Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Mathematical modelling for the prediction of properties and performance characteristics of needlepunched geotextiles

T.H SHAH & S. C. ANAND, Faculty of Technology, Bolton Institute, Bolton, UK
V.R. CADDICK, Geofabrics Ltd. Liversedge, West Yorkshire, UK.

ABSTRACT: Relationships between the various factors involved in the manufacture of needlepunched geotextiles, their basic dimensional properties and performance characteristics were developed. Multivariate regression analyses were utilized to formulate empirical models in order to predict the performance characteristics from the basic fabric elements. The main variables employed in this mathematical modelling study were; punch density (PD), depth of needle penetration (NP), web area density (WAD), fabric area density (FAD), fabric thickness (FBT), fabric bulk density (FBD), puncture resistance (CBR), tensile strength in machine direction (TMD) and tensile strength in cross machine direction (TXMD). Statistical analyses of the breaking extension ranges in the machine and cross machine directions were also performed. The empirical relationships developed showed that it is possible to predict the performance of the needlepunched geotextiles accurately on the basis of their fundamental properties, obtained under a given set of fibre, machine and fabric parameters. These mathematical models have been validated for a very wide range of manufacturing parameters and performance characteristics of needlepunched geotextiles.

1 INTRODUCTION

Geotextile fabrics are used in numerous civil engineering applications for reinforcement, filtration, separation, drainage and erosion control. Fabric structures used in geotextiles have evolved considerably over the last forty years. In the early years, simple fabrics such as carpet backings or tarpaulins were used as geotextiles, however, in this day and age, the geotextile characteristics must be adequately defined if they are to be used in any civil engineering application. These materials are required to provide the desired strength and abrasion resistance to withstand installation and application stresses to create effective and long-term solutions (Karl Mayer, 1989).

Geotextiles can be woven, knitted, nonwoven, knotted and composite structures of the various types. However, in the Western world nonwoven fabrics represent over 70% of the geotextile market. Nonwoven geotextiles are made from either extruded continuous filaments or staple fibre webs which are bonded by a variety of techniques. One of the common methods employed in geotextiles is needlepunching of staple fibre webs but the structures obtained are complex, since many factors - such as fibre properties, web characteristics, needling parameters and finishing processes - have a major influence on the final fabric properties and performance characteristics.

Geotextiles are considered to be one of the highest growth areas of the world technical textile market (Byrne, 1997). The average world growth of geotextiles during 1995 to 2005 is predicted at around 8.6%, while the growth is particularly strong in Asia, which is expected to be well above 12%. The size of the global geosynthetics' market, which includes geotextile products, is estimated to be 1.84 million tonnes by year 2005 (www.nonwovens.com, 2001). In 1997, the world nonwoven geotextile market was valued at just under US$800 million, with approximately one billion square metres being shipped globally (Texcon, 1997).

The performance characteristics of geotextiles are greatly influenced by the material of the textile (Wildhaber, 1999) and structural mechanics of the fabric imparted by the manufacturing processes. There are several material/process variables that can influence the performance of a geotextile for a specific application. For example, the most important variables for the production of geotextiles for hydraulic applications are considered to be fibre fineness, fibre length, web type and area density, depth of the penetration of needles and punch density as well as the various finishing processes that can be applied to the fabric. In this research programme we related a number of performance characteristics of needlepunched geotextiles with their basic parameters or elements and the manufacturing process parameters.

2 MANUFACTURE OF NEEDLEPUNCHED NONWOVEN GEOTEXTILES

Needlepunching is a very versatile method for manufacturing nonwoven fabrics. These fabrics are often used as geotextiles and are produced by the penetrating action of barbed needles through a fibrous web, which can be prepared in a variety of orientations (e.g. random, cross, parallel, composite, etc.). The physical action of the needle pushes surface fibres through the web to form fibre plugs or tufts, which are interlocked by the surrounding fibres contained within the web. When sufficient amount of fibre is displaced in this manner, the web is reinforced to form a fabric.

