About the Lecturer - IGS 1995

G. Venkatappa Rao graduated in Science from Andhra University and in Civil Engineering from Birla Institute of Technology and Science (BITS), Pilani. Thereafter, he pursued his post graduate studies in Soil Mechanics and Foundation Engineering at Indian Institute of Science, Bangalore and obtained his Ph.D.

After a brief stint in BITS, Pilani, he joined the Faculty of Civil Engineering at IIT Delhi in 1975. Since 1985 he is serving as Professor of Civil Engineering and currently, he is the Head of the Department of Civil Engineering. Over the years, his research interests included Soil and Rock Mechanics, Marine Technology and Transportation Engineering, and currently Geosynthetics. He guided 15 Ph.D. theses and 58 M.Tech. theses and published over 175 technical papers in various National and International Conferences and Journals and many books.

His work was recognised by the Indian Geotechnical Society (IGS) by 12 awards for best papers and best thesis. He brought out a publication for the IGS titled "The Indian Geoguide" (1986). He served the IGS as its Honorary Secretary and Editor of the Indian Geotechnical Journal and in many other capacities. He was also the Organising Secretary of the 13th International Conference on Soil Mechanics and Foundation Engineering held in New Delhi in 1994. Currently, he is the Chairman of the Delhi Chapter of the IGS.

For his outstanding contributions to R&D in Geosynthetics, Prof. Rao was awarded the Central Board of Irrigation and Power (CBIP) Jawaharlal Birth Centenary Award for the year 1994.

He was also instrumental in instituting the the Asian Society for Environmental Geotechnology (at the CBIP), of which he is currently the President (Protem).

He has served and is currently serving several technical committees national and internationally including the membership of the Standing Technical Advisory Committee of Ministry of Surface Transport, Highway Research Board and as Member of Editorial Board of ASTM, Journal of Geotechnical Engineering. He is also a consultant and advisor for many Foundation and pavement problems in the country and the neighbourhood.

His books on Engineering with Geosynthetics (1990) (as editor and principal author), Airport Engineering (1992) and Principles of Transportation and Highway Engineering (1996) are published by Tata McGraw Hill. He also brought out, as a principal author and editor, a state-of-the-art volume entitled "Use of Geosynthetics in India - Applications and Potential" for the CBIP in 1989. The CBIP has just released his manual on ."Erosion Control with Geosynthetics".

Prof. Rao is responsible for initiating teaching and research in Geosynthetics at IIT Delhi in 1986. Apart from several M.Tech. and Ph.D. theses, he organised as many as 12 national workshops around the country, 2 International workshops and coordinated 3 National Research Projects sponsored by the Ministry of Surface Transport and Department of Science and Technology.

He is currently the Chairman of the Bureau of Indian Standards' Committee on Geosysnthetics, a Member of the TC-9, ISSM&FE committee on Geotextiles and Geosynthetics and is now deeply involved in developing natural geotextile products under a major research initiative sponsored by the United Nations Development Programme (UNDP) and the Ministry of Textiles.

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IGS Lecture 1995

Geosynthetics in the Indian Environment

G. Venkatappa Rao

Introduction

The earliest of civilizations used natural materials to improve soil behaviour. For instance, in the *zigguraut*s of Babylonia, woven mats of reeds were used and in the construction of the Great Wall of China, tree branches along with leaves were placed. In India, it is common to see dry branches and leaves of trees being used to reinforce soft soil (or softened shoulder on the roadside) on which heavy laden trucks get bogged down during monsoon. In the vast waterfront areas of Kerala, it has been an age old custom to spread coconut leaves on the ground before gravel/aggregate is laid over a road formation. Nature itself exercises control on erosion through vegetation (more specifically by the fine well spread roots which while supporting the plant upright, also hold the soil together). Walking on stolons of trees has enabled man to cover even marshy lands. Such examples are plenty. In British India, a certain Col. Powell, while constructing retaining walls found that the thickness of the wall could be reduced by incorporating construction waste like bamboos,. canvas, etc. into the backfill. Textile material was perhaps first used in road construction in South Carolina in the early 1930's. One of the first mills to produce jute geotextile, popularly known as Soil Saver was established in Calcutta in the early forties. In the Ludlow Jute Mills a separate line was then established to manufacture this industrial by-product (as it was made from jute caddies, meaning waste jute). It was and even now an export oriented product.

The first use of a woven synthetic fabric for erosion control was in 1950's in Florida by Barrett. In the 1960's geotextiles were extensively used for erosion control both in Europe as well as in the U.S.A. Later in 1969, Giroud used non-woven fabrics as a filter in the upstream face of an earthen

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dam. The real fillip to the use of woven fabrics came through their confident use in Netherlands to build storm resistant structures over soft soils on the sea front. With such humble beginnings, geotextiles or related products or geosynthetics as they are now called, are now being increasingly used the world over for every conceivable application in civil engineering, be it in roads, foundations or earth and earth retaining structures. Their current annual use is estimated to be over 1000 million sq m and after attaining a growth rate of the order of 24 percent is now stabilized at around 8 percent per annum. Their use in India has been very limited (Kaniraj and Venkatappa Rao, 1994).

The Indian Scenario

Geosynthetics were introduced to Indian engineers by the Central Board of Irrigation and Power in 1985 when they organized the first National Workshop on Geomembranes and Geotextiles. Ever since, the subject began to be commonly discussed at various Indian Geotechnical Conferences and local experiences began to be exchanged. Textile manufacturers began to diversify their product range to include geotextiles. The first 3-week short course on the subject "Geotextiles in Civil Engineering" was organized by the Indian Institute of Technology, Delhi in the year 1987.

The first State-of-the-art volume on "Use of Geosynthetics in India - Experiences and Potential" was brought out by the Central Board of Irrigation and Power in 1989 (Venkatappa Rao and Saxena, 1989). This was a compilation of the field trials in the country which helped other engineers to gain confidence in the use of geotextiles. It also emerged that out of the many and varied uses of geosynthetics the world over, some could be adopted in the country. This was the focus of discussion in the 3-day National Workshop on Engineering with Geosynthetics, organized in Delhi under the aegis of Delhi Chapter of the Indian Geotechnical Society in 1990 (Venkatappa Rao and Raju, 1990). Over the years, several academic and research institutions notably Indian Institute of Science, Bangalore, Indian Institutes of Technology at Delhi, Kanpur, Bombay and Madras and University of Roorkee, Central Building Research Institute, Roorkee, Central Road Research Institute, New Delhi, Research and Designs Standards Organisation, Lucknow and Gujarat Engineering Research Institute, Vadodara, have started focussing attention on this new wonder material. The field experiences have begun to mount, be it of the Indian Railways, Indian Navy (Nhawa Sewa Project, Bombay), Calcutta Port Trust, Calcutta, U.P. Public Works Department, Delhi Administration and the Ministry of Surface Transport (Roads Wing) ADB Projects on NH-1. Further, the Government of India has sponsored various research schemes through the Central Board of Irrigation and Power, Department of Science and Technology and the Ministry of Surface Transport (Roads). Attempts are also being made by the

Bureau of Indian Standards to standardize the testing procedures and to bring out design guidelines.

Theme of the Lecture

The significant developments in the regional and more particularly the Indian context have already been briefly highlighted. The opening of the Indian market to the entry of foreign materials and technology and the awakening of the people and Government to the dire need of infrastructure and that this development cannot be done without adaptation of new technology to make the structures cost-effective and enduring has brought forth another aspect for serious consideration amongst Indian civil engineers. This is a major breakthrough in the Indian environment. Simultaneously to be kept in focus is the aspect of environmental changes that this developmental process may bring out. Sustainable development with minimum degradation should be the basis for use of any new technology. That this can be done rationally, confidently and economically with geosynthetics is evident by the vast experience amassed around the world and even with the limited experiences we in India have gathered. It is well established that the environmental engineering applications include pollution control, erosion control, architectural appearance and domestic environment. These help in soil and resource conservation.

On the other hand one should not be tempted to imagine that Geosynthetics are magic materials to yield excellent results, without due consideration of the problem at hand or due understanding of the soil-geosynthetic material. Such an approach may only lead to disaster. While caution needs to be exercised, the future appears to be highly promising with stronger and more durable geosynthetics emerging into the market and tie ups for manufacture are being finalised with MNC's.

With this in view, this lecture deals with an overview of the geosynthetics that are now available to the Indian engineers, their testing and characterization, the relevant findings of the Indian researches on the subject and typical case histories, each one of which is a landmark in the Indian context. It finally concludes with an identification of the gaps in research and the policy initiatives the government authorities need to take to make geosynthetics a worthy material worth every rupee and geosynthetics a new civil engineering discipline. I begin this lecture by paying tributes to the forerunners of the subject, to mention a few, Dr. J.P. Giroud, Professor Jean Pierre Gourc, Professor Alan McGown and Professor Robert M. Koerner and to those who introduced the subject in India, Shri K.R. Datye and Dr. C.D. Thatte and the one who introduced to me this exciting topic, Professor T. Ramamurthy. Some of the novel ideas on ground improvement and soil reinforcement were presented by Datye (1982) in his Fourth IGS Annual

Lecture. I dedicate this lecture to all my masters' and research students who supported me in this voyage with enthusiasm.

I shall now deal with the following aspects:

- Geosynthetics – The Wide Variety
- The Functions
- Raw Materials
- Mechanical Property Characterization
- Fabric Design
- Soil Reinforcement
- Geosynthetic Reinforced Soil Walls
- Landslide Protection
- Geosynthetics in Pavements
- Land Fills
- Geosynthetics with Natural Fibres
- Erosion Control
- The Future

Geosynthetics – The Wide Variety

Geosynthetics are currently being defined as civil engineering materials that are synthesized for use with geological materials like soil, rock (or any other geotechnical engineering related material) to improve or modify its behaviour. It is a generic term which includes -

- Geotextiles
- Geogrids
- Geomembranes
- Geocomposites
- Geonets and other products, geomats, geomeshes, geowebs etc.

Geotextiles are permeable textile materials and may be woven, non-woven or knitted. Figure 1 shows Scanning Electron Microscopic views of typical geotextiles. Depending on the weaving technology and the fibres used (polymer used, and the technology of drawing) the strength of woven fabrics can be as high as 1100 kN/m at 5% elongation. On the other hand the non-woven geotextiles are better known for their filtration and drainage in view of their high porosity. Even when thin and of low strength they can act as separators.

A **Geogrid** is a planar structure formed by a regular network of tensile elements with apertures of sufficient size to allow interlocking with surrounding soil, rock/earth. They are also characterized by high dimensional stability, high strength and high tensile modulus at very low elongation (achieved by patented processes of orientation of polymer molecules). They

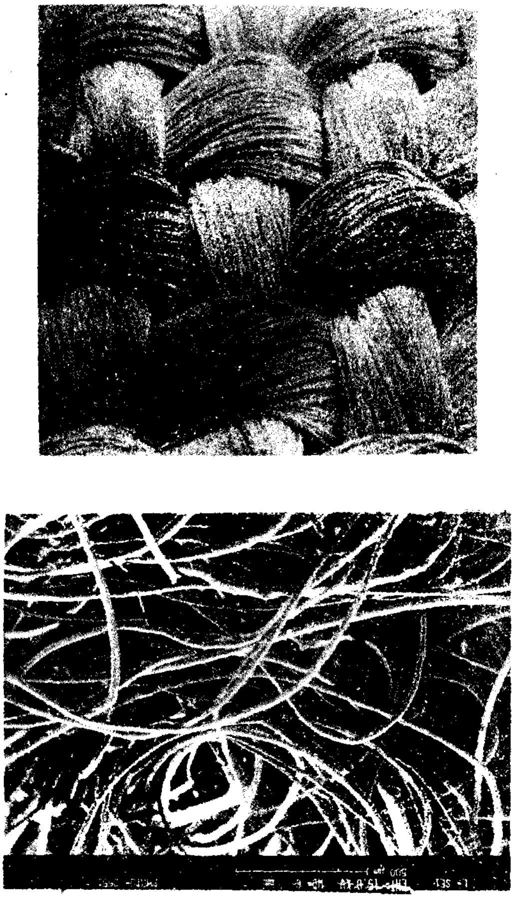


Figure 1 : Scanning electron microscopic views of (a) Woven geotextile (b) Non-woven geotextile

are of two varieties, viz., uniaxially oriented (mono-oriented) and biaxially oriented (bioriented), as shown in Fig. 2, with enhanced strength in one or both the directions. They are primarily used for soil reinforcement.

A **Geomembrane** is a continuous membrane type linear/barrier composed of materials of low permeability to control fluid migration. The materials could be asphaltic or polymeric or a combination thereof.

When Geotextiles/geogrids/geomembranes are combined with woven or non-woven geotextiles or geogrids for specific applications like drainage, erosion control, bank protection, etc., they are designated as **Geocomposites**. One typical example is bentonite geocomposites, or geosynthetic clay liners (GCL) which consist of geotextiles with bentonite filled pores. When in

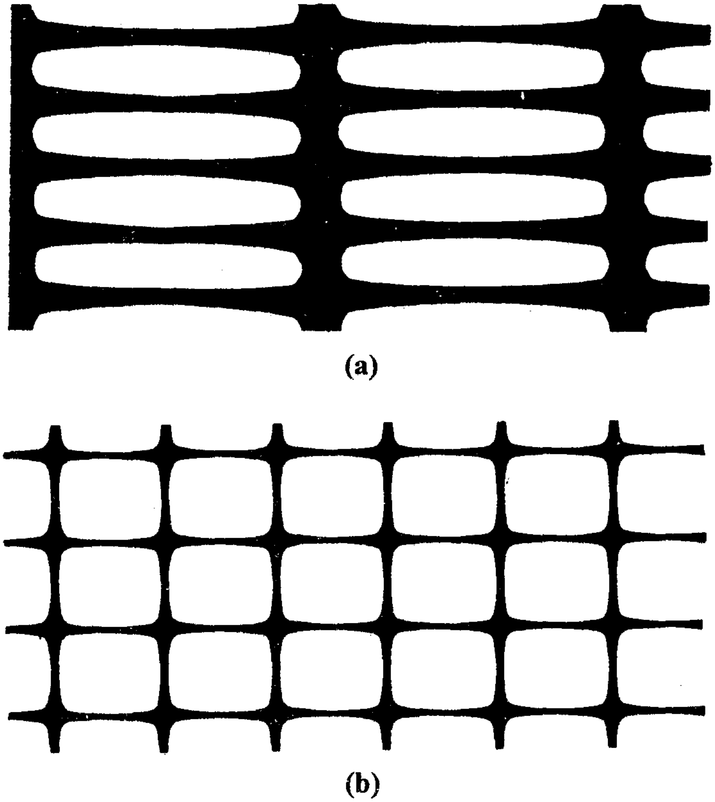


Figure 2 : Geogrids (a) uniaxially oriented (mono-oriented) (b) biaxially oriented (bi-oriented)

contact with water, the bentonite causes the pores to swell, thereby forming a water tight sheet or offer protection to geomembranes.

Geonets/Geomeshes are extruded polymer meshes and look like geogrids (but of substantially lower strength). Their function is hydraulic - as they are used to drain water in a horizontal plane. They also provide space between say, two nonwoven geotextiles to minimise clogging or between two geomembranes to recover any possible leakage from either of the membranes.

Geomats and **Geowebs** could be coarse woven or joints obtained by partial melting made of strips, rigid filaments or extracted strands. They are generally flexible and junctions of overlapping strands not firmly connected. They can be synthetic or natural. Figure 3 shows woven jute and coir mattings. There are also three-dimensional mattresses commonly used in erosion control, as shown in Fig. 4 as well as staple fibres, continuous filaments or microgrids used as admixture to strengthen soil.

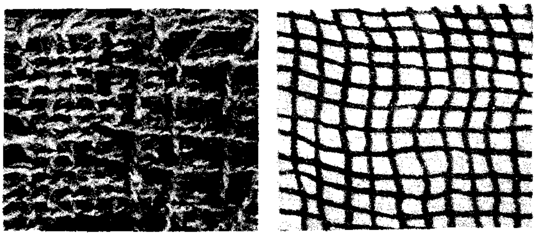


Figure 3 : (a) Coir matting (b) Jute matting

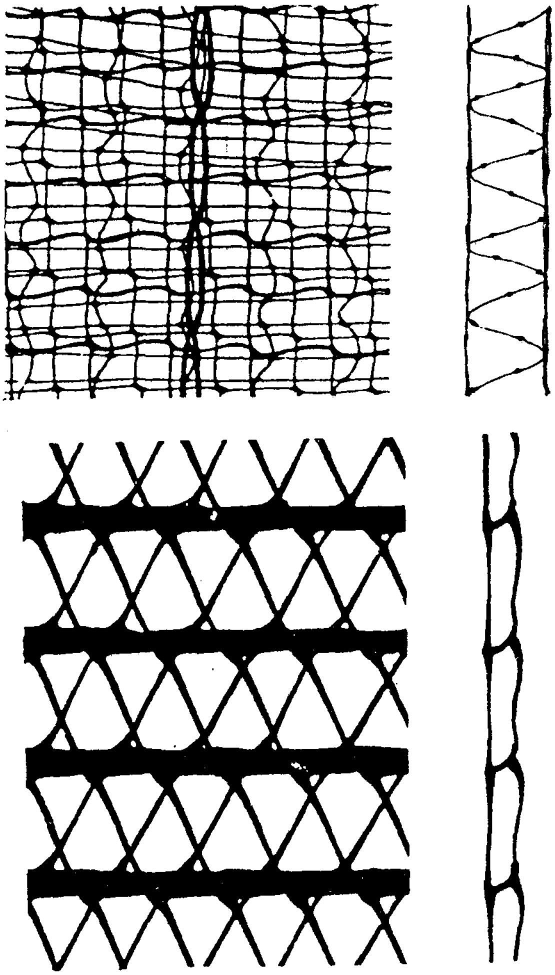


Figure 4 : Views of some 3-dimensional mattresses

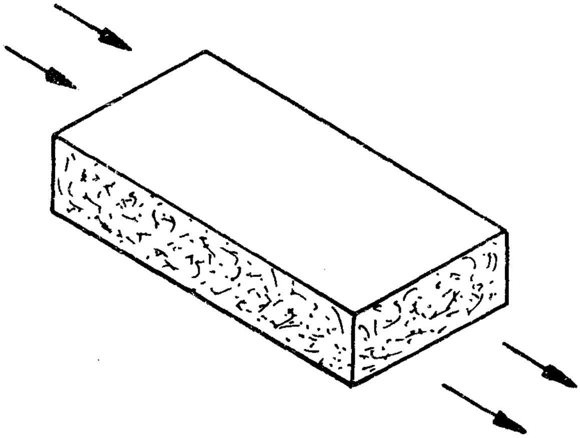


Figure 5 : Drainage function of a geosynthetic

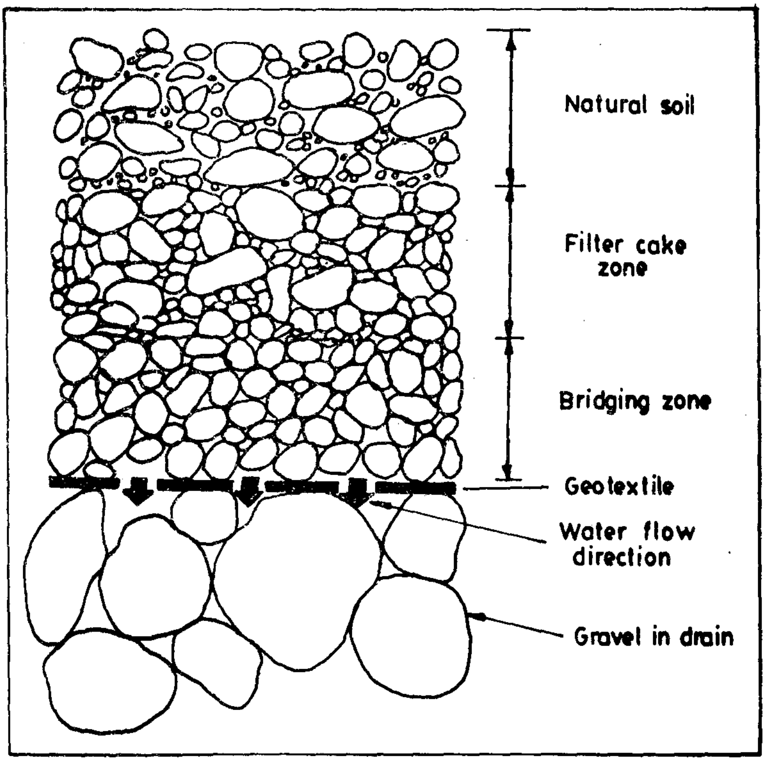


Figure 6 : Filteration function of a geosynthetic

Functions

Geosynthetics serve the following basic functions.

Fluid Transmission

A geosynthetic can collect a liquid or a gas and convey it along its own plane, as in Fig. 5, thus providing fluid transmission. This is conventionally termed as drainage function and is useful in strip drains and chimney drains.

Filtration

A geosynthetic acts as a filter when it allows liquid to pass normal to its own plane, while preventing most soil particles from being carried away by the liquid current, as illustrated in Fig. 6. This function comes into picture in strip drains, chimney drains, French drains and erosion control.

Separation

When placed between a fine soil and a coarse material (gravel, stones etc.), a geosynthetic prevents the fine soil and the coarse material from moving under the action of repeated applied loads as shown in Fig. 7.

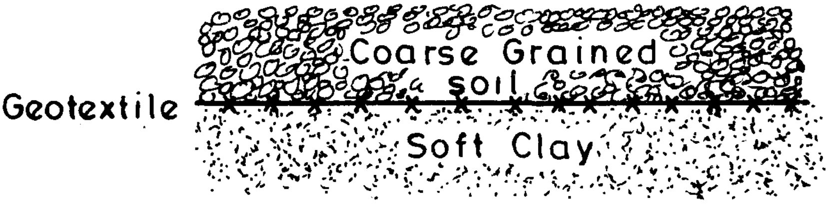


Figure 7 : Separation function of a geosynthetic

Reinforcement

A geosynthetic protects a material when it alleviates or distributes stresses and strains transmitted to the protected material. This can be

- as tensioned membrane when placed between two materials with different pressures, say in a pavement, as in Fig. 8.
- as tensile member, in a reinforced soil structure to provide tensile modulus and strength through interface friction, as in Fig. 9.

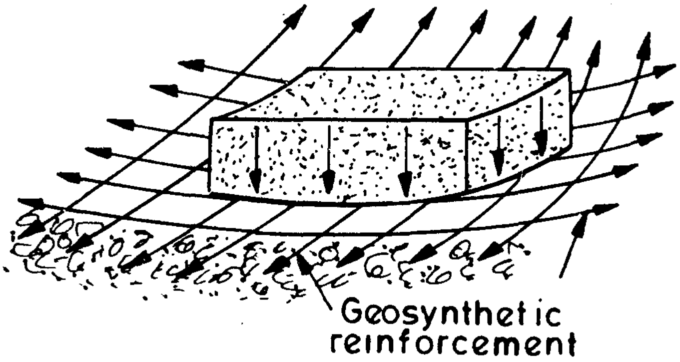


Figure 8 : "Tensioned Membrane" function of a geosynthetic

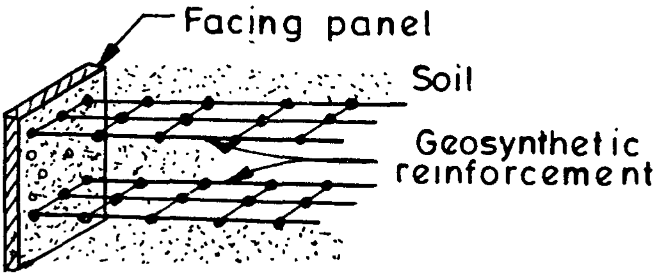


Figure 9 : "Tensile Member" function of a geosynthetic

Moisture Barrier

A geosynthetic (geomembrane) may act as a barrier for flow of water or any other fluid - hazardous or otherwise. The simplest example for this is canal lining as in Fig. 10.

