A STUDY ON PERMEABILITY OF SOILS REINFORCED WITH RANDOMLY DISTRIBUTED FIBRES

A DISSERTATION

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requirements for the award of the degree
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By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled **"A STUDY ON PERMEABILITY OF SOILS REINFORCED WITH RANDOMLY DISTRIBUTED FIBRES"**, in partial fulfilment of the requirements for the award of Degree of **MASTER OF ENGINEERING** (Civil) with specialization in **Geotechnical Engineering** of the University of Roorkee, Roorkee is an authentic record of my own work carried out during the period from July 1995 to February 1996 under the guidance of **Dr. Gopal Ranjan**, Professor and Head, Department of Civil Engineering, University of Roorkee, Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

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Date : 20/02/96
Place : Roorkee

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Fibre reinforced soil known as "*plysoil*" is a composite material obtained by mixing randomly distributed discrete fibres to soil. The technique of fibre reinforcement is in much way similar to soil stabilization by cement, lime and other additives. The main advantages of RDFS are the simplicity in mixing, maintenance of strength isotropy and absence of potential planes of weakness which may develop parallel to the oriented reinforcement.

RDFS having got numerous advantages, it has been considered as an alternative to granular material in stone/granular piles. Various studies have been reported on load-deformation behaviour of clay treated with sand-fibre columns. However, only a few studies have been reported on the compressibility characteristics of clay treated with sand-fibre columns.

The present study is aimed to study the compressibility characteristics of clay treated with sand-fibre columns. A well planned consolidation test programme, to study the influence of various parameters viz., relative core area (defined as the ratio of area of sand-fibre column to the area of clay sample) and fibre characteristics (fibre type and fibre content), have been carried out on locally available clay treated with sand-fibre columns. The relative core areas have been varied from 0.00 to 0.44. Two types, namely synthetic (polypropylene) and natural (coir), of fibre have been used to study the influence of type of fibre. The effect of fibre content has been studied with 1% and 2% fibre contents.

An exhaustive and well planned permeability test programme has been carried out to study the permeability characteristics of RDFS. The influence of various parameters viz., soil type, dry density and fibre characteristics (fibre type, fibre content and aspect ratio) has been investigated. Two types of soils namely sand and silt have been used to study the permeability of fibre reinforced soil. The effect of dry density

has been investigated through three different densities (1.00 γ_{dmax}, 0.95 γ_{dmax} & 0.90 γ_{dmax}). The effect of type of fibre has been brought out by considering two types of fibres namely synthetic (polypropylene) and natural (coir). Also, the effect of fibre content has been investigated by varying it from 0.5 to 4%.

Analysis of consolidation test results indicates that there is decrease in the compressibility of clay with the introduction of sand-fibre columns and further, compressibility of composite clay decreases with increase in relative core area. A significant decrease in the volume compressibility coefficient as well as compression index of composite clay has also been observed. Whereas consolidation of clay expedites with the introduction of sand-fibre column.

The permeability tests indicate that randomly distributed fibre reinforced sand is isotropic as far as coefficient of permeability is concerned.

The results of permeability tests indicate that the permeability of soil decreases initially with the addition of synthetic fibres and later increases with the further addition of synthetic fibres. This trend is identical to synthetic and natural fibers tested. Further the aspect ratio of fibre has practically no influence on the permeability of RDFS.

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CHAPTER - I

INTRODUCTION

1.1 GENERAL

Utilization of poor subsoil deposits for Civil Engineering construction poses the problem of low bearing capacity and excessive settlements spread over long periods of time. Technically viable and economically feasible approaches to utilize these poor subsoil deposits are different ground improvement techniques. Though the basic concepts of ground improvements namely densification, drainage etc. are age old and are still valid, however, efforts are on to develop better and still better methods for ground improvement (Ranjan, 1989). The present trend emphasizes on "soil-reinforcement" i.e., reinforcing soil in different forms using different materials. Reinforcement in the form of sheets, strips, bars, grids or fabric is introduced in the soil to improve the overall soil behaviour. This material is termed as "reinforced earth".

In such an orderly reinforced soil, a possible disadvantage is that the strengthening is confined to specific directions with possible weakness in other directions or surfaces (McGown et al, 1978). Further, skilled labour is required to place the reinforcement at preferred directions in different layers.

Recent studies (Charan, 1995) indicate that soil characteristics can be improved by mixing randomly distributed discrete fibres to the soil. This randomly distributed fibre reinforced soil known as 'plysoil' (Mc.Gown et.al,1978) is similar to stabilization by admixture in its preparation. The discrete fibres are simply added and mixed with soil much the same way as cement, lime or other admixtures. One of the prime advantage of randomly distributed fibre reinforced soil is the maintenance of strength isotropy with absence of potential plane of weakness that may develop in case of the oriented reinforcement. Further, the fibre-reinforcement causes significant improvement in shear strength, behaviour as an anisotropic material with increased effectiveness and bearing capacity (Busching et.al, 1969).

Randomly distributed fibre reinforced soils (RDFS) can be advantageously utilized as a ground improvement technique, in the case of embankments, subgrade and in similar other problems. Sand-fibre columns may also be utilized to treat deep deposits of soft clay.

1.2 OBJECTIVE OF STUDY

A large number of ground improvement techniques are currently available (Ranjan 1989, Rao 1993). Designers have option to choose a particular technique, depending upon the site conditions and economic viability. Many of the ground improvement techniques e.g., preload actuated sand drains, band drains, granular piles/stone column, serve as means of expediting excess pore water dissipation and accelerating settlement rates in addition to the reinforcing effect they provide.

Gray and Al-Refeai (1986) suggested sand-fibre columns as an alternative to granular piles to stabilize soft/weak clay deposits. Recent studies (Pan et.al. 1994, Singh 1995) on triaxial compression tests and consolidation tests on soft clay samples installed with mandrels of cement mixed soil and randomly mixed fibre reinforced sands have established the utility of RDFS columns. However, the permeability of RDFS is the most important property which plays a significant role in establishing their suitability. Since, only scanty information is available on the subject, it has been planned to study the isotropy and permeability characteristics of randomly distributed fibre reinforced soil. Further, consolidation tests are planned to establish the suitability of plysoil (RDFS) as an alternative to the granular material used in stone/granular piles.

In order to investigate the suitability of "RDFS" as an alternative to the granular material used in stone/granular piles, consolidation tests have also been conducted to study the effect of various parameters.

- Fibre parameters - fibre type, fibre content.
- Soil-parameters - relative core area

The permeability characteristics of "RDFS" has been studied to bring out the influence of various parameters

* Soil parameters - soil type and dry density.
* Fibre parameters - fibre type, fibre content and aspect ratio.

1.3 ORGANIZATION OF THESIS

The thesis has been presented in five chapters. A brief scope of each chapter has been outlined in the following paragraphs.

Chapter I deals with the introduction part. A brief introduction about soil reinforcement techniques and the object of present study has been highlighted.

Chapter II presents the review of literature on soft-clay improvement techniques. A detailed review pertaining to the sand-fibre columns has been presented. Various strength characteristics of "RDFS", in terms of shear strengths and unconfined compressive strength values has been dealt in detail and critically reviewed.

Chapter III describes the details of experimental programme and properties of the material used. The preliminary tests carried out to determine the various properties of materials used are also described. The description of equipments used, methods of preparing samples and testing procedures have been given in detail.

Chapter IV brings about the analysis of test results and their discussion. The effect of various parameters on the behaviour of composite sample and on the permeability of randomly distributed fibre reinforced soil has been discussed in detail.

On the basis of the present study the conclusions drawn have been presented in Chapter VI.

REVIEW OF LITERATURE

2.1 INTRODUCTION

Soil improvement is one of the oldest but, still the most intriguing technique of all common execution methods of Civil Engineering. Though, the basic concepts of ground improvement, viz., drainage, densification, cementation, reinforcement, drying and heating are age old and are in practice even today, yet efforts to develop better and still better techniques for soil improvement are going on to force the soil to behave according to the project requirements rather than having to change the project to meet the limitations due to weak subsoil.

In an endeavour to develop the new techniques for ground improvement, Vidal in 1960, developed a new technique, known as "reinforced earth" for the improvement of soil. The concept of reinforcing the soil is not new, the basic principles are demonstrated abundantly in nature by the action of roots. The construction of clay bricks reinforced with reeds or straw are known to have been used in 5th and 4th century B.C. Chinese used wood, bamboo, strew etc.as means of reinforcement for the soil improvement.

Vidal's concept of reinforcing the soil, is based on the concept of development of interaction between the soil and reinforcement due to soil reinforcement friction. This resultant interaction between the soil and reinforcement transmits the stresses in the soil mass to the reinforcement and thereby, the reinforcement under stress in soil behaves as a homogeneous composite material with improved engineering properties. Vidal's "reinforced earth" concept has set another mark for the rapid development of ground improvement techniques. Much fundamental work has been carried out by Laboratories de Points et Chauses (LCPC) in France (Schlosser, 1977), Dept. of Transport, United States (Walkinshaw, 1975) and Department of Transport United Kingdom (Murrey 1977). This work led to the introduction of improved forces of reinforcement e.g. geo-fabric, geo-grid etc. (Forsyth, 1978).

This has again led to various forms of reinforcements, either in form (stips, sheets, grids, bars or fibres), texture (rough or smooth), or relative stiffness (high such as steel or low such as fabrics and fibres). A distinction has been made by Mc.Gown et al. (1978), between high modulus and low modulus reinforcements. He classified them into two major categories : (a) ideally inextensible inclusions (i.e. metal strips and bars) and (b) ideally extensible inclusions (i.e. natural and synthetic fibres, plant roots and polymeric fibres). The soil reinforced with inextensible inclusions is generally known as "reinforced earth" (Vidal, 1969) whereas the soil reinforced with extensible inclusions is termed as "plysoil" (McGown, et al, 1978).

The comparative behaviour of *"reinforced earth"* and *"plysoil"* has been presented in Table 2.1.

A glance of Table 2.1 indicates that the plysoil (RDFS) provides strengthening of soil. More importantly it provides greater extensibility (ductility) and smaller loss of post peak strength as compared to soil alone or to reinforced earth.

Having established that the "plysoil" has numerous advantages, studies are in progress to study the suitability of this *"plysoil"* as an alternate material for cement columns/lime columns/granular columns for the improvement of soft clay deposits.

As the scope of soil improvement is very wide, the present review of literature has focussed only to the techniques for improvement of deep soft clay deposits.

2.2 TECHNIQUES FOR IMPROVEMENT OF SOFT CLAYS

A large number of methods have been developed to increase the bearing capacity and to reduce the settlements of deep soft clay deposits. The application of these methods depends on several parameters such as shear strength, compressibility and permeability and thickness of compressible layers, type of structures and economy. Broms(1985) indicated

Table :2.1

Comparative Behaviour of Soil Reinforcement (McGown, et al., 1978)

Type of reinforced soil	Type of reinforcement	Stress-strain behaviour of reinforcement	Role and function of reinforcement
Reinforced earth (Vidal, 1969)	Ideally inextensible inclusions (metal strips, bars, etc.) $E_r/E_s > 3000^*$	Inclusions may have rupture strains which are less than the maximum tensile strains in the soil without inclusions, under the same operating stress conditions ; i.e. $(\varepsilon_r)_{rup} < \varepsilon_{max}$ Depending on the ultimate strength of the inclusions in relation to the imposed loads these inclusions may or may not rupture.	Strengthens soil (increases apparent shear resistance and inhibits both internal and boundary deformations. Catastrophic failure and collapse of soil can occur if reinforcement breaks.
"Plysoil" (McGown et al, 1978)	Ideally extensible inclusions (natural and synthetic fibres, roots, fabrics "geotextiles") $E_r/E_s < 3000^*$	Inclusions may have rupture strains greater than the maximum tensile strains in the soil without inclusions, i.e. $(\varepsilon_r)_{rup} > \varepsilon_{max}$ These inclusions cannot rupture, no matter their ultimate strength or the imposed load.	some strengthening but more importantly provides greater extensibility (ductility) and smaller loss of post peak strength compared to soil alone or to reinforced earth

$^*E_r/E_s$ = the ratio of reinforcement modulus (longitudinal stiffness) to average sand modulus. The limits shown are tentative.

methods of the stabilisation of soft soils

(a) Drains such as geodrain, alidrain, colbond etc.
(b) Lime columns
(c) Cement columns
(d) Grouting
(e) Stone columns/Granular piles.

2.2.1 Sand Drains

Moran (1926) was the first to introduce sand drains to improve the drainage of soft clay deposits and to reduce time for consolidation. It has been reported (Broues, 1979) that sand drains increase the consolidation rate mainly during the primary phase while the effect in the rate of secondary consolidation in general is small. A number of methods (Barden and Younary, 1969) have been proposed to analyze the effectiveness of sand drains which take into account factors such as the smear zone around, the change of permeability and compressibility of the soil that takes place during consolidation.

The basic equations governing radial flow were derived by Boron (1947) and by Kjelwan (1948). Carillo (1942) has shown that the pore pressure distribution at both radial and vertical flow can be determined by combining the solutions for radial and vertical flow. The degree of consolidation (U) at both radial and vertical flow can be determined from the equation.

$$(1 - U) = (1 - U_r)(1 - U_v) \qquad (2.1)$$

where U_r is the degree of consolidation at radial flow. U_v is the degree of consolidation at vertical flow.

Solutions are available for both free strain and equal strain in the soil around the drains. The strain in the vertical direction is assumed at equal strain to be constant and independent of the radial distance from the drains. At free strain, the strain distribution is not uniform. It varies between the drains and depends on the change of the pore water pressure that takes place in the soil.

Youshikuni and Nakando (1974) considered permeability of the drain material (sand) and found that the permeability affects the consolidation rate. The degree of consolidation is approximately estimated from the relationship (Kjelhan, 1948) as

$$U = 1 - e^{\frac{-c_v . t}{B}} \qquad (2.2)$$

where U = coefficient of consolidation

$$B \text{ is constant } = \frac{S^2}{8} \left(\ln\frac{S}{d} - \frac{3}{4}\right) \qquad (2.3)$$

S is the spacing and 'd' dia of drains

2.2.2 Lime Piles

Both slaked and unslaked lime has been used successfully to stabilize soft clay. By adding lime to soils, the plastic limit of the soil is increased while the plasticity index and the swelling potential are reduced (Brouss, 1985).

There are differences in opinion about the effectiveness of the method since the diffusion rate of lime in uniform clay is very slow and the success of the method depends primarily on the migration of lime into fissures of the soil (Landy and Greenfield, 1968).

The ultimate bearing capacity of a confined lime column at the depth Z is given by (Brooms, 1978)

$$q_{ult} = q_{o,ult} + (Z\rho g + k\, C_u)k_p \qquad (2.4)$$

where $q_{o,ult}$ is the ultimate strength of an unconfined column, C_u is the undrained shear strength of the surrounding unstabilized soil and k_p is the coefficient of passive earth pressure and k is a coefficient which relates the limit pressure in expanding cavity with the undrained shear strength.

2.2.3 Cement Columns

Cement columns have also been used to improve the strength of soft clay deposits . Pan et al.(1994) reported test data of triaxial compression tests and oedometer tests on the soft clay installed with mandrels of cement mixed soil. They reported that the stress strain curves are almost linear at early stage, especially as the relative columns area (i.e. the ratio of the cross sectional area of the mandrel and that of the sample) is greater than 20% and a_w, cement content greater than 15%. It has also been reported that the greater the values of A_s and a_w, the more obvious is the peak of the curve and the smaller the corresponding strain and the undrained shear strength increases with the increase of a_w.

Pan et.al. carried out oedometer tests also on soft clay with cement columns. They stated that the compression of the composite sample increases with increase in the vertical pressure P and the compression is very small until P exceeds P_y known as yield pressure. They also reported that P_y usually increases with increase in a_w and A_s an soft clay installed with cement columns behaves similar to that of an over consolidated clay.

2.2.4 Grouting

Use of grouting to augment the stability of deep excavations and tunnels in very soft clay deposits is becoming common, due to higher degree of reliability, despite higher costs. The method is however mainly used to tackle special problems like underpinning of structures or when other less expensive ground improvement methods cannot be used. The columns of cement mortar or soil-cement after the jet grouting can be used as foundation for structures or as lateral support in deep excavation.

2.2.5 Stone columns / Granular piles

Stone columns/granular piles are gaining popularity as an effective technique to increase the bearing capacity and to reduce the settlements of deep deposits. The consolidation rate of soil increases since they act as vertical drains in the soil. The load distribution between the column and the unstabilized soil depends on the relative stiffnesses. Ranjan and Rao (1986) developed a theory for the load distribution between the column and surrounding soil. Ranjan and Rao (1985) also developed a simple theory to predict the settlements of soft clay installed with stone columns by giving an equivalent volume compressibility coefficient. This is given by the following eqn. 2.5.

$$m_{veq} = \frac{1}{\alpha EP + (1-\alpha) ES} \quad (2.5)$$

The ultimate bearing capacity of a single granular pile installed in a weak sub soil deposit (Rao 1982, Ranjan and Rao 1986) is given by eqn. 2.6.

$$q_{ult} = (q_{ult1} + q'_{ult}) \quad (2.6)$$

For cohesionless soil (c = 0)

$$q_{ult1} = k\, \sigma_m\, F'_q \quad (2.7)$$

and $q'_{ult} = k\, \sigma'_m\, F'_q$ (2.8)

where $\sigma_m = 1/3(1+2\ K_0)\sigma_v$ (2.9)

and $\sigma'_m = 1/3\ (1 + 2k_0)q_s$ (2.10)

Here σ_m is the effective mean normal stress, σ_m' increased effective mean normal stress and K a constant which is assigned a value equal to 6. F_q is Vesic's dimensionless cylindrical cavity expansion factor (Vesic, 1972) which is found to vary with rigidity index, I_r given by eqn. (2.11)

$$I_r = \frac{E'_3}{2(1+\mu)[C_u + \delta_m \tan\phi]} = \frac{G}{S} \qquad (2.11)$$

where μ is the Poisson's ratio, ϕ the angle of internal friction and E_s the measured elastic modulus of the soil which increases with increase in confining stress. The corrected soil modulus E_s' for equation 2.11 is found from equation (Rao, 1982)

$$E_s' = E_s (\sigma_m/\sigma_1)^{0.5} \qquad (2.12)$$

Also the modular ratio, m is given by

$$m = \frac{E_p}{E_s} \qquad (2.13)$$

where E_p and E_s are the modulii of pile material and the surrounding soil respectively.

Rao (1982), Ranjan and Rao (1986) used the above equations to compute the load shared between the pile q_p and the surrounding soil q_s as given by the following equations

$$q_p = q\left(\frac{E_p}{\alpha E_p + \{1-\alpha\}E_s}\right) = q\{E_p/E_{eq}\} \qquad (2.14)$$

$$q_s = q\left(\frac{E_p}{\alpha E_p + \{1-\alpha\}E_s}\right) = q\{E_s/E_{eq}\} \qquad (2.15)$$

For cohesive soils : ($\phi = 0$, $\mu = 0.5$, $K_o = 1$)

$$F_q' = 1, \quad \sigma_m = \sigma_v,$$

Hence equation 2.11 becomes

$$I_r = (E_s'/3C_u)\,(\sigma_v/\sigma_1)^{0.5} \qquad (2.16)$$

$$\text{and} \quad F_c' = 1 + \text{Ln}\, I_r \qquad (2.17)$$

The average value of $(1+\text{Ln}\, I_r)$ is taken as 5 (Rao 1982, Mori 1979, Rao and Ranjan 1986). Using equations 2.16 & 2.17 and values of F_q', F_c' in equation 2.6 and 2.7,

$$q_{ult1}' = K(0.5\,\gamma_{sub}\,L_c + 5Cu) \qquad (2.18)$$

$$q_{ult}' = K(q_s + 5Cu) \qquad (2.19)$$

Hence the ultimate bearing capacity of a single granular pile installed in a soft clay deposit becomes

$$q_{ult} = K(10C_u + q_s + 0.5\,\gamma_{sub}\,L_c) \qquad (2.20)$$

If d is the diameter of installed pile, and $L_c = 5d$

$$q_{ult} = K(10C_u + q_s + 2.5\,\gamma_{sub} d) \qquad (2.21)$$

where γ_{sub} is the submerged unit weight of the soil surrounding the pile.

Ranjan and Rao (1985) also proposed the following equations to predict the settlements of soft clay deposit installed with stone/granular columns.

$$\Delta H = \sum_{i=1}^{n} q.m_{veq}.h \qquad (2.22)$$

where ΔH = settlement of composite mass

q = total applied stress

m_{veq} = coefficient of equivalent volume compressibility of the composite mass is represented by

$$m_{veq} = \left[\frac{1}{\alpha E_p + (1-\alpha)E_s}\right] \qquad (2.23)$$

α = replacement factor = A_p/A

E_p and E_s = the measured modulii of the pile material and the surrounding soil.

h = thickness of layer.

The settlement of the composite soil can be determined by using the m_{veq} as given below

$$\Delta H = q.m_{veq}.h \qquad (2.24)$$

Where ΔH - Settlement of composite soil

q - total applied stress

h - thickness of layer.

2.3 Sand Fibre Columns for Improvement of Soft Clay

In order to assess the suitability of sand fibre columns for improving soft clays, a well planned experimental programme in triaxial tests on soft clay installed with central sand fibre core (i.e. sand fibre column) has been carried out (Singh, 1995). Singh (1995) investigated the influence of relative core area (i.e. the ratio of area of the core to the area of sample), amount of synthetic fibres in the core and the confining stress on the strength of soft clay.

2.3.1 Stress strain behaviour :

A typical plot of deviator stress axial strain of soft clay reinforced with sand fibre-column of relative core area 0.38 under confining stress of 75, 150 and 300 kPa is presented (Fig. 2.1). A glance of the Fig.2.1 indicates that untreated clay sample attains peak stress at around 10% axial strain which then remains almost constant upto 20% axial strain whereas the clay samples reinforced with sand fibre columns do not exhibit any peak stress. The stress-strain curves of clay treated with sand-fibre column indicate a rising trend even upto axial strain of 20%, exhibiting a ductile behaviour of composite soil.