The structure and properties of needlepunched fabrics can be precisely engineered by varying the web, machine and fibre parameters, therefore, it is possible to produce geotextiles having the desired characteristics for a specific application by manipulating and fine tuning these parameters. The effect of web area density on geotextile properties is complicated by the interaction of this variable with other variables such as the needling parameters. Fibre orientation in the web is particularly important in relation to the fabric tensile properties. The choice of optimum parameters to produce the required geotextiles is normally based on experience and trial and error, which is followed by testing of the important fabric properties.

2.1 *Production of Geotextiles on the Industrial Line*

A series of Medium Performance (MP) needlepunched geotextiles were produced on a 6-metre wide, industrial, nonwoven line. The line consisted of a card, cross lapper, a pre-needling machine, and a needlepunching machine with two needle boards to enable simultaneous needling of the web from both sides. The punch density, needle penetration and the web movement were kept constant during the manufacture of these fabrics.

2.2 Production of Geotextiles on the Laboratory Machine

Medium Performance geotextiles were also produced on a 1-metre wide laboratory needlepunching machine. The cross-laid, pre-needled, polypropylene fibre web was made on the above-mentioned industrial line. The web was used to prepare a series of Medium Performance geotextiles on the laboratory machine. In order to study the influence of the main machine parameters – web area density (WAD), needle penetration (NP) and punch density (PD) - on the properties of the geotextiles produced, a wide range of the machine parameters i.e. needle penetration and punch density were employed in the production of these fabrics. The type of fibre, needle type, needle-board design and needle-board density were kept constant for the entire series of geotextiles.

3 TESTING OF GEOTEXTILES

A series of standard tests were performed on all of the geotextiles produced to determine their fabric area density (EN965, 1995), thickness (EN964-1, 1995), puncture resistance (EN ISO 12236, 1996), tensile strengths in the machine and cross machine directions (EN ISO 10319, 1996), and breaking extensions in the machine direction (BEM) and cross machine direction (EN ISO 10319, 1996).

4 MODELLING TECHNIQUE

Multiple regression analysis is a technique that can explore the relationship between several variables. It is a multivariate technique and is an extension of simple linear regression, which can be used to examine the effect of a single variable whilst holding the contribution of the other variables constant.

The simplest relationship between an independent variable and a dependent variable is linear and can be expressed by the following equation:

$$Y = a + bX \tag{1}$$

Where,

Y = predicted value (dependent variable)

X = predictor value (independent variable)

a = the intercept (regression constant)

b = slope or gradient of the line

In multiple regression the equation is of the following form:

$$Y = a + b_1X_1 + b_2X_2 + \text{---------} \; b_nX_n \tag{2}$$

In the general multiple regression equation, the dependent variable is seen as a linear function of more than one independent variables. In the above equation the subscript identifies the independent variables.

After a careful examination of the available data, it was decided to use the multiple regression method to develop the mathematical models to relate the machine parameters, dimensional properties and performance characteristics of the needlepunched geotextiles produced.

5 DEVELOPMENT OF MATHEMATICAL MODELS

Multiple regression analysis was carried out using the SPSS Version 8 software. Several mathematical models were developed to predict the various performance characteristics from the geotextile properties.

5.1 Geotextile Dimensional Properties and Performance Characteristics

The main independent variables employed were: fabric area density (FAD), fabric thickness (FBT) and fabric bulk density (FBD). These variables were selected because these are the basic fabric parameters that describe the amount of fibre contained per unit volume of the fabric. These basic fabric parameters control the fabric's dimensional and mechanical properties, which in turn determine the performance characteristics of the geotextile materials. The dependent variables were: puncture resistance (CBR), tensile strength in machine direction (TMD) and tensile strength in cross machine direction (TXMD). The empirical models obtained are presented in Table1. A part of this work has already been reported elsewhere (Shah et al, 2001).

Table 1. Predictive models based on geotextile dimensional properties and the functional performance characteristics.