Geosynthetics may also serve other functions such as 'cushion' and 'protection'.

Applications

Table 1 indicates the general and now widely accepted applications of Geosynthetics. Some of these applications are discussed in the following in reference to the work carried out at IIT Delhi.

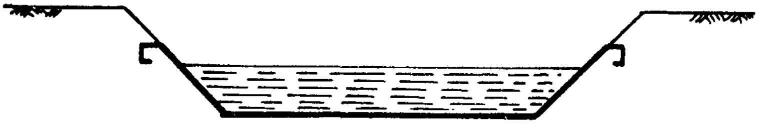


Figure 10 : Geomembrane in canal lining

Raw Materials

The materials used in the manufacture of geosynthetics are either polymeric or natural. The most commonly used polymers are polypropylene, polyester and polyethylene. Usually they are of high tenacity which is obtained by drawing the filaments or orientating the molecules so as to form a linear chain. Other polymers used, more commonly in geomembranes are Butyl Rubber, Chlorinated Polyethylene (CPE), Chlorosulphonated Polyethylene (CSPE), Ethylene Propylene Diene Monomer (EPDM), Polychloroprene (Neoprene) and Polyvinyl chloride (PVC). The general Physical and chemical properties of these materials are summarised in (Bhatia 1990, Venkatappa Rao, 1995b).

Although many geosynthetics are produced without any additive, in many others, additives are mixed with the basic material at various stages of manufacturing process, to improve

i) ultraviolet stability (which in most cases may not be needed for polyester) to reduce photo oxidation for possible exposure to sun rays,

ii) chemical stability for longer life (e.g. anti-oxidants, to limit thermo-oxidative degradation),

iii) thermal stability, for use with asphaltic admixtures,

iv) biostabilizers to protect from attack by micro-organisms, and

v) other chemicals to assist in the manufacturing process and pigments, etc.

On the other hand, natural fibres like jute and coir are primarily cellulosic (Table 2) and biodegradable. The rate of degradation depends on the amount of lignin which reduces the rate.

Table 1
Geosynthetic Application Summary

Application	Primary function	Products
Subgrade/Pavement Stabilization	Separation Reinforcement Filtration	Geotextile/geogrid
Railroad Trackbed Stabilization	Drainage Separation Filtration	Geotextile/geogrid
Asphalt Overlay	Stress relieving layer Waterproofing	Geotextile/geogrid
Soil Reinforcement		
Embankments	Reinforcement	Geotextile/geogrid
Steep Slopes	Reinforcement	Geogrid/geotextile
Vertical Walls	Reinforcement	Geogrid/geotextile
Subsurface Drainage (French drains)	Filtration	Geotextile
Subsurface Drainage	Filtration Fluid transmission	Prefabricated drainage Composites
Erosion Control Filter (under rip-rap)	Filtration Separation	Geotextile
Surficial Erosion Control	Turf reinforcement	Erosion control mats Fabric forming mats
Canal/pond lining	Moisture barrier	Geomembrane
Land fills	Separation Filtration Drainage Reinforcement Barrier	Geotextiles/geogrids/ Geomembranes/ Geosynthetic clay liners
Geomembrane protection	Protection/cushion	Geotextile

Table 2
Chemical Composition of Natural Fibres

Material	% Cellulose	% Lignin
Jute	59	14
Coir	49	46

Property Characterization

The properties of geotextiles/geosynthetics provide a means of communication between producers, users and designers. They are required for (Christopher, 1989) :

(i) Quality control for products both during production and during installation,

(ii) Determination of the suitability of the material for the specific application/functional requirement,

(iii) Comparison between products for selection, and

(iv) Specification of a product for specific application.

The quality control tests must be possible for conducting quickly, efficiently and regularly during production. On the other hand, the tests to assess suitability for functional requirements will necessarily be detailed and involved and are likely to be time-consuming and expensive.

The basic requirements of specifications for geotextiles should include the following items, Murray and McGown (1982) :

i) identification of design procedures to be followed for specific applications,

ii) limiting values of geotextile properties, measured according to standard test procedures, which may be adopted in design,

iii) procedures for transporting, storing and handling geotextiles,

iv) construction installation procedures, and

v) limiting values of geotextile properties, measured according to standard test procedures for the purpose of quality control.

As such a typical list of important properties of geotextiles required for reinforcement function may thus include :

A. Basic Physical Properties

Constituent material and method of manufacture, Mass per unit area, Thickness, Roll width and Roll length.

B. Mechanical Properties

Tensile strength, Tensile modulus, Interface friction, Fatigue resistance, Creep resistance and Seam strength

C. Hydraulic Properties

Opening size, Permittivity, Transmissivity and Gradient ratio

D. Constructability/Survivability Properties

Strength and Stiffness, Puncture resistance, Tear resistance, Cutting resistance, Inflammability and Absorption

E. Durability (Longevity)

Abrasion resistance, Ultra-violet stability, Temperature stability, Chemical stability, Biological stability and Wetting and Drying stability.

All these may not be important for every application.

Types of Testing

An aspect that is increasingly being realised is that by and large the testing carried on geosynthetics corresponds to the "In isolation" category, first categorized by Murray and McGown (1982). Barring the determination of soil-geosynthetic interface friction behaviour, the properties are rarely determined through "in-soil confinement" primarily because of the complexities involved in such a testing.

It is now generally recognised that two classes of testing are possible viz., Index tests and performance tests. Index tests in most cases do not produce an actual property value, but rather, a value or indicator from which the property of interest can be qualitatively assessed. When determined using identical test procedures, index tests can be used as a means of product comparison and can be used for specification and quality control evaluation. They are generally rapid and efficient to perform (Christopher, 1989).

On the other hand performance tests require testing of the geosynthetic with a soil to obtain a direct assessment of the property of interest. They provide a direct measure of the influence of the soil on the particular geotextile property and in turn, the influence of the geotextile on the soil property. Hence they should be performed under the direction of the design engineer. Thus they are usually conducted on pre-selected geotextiles (based on index properties).

It should also be recognised that certain properties become more important during certain phase of construction. For instance for a geotextile, in reinforcement application burst, puncture and tear are vital during construction phase, and creep is vital if it is a permanent structure.

Standard methods of testing are evolved in several countries (e.g. ASTM, BS, DIN etc.) and a number of international organizations, (EDANA, RILEM among others). ISO and CEN are actively engaged in the task of evolving common standards. In India some standards have been brought by the Bureau of Indian Standards.

Basic Physical Properties

Mass per Unit Area

This parameter is important, because in a given type of geosynthetic the cost is directly proportional to the mass per unit area. It is also necessary for quality control. All the mechanical properties are directly related to this parameter.

Thickness and Compressibility

Thickness is one of the basic physical properties used for quick control of the quality of geotextiles. It is measured at a specific pressure of 2 kPa. Thickness usually ranges from 0.25 to 7.5 mm. Figure 11 presents change in thickness under pressure for woven and needle punched geotextiles. For most geotextiles, except needle punched fabrics, the compressibility is very low.

Mechanical Properties

Grips were fabricated at IIT Delhi to conduct different tensile tests. Considerable testing has been carried out since 1987 (e.g. Venkatappa Rao and Pandey, 1987; Venkatappa Rao et al. 1989). The tests were carried out on a constant rate of extension universal testing machine INSTRON 1195 with load cells and strip chart recorder.

Geotextiles Tested

Five needle-punched nonwoven geotextiles made up of polypropylene staple fibres (6 denier) and one multifilament plain woven geotextile, manufactured in India were tested. The physical properties of these geotextiles are given in Table 3.

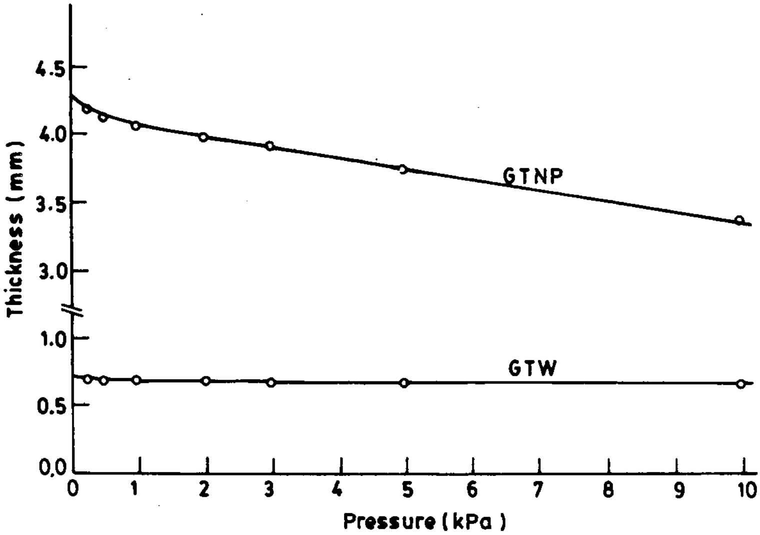


Figure 11 : Variation of thickness with applied pressure of geotextiles (after Shamsher 1992)

Strip Tensile Test

Using these results, the average load-strain relationships are presented in Figs. 12 and 13 for all the geotextiles in machine and cross-machine directions respectively. It is evident that nonwoven geotextiles have higher failure strain as compared to the woven geotextile W_1 and that nonwoven geotextiles are not truly isotropic.

Wide Width Tensile Test

Figures 14 and 15 present the average load-strain relationships for all the geotextiles in machine direction and cross-machine direction respectively. The peak tensile loads in the case of wide width tensile test, in general, are smaller than the strip tensile test. The failure strains of wide width tensile tests are, however, found to be larger in both the directions in all the geotextiles as compared to the narrow strip tensile test.

Grab Tensile Test

The results obtained for the grab tensile tests of the geotextiles in machine and cross machine directions are presented in Table 3.

Table 3
Summary of the strength tests of geotextiles

Geotextile	NW1	NW2	NW3	NW4	NW5	W1
Type	NW-NP	NW-NP	NW-NP	NW-NP (RI)	NW-NP (RI)	W(P)
Thickness (mm)	2.13	4.15	2.07	2.02	2.06	0.58
Mass/area (g/m^2)	290	470	195	240	205	206
O_{95} (μm)	84	97	147	117	147	102
Strip Tensile Test						
Peak Load (kN/m)						
(i) Machine direction	21	15.5	4.5	4.2	5.2	33.6
(ii) Cross-machine direction	26.8	22.5	3.5	3.0	3.9	24.7
Strain (%) at failure						
(i) Machine direction	57	86.5	75	70	65	23.5
(ii) Cross-machine direction	72	100	106	120	93	19

Table 3 contd.

Wide Width Tensile Test						
Peak Load (kN/m)						
(i) Machine direction	16	15.1	5	2.9	8.6	27.1
(ii) Cross-machine direction	18	19.7	3.2	2.1	5.8	18.5
Strain (%) at failure						
(i) Machine direction	85	100	76	90	90	25
(ii) Cross-machine direction	92.5	80	113	160	137	20
Grab Tensile Test						
Peak Load (kN/m)						
(i) Machine direction	183	152	33	32.5	38.6	184
(ii) Cross-machine direction	173	162	27.3	31.6	31	192
Strain (%) at failure						
(i) Machine direction	173	162	27.3	31.6	31	192
(ii) Cross-machine direction	105	115	105	128	120	32

Table 3 contd.

Puncture Test						
Peak Load (kg)	52.6	72.0	26.7	26.3	27.1	62.0
Deformation (mm)	32	15	18	18	19	12
CBR Plunger Test						
Peak Load (kg)	182	325	74	61	85	370
Deformation (mm)	40	50	60	55	55	30
Trapezoid Tear Resistance Test						
Peak Tear Resistance (kg)						
(i) Machine direction	35	50	15.5	16.4	14.6	132
(ii) Cross-machine direction	59	82	12.5	14.5	11.5	100
Deformation (%)						
(i) Machine direction	40	60	90	80	80	14
(ii) Cross-machine direction	60	60	90	110	90	30

NW-NP : Nonwoven Needle-punched Geotextile
NW-NP (RI) : Nonwoven Needle-punched Resin Impregnated Geotextile
W(P) : Plain Woven Geotextile

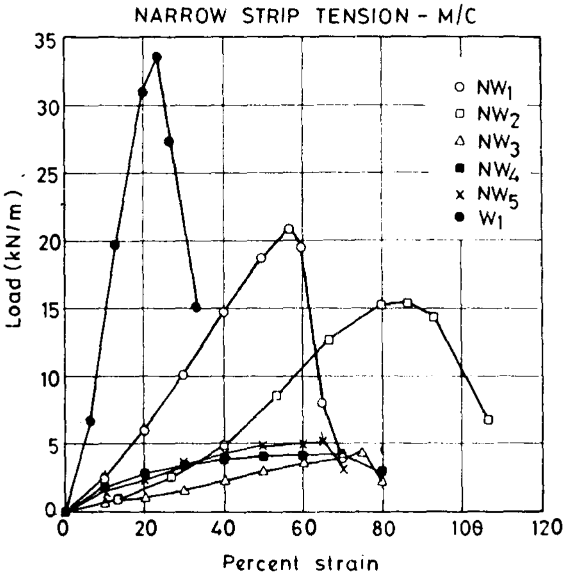


Figure 12 : Strip tensile test results on geotextiles in the machine direction (after Pradhan, 1993)

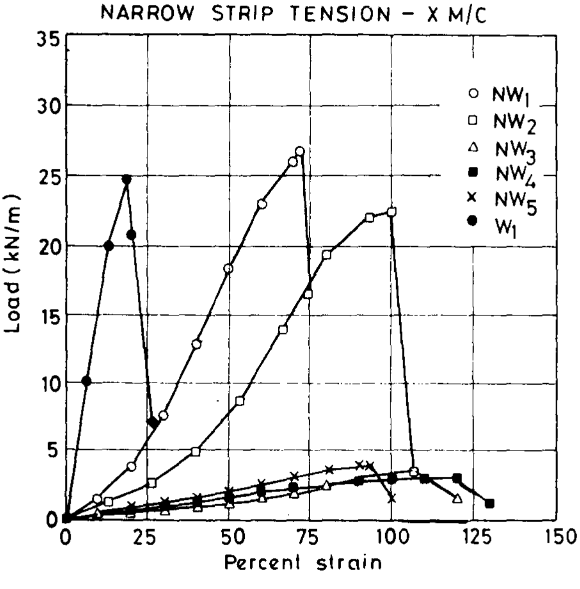


Figure 13 : Strip tensile test results on geotextiles in the cross-machine direction (after Pradhan, 1993)

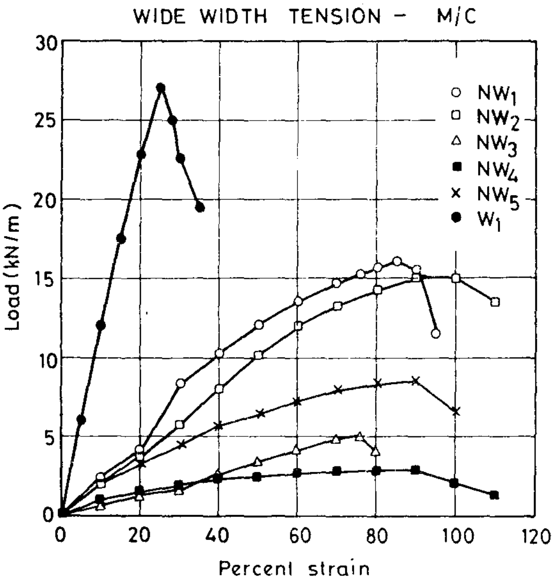


Figure 14 : Wide width tensile test results on geotextiles in machine direction (after Pradhan, 1993)

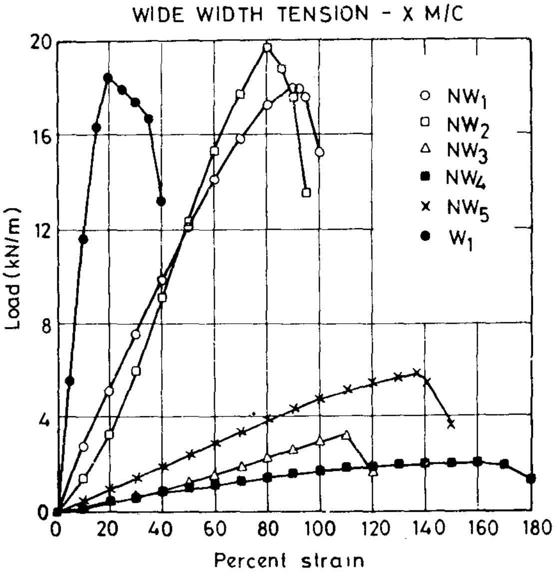


Figure 15 : Wide width tensile test results on geotextiles in cross-machine direction (after Pradhan, 1993)

Creep

In soil reinforcement creep needs special attention in view of the fact that some structures may need to be designed for over 100 years of life. Limited work was carried out at IIT Delhi on creep. A creep gang was fabricated to accommodate 12 wide strip specimens at a time, which can be tested at 20 ± 2°C. Typical elongation curves obtained for an indigenous woven geotextile is presented in Fig. 16. (Venkatappa Rao, 1992). It is evident that this fabric is hardly suitable as reinforcement.

Interface Friction

Geosynthetic-soil interface friction is one of the two factors governing the design and performance of reinforced soil structures. The value is used to determine the bond length of the geosynthetic needed beyond the critical zone. By modifying the existing direct-shear apparatus; both modified direct shear tests and pull-out apparatus were fabricated. Some preliminary results were reported by Venkatappa Rao and Pandey (1988). Subsequently testing was carried out on various kinds of granular soils, clay soils, mine tailings, etc. for their interface friction with woven and non-woven geotextiles and geomeshes. (Due to lack of space this aspect is not being presented in detail).

Construction Survivability Properties

Grab Tensile Test

In a way, grab tensile test may be considered as simulating a field

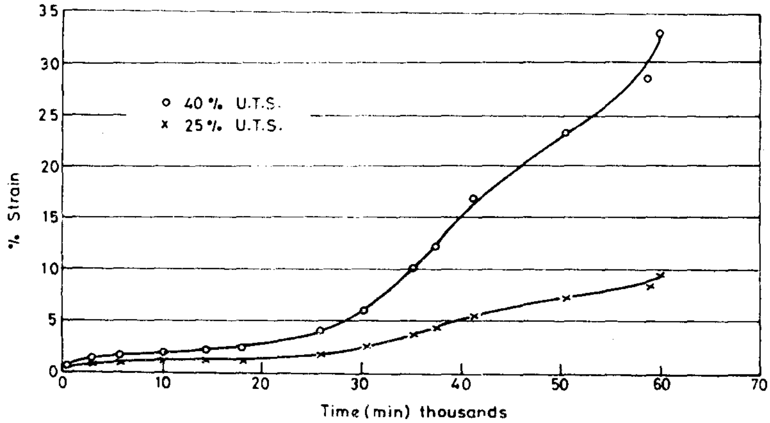


Figure 16 : Creep test result on a geotextile (after Venkatappa Rao, 1992)

situation of separation in unpaved roads. From the view point of survivability criteria during construction, geotextiles NW_3 and NW_4 having grab strength less than 36 kg cannot be used for filtration and erosion control applications.

Puncture Tests

Table 3 summarises the results of the puncture tests (as per ASTM) and CBR push through tests. It is observed that the puncture resistance of nonwoven geotextiles NW_3, NW_4 and NW_5 are nearly the same which is about 27.0 kg. These geotextiles, therefore, can be used only in drainage trenches or below concrete and should be provided with a cushion of sand. No protective armour should be dropped on these geotextiles which may puncture the geotextile.

Trapezoidal Tearing Strength Test

The geotextiles' resistance to propagating a tear was determined by ASTM trapezoidal tearing strength test. Table 3 presents the summary of the test results. As observed in the grab strength and puncture tests, it is found that the geotextiles NW_1, NW_2 and W_1 have very good resistance to tearing regarding the filtration and erosion control applications. However, the geotextiles NW_3, NW_4 and NW_5 can be used only if they are protected as specified in the AASHTO-AGC-ARTBA Task Force 25 survivability criteria.

Tension Tests on Geogrids/Geomeshes

To understand the in-isolation behaviour of geomeshes under uniaxial loading, tensile tests; both quality control and index tests have been carried out (Venkatappa Rao et al., 1989a, 1990b; Katti, 1992). Special grips were developed for conducting strength and other related tests on geogrids/ geomeshes. To enable the specimen preparation, jig plates were also developed. The average load-strain curves for 200 mm wide specimens (with a gauge length of 100 mm) in machine and cross-machine directions at a deformation rate of 200 mm/min are illustrated in Fig. 17. It is seen that the peak loads of 7.14 kN/m and 6.47 kN/m are reached at 45% and 50% strain in the machine and cross-machine directions respectively.

Typical results obtained at various deformation rates are presented in Fig. 18.

Creep Tests

Wide width geomesh specimens in the cross-machine direction were subjected to sustained loads in the range of 2.16 kN/m to 4.42 kN/m. These values approximately correspond to 38% to 78% of the wide width

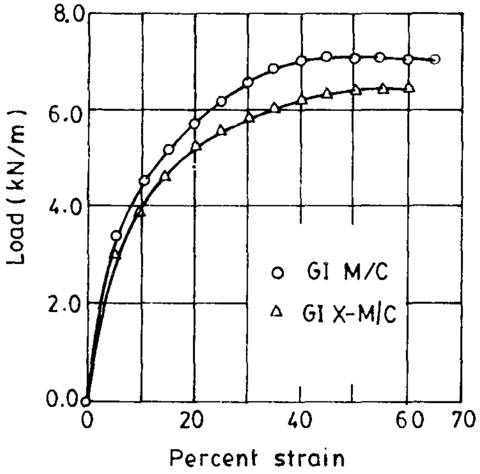


Figure 17 : Wide strip tensile test results on geomesh (after Katti, 1992)

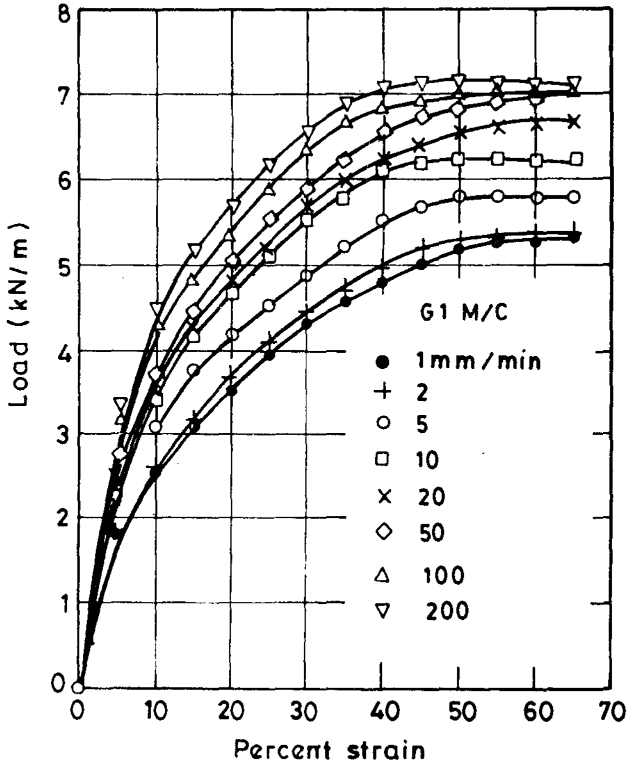


Figure 18 : Wide strip tensile test results on geomesh at different deformation rates (after Katti, 1992)

in-isolation tensile strength values obtained at a deformation rate of 10 mm/min (BS 6906 Part I). Figure 19 shows the deformations with time for the various loads.

