaluation of Tested Backfills

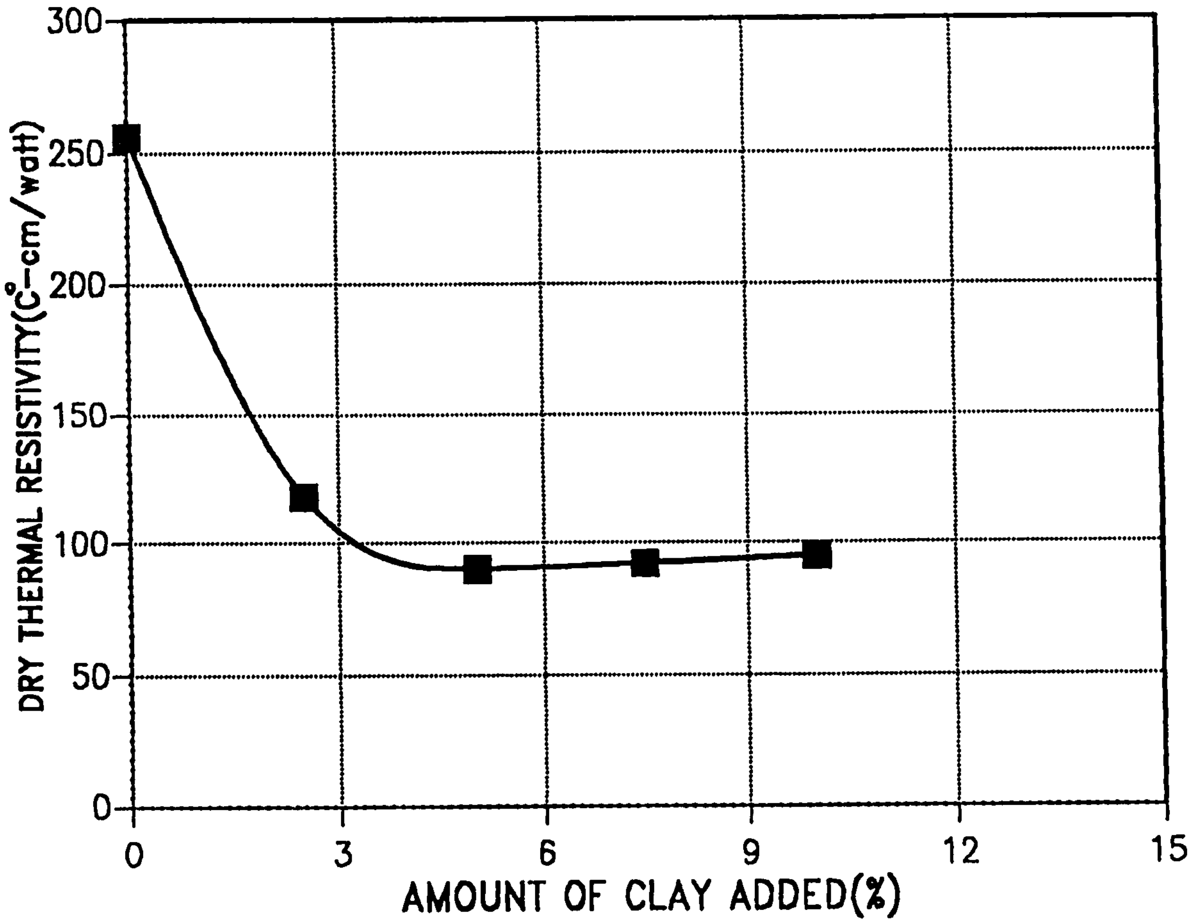

Fig.4.47 Effect of Amount of Clay on Dry Thermal Resistivity

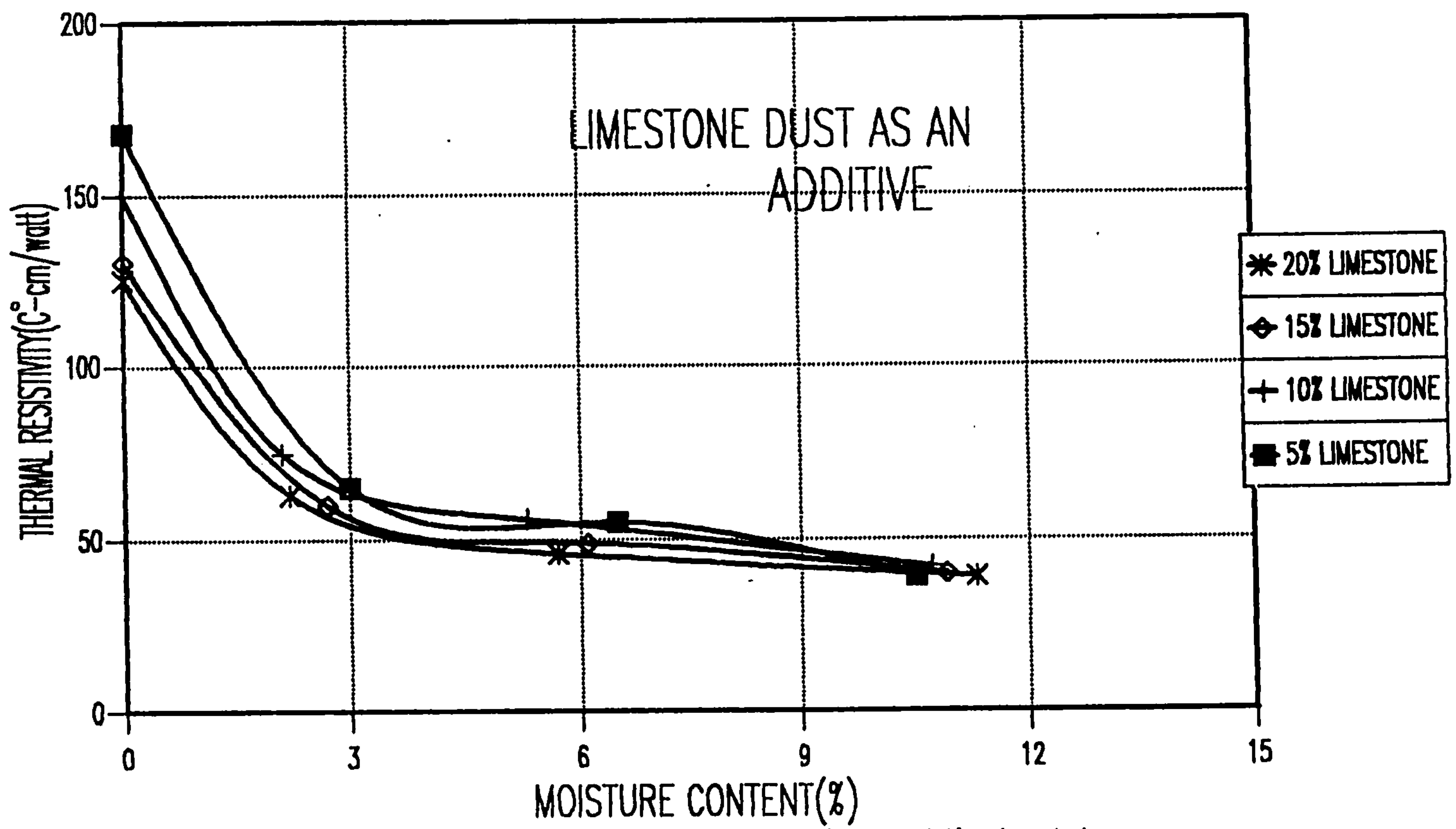

Fig.4.48 Thermal Resistivity–Moisture Content Relationship for Sand–Limestone dust

Table 4.12. Thermal Resistivities of Sand-Limestone Backfills

Backfill	γ_d (g/cm^3)	Wet ρ °C-cm/watt	Dry ρ °C-cm/watt	Percentage Reduction in Dry ρ
Base Material	1.77	42	256	-
5% Limestone Dust	1.81	39	168	34%
10% Limestone Dust	1.82	42	150	41%
15% Limestone Dust	1.84	40	130	49%
20% Limestone Dust	1.84	39	125	51%