2.3.2 Shear strength

The strength of soft clay reinforced with sand fibre columns defined in terms of major principal stress at failure is affected by relative core area, fibre content and confining stress (Singh, 1995). Further, it has been reported that strength of the composite sample increases with the increase in relative core area (Fig. 2.2). The increase in strength has been observed to be of the order of 36%, 60%, 78% and 152% of the soft clay with relative core area 0.09, 0.25, 0.36 and 0.56 repectively for sand-fibre weight of 2% and confining stress of 150 kPa (Fig. 2.2). The strength of the composite soil also depends upon the confining stress. The strength of the composite soil is more at higher confining stress (Fig. 2.3). The strength increases with increase in fibre content in the column.

2.3.3 Behaviour of soft clay treated with sand column, granular column and sand-fibre column :

In order to compare the behaviour of soft clay treated with sand-fibre column vis-a-vis sand column and granular soil column, Singh (1995) carried out triaxial tests on the soft clay samples treated with sand columns and granular soil columns.

Table 2.2 shows the gain in strength of soft clay treated with granular columns, sand columns and sand-fibre columns, over untreated clay for different relative core area at confining stress of 150 kPa and fibre content of 1%.

Table : 2.2

Comparative Gain in Strength of Soft Clay Treated with Sand Columns, Granular Columns and Sand-Fibre Columns

Relative Core area of columns	Gain in strength +			
	untreated clay	sand columns	Granular columns	sand-fibre* columns
0.00	1.00	1.00	1.00	1.00
0.29	-	1.07	1.13	1.19
0.25	-	1.21	1.33	1.51
0.36	-	1.30	1.45	1.73
0.56	-	1.60	2.10	4.08
1.00	-	2.54	2.89	5.54

\+ Fibre content in sand-fibre column = 1%

* Confining stress = 150kPa.

A glance of Table 2.2, indicates that the gain in strength of clay treated with sand-fibre columns is more than the gain in strength of clay treated with sand/granular columns. It implies that sand-fibre columns render higher strength than the sand/granular columns and will be more effective than the usual sand/granular columns.

2.4 FIBRE REINFORCED SOIL

The mode of placement of fibres is an important aspect of the "plysoil". The fibres may be placed at certain preferred direction or they may be randomly distributed in soil mass. Depending upon the placement of the reinforcement, the fibre reinforced soil may be categorized as:

(a) **Oriented fibre reinforced Soil** : In this case the fibres are placed along a certain direction or at a certain angle with respect to shear failure plane.

(b) **Randomly distributed fibre reinforced soil :** In this case the fibres are mixed with soil in the same manner as cement, lime, fly ash etc. resulting into randomly distributed fibres.

2.4.1 Randomly Distributed Fibre Reinforced Soil :

In case of randomly distributed fibre reinforced soil (RDFS) discrete fibres are simply added and mixed with soil, much the same way as the admixtures. Randomly distributed fibre reinforced soil provides greater extensibility (ductilily) and smaller loss of post peak strength as compared to soil alone or to reinforced earth. Shear strength characteristics of soil improves significantly with the addition of discrete fibres, both synthetic and natural (Ranjan et al. 1994 a & b). It has been established that load deformation characteristics of soil can be improved by inclusion of fibres. Fibre reinforced soil exhibits greater extensibility and small losses of peak strength i.e. greater ductility in the composite material as compared to unreinforced soil or soil reinforced with high modulus inclusions (Gray and Al-Refai 1956: Maher and Gray 1990 and Ranjan et al 1994).

Further, "RDFS" is advantageous since it maintains strength isotropy with the absence of potential places of weakness which may develop parallel to the oriented reinforcement (Charan, 1995).

Maher (1988), Gray and Maher (1989) and Maher and Gray (1990) carried out a series of triaxial compression tests on sands reinforced with randomly distributed discrete fibres both natural and synthetic. They reported that randomly distributed fibre inclusions significantly increased the ultimate strength of sands.

A series of triaxial compression tests on cohesionless soil reinforced with randomly distributed discrete fibres, both synthetic (polypropylene) and natural (coir) have been carried out by Charan (1995). Variation of shear strength (i.e. major principal stress at failure) with fibre content for polypropylene fibre reinforced fine sand is shown in Fig.2.4. It is apparent from the figure that the strength of soil increases with increase in fibre content. It is also reported that the rate of increase is higher at lower fibre content (i.e. $w_f \leq 2\%$) and the relative gain in strength is small at higher fibre content.The strength of fibre reinforced sand also increases with an increase in fibre aspect ratio (Charan, 1995).

The influence of fibre inclusions on c-ϕ values of soils, has been studied by Setty and Rao (1987) and Setty and Murthy (1990) by carrying out triaxial compression tests on soil reinforced with randomly distributed polypropylene fibres. They reported that soils exhibited significant increase in cohesion intercept, c and a slight decrease in angle of internal friction ϕ with an increase in concentration of fibres. It was reported that though the angle of internal friction, ϕ slightly decreases, yet the shear strength , s (i.e. $s = c + \sigma \tan\phi$) of the soils increases due to fibre inclusions.

2.5 CONCLUDING REMARKS

A critical review of literature on randomly distributed fibre reinforced soil reveals that most of the studies have been carried out to investigate the influence of soil-fibre parameters (i.e. fibre content, aspect ratio, surface friction and soil type) on the stress-deformation, stress-strain behaviour, strength increase and California Bearing Ratio (CBR). No study has been reported on the investigation of influence of soil-fibre parameters on the drainage characterstics of *"plysoil"* which is the most important property in accelerating the consolidation of soft clay and draining out of water from subgrade.

Keeping in view the lack of information in the available literature, it is planned to study the suitability of randomly distributed fibre reinforced soil as an alternative to granular material and to study the effect of soil fibre parameters on the drainage characteristics of randomly distributed fibre reinforced soil.

No study has been reported on the investigation of isotropy of the randomly distributed fibre reinforced soil, though it has been stated that randomly distributed fibre reinforced soil got strength isotropy. Therefore, it was planned to study to investigate the isotropy of randomly distributed fibre reinforced soil through permeability tests.

The drainage characteristics of randomly distributed fibre reinforced soil have also not been investigated so far. To fill these voids it was planned to investigate the influence of various fibre parameters (i.e. fibre content, aspect ratio and type of fibre) on the permeability characteristics of randomly distributed fibre reinforced soil.

The suitability of mixture of sand and fibre as an alternative to the granular material used in stone/granular columns has also been investigated through consolidation tests.

EXPERIMENTAL PROGRAMME

3.1 GENERAL

The details of experimentation are described in detail in this chapter. The influence of fibre parameters namely type, aspect ratio and weight fraction and relative core area of sand-fibre column on consolidation characterstics of soft clay reinforced with sand-fibre columns have been studied through consolidation tests. Also, the influence of fibre parameters namely, type, aspect ratio and weight fraction on permeability characteristics of sand and silt at different densities has been studied by carrying out the permeability tests.

The various materials used, their properties, the details of testing equipments and the test procedures have been described in detail in the following sections.

3.2 TEST MATERIALS

The various properties of soils and fibre used in the present study have been described in this section.

3.2.1 Soils

Clay and sand have been used to carry out the consolidation tests to investigate the compressibility characterstics of soft clay reinforced with sand-fibre columns. Sand and silt have been used to study the permeability characteristics of these soils reinforced with fibres.

(A) Clay

The locally available clay called "Dhanauri clay" has been used in the present investigation for consolidation tests. Primilinary tests namely, water content determination, specific gravity test, hydrometer analysis, unconfined compressive strength test,etc. have been carried out as per the relevant Indian Standard Codes of Practices to identify and classify the soil. The various properties of clay determined are listed in Table 3.1.

TABLE : 3.1

Properties of clay used

1.	State	disturbed
2.	Grain size	<75μ
3.	Specific gravity of solids	2.67
4.	Liquid limit	52%
5.	Plastic limit	29.5%
6.	Plasticity index	22.5%
7.	Unconfined compressive strength,kg/cm^2	0.40 at moisture content 32%
8.	Soil classification as per IS:1498-1970	CH
9.	Maximum Proctor's dry density	1.78 g/cc at OMC of 28%

(B) Sand

Locally available sand has been used in the investigation to study the effect of sand-fibre column installed in soft clay and to study the effect of fibre on the permeability characterstics of sand with fibre. Various primilinary tests viz., grain size analysis, specific gravity and maximum and minimum void ratios have been carried out as per relevant Indian Standard Codes of Practices. The grain size distribution curve is shown in Fig.3.1. The various properties of sand determined are tabulated in Table 3.2.

TABLE 3.2
Properties of Sand

1.	Average grain size, D_{50},mm	:	0.30
2.	Coefficient of uniformity, C_u	:	2.29
3.	Specific gravity, G	:	2.62
4.	Maximum void ratio, e_{max}	:	0.797
5.	Minimum void ratio, e_{min}	:	0.425
6.	Classification as per IS : 1498-1959	:	Fine Sand (SP)
7.	Maximum Proctor's dry density	:	1.65 g/cc

(C) Silt

A non-plastic silt passing through 75μ seive has been used in the investigation to study the effect of fibre on the premeability characteristics of silt with fibre.

3.2.2 Fibre

Two different types of fibres viz., synthetic and natural have been used in the present investigation to study the influence of fibre characteristics i.e. type of fibre, aspect ratio and fibre content on compressibility characteristics of clay treated with sand-fibre columns and drainage characteristics of sand and silt. The synthetic fibre used in the investigations is "polypropylene"fibre manufactured from high density polypropylene and polyethylene. The natural fibre used is "coir" fibre. The various characteristics of fibres used in the present investigation are summarised in the following Table 3.3.

TABLE 3.3
Characteristics of Fibres

1.	Fibre type	Polypropylene	Coir
2.	Diameter, mm	0.3	0.2
3.	Aspect ratio, l/d	50, 75, 100	50
4.	Specific gravity	0.92	0.75
5.	Tensile strength, kPa	1.5×10^5	1.0×10^5
6.	Tensile modulus, kPa	3.0×10^6	2.0×10^6
7.	Coefficient of friction	0.41	0.60

3.3 PREPARATION OF RDFS

Firstly, the quantities of sand or silt, fibre and water to be mixed to get the desired density are determined. These three quantities are mixed thoroughly by hand to get uniform mixture. Once the mixture is mixed thoroughly, it is left for a period of about 10 to 15 mts.for moisture equilibrium before it is used for core in consolidation test or permeameter mould.

3.4 EXPERIMENTAL PROGRAMME

3.4.1 Types of Test

Two different types of test were conducted in the present study. These are :

* Consolidation test
* Permeability test

3.4.2 Consolidation Tests

Consolidation tests, on soft clay installed with sand-fibre columns, have been carried out to study the effect of relative core area, type of fibre and fibre content on the compressibility and permeability characterstics of composite sample. The following aspects have been studied through consolidation tests.

* Effect of relative core area on the compressibility and permeability characterstics of composite soil.
* The effect of type of fibre on the compressibility and permeability charactersitcs of composite soil.
* Effect of fibre content on the compressibility and permeability characterstics of composite soil.

The various test parameters adopted during the consolidation tests are summarised in the Table 3.4.

TABLE 3.4

Parameters adopted for consolidation test

S.No.	Parameters		Level
1.	Soil	: (a) clay	Soft clay (CH)
		(b) sand	Fine sand (SP)
2.	Dry density	: (a) clay	1.65 g/cc (adopted)
		(b) sand	1.63 g/cc (adopted)
3.	Fibre	: (a) type	synthetic (polypropylene) natural (coir)
		(b) Fibre content (w_f)%	0.0, 1.0, 2.0
4.	Relative core area of sand-fibre column (Ar)*		0.00, 0.16, 0.28, 0.44.
5.	Load incre ment (kPa)		00, 25, 50, 100, 200, 400,800

* defined as ratio of area of core to area of sample.

The details of test equipment, sample preparation and testing procedure have been described in the following sections.

(A) Test Equipment

Consolidation tests have been performed on specimen of 20mm thick placed in confining metal ring of 75mm diameter. A fixed-ring type consolidation loading system is used to carry out the experiments in the laboratory.

A split cylindrical mould has been used to compact the clay at the desired dry density. A manually operated jack has been used to push the clay sample into the consolidation ring. Thin walled steel tubes of diameter 2.5, 3.0, 4.0, 5.0 cm have been used to make different cores in the clay sample. A wooden piece has been used to compact "RDFS" into the core of the clay sample.

(B) Preparation of Composite Sample

The preparation of composite sample involves two steps viz.,

1. Preparation of clay sample
2. Installation of sand-fibre column

1. Preparation of clay sample :

Air dried clay passing through 75μ seive is taken and its moisture content is determined. Required quantity of water to achieve the desired density is mixed with clay thoroughly to get an uniform mixture. The moist clay is then kept in polythene bags for 24 hours for moisture equilibrium. The clay is divided into three equal parts and each layer is put into the cylindrical split of mould of diameter 75 mm and height 150 mm. Each layer is lightly compacted and after putting the last layer, it is finally compressed statically through a manually operated jack.

Consolidation ring is kept at the bottom side of the mould and clay is pushed from the top. After pushing the required thickness of clay into the ring, it is cut by a synthetic thread from the mould. Similarly, other samples are also cut. The surfaces of the clay samples are trimmed off smoothly with a knife.

2. Installation of sand-fibre column :

Once the clay sample is prepared, the desired diameter of central core is cut out with the help of a thin walled steel tubes by pushing it smoothly carefully vertically down as shown in Fig. 3.2. "RDFS" prepared (as described earlier in section 3.3) is subsequently compacted at required density into the core as shown in Fig.3.3. The composite sample is ready for consolidation test.

(C) Test Procedure :

The consolidation test procedure is briefly described below :

* The prepared composite sample is carefully transferred into the consolidometer with saturated porus stones placed at upper and bottom faces.
* The assembled cell is then mounted on the loading frame and is allowed for saturation for 24 hours before application of the load. The loading frame is shown in Fig. 3.4.
* The load is applied in a geometric progression with a load ratio $\Delta p/p = 1$ with a typical load sequence of 25, 50, 100, 200, 400, 800 kPa.
* The sample deformations are recorded by dial gauges of least count of 0.01mm at elapsed times of 0.0, 0.25, 1.00, 2.25, 4.00, 6.25, 9.00, 12.25, 16.00, 20.25, 25.00, 36.00, 49.00, 60, 120, 240 minutes or till the dial reading has become almost constant.

3.4.3 Permeability Tests

Falling head permeability test has been conducted on sand and silt to study the effect of fibre type, fibre content and aspect ratio on the drainage characterstics at different densities.

First permeability tests conducted to ascertain the isotropy of "RDFS" have been described herein.

3.4.3.1 Test for Isotropy

The various parameters adopted for isotropy tests have been summarised in the following table :

TABLE 3.5

Parameters adopted for the Isotropy Tests

1.	Soil type	Fine Sand (SP)
2.	Drydensity, g/cc	1.65 g/cc
3.	Fibre	Polypropylene
4.	Fibre content	0.5%
5.	Aspect ratio	50
6.	Angles at specimens obtained	0^{o}, 30^{o}, 90^{o}

The various steps involved in the preparation of "RDFS", compaction of the "RDFS" and extraction of sample at different directions have been discussed in the following sections.

(A) Compaction of the plysoil

The mixture prepared as described in the earlier section (3.3) is divided into three equal parts. Each layer is put in a box of predetermined volume and spread uniformly. Each layer is then compacted with a hammer of 11kg giving 30 blows. All the "RDFS" is compacted into the box by trial and error method to achieve the desired density. After compacting all the plysoil, the surfaced is trimmed off smoothly with the help of a steel strip. The sample is now set ready to extract the test specimens at different angles for isotropy test in permeameter mould.

(B) Extraction of Test Specimen

* Once "RDFS" has been compacted in a bigger box the test specimens are obtained at three different angles with the vertical viz. 0^{o}, 30^{o} &

90^{o}. First, a sample is obtained by putting the permeability mould upside down and pressing it down slowly. Once, the mould is pushed into "RDFS" upto the full depth of the mould with plysoil is taken out carefully by removing the soil surrounding the mould. This is transferred to the drainage base plate and the falling head method is conducted as per the procedure described in the permeability tests section.

* Next, the test sample is obtained in horizontal direction i.e. at 90^{o}. The specimen has been obtained by keeping the permeability mould horizontally and pushing it into "RDFS" gradually till the complete mould is pushed in. The mould is removed by carefully removing the surrounding soil. The specimen is taken out carefully and transferred to the drainage base plate.

* Finally, test sample is obtained at 30^{o} angle. To obtain the sample at 30^{o} angle, first the surface of the box is cut so as to get an inclined surface of 30^{o}. Then the permeability mould is kept parallel to the inclined surface and pushed into plysoil smoothly by removing the surrounding soil simultaneously. After pushing the mould completely into soil, the mould is taken out carefully and transferred to the drainage base plate.

3.4.3.2 Permeability tests

The various parameters adopted for permeability test have been summarised in Table 3.6.

TABLE 3.6

Parameters adopted for permeability tests

S.No.		Parameters		Level
1.	Soil :	(a)	Sand	Fine sand (SP)
		(b)	Silt	Non-plastic
2.	Fibres:	(a)	Type	Synthetic (Polypropylene) natural (coir)
		(b)	Content (w_f%) by wt	0.0, 0.5, 1.0, 2.0, 4.0
		(c)	Aspect ratio	50, 75, 100
3.	Densities :		Dry density	1.00 γ_{dmax} 0.95 γ_{dmax} 0.90 γ_{dmax}

The following sections explain the steps involved in mixing of fibre with sand on silt on compaction of composite soil into the permeability mould.

(A) Test Equipment :

Falling head permeability test is carried out with a permeameter confirming to the Indian Standard Code of Practice (IS 11209-1985). A compaction rammer of 2.5 kg is used to compact the soil into the mould. A graduated glass tube of diameter 13mm fixed to a stand has been used to vary the water head. A timer is used to record the time required for the head to fall from h_1 to h_2.

(B) Preparation of Test Specimen :

The steps involved in the preparation of the test specimen has been explained in the following steps.

* The quantity of "RDFS" (as described in section 3.3) is determined for the desired density.

* The required quantity of "RDFS" is divided into three equal parts. Each part is put into the mould fixed to a base plate and is given 25 blows with the specified hammer of 2.5 kg.
* After compacting the mixture, the surface of the mould is trimmed smoothly with a knife. Any fibre projecting outwards is cut off with scissors and the edges are cleaned.
* The sample is now ready for the test.

(C) Test Procedure :

The test procedure of the falling head permeability test is as per IS:2720 (Part 17)-1986 has been described briefly herein.

1. The mould with the composite soil is assembled to the drainage base plate.
2. Filter papers are placed between the soil specimen and the porus stones on both top and bottom sides and collar is fixed.
3. The outlet of the mould is connected to the stand pipe and water is allowed to flow in for the saturation of the sample. Water is allowed to flow in till the water has travelled upto 5 to 10 mm above the top of the soil specimen.
4. The remaining portion of the mould is gradually filled with water without disturbing the surface of the soil specimen and the outlet is disconnected.
5. Cover plate is then fixed to the mould with a washer.
6. Water inlet of the mould is connected to the stand pipe filled with water and it is ensured that no air bubles are entraped in the pipe. The test set up has been shown in the Fig. 3.4
7. Water is allowed to flow through the soil specimen untill a steady flow is established.
8. The time required for the head to travel from h_1 to h_2 is recorded with the help of a stop watch. The heads h_1 and h_2 are chosen such that the time taken for water to fall from h_1 to

$\sqrt{h_1 h_2}$ and the time taken for water to fall from $\sqrt{h_1 h_2}$ to h_2 is equal.

9. The above procedure is repeated for different heads.

3.5 Typical Test Results

Typical results of consolidation test and permeability test have been presented in the following sections.

3.5.1 Consolidation Test

The compressibility charecterstics of clay treated with sand-fibre column have been investigated through consolidation tests. A typical e-log p curve for clay treated with sand-fibre column of relative core area 0.28, fibre content, 1% and aspect ratio, 50 is shown in Fig. 3.6. The e-log p curve of pure clay has also been incorporated to the behaviour of clay treated with sand-fibre column with pure clay.

3.5.2 Permeability Test

Permeability tests have been carried out to study the effect of various parameters viz., soil type, dry density of soil and fibre charecterstics (type of fibre, fibre content and aspect ratio) on the permeability charecteristics of randomly distributed fibre reinforced soil.

A typical plot showing the variation of permeability with fibre content of sand reinforced with randomly distributed polypropylene fibre of aspect ratio 50 and at drydensity of maximum drydensity is shown in the Fig. 3.7.

ANALYSIS AND DISCUSSION OF RESULTS

4.1 GENERAL

In this chapter, analysis of consolidation test results and of permeability have been presented and discussed. The result of consolidation tests of soft clay treated with sand-fibre columns with different relative core areas, fibre contents and type of fibre have been discussed first.Test results of permeability tests conducted to study the isotropy of randomly distributed fibre reinforced soil have been discussed next and finally the results of permeability tests highlighting the influence of various parameters viz. soil type, dry density and fibre characteristics (i.e. fibre type, fibre content, and aspect ratio) on the permeability of randomly distributed fibre reinforced soil have been discussed.

4.2 CONSOLIDATION TEST RESULTS

As discussed earlier, Gray and Al-Refai (1986) suggested sand-fibre column as an alternative to stone column/granular pile. To ascertain the suitability of these sand-fibre columns, consolidation tests have been carried out.To study the effect of various parameters viz., relative core area, type of fibre and fibre content have been studied through the experimental programme.

4.2.1 Effect of relative core area

Sand-fibre mixture being stiffer material as compared to the soft clay, the area/volume of the sand-fibre mixture introduced in the soft clay will influence the overall performance of composite material. Hence, the relative core-area i.e. the core area of sand-fibre column in relation to the total clay sample will influence the consolidation characteristics of composite clay..

(a) e-log p curve

The e-log p curves of pure clay sample i.e. with zero relative core area and with 0.28 relative core area are shown in Fig. 4.1. The e-log p curve of pure clay sample (i.e. relative core area = 0), is identical to that of a typica! curve of a normally consolidated clay. However, the introduction of sand-fibre column brings in a marked change in the e-log p curve. The curve indicates an initial curved portion analogous to that of an over consolidated clay followed by straight line, as for a normally loaded clay. The void ratio of sample increases with the introduction of sand-fibre column thereby reducing the compression of the composite sample (Table 4.1). Further, a glance of Table 4.1 indicates that the change in void ratio between constant range of pressure is less for sample with sand-fibre core as compared to sample with no sand-fibre column.