Interface Friction Behaviour of Geomeshes by Pullout Tests

To understand the in-soil behaviour of geomeshes, two types of tests have been developed viz., the modified direct shear box tests and the pull-out tests (Venkatappa Rao, Kate and Katti, 1989b). The pull-out test set-up developed consisted of a tank having dimensions 600 × 600 × 400 mm. Normal loads can be applied using hydraulic jack as shown in Fig. 20. One side wall is provided with a slit of dimension 20 × 240 mm. This can be covered with plates having required slit openings for testing a given type of geosynthetic.

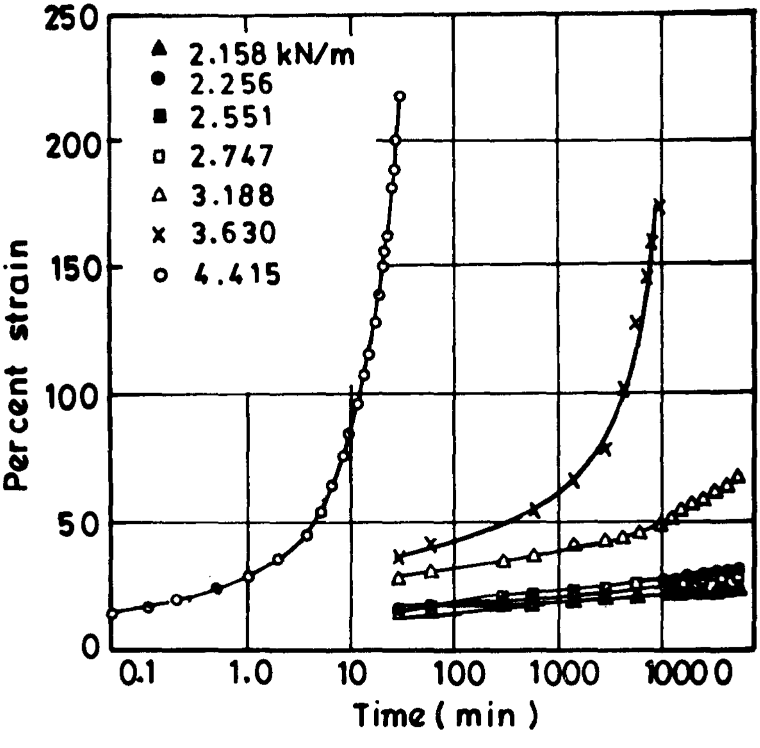


Figure 19 : Variation of Strain with Time for Geomesh at Different Deformation Rates (after Katti, 1992)

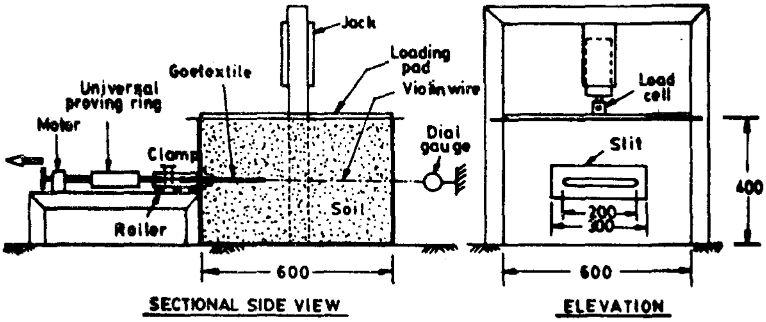


Figure 20 : Line diagram of pullout test apparatus (after Katti, 1992)

Figures 21 and 22 present the shear stress v/s shear displacement curves for embedment lengths 200 and 100 mm respectively at different normal stresses upto 7 kN/m^2 for tests on Mumbra sand (Venkatappa Rao et al., 1989; Venkatappa Rao et al., 1990a). From Fig. 23 it is seen that the specimen with embedment length 100 mm appears to be failing by slip and with tensile strength more than adequate, whereas the longer specimen (200 mm) appears to be having better anchorage and this specimen seems to be partially yielding.

The variation of coefficient of friction obtained in a Vidal type of modified shear box (30 × 30 cm) for the sand-geomesh interface is presented in Fig. 24.

Hydraulic Behaviour

Since the first ever use of geotextile as an alternative to a granular filter in the reconstruction of the storm-lashed coast of Florida, USA in 1958, geotextiles are being increasingly used as a replacement of graded filters. It has been found that geotextiles provide technical improvement lowering either the construction costs or the maintenance costs or both. Their relatively small pore sizes and good mechanical properties have allowed geotextiles as a substitute for several granular layers as shown in Fig. 25. Some specific applications of geotextiles as filter are: behind retaining walls, in earthfill dams, beneath erosion control works, and as silt fences and French drains.

A general and broad overview of the hydraulic behaviour of geotextiles indicates that,

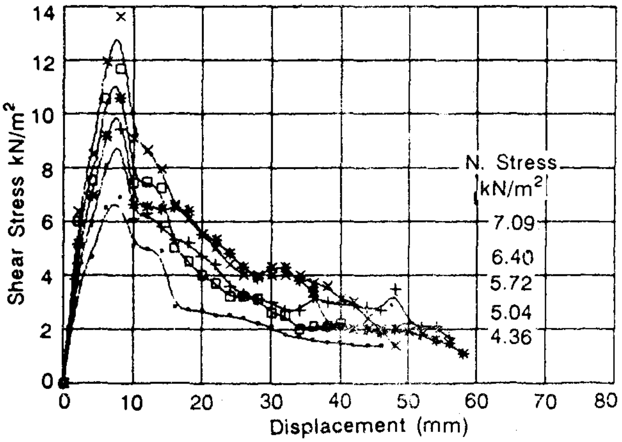


Figure 21 : Shear stress vs shear displacement curves for pullout test for embedment 100 mm on Netlon CE131 and Mumbra sand (after Venkatappa Rao, Kate and Katti 1990)

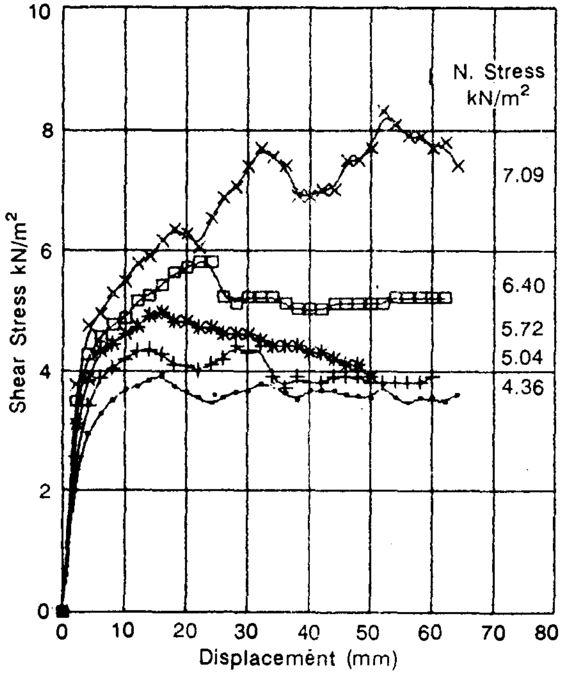


Figure 22 : Shear stress vs shear displacement curves for pullout test for embedment 200 mm on Netlon CE131 and Mumbra sand (after Venkatappa Rao, Kate and Katti 1990)

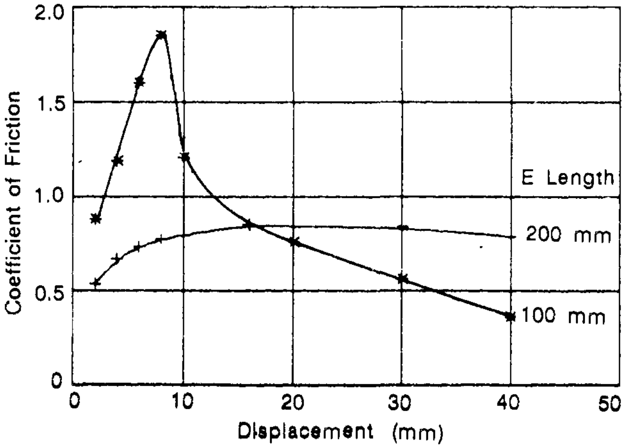


Figure 23 : Variation of coefficient of friction with displacement in pullout test, on Netlon CE 131 and Mumbra Sand (after Venkatappa Rao, Kate and Katti 1990)

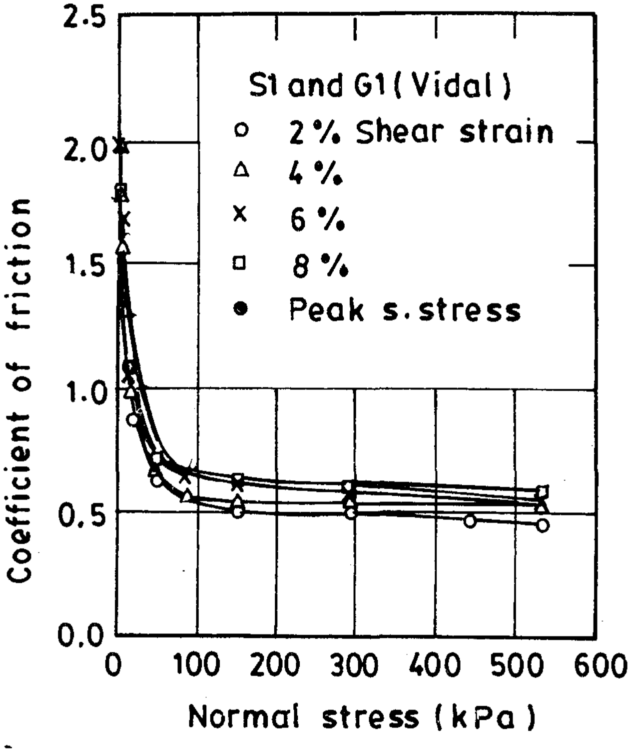
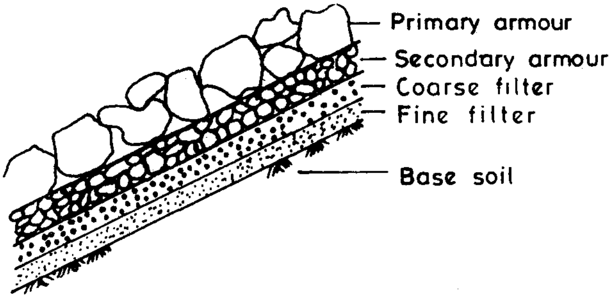
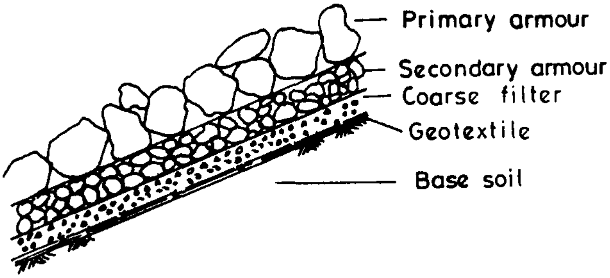


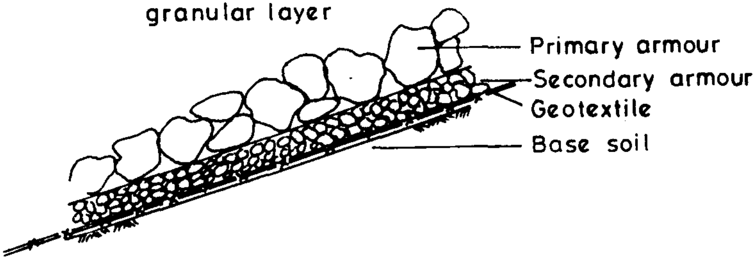
Figure 24 : Variation of coefficient of friction obtained in modified shear box for geomesh (after Katti, 1992)



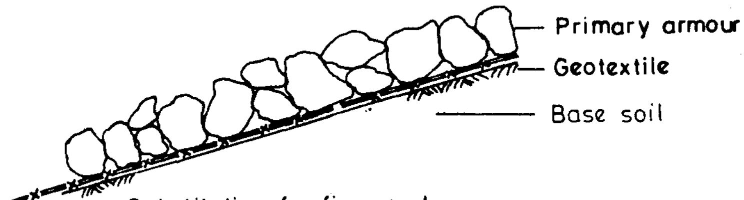
Graded filter



Substituting for fine granular layer



Substituting for fine and coarse granular layers



Substituting for fine and coarse granular layers and secondary armour

Figure 25 : Graded aggregate filter and geotextile filter systems under rip-rap slope protection

i) a geotextile is normally chosen for filtration and drainage applications depending on its characteristic properties such as opening size and permeability. In addition, geotextile should function smoothly without having a significant number of openings clogged by soil particles in the long run,

ii) geotextiles' porometry determines the adequacy of its ability to retain soil particles, and

iii) geotextiles' long term filtration behaviour is determined by

   a) gradient ratio test, and

   b) long term filtration test.

Different experimental methods are available for the evaluation of geotextile's pore sizes. A well defined simple method of short duration that allow the determination of the porometry of all types of geotextiles is preferred which simulates the field condition and presents reproducible results. Though several methods of pore size determination exist, no procedure has yet been identified as a satisfactory standard in yielding a correct value.

The gradient ratio test developed by the US Corps of Engineers is used to test the clogging potential of sands and sandy silts with woven geotextiles. For other cases, a long-term filtration test is recommended but the test method is yet to be standardized. Consequently, basic differences are seen in types of devices used, nature of soils, amount of soil, soil placement and hydraulic gradient applied.

A system instability is observed at the beginning of the filtration test and soil compaction dominates the initial flow. This unstable filtration behaviour is particularly influenced by the amount of fine soil particles and the soil density. To study some of these aspects, an experimental program was conducted by Pradhan (1993) the salient features of which are detailed below.

Hydrodynamic Sieving Test

In the hydrodynamic sieving test apparatus developed (Fig. 26) the geotextile specimen, loaded with a certain quantity of glass bead fraction, is continuously rotated in a water trough forcing the glass beads to pass through the geotextile openings. After a test period, long enough to ensure that all fine particles had passed, the percentage passing of different fractions determines the porometry of the geotextile investigated. The apparatus shown in Fig. 26 essentially consists of the following :

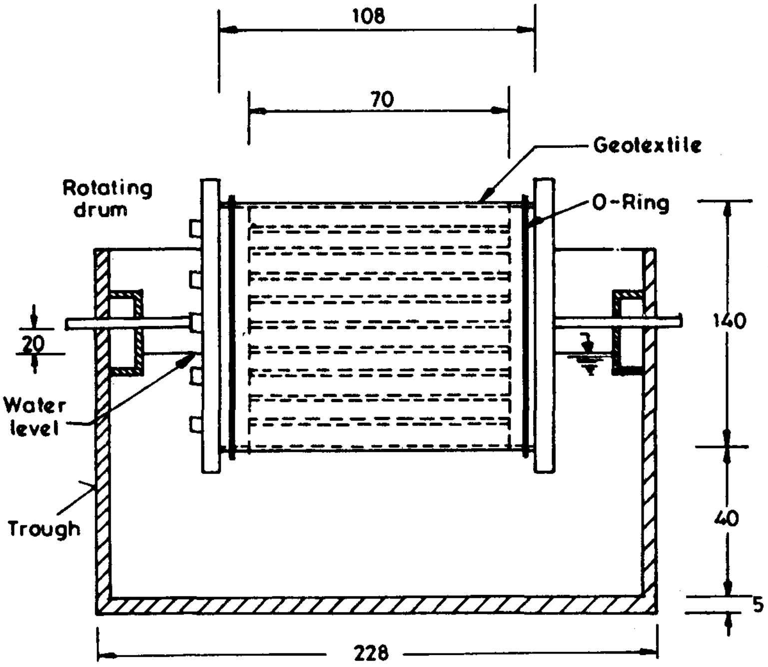


Figure 26 : Principal features of hydrodynamic sieve apparatus (after Pradhan, 1993)

i) A test drum of 140 mm diameter and 70 mm unobstructed length provided circumferentially with equally spaced 16 numbers of 4 mm diameter rods to hold the geotextile in position.

ii) A trough, to contain the test drum supported on a horizontal axis facilitating free rotation and capable of being filled with distilled water to a level 20 mm below the drum axis. The drum is mounted so as to allow an unobstructed clearance of 40 mm between the trough and the geotextile.

iii) A motor drive capable of rotating the drum at a speed of 5 rpm to 30 rpm.

By conducting a preliminary investigation, the optimal working conditions of the apparatus for a fractionated spherical glass beads of 50 g that were selected are: i) A cycle speed of 20 rpm, and ii) A test duration of 1500 cycles.

Table 4 presents the O_{95} values with dry sieve test as compared to hydrodynamic sieve test which is attributed to the non-renewal of the geotextile specimens for different glass beads. In case of dry sieving method, the glass beads entrapped in the geotextile fabric structure are possibly released when the consecutive larger fractions were sieved in the same geotextile specimen. On the other hand, a new geotextile specimen used for each glass bead fraction in the hydrodynamic sieve test provides more representative O_{95} value because of the larger surface tested.

The investigations on the dry sieving and rotating type hydrodynamic sieving test methods did not yield significant difference in O_{95} values. The latter test is preferable for the following reasons:

i) In the dry sieve test method, the vibratory movement is not well defined and gives divergent results.

ii) The simulation in Hydrodynamic methods is more closer to the field condition.

iii) The presence of water eliminates the influence of electrostatic charges.

iv) The coefficient of variance of O_{95} value is less than the dry sieve test method indicating good reproducibility of the test method.

Table 4
Summary of the O_{95} values of geotextiles obtained from dry sieving and hydrodynamic sieving test methods

Geotextiles	Thickness (mm)	Mass/area (g/m^2)	O_{95} dry sieving test (ASTM) (μm)	O_{95} hydrodynamic sieving test (μm)
NW_1	2.13	290	84	80
NW_2	4.15	470	97	87
NW_3	2.07	195	147	140
NW_4	2.02	240	117	103
NW_5	2.06	205	147	135
W_1	0.58	206	102	106

Permittivity Test

Both constant head and falling head permeameters are used for measuring normal permeability. ASTM : D4491-85 specifies permittivity test using constant head and falling head permeameters. The constant head test is carried out using a head of 50 mm of water. The apparatus developed at IIT, Delhi, shown in Fig. 27, can be used to determine the coefficient of permeability and the permittivity of a circular geotextile specimen (20 mm thick) under a given stress at a given head.

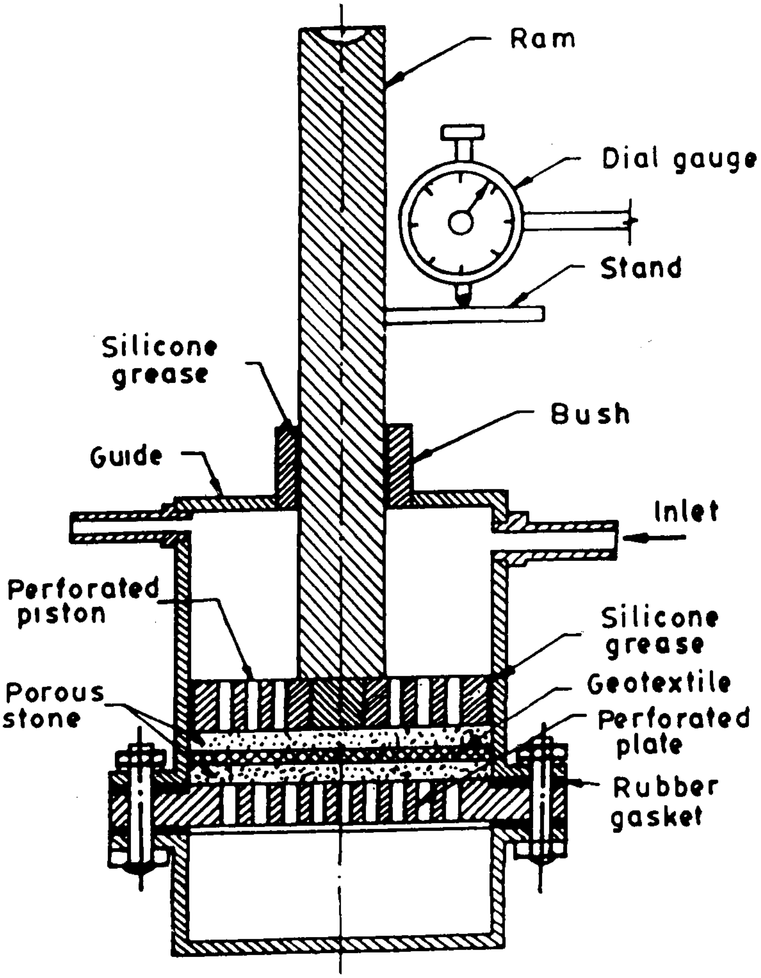


Figure 27 : Permittivity apparatus - assembly drawing (after Venkatappa Rao, Pradhan and Gupta 1990)

The coefficient of normal permeability (K_n) response with the applied normal stress for the geotextiles is presented in Fig. 28. This figure indicates an exponential decrease in the K_n with the increase in the normal stress in nonwoven geotextiles, where the portion of the curves at normal stress less than 50 kPa is normally due to a decrease in the thickness. The rate of decrease of K_n with increasing normal stress is different from one geotextile to another depending on the nature of fibres and the bonding processes.

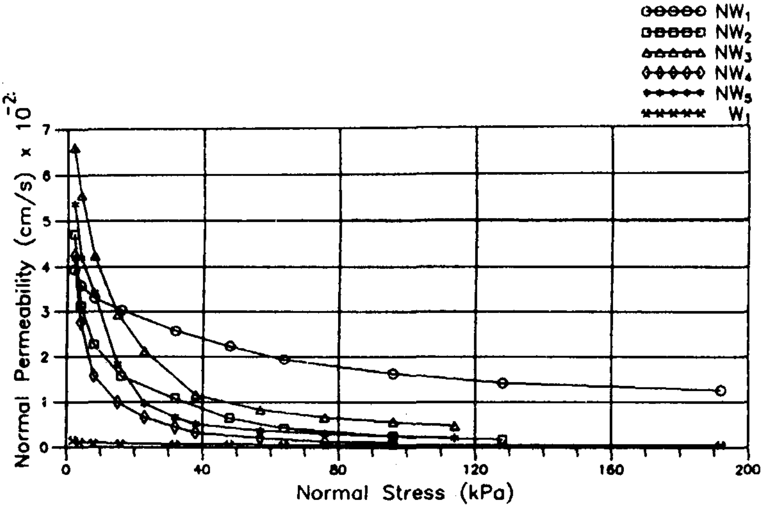


Figure 28 : Coefficient of normal permeability versus normal stress of geotextiles (after Pradhan, 1993)

The thickness versus the applied normal stress of geotextile NW_1 for multiple layers is shown in Fig. 29, which in a way explains the behaviour observed in Fig. 28.