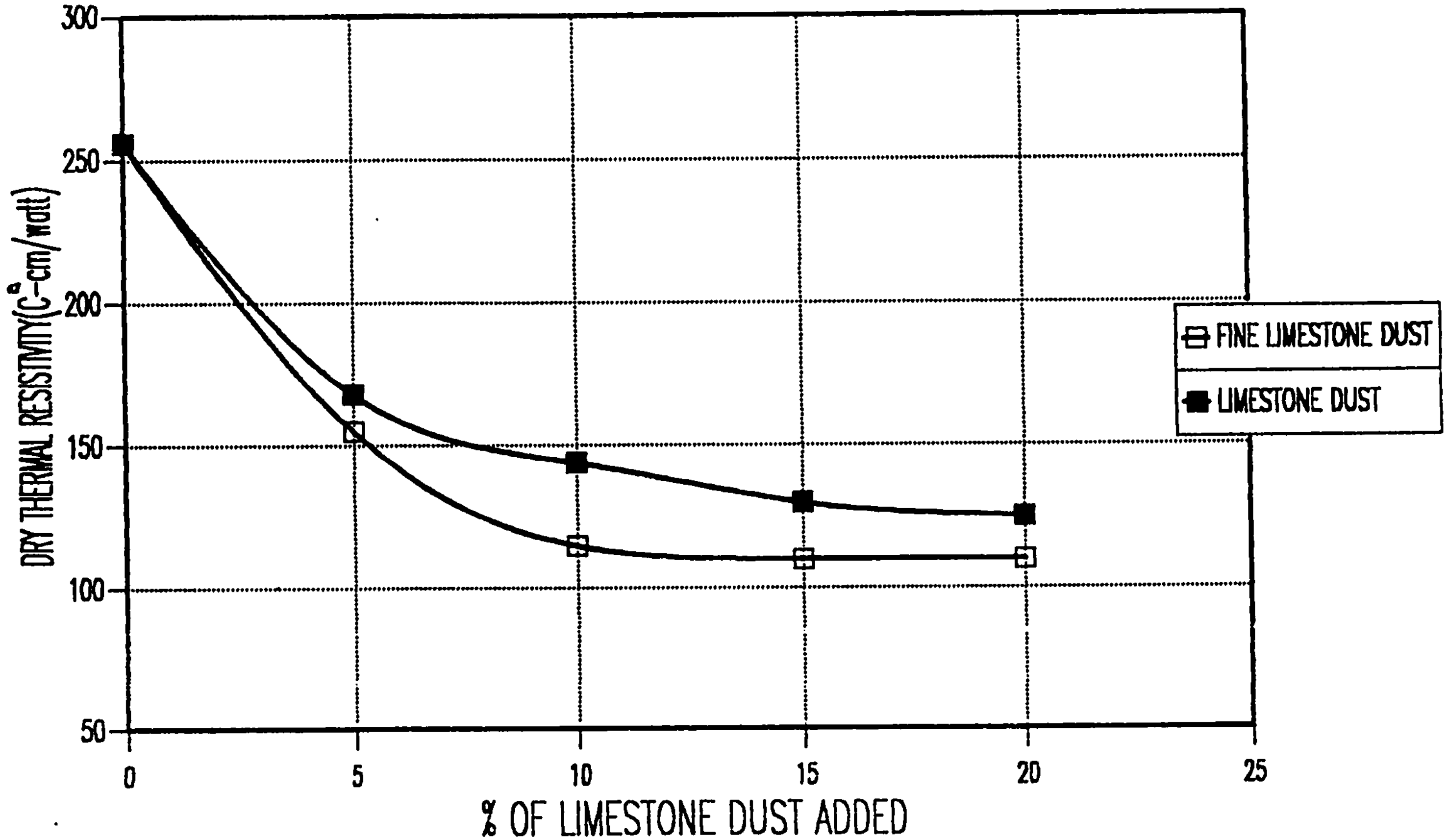

Fig.4.49 Effect of Amount of Additive on Dry Thermal Resistivity

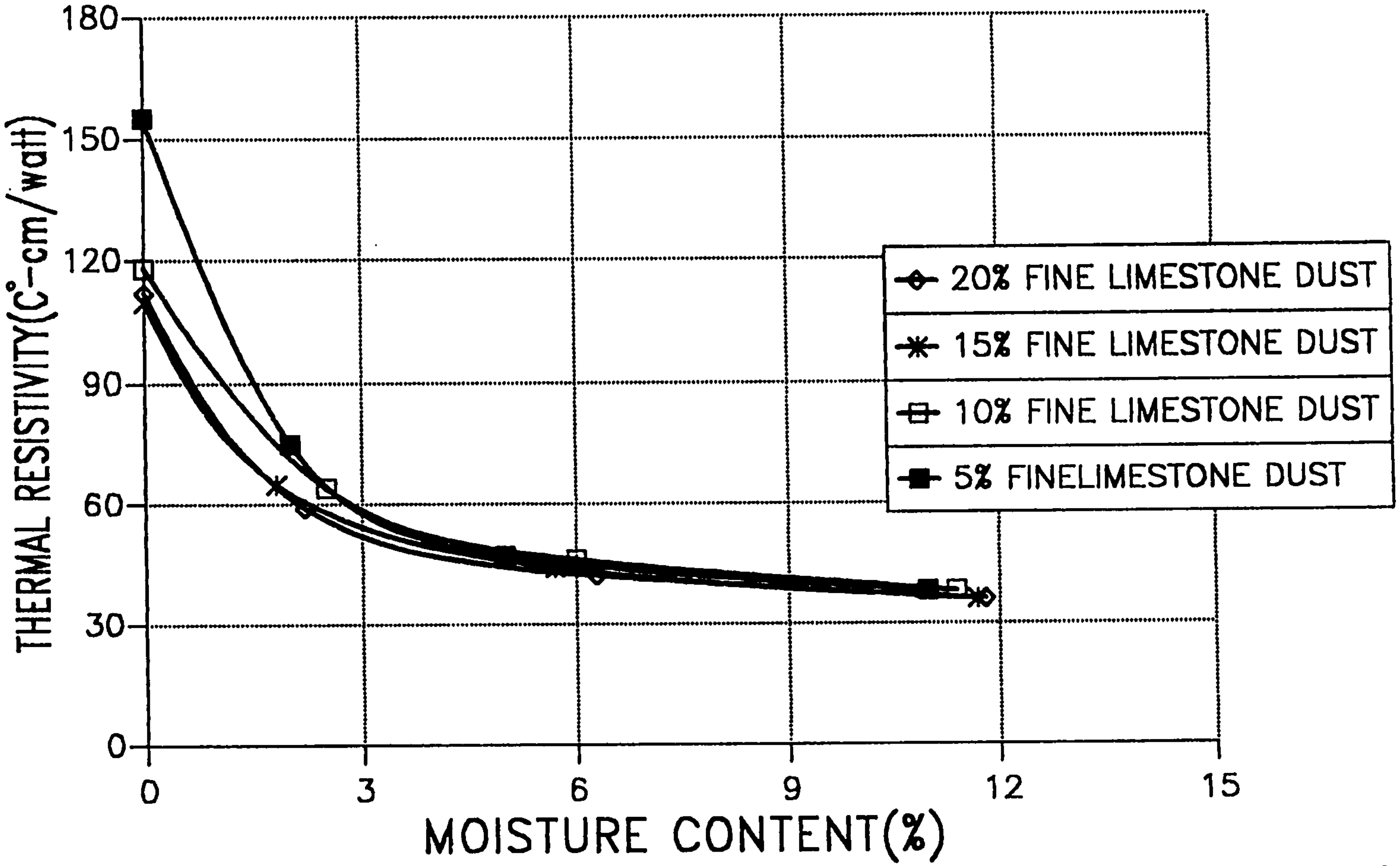

Fig.4.50 Thermal Resistivity-Moisture Content Relationship for Sand-Fine Limestone Back

Table 4.13. Thermal Resistivities of Sand-Fine Limestone Backfills

Backfill	γ_d (g/cm^3)	Wet ρ °C-cm/watt	Dry ρ °C-cm/watt	Percentage Reduction in Dry ρ
Base Material	1.77	42	256	-
5% Fine Limestone Dust	1.84	39	155	39%
10% Fine Limestone Dust	1.86	38	115	55%
15% Fine Limestone Dust	1.89	36	110	57%
20% Fine Limestone Dust	1.88	36	112	56%

Table 4.14 shows the two criteria used for evaluation of thermal backfills which are optimum amount of backfill additives at which minimum dry thermal resistivity could occur and the reduction in the dry thermal resistivity compared with that of untreated dune sand. As shown in Table 4.13, the minimum optimum amount of backfill additives is 5% for both clay and cement compared with a maximum of 15% for marl and limestone dust and a moderate value of 10% for the fine limestone dust. However, it cannot be concluded that clay-sand backfills are more cost effective than fine limestone dust - sand backfill. The cost of 5% clay could be higher since clay soils are not abundant in many parts of the Kingdom while limestone dust is a waste material of limestone aggregate quarries throughout the Kingdom. Referring to results presented earlier, they indicate that only 2.5% of clay is adequate to achieve a dry thermal resistivity below 120°C-cm/watt which is a very small amount indicating that clay-sand backfills might be cost effective in areas where clay soils are readily available. Cost estimation of these backfills should be carried out to determine the most effective one based on the cost of raw material of additives and their proportions. It is to be noted that the optimum amount of cement was considered to be 5% although the 10% cement-sand backfill gave lower dry thermal resistivity . However, the 10% cement backfill was very hard and hence was not considered as an optimum. The economical selection of backfill materials must also include the thermal stability criteria of the native soil first. Based on the maximum heat generation and cable geometry of the cable system, the designer may find

Table 4.14. Summary of Results of Different Backfills

Backfill Type	Optimum Amount of Backfill (%)	Dry ρ at Optimum Amount of Backfill	% Reduction in Dry ρ
Cement	5	140	45%
Marl	15	150	41%
Clay	5	90	65%
Limestone Dust	15	130	49%
Fine Limestone Dust	10	115	57%

that it is more economical to establish the stability criteria for the native soil and operate within those constraints.

Considering the dry thermal resistivity , clay-sand additives appear to be the most effective. A dry thermal resistivity of 90°C-cm/watt has been achieved with only 5% of clay which represents 65% reduction compared to the untreated sand. The 10% sand-fine limestone backfill resulted in a value of 115°C-cm/watt. The values of the dry thermal resistivities for both of the above backfills are lower than the 120°C-cm/watt suggested by specifications.

It appears that the particle size of the additive affects the minimum dry thermal resistivity of the backfill. Clay which is the finest additive investigated in this study was the most effective in reducing dry thermal resistivity . Low dry thermal resistivity was possible by adding just 2.5% of this additive and the same thing can be noticed with the fine limestone dust. The fine limestone dust which has the same mineral composition as that of the limestone dust gives better results as shown in Figure 4.49. This behavior can probably be attributed to an increase in packing efficiency of smaller sized additive particles in the vicinity of the dune sand grain contact points.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

This thesis consists of an experimental study to determine factors that affect thermal resistivity of soils by utilizing the thermal needle method. It also consists of a laboratory investigation of thermal resistivity of backfill materials using different additives to a sandy soil. The results of this study have practical application to the design of underground heat sources and development of thermal backfill materials for improving the heat transfer between soil and buried electric power cables.

The accuracy of the thermal needle method was discussed in Chapter 3 of this thesis. Since this method is based on the line heat source theory, the experiments were carried out in such a way as to minimize errors and to limit deviations from the line heat source theory. The general design features of and the supporting instrumentation for the probe measurement system are described. The determination of geotechnical properties of tested soils and specimen preparation procedures for thermal needle method are also presented.

Natural soils selected to achieve the first part of this study covered a wide range of particle sizes and consist of different minerals. The stage drying technique was used to develop the thermal resistivity - moisture content relationships at two different dry densities for every natural soil. The main factors affecting thermal resistivity of soils such as moisture content, dry density, initial moisture content of the soil, mineral composition and other related properties were investigated. The results are presented and discussed in Chapter 4 of this thesis.

Backfills used in this study consist of a base material which is dune sand and small amounts of additives such as Type I cement, limestone dust, clay and marl. Selection of dune sand as a base material was made because of its general availability, low cost and because of the low thermal resistivity of the quartzitic particles of the dune sand. Based on the results obtained, an evaluation of these backfills was presented also in Chapter 4.

5.2 Conclusions

The major conclusions of this investigation are as follows :

1. The transient thermal probe is a relatively quick, effective method for measuring the soil thermal properties. Valid results can be obtained if the test conditions approximate, as closely as possible the line source heat theory. If this method is used with the stage drying technique, then a close simulation of actual behavior in the field can be achieved.

2. The thermal resistivity of a specific soil can be reduced significantly by increasing either the dry density or the moisture content.

3. Considering thermal resistivity - moisture content relationship, this study indicates that three stages can be defined. Stage I exists from zero moisture content up to a moisture content which is just below the critical moisture content. A dramatic reduction of thermal resistivity occurs in this stage. Stage II exists near the critical moisture content and during this stage, thermal resistivity decreases rather slowly compared to stage I. Stage III is the wet stage in which thermal resistivity is nearly constant and exists up to saturation.

4. This investigation indicates that critical moisture content increases as the amount of fines increases whereas for a given soil, it decreases as its dry density increases.

5. Based on stage drying results, mineral composition of the soil affects the wet thermal resistivity of the soil and has almost no effect on dry thermal resistivity specially for soils which exhibit cementitious properties upon drying and for cohesive soils. The presence of high percentage of quartz tends to reduce wet thermal resistivity whereas presence of appreciable amount of higher thermal resistivity minerals such as salts, dolomite and clay minerals have the reverse effect.

6. Based on stage drying results, cementitious and cohesive soils can have low dry thermal resistivity compared to clean sands although they have generally higher wet thermal resistivities . The photomicrographs of the soil structure indicates that during the

process of drying, the structure of these soils goes through different magnitudes of changes. By drying these soils, the soil interparticle contact area is increased which in turn would act to lower dry thermal resistivity .

7. This investigation indicates that there is an optimum initial compacting moisture content at which minimum dry thermal resistivity can be achieved. Compacting the soil at a water content in excess of optimum will produce only a minimal decrease in dry thermal resistivity . The results of this study indicate also that the optimum moisture content derived from the compaction curve could be used as a conservative approximation of the optimum compacting moisture content required to achieve minimum dry thermal resistivity in the absence of thermal resistivity data.

8. Thermal resistivity data indicate that most of the tested natural soils resulted in dry thermal resistivities in excess of 120°C-cm/watt required by specifications which indicates a need for backfill materials whose thermal resistivity are low even while subjected to high temperatures for prolonged periods.

9. Out of the additives used in this study to treat dune sand backfill materials, clay and fine limestone dust were found to be more effective. Compared to untreated dune sand which has a dry thermal resistivity of 256°C-cm/watt, the addition of 5% clay and 10% fine limestone dust to the dune sand resulted in dry thermal resistivity of 90 and 115°C-cm/watt which means a reduction of

about 65% and 57% respectively.

10. Based on thermal resistivity data of backfills, it appears that the particle size of the additive affects the minimum dry thermal resistivity of the backfill. The finer is the particle size of an additive the lower is minimum dry thermal resistivity that can be achieved for the same base material. This behavior can be probably attributed to an increase in packing efficiency of smaller sized additive particles in the vicinity of the base material grain contact points.

5.3 Recommendations

Based on the results of and the conclusions drawn from this study, the following recommendations for future work are suggested:

1. The influence of geotechnical properties on other thermal properties such as heat capacity and thermal diffusivity of soils although they are less important than thermal resistivity in practice should be studied for better understanding of heat transfer characteristics of soils.

2. A thermal stability study of natural soils and backfills should be conducted to ascertain the cable operation parameters and the associated time required to dry the initially moist soil for different initial moisture contents and different power inputs.

3. It is very common for multiple heat sources to be located within a

close enough proximity to each other that the assumption of a single, independent heat source may not be valid. It is recommended that future experimental studies incorporate this factor in order to provide information on the heat transfer characteristics of underground thermal systems which cannot be considered as a single heat source.

4. Long-term, field experiments should be designed and conducted to evaluate the performance of the various backfill materials.

5. A comprehensive cost study should be conducted to identify the design situations for which the use of thermal backfills is economically justifiable.

