Review Article

Bulk and physical properties of needle-punched nonwoven fabrics

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Bulk and physical properties of needle-punched nonwoven fabric depend on the nature of component fibre, the manner in which the fibres are arranged in the structure and the degree of consolidation. A proper understanding of the role of different parameters on fabric properties is important for designing the fabric suitable for its use. Normally, the longer and finer fibre in the web leads to greater fabric strength, provided the fibre breakage is controlled. The increase in needle density and penetration improves the fibre consolidation, but beyond a certain limit the fibre damage becomes greater, leading to deterioration in fabric characteristics. Higher fabric weight and introduction of scrim generally improve the functional properties of fabric. Finishing operation is opted in the cases where some special requirements are to be fulfilled. This paper is intended to develop some understanding about the bulk and physical properties in relation to raw material, machine parameters and process variables.

Keywords: Air permeability, Bending length, Compressional properties, Fabric density, Needle penetration, Needle-punched fabric, Needle punch density, Tenacity

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1 Introduction

Bulk and physical properties of fabric determine fabric performance during use and fabric serviceability. Physical properties of fabric are directly or indirectly influenced by the bulk of the material, whereas bulk properties have direct relationship with thermal and compressional behaviour of fabric. The properties of nonwoven products differ widely from one another, because of the wide variety of available fibrous raw materials and many possible methods of locking or bonding the basic fibrous webs. The finished nonwoven fabrics are designed for specific end uses and therefore, the selection of fibre type, binder system, technique and equipment used in their manufacture determines their characteristics. Out of various manufacturing techniques of nonwoven fabrics, needle punching is the second most popular technique after spunbonding and widely used in various engineering applications. The world produced 1.1 million tonnes of needle felts in the year 2000, of which 800,000 tonnes (~35%) needle felts used new fibres and the rest used reclaimed and recycled fibres. The use of new fibres is increasing and it is expected that by the year 2005, the usage of new fibres in needle felts will reach 1 million tonnes and by 2010 this will rise to 1.16 million tonnes. The characteristics and production of needle-punched fabric can be easily distinguished from the other type of fabrics.

Needle-punched fabrics tend to fall into 12 general categories: geotextiles, automotives, filtration, medical, apparel, papermaker’s felt, marine, industrial, sports, home furnishings, aerospace and of course the dreaded other category, e.g. agriculture textiles, heat and sound insulation. Because the needle punching industry is so diverse and multifaceted, there are many niche market possibilities for which needle-punched products can be produced. There are numerous quality parameters related to end use application of needle felt fabric. In this paper, only bulk and physical properties of nonwoven fabric in relation to process and raw material variables have been reported.

2 Properties of Needle-punched Nonwoven Fabrics

The properties of needled fabrics depend on the nature of component fibres and the manner in which fibres are arranged in the structure. Fibre properties, such as dimension, mechanical and surface, have both direct and indirect effects on fabric properties. Fibre
properties along with the various machine and web parameters contribute to the structure that emerges from the needling operation. The relationship between various factors is shown in Fig. 1. Factors which influence the properties of needle-punched fabric are given below.

**Raw material variables**
- Fibre type
- Fibre length, fineness, cross-section, crimp, contour
- Mechanical properties of fibres

**Web characteristics**
- Orientation of fibre in the web (parallel-laid, cross-laid or random-laid)
- Web weight and uniformity
- Presence of scrim

**Machine design parameters**
- Needle density on board
- Pattern arrangement of needles in the needle board
- Type of needle/needle shape, size, number of barbs
- Single or both sided needling
- Pre-needling/finish needling
- Straight/inclined punching/elliptical needling
- Special arrangement for pattern fabric

**Machine variables**
- Needle punch density
- Needle penetration
- Entry and exit speeds

**Finishing**
- Heat setting
- Calendering
- Chemical bonding
- Coating
- Lamination

Fig. 2 shows a schematic diagram of needle punching machine. Bulk properties of fabric are dependent on porosity and pore structure of needled fabric. Porosity level of needled fabric is fairly high and fabric possesses a wide pore size distribution. Further, they are multi-dimensional and inter-connected in a fibrous network. Various properties of fabric are related directly or indirectly to the pores present in the fibrous material. The pore size can be defined in many forms, e.g. its volume, surface area, maximum diameter, equivalent diameter, average diameter and minimum diameter. Each of the above dimensions may be critical in certain end use application. Pore volume is the dominant factor that determines capacity for liquid uptake. Pore structure of nonwoven fabrics has strong dependence on the fibre characteristics, web weight and process variables. However, there is lack of investigation on the influence of various factors on pore structure.