Transmissivity Test

The transmissivity test is necessary for drainage applications. The permeameters can be of parallel or radial flow type. In either case, flow occurs along the plane of the permeameters. In the apparatus developed (Fig. 30), flow occurs radially outward from a central hole to the periphery of a circular specimen. This permeameter measures the in-plane permeability of all types of geotextiles under various normal stresses.

The plot of the coefficient of in-plane permeability (K_p) versus the applied normal stress for the nonwoven geotextiles is presented in Fig. 31. This figure clearly indicates an exponential decrease in the K_p with the

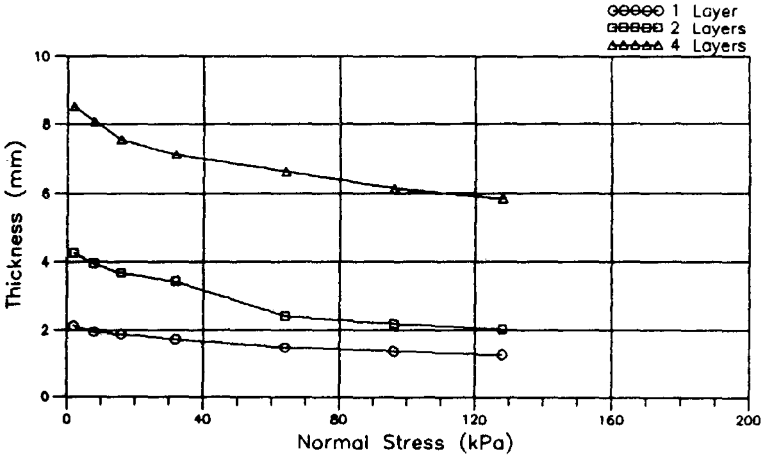


Figure 29 : **Variation of thickness of geotextile NW1 with normal stress for different layers (after Pradhan, 1993)**

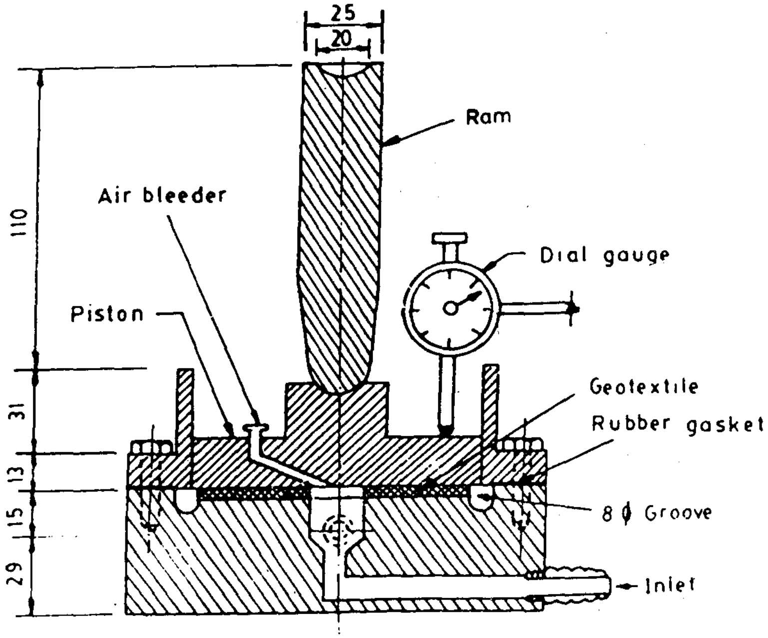


Figure 30 : **Transmissivity apparatus - assembly drawing (after Venkatappa Rao, Pradhan and Gupta, 1990)**

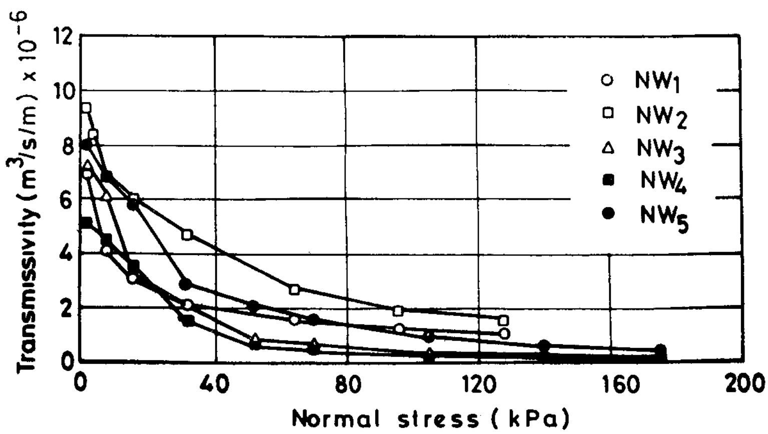


Figure 31 : Transmissivity - normal stress plots for various geotextiles (after Pradhan, 1993)

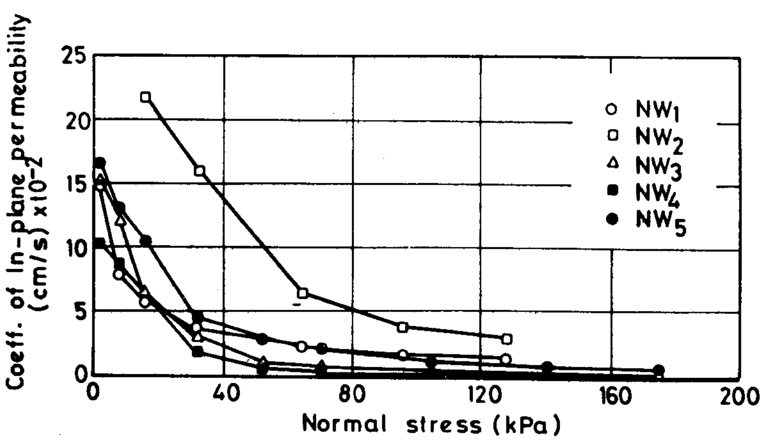


Figure 32 : Variation of coefficient of in-plane permeability of geotextiles with normal stress (after Pradhan, 1993)

increase in the normal stress upto around 80 kPa, beyond which K_p approaches asymptotically a constant value. The transmissivity (Θ) also decreases exponentially with increasing normal stress as presented in Fig. 32.

Geotextile-Soil Filtration Test

In order to carry out geotextile-soil filtration test, constant head permeameter was designed and fabricated. Figure 33 shows the schematic design of the permeameter developed (Venkatappa Rao et al., 1992) in which both the long-term flow test as described by Koerner and Ko (1982) and the

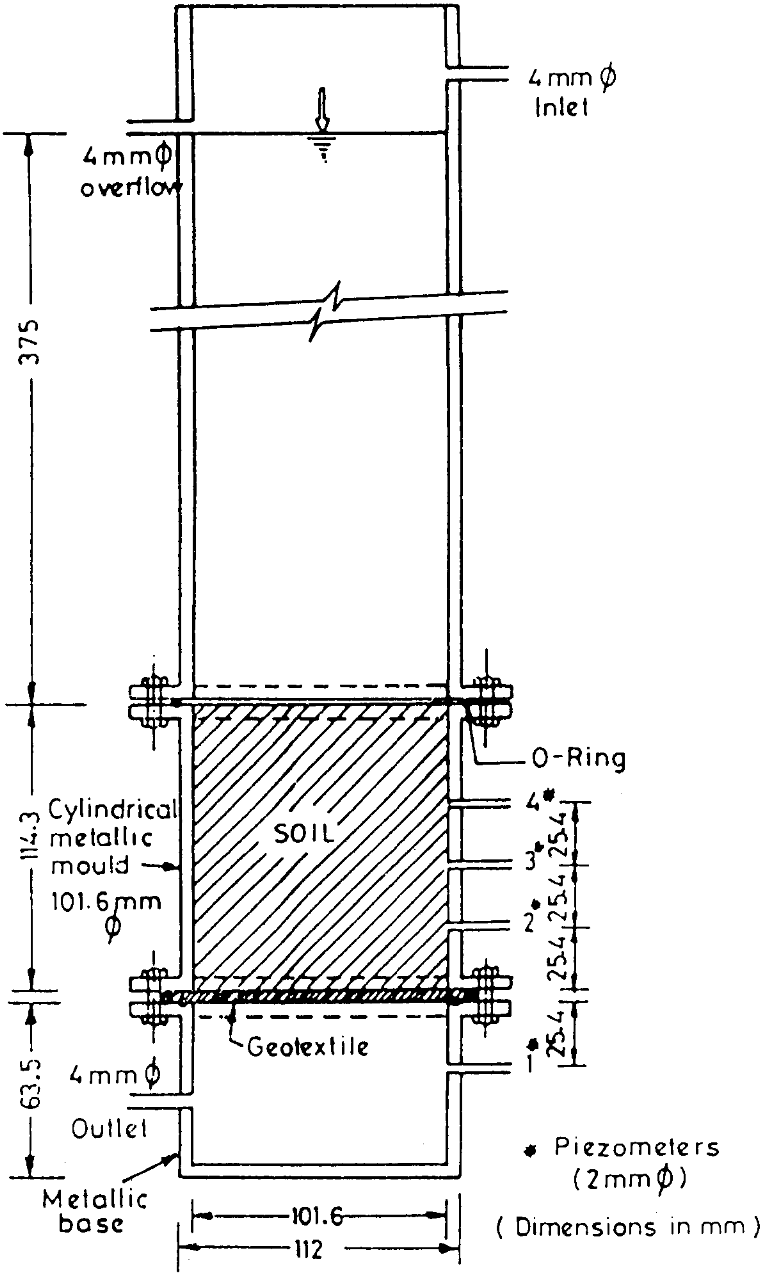


Figure 33 : Schematic diagram of long-term permeameter (after Venkatappa Rao, Gupta and Pradhan, 1992)

gradient ratio as specified by the US Army Corps of Engineers (1977) can be conducted simultaneously for different soils. The permeameter consists of three components, viz.,

(i) a metallic cylindrical mould to hold the soil (101.6 mm diameter and 114.3 mm length),

(ii) a hollow cylindrical base over which geotextile can be placed, and

(iii) a water column above the mould.

The mould and the base are provided with piezometers as shown in the figure to facilitate measurements of the piezometric heads of the soil geotextile system. Piezometer 1 measures the tailwater elevation whereas piezometers 2 to 4 measure the hydraulic head in the soil. Soil is directly compacted to a specified density in the mould with a Proctor hammer. The geotextile specimen (supported by a screen) is then placed securely in between the mould and base. A filter paper and a metallic screen are placed over the specimen before assembling the water column. A constant water head of 375 mm above the soil is maintained in the water column so that accurately measurable volume of flow can be obtained. In order to study the worst effect of geotextile-soil clogging, slurry soil samples are also tested.

Long-Term Filtration Behaviour

Filtration behaviour of geotextile-soil systems was studied on soils of different fines content placed at different densities. Over seventy tests were conducted on six different geotextiles. The gradient ratios of the systems were also determined from the hydraulic gradient of different soil layers. The tests were conducted until the values of the coefficient of permeability and the gradient ratio stabilise and, therefore, these tests are not terminated after a predetermined time.

Figure 34 presents the results of long-term coefficients of permeability of geotextile NW_1 and soil with various percentages of the fine contents upto 60% compacted at respective maximum Proctor densities. The first test in this series used only Ottawa sand (i.e. without addition of the fine soil), at a density of 14.5 kN/m^3. In this case, as the sand is uniformly graded, water can flow easily through the large voids. The initial permeability of the system is 8.2×10^{-3} cm/s, which stabilises approximately after 45 hours at a value of 4.8×10^{-3} cm/s. No loss of soil particles was observed during this test which is evident by the shape of the curve. The sand particles moving towards the geotextile yield a denser soil structure. The flow of water, thus, decreases

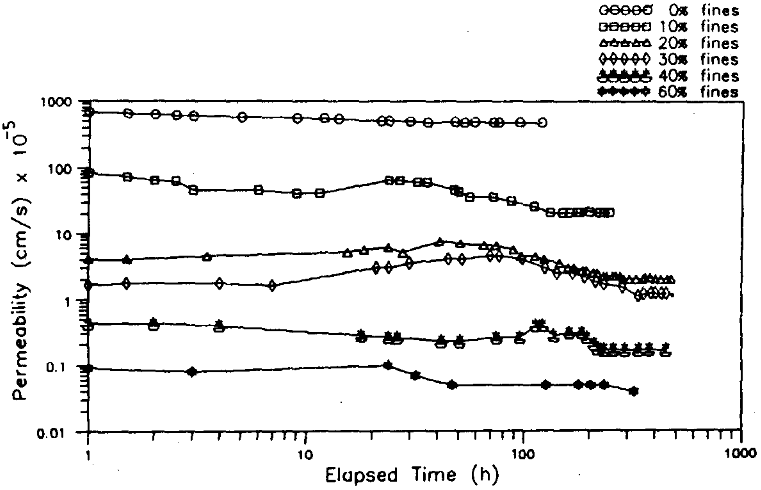


Figure 34 : Long-term permeability of geotextile NW1 and soils at Proctor densities (after Pradhan, 1993)

with time and the permeability of the geotextile-soil system reaches a constant value after a long filtration period.

When fines are mixed with Ottawa sand, one may surmise that the fines occupy the void structure formed by the sand alone, thereby decreasing the permeability of the system. This is evident from the density measurements of the soil mixtures, which results in a decrease of the permeability of the system.

An unstable flow behaviour is observed at the beginning of each of the filter systems with fines, indicating movement of fine soil particles towards the geotextile. Since the soil mixtures used are compacted to their maximum Proctor densities, movement of fine soil particles was prevented in the compacted soil matrix. However, the fine particles adjacent to the geotextile move towards it in the filtration process. Initially, some fine particles pass through the geotextile increasing the system permeability. Loss of soil increases the permeability of the system by a significant amount due to a gradient increase in the system. Simultaneously, the geotextile openings are plugged by the moving soil particles, reducing the permeability of the system. This reduction in permeability was observed until a stabilized flow condition is attained. The decrease in permeability was more pronounced in low fine content soils where fine soil particles are easily moved towards the geotextile as compared to higher fine content soils.

Figure 35 presents the flow behaviour of slurry soils. Unstable flow behaviour was also observed at the beginning of the test as observed in the compacted soils. This initial unstable flow behaviour is influenced not only by the plugging of geotextile openings (decrease in flow rate) and soil loss (increase in flow rate) but also accompanied by the large reduction in flow rate due to the consolidation of loosely placed slurry soils. Consolidation of these slurry soils increases the density which causes a rapid decrease in flow rate until it reaches a stabilized flow condition. The time taken for this initial unstable period was found to be more with the system fine content. The consolidation of loosely placed slurry soil accentuated to the continuous plugging of geotextile apertures to provide rapid decrease in the flow rate.

Similar to the compacted soil mixtures it is noticed that the time taken to attain the stabilized flow condition increases with soil fine contents.

The study attempted to study the GR values at 24 hours as specified by the US Corps of Engineers (1977) as well as for the long-term stabilized state, as shown in Fig. 36. Variation in the value of GR was observed during the initial unstable condition which eventually stabilised after a long duration. Higher stabilized GR values were observed for the higher fine content soil which is attributed to the dense structure of the soil mass. Fairly constant GR value of 0.5 is observed for 10% fine content soil which is due to the fact that the hydraulic gradient across the geotextile and 25 mm of soil is of the same magnitude as that of the adjacent 50 mm of soil during the

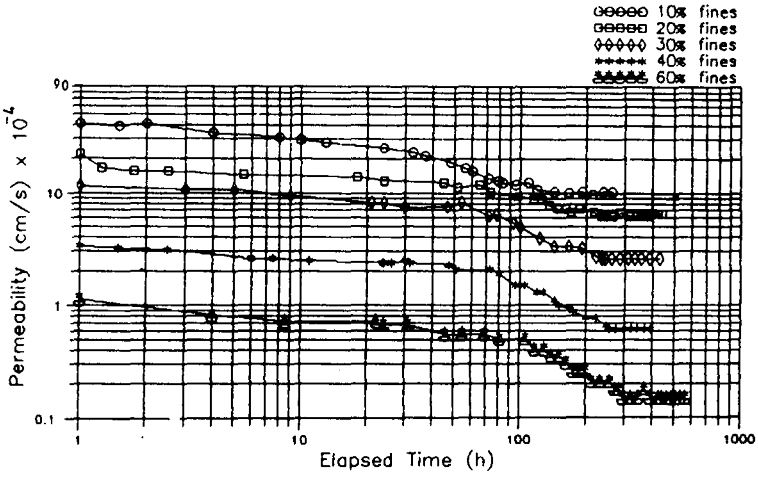


Figure 35 : Long-term permeability of geotextile NW1 and soils in slurry state (after Pradhan, 1993)

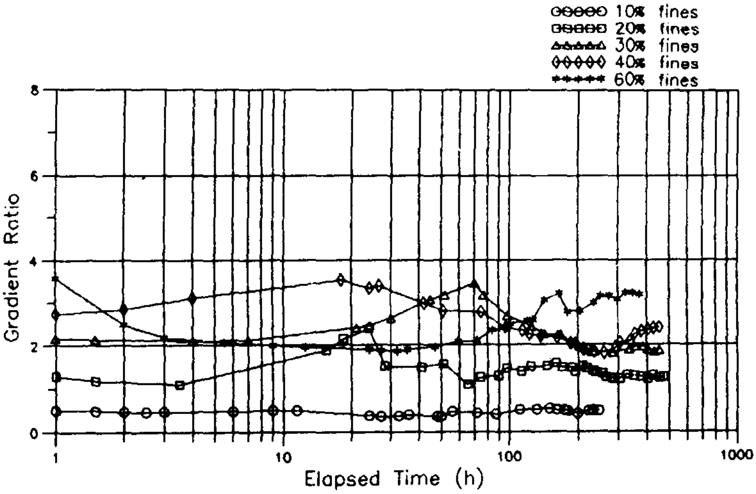


Figure 36 : Long-term gradient ratio behaviour of geotextile NW1 and soils at Proctor densities (after Pradhan, 1993)

long-term flow condition. The GR values of less than unity obtained in this case signify that the relative hydraulic gradient across the geotextile and 25 mm thick soil is less than the hydraulic gradient across the adjacent 50 mm thick soil.

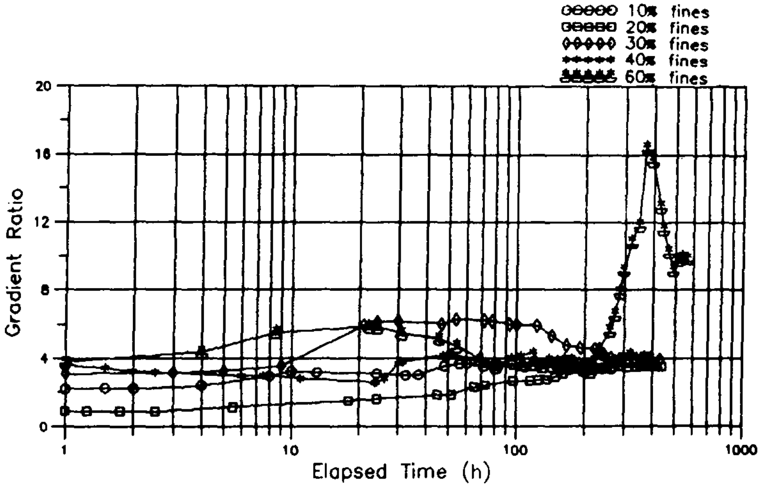


Figure 37 : Long-term gradient ratio behaviour of geotextile NW1 and soils in slurry state (after Pradhan, 1993)

Figure 37 depicts the gradient ratio of the geotextile soil systems in slurry state which facilitates the study of the worst clogging behaviour. The geotextile-soil system in slurry case is influenced by the consolidation of loose soils and plugging of geotextile openings causing a large drop in hydraulic head. However, escape of fine soil particles adjacent to geotextile filter during the initial period decreases the pressure head across the geotextile-soil interface. The observed increase in gradient ratio occurs perhaps after the escape of fine soil particles is completed and pressure head across the geotextile-soil interface increased due to plugging of the geotextile openings. The long-term gradient ratio was also found to attain equilibrium once the pressure head within geotextile-soil system stabilises. Higher stabilized GR values were obtained for the higher fine content soils.

From Figs. 38 and 39, it is evident that the 24 hour GR of the systems does not indicate a clear trend as the stabilisation time differs for different fine content soils and soil densities. The 'Corps of Engineers' gradient ratio test which was recommended primarily for non-cohesive soils needs to be prolonged until the stabilisation of the system for the soils other than cohesive soils.

From the foregoing, it may be noted that the clogging potential of geotextile-soil system diminishes with the increase in soil density and a long-term stabilized GR is to be determined for soils containing fine soil particles (≤ 0.075 mm) instead of 24 hour gradient ratio.

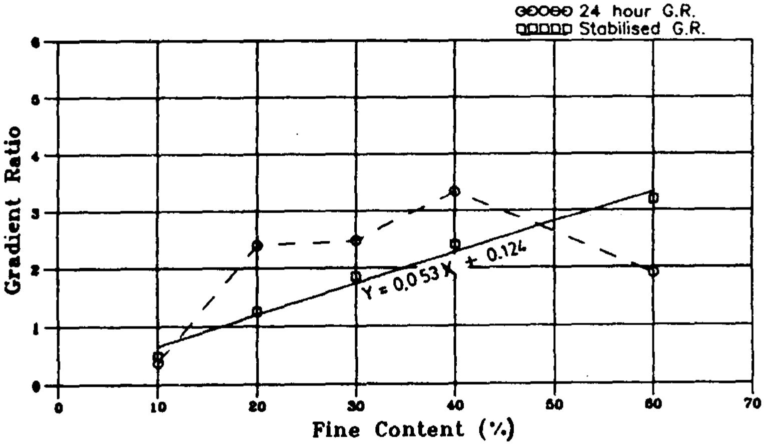


Figure 38 : Gradient ratio - percentage fine content relationships at 24 hour and stabilized condition for geotextile NW1 and soils at Proctor densities (after Pradhan, 1993)

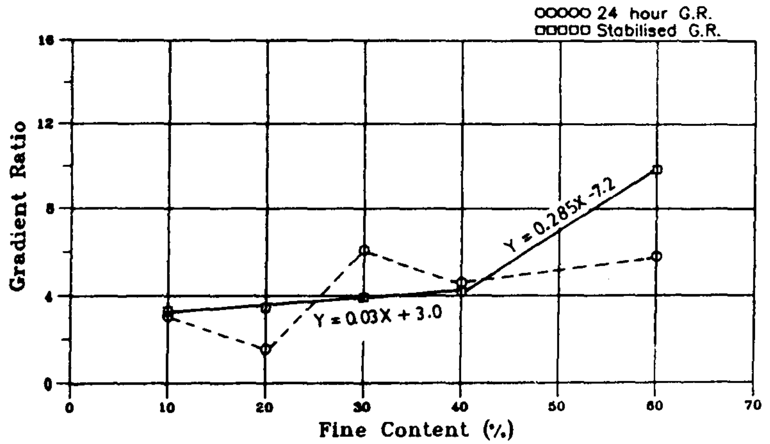


Figure 39 : Gradient ratio - percentage fine content relationships at 24 hour and stabilized condition for geotextile NW1 and soils at slurry state (after Pradhan, 1993)

Geotextile French Drains in Indian Rural Roads

Rural roads in India are typically constructed by laying a single course of brick on edge over the compacted subgrade. Irrespective of the season, rural roads in India have invariably been observed to have puddles of water standing on the surface, regardless of whether or not they have been provided with a side trench. They are usually in a deplorable state, caused not only by rainfall/poor drainage but also by sewage accumulating on the surface. It is widely known that a major cause of damage to rural roads is the accumulation of water on the surface and inadequate drainage of the road system. Such accumulations make the road surface not only impassable but also hazardous from the environmental viewpoint. An internally flooded road surface, allows wheel loads to be transmitted directly to the subgrade, with little or no reduction in intensity. It is widely known that good surface and subsurface drainages are important in maintaining the integrity and performance of the road structure in unsurfaced rural roads, where rainwater can penetrate the base very easily. The principal functions of a road-edge drainage system are to drain off the surface runoff, intercept ground-water inflows, thereby prevent weakening of the subgrade.