Predicted Variable	Regression Equation	R
CBR (kN)	CBR = 0.003FAD + 0.8FBT - 1.0	0.990
TMD (kNm^{-1})	TMD = 0.01FAD + 5.2FBT – 12.8	0.998
TXMD (kNm^{-1})	TXMD = 0.043FAD + 5.4 FBT – 9.0	0.987

The simple linear regression analysis of the data showed that it is possible to make an approximate prediction of the performance characteristic of the geotextile based on any one of the basic fabric elements such as fabric area density. However, these predictions are not adequate to be used as design criteria in any critical application of the geotextile. The multivariate analysis showed that any two of the three fabric parameters (FAD, FBT, FBD) could be used to predict any of the performance characteristics (CBR, TMD, TXMD) of the needlepunched fabrics with reasonable accuracy. However, the empirical models based on the FAD and FBT (Table 1) yielded the most accurate predictions of the performance characteristics for the Medium Performance geotextiles.

Figures 1-3 illustrate the relationships between the measured and predicted CBR, TMD and TXMD values for the Medium Performance geotextiles. The predicted values have been calculated from the equations given in Table 1. The lines drawn at 45^o and the scatter of the points around these lines give good indication of the accuracy of these models.

Jones et al (2000) pointed out the difficulties associated with the specifications of protection geotextiles using the fabric area density as the only criterion. They produced three needlepunched nonwoven geotextiles of similar area density (Table 2) which showed significant differences in their performance characteristics. These results also showed that all three geotextiles exhibited significantly different thickness values. The empirical models developed and reported in this paper clearly show that the fabric thickness is also an important parameter to consider in predicting the performance of the geotextile, produced using the same process and fibre parameters.

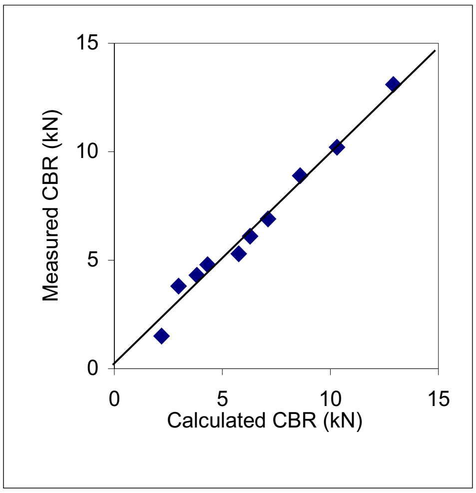

Figure 1. Relationship between measured and calculated CBR values.

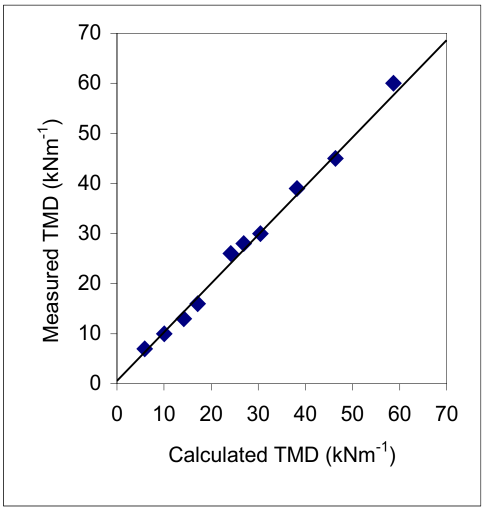

Figure 2. Relationship between measured and calculated TMD values.

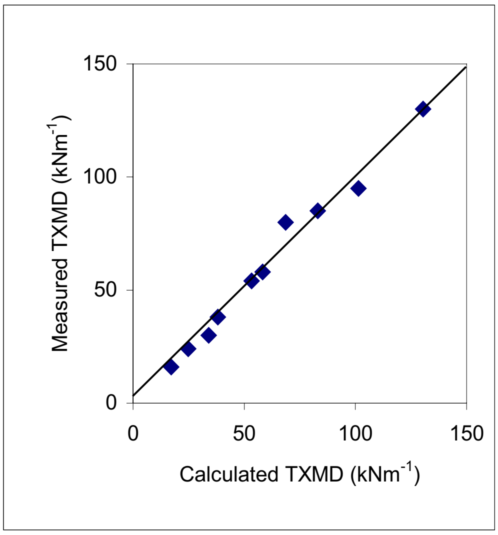

Figure 3. Relationship between measured and calculated TXMD values.