In case of needle-punched fabric, the slippage of fibres is a dominating factor in the deformation of fabric, influencing its tensile behaviour. The physical properties of needle-punched nonwoven fabrics are directly or indirectly affected by bulkiness of fabric. The later parameter is inversely proportional to the fabric density. From the measurement of fabric thickness and weight per unit area, the fabric density can be calculated using the following relationship:

\[
\rho_w = \frac{F_w}{L \times 10^3}
\]

where \(\rho_w\) is the fabric density (g/cm\(^3\)); \(F_w\), the fabric weight (g/m\(^2\)); and \(L\), the fabric thickness (mm).

Selection of machine and finishing process depends on the quality and characteristics of final product. For a given set-up, the properties of needled fabric are governed by raw material, web characteristics and process variables. A proper understanding of the effect
of different parameters on fabric properties is important for designing the fabric suitable for its use. However, the engineering of fabric properties, in some cases, is very difficult. High strength combined with softness is one of the most difficult property combinations to achieve, because the geometrical factors that permit high strength also lead to increased stiffness. Consolidation of needled fabric, fibre characteristics and its orientation influence the above parameters very strongly. In some cases where fabric undergoes mechanical and chemical finish, the bulk and physical characteristics change significantly. By heat setting, the dimensional stability of the fabric improves. Change in surface characteristics can be obtained by calendaring, coating and lamination. To strengthen the needled fabric, it can also be chemically bonded. However, in some situation where use of chemically bonded nonwoven fabric is not advisable, e.g. bandage material, the needle-punched fabric is thermally bonded. In a particular finish operation, process variables (calendering pressure, temperature and time) have strong influence on the said characteristics. In a study\textsuperscript{24}, the influence of calendar roller pressure and heat setting on nonwoven filter fabric is found to be very significant. With the increase in calendar roller pressure, the fabric thickness and air permeability decrease up to a point and thereafter they remain nearly constant. Heat setting brings down the thermal shrinkage and therefore the optimum heat setting time is desirable. The thickness and air permeability of fabric increase after heat setting. In nonwoven moulded automobile carpets, needle-punched fabric is coated with acrylic binders to improve its strength. After curing, the fabric is laminated with LDPE powder or film to enable its moulding. It is observed\textsuperscript{25} that the time for pre-heating and pressing in moulding are critical factors affecting quality of moulding. They are determined by the type of fibre, basis weight of the carpet and type of binder.

2.1 Effect of Web Parameters

The web parameters that affect the properties of needle-punched fabric include fabric weight per unit area, fibre orientation in the web and web composition. The composition of web includes type of fibres, cross-section, length and fineness.

2.1.1 Fibre Type

The nature of fibre has a considerable influence on the behaviour of fibres, during both processing and use\textsuperscript{26-28}. The effect of fibre type (rayon, acrylic fibre, wool, jute and cotton) on the properties of needled fabric shows that some fabrics exhibit stick-slip behaviour in extension and others deform smoothly. The rayon, acrylic, jute, jute/polypropylene and jute/viscose fabrics show stick-slip oscillations, whereas cotton and wool give smooth curves with no noticeable vibrations. The stick-slip behaviour of the needled fabric during extension can be related to the frictional properties of its constituent fibres\textsuperscript{10,28-30}. Rayon webs consolidate more easily on needling than acrylic or wool webs\textsuperscript{28}. Comparison of fabric stress-strain curves shows that the wool fabric has the greatest extensibility and the rayon fabric possesses maximum stiffness and strength\textsuperscript{10,20}.

2.1.2 Fibre Cross-section, Length and Fineness

To bring out some desirable characteristics in synthetic fibres suitable for end use, the fibre manufacturers usually modify chemical and physical structures of the existing popular fibres. As a result, many more variants, such as conjugate fibres, low and high shrink fibres, hollow fibres, split fibres, fibres with trilobal, multilobal and other profiled cross-sections and micro fibres, are available for use in needle-punched nonwoven fabrics.