Designing road-edge drains involves defining all sources of water and drainage methods capable of intercepting and removing runoff to prevent its accumulation in the road surface. Conventional methods of edge-drain construction for low-cost rural roads usually include either a longitudinal open ditch (Fig. 40) or a gravel-filled trench drain (Fig. 41) along the road

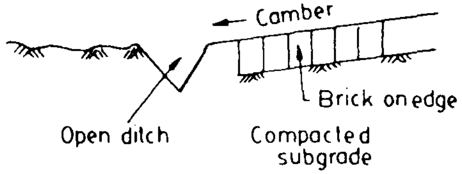


Figure 40 : Typical cross-section of a rural road with an open ditch

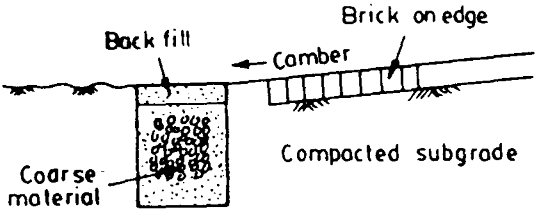


Figure 41 : Typical cross-section of a gravel filled French drain

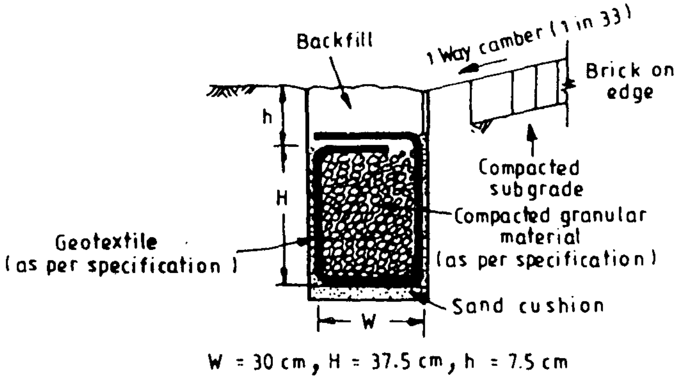


Figure 42 : Typical geotextile-wrapped road edge drain for rural roads

edge. The open ditch may collapse and cease to function during heavy flow, while gravel-filled trench drains are prone to clogging owing to migration of fine particles into the interstices of the gravel. A conventional trench drain requires a graded aggregate filter containing comparatively small aggregates. Consequently, a large drain cross-sectional area is required to transmit adequate flow volume. Furthermore, most natural aggregate deposits are variable in gradation from point to point in a borrow area and cannot be depended on for consistency. The use of geotextile French drains as shown in Fig. 42 provides a simple and more effective means of achieving a multilayer filter than conventional drains. Such French drains have been suggested by Christopher and Holtz (1985) and used extensively for improving the drainage of urban road systems, which are generally paved. They help not only in mitigating the problem of surface accumulation of water but also in improving the flow capacity, performance, serviceability, and useful life. The inclusion of an effective drainage system definitely increases the initial cost of the road but its omission adversely affects the serviceability and useful life, resulting in high maintenance costs.

These geotextile-wrapped French drains have also been successfully used to solve problems such as landslides and freezing/thawing of roads.

A research project entitled 'Use of Geotextile Drains in Rural Area - A Field Study' was undertaken at the Indian Institute of Technology, Delhi, in collaboration with the Centre for Agrarian Research, Training and Education (CARTE), Ghaziabad, India. The project was sponsored by the Department of Science and Technology, Government of India. This project is perhaps the first attempt of its kind aimed at improving the performance of rural roads.

The area chosen for the study is located in the Indo-Gangetic alluvial zone, where the common soil is silt. In these areas, 80% of the annual rainfall occurs in the three monsoon months and is of high intensity and short duration.

The presence of a geotextile filter leads to the development of a natural filter and enables larger and more permeable aggregates within the drain to be used. It prevents contamination of the drain core and eliminates the risk of road detritus and backfill soil entering the drain core. A geotextile filter needs to satisfy the following two conflicting requirements simultaneously, i.e.:

(i) to prevent significant particle movement from the adjacent soil into the drainage, and

(ii) to provide sufficient hydraulic conductivity to permit the free flow of water into the drain.

Field Trial

Harsaon, a village on the outskirts of Ghaziabad township, nearly 30 km from Delhi on the National Highway No. 24 was selected for the trial. The general condition of the village road in May 1990, was poor when longitudinal open ditches ceased to function owing to clogging. A stretch nearly 100 m long was selected near one end of the village, where it was possible to discharge into a nearby pond. There are houses on both sides of this road, and household sewage is directly led into the road-edge drain. The drain is designed for a gradient of 1:120. The effluent from the neighbourhood would first be collected in Manhole-I and then led to the geotextile-wrapped drain. A catchpit is provided at a sharp turn for maintenance and inspection of the drain. Manhole-2 is provided at the end of the drain, whence the effluent is discharged to the existing pond. The outfall level is kept higher than the maximum expected water level of the pond to avoid back flow. The in-situ soil is mainly alluvial silt with fine sand. The physical properties of the soil are % sand 42, % silt 56, % clay 2, liquid limit 26% and plastic limit 18%.

Suitable geotextiles were selected by examining their filter and permeability characteristics as specified by filter criteria of the US Forest Service and Transportation Agencies. A conventional graded filter would require to be graded over the range of 0.6 – 6.0 mm for this site. The maximum pore size, O_{95}, of the fabric for this type of soil is 130 μm. Two types of needle-punched polypropylene-fibre geotextiles were chosen (as detailed in Venkatappa Rao, Gupta and Pradhan, 1993). Flow rates and the coefficient of normal permeability are also determined. For the clogging potential of the geotextiles, gradient ratios were determined by using 60% sand and 40% fine soils. The geotextiles used were having a mass per unit area of 205 and 220 g/m^2.

Construction was carried out as per Christopher and Holtz (1985). Household waste is directly led into Manhole-I, which is required to be cleaned periodically. Geotextile and metallic screens were provided at the beginning of the drain to prevent solid wastes from being carried into the geotextile drain. A perforated steel sheet was also provided in the manhole to prevent contamination of the drain core. Manhole details are presented in Fig. 43.

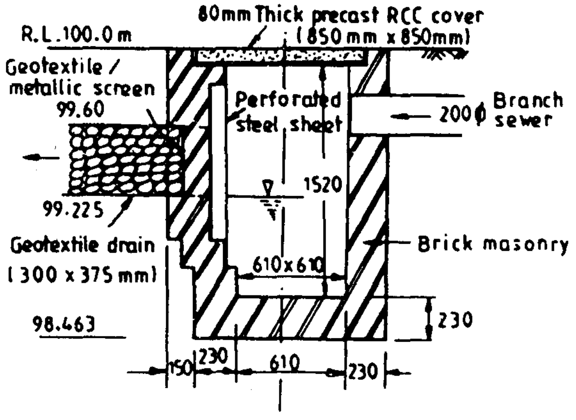


Figure 43 : Details of manhole (after Venkatappa Rao, Gupta and Pradhan, 1993)

The system was found to be working satisfactorily. The details of the study are described in detail in Venkatappa Rao et al. (1993).

Geotextile Fabric Design

At the Textile Technology Department of Indian Institute of Technology, Delhi a successful attempt has been made by Professor. P.K. Banerjee and co-workers towards –

i) quantifying relations between the properties of raw material, process variables and relevant fabric properties of needle punched staple fibre, geotextile fabrics meant primarily for hydraulic functions, and

ii) development of computer programs that would enable a fabric manufacturer to choose the optimum path for designing tailor-made geotextiles.

Material and Process Variables

After an extensive review of literature, five material/ process variables, viz.,

- fibre fineness (FD)
- fibre length (FL)
- batt areal density (BAD)
- depth of penetration of needle (DOP), and
- punching density (PD)

have been identified as the most important factors. By the prevailing commercial range, five levels of each factors were chosen for polyester and polypropylene fibres respectively (the most commonly used fibres) as indicated in Tables 5 and 6 respectively.

An orthogonal, rotatable, central composite experimental design (CCD) of second order was used for sampling plan. Employing a full factorial design, (Table 7) 59 fabric samples from polyester fibres and 36 fabric samples from polypropylene fibres were developed on a needle punching machine (manufactured by 'Asselin' of France) employing transverse laying principle.

Fabric Properties

The geotextile samples thus produced were subsequently tested for evaluation of various properties relevant to hydraulic applications, which were broadly classified in three groups. The Group-1 represents the tests related to the dimensional properties of the geotextile, like change in width, areal density, thickness under various pressures, compressibility, recovery behaviour, and bulk density. The Group-II tests are related to the sustaining ability of geotextile against constructional hazards and these are the tensile strength, breaking elongation, tear strength, bursting strength, puncture strength, penetration resistance, etc. Tests of Group-III evaluate geotextile properties related to their hydraulic behaviour, viz., in-plane and cross-plane flows under various hydraulic gradients and normal pressures and fabric pore characteristics. Characterization of fabric pores was carried out by the dry sieving method as well as by the modified mercury intrusion method.

Programme of Work

As a result of these 28 different tests carried out on each of the 95 samples, about 40,000 data were created. In an effort to provide a compact shape as well as a mathematical form to this large volume of test data various statistical techniques were employed with different data .sets. Test results obtained, after being subjected to relevant statistical treatments, were used for

Table 5
Different input variables and their levels for polyester fabrics (after Dey, 1995)

Level Nature	Variables	Level of Variables				
		Axial point ($-\alpha$)	Factorial point ($-\beta$)	Center point (O)	Factorial point ($+\beta$)	Axial point ($+\alpha$)
Coded	All	-2.378	-1	0	+1	+2.378
Actual	Fibre fineness (denier) (X_1)	2.12	3.5	4.5	5.5	6.88
	Fibre length (mm) (X_2)	39.33	60.00	75.00	90.00	110.67
	Web weight (g/m^2) (X_3)	8.05	11.5	14.0	16.5	19.95
	Punch density (Punch/cm^2) (X_5)	50.00	160.0	240.0	320.0	430.0

Table 6
Different design input variables and their levels for polyester fabrics (after Dey, 1995)

Nature of Value	Variables	Level of Variables				
		Axial point ($-\alpha$)	Factorial point ($-\beta$)	Center point (O)	Factorial point ($+\beta$)	Axial point ($+\alpha$)
Coded	All	-2	-1	0	+1	+2
Actual	Fibre fineness (denier) (FD)	3.0	6.0	9.0	12.0	15.0
	Fibre length (mm) (FL)	45.0	60.0	75.00	90.0	105.0
	Batt areal density (g/m^2) (BAD)	140.0	240.0	340.0	440.0	540.0
	Depth of penetration (mm) (DOP)	9.00	11.5	14.0	16.5	19.0
	Punch density ($Punch/cm^2$) (PD)	80.0	160.0	240.0	320.0	400.0

Table 7
Breakup of treatment combinations (after Dey, 1995)

Fibre	No. of variables	Nature of design	No. of Treatments/Trials			
			Factorial	Axial part	Centre part	Total
Polyester	5	Full factorial	$2^5 = 32$	$2 \times 5 = 10$	17	59
Polypropylene	5	Half factorial	$2^{5-1}=16$	$2 \times 5 = 10$	10	36

developing statistical models. The Stepwise regression method, a multiple regression technique, was employed for developing the models of geotextile responses under change in any input variables. Thus for each geotextile property evaluated, one second order regression model was worked out.

Results and Analysis

The details of the study and results are available in Dey (1995). The manner of analysis is included herein by considering a few cases.

Interaction effect of Fibre Length (FL) and Punch Density (PD) on in-plane flow of polypropylene fabric presented in Fig. 44 shows that the maximum value of the flow can be achieved at the higher level of either variables (FL and PD) when the other variable is at its lower level. This suggests that the selection of the level of these variables should be done after considering their effects on other fabric properties. Interaction effect of FD and PD shown in Fig. 45 reveals that PD does not have any significant

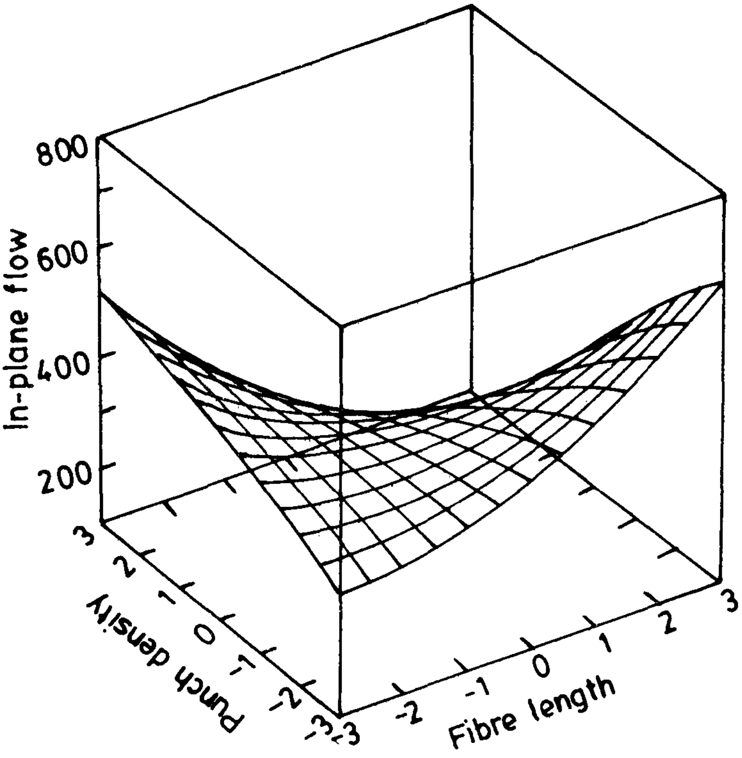


Figure 44 : Interaction effect of fibre length and punch density on in-plane flow of polypropylene fabric (after Dey, 1995)

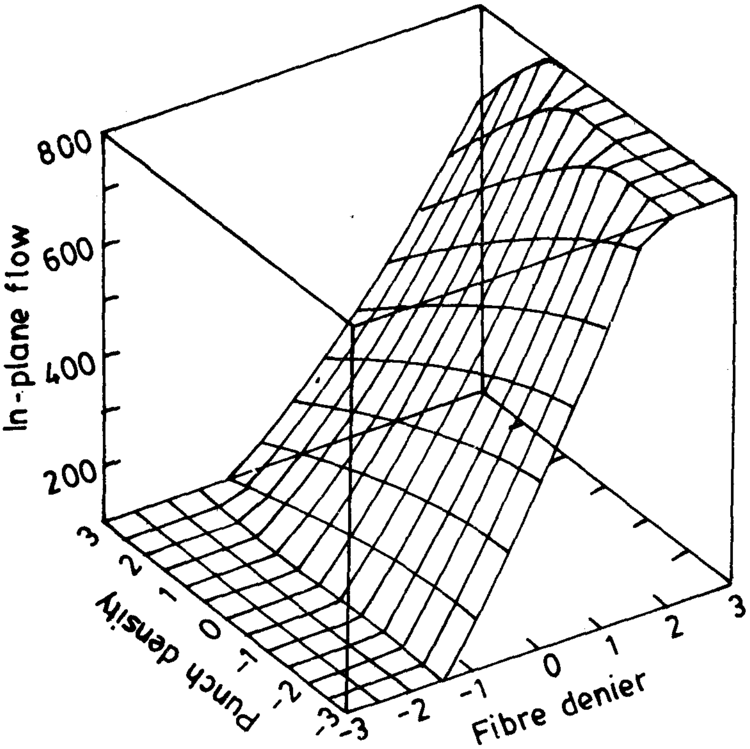


Figure 45 : Interaction effect of fibre diameter and punch density on in-plane flow of polypropylene fabric (after Dey, 1995)

effect on flow at lower level of FD, whereas for higher level of FD the flow decreases sharply with the increase in PD. Therefore, a combination of higher level of both PD and FD should be used cautiously, otherwise at this level slight increase in PD will strongly affect the in-plane flow properties negatively. The interaction effect of Depth of Penetration (DOP) of needle and PD on in-plane flow presented in Fig. 46 shows that a combination of lower level of both the variables maximises the flow property; whereas, with the increase in either variables the flow property decreases monotonically. At higher level of DOP, the parameter PD has a mild positive effect on in-plane flow properties.

Comparison Between Effects of Input-variables of Hydraulic Properties of Polyester and Polypropylene Fabrics

Table 8 depicts a comparative list of the combinations of levels of different input variables required for optimization of various hydraulic properties. In the process of optimization, the effects of FD and DOP are

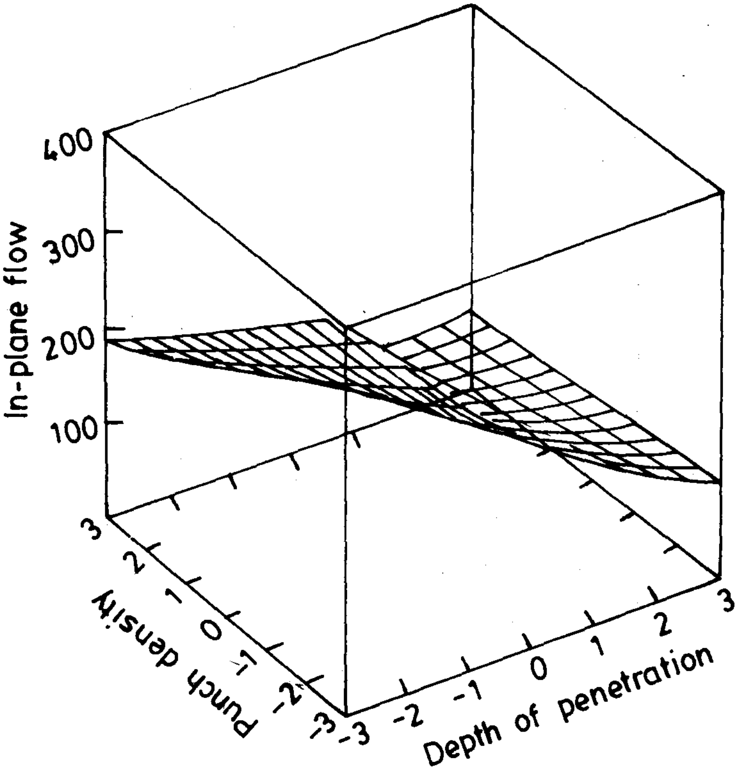


Figure 46 : Interaction effect of depth of penetration and punch density on in-plane flow of polypropylene fabric (after Dey, 1995)

almost identical for both polyester and polypropylene fabrics. FL shows the greatest dissimilarities in its effect on the optimization process.

As far as flow behaviour is concerned, BAD shows quite a substantial disagreement in its effect. Thus, for minimizing the in-plane flow behaviour of polyester fabric, a low level of BAD is needed, but polypropylene fabric needs a moderate to moderately high level of BAD. However, on properties related to porometry there does not exist any difference in trend in this regard. PD does not have any direct effect on mean pore radius and permittivity of polyester fabrics, whereas a low level of PD is desirable for achieving maxima of the above properties of polypropylene fabrics. Similarly, a moderate value of PD facilitates the minimization of AOS of polyester fabric, whereas high values of the same is needed for polypropylene.

Similar to the effect of BAD on in-plane flow behaviour, FL has an identical effect on cross-plane flow behaviour. FL does not have any effect on PP fabric porosity, but a low to moderate FL is needed for minimization

Table 8
Comparison between levels of input variables required for optimising hydraulic properties of polyester and polypropylene fabrics (after Dey, 1995)

Properties	Direction of optimization	Polyester					Polypropylene				
		FD	FL	BAD	DOP	PD	FD	FL	BAD	DOP	PD
Porosity	↑	H	M$^-$	L	L	L	H	-	L	L	L
AOS (0_{95})	↓	L	H	H	M$^+$	M	L	M	M$^+$	H	H
Mean radius 25	↑	H	L	L	L	L	H	L	L	L	L
Mean distribution radius	↑	H	L	L	L	-	H	L	L	L	L
Pore size distribution parameter	↑	H	L	L	L	L	H	L	L	L	L
Inherent transmissivity^{-1}	↑	M$^+$	L	L	L	L	M$^-$	L	M	L	M$^-$
Inherent permittivity^{-1}	↑	m$^+$	l	l	l	-	h	m	l	l	M$^-$
Inplane flow	↑	H	L	L	L	L	H	L	M$^+$	L	L
Cross plane flow	↑	M$^+$	L	L	L	L	H	M	L	L	L

L : Low
M$^-$: Low moderate
M : Moderate
M$^+$: Moderately high

H : High
↑ : Maximisation of response
↓ : Minimisation of response

of porosity of polyester fabrics.

For minimizing the AOS value, a longer fabric length is needed for polyester fabrics; whereas, a moderate fibre length can achieve the same target for polypropylene fabric.

Broad Conclusions

In addition to the regression models pertaining to each fabric property, some more statistical models were worked out, viz.,

- Thickness at different normal pressures both during loading and unloading sequence, i.e. during compression and recovery phases with the applied pressure were excellently fitted with a logarithmic and a power series curves respectively by using the least square technique.
- Regression analysis was carried out to find out the relationships among different survivability properties. Cross-machine direction strength is found to be most closely related with other survivability properties.
- In-plane and cross-plane flow data at different normal pressures and hydraulic heads were fitted with a modified hyperbolic model with three parameters. These parameters are good indicators of the geotextile flow behaviour and used for characterising the flow behaviour of geotextile.
- To quantify the pore size distribution curve obtained through the mercury porosimetry test, a standard distribution involving one parameter (Rayleigh distribution) was successfully fitted with the porosimetry data.
- Excellent correlation exists between all flow properties and pore size distribution parameter obtained through mercury porosimetry data.

An intensive analysis of the regression models relating the individual fabric properties with fabric production parameters lead to the following conclusions:

- For satisfactory hydraulic function, a needle punched geotextile should exhibit a degree of structural mobility which is negatively correlated with the survivability properties of geotextile.