6. Because of the low dry thermal resistivity of sand clay backfills, additional thermal resistivity data should be conducted on other available types of clay. Further study on limestone as an additive should be conducted. Also, different chemicals available commercially should be studied as additives to sand.

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APPENDIX

X-ray diffraction and X-ray fluorescence

analysis for tested samples

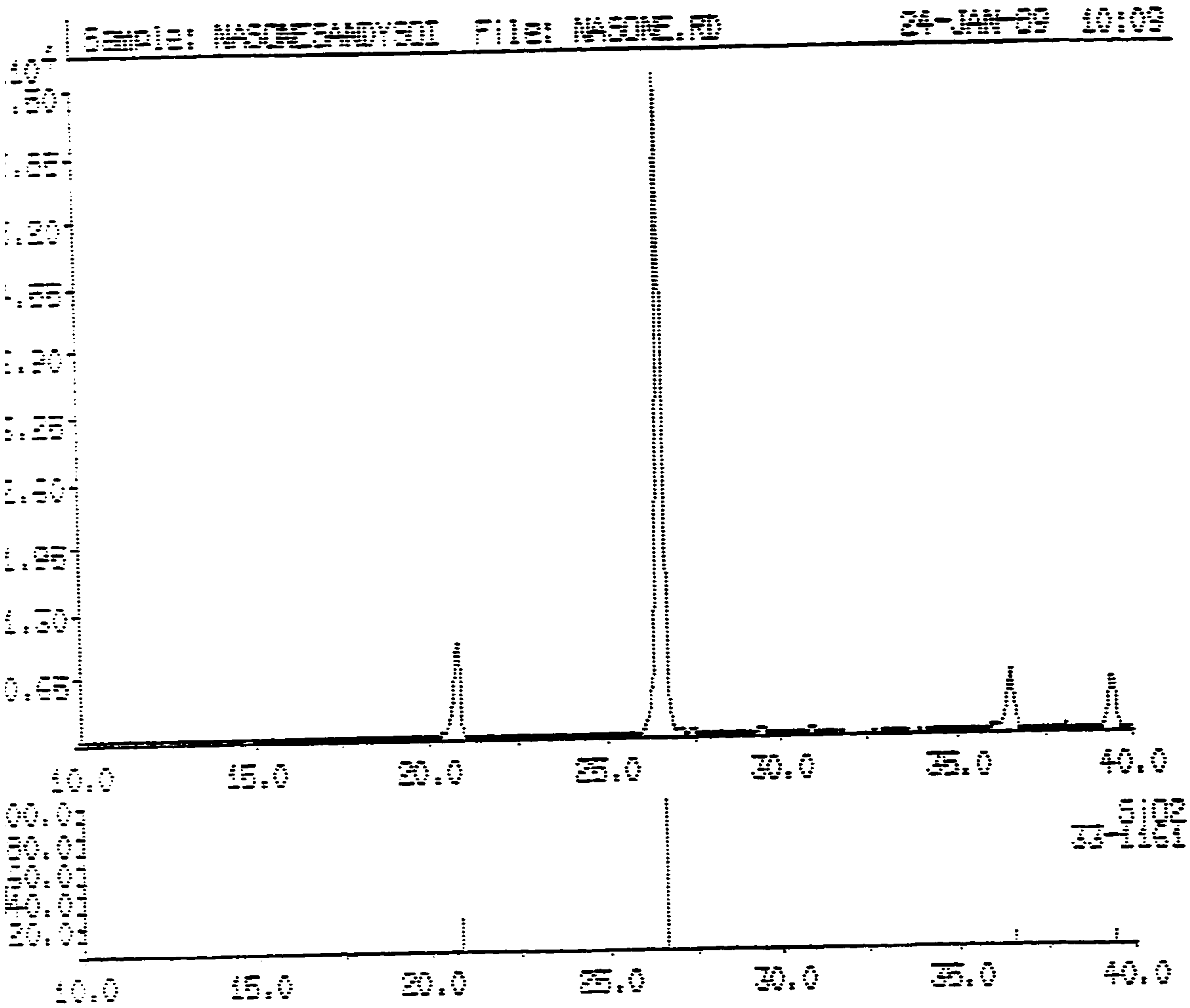

Fig. 1: X-Ray Diffraction Analysis of Sample #1 (Dune Sand)

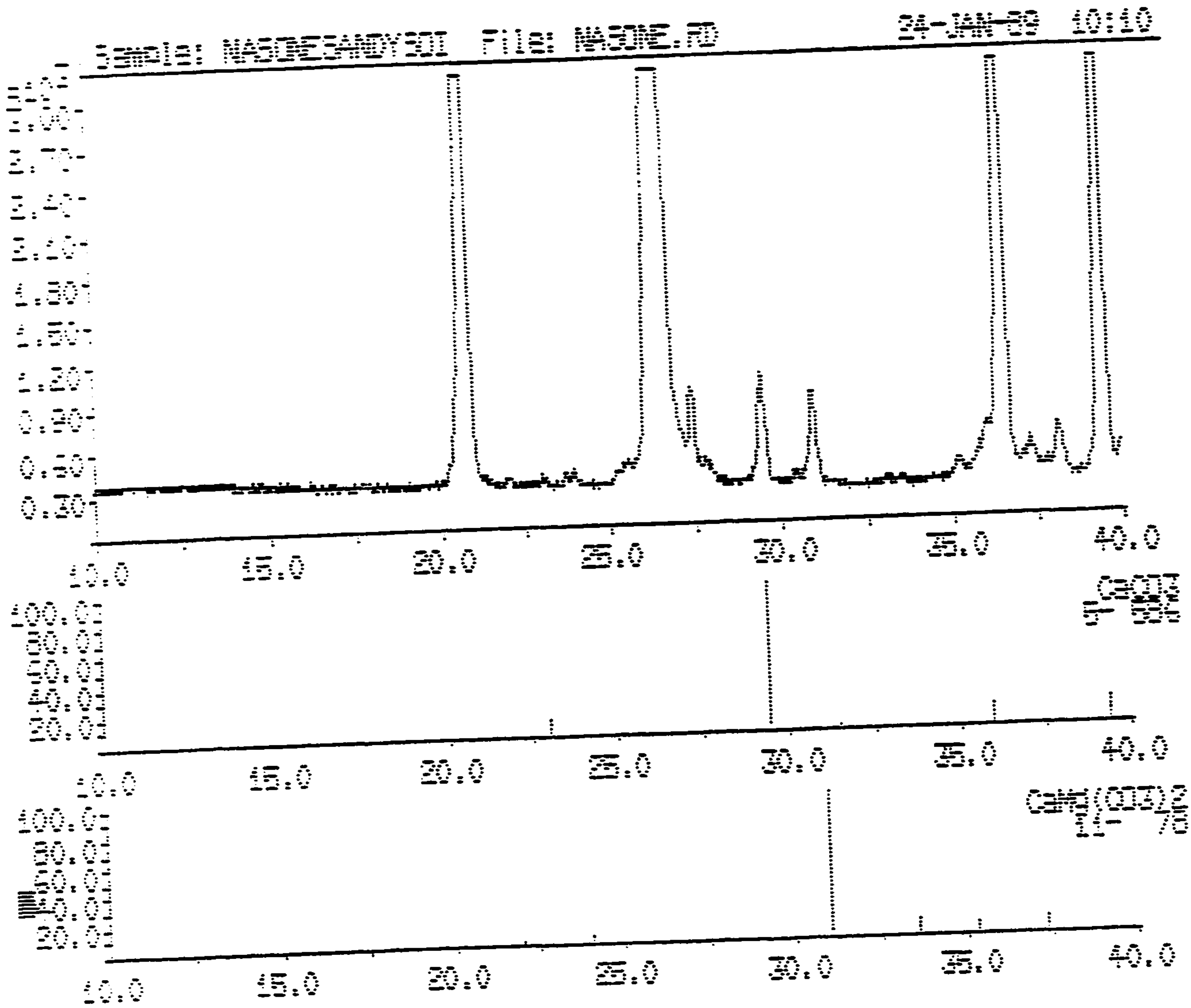

Fig. 1: X-Ray Diffraction Analysis of Sample #1 (Dune Sand) (Continued)

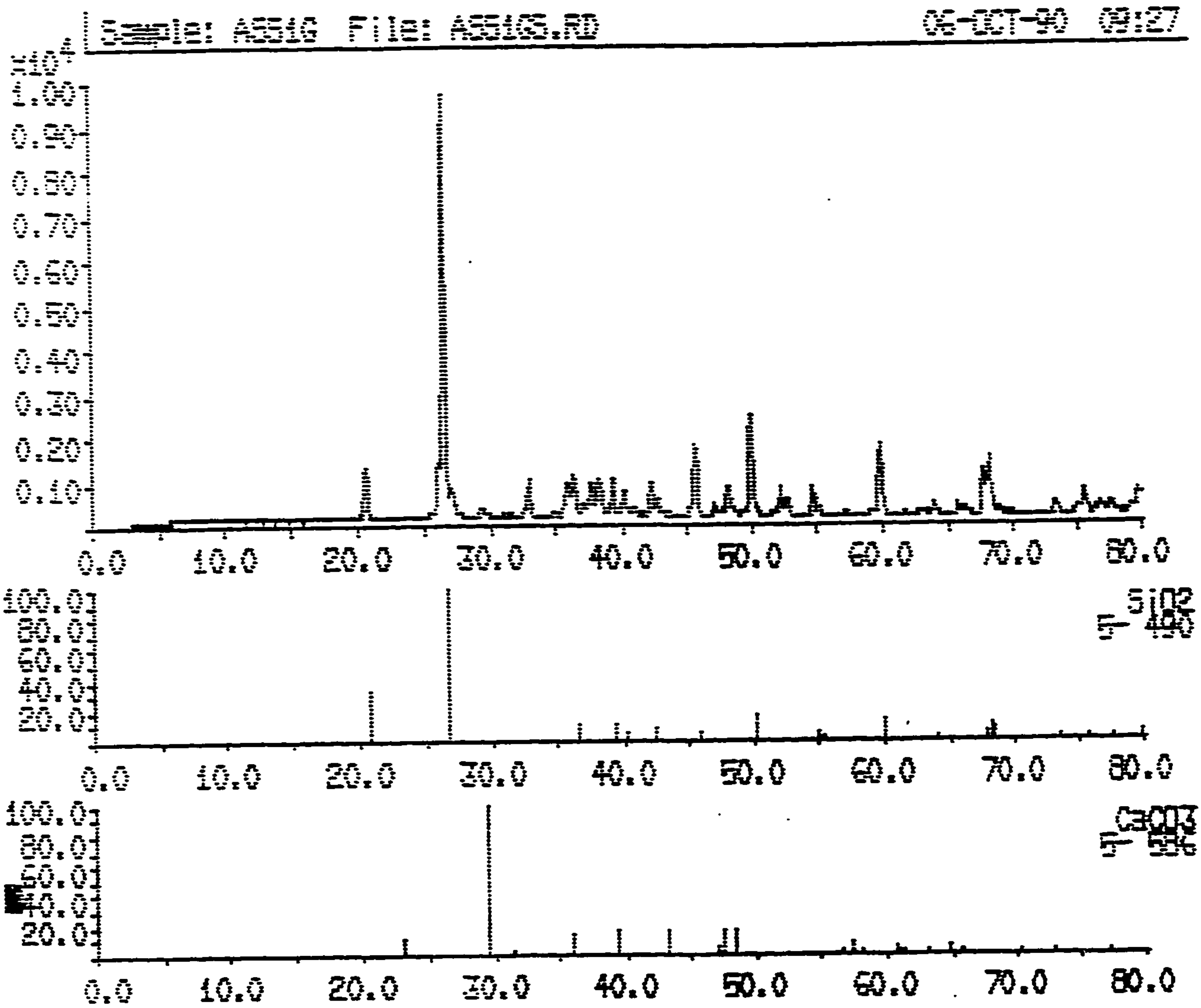

Fig. 2: X-Ray Diffraction Analysis of Sample #4 (Jubail Sand)