TABLE : 4.1

Void ratio of composite sample

Pressure kPa	Void ratio			
	relative core area,0.00	change in void ratio	relative core area,0.28	change in void ratio
25	0.69	-	0.73	-
50	0.65	0.04	0.71	0.02
100	0.60	0.05	0.69	0.02
200	0.55	0.05	0.65	0.04
400	0.48	0.07	0.59	0.06
800	0.40	0.08	0.54	0.05

The e-log p curves of composite sample for different relative core areas (i.e. 0.16, 0.28 & 0.44) are shown in Fig. 4.2. A glance of Fig. 4.2, indicates that at a constant pressure, the void ratio of composite sample increases with increase in relative core area from 0.16 to 0.44 (Table 4.2). It may also be noted from Fig. 4.2 that the initial part of e-log p curve becomes more flater with increase in relative core area signifying the increase in preconsolidation pressure. The preconsolidation pressures of composite sample determined for different relative core areas are also summarised in Table 4.2. A glance of the table indicates that the preconsolidation pressure of clay increases with increase in relative core area of sand-fibre column. This suggests that behaviour of clay with sand-fibre column tends to that of over consolidated clay.

TABLE : 4.2
Void ration and preconsolidation pressure of composite sample with different relative core areas

relative core area	void ratio*	preconsolidation pressure, kPa
0.00	0.55	-
0.16	0.61	120
0.28	0.65	160
0.44	0.70	215

* Pressure = 200 kPa

An attempt has also been made to compare the results of present work with those of Singh (1995). A glance of Fig. 4.3 indicates that the results of present work are in agreement with those of Singh (1995).

The variation of coefficient of volume compressibility, m_v of composite sample with relative core area for different pressure ranges is plotted in Fig. 4.4. It may be noted that the trend in variation of m_v with increasing relative core area at lower pressure range (< 25 kPa) is different than that at higher pressure ranges i.e. >25 KPa. At low pressures(<25kPa) may be the central sand-fibre core does not have a close contact with clay resulting into a higher void ratio and accordingly higher m_v value since pressure is low. However, as the magnitude of pressure increases (>25 kPa) a proper contact is developed and presents a definite trend.

For a constant pressure range, m_v decreases with increase in relative core area.This trend is noted for all the ranges tested i.e upto 800kPa. Further, at a constant relative core area, m_v value is higher at lower pressure range.This is in order.

The test results thus indicate that the compressibility of the clay reduces with the installation of sand-fibre column and the reduction in compressibility decreases with increase in relative core area.

(b) Time taken for 90% of degree of consolidation

The sand-fibre mixture being more permeable than the clay, reduces the time taken for water to flow and accelerates the degree of consolidation. The variation of t_{90} with relative core area has been shown in Fig. 4.5. A glance of the figure indicates that t_{90} decreases with increase in relative core area.This is in order. Also the percentage decrease of t_{90}, with increase in core area is shown Table 4.3. The results indicate that as the relative core area is increased to 0.16, the percentage reduction in time is about 72% however with the further increase in relative core area, t_{90} though decrease but not at the same rate.

Table - 4.3

Time taken for 90% of degree of consolidation

relative core area	t_{90}, mts		percentage decrease	
	* 0-25	* 25-50	* 0-25	* 25-50
0.00	36.0	22.00	-	-
0.16	9.0	6.25	75%	72%
0.28	6.4	4.80	83%	78%
0.44	5.0	3.90	86%	82%

*pressure range, kPa

(c) Permeability of Composite Sample

Fig. 4.6 shows the variation of permeability of composite sample with relative core area for different pressures. It can be seen, from Fig. 4.6, that the permeability of composite sample increases with increase in relative core area. Thus introduction of permeable core area increase in permeability of composite sample . The rate of increase of permeability is higher at lower pressure ranges. The percentage increase in permeability of composite sample is also shown in Table 4.4. The trend is similar to that observed in case of t_{90} with increasing relative core area.

Table - 4.4
Permeability of composite sample

relative core area	permeability, kx10^{-5} cm/s		percentage decrease	
	0-25*	25-50*	0-25*	25-50*
0.00	4.7	5.5	-	-
0.16	26.3	16.33	460%	198%
0.28	36.2	19.82	670%	260%
0.44	42.5	22.55	805%	310%

*pressure range, kPa

(d) Compression index

Utilising the e-log p curves, effect of relative core area on the compression index defined as the slope of straight line portion of e-log p curve, has also been evaluated for different relative core areas (i.e 0.00, 0.16, 0.28 & 0.44). The results are tabulated in Table 4.5. Also the variation of coefficient of compression index with relative core area is plotted in Fig. 4.7. A glance of Table 4.5 and also Fig. 5.7 indicates that for the relative core areas tested, the compression index of composite samples decreases practically linearly with increasing relative core area.

TABLE : 4.5
Coefficient of compression index of composite sample with different relative core areas

relative core area	compression index	percentage decrease
0.00	0.272	-
0.16	0.234	14%
0.28	0.184	22%
0.44	0.138	25%

4.2.2 Effect of type of fibre

The effect of type of fibre on the consolidation characteristics of composite sample has been carried out with two types of fibres namely, synthetic (polypropylene) and natural (coir) with relative core area 0.28 and fibre content, 1%. The analysis of the effect of the type of fibre has been discussed in the following sections.

(e) e-log p curve

The variation of void ratio with pressure of composite sample for different type of fibre is shown in Fig. 4.8. A glance of figure indicates that the nature of e-log p curve in the two types of fibres is practically identical except that the void ratio is higher for sample with polypropylene fibres. However, the preconsolidation pressure of composite sample with coir fibre is less than that of composite sample with polypropylene fibre. It may also be noted from the figure that 'c_c' also is lower for composite sample with polypropylene fibre. This can also be observed from Table 4.6.

TABLE : 4.6

Preconsolidation and coefficient of compression index of composite sample with different type of fibres

Type of fibre	preconsolidation pressure, kPa	compression index
polypropylene	160	0.184
coir	90	0.215

Relative core area = 0.28

Fibre content = 1%

The coefficient of volume compressibility coefficient has also been plotted for the two different type of fibres used in the study. The variation of coefficient of volume compressibility with pressure has been shown in Fig. 4.9. A glance of Fig. 4.9 that the coefficient of volume compressibility increases for composite sample with coir. These observations indicate that sand-coir fibre columns are more compressible than those of polypropylene fibre.

4.2.3 Effect of Fibre Content

The influence of fibre content on the consolidation characteristics of composite sample has also been evaluated carrying out the consolidation tests varying percentages of polypropylene fibre i.e. 1% and 2% for relative core area, 0.28.The variation of void ratio with pressure of composite sample is shown in Fig. 4.10. A glance of figure indicates that the void ratio slightly increases with increase in fibre content though the nature of e-log p in both cases is practically identical. Polypropylene fibre being incompressible material, increases the void ratio signifying the less compression of the composite sample. It may also be observed from Table 4.7 that the preconsolidation pressure increases slightly with increase in fibre content and also, as shown in Table 4.7, the coefficient of compression index, c_c decreases with the increase in fibre content.The decrease in c_c is about 10% from 1% to 2% fibre content.

TABLE : 4.7

Void ratio, preconsolidation pressure and compression index of composite sample with two different fibre contents

fibre content	void ratio*	preconsolidation pressure, kPa	compression index
1%	0.69	160	0.184
2%	0.71	180	0.166

* Vertical pressure = 200 kPa
Relative core area = 0.28
Type of fibre = Polypropylene

The variation of coefficient of volume compressibility of composite sample has also been shown in Fig.4.11. A glance of the figure indicates that coefficient volume compressibility also decreases with increase in fibre content. This again shows that the compressibility of composite sample decreases with increase in fibre content.

4.3 PERMEABILITY TEST RESULTS

4.3.1 General

Permeability is defined as the property of soil which allows the seepage of fluids through its interconnected void spaces. This property is one of the most important soil aggregate property and has much significance in many types engineering problems. The basic parameters affecting the permeability have been discussed herein.

Darcy in 1856, gave an empirical formula for the quantity of water 'q' per sec. flowing through a cross-section of area of soil under hydraulic gradient is as :

$$q = kiA \qquad (4.1)$$

where, k is termed as coefficient of permeability and has the unit of velocity.

Poiseuille's law, which defines the relationship governing the flow of water through round capillary tubes of small diameter, has also been utilised for soils to understand the factors affecting flow through soils and it is formulated as

$$Q = \left[D_s^2 \frac{\gamma_w}{\mu} \frac{e^3}{1+e} \right] iA \qquad (4.2)$$

From comparison of this equation with Darcy's law (Eqn. 4.1) it follows that

$$k = D_s^2 \frac{\gamma_w}{\mu} \frac{e^3}{1+e} C \qquad (4.3)$$

where, D_s = is the average grain size
γ_w = is unit weight of water
μ = is viscosity of fluid
e = is void ratio
C = constant

From equation 4.3, the factors affecting the permeability may be listed as

(1) grain size
(2) properties of pore fluid
(3) void ratio

(1) Effect of grain size

As expressed by equation 4.3, the coefficient of permeability is proportional to the square of average grain size of soil.

Allen and Hazen (1969) found that permeability of sands could be roughly expressed as

$$k = c\, D_{10}^{2} \tag{4.4}$$

where, c is a constant, is equal to 100 if k is expressed in cm/s and is equal to 10 if k is expressed in mm/s.

(2) Effect of properties of fluid

Equation 4.3, indicates that coefficient of permeability or permeability is directly proportional to the unit weight, γ_w and inversely proportional to the viscosity μ. Values of γ_w are essentially constant, but values of μ vary with temperature. The coefficient of permeability is generally expressed at a temperature of $20^{o}C$ and at any other temperatures, the coefficient of permeability can be obtained from the following equation.

$$\frac{k_{20}}{k_T} = \frac{\mu_T}{\mu_{20}} \tag{4.5}$$

where, k_T, k_{20} = coefficient of permeability at $T^{o}C$ and $20^{o}C$ respectively.

μ_T, μ_{20} = coefficient of viscosity at $T^{o}C$ and $20^{o}C$ respectively

(3) Effect of void ratio :

From equation 4.3, the relationship of permeability values in a given soil, at a given temperature, under any two conditions of structure and void ratio, is given by

$$k_1 : k_2 = \frac{e_1^{\,3}}{1+e_1} : \frac{e_2^{\,3}}{1+e_2} \qquad (4.6)$$

Another approach (Zunker, F. 1930) give the relationship as

$$k_1 : k_2 = e_1^{\,2} : e_2^{\,2} \qquad (4.7)$$

The above relationship (eqn. 4.6) is valid only for cohesionless soils.

Currently, additives are used in the soil to improve their engineering performance. However, the equation 4.3 does not include the influence of these additives on the permeability of the soil.

The influence of various parameters related to additives are discussed in the following sections.

4.4 ISOTROPY TEST FOR PERMEABILITY

As discussed earlier (Section 3.4.1) samples were prepared for tests in permeameter to ascertain the isotropic behaviour of RDFS. As a test case samples of sand (SP) were prepared at a dry density of 1.65 g/cc (γ_{dmax}) with 0.5% polyproplene fibres of aspect ratio (length/diameter = 50). Samples were prepared at 0^o, 30^o and 90^o. The test results are presented in Table 4.8. A glance of the table indicates that the permeability of samples obtained in different directions (0^o, 30^o, 90^o) is practically the same. This implies that the 'RDFS' may be considered as isotropic as far the coefficient of permeability is concerned.

Table 4.8

Permeability of RDFS in different directions

Sl. no.	Sample Orientation	Coefficient of permeability, $k \times 10^{-3}$ cm/s
1.	0^o	3.00
2.	30^o	3.60
3.	90^o	3.10
	AVERAGE	3.23

4.5 INFLUENCE OF VARIOUS PARAMETERS ON PERMEABILITY

Permeability tests have been carried out to investigate the influence of various parameters viz., soil type, dry density and fibre characteristics (i.e. fibre content, aspect ratio and type of fibre). The results of these tests have been discussed herein.

4.5.1 Effect of type of soil

Two types of soils namely sand (SP) and silt (ML) have been used to study to variation of permeability of soils reinforced with fibres. The permeability of sand is found to be 2.84×10^{-3} cm/sec which is in the normal range of permeability of sand (5×10^{-2} to 1×10^{-3} cm/s). The permeability of silt is found to be 3.856×10^{-5} which is in the general range of permeability of silt (5×10^{-4} to 1×10^{-5} cm/sec).

4.5.2 Effect of dry density

Three different densities, viz. 1.00 γ_{dmax}, 0.95γ_{dmax} and 0.90 γ_{dmax} have been chosen to study the effect of dry density on the permeability randomly distributed fibre reinforced soil. The variation of permeability with dry density for different fibre contents (w_f) has been shown in Fig.4.13. It is apparent from the Fig.4.13 that the permeability decreases with increase in dry density for different fibre contents. This is in order as with the increase in dry density, the soil is densely packed reducing the voids/open space.

4.5.3 Effect of fibre content

The effect of fibre content on permeability has been investigated by varying the fibre content in the sample from 0.5 to 4.0% . Fig.4.14 shows the variation of permeability with fibre content of sand reinforced with randomly distributed (polypropylene) with fibres. Fig. 4.14 shows that the permeability of sand decreases addition of small content (0.5% weight fraction) of polypropylene and, it starts increasing as the weight fraction is increased.This trend in increase in permeability with increase in fibre content continues upto 4.0% of fibre weight fraction.

The reason for such a behaviour could be that when fibre is added to the sand the flow of water is interrupted by the fibre and it increases the path of the water to flow. This causes the increase in time taken for the water to travel through the sample leading to the reduction of permeability of sand. However, as the weight fraction of the fibres is increased, the permeability increases. This behaviour possibly is due to the fact that when more fibre are added to sand, the space occupied by sand is occupied by fibre creating some sort of voids in the samples. These voids provide passage to the water thereby reducing the length of the path to travel and leads to increase in permeability.

At higher percentage of fibre content, the fibre being very light in weight compared to the soil the volume occupied by fibre is very high. This causes the reduction in dry density of sand reinforced with randomly distributed fibre. The reduction in dry density again leads to the increase in permeability.

Fig.4.15 shows the variation of permeability with fibre content of silt reinforced with randomly distributed fibres. A glance of Fig.4.15 indicates that the permeability of silt also decreases with the addition of fibre and it increases with increase in the fibre content. This indicates the same trend as observed in case of sand. The variation of permeability with fibre content of silt mixed with fibre for different dry densities has also been shown in Fig. 4.16. It can be seen from the figure that the permeability increases with decrease in dry density.

4.5.4 Effect of aspect ratio

The effect of aspect ratio (length/diameter) on the permeability of sand reinforced with polypropylene fibre has also been investigated. The variation of permeability with aspect ratio (50, 75, & 100) at a dry density of maximum dry density is shown in Fig.4.17. The results indicate that aspect ratio has no influence on the permeability of sand reinforced with randomly distribution fibres.

The volume of fibre remains same for different aspect ratio at a specific fibre content. This provides nearly the same degree of barrier to the flow of water through the sand reinforced with randomly distributed with fibres.

A similar variation is observed for a dry density of $0.95\gamma_{dmax}$ which can be seen from Fig.4.18.

4.5.5 Effect of type of fibre

To study the effect of type of fibre on the permeability characteristics of randomly distributed fibre reinforced soil (RDFS) tests have also been carried out with natural fibre (coir).

The variation of permeability of sand reinforced with coir (l/d=50) with fibre content has been shown in fig.4.19. A glance of Fig.4.19 indicates that the permeability of sand decreases continuously with increase in fibre content. Coir being very light in weight, the volume of coir is very larger than the soil when coir fibres are added to the soil, it prevents the flow of water through the soil causing reduction in permeability. The increase in fibre content increases the volume of the coir and being compressible, it reduces the permeability soil rapidly.

The variation of permeability of sand reinforced with randomly distributed fibres with fibre content for two types of fibres has been shown in Fig.4.20. Fig.4.20 indicates that the permeability of sand decreases with addition of 0.5% polypropylene fibre and increases with increase in fibre content, whereas the permeability of sand continuously decreased with addition of coir. Coir being light in weight the volume of coir is more than polypropylene and coir is more compressible than polypropylene. These properties of coir, high in volume and more compressible than polypropylene, causes the reduction in permeability of sand continuously with increase in fibre content.

The permeability of sand with coir, as can be seen from the Fig.4.20 is higher than with polypropylene upto 1.0% fibre content. Coir being a natural product the water tends to travel along the coir fibres whereas the polypropylene being a petroleum product water does not travel along the polypropylene as water has a tendency of repulsion with petroleum products. This possibly is the reason for the permeability of sand with coir to be more than with polypropylene. At higher percentage of fibre contents, the coir being lighter than polypropylene the volume of coir is very high and being compressible than polypropylene it does not allow the water to flow through the sand. Where as the polypropylene being incompressible it creates same sort of voids in the sand and provides passage for the water to flow through the sand thereby increasing the permeability.

CONCLUSIONS

A series of exhaustive consolidation and permeability tests were planned and carried out to study the effect of various parameters viz., soil type, dry density, fibre content, aspect ratio and fibre type on the permeability characteristics. Consolidation tests are also conducted to study the behaviour of soft clay treated with sand-fibre columns. Analysing the test results, the following conclusions have been drawn based on the above test results.

A. Consolidation tests

1. The introduction of sand-fibre column in clay samples changes the e-log p curve to clay sample from that of a normally loaded clay to that of an overconsolidated clay. Also, the preconsolidation pressure of composite samples i.e. with sand-fibre core increases with increase in core area.

2. The coefficient of volume compressibility of composite samples decreases with the increase in relative core area. Also, the coefficient of volume compressibility of the composite sample decreases with increase in fibre content.

   The coefficient of volume compressibility composite sample with coir fibres is more than those with polypropylene. Though at higher pressures the difference reduces.

3. Time required for 90% of degree of consolidation of composite sample decreases significantly with the introduction of sand-fibre column. This implies that compressibility of soft clay reduces with the introduction of sand-fibre column.

4. Permeability of composite sample increases with increase in sand-fibre column core area

5. The compression index of clay samples reduces significantly with the introduction of sand-fibre column indicating that the composite samples are relatively less compressible. However, the compression index decreases with increase in core area of sand-fibre column.

B.Consolidation tests

1. Permeability of randomly distributed fibre reinforced soil in different directions is practically same indicating that randomly distributed fibre reinforced sand is isotropic as far as the coefficient of permeability is concerned.

2. The Permeability of randomly distributed fibre reinforced sand and also non-plastic silt decreases with the increase in dry density of the soil.

3. Permeability of randomly distributed fibre reinforced sand and also non-plastic silt decreases with the addition of fibre (polypropylene) and increases with increase in fibre content.

4. The aspect ratio of fibre (polypropylene) has got not much influence on the permeability of randomly distributed reinforced sand.

5. In general, the trend in influencing permeability characteristics of coir reinforced sand are identical to those reinforced with polypropylene fibre.

SCOPE FOR FURTHER RESEARCH

To understand the behaviour of *plysoil* completely and utilise it effectively as means for the improvement of soils, the further aspects to be carried out are :

(i) Model laboratory and field investigation on single/group of sand-fibre columns to observe the following.

   (a) Load-sharing behaviour of column and surrounding soil.

   (b) Diameter, spacing and length of columns.

(ii) Behaviour of fibre reinforced soils under dynamic and cyclic loading conditions.

(iii) Use of fibres in conjunction with soil stabilizing admixtures.

REFERENCES

Al-Refer T.O. (1991), "Behavior of Granular Soils Reinforced with Discrete Randomly Oriented Inclusions", J. Geotextiles and Geomembranes, Int. Geotextile Society, Elsevier Science Publishers, England, 10(4), pp '319-333.

Abdersland ,O.B. and **Khattak, A.S. (1979)**, "Shear Strength of Kaolonite/Fiber Soil Mixtures", Proc. International Conference on Soil Reinforcement, Vol. I. Paris, France, pp 11-76.

Bowels, J.E. (1986), "Engineering Properties of Soils and Their Measurements", McGraw-Hill Book Company, New York.

Bowles, J.E. (1988), "Foundation Analysis and Design", McGraw-Hill Int. Book Company, New York.

Broms, B. (1979), "Problem and Solution to Construction on Soft Clay", Porc. 6th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Vol.2, Singapore, pp 3-40

Carillo, N.J.(1942), "Simple Two- and Three Dimensional Cases in the Theory of Consolidation of Soils," Journ. of Mathematics and Physics, Vol.21, pp. 1-5.

Charan, H.D. (1995), " Probabilistic analysis of randomly distributed fibre - reinforced soil", Deptt. of Civil Engineering, University of Roorkee, Roorkee, Doctoral Thesis.

Datye, K.R., and **Nagaraju, S.S. (1985)**, "Desogm Approach and Field Control Stone Columns", Proc. Tenth Int. Conf. of Soil Mechanics and Foundation Engineering, Stockholm, Sweeden, Vol.3, pp 637-644

Gray, D.H. and **Maher, M.H. (1989)**, "Admixture Stabilization of Sand with Descrete Randomly Distributed Fibers", Proc. XIIth Int. Conf. on Soil Mechanics and Foundation Engineering, Rio de Janeio, Brazil, pp 1363-66.

Hoare, D.J. (1979), "Laboratory Study of Granular Soils Reinforced with Randomly Oriented Discrete Fibres", Proc. of the Int. Conf. on Soil Reinforcement, Vol.I, Paris, France, pp 47-52.

IS-2720 (3) - 1980, "Methods of Tests for Soils - Determination of Specific Gravity - Section 1, Fine Grained Soils", Bureau of Indian Standards.

IS-2720(3) -1980, "Methods of Tests for Soils - Determination of Specific Gravity - Section 2, Fine, Medium and Coarse Grained Soils", Bureau of Indian Standards.

IS-2720(4) - 1985, "Methods of Tests for Soils - Grain Size Analysis". Bureau of Indian Standards.