Table 9
Properties of geosynthetics used in triaxial testing

Designation	Structure	Polymer	Mean pore size (micron)	Thickness (mm)	Mass per unit area (g/m^2)	Tensile strength (kN/m)	Extension at failure (%)	Secant modulus @ 10% elongation (kN/m)
GTW	Woven	Polypropylene	25	0.70	270	MD 37.00 CD 33.90	MD 28.0 CD 26.0	170.0
GTNP	Non-woven	Polypropylene	75	4.02	275	MD 14.41 CD 14.03	MD 56.6 CD 66.5	1.1
GG	Grid	High density Polypropylene	-	3.30	730	MD 7.80 CD 6.50	MD 34.0 CD 43.0	60.0

MD = Machine direction
CD = Cross machine direction

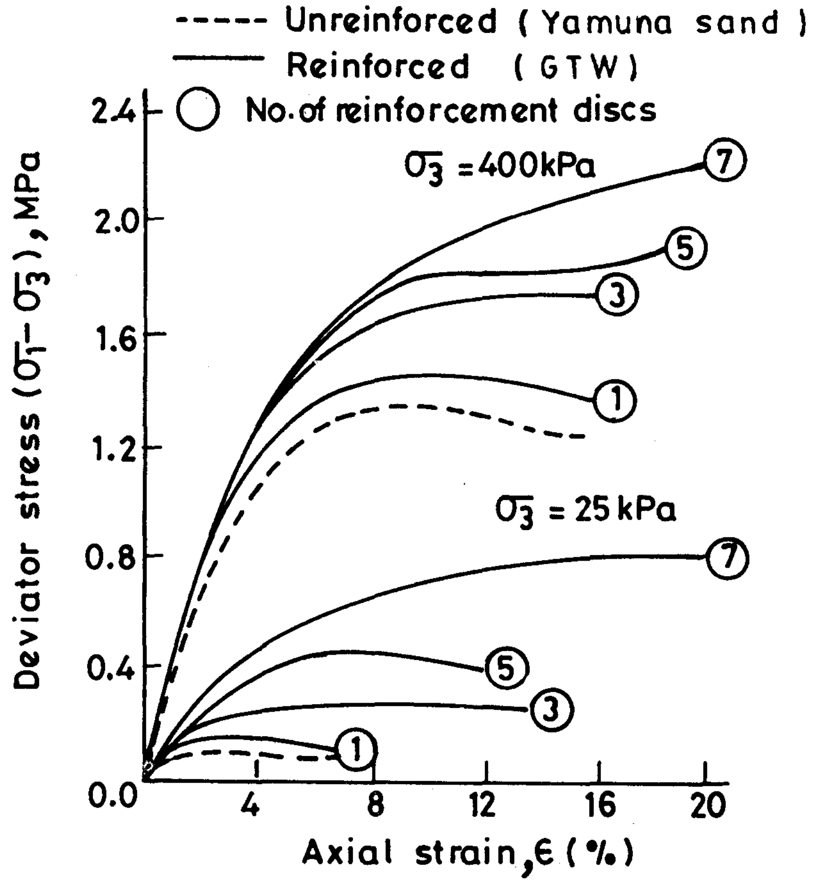


Figure 47 : Stress-strain relationship for sand Y reinforced with woven fabric

- Higher fibre denier consistently improves flow properties whereas higher fibre length and batt areal density improve survivability properties and reduced compressibility and recovery.

- The difference between polypropylene and polyester fibres with respect to the effects of the five selected input variables on various properties are primarily due to greater thickness, higher bending rigidity and higher cohesive drag of polypropylene fibre.

Soil Improvement with Geosynthetics

The technique of soil reinforcement is being extensively used, since the last two decades, in a variety of applications ranging from earth retaining structures to subgrade stabilization. It is one of the most successful and reliable techniques and is fast replacing the other conventional improvement methods.

Triaxial tests have been conducted to understand the strength behaviour of micro-mesh as well as oriented layered reinforced sands. The results have been used to assess the influence of such reinforced material overlying clay beds on foundations (Shamsher, 1992).

Experimental Work

The investigation reported in detail in Venkatappa Rao et al. (1994) was carried out on two granular materials viz., fine grained micaceous Yamuna sand (S1) and crushed stone dust (S2) comprising of subangular particles. Three geosynthetics GTW, GTNP and GG (properties included in Table 9) were used as oriented circular disc reinforcements. The geomesh (GG) cut into pieces of sizes 30 × 30 and 50 × 50 mm was used as micro-mesh (GMM) reinforcement. Specimens of saturated cohesionless soil (100 mm diameter and 200 mm high) were prepared in a conventional manner.

The density of Yamuna sand used was $15 \pm 0.2\ \text{kN/m}^3$ and that of stone dust $17.8 \pm 0.2\ \text{kN/m}^3$. The specimens, after consolidation were sheared in drained condition at a deformation rate of 0.2 mm/minute.

Stress-Strain Relationships

The typical stress-strain curves for Yamuna sand reinforced with woven fabric are illustrated in Fig. 47, which indicate the improvement in behaviour.

The summary of the typical triaxial test results is presented in Figs. 48 and 49 for geotextiles and in Tables 10 to 12 for geomeshes.

Bearing Capacity Ratio

For the analysis, a square footing (width, B) placed at depth, D_f below ground level and resting on sand layer overlying a clay bed has been considered (Fig. 50) The values of B and D_f adopted were 1.25 m and 1.00 m respectively and the clay as having unit weight of $15.70\ \text{kN/m}^3$, and an undrained cohesion (c) of 19 kPa. In all, six cases have been analysed.

The ultimate bearing capacity (UBC) has been computed using Meyerhof's theory (1974). The UBC of reinforced sand (q_{uR}) can be expressed as

$$q_{uR} = q_{uS} + \Delta q_u$$

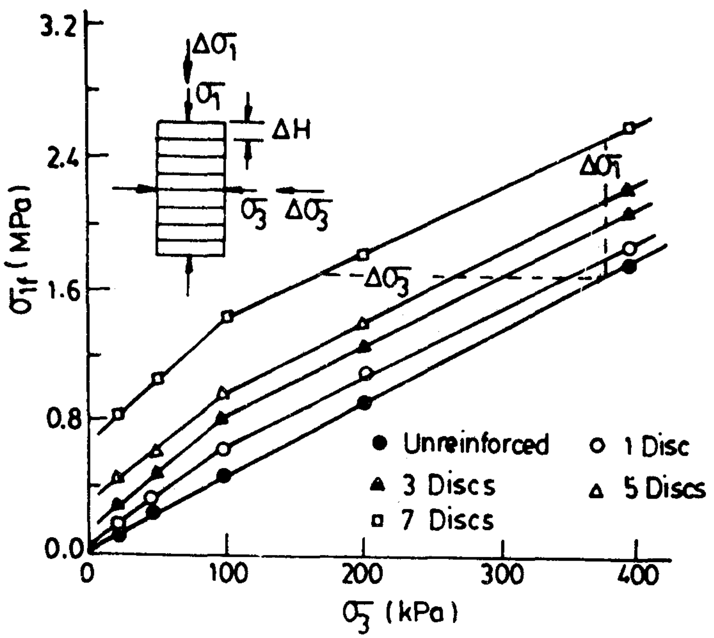


Figure 48 : Variation between σ_{1f} and σ_3 for sand S1 reinforced with geotextile GTW (after Venkatappa Rao, Kate and Shamsher, 1994)

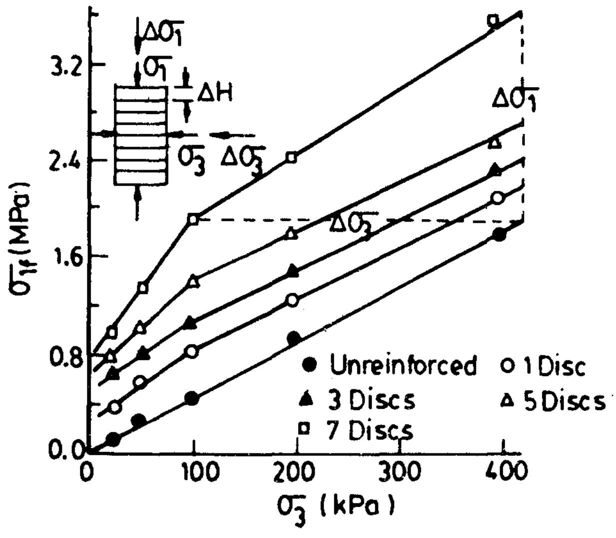


Figure 49 : Variation between σ_{1f} and σ_3 for S and S1 reinforced with geotextile GTNP (after Venkatappa Rao, Kate and Shamsher, 1994)

Table 10
Strength parameters for geogrid disc reinforced sand S2
(γ = 17.8 kN/m^3)

σ_3 (kPa)	Parameter	No. of reinforcement discs			
		0	1	2	7
<100	ϕ' (deg.)	44.4	51.4	57.0	60.0
	c' (kPa)	0	0	0	0
>100	ϕ' (deg.)	44.4	38.7	38.7	40.5
	c' (kPa)	0	9.6	115.0	146.0

Table 11
Strength parameters for GMM reinforced sand SI

σ_3 (kPa)	Parameter	Loose sand (γ = 14.0 kN/m^3)		Dense sand (γ = 160.0 kN/m^3)			
		Mesh %		Mesh %			
		0	1.40	0	0.24	0.72	1.40
<50	c' (kPa)	0	0	0	0	0	0
	ϕ' (deg)	36.9	44.0	40.6	44.0	46.5	48.0
50-200	c' (kPa)	0	43.8	0	25	33	57
	ϕ' (deg)	36.9	37.0	40.6	38.5	39.0	39.0

Table 12
Strength parameters for GMM reinforced sand (S2)

σ_3 (kPa)	Parameter	Mesh %				
		0	0.24	0.48	0.72	1.40
<50	c' (kPa)	0	0	0	0	0
	ϕ' (deg)	44.4	48.8	50.1	51.4	54.0
50-200	c' (kPa)	0	21	36	36	65
	ϕ' (deg)	44.4	45.5	45.5	46.6	46.0

where, q_{uS} = UBC of sand, and
Dq_u = change in UBC due to reinforced inclusion

Hence,

$$q_{uR} / \Delta q_u = 1 + \Delta q_u / q_{uS}$$

or bearing capacity ratio,

$$BCR = 1 + \Delta BCR$$

where, ΔBCR = change in BCR.

Using the values of UBC the bearing capacity ratios have been calculated for various H/B ratios (where H = thickness of granular layer, below the foundation) and presented in Fig. 50 for GMM reinforced sand (S2). In general, it can be seen that the BCR increases with increase in H/B upto a value of around 1.5, beyond this, the increase is insignificant. The figure further shows an increase in BCR with increasing mesh percentage which is as expected. The maximum BCR obtained in this study is over 3.

Similar conclusions may be drawn from Fig. 51 which presents results for GMM reinforced sand (S1) in loose and dense conditions. Also higher BCR values are observed for sand in loose condition.

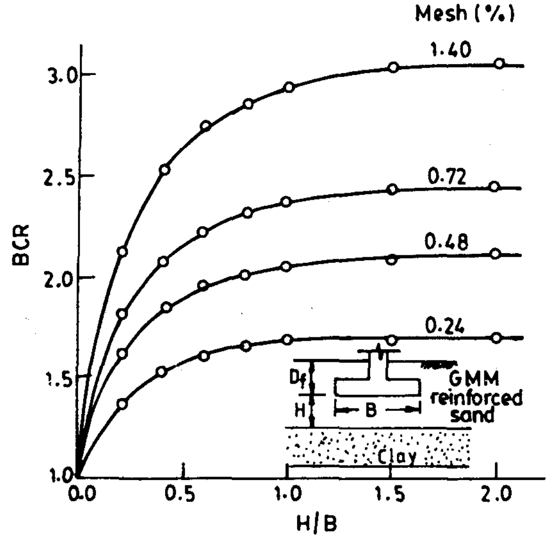


Figure 50 : Variation of BCR with H/B for GMM reinforced sand S2 overlying clay (after Venkatappa Rao, Kate and Shamsher, 1994)

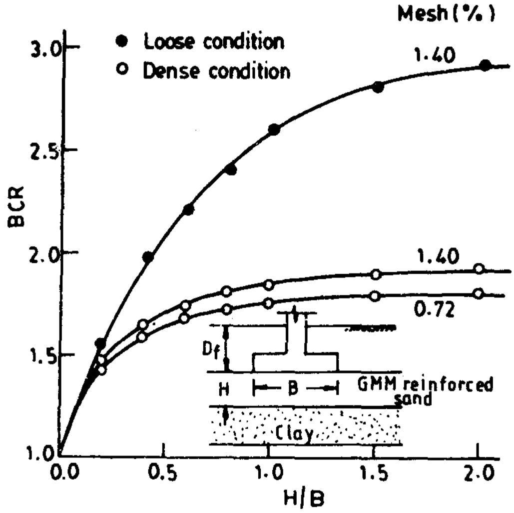


Figure 51 : Variation of BCR with H/B for footing on reinforced sand S1 overlying clay (after Venkatappa Rao, Kate and Shamsher, 1994)

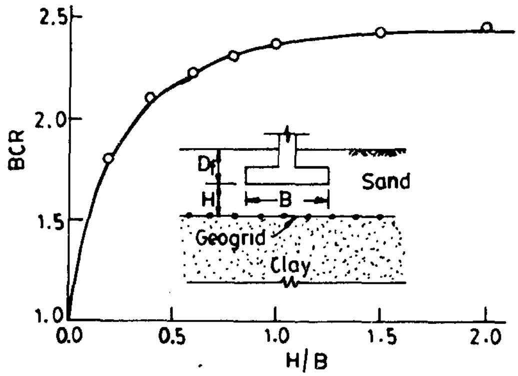


Figure 52 : Variation of BCR with H/B for reinforced sand S2 with GG layer at interface (after Venkatappa Rao, Kate and Shamsher, 1994)

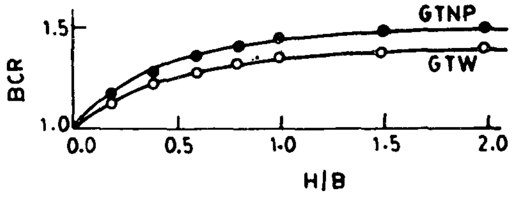


Figure 53 : BCR variation with H/B for sand S1 reinforced with geotextile layer at interface (after Venkatappa Rao, Kate and Shamsher, 1994)

The results for single layer of geosynthetic placed at sand-clay interface are illustrated in Fig. 52 for geomesh and sand (S2)-clay interface and in Fig. 53 geotextile at sand-clay interface. These figures show curvilinear increase in BCR with H/B upto H/B of 1.5, beyond which the increase is insignificant.

Settlement

The consolidation settlement for different cases has been estimated by dividing the entire clay bed of thickness Hc into six sub-layers each of thickness 0.5 B, and the effective stresses required for settlement computations have been worked out accordingly at the centre of each such sub-layer. For the case of footing directly resting on clay layer, the pressure increment at the centre of each sub-layer due to the loaded footing has been computed using Boussinesq's pressure isobars. Other cases of two layered system wherein footing rests in sand (unreinforced/reinforced) overlying clay bed the method suggested by Fox (1948) has been used to compute the required axial interface stresses. The consolidation settlement(s) for different cases have been estimated from the consolidation settlement equation assuming the values of compression index and initial void ratio as 0.35 and 1.1 respectively.

The influence of GMM reinforcement on the consolidation settlement is illustrated in Fig. 54 which shows the variation of settlement with H/B ratio for different mesh percentages in sand S2. It is evident that the reinforcement does reduce the settlement, but the reduction in settlement is marginal in comparison with unreinforced sand. Similar trends have been noticed for the case of GMM reinforced sand S1 both in loose and dense state.

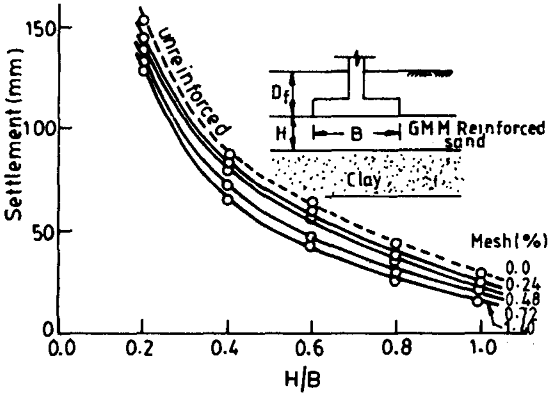


Figure 54 : Variation of settlement with H/B for footing on GMM reinforced sand S2 overlay clay (after Venkatappa Rao, Kate and Shamsher, 1994)

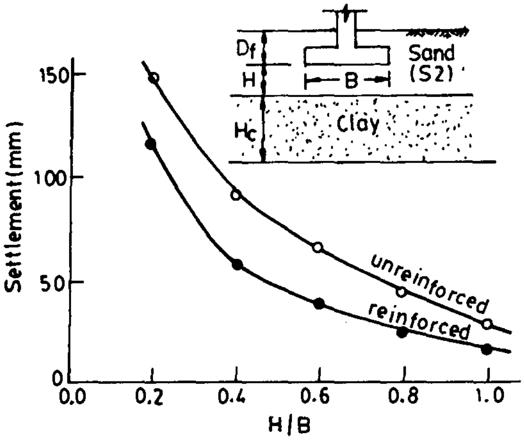


Figure 55 : Variation of settlement with H/B for footing with GG and interface (after Venkatappa Rao, Kate and Shamsher, 1994)

In case of sand S2 reinforced with layer of geomesh GG placed at interface of sand and clay, the settlement decreases with increase in H/B ratio as illustrated in Fig. 55 The reduction in settlement due to introduction of geogrid layer is again marginal.

It may thus be inferred that geomesh reinforcement (in the form of GMM or layers of GG) contributes significantly to BCR improvement but is hardly influential in reducing the settlement. These observations more or less substantiate the earlier work on geogrid layer reported by Yamanouchi (1972) and Yasudharee et al. (1986).

Reinforced granular trench

An analysis has been carried out to understand the changes brought out in ultimate bearing capacity of a footing on granular trench (Fig. 56) when the reinforcements are introduced into the trench materials, following the procedure developed by Madhav and Vitkar (1978). For this, the weak clay deposit has been assumed to possess cohesion (c_2) of 20 kPa. The values of cohesion c_R of reinforced material for granular trench (c_1 is replaced by c_R for reinforced material) obtained from the results of triaxial tests. The footing was assumed to be placed at a depth (D_t) of 1.0 m below ground level and rests directly on granular trench. The footing widths (B) varied are 1.0, 1.5 and 2.0 m. The granular trench width (A) is so varied as to obtain A/B ratios from 0.8 to 2.0.

The typical variations of BCR with A/B ratio for different values of B are illustrated in Fig. 56 for sand S2 with GMM. There is a bilinear increase

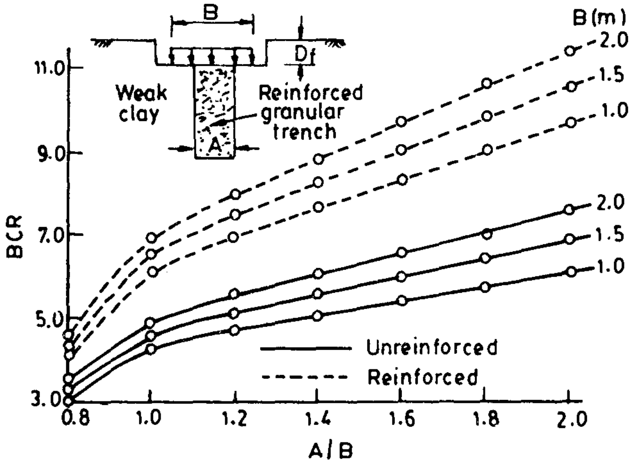


Figure 56 : Variation of BCR with A/B for GMM reinforced sand S2 (after Venkatappa Rao, Kate and Shamsher, 1994)

in BCR with increase in A/B ratio for both unreinforced as well as reinforced granular trench. Similar results have been observed for other types of reinforcements.

Extensive studies have also been conducted on the bearing capacity aspects by Professor A. Sridharan and co-workers at Indian Institute of Science, Bangalore and on the settlement aspects by Professor M.R. Madhav and co-workers at Indian Institute of Technology, Kanpur.

Case Studies

Single layer separator/reinforcement has often been successfully used in India in several situations typically in drilling pads for oil drilling rigs located on soft soils, hard standages for steel yards and in some cases in foundations of large diameter oil storage tanks on soft/swelling soils.

Ghoshal and Som (1989) described the successful use of a spun bonded geotextile (170 g/m^2) in the construction of an offshore fabrication yard at a site reclaimed by dredged silt from the river Hooghli about 16 km downstream of Haldia port. The yard was meant for movement in tandem of cranes of 250 t capacity weighing upto 200 t on the soft silty clay/clayey silt (with SPT = 2 – 4 in the top 8 m) constructed in 1984/85, the yard is still performing well, which is also proven by the settlement observations.

Reinforced Soil Walls

Modern applications of soil reinforcement appeared in 1960's with the introduction of Reinforced Earth retaining walls. The beneficial effect of incorporating tensile inclusions within a soil mass was recognised and has been demonstrated by the successful construction of numerous reinforced soil walls.

Model Studies

Geosynthetic reinforced retaining walls have a great potential for use due to their simplicity in construction, usefulness in projects in remote and inaccessible areas and in urban localities where availability of space is a problem. In an attempt to promote this technique, an extensive study was carried out at under a Research Scheme sponsored by the Department of Science and Technology, Government of India. In the earliest model studies, indigenous woven and non-woven geotextiles were used in a wrap around technique (Venkatappa Rao and Kate, 1990). Subsequently to bring out the use of HDPE slit film woven sacking material that is available in India at an unbelievably low cost, model studies were conducted with this material as bag facing as well as tie back reinforcement. These studies (Venkatappa Rao, 1992) have demonstrated that such a technique can be used in non-critical structures for low height walls upto 3 m with a surcharge of 2 t/m^2. Also model studies were conducted (Katti, 1992) in which the bag facing was wrapped around with geomesh available in the country (Venkatappa Rao et al., 1993) as part of a research project sponsored by the Department of Science and Technology, Government of India.

Field Use

The first soil reinforced structure was built in Ludhiana in a road over bridge approach under the Ministry of Surface Transport (Roads Wing) wherein geosynthetic strips have been as reinforcing element and precast concrete panels are used as facia. Similar construction has also been just completed at Pugwara in Punjab.

At the Visweswaraya Setu (Road over rail bridge) in Delhi, the Public Works Department, Delhi Administration, has successfully constructed a 58.1 m length of geogrid reinforced wall with precast concrete facia elements with average height of 6 m using fly ash as the fill material. This wall was built on a geogrid reinforced mattress wherein again PFA was used. With all these novel features, this is the first construction of its type in India. A similar construction is under consideration by Public Works Department, Delhi Administration at the Yamuna Bazar intersection near Red Fort.

FEM Studies

At the present time, geosynthetic reinforced soil walls are being essentially designed using limit equilibrium methods in a manner similar to the design of conventional gravity type retaining wall considering external and internal stability independently. The behaviour of reinforced soil walls is yet to be thoroughly understood. The predictive exercise undergone at the Royal Military College (RMC), Canada clearly demonstrated that the existing conventional methods do not give a rational understanding of the complex behaviour of reinforced soil wall.

To facilitate a detailed understanding of vertical faced geosynthetic reinforced soil walls, extensive studies were carried out by Raju (1994) using the Finite Element Method. A computer program, GEOWALL, written in Fortran 77, has been developed for the elasto-plastic analysis. The program has the provision for eight-noded solid elements, six-noded interface elements and three-noded line elements.

To verify the GEOWALL program, pullout test data as reported by Toshiaki et al. (1990) was successfully simulated (Sharma et al., 1994). The reported data by Bathrust et al. (1988) of the RMC test wall was also used to compute the behaviour of test wall. The computed values of deformation, vertical pressures and connection loads using GEOWALL are found to be close to those observed by Bathrust and Koerner (1988) (Sharma et al., 1995).

A parametric study of various factors such as spacing of the reinforcement, length of the reinforcement, shear strength parameters of fill and facing rigidity, which influence the behaviour of reinforced soil wall, was conducted. The study revealed the following important aspects.

i) The load carrying capacity of reinforced soil increases substantially with increase of angle of shearing resistance of the fill. Hence, it is advisable to concentrate on better compaction in field. However, the best advantage of fill properties with regard to the ultimate carrying capacity can be achieved only when they are utilised with stiffer facings.

ii) The vertical stress near the facing is substantially lower than normal vertical stress. Hence, normal overburden pressure may be taken for design rather than trapezoidal or Meyerhof distributions.

iii) Rigid facing is highly advantageous for better stability of the wall.

iv) The locus of maximum tensile force in the reinforcement approaches the Rankine failure line as the length of the reinforcement is reduced.

v) The deformations of the facing are substantially lower (move so for stiffer facing) for higher angles of shearing resistance of the fill.