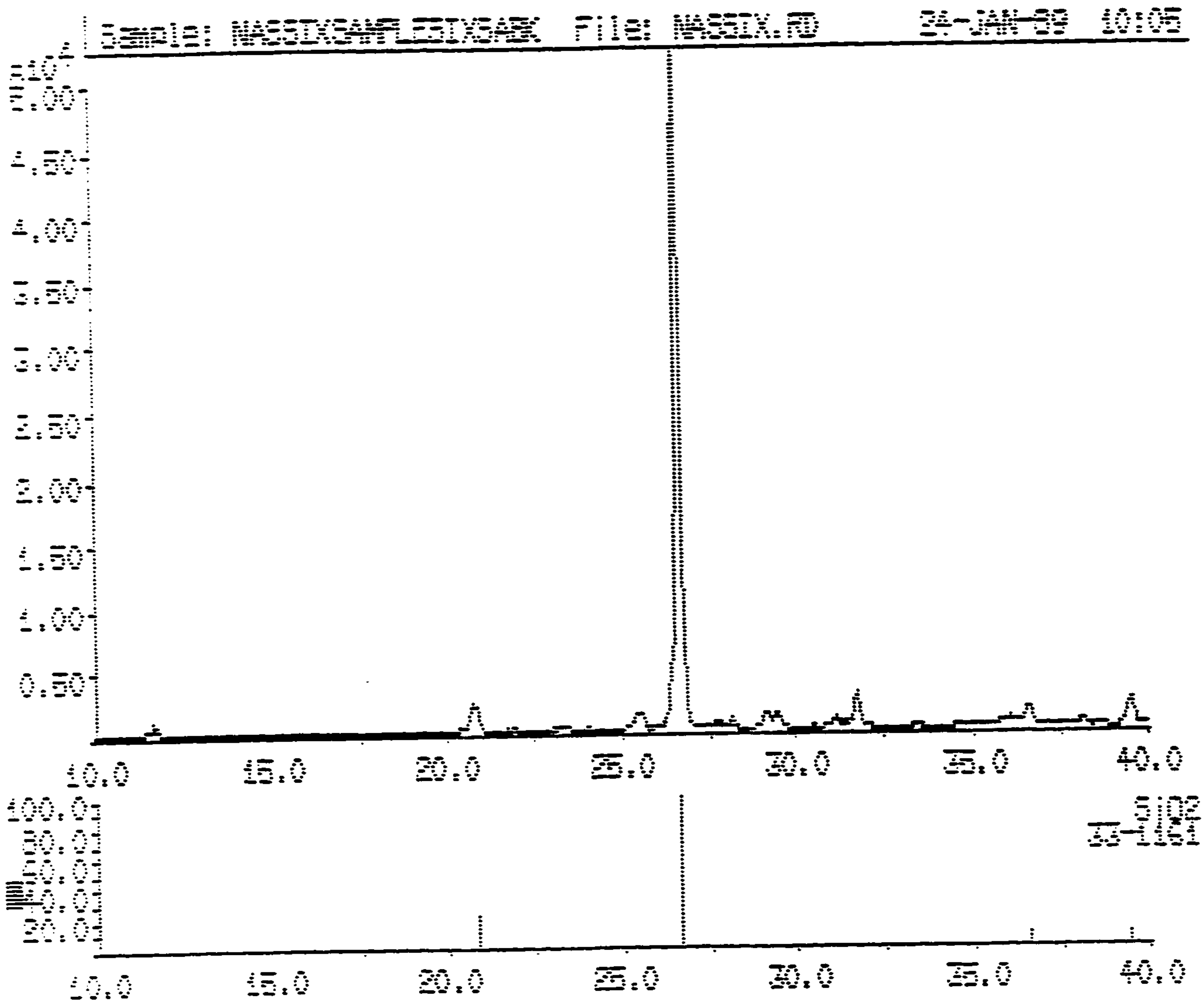

Fig. 3: X-Ray Diffraction Analysis of Sample #6 (Sabkha)

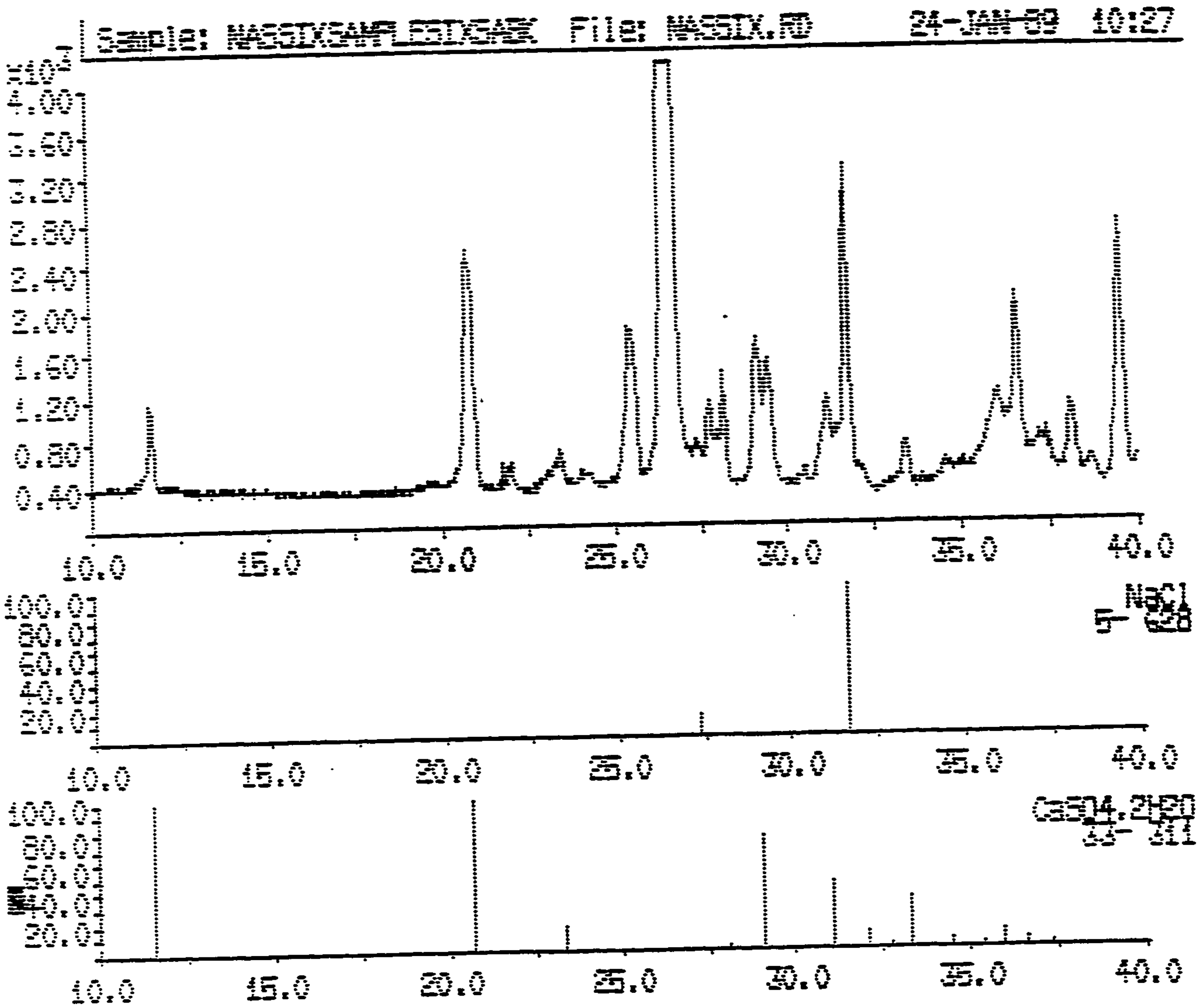

Fig. 3: X-Ray Diffraction Analysis of Sample #6 (Sabkha) (Continued)

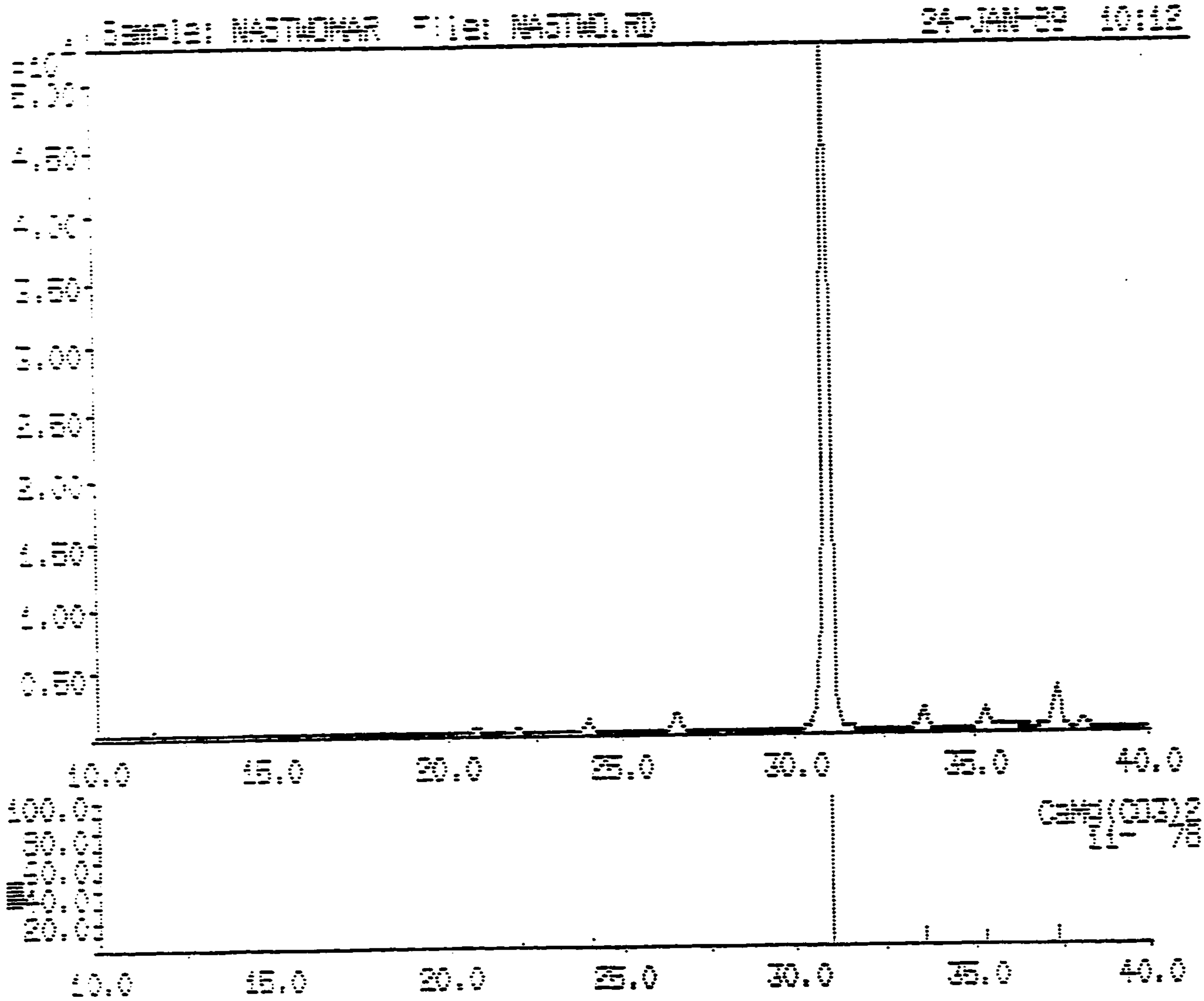

Fig. 4: X-Ray Diffraction Analysis of Sample #7 (Marl)