IS-2720(7) - 1980, "Methods of Tests for Soils - Determination of Water Content Dry Density Relation Using Light Compaction", Bureau of Indian Stadards.

IS-2720(17)-1986, "laboratory Determination of Permeability "Bureau of Indian Standards.

IS-11209-1985, " Mould Assembly for Determination of Permeability of Soils".Bureau of Indian Standards.

Kjellman, W.(1952), "Consolidation of Clay by means of Atmosphere Pressure," Proc. Conf. on Soil Stabilization, MIT, pp. 258-263.

Maher, M.H. and **Gray, D.H. (1990),** "Static Response of Sands Reinforced with Randomly Distributed Fibres", J. Geotechnical Engineering Division, ASCE, Vol. 116(1), pp 1661-1677.

McGown, A., Andrawes, K.Z. and **Al-Hasani, M.M. (1978),** "Effect of Inclusion Properties on the Behaviour of Sand", Geotechnique, Vol. 28(3), pp 327-346.

Mitchell, J.K. et al. (1991) "Soil Improvement - General Report", Xth Int. Conf. on Soil Mechanics and Foundation Engineering, Stockholm, Vol.4, pp 1065-1122.

Murray, R.T.(1973), "Embankments constructed on Soft Foundations: Settlement Studies near Oxford," Transp. Road Research Laboratory, 19 pp.

Pan, Q.Y. et al. (1974), "Some Aspects of the Soft Clay Ground Improved with Cement Columns", XIII, ICSMFE, New Delhi, India, pp 1223-1226.

Ranjan, G. and **Rao, B.G. 1983)1,** "Skirted Granular Piles for Ground Improvement", Proc. VIII European Conf. on Soil Mechanics and Foundation Engineering, Helsinki, Vol.3, pp 1147-1156.

Ranjan, G. (1989), "Ground Treated with Granular Piles and its Response Under Load", Indian Geotechnical Journal , Vol.19(1), pp 1-86.

Schlosser. F.(1977), "Experience on Reinforced Earth in France", Symp. on Reinforced Earth and Other Composite Soil Technique Heriot-Watt University, TRRL.

Singh, B. (1995), "Load-deformation behaviour of soft clay reinforced with sand fibre columns", M.E. Thesis, Department of Civil Engineering, University of Roorkee, Roorkee.

Thomson, J.C. (1988), "The Role of Natural Fibres in Geotextile Engineering", Proc. of First Indian Geotextile Conf. on Reinforced Soil and Geotextiles, pp G/25-29.

Vidal, H. (1969), "The Principle of Reinforced Earth", Highway Research Record No. 282, USA.

Yoshikuni, H. and Nakanodo, H. (1974), "Consolidation of Soils by Vertical Drain Wells with Finite Permeability," Soils and Foundations, Vol. 14, No.2, pp.35-46.

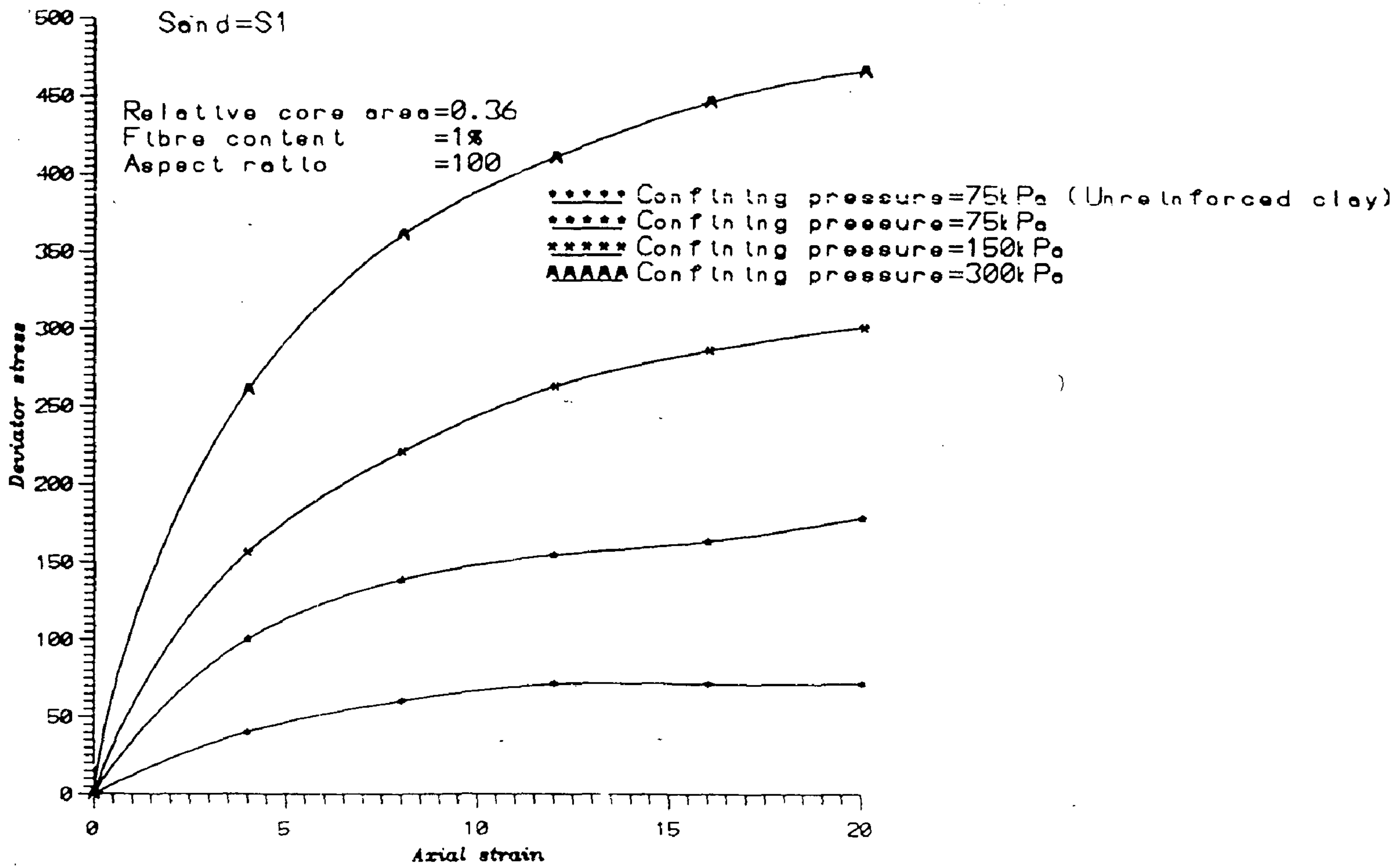


Fig. 2.1 A typical plot of deviator stress-axial strain of soft clay reinforced with sand-fibre column (After Singh, 1995)

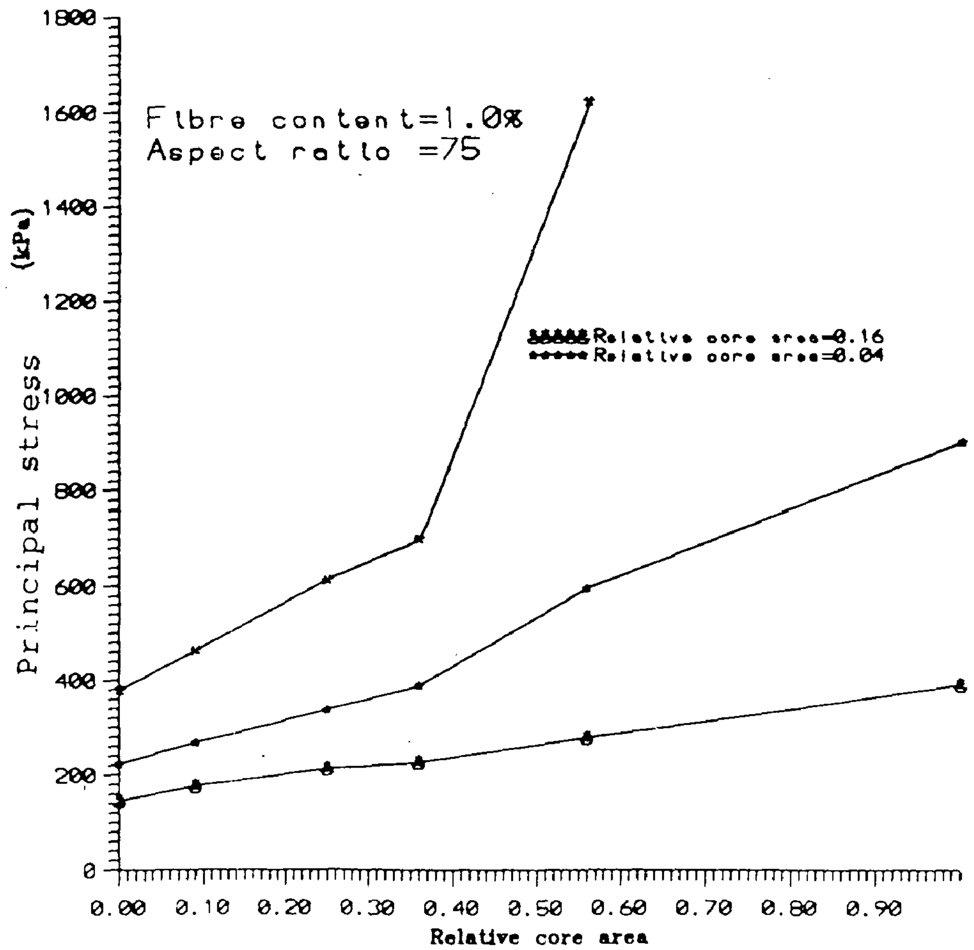


Fig. 2.2 Variation of principal stress at failure with relative core area of sand-fibre column of composite sample (After Singh, 1995)

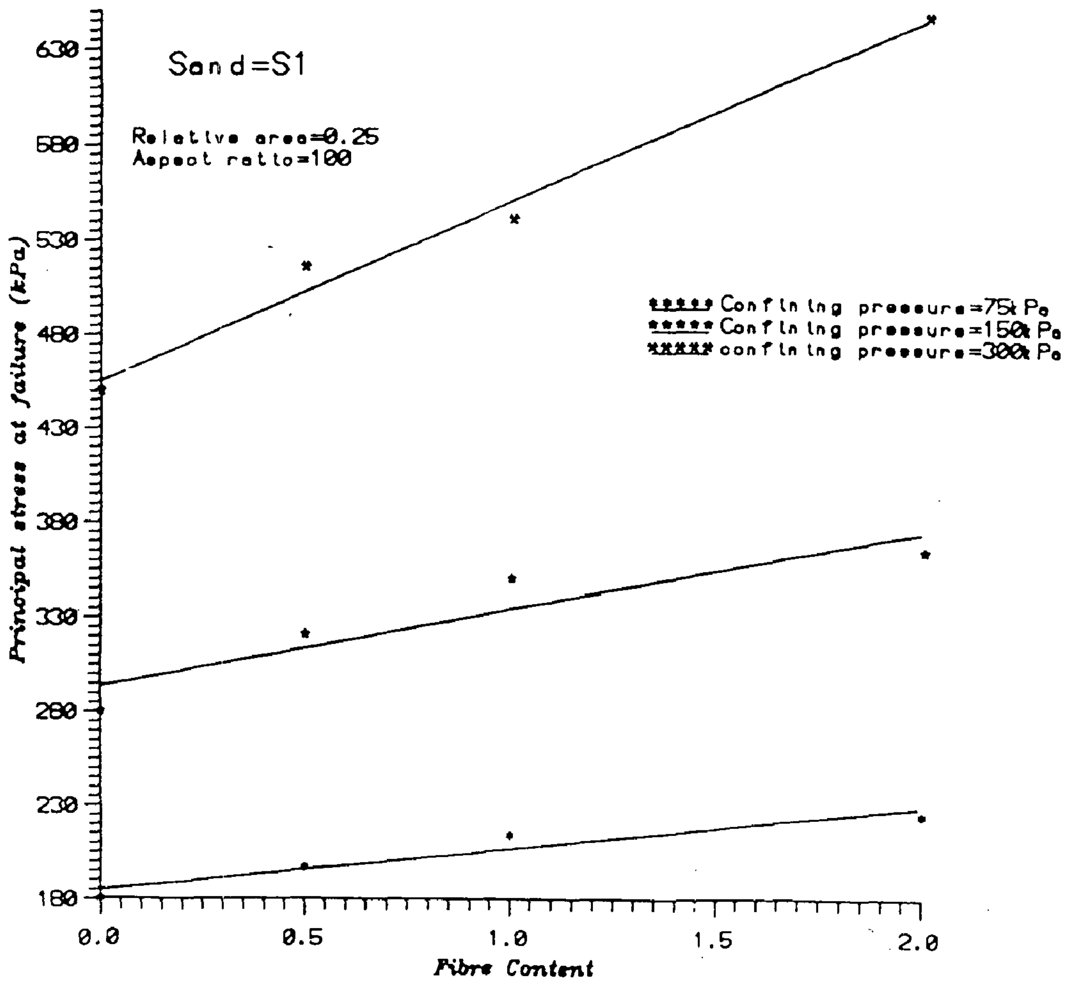


Fig. 2.3 Variation of principal stress at failure with fibre content in the sand-fibre column of treated clay sample (After Singh, 1995)

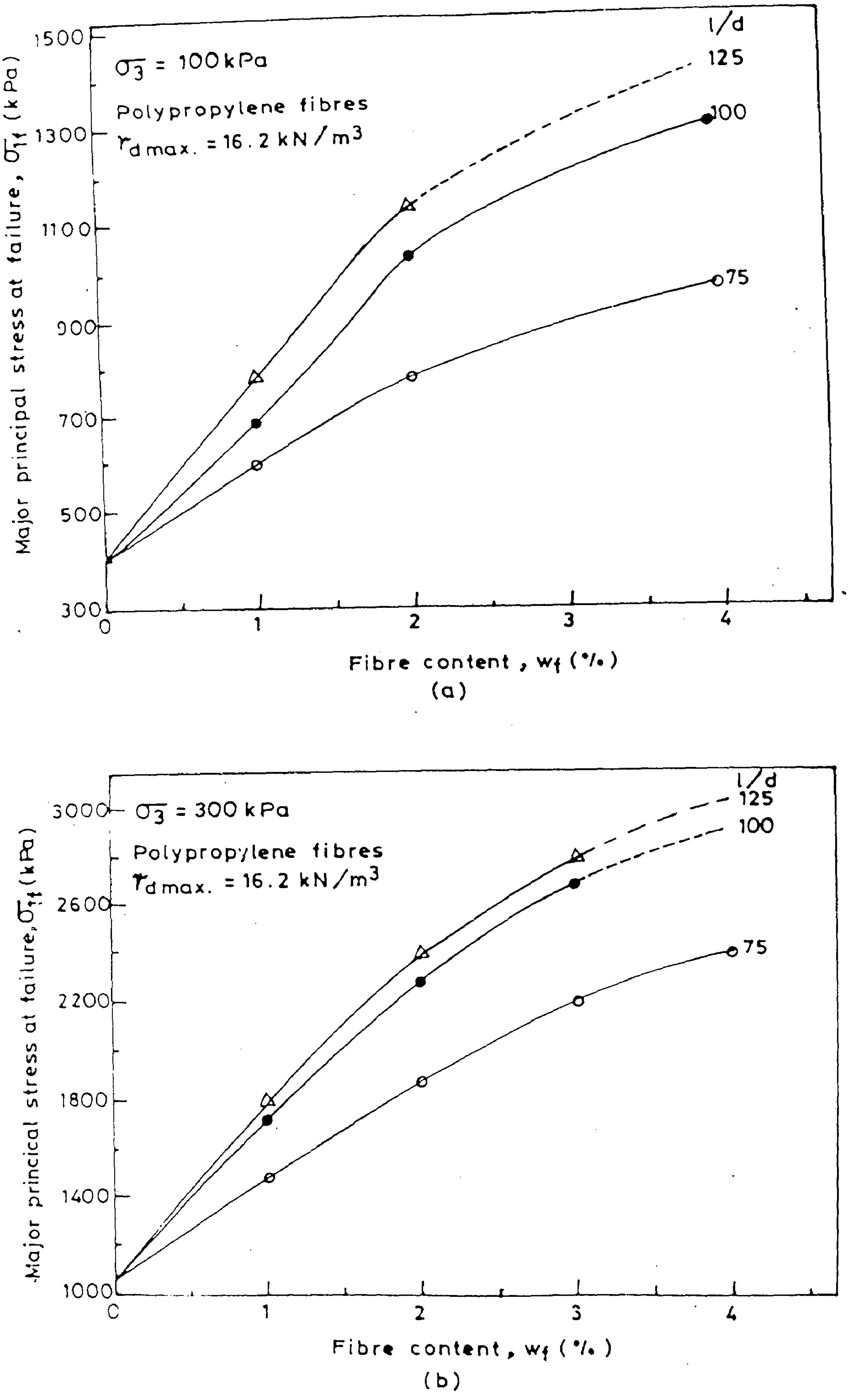


Fig. 2.4 Effect of fibre content on the strength of polypropylene fibre reinforced fine sand: (a) σ_3=100kPa and (b) σ_3=300kPa (After Charan, 1995)

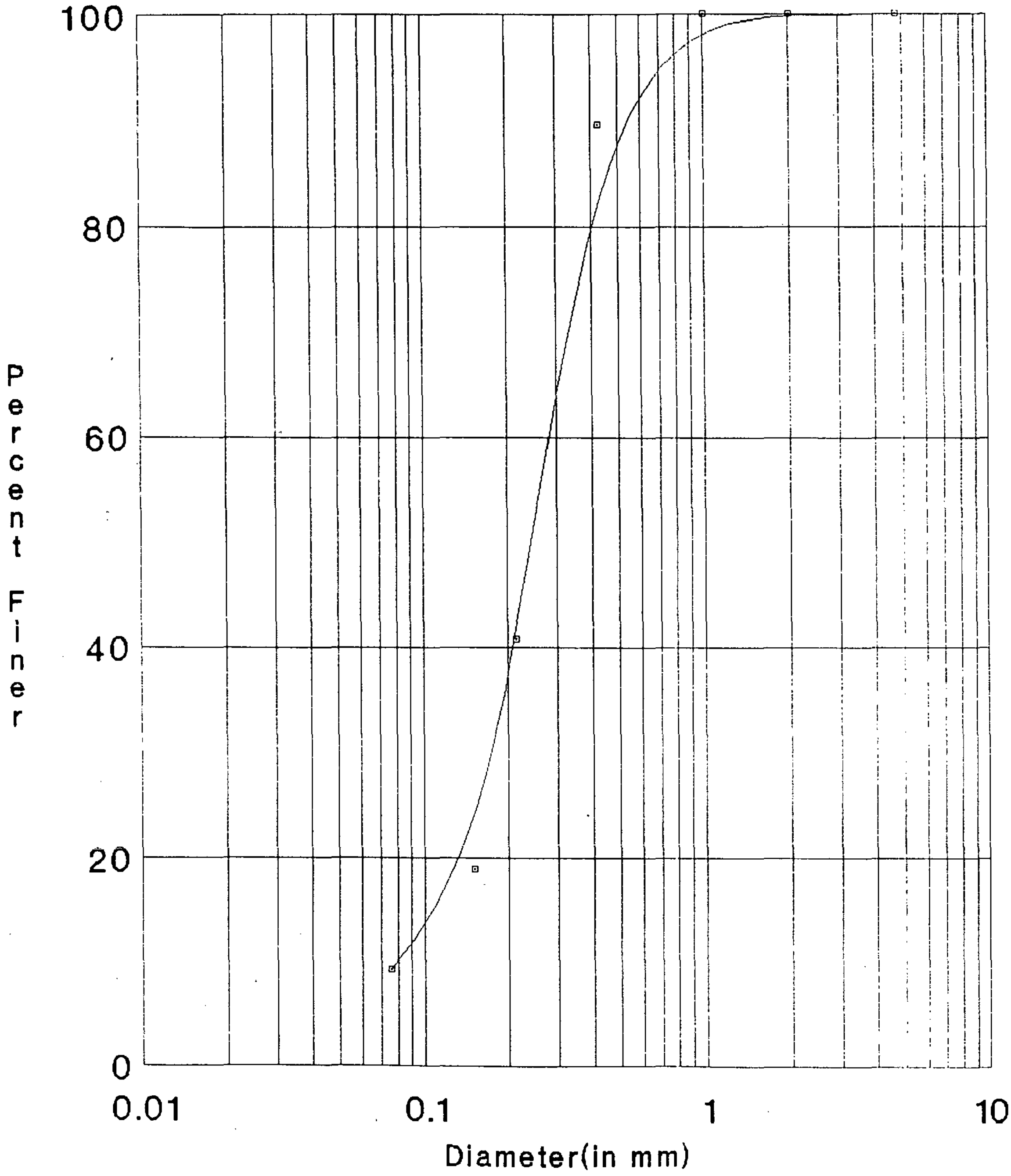
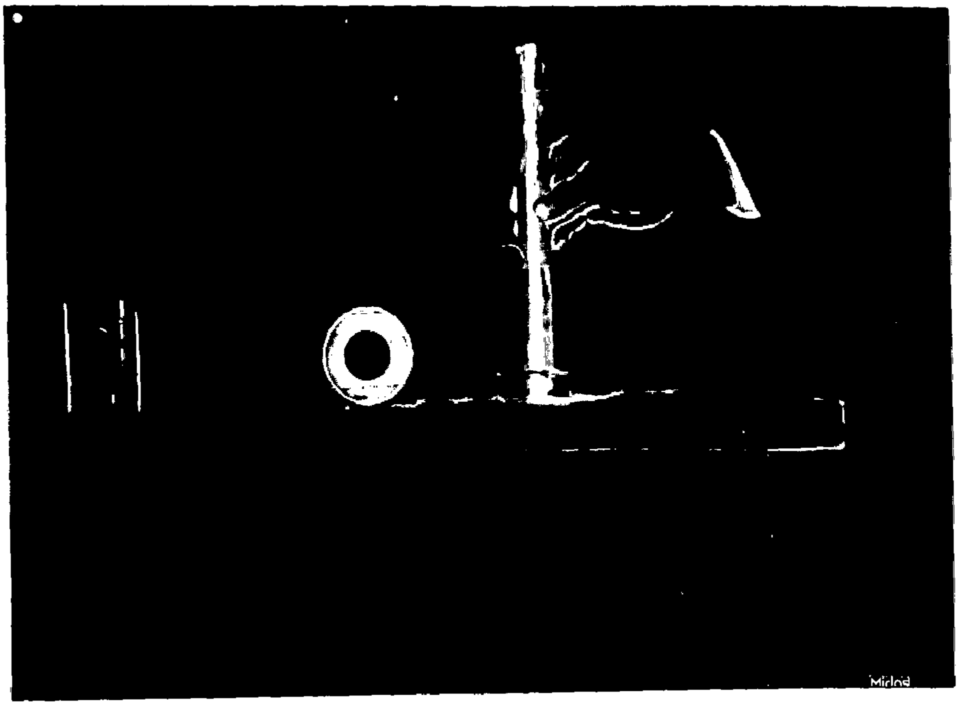
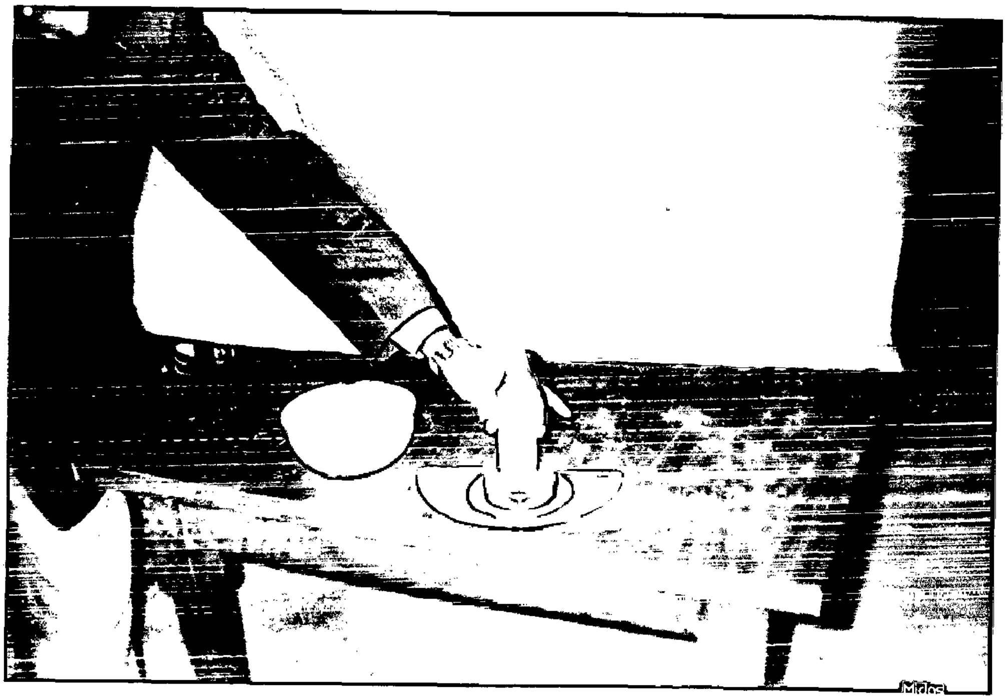