On the whole, it is concluded that the current practices of design based on limit equilibrium methods are indeed conservative.

Land Slide Protection

Most hill regions in the fragile Himalayas be it in Uttar Pradesh, Himachal Pradesh, Jammu and Kashmir, the North-eastern Hill states or the Nilgiri Hills in Tamil Nadu, land slides pose a recurring problem. They damage the highway structures as well as endanger the thickly populated hill towns. There are many classic examples of continuing problems, say, on the Jammu-Srinagar National Highway.

The construction of geosynthetic gabion reinforced soil wall to stabilize the Mussourie-Chamba bypass was the first successful use of geosynthetic solution for this kind of problems (Bhandari and Garg, 1989). Unfortunately, this example has not been followed at other problematic areas. For instance, in many of the water resources projects as well as new railway projects considerable (sometimes indiscriminate) blasting results in instability of the region, exposure of fresh rock face, appearing like an eye sore. In such cases geosynthetics offer convenient economic and permanent solutions, as indicated in Fig. 57. More so, because they can be made green.

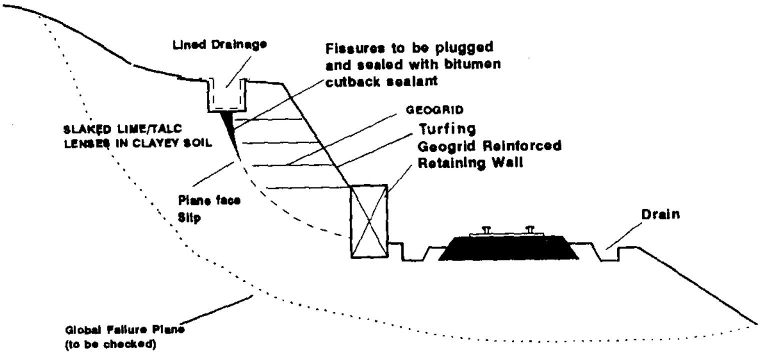


Figure 57 : Use of geosynthetics in landslide repair

Pavements

Geosynthetics are being extensively used in road and airport flexible pavements and in overlays. In unpaved roads (having no black top), introducing a very thin non-woven geotextile is found to be of advantage for soft subgrades primarily through separation (thus minimising pumping) and partly through reinforcement. The Central Road Research Institute, New Delhi, has undertaken several trials using geotextiles for road underlays in the rural and command area roads of Gujarat and Maharashtra, over black cotton soils. Introducing bitumen impregnated non-woven geotextiles is also known to improve the pavement behaviour in case of reinforced surface dressing as well as flexible overlays – the improvement primarily being brought about through impermeability. Strips of indigenous bitumen impregnated needle-punched geotextiles have been successfully used in Madurai and Ahmedabad runways as early as 1985. Their use is believed to have helped in controlling the cracks. After 2 years of installation, only micro-cracks were noticed whereas in untreated sections cracks began to appear. Recently (1995) they have also been used in overlaying the runway at Chandigarh airport. In overlays, introduction of a geogrid effectively reduces reflection cracking. Geogrids at the subgrade-subbase interface or at the base-subbase interface or at the base-surface course interface could also improve the pavement behaviour by reducing cracking and rutting. A geomembrane encapsulated layer can control moisture migration in expansive soils. Heavy duty geocomposites can be put to use in strategic locations when heavy vehicles can directly move over them. Geosynthetics are thus a great boon for ease in construction over soft soil as well as for long term performance of road pavements. Despite the many advantages geosynthetics offer, the design methodology prevalent is rather empirical, the notable exception being that of the methods proposed by Giroud and Noiray (1981) and Giroud et al. (1984). This is perhaps due to the paucity in understanding the resilient behaviour of geosynthetic included pavements.

Triaxial Behaviour Under Cyclic Loading

Whereas the subgrade soils and granular materials have been adequately characterized for their resilient behaviour their responses with a geosynthetic inclusion needs attention. At attempt in this direction was reported (Venkatappa Rao et al., 1991b) through triaxial testing of 76 mm high and 38 mm diameter composite samples consisting of silt and sand separated by a non-woven geotextile. Further studies have been conducted as part of a Research Project sponsored by the Ministry of Surface Transport (Roads Wing), Government of India. To simulate the granular layer - subgrade interface in a better way, a composite specimen (100 mm dia and 200 mm high) the bottom half of which was silt and the top half was of wet mix macadam (WBM, modelled to suit the size of the specimen) was prepared. The two halves can be separated by

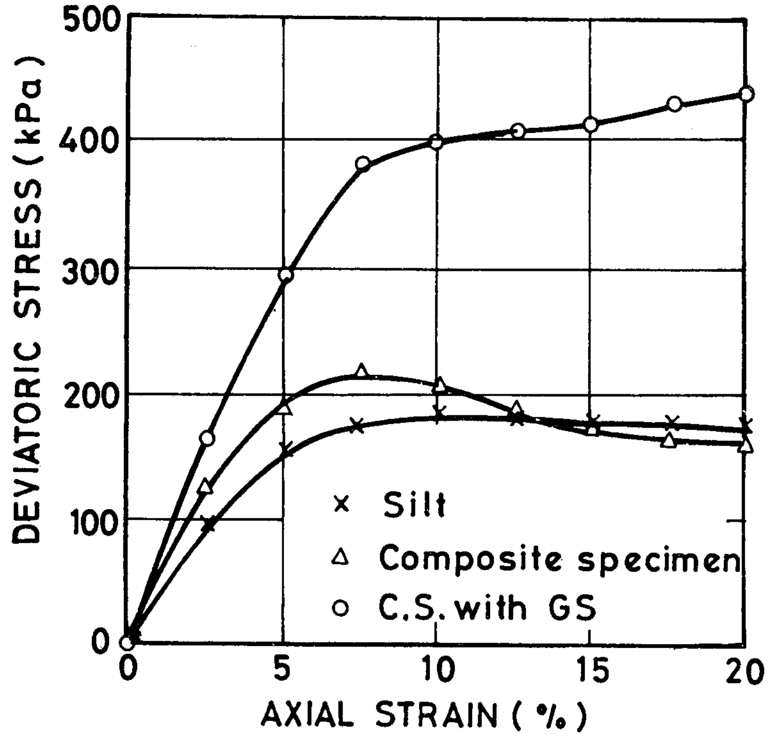


Figure 58 : Stress-strain curves for composite specimens at σ_3 = 200 kPa (after Venkatappa Rao, 1994)

a geosynthetic. Figure 58 shows the stress-strain behaviour obtained at a confining pressure of 200 kPa in a monotonic consolidated undrained triaxial test. It is evident that the deviator stress of the composite specimen at 5% axial strain yields about 20% improvement over that of the silt specimen. But introduction of a needle punched polypropylene geotextile (GSM : 290 g/m^2, thickness = 2.13 mm) has improved the stress-strain behaviour of the composite specimen markedly. When subjected to a cyclic load of 1000 N, the results presented in Fig. 59 reveal that large permanent axial strains occur. The permanent axial strain for 2000 cycles is as high as 35% at a σ_c = 100 kPa. This value drops to 16% with introduçtion of a non-woven geotextile. Similar behaviour was noticed at other cyclic loads. The near constant permanent strains of reinforced specimens beyond 1000 cycles (i.e. upto 5,000 cycles) was also encouraging. This study thus amply demonstrated the advantages to be gained even by using non-woven geotextile in reducing the rut depth. The variation of resilient modulus is presented in Fig. 60. It is evident that the resilient modulus shows significant improvement both at small as well large number of load repetitions.

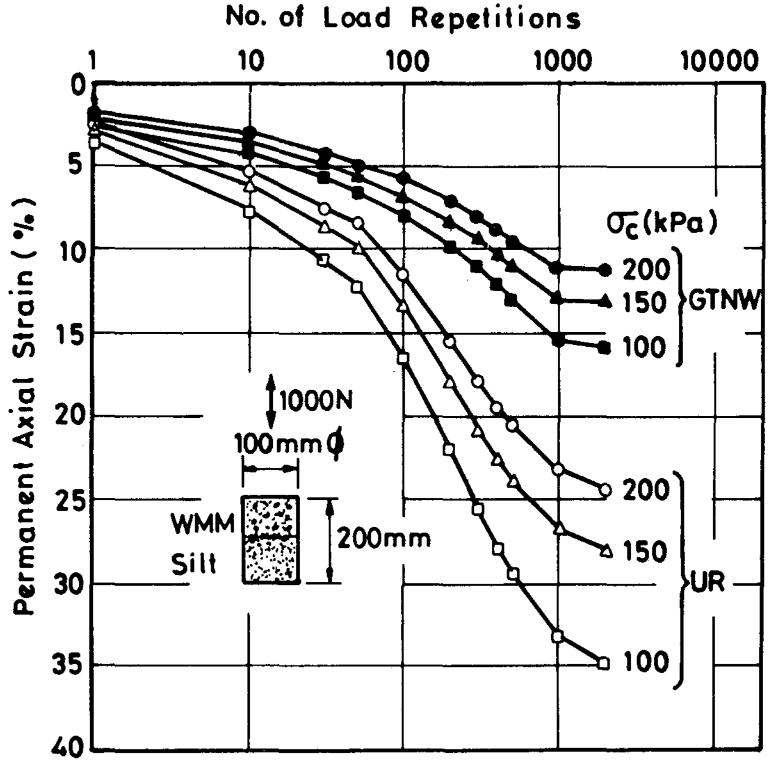


Figure 59 : Variation of permanent axial strain with load cycles in triaxial test (after Venkatappa Rao, 1994)

Model Testing

Model tests were conducted (by Sheogopal, 1995) using a perspex tank of 350 mm × 350 mm × 420 mm which can be placed in a cyclic load machine. The static loading behaviour of the models of Series A and B with saturated silt subgrade having a dry unit weight of 15.0 kN/m^3 and different thickness of WBM is presented in Fig. 61. The geosynthetic inclusions used in the reinforced models at the WBM subgrade interface were GTNW1 and Geogrid. The load was applied through a 10.0 cm diameter plate at a test speed of 2.0 mm/min. In general, it was observed that geosynthetic inclusion improves the load bearing capacity of the models substantially. It is also evident that there is more improvement with geogrid (GG) than the non-woven geotextile (GTNW1) for both the series. The unreinforced models depict a punching type shear failure, whereas for the reinforced model tends towards general shear failure.

Comparative behaviour of the unreinforced, GTNW1 and GG reinforced

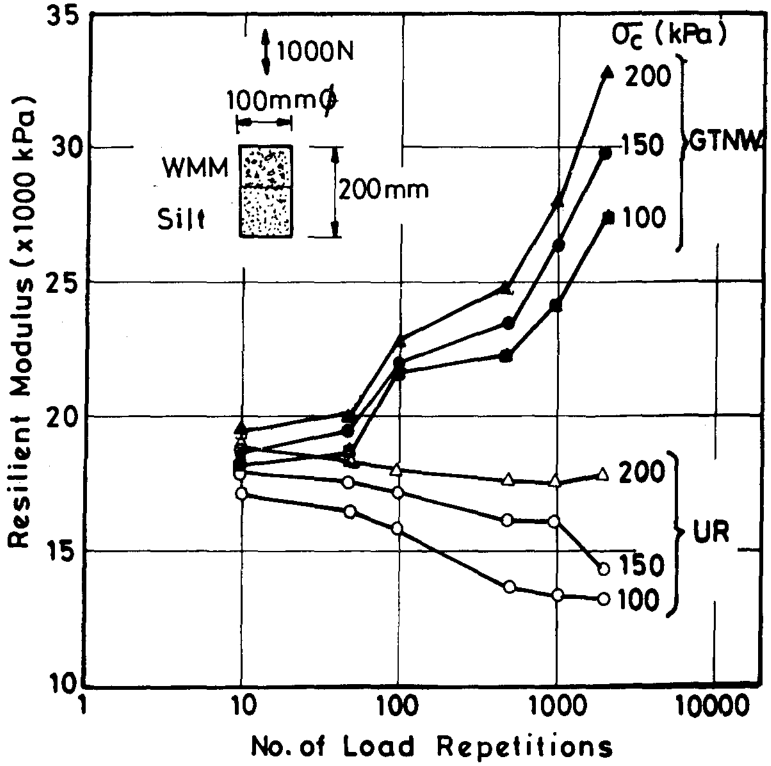


Figure 60 : Variation of resilient modulus with load cycles in triaxial test (after Venkatappa Rao, 1994)

models under repeated load of 3000 N is depicted in Fig. 62. The geogrid reinforcement shows improved performance over GTNW1 reinforcement in retarding the permanent deformation of the system. For a permanent deformation of 5 mm the number of load repetitions carried by unreinforced, GTNW1 and GG reinforced models are 25, 55 and 80 respectively and for a permanent deformation of 10 mm the corresponding load repetition values are 250, 400 and 1100.

Figure 63 shows the variation of apparent resilient modulus (AM_R) with number of load repetition (N) of all the models under repeated loads of 3000 N and 5000 N. For the GG reinforced model there is a distinct increase in AM_R with N for both the repetitive loads.

From the extensive investigations conducted (Sheogopal, 1995), the following conclusions emerge:

i) The permanent axial strain of the composite specimens is reduced

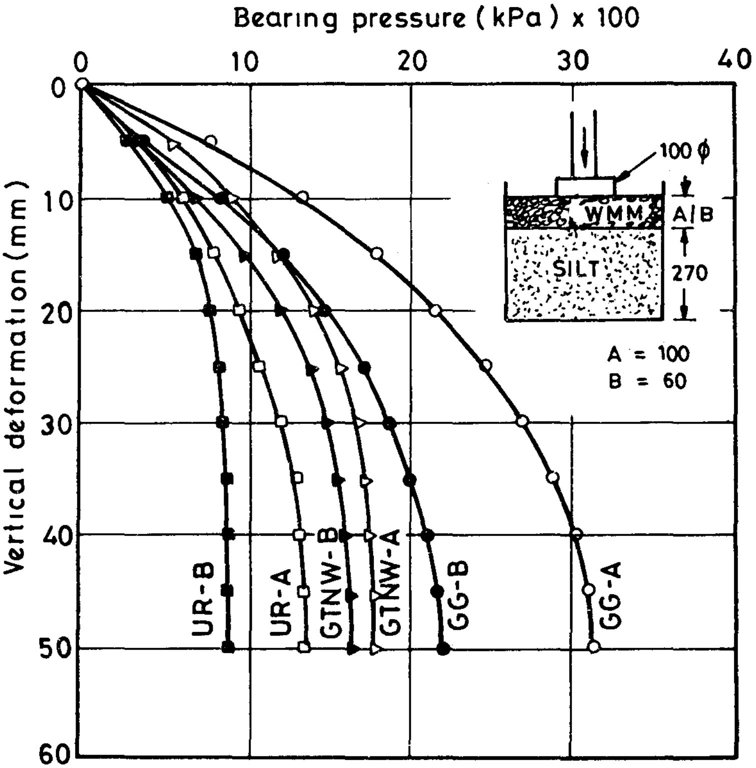


Figure 61 : Bearing pressure vertical deformation curves in model pavement tests (after Sheogopal, 1995)

substantially (upto 56 percent) due to GTNW1 inclusion and this effect was found to be more pronounced at lower confining pressure.

ii) The resilient modulus (M_R) of the unreinforced specimens decreases with N (with few exceptions) whereas it increases for the specimens with GTNW1 the percent increase in M_R being upto 107 percent at higher N values.

iii) For a given repeated axial load, the M_R of the specimens increases due to an increase in confining pressure and the improvement in M_R due to GTNW1 inclusion was found to be more at low confining pressure.

iv) The permanent axial strain (ε_p) of the specimens with and without GTNW1 is related to the repeated deviatoric stress levels (q_r) normalised with confining pressure (σ_3) by the equation:

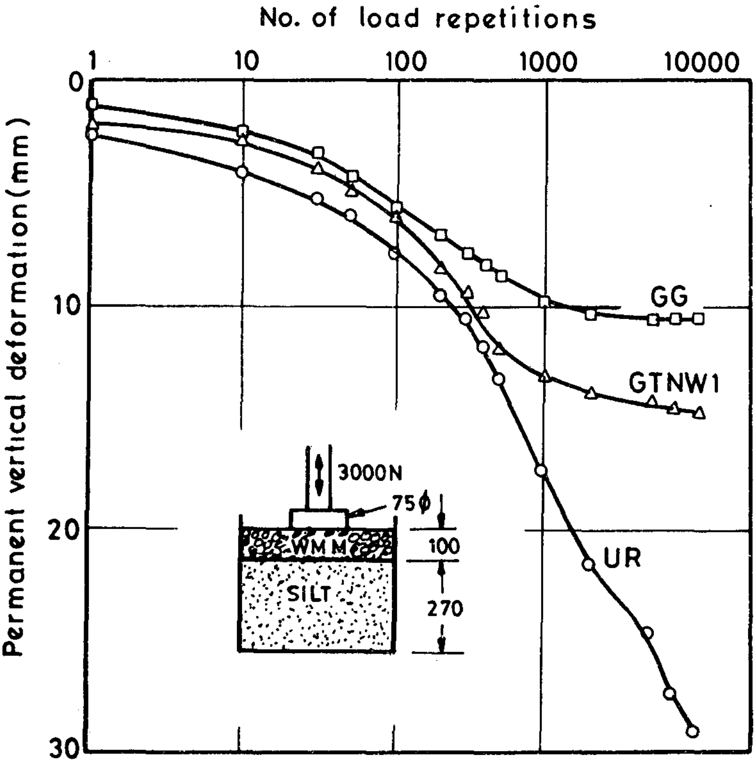


Figure 62 : Variation of perment deformation with load repetitions in model pavement tests (after Sheogopal, 1995)

$$\varepsilon_p = m\,(q_r / \sigma_3)$$

where, m = 0.05 to 0.14 - for composite specimens, and
= 0.03 to 0.06 - for composite specimens with GTNW1.

v) The permanent deformation of the models reduced substantially (upto 88 percent) due to geosynthetic inclusions and in general, this effect increases with number of load repetitions.

vi) Under similar test conditions, the apparent resilient modulus (AM_R) of geosynthetic reinforced models is higher compared to unreinforced models at any specified number of repetitions and increase in AM_R is more pronounced at higher number of repetitions.

vii) Models with geosynthetic, particularly GTW (woven geotextiles)

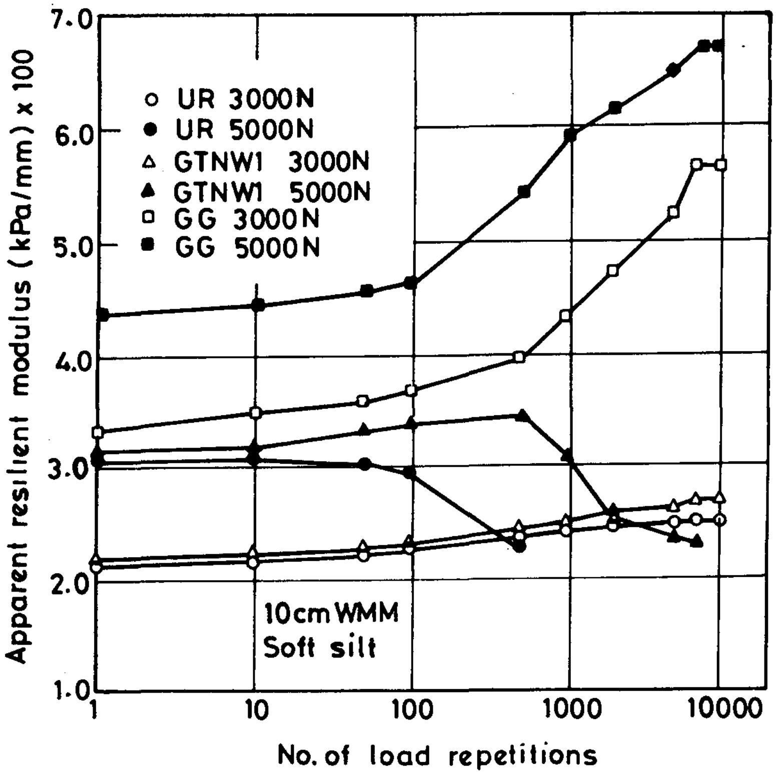


Figure 63 : **Variation of apparent resilient modulus with load repetitions in model pavement test (after Sheogopal, 1995)**

and GG, attained an equilibrium state in respect of permanent deformation after certain load repetitions, beyond which the model behaves more or less elastically, in other words, the increase in permanent deformation ceases. On the other hand, GTNW2, GTNW1 and unreinforced models also showed such behaviour but comparatively after much higher number of repetitions.

viii) Thin bituminous surfacing provides structural support to the system upto the first few hundred load repetitions and once it gets punctured, the model behaves in the same manner as that without surfacing.

Dixit (1995) has conducted a series of tests on model pavements comprising WBM as base course and Delhi silt/kaolinite clay as subgrade, under repetitive loading. The same type of models have also been tested under static loading. From these two series of tests, typical figures of static and repetitive loading are plotted on the same deformation axis and are shown in Fig. 64 for WBM + Kaolinite clay models (Venkatappa Rao et al., 1995). Thus corresponding to each deformation (rut, r) a value of static load P_s (r) and a pair of values [P_n, N(r)] are obtained from these plots for both the test series as per Delmas et al. 1986. Closely following their approach, the resulting fatigue behaviour is depicted in Fig. 65. These curves are similar in trend to the fatigue relationship as obtained by them. Furthermore, P_n / P_s values for reinforced models are less than those of unreinforced models.

The following fatigue relationship was suggested by De Groot et al. (1986).

$$P_s/P_n = (N)^{0.16}$$

where P_s = static failure load for a static test, and
P_n = the allowable load for N applications.

Table 13 presents the values of exponent in the relationship.

From this analysis it can be concluded that the models reinforced with GG-1 and GTW show better performance than any other reinforced models and the models reinforced with GG-1 and GTW can sustain higher number of repetitions for a particular rut depth or in other words they show higher bearing pressure at the same number of repetitions.