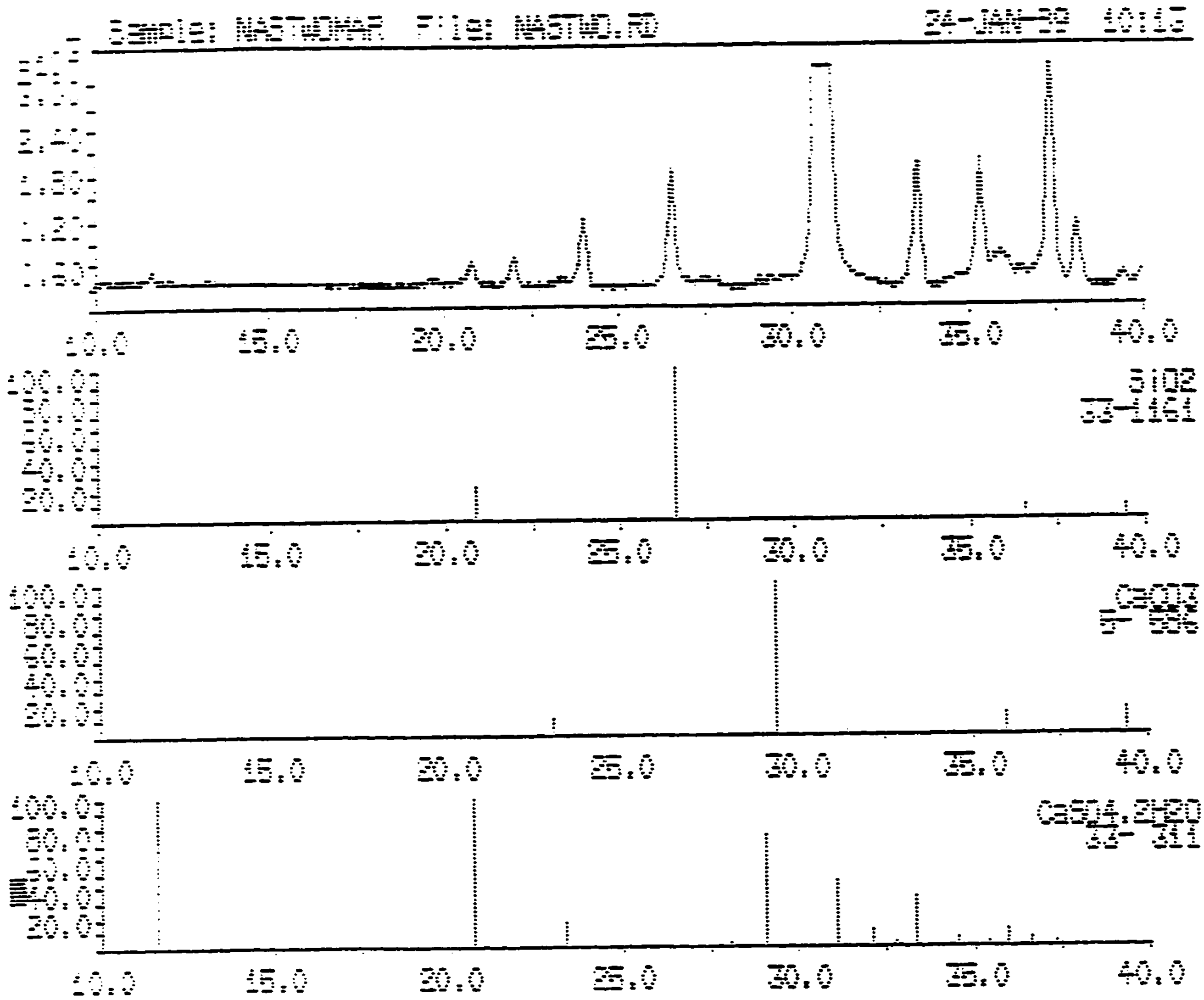

Fig. 4: X-Ray Diffraction Analysis of Sample #7 (Marl) (Continued)

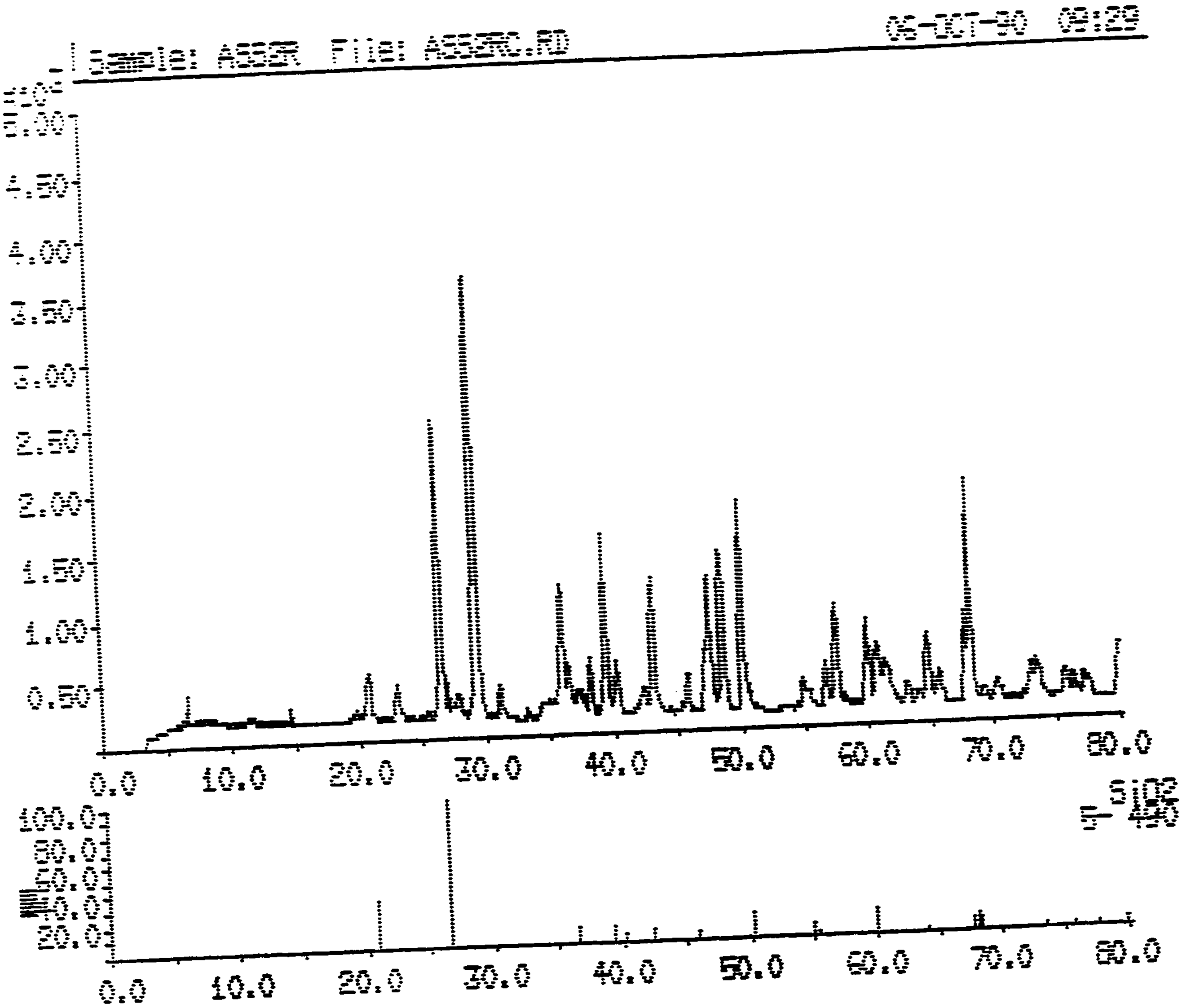

Fig. 5: X-Ray Diffraction Analysis of Sample #8 (Sandy Clay)

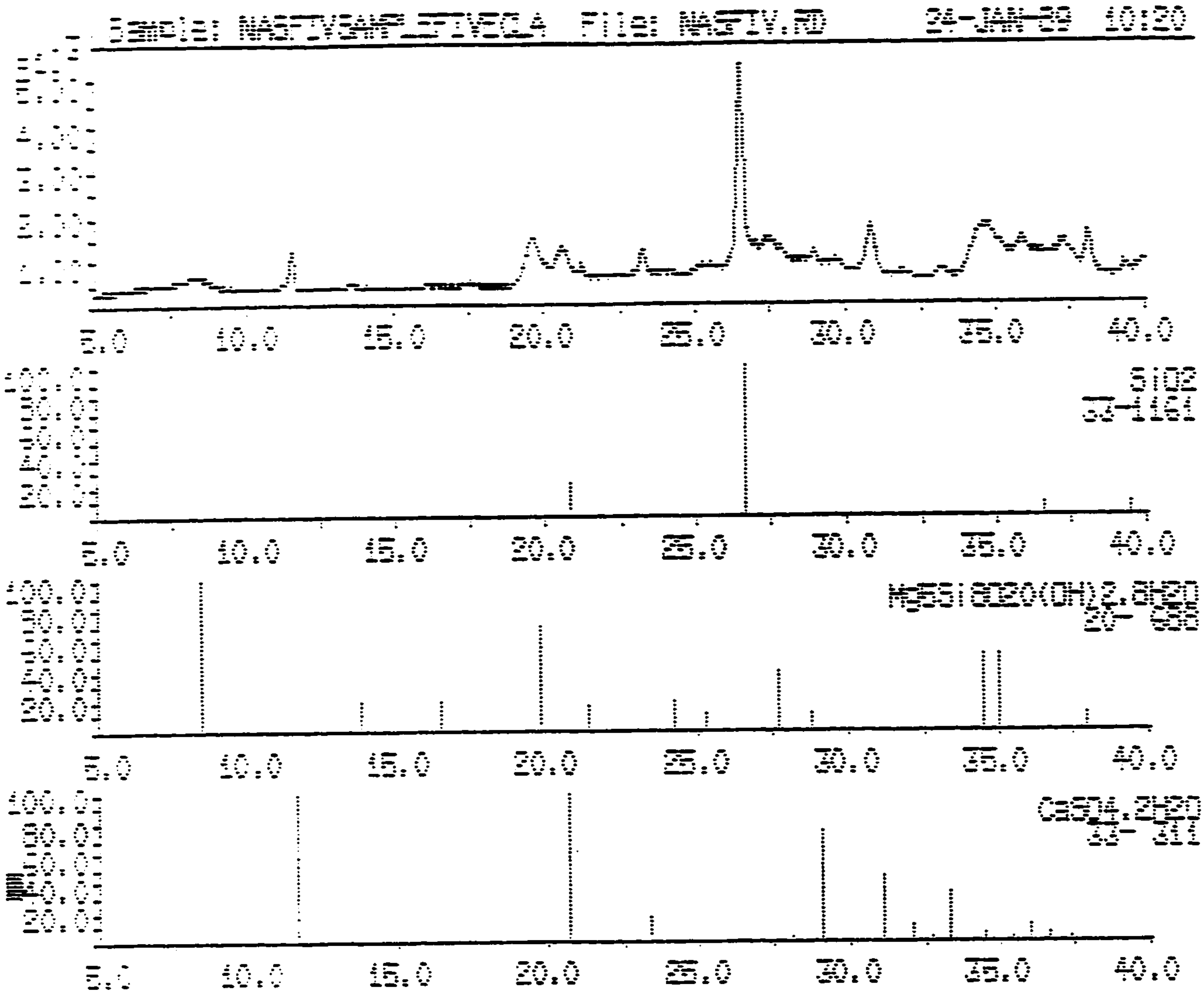

Fig. 6: X-Ray Diffraction Analysis of Sample #9 (Clay)