Fig. 3.1 Particle size distribution curve for sand



3.2 Cutting of Central core in Caly Sample



3.3 Compaction of Plysoil into the Core

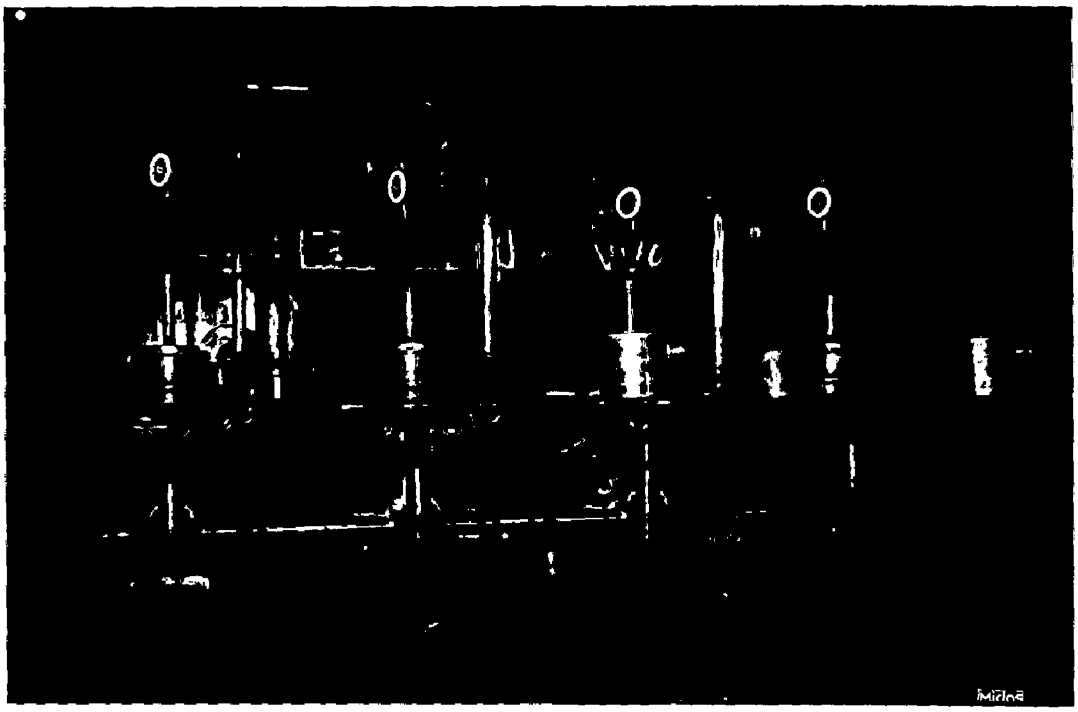


Fig.3.4 Loading frame for Consolidation test.

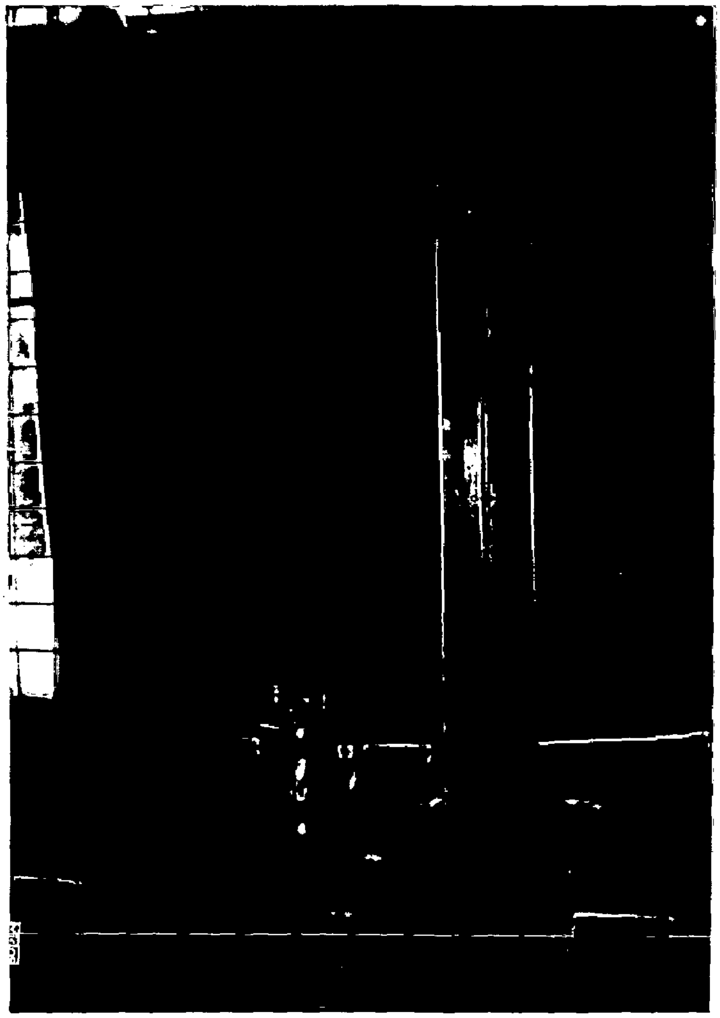


Fig.3.5 Falling head method Test set-up.

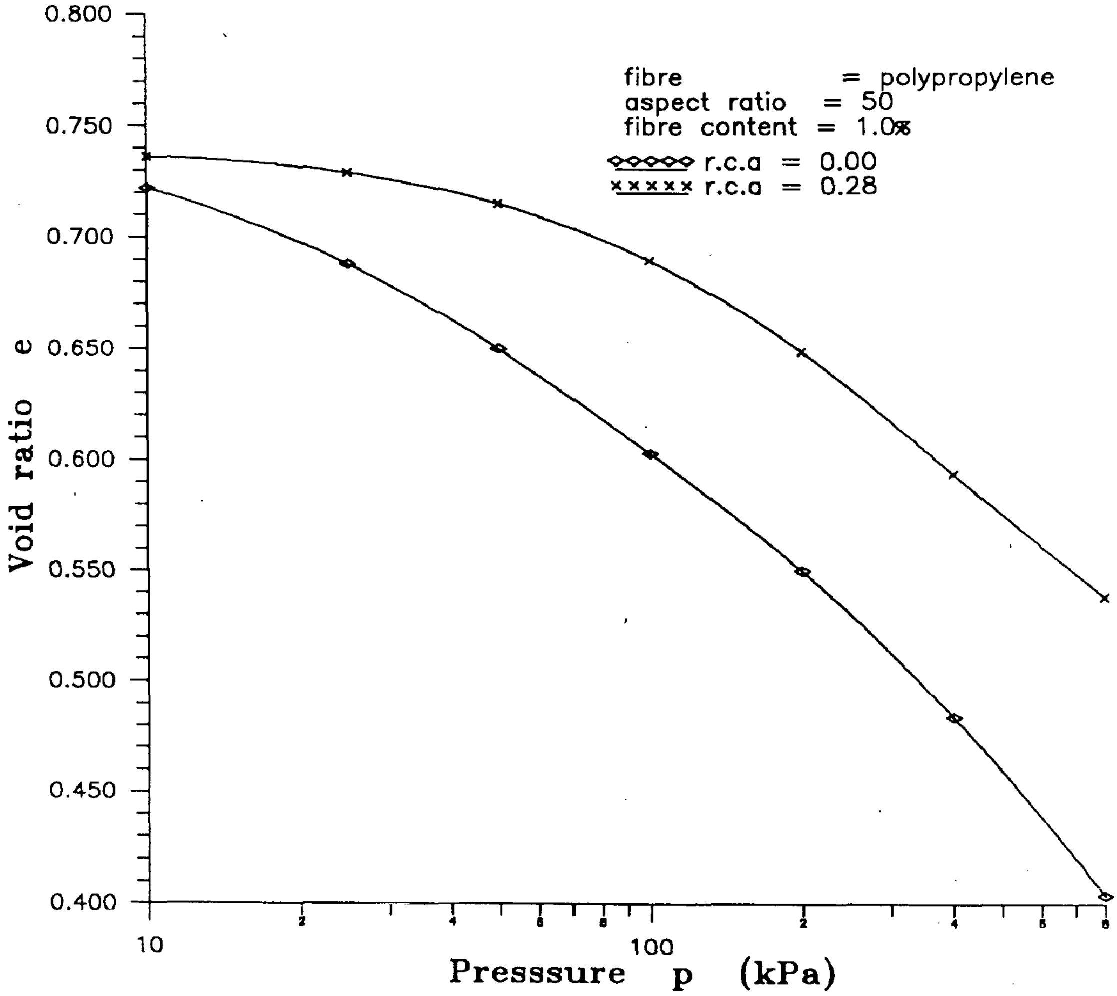


Fig. 3.6 variation of void ratio with pressure of pure clay sample and of sample with 0.28 relative core area

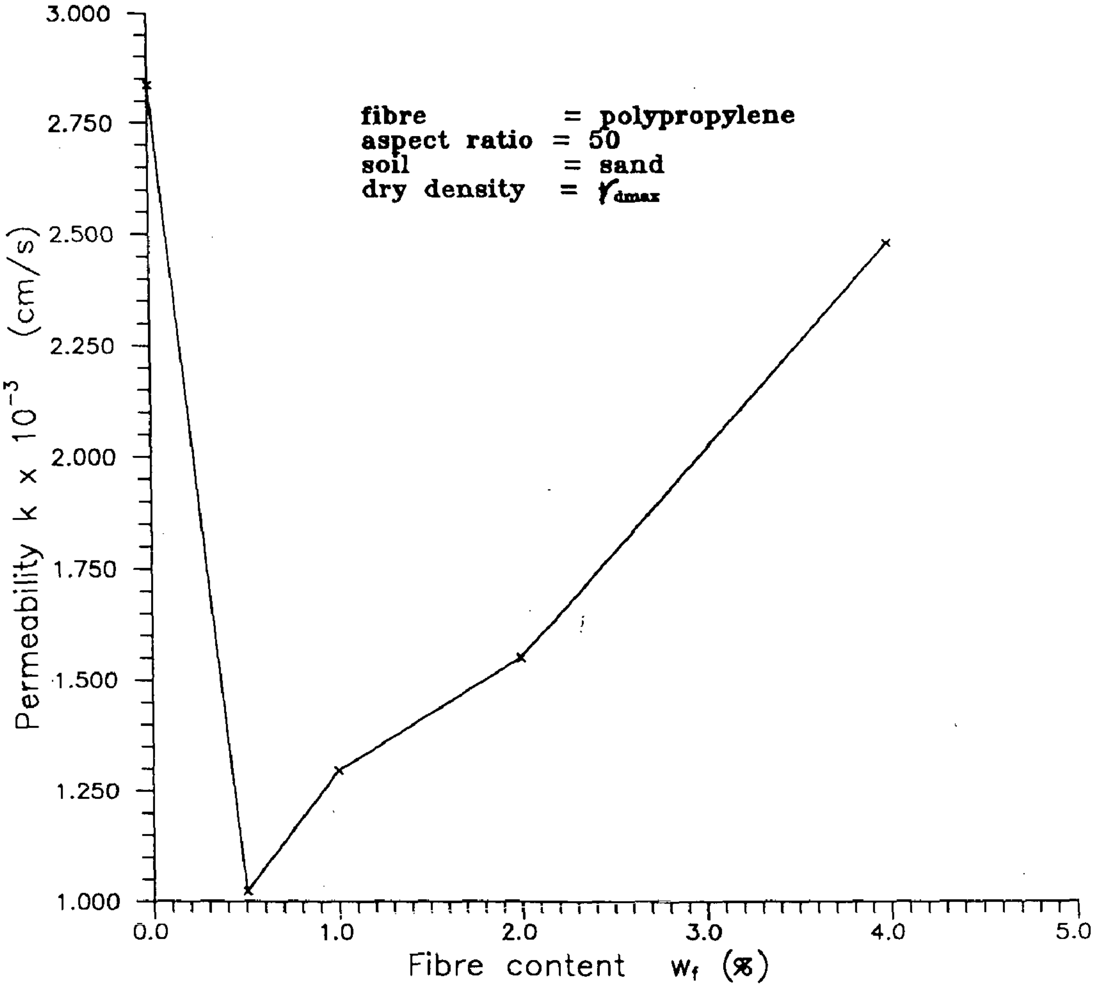


Fig. 3.7 Variation of permeability of randomly distributed fibre reinforced sand with fibre content

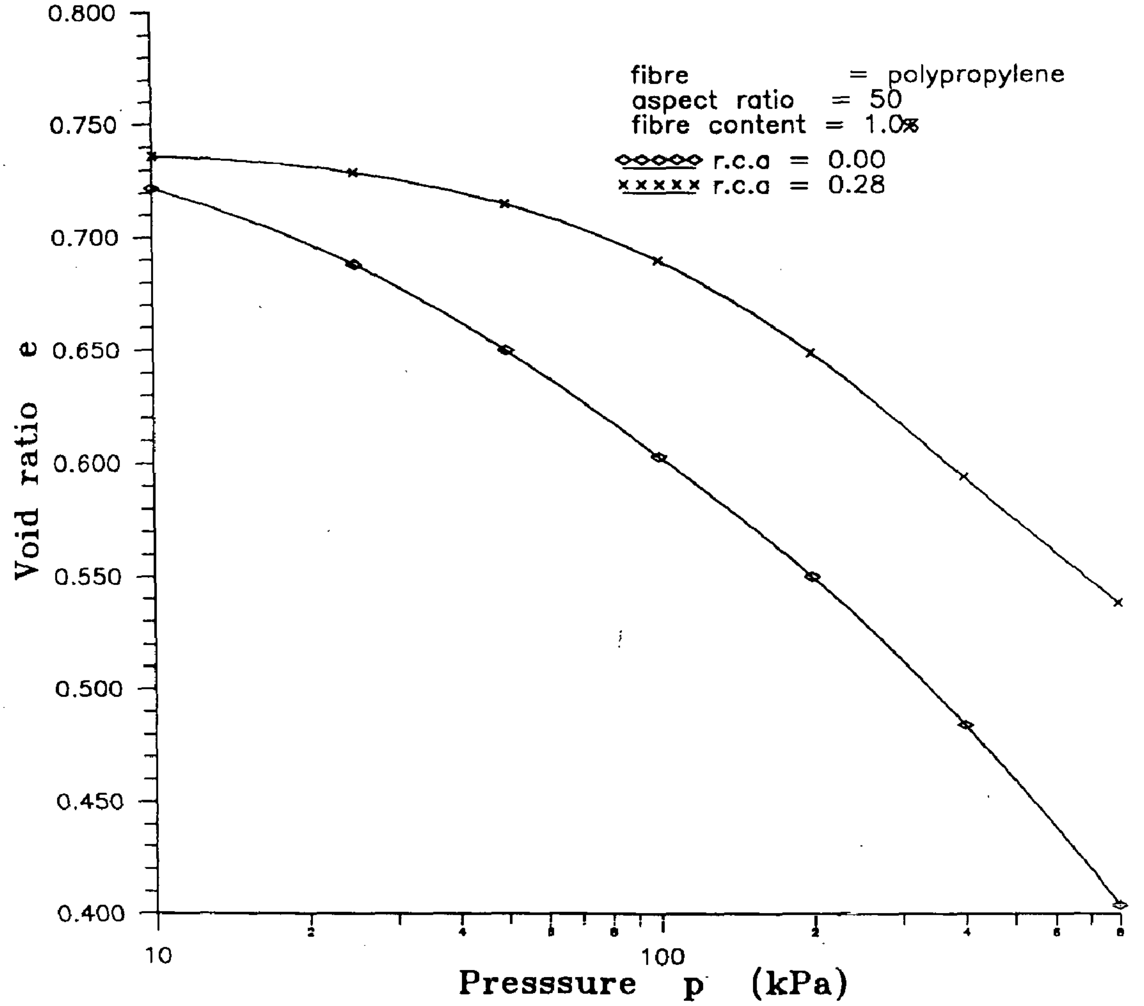


Fig. 4.1 variation of void ratio with pressure of pure clay sample and of sample with 0.28 relative core area

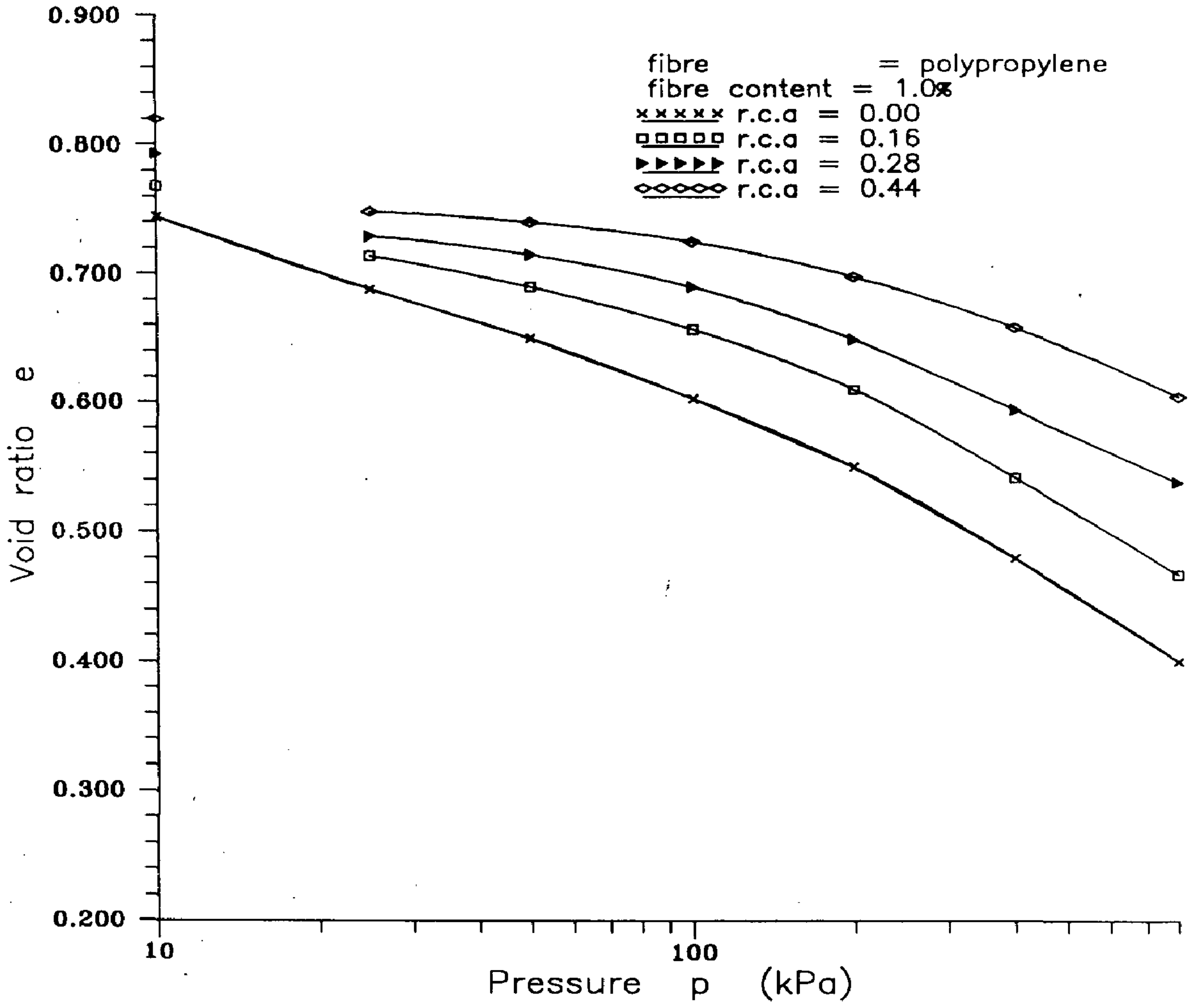


Fig. 4.2 Variation of void ratio with pressure of composite sample with different relative core ares.