A comparison between the CBR, TMD and TXMD values reported by Jones et al (2000) and those predicted from our empirical models (given in parenthesis), using the area density and thickness values reported by these authors for the Medium Performance geotextiles (geotextile A), show that it is possible to predict the functional properties of these geotextiles from their area density and thickness values with good accuracy.

Table 2. Results of index testing of three different geotextiles of similar area density.

Property	Unit	Geotextile A	Geotextile B	Geotextile C
Mass	gm^{-2}	1000	1000	1000
CBR	kN	11.44	7.97 (7.71)*	7.35
TMD	kNm^{-1}	44	38 (36)*	24
TXMD	kNm^{-1}	110	78 (75)*	66
Thickness	mm	6.22	7.14	11.35

* Values obtained from empirical models developed in this work.

5.2 Geotextile Dimensional Properties and Machine Parameters

In order to determine the effect of the major process parameters (WAD, NP and PD) on the dimensional properties (FAD and FBT) of the needlepunched geotextiles, a series of Medium Performance geotextiles were prepared on the laboratory needlepunching machine as described earlier. The ranges of the process variables used in this modelling study were chosen to incorporate the values commonly employed in the industrial production of the needlepunched nonwoven geotextiles for a wide range of applications. The selected ranges of the three process parameters were: 400-1200 gm^{-2}, 150-350 punches/cm^2 and 8-16mm for web area density (WAD), punch density (PD) and depth of needle penetration (NP), respectively.

Mathematical relationships were developed between the machine parameters (WAD, NP and PD) and the dimensional properties (FAD and FBT). The empirical models developed by multivariate regression analysis, using SPSS software, are given in Table 3.

Table 3. Predictive models based on machine parameters and dimensional properties of medium performance geotextiles.

Predicted Variable	Regression Equation	R
FAD (gm^{-2})	FAD = 1.48WAD + 0.62PD + 26.5NP - 495	0.989
FBT (mm)	FBT = 0.006WAD – 0.0085PD – 0.58NP +10.7	0.973

Web area density (WAD) is considered to be the major contributor to the dimensional properties (FAD and FBT) of the needlepunched fabrics. However, the effect of WAD on the fabric properties is complicated by its interaction with the needling variables. If the WAD is increased under constant needling conditions, then a more open and thicker fabric will result, as more fibres will escape the needling action.

Therefore, it seems that web area density alone cannot provide an accurate estimate of the dimensional properties of the needlepunched geotextiles produced. The influences of the process parameters must be incorporated in the formulation of empirical models in order to predict the dimensional properties of the geotextiles accurately.

The results show that in general the thickness of the geotextile increases with increasing web area density and decreases with increasing punch density and depth of needle penetration values. The fabric area density (FAD) increases almost linearly with WAD. The influence of needle penetration and punch density on the FAD is not as strong as that of WAD, however, the value of FAD increases with increasing PD and NP values.

The accuracy of the empirical models developed for the prediction of fabric dimensional properties was evaluated by plotting the predicted values against the experimental values. The results are illustrated in Figures 4 and 5 for fabric area density (FAD) and fabric thickness (FBT), respectively. These results show that the predicted results correlate extremely well with the experimental data obtained. The excellent correlation coefficient values also confirm the accuracy of the predicted results.

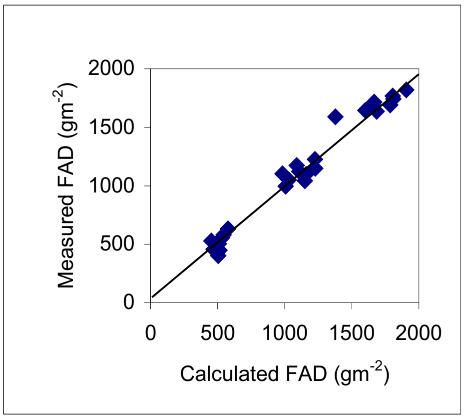

Figure 4. Relationship between measured and calculated FAD values.