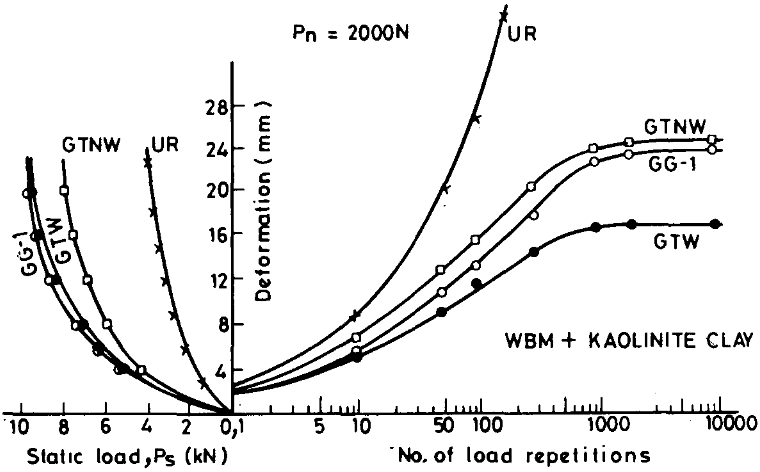


Figure 64 : Static and cyclic load test results on model pavements (after Venkatappa Rao, Gupta and Dixit, 1995)

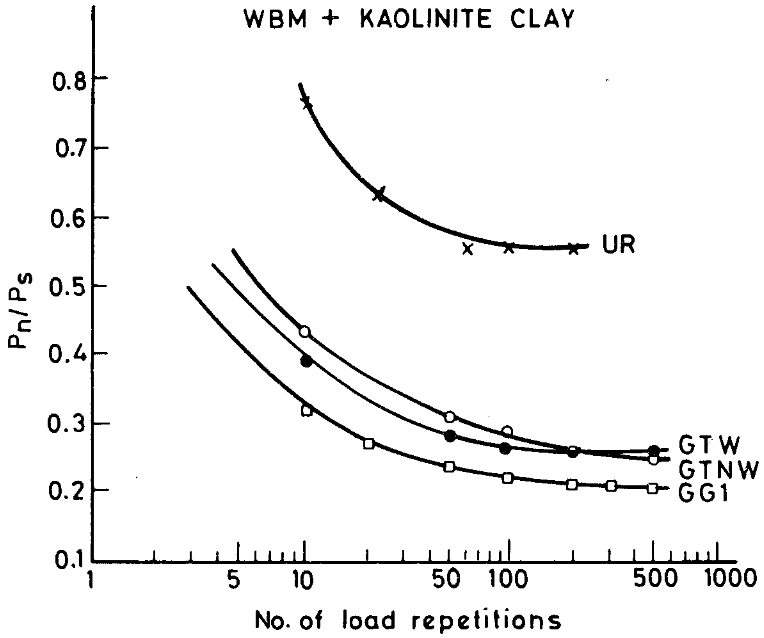


Figure 65 : Fatigue behaviour of model pavements (after Venkatappa Rao, Gupta and Dixit, 1995)

Table 13
Summary of the Values of exponent x in the Fatigue Relationship

Type of Series	Values of x in the empirical relations, Ps/Pn = $(N)^x$				
	UR	GTW	GTNW	GG-1	GG-2
WBM + Delhi silt	0.15	0.23	-	0.26	0.17
WBM + Kaolinite clay	0.15	0.29	0.22	0.29	-

Reflection Crack Retardation Tests

A modest laboratory testing programme was conducted to study the reflection crack growth and its control using geogrid reinforcement in asphalt concrete beams. Rectangular specimens of 500 mm x 150 mm x 150 mm were statically compacted using Bitumen of penetration 80/100 following Marshall optimum conditions. Details of compaction etc. are reported in Venkatappa Rao et al. (1991a).

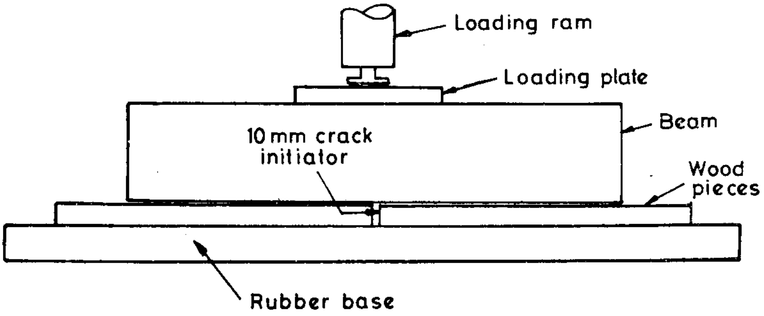


Figure 66 : Test setup for reflection crack retardation tests (after Venkatappa Rao et al. 1991a)

Cyclic loading was used to simulate traffic loading in terms of maximum and minimum limits of loads and frequency. Load cycling limits of 0 – 2.95 kN (300 kg) were used that gave a frequency of 0.87 Hz. The test set up is shown in Fig. 66. Weak subgrade was simulated by a rubber sheet. Old cracked rigid pavement was simulated by two 25 mm soft wood pieces. The crack was represented by a gap of 10 mm between two halves of wooden plates. Figure 67 shows the crack growth of test on a unreinforced beam. Figure 68 shows reflection crack deflection tests in a reinforced beam. Table 14 summarises the observations.

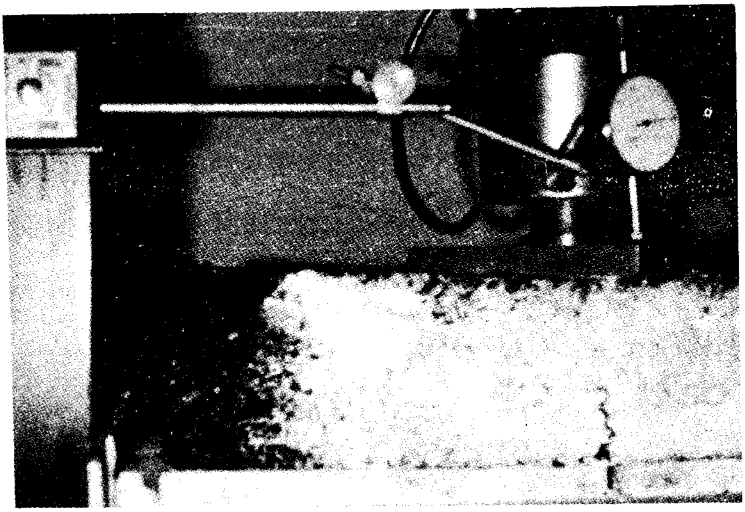


Figure 67 : Reflection crack unreinforced asphaltic beam (after Venkatappa Rao et al. 1991a)

Figure 68 : Reflection crack retardation and deflection of geogrid reinforced beam (after Venkatappa Rao et al. 1991a)

Microcracking occurred in all the beams in the range of 100 to 370 cycles. In the case of unreinforced beam, wide distinct cracks occurred on both beam faces in the stressed zone very early. The crack reached a height of 4.5 cm at only 1500 cycles.

In the case of reinforced beams, microcracks appeared in the same range. However, the cracks were deflected after reaching the lower interface between geogrid and asphalt concrete. This behaviour can be attributed to the presence of stiff geogrid-asphalt concrete layer in the path of the crack which inhibits crack propagation in the vertical direction. The interlock of asphalt concrete in geogrid openings and its confinement facilitates the formation of this stiff interlayer. Once the crack reaches the lower interface of geogrid, the energy at the crack tip is insufficient to fracture the material of the grid. The crack, therefore, takes the path of least resistance and moves along the lower interface until the fracture energy is insufficient for any further progress.

Land Fills

In the recent past, the waste generation rate particularly in metropolitan cities in our country is showing an increasing trend with an increase in population and migration of people to the cities. It emphasizes the dire requirement of Landfills in Indian municipal waste management.

Table 14
Summary of Reflection crack retardation tests

Sl. No.	Beam Designation	Reinforcement Location	Cyclic Loading		No. of cycles to Micro-cracking	Remarks
			Limit, kN	Frequency, Hz		
1.	Control	Nil	0-2.95	0.87	273	Failure at 1500 cycles, 4.5 cm crack height.
2.	2R	0.8d	0-2.95	0.87	263	No change in crack size at 5000 cycles. Test stoped at 5000 cycles.
3.	3R	0.5d	0-2.95 0-3.93	0.87	370	No change in crack status upto 5000 cycles.
4.	4R	0.75d	0-2.95	0.87	223	– do –
5.	6R	0.9d	0-2.95	0.87	100	– do –

d = Depth of beam

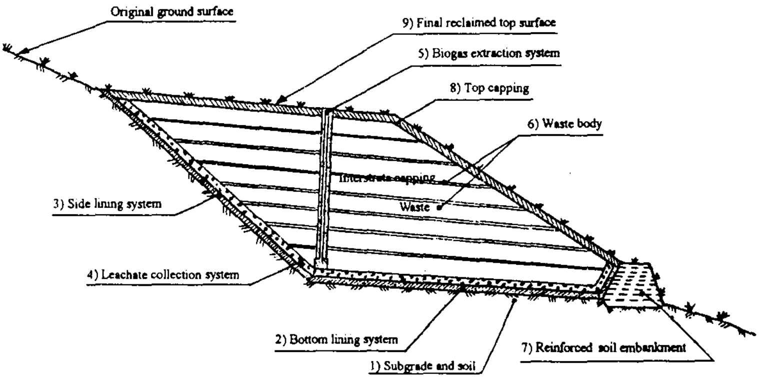


Figure 69 : Typical sanitary land fill

Today, the waste disposal system is done in the outskirts of a city in the form of open dumps, which cause severe epidemic hazards to the inhabitants in the surrounding areas. We also resort to burning the waste. Though this reduces the quantum of waste, but pollutes the atmosphere with the huge amount of organic and inorganic gases. In addition, the leachate in the waste contaminates the ground water sources.

In countries like India, climate will vary substantially between regions as well as between seasons. This, coupled with social differences in the use of conventional heating and cooking resources and facilities, can further complicate the waste arising picture, at least for the composition of wastes. The variation in waste composition and quantity between different states and regions (and even local environment within a region), coupled with often extreme differences in climate, are important factors influencing the type of collection and downstream waste treatment/disposal practices needed. Waste disposal by land filling is the most popular method which is currently in practice in Western countries. It represents the only technology for ultimate disposal of wastes. A typical sloped sanitary land fill is shown in Fig. 69. Geosynthetics play a key role in such land fills.

Evaluation of the Geosynthetic Reinforced Mineral Sealing (Clay) Layers

The lining/liner system plays a key role in forming a barrier between the waste and environment. Out of these the basal lining systems are subjected to heavy surcharge due to waste heaps.

Realising this the geotechnical performance of the clay liner systems were evaluated by Professor Jessberger at Ruhr-University in the Bochum large geotechnical centrifuge. The investigations have revealed that the mineral sealing layers will lose their integrity function with non-uniform

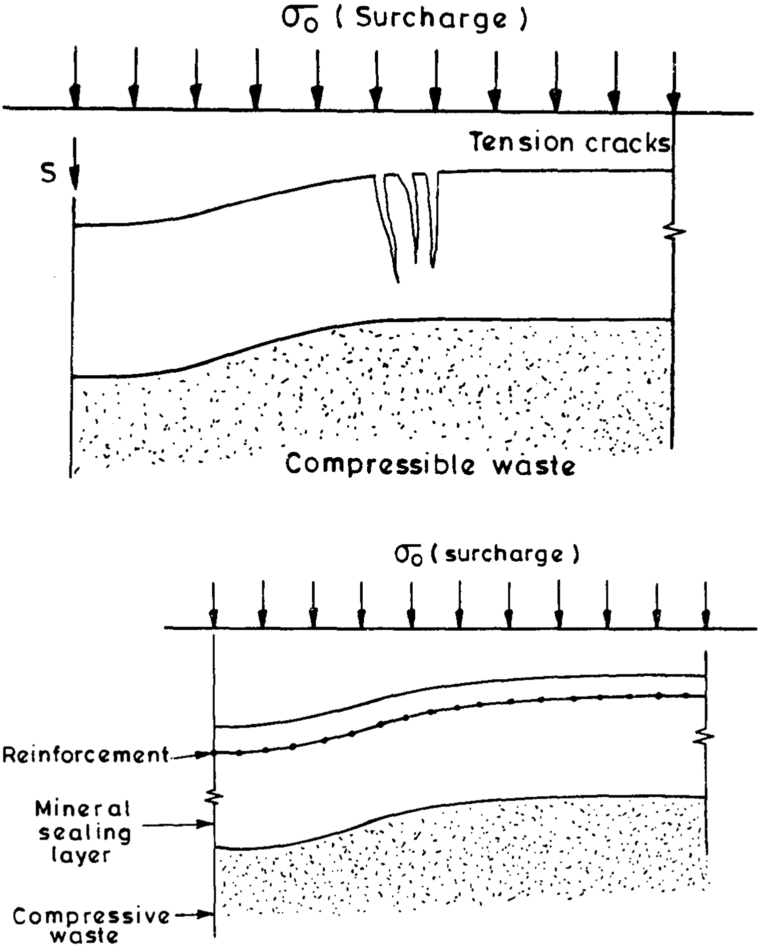


Figure 70 : Deformation pattern of
a) a top mineral sealing (clay) liner
b) a top mineral sealing (clay) liner with reinforcement

settlements, if the liner system is subjected to cracking (Fig. 70a). Presently studies are being concentrated in evaluating the behaviour of surface lining systems with a geosynthetic layer reinforcing the clay liner (Fig. 70b).

Geotextiles with Natural Fibres

Geotextiles with natural fibres such as jute, coir and sisal are emerging as an alternative to polymeric geotextiles for application in temporary or in non-critical structures, where a shorter life span may be adequate.

In view of the inadequate information on the engineering characteristics, biodegradability and the behaviour in different applications, an exclusive laboratory test programme and a field trial were designed on the following natural materials from Indian sources,

i) coir fibre and coir yarns,
ii) woven coir and jute geotextiles,
iii) non-woven coir geotextiles with and without HDPE scrim, and
iv) coir mattings of two different aerial densities.

Characterization of these materials is important as no data exists and standard procedures for testing and evaluation exist. The work conducted by Balan (1995) included an evaluation of

a) the physical characteristics of these materials, and the biodegradability behaviour of coir/jute geotextiles in different soil environment, and

b) the comparative performance of natural fibre strip drains of different types.

Some important observations are :

i) Based on the results obtained from thickness measurements, it is recommended that the thickness of natural geotextiles can be determined as the value corresponding to a normal pressure of 2 kPa after one minute of application of pressure.

ii) The tensile strength of woven geotextiles of coir and jute is generally not influenced by the width, length of sample and the deformation rate used. Based on the results of the extension test results it is recommended that the tensile strength of natural geotextiles can be taken as that corresponding to wide width specimen (200 mm wide × 100 mm length) at a deformation rate of 10 mm/min determined in a constant rate of extension machine.

iii) Accelerated degradation studies on specimens of jute fabric/coir yarn, revealed the fact that the degradation of coir/jute geotextiles is very complex in nature. From the overall behaviour of natural geotextiles in burial and considering the rate of degradation in sand and clay it can be presumed that natural geotextiles of jute and coir can have a life of more than one and two to three years respectively.

Four different varieties of natural fibre strip drains made of non-woven coir geotextiles are core and woven jute/HDPE as filter sleeve has been developed. Their performance in consolidating soft soil was compared with two other varieties of natural fibre drains made of woven jute as filter sleeve and coir rope/jute rope as core. For this along with other testing model tests were conducted to study the efficacy (Venkatappa Rao, Hariprasada Rao and Balan, 1994). Also a drain discharge test apparatus was developed (Venkatappa Rao and Balan, 1995).

Erosion Control

India has about 25% of its geographical area under mountainous terrain. Over 80% of the annual rainfall, occurs from June to October. This leads to flooding causing environmental degradation which in itself is caused by excessive grazing, road construction, mining and unscientific farming practices. This results in an estimated soil loss of the order 6000 million tonne per annum. Thus the importance of erosion control need hardly be emphasized in the Indian context.

The various causes of erosion, the different geosynthetic solutions available are detailed in a recent (1995) publication "Erosion Control with Geosynthetics" by the CBIP. Experiences have been gained in the country in using polymeric geomeshes (at Ghaziabad bypass by UP PWD), gabion mattress underlain by needle punched geotextile (on Gandhar river, Gujarat by GERI), grouted mattress (Kakarpar canal, Gujarat) (Parikh and Shroff, 1989) and in many other ways and locations.

The 1993 Market survey on erosion control materials reveals that 55 percent to 65 percent of them comprise natural material. As India produces around 66 and 44 percent of the world share of coir and jute fibres respectively, India should occupy a pre-eminent position in production, use and international marketing of natural geotextiles.

The ability of natural fibres to absorb water and to degrade with time are its prime properties which give them an edge over synthetic geotextiles for erosion control purposes.

The "drapability" factor of natural geotextiles (due to their flexibility) allows them to conform closely to the terrain, i.e. the ability to follow the contours of the slope and staying in intimate contact with the soil.

Natural geotextiles can be used where vegetation is considered to be the long term answer to slope protection and erosion control. They have a number of inherent advantages:

i) they give protection against rainsplash erosion,
ii) they have the capacity to absorb even upto 5 times their own weight,
iii) they reduce the velocity and thus the erosive effect of runoff, by functioning as series of mini check dams,
iv) they help retain the seeds, even in steep terrain,
v) they maintain humidity in the soil and atmosphere,
vi) they probably mitigate the extremes of temperature and
vii) they biodegrade, adding useful mulch to the soil.

From literature one also notes that erosion control measures with jute based geotextiles had given a good response but the textile degraded after about one year. In the more severe situations, either because of climate or steepness of slope, a longer period of function by the geotextile is required. This is also the case where one prefers to select species compatible with surrounding native vegetation, such species, being inevitably slower growing than the commonly sown productive species used in lowland situations. The combination of slow growth and short growing season may mean that species barely become functional within a season in terms of surface erosion control. Coir based geotextiles provide both the advantages of biodegradable geotextiles and the longevity required where plant establishment might be slow (upto 3 years).

Several successful case studies have been reported by Central Road Research Institute, New Delhi and others in use of jute and coir matting for erosion control in different hill regions of the country.

Jute Geotextiles can be made available in various weights for different applications requiring varying degrees of protection. More varieties are being developed at Indian Institute of Technology, Delhi through a Research Project sponsored by UNDP/Ministry of Textiles, Govt. of India. The materials are also accepted worldwide and are being promoted by International Trade Centre, UNCTAD/GATT, Switzerland. They may also be treated for smoulder resistance where local regulations or fire hazards require such a product.

A study was conducted in Western Ghats (Balan, 1995; Venkatappa Rao and Balan, 1996) wherein coir mattings have been used for erosion control in a rubber plantation. The coir matting could prevent successfully the surfacial erosion of particles along the surface of the slope and helped in sedimentation of soil even on previously exposed rock surfaces, presumably through the action of a series of check dams as mentioned in literature.

Suggestions for Future Research and Development

- There is a need to establish a geosynthetic testing facility with in-house capabilities to test all geosynthetic products - polymeric as well as natural. Though attempts are being made to develop this at IIT Delhi, it further needs strengthening. It is required to understand the durability of the large variety of geosynthetics in the Indian context particularly because of the large variations in the climatic conditions, terrain and the soil.

- Attempts should be made to develop rational design and construction guidelines for reinforced soil walls, reinforced slopes, etc. There is also a need to develop these specifically in relation to the use of geosynthetic reinforced soil wall technique in urban bridge approaches and sound barriers. Methods of controlling the severe erosion on embankments, hill slopes and flood banks need to be studied such that their devastating effect. is minimised.

- The experiences gained in the country need to be well documented and database created. This will help in building up confidence in the use of geosynthetics. It will thus lead to development of relevant standards in the country.

- Jute and coir have tremendous potential in India as well as the rest of the world for environment friendly applications. India being one of the largest producers of such fibres, greater emphasis needs to be paid to research and development on these materials.

- In addition, to save the conventional materials like timber or maximise the use of the enormous quantities of plastic waste being created, the following applications can be effective :

  (i) Used car/scooter tyres can be used to retain the river banks which are prone to flood erosion. These can be tied back with suitable reinforcing elements.

  (ii) HDPE sacks can be filled up with soil to form bags that can be used as facia elements again, to protect flood embankments.

  (iii) Shredded LDPE/PP shopping bags can be used as an admixture to reinforce granular material.

  (iv) Woven slit film bags of HDPE filled with granular material can be effectively used as a replacement for timber sleepers as is being done in Norway and other countries.

Research needs to be focussed on these as well.

Conclusions

Before the geosynthetics can be put to effective use, their characterization is of utmost importance. This has been the primary emphasis of the work carried out - develop/fabricate apparatus for testing and evaluation.

The major findings include –

i) The 'US Corps of Engineers' gradient ratio test which was recommended primarily for non-cohesive soils, needs to be modified to continue until the system is stabilized for soils other than granular soils.

ii) Use of micromesh and oriented reinforcement in foundations improves the bearing capacity. Their contribution towards settlement reduction is only marginal.

iii) The use of geosynthetics in unpaved roads reduces the permanent deformation and increases the modulus of resilience significantly. Geogrid reinforcement results in retardation of reflection cracks in overlays. Thus the selection of the right geosynthetic in a specific site/job should take into consideration the aggregate, subgrade and the expected loading.

iv) A beginning has been made to characterize the jute and coir mattings that are available in India and to develop new products for wider applications.

v) Erosion control can be successfully done by using coir matting.

In the physical and current fiscal environment in India, the scope for geosynthetics is vast. Typically, their use can be in the following :

- Erosion Control
- Land Slide Mitigation
- Urban Bridge Approaches
- Retaining Walls and Steep Slopes
- Land Reclamation
- Sanitary Land Fills
- Waste Retention Structures

In conclusion, it is worthwhile recalling the words of the Father of Soil Mechanics :

> *"Throughout history man has progressively transformed the natural environment.*
>
> *Man can choose how to use technology and by intelligent use can protect the environment without relinquishing progress.*
>
> *Geotechnical research develops in this context: supply of new technology and new geotechnical solutions with minimum environmental impact."*
>
> *Karl Terzaghi*

These words are probably equally relevant in the present context emphasizing the need of the new materials like geosynthetics in the construction of civil engineering structures which provide better environment as well as help build environmental control structures.

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Geosynthetics in the Indian Environment

G. Venkatappa Rao

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From historic times, natural materials like coir, brush wood and timber have been used in the Indian continent to facilitate construction. Modern geosynthetics have begun to appear as engineered materials around only 1985. Today, India is on the verge of take-off for using geosynthetics with more confidence after having had used them successfully in several field trials and also through concerted theoretical understanding coupled with laboratory studies. The lecture focuses attention on the process of development and understanding that has been generated in India over the last decade highlighting the research conducted at IIT Delhi.

After presenting a wide variety of geosynthetics currently available to the civil engineer, the multifarious functions that are performed by geosynthetics are brought forth along with the delineation of the characteristics one looks for in the raw materials. Thereafter, the mechanical property characterisation has been dealt with in detail including the apparatus developed and typical results of geosynthetic products that are currently available in India.

The factors influencing the fabric design of needle-punched non-woven geotextiles have been brought forth in considerable details based upon the investigations carried out jointly with the textile engineers. After bringing out the role of geosynthetics in reinforcement through several series of conventional triaxial tests, the utility of reinforcement in geosynthetic reinforced soil walls and landslide protection is brought out. Also brought out in the subsequent section is the improvement in the performance of pavements with geosynthetic inclusion not only in terms of monotonic loads but also repetitive loads. The results have been confirmed by model testing as well.

From the environmental point of view, landfills for both municipal wastes and hazardous wastes are becoming increasingly necessary in the country. This aspect has been brought forth emphasising the role of geosynthetic reinforced clay lining systems.

With the abundance of natural fibres like jute and coir in the country, they can be put to use effectively after delineating their biodegradation characteristics. This has been brought forth after describing methods of characterisation of such materials which are yet to be standardised in the same way as polymeric products. The role of natural geotextiles in the development of strip drains as well as erosion control is brought forth subsequently.

The lecture concludes with suggestions for future research and development and delineating the scope for geosynthetics in the physical and current fiscal environment in India in terms of their use in Erosion Control, Land Slide Mitigation, Urban Bridge Approaches, Retaining Walls and Steep Slopes, Land Reclamation, Sanitary Land Fills and Waste Retention Structures.

KEY WORDS : Drainage, Erosion Control, Fabric Design, Field Trial, Filtration, Fluid Transmission, Geosynthetics, Landfill, Properties, Reinforcement, Separation.