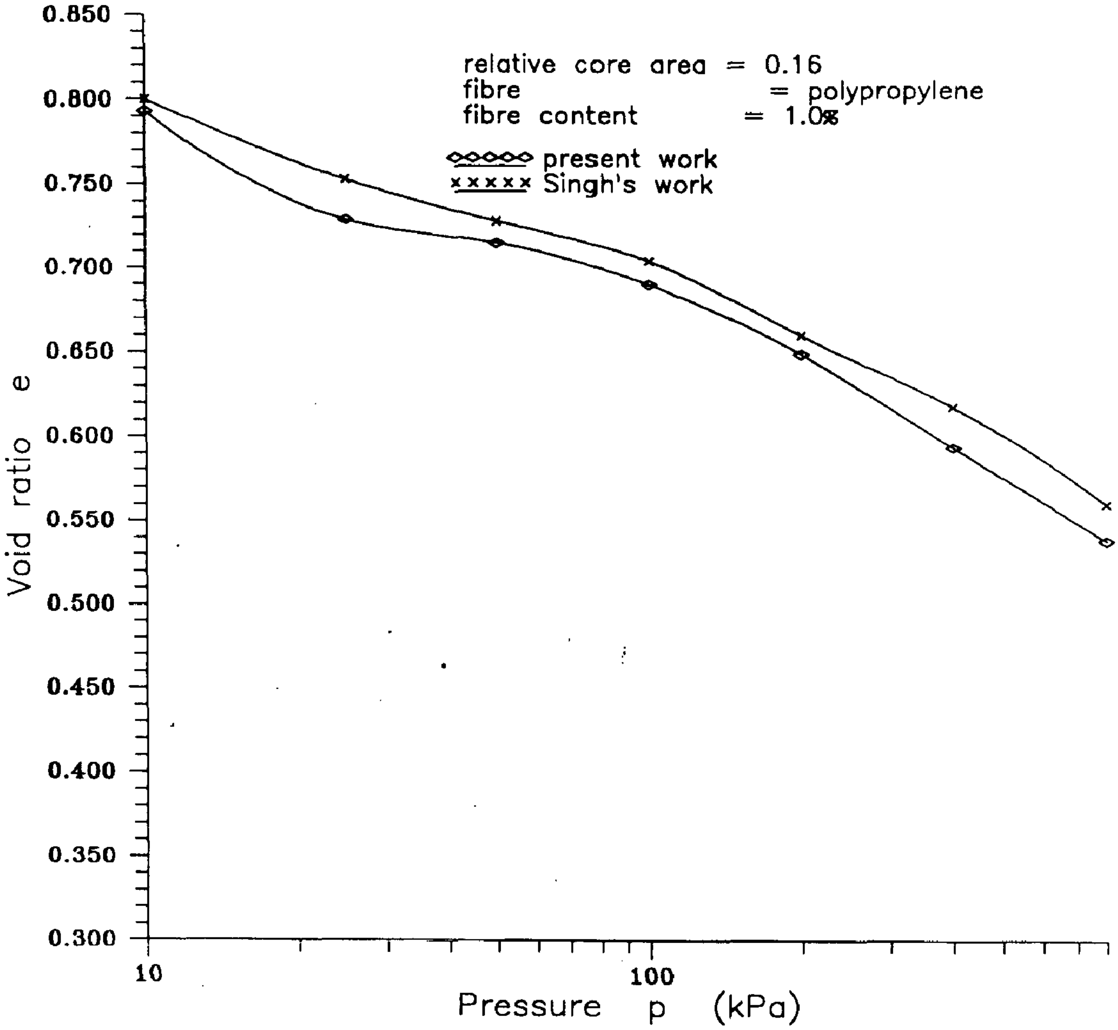


Fig.4.3 Comparison of variation of void ratio with pressure of composite sample of present study with Singh(1995)

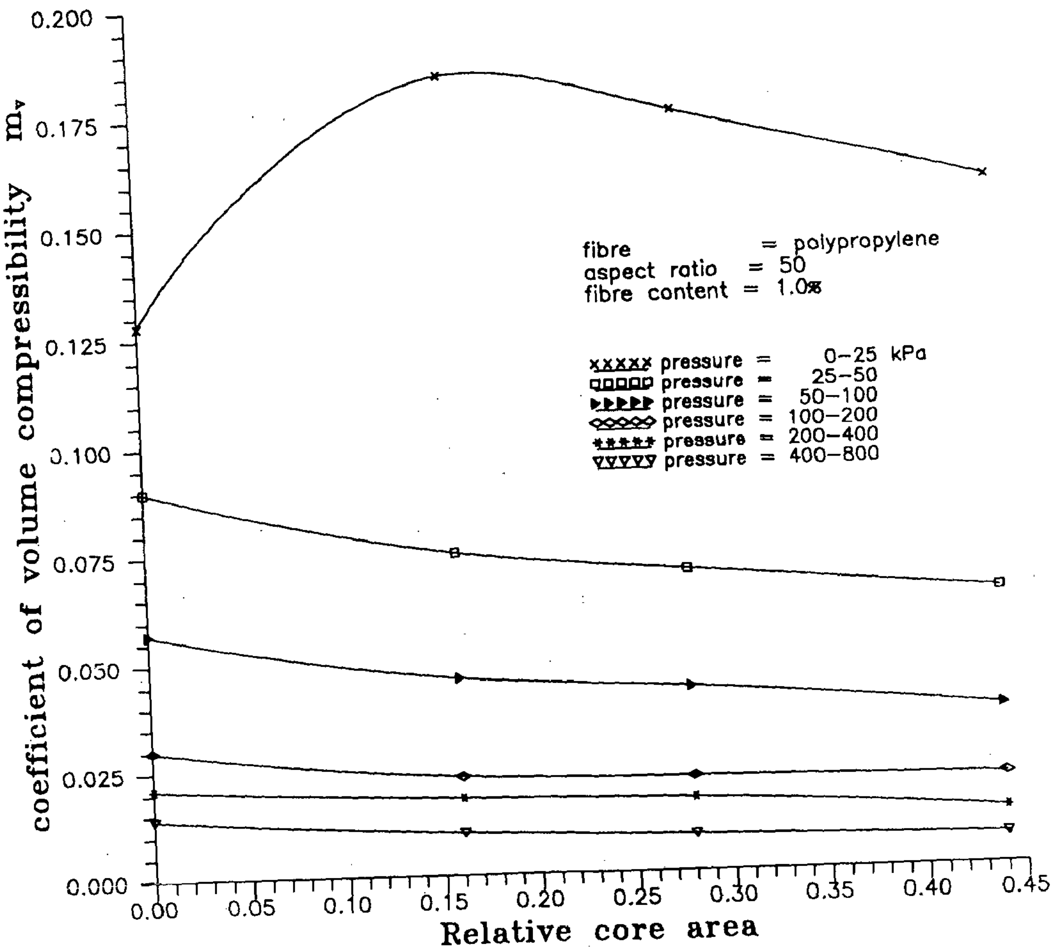


Fig.4.4 Variation of coefficient of volume compressibility with pressure of composite sample with different relative core areas

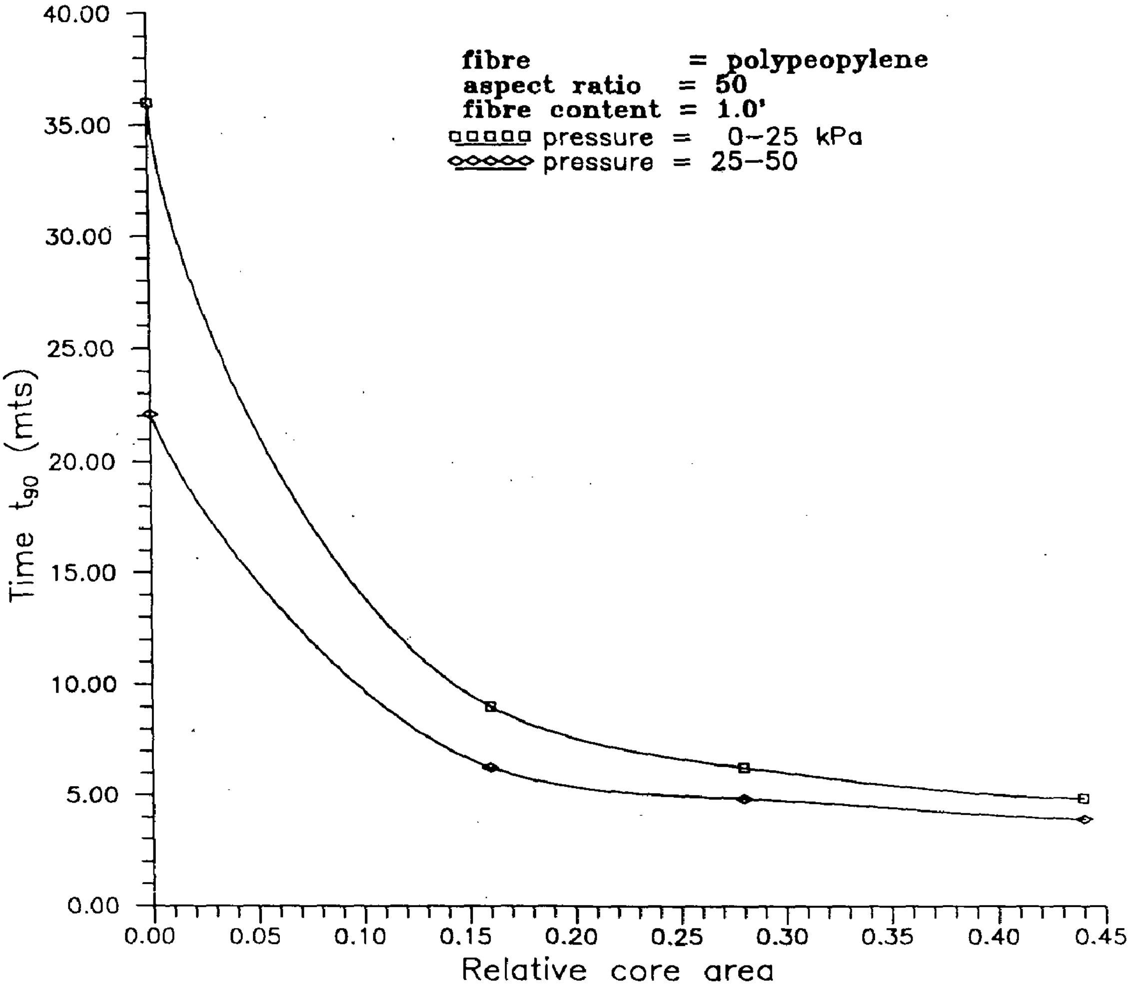


Fig.4.5 Variation of time t_{90} with relative core area of composite sample

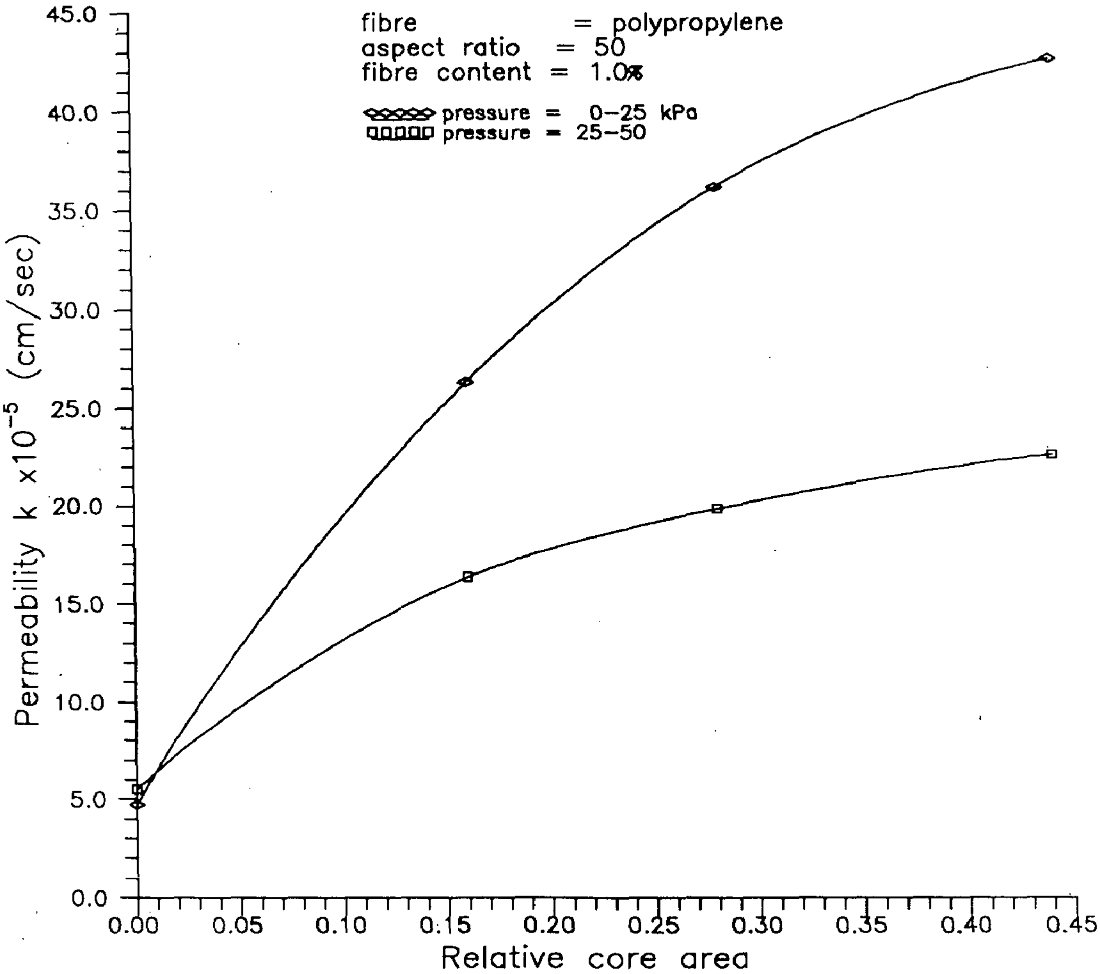


Fig. 4.6 Variation of permeability with relative core area of composite sample

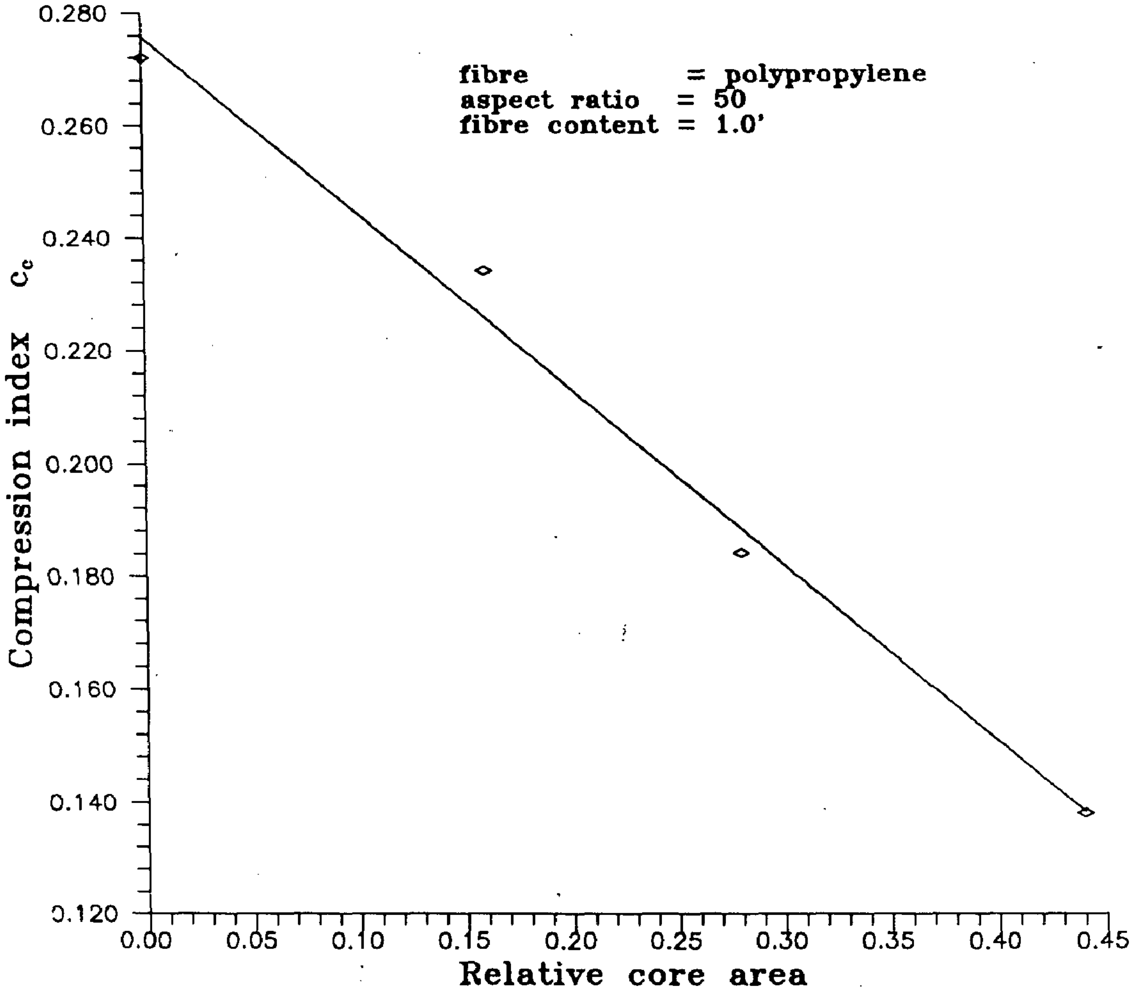


Fig.4.7 Variation of compression index with relative relative core area of composite sample

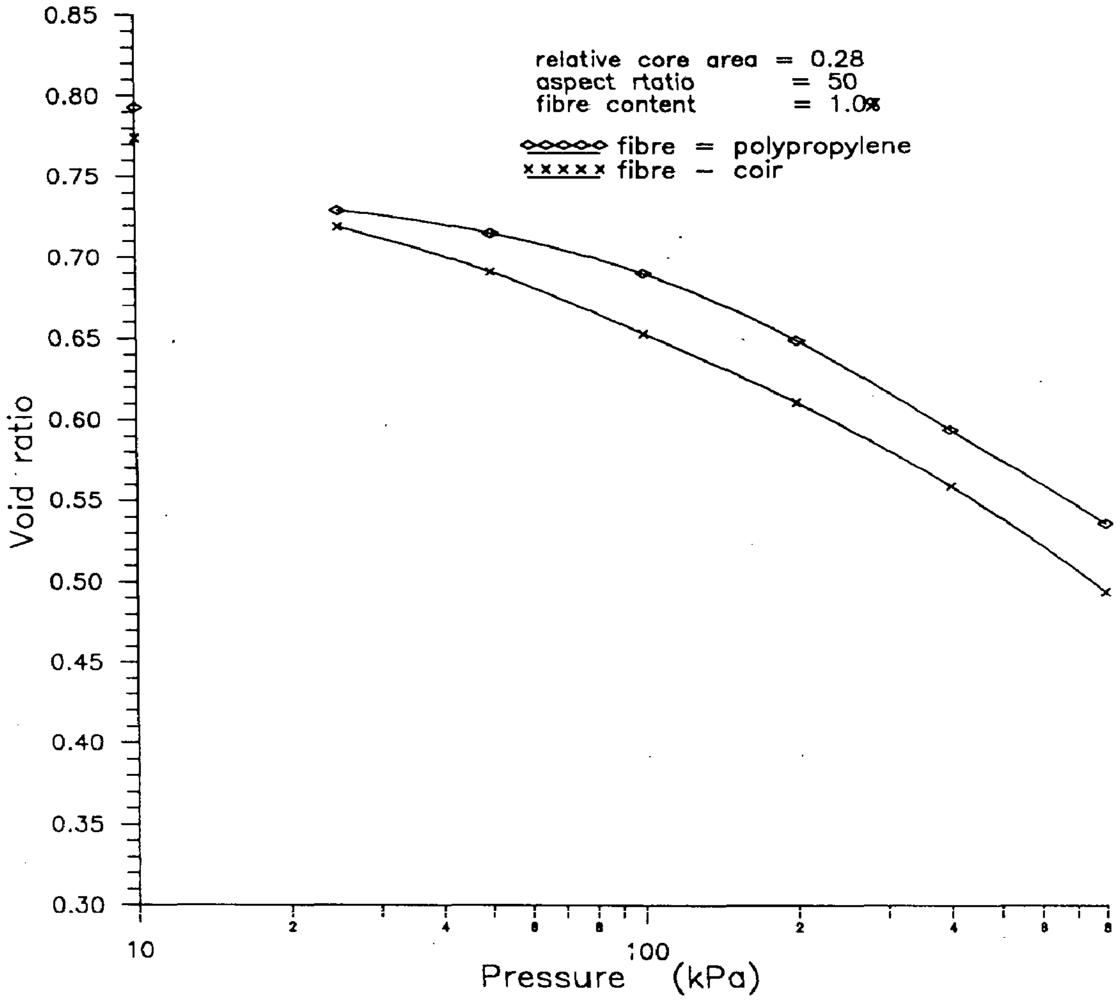


Fig. 4.8 variation of void ratio with pressure of composite sample for different type of fibres