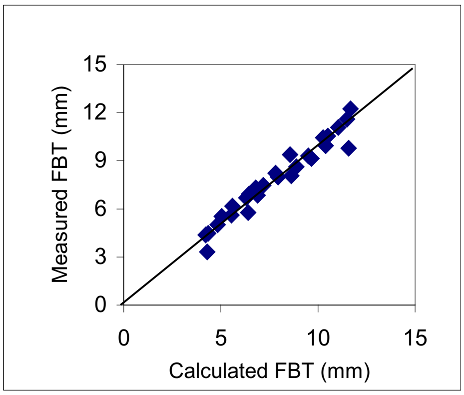

Figure 5. Relationship between measured and calculated FBT values.

6 ANALYSIS OF THE BREAKING EXTENSION VALUES

The breaking extension values of the Medium Performance fabrics followed a somewhat different pattern of behaviour as compared to the CBR and tensile strength values. The breaking extensions exhibited a very narrow range for fabrics having a very wide range of area density values. For example, for Medium Performance fabrics with fabric area density range of 200 to 2000 gm^{-2}, the breaking extension values varied between 140% - 160% and 90% - 120% in the machine direction and cross machine direction respectively. The data suggested that the mean breaking extension values could represent the actual breaking extension values for the Medium Performance needlepunched geotextile. In order to confirm this hypothesis, Student's t test was applied to the breaking extension data. The results given in Table 5 show that the calculated t values for the breaking extension - in machine (BEM) and cross machine (BEX) directions – for both series of fabrics.

The calculated t values for BEM and BEX are well below the expected value of 2.4, a value that must be reached at 5% significance level for nine degrees of freedom. This means that the differences between the individual and the mean values are not significant and could have arisen due to experimental error, therefore, the mean percentage breaking extension values of these geotextiles can represent the breaking extension ranges obtained in both in machine and cross machine directions.

Table 5. Significance of the range of breaking extension values for medium performance (MP) geotextiles.

Value	BEM	BEX
Range (%)	140-160	90-120
Mean (%)	149.5	100
Degrees of freedom	9	9
Expected t value for 5% significance	2.4	2.4
Calculated t value	0.55	1.8

7 CONCLUSIONS

It has been established that the models based on the fundamental fabric properties – area density and fabric thickness – are quite effective for predicting the fabric performance characteristics, such as CBR puncture resistance and tensile strength, of the needlepunched geotextile fabrics. The models developed for the prediction of the dimensional properties of the geotextiles, based on the process parameters employed in their production, also exhibited good accuracy and were validated for a wide range of medium performance geotextiles. The overall objective of this research is to develop computer-based expert systems for the prediction of durability and performance characteristics of geotextiles manufactured by the needlepunching process.

8 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support and cooperation provided by the Department of Trade and Industry UK, Geofabrics Limited, Liversedge, UK and Bolton Institute, UK.

9 REFERENCES

Byrne, C. 1997. Techtextil – Symposium, Germany, 12th May .

EN 965. Geotextiles and geotextile related products, Determination of mass per unit area.

EN 964-1:1995. Geotextiles and geotextile related products, Determination of thickness at specified pressures part 1- single layer.

EN ISO 10319. 1996. Geotextiles and geotextile related products, wide width tensile test.

EN ISO 12236. 1996. Geotextiles and geotextile related products, Static puncture test (CBR test).

Jones, D.R.V; Shercliff, D.A; Nixon, N. 2000. Difficulties associated with the specifications of protection geotextiles using only unit weight. Proceedings of the Second European Geosynthetics Conference, Bologna, Italy, October,Vol. 2, pp.551-555.

Karl Mayer Textilmaschinenfabrik GmbH. 1989. The Karl Mayer Guide to Geotextiles, Germany.

Nonwovens.com/facts/markets/geotex.htm . 2001.

Shah, T.H; Subhash, S.C; Caddick, V.R. 2001. Prediction of properties and performance characteristics of needlepunched geotextiles by mathematical modelling. Proceedings of the Textile Technology Forum, IFAI Expo 2001, Nashville, USA, October.

Texcon Conference proceedings, Ahmedabad, India, 15th Dec. 1997.

Wildhaber, J. 1999.Geotextiles – attributes, applications, and manufacture, Nonwoven Industrial Textiles, November, 46.