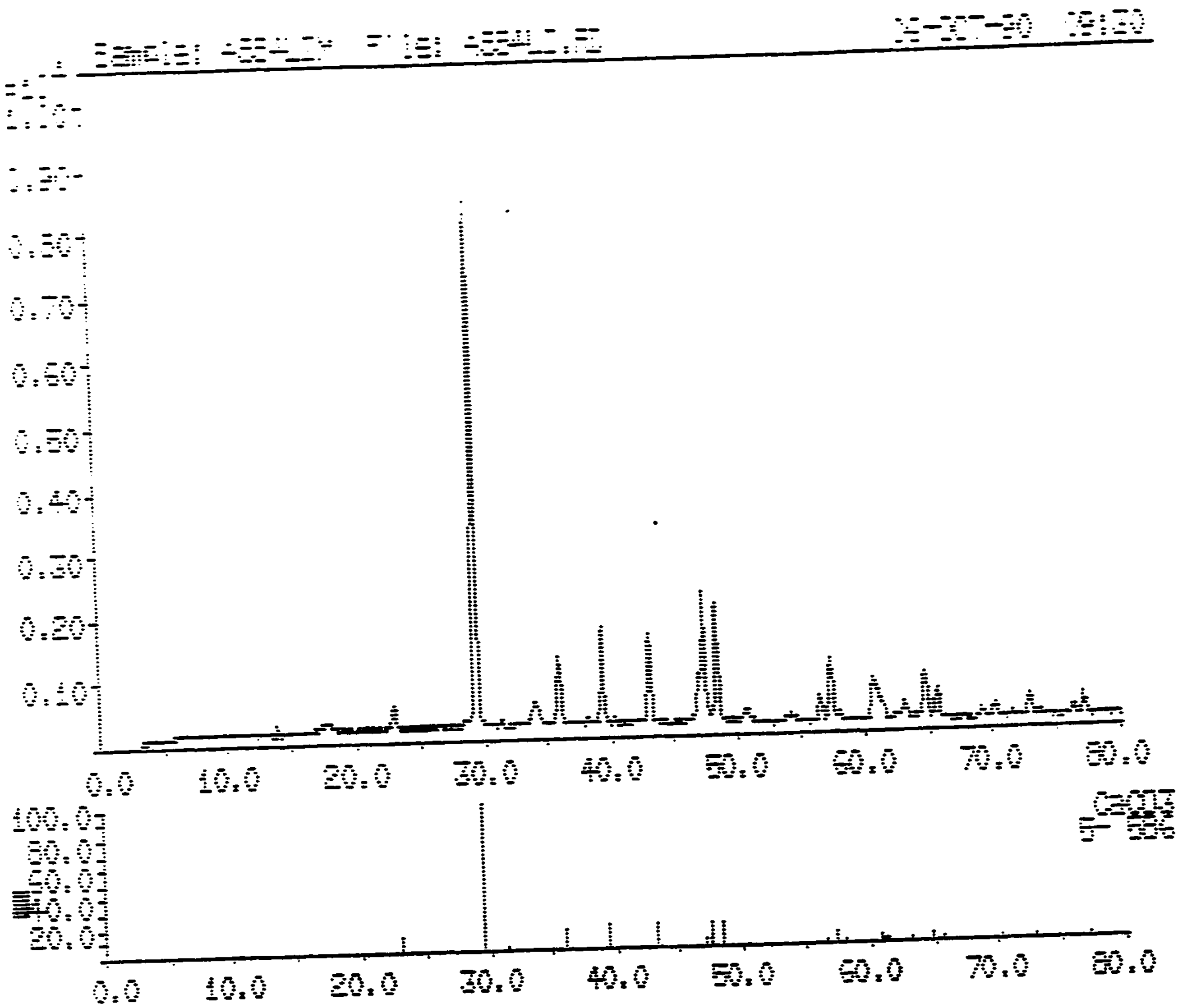

Fig. 7: X-Ray Diffraction of Limestone

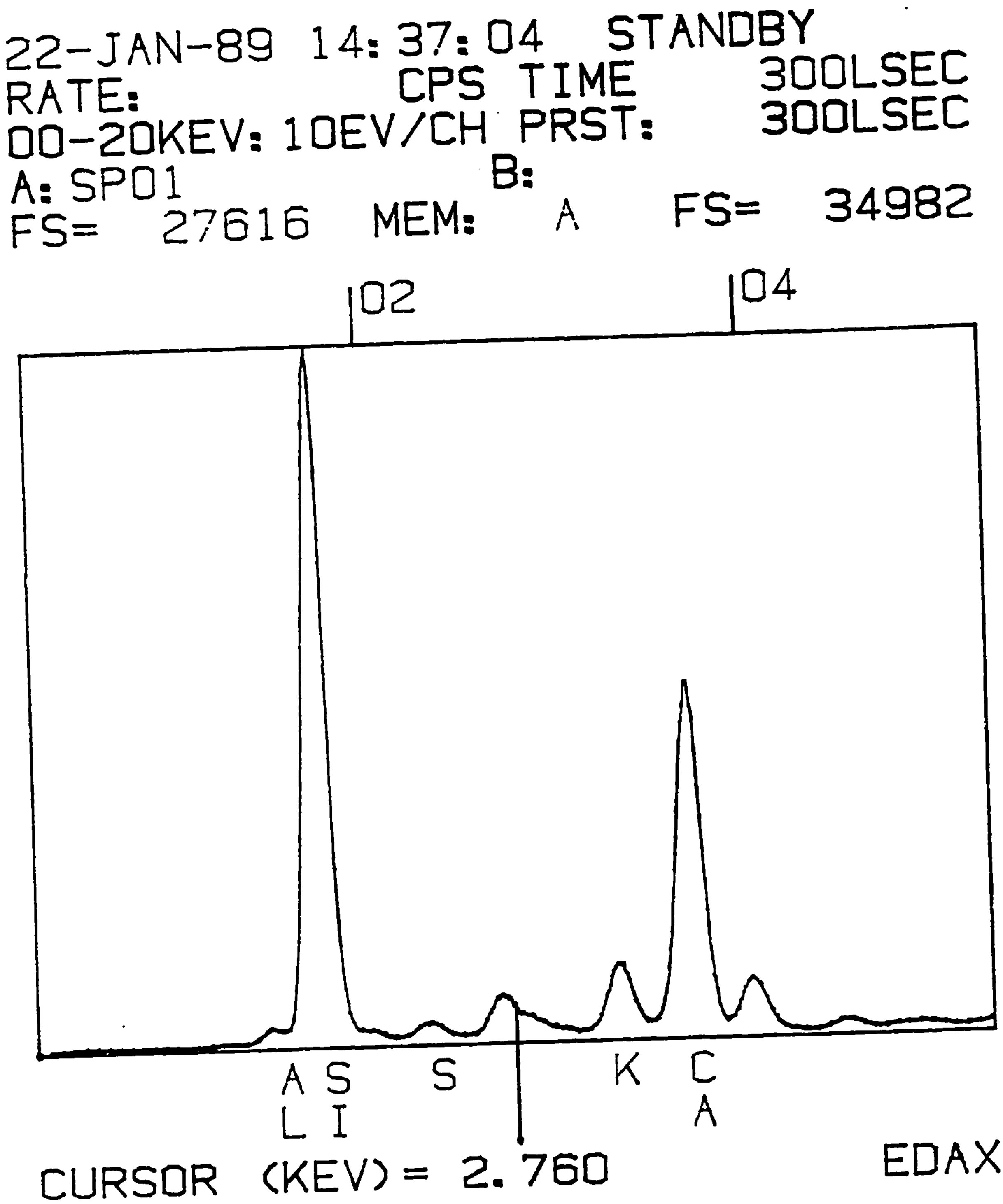

Fig. 8: X-Ray Fluorescence Analysis of Sample #1 (Dune Sand)

Table 1: The Chemical Composition of Sample #1 (Dune Sand)

Component	Conc (%)
AL OXIDE	2.555
SI OXIDE	36.645
S OXIDE	0.904
K OXIDE	4.259
CA OXIDE	55.636
TOTAL	100.000

Table 2: The Chemical Composition of Sample #2 (Beach Sand)

Component	Concentration (%)
AL OXIDE	2.555
SI OXIDE	53.201
S OXIDE	3.043
K OXIDE	4.447
CA OXIDE	37.054
TOTAL	100.000

Table 3: The Chemical Composition of Sample #3 (SCECO Backfill)

Component	Concentration (%)
AL OXIDE	2.539
SI OXIDE	62.472
S OXIDE	1.418
K OXIDE	5.571
CA OXIDE	28.000
TOTAL	100.000

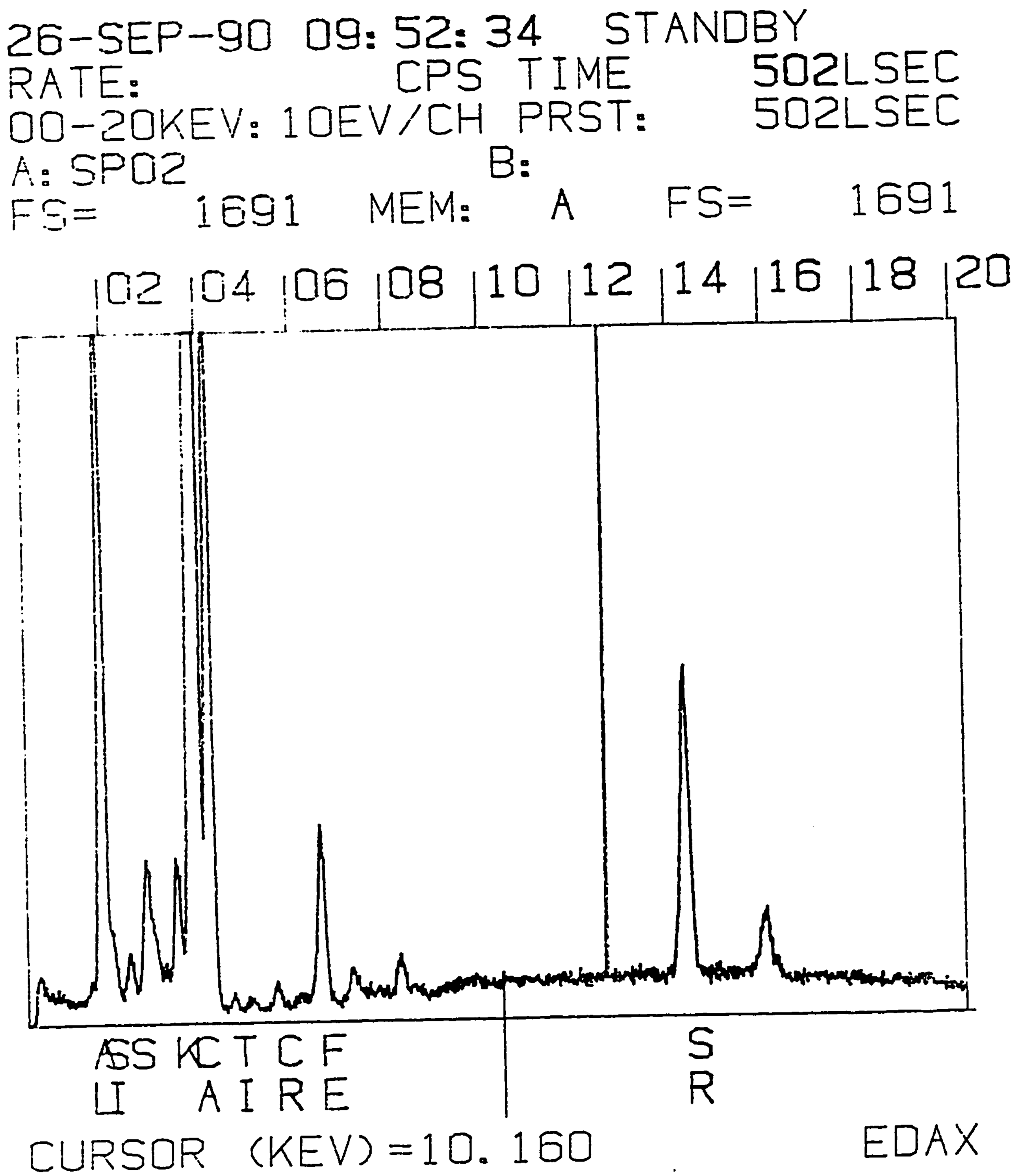

Fig. 9: X-Ray Fluorescence Analysis of Sample #4 (Jubail Sand)

Table 4: The Chemical Composition of Sample #4 (Jubail Sand)

Component	Concentration (%)
AL OXIDE	1.044
SI ODIXE	22.650
S OXIDE	0.500
K OXIDE	1.570
CA OXIDE	69.128
TI OXIDE	0.328
CR OXIDE	0.319
FE OXIDE	1.846
SR OXIDE	2.614
TOTAL	**100.000**