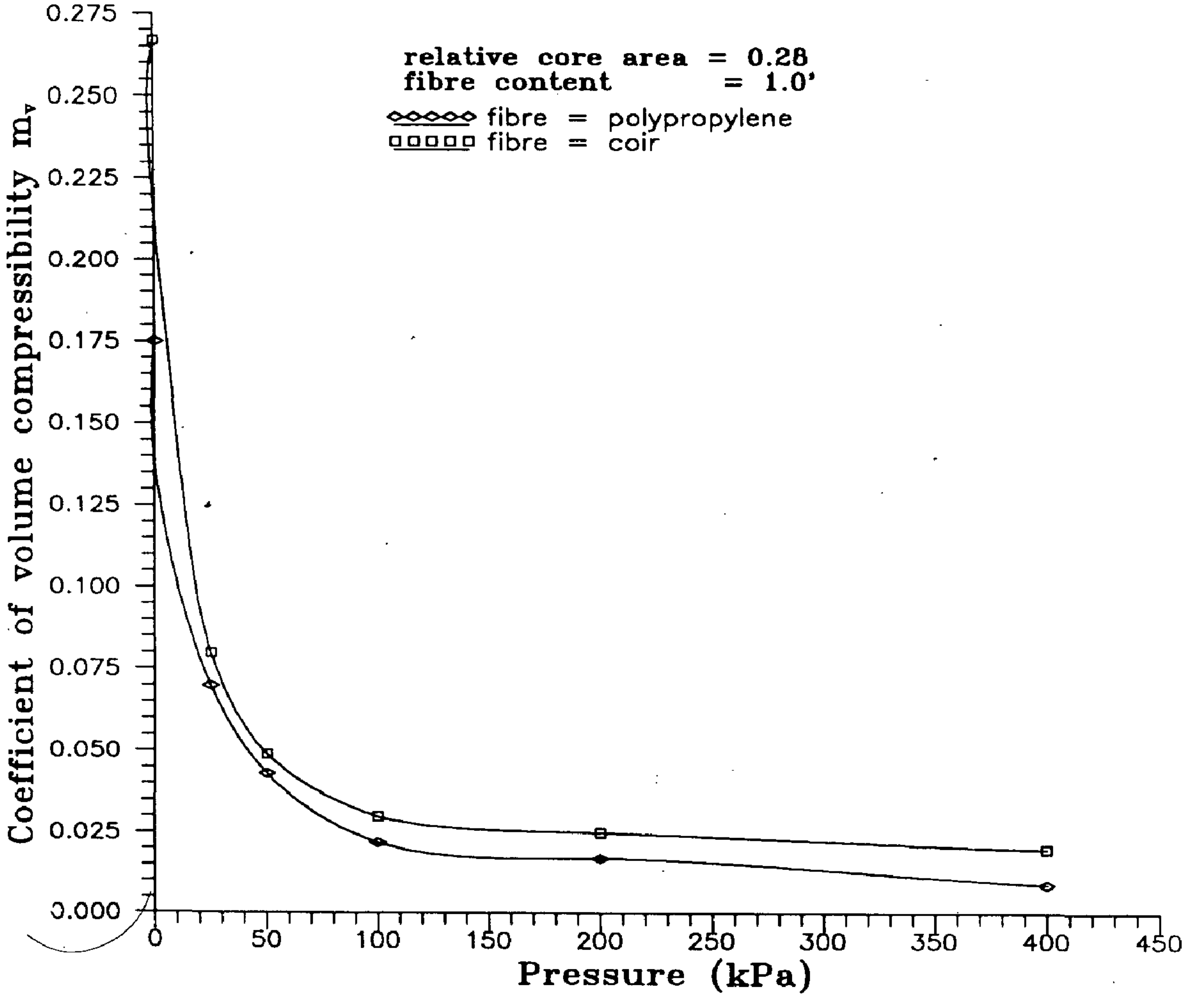


Fig. 4.9 Variation of coeftficient volume compressibility with pressure of composite sample for different type of fibres.

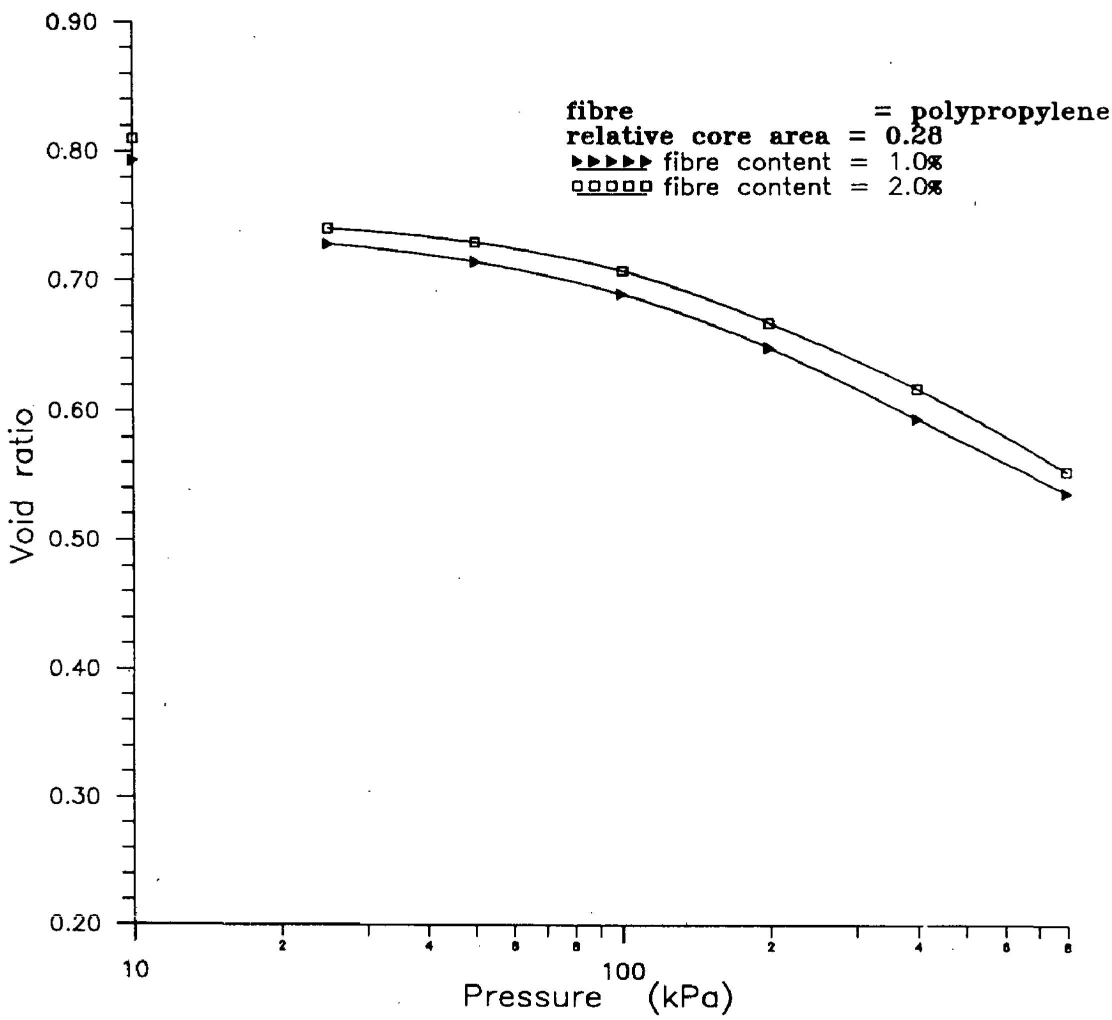


Fig. 4.10 variation of void ratio with pressure of composite sample for different fibre contents

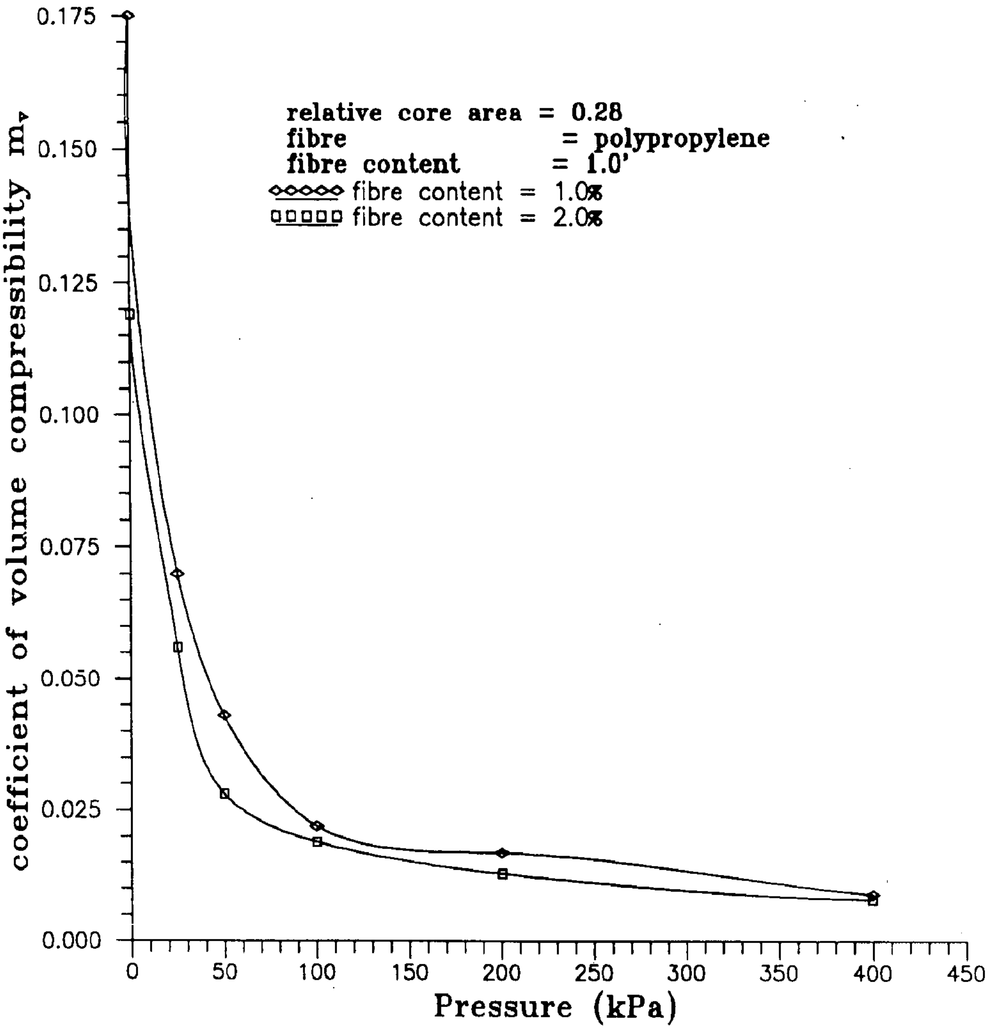


Fig. 4.11 Variation of coefficient of volume compressibility with pressure of composite sample for different fibre contents

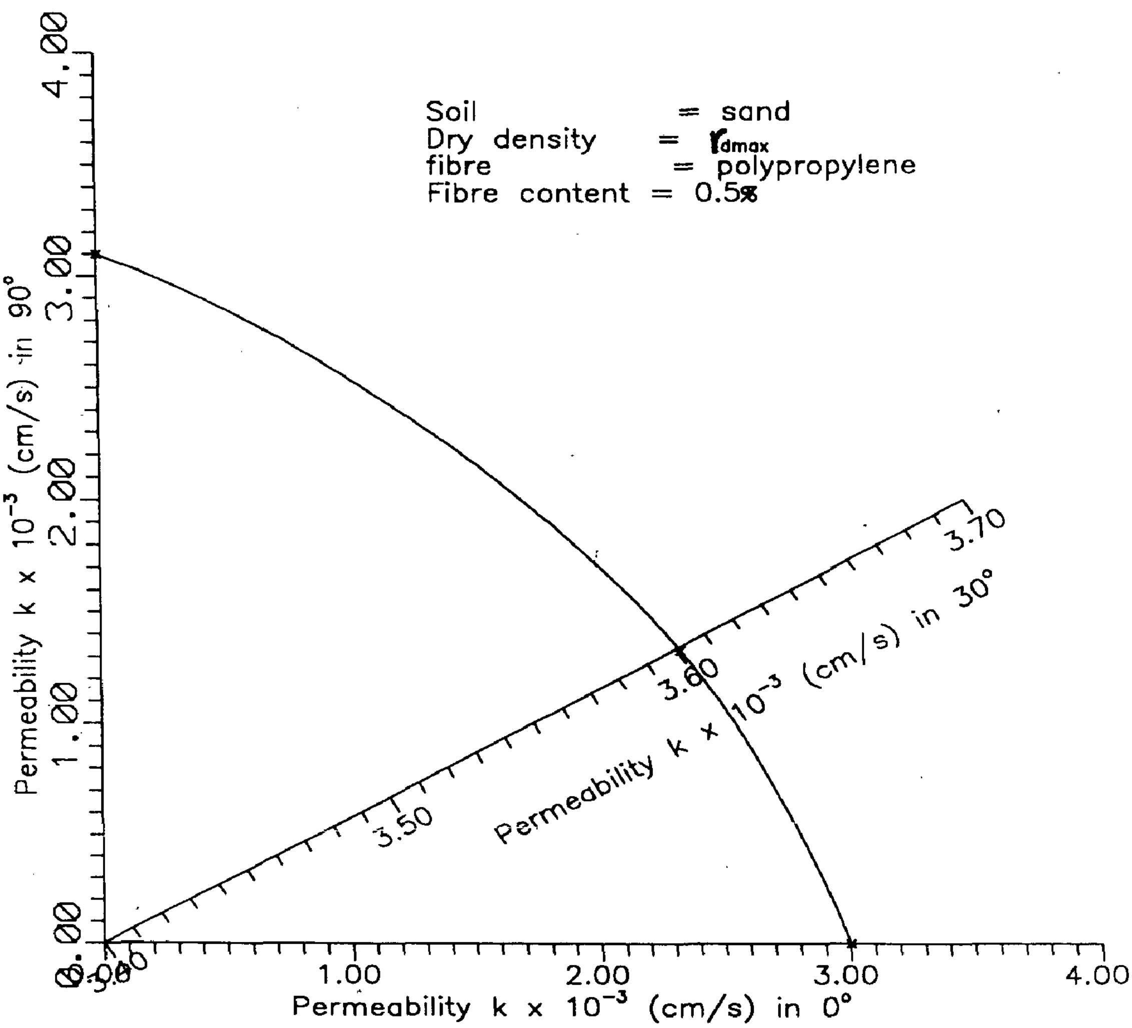


Fig. 4.12 plot showing the variation of permeability in different directions

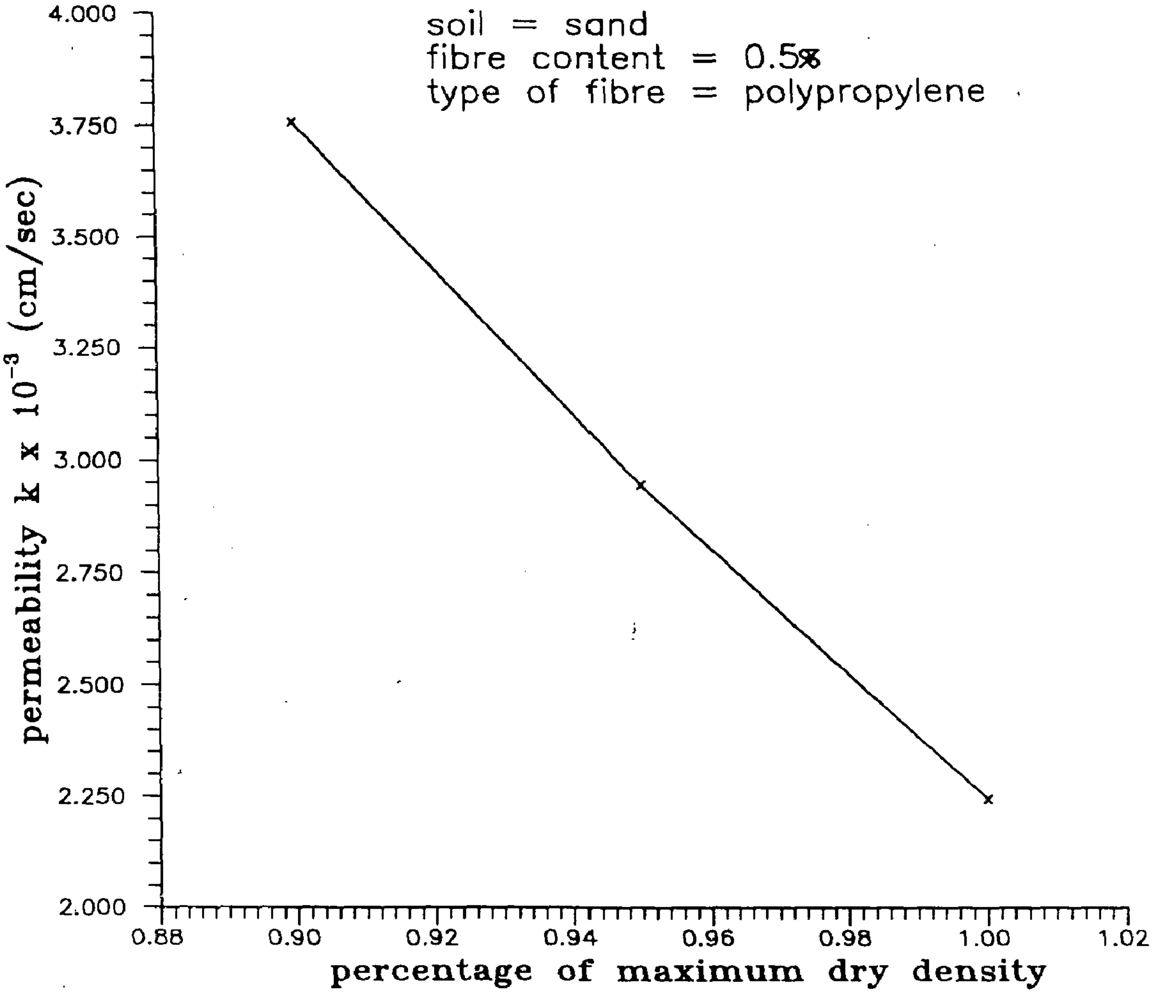


Fig.4.13 variation of permeability of randomly distributed fibre reinforced sand with dry density

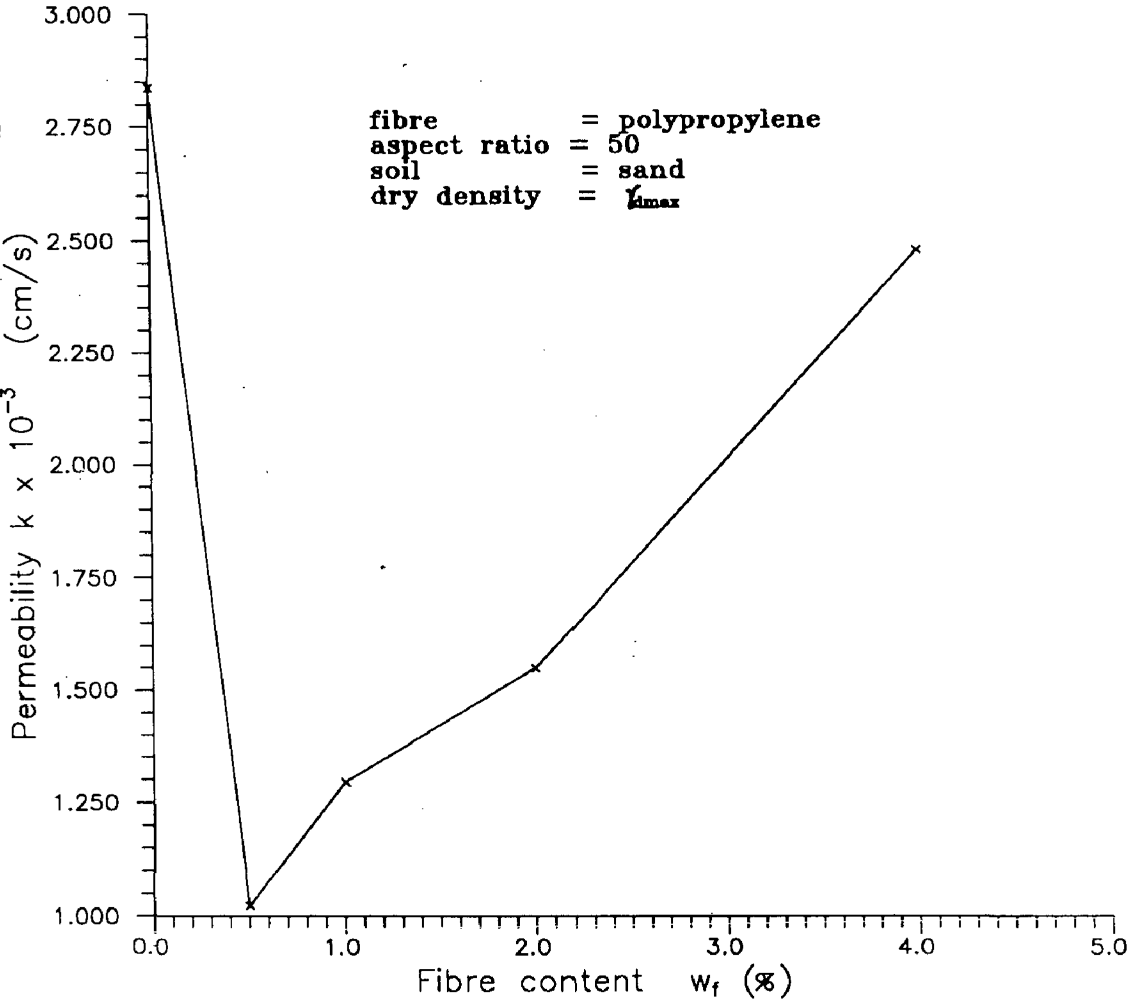


Fig. 4.14 Variation of permeability of randomly distributed fibre reinforced sand with fibre content

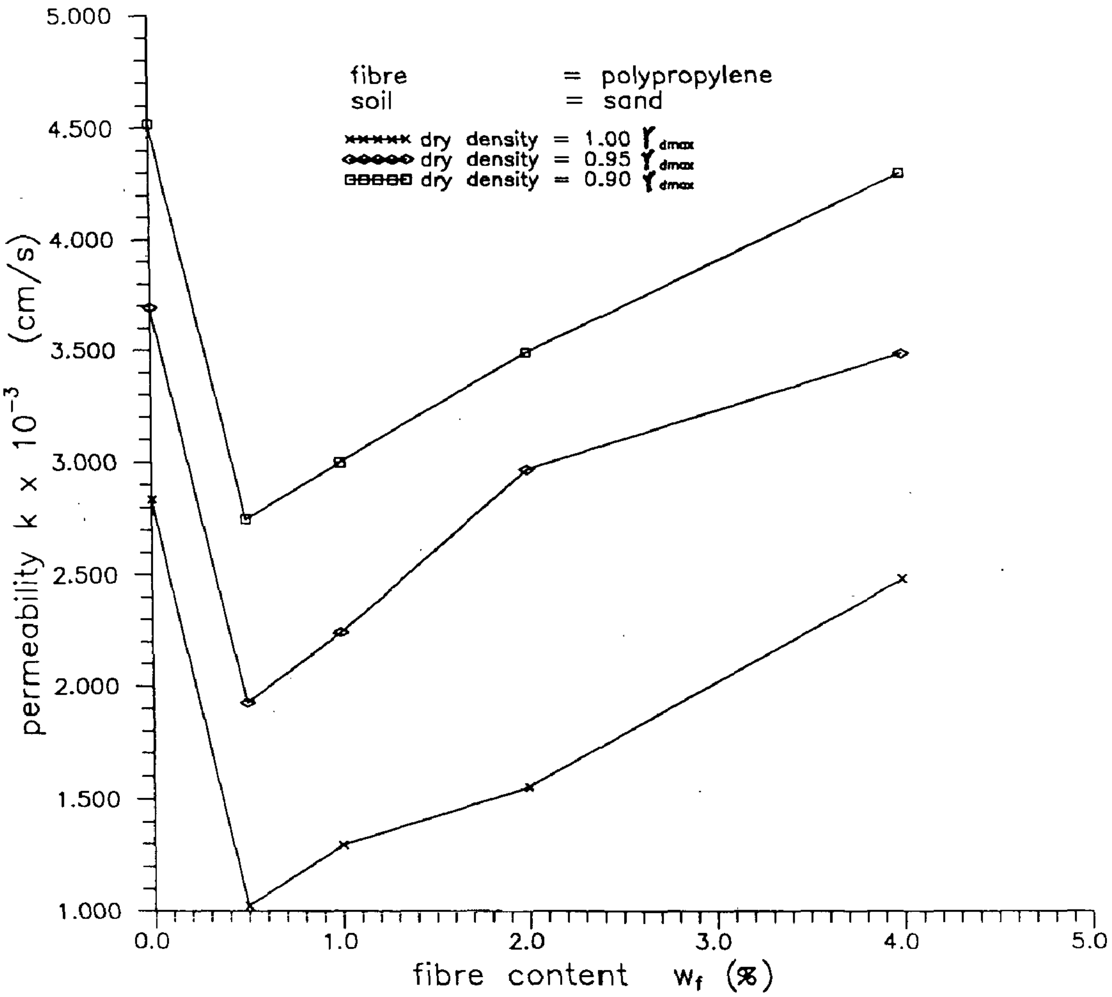


Fig. 4.15 variation of permeability of randomly distributed fibre reinforced sand with fibre content for different densities

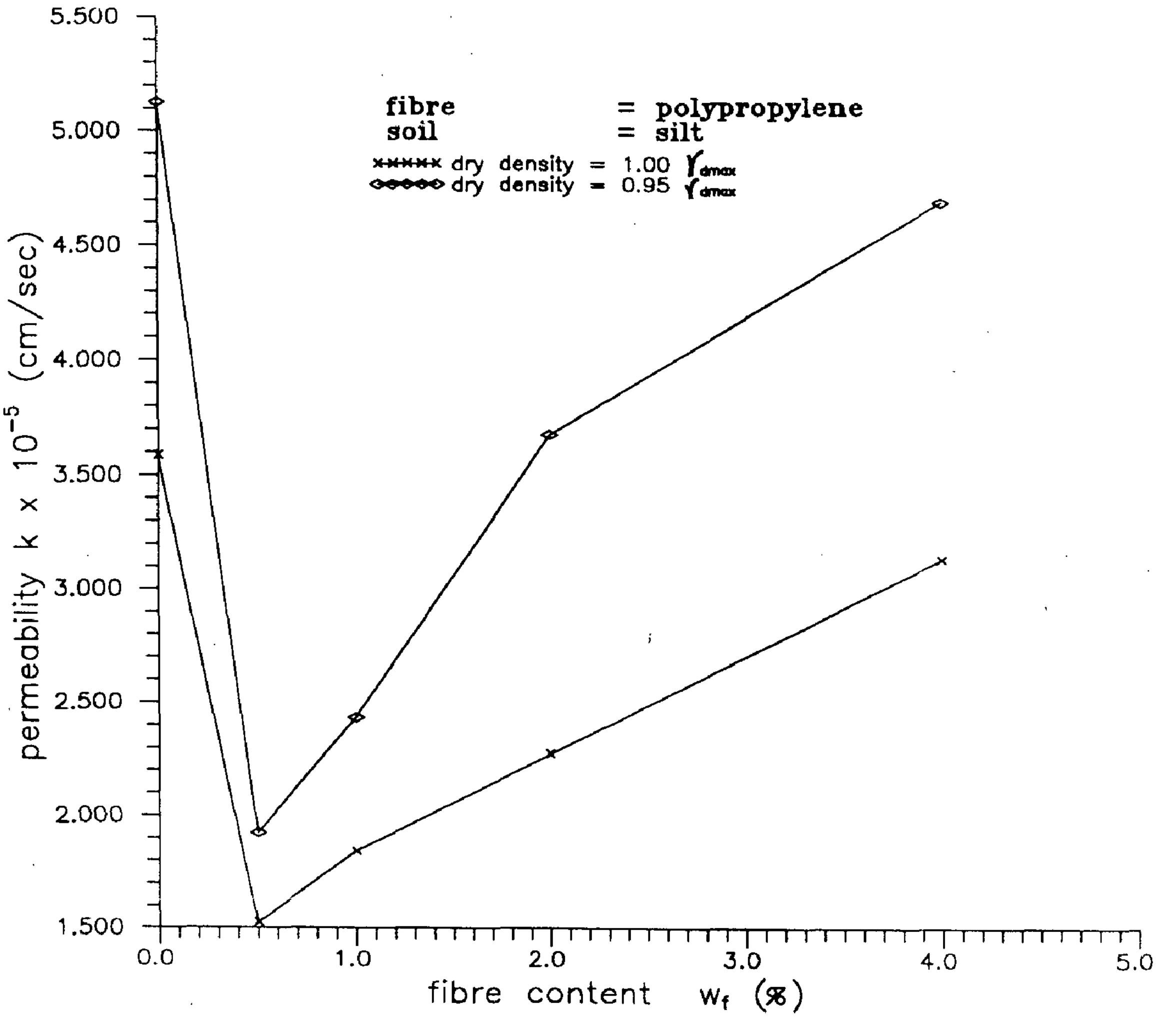


Fig.4.16 variation of permeability of randomly distributed fibre reinforced silt with fibre content for different densities.

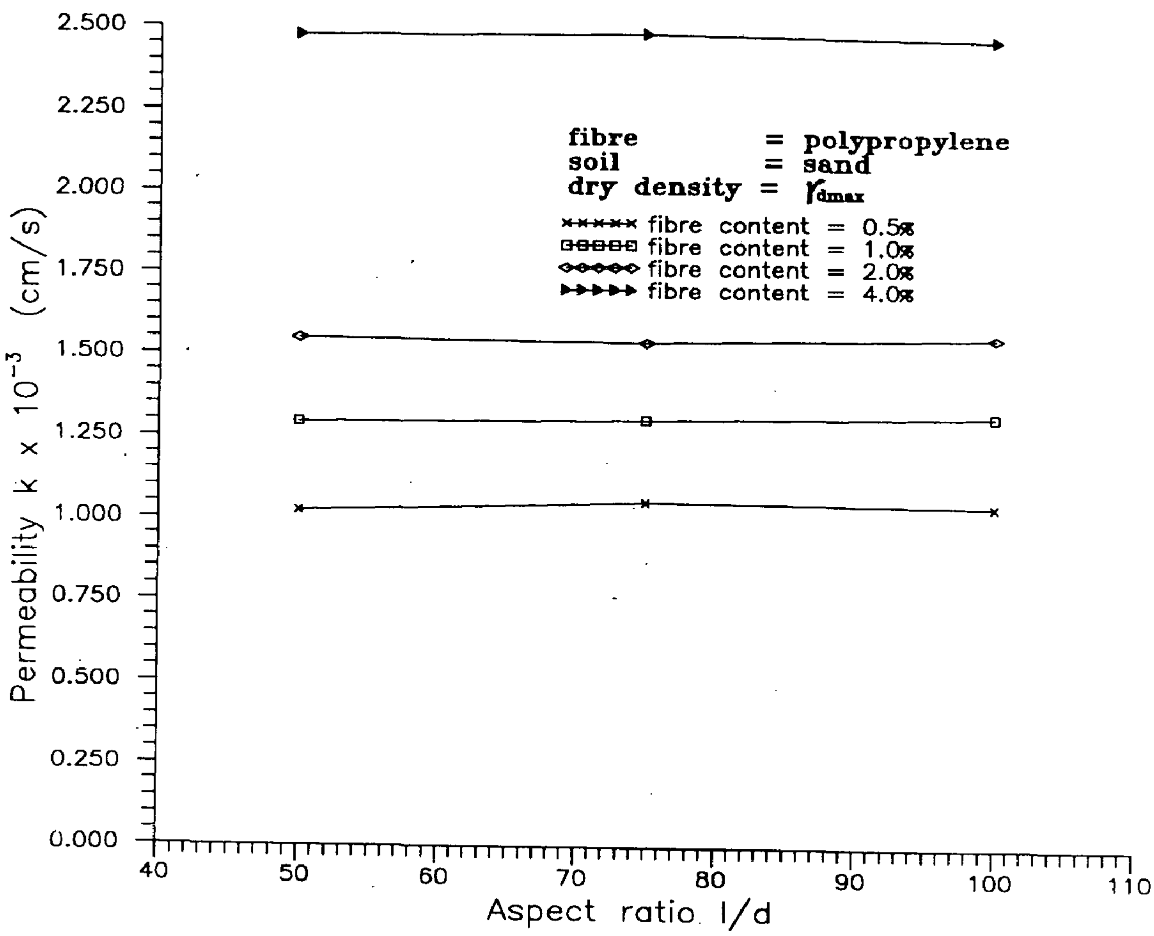


Fig.4.17 Variation of permeability of randomly distributed fibre reinforced sand with aspect ratio

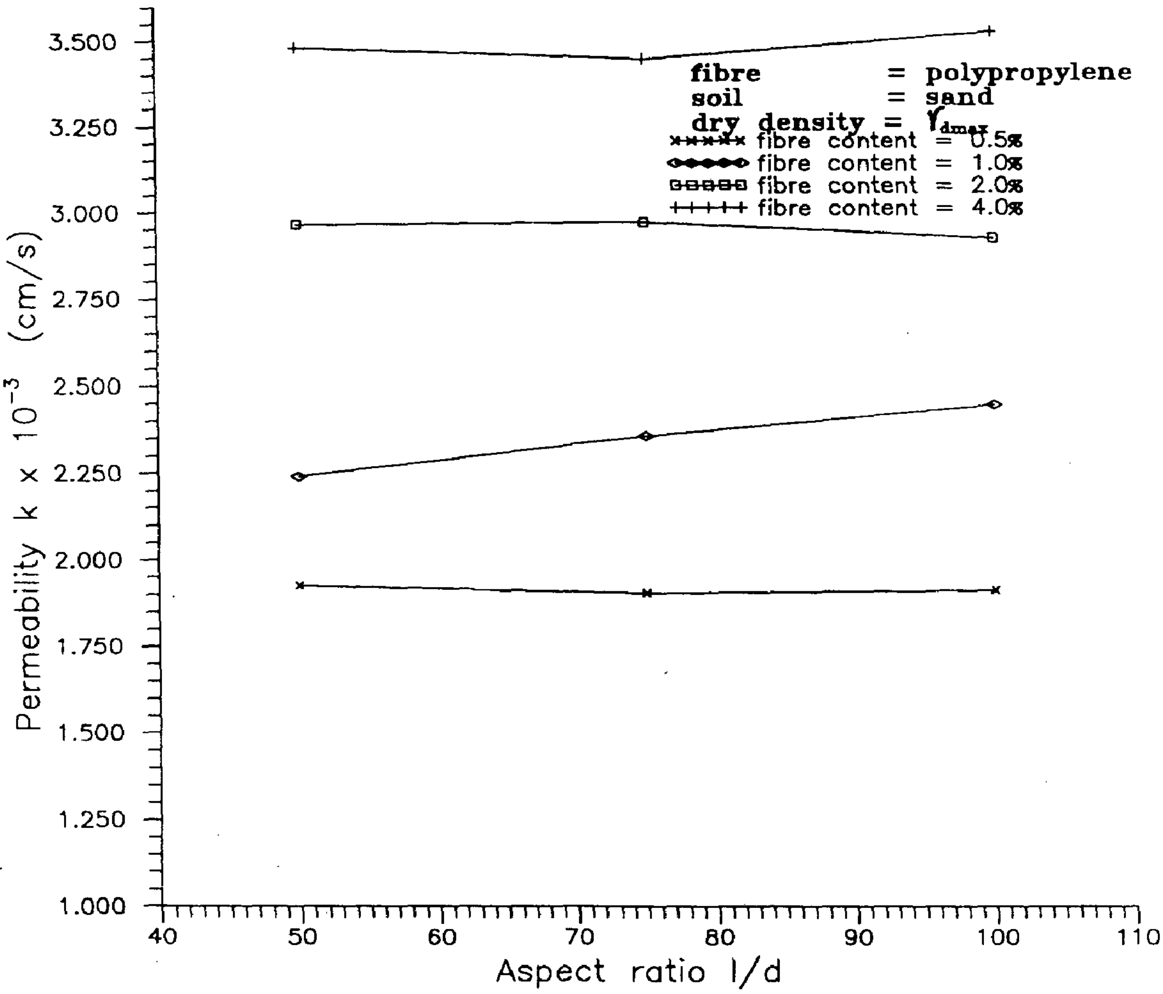


Fig. 4.18 Variation of permeability of randomly distributed fibre reinforcer sand with aspect ratio

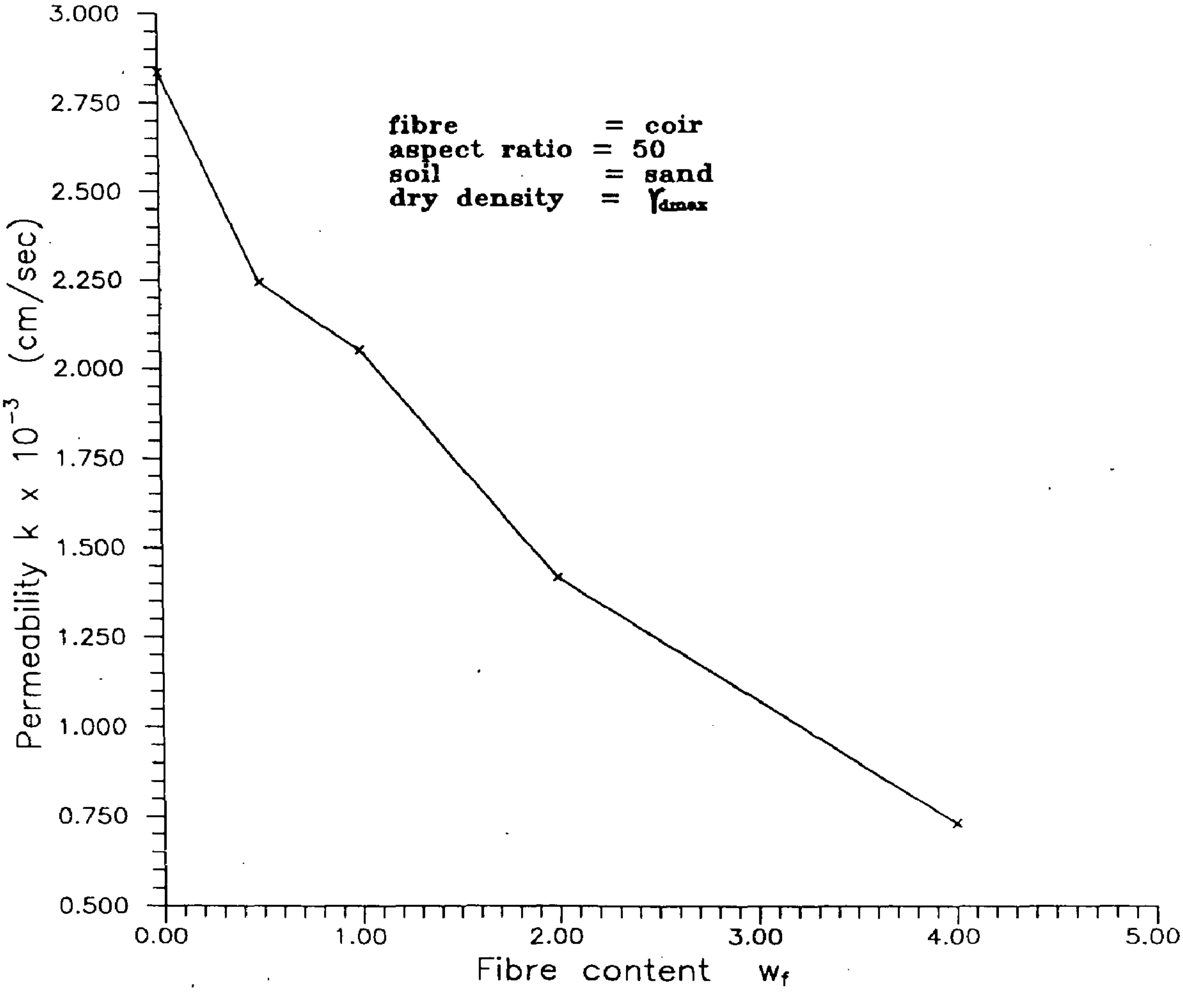


Fig. 4.19 Varition of permeability of randoly distributed fibre reinforced sand with fibre content

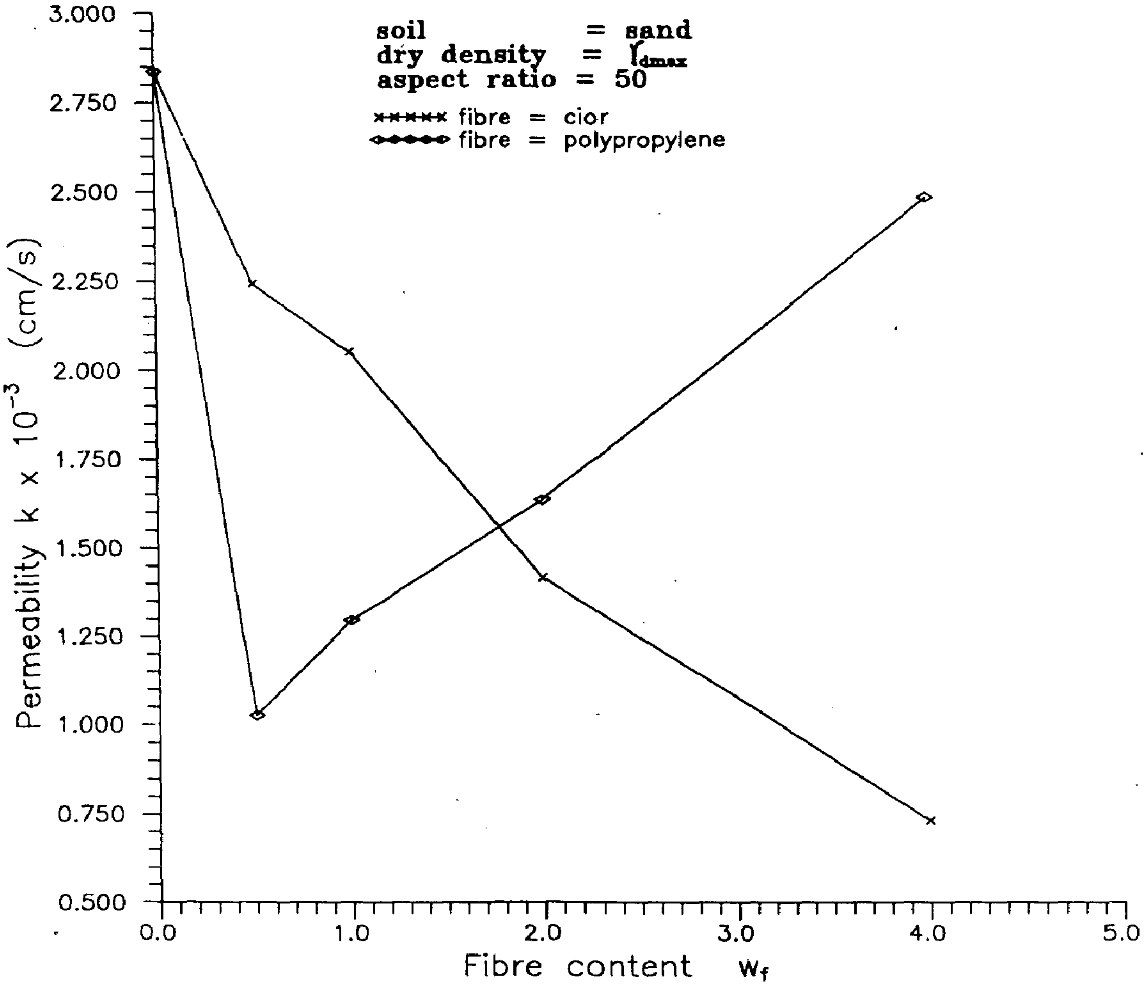


Fig. 4.20 Variation of permeability of randomly distributed fibre reinforced sand with two different fibres