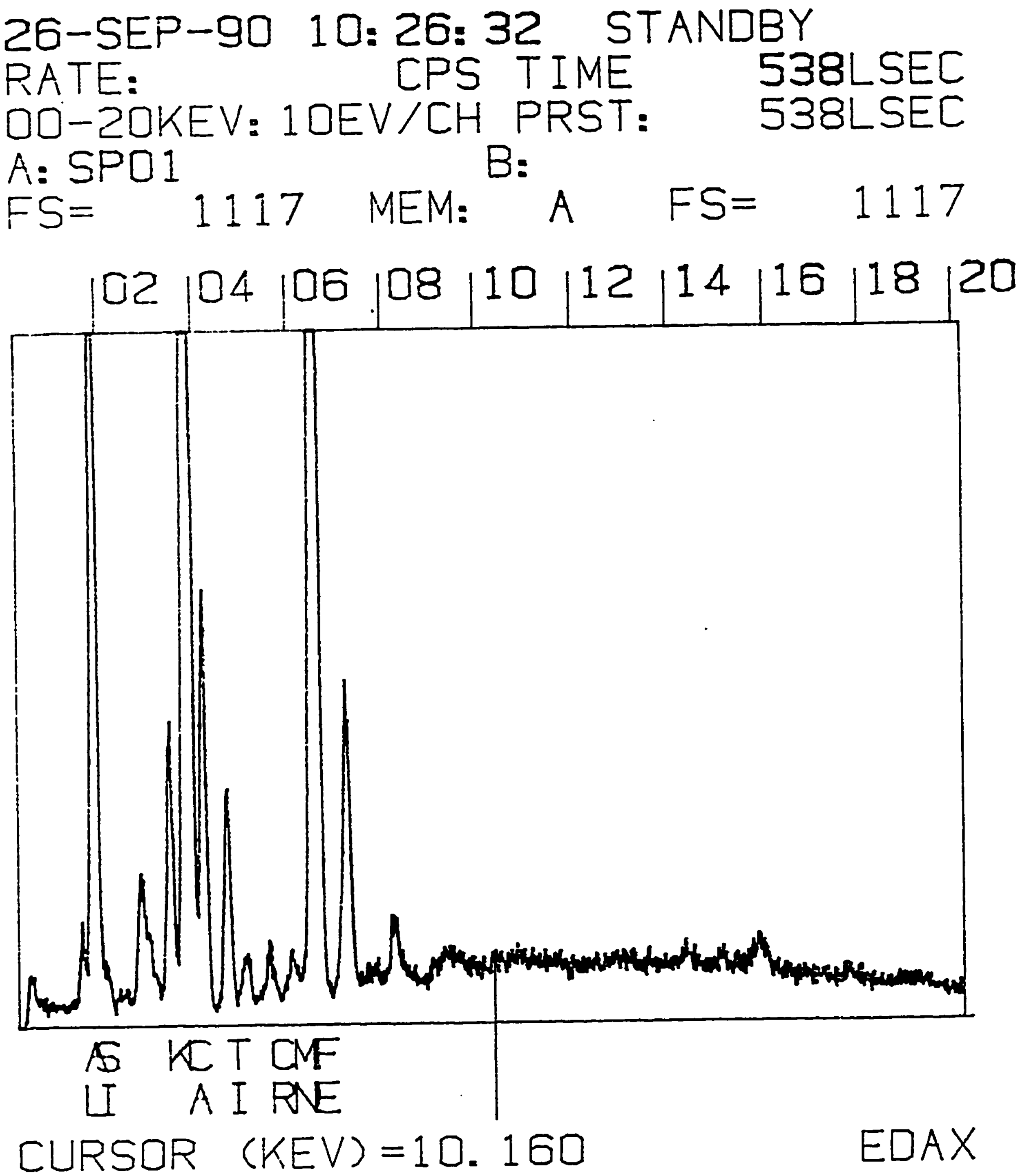

Fig.10: X-Ray Fluorescence Analysis of Sample #5 (Riyadh Sand)

Table 5: The Chemical Composition of Sample #5 (Riyadh Sand)

Component	Concentration (%)
AL OXIDE	3.782
SI ODIXE	36.564
K OXIDE	3.452
CA OXIDE	35.477
TI OXIDE	3.794
CR OXIDE	0.673
MN OXIDE	0.316
FE OXIDE	15.942
TOTAL	100.000

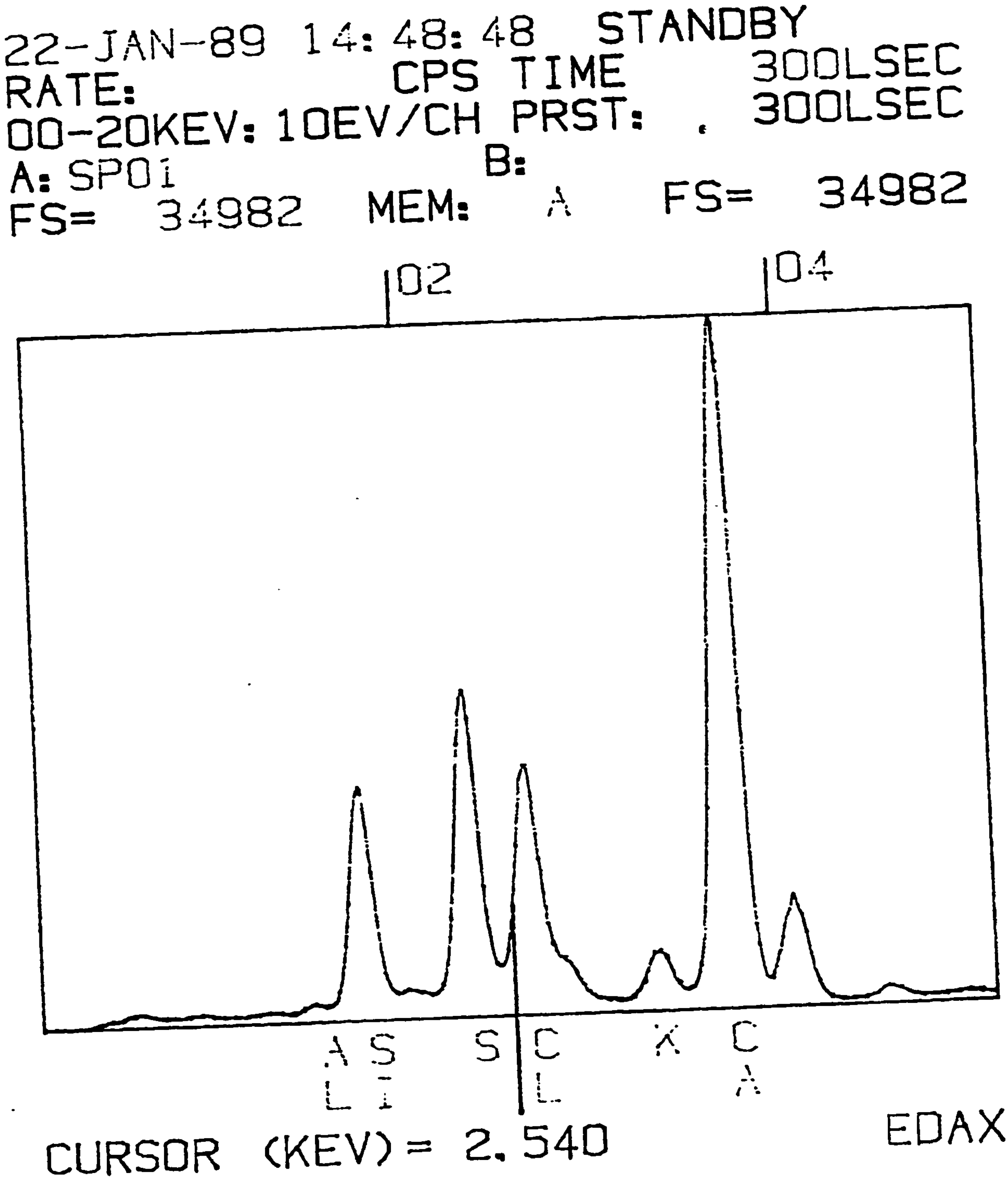

Fig.11: **X-Ray Fluorescence Analysis of Sample #6 (Sabkha)**

Table 6: The Chemical Composition of Sample #6 (Sabkha)

Component	Concentration (%)
AL OXIDE	1.450
SI ODIXE	16.866
S OXIDE	11.536
CL OXIDE	15.739
K OXIDE	3.560
CA OXIDE	50.849
TOTAL	100.000

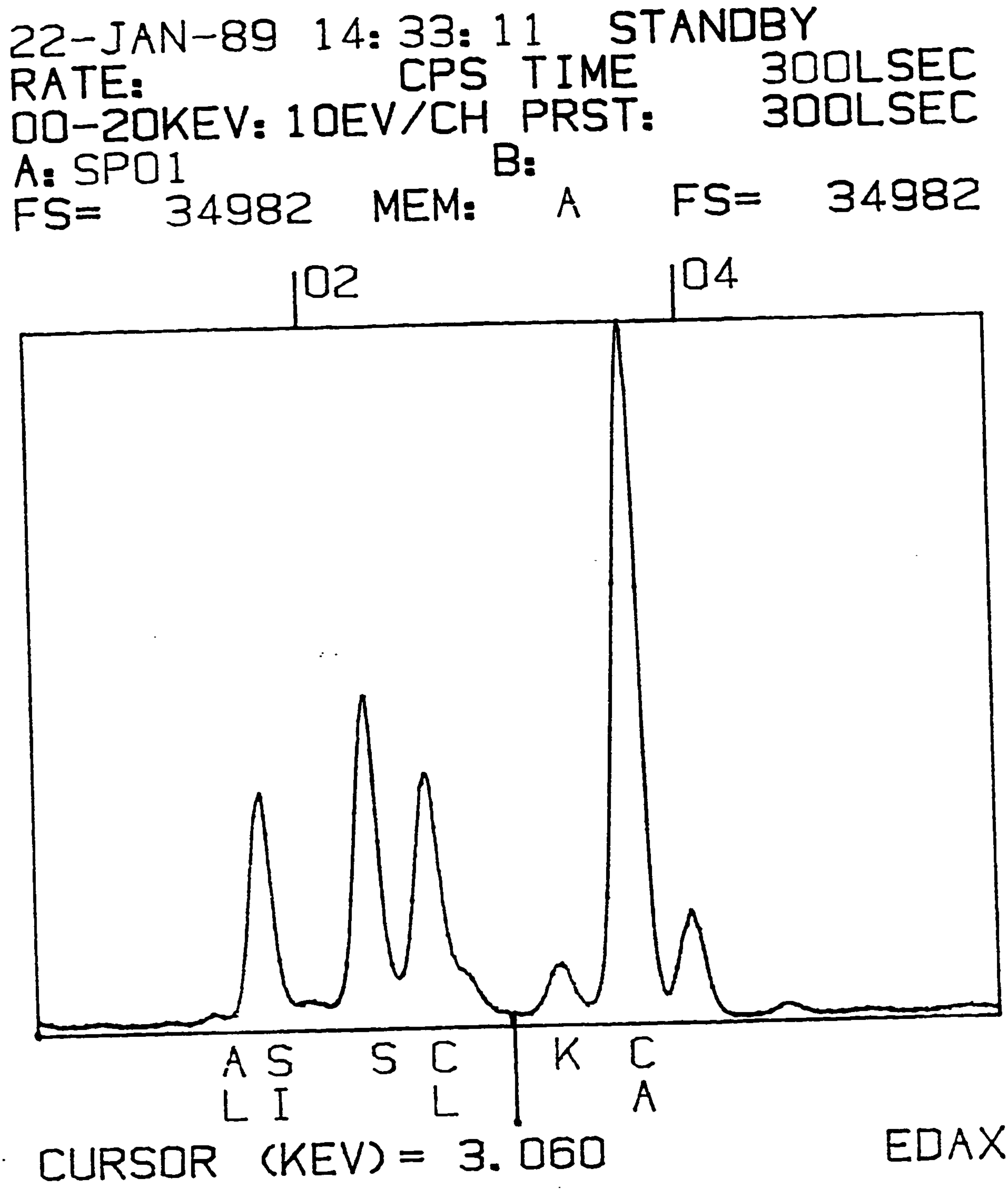

Fig.12: X-Ray Fluorescence Analysis of Sample #7 (Marl)

Table 7: The Chemical Composition of Sample #7 (Marl)

Component	Concentration (%)
AL OXIDE	0.875
SI ODIXE	5.701
S OXIDE	0.429
K OXIDE	1.745
CA OXIDE	91.251
TOTAL	100.000

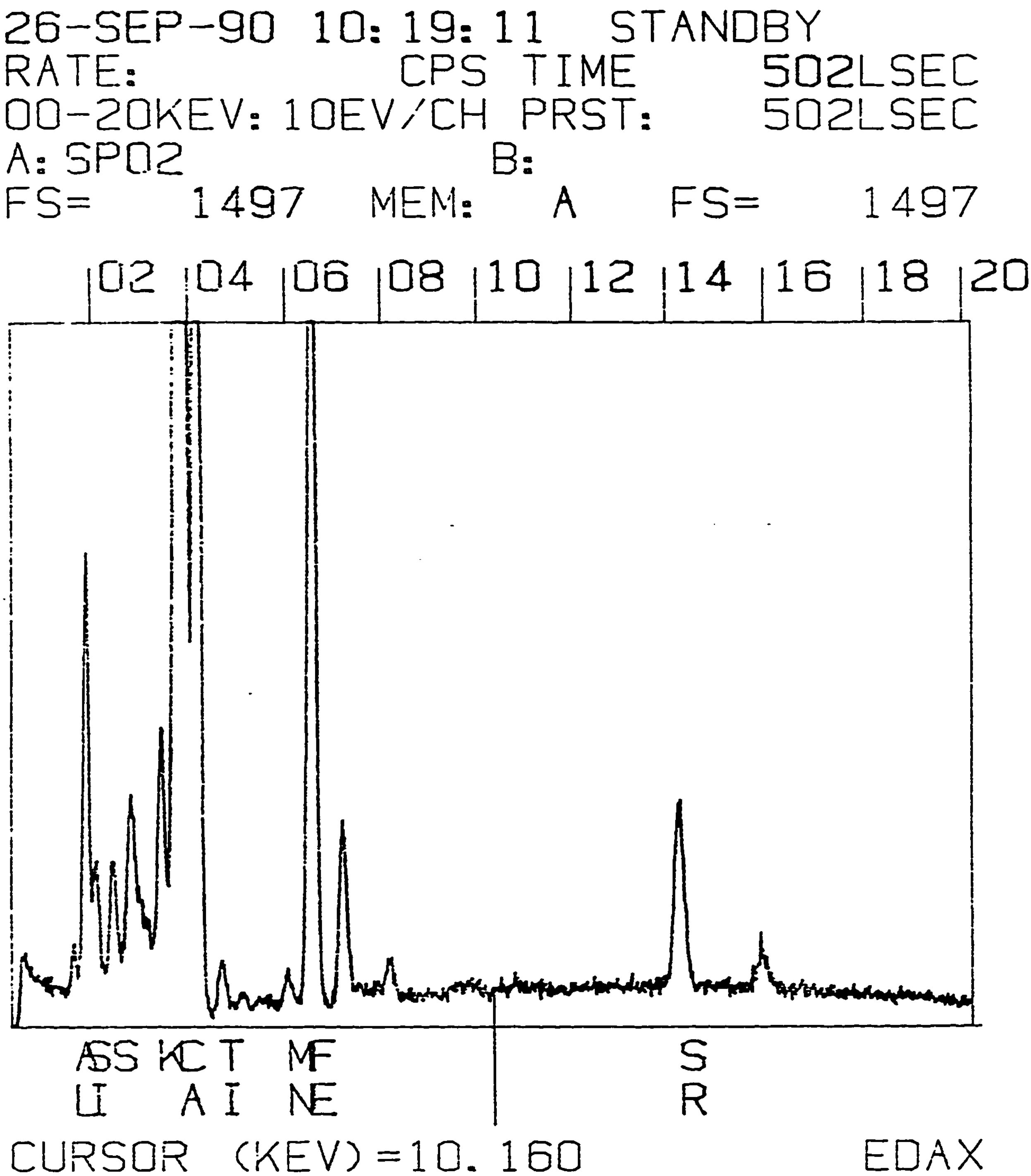

Fig.13: X-Ray Fluorescence Analysis of Sample #8 (Sandy Clay)

Table 8: **The Chemical Composition of Sample #8 (Sandy Clay)**

Component	Concentration (%)
AL OXIDE	1.361
SI ODIXE	7.410
S OXIDE	0.766
K OXIDE	1.268
CA OXIDE	79.789
TI OXIDE	0.815
MN OXIDE	0.233
FE OXIDE	6.970
SR OXIDE	1.388
TOTAL	100.000

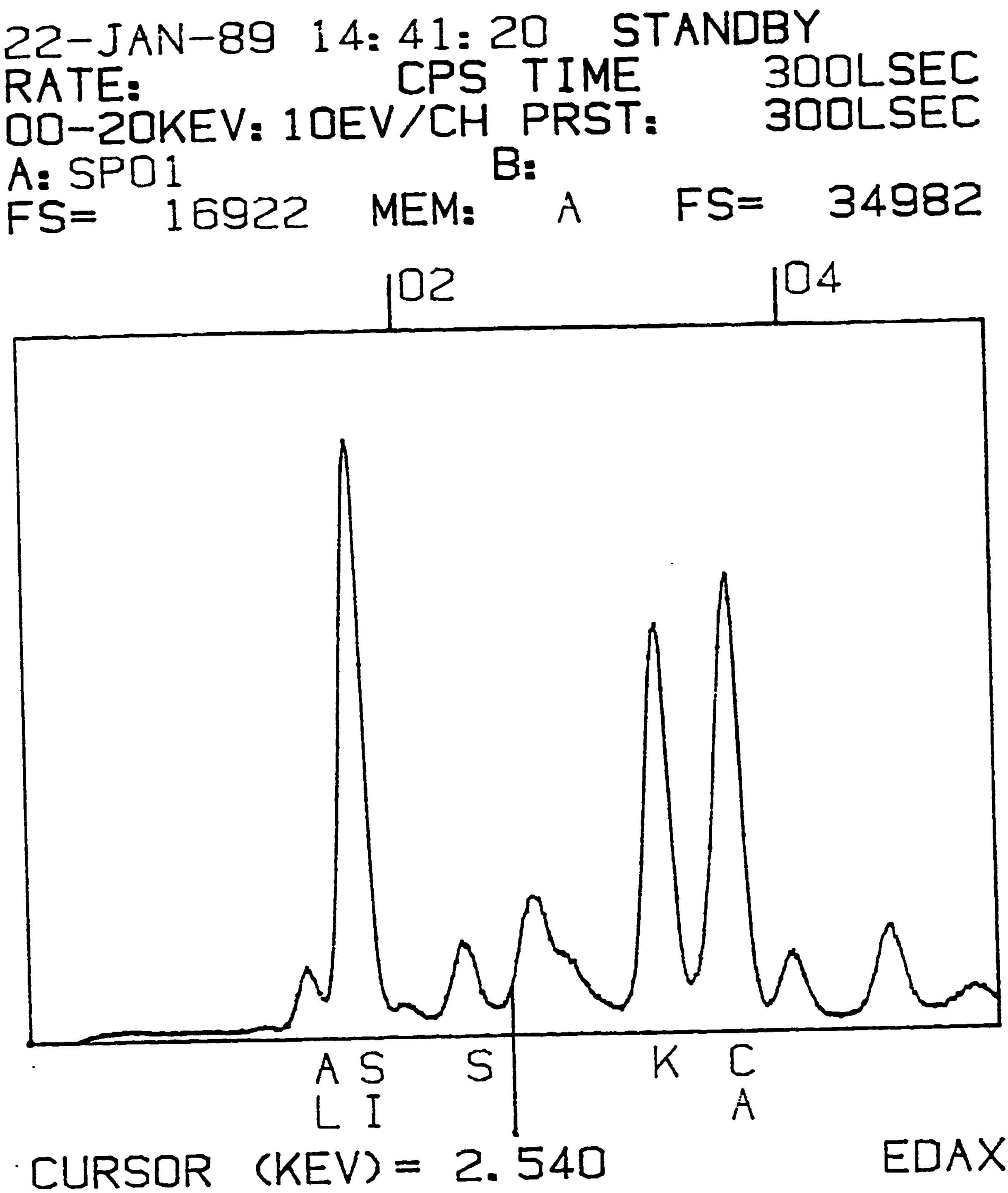

Fig.14: X-Ray Fluorescence Analysis of Sample #9 (Clay)

Table 9 : The Chemical Composition of Sample #9 (Clay)

Component	Concentration (%)
AL OXIDE	6.567
SI ODIXE	40.008
S OXIDE	3.529
K OXIDE	22.225
CA OXIDE	27.670
TOTAL	100.000

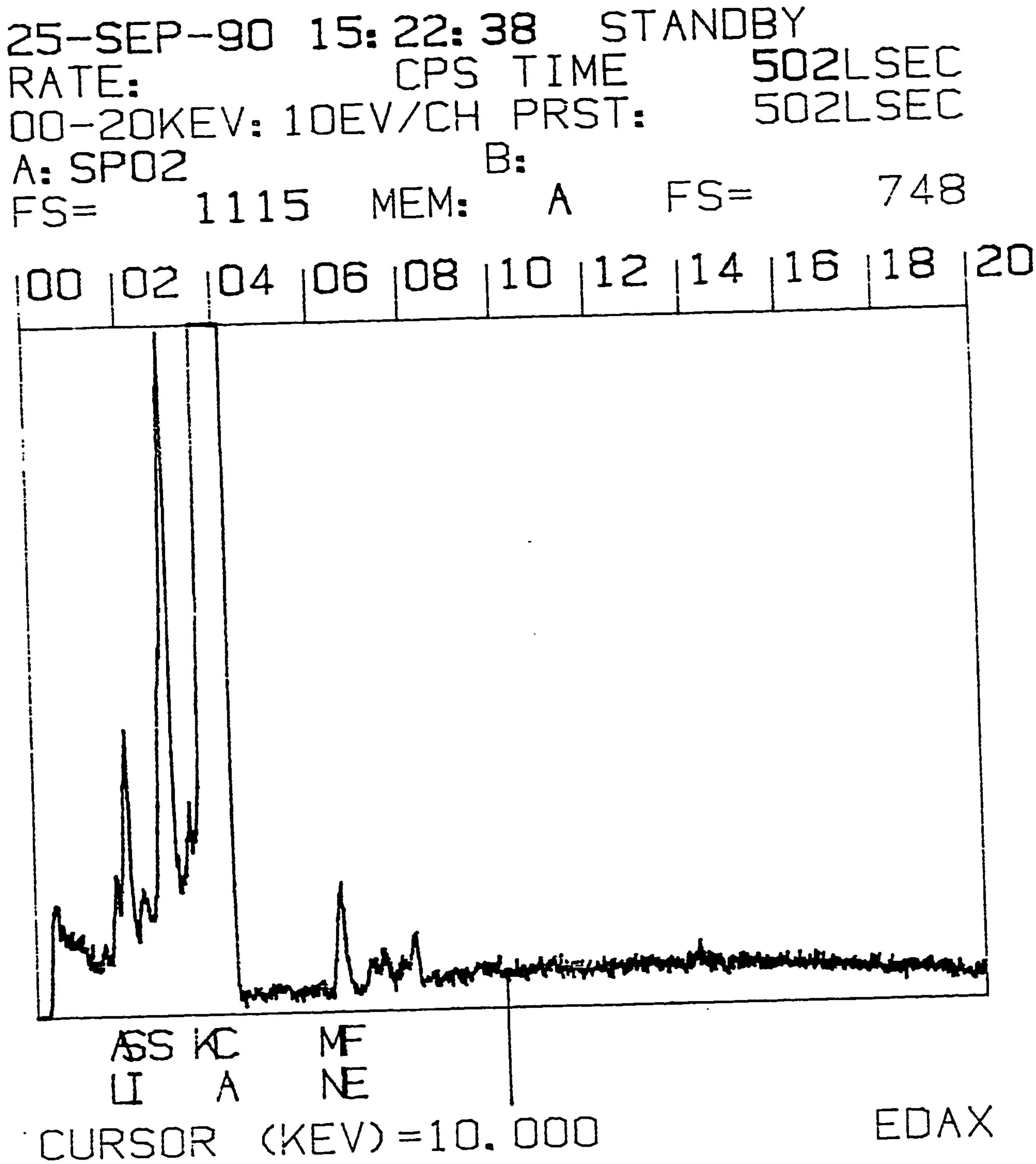

Fig.15: X-Ray Fluorescence Analysis of Limestone

Table 10: The Chemical Composition of Sample #10 (Limestone)

Component	Concentration (%)
AL OXIDE	0.316
SI ODIXE	0.826
S OXIDE	0.130
K OXIDE	0.223
CA OXIDE	97.957
MN OXIDE	0.066
FE OXIDE	0.482
TOTAL	100.000