Hollow fibres have tubular cross-section which results in increased bulk followed by trilobal and normal round fibres\textsuperscript{31}. Greater surface area is also responsible for lower effective density, thus providing a higher cover power. Use of hollow fibres in geotextiles, air filters and nonwoven carpets is already claimed\textsuperscript{32}.

Debnath et al.\textsuperscript{33} found that the fabric thickness is minimum for hollow fibres fabric and maximum for trilobal fibres, which is due to the low crimp frequency of hollow fibres. It was also observed that the hollow fibre fabrics have higher air resistance owing to their closer packing, effectively reducing the air gap in the fabric. But in case of trilobal fibre fabric, the higher bulk and protrusion of lobes in the fibre prevent close packing of fibres in the fabric, resulting in higher air space and reduced pressure drop. However, in a later study\textsuperscript{34}, it was reported that the hollow fibre fabric exhibits higher air permeability followed by trilobal and normal round fibre fabrics. This contradiction with earlier finding is due to the dominance of fabric density which is lowest in hollow fibre fabric.

Hollow fibre fabrics show higher tenacity at each level of fabric weight followed by trilobal and round fibre fabrics respectively\textsuperscript{33,34}. This is due to the following two factors: (i) the higher bulk of hollow and
trilobal fibres provides higher surface area, which, in turn, increases the fibre cohesion, and (ii) the higher tenacity of hollow and trilobal fibres compared to that of round fibres gives less breakage of fibres during needling, resulting in corresponding increase in strength. Apart from that, the stronger fibre is expected to produce stronger fabric. It was also reported that the hollow fibre fabric exhibits highest breaking elongation and bursting strength followed by trilobal and round fibre fabrics. However, at any level of fabric weight, the trilobal fibre fabric shows highest abrasion resistance followed by round and hollow fibre fabrics. Fabric made from trilobal polyester fibre requires more needling density, and higher depth of needle penetration and weight or any of these parameters to obtain the same effect of bending stiffness as in case of normal polyester fabric.

Fibre friction influences the properties of needled fabric in two ways: high friction leads to greater consolidation as more fibres are pulled down, and greater resistance to slippage in the resulting needled fabric. Fibre length plays a very important role in the tenacity of needled fabric. Lunenschlos found that the longer fibre lengths result in higher strength, higher felt density and less air permeability. A small increase in length causes a marked increase in stiffness and strength, owing to the reduced effect of slippage at fibre ends. Because of lower mobility of fibres in the fleece, a greater fibre length always produces greater thickness. The effect of fibre length is amplified by higher punch density and lower fleece mass.

The effect of fibre fineness on the bulk and physical properties of nonwoven fabric is significant. The dimensional stability is reduced and since the fibres are more compressible, the thickness is also reduced. Finer fibre fabric results in lower air permeability than coarse fibre fabric. This is because, with the increase in fineness, there is an increase in total number of fibres present, which, in turn, increases the total surface area of the fibres, exposed to the flowing air. Further, due to greater consolidation during needling, the magnitude of air resistance increases. Use of finer and longer fibres will lead to greater fabric strength, if fibre damage is avoided. In a later study, it was observed that the fabrics made from fibre of intermediate fineness (3.3 dtex, instead of 1.3 dtex and 6.6 dtex) result in improved mechanical performance in terms of tenacity, abrasion resistance and bursting strength. However, the breaking elongation of fabric decreases as the fibre becomes finer.

In some filtration and drainage applications of geotextile material, layered nonwoven fabric performs better than a single fibre fabric. The compressibility and per cent energy loss increase initially with the increase in finer fibre content and then decrease as the percentage of finer fibres is further increased in a layered fabric. However, in case of single fibre fabric, the compressibility and per cent energy loss increase, but after a certain level, these parameters start decreasing with the increase in fibre linear density. The number of compression recovery cycle has marked effect on the compressional and related parameters of fabric.

### 2.1.3 Web Orientation

Fibre orientation in the web is particularly important in relation to fabric tensile properties. Aerodynamic random-laid webs produce a more bulky and balanced structure with regard to fibre orientation distribution. In a study on needle-punched parallel-laid jute fabrics, it is found that the fabrics have considerably higher strength in machine direction than in cross-direction and 45° to the machine direction. Parallel-laid fabrics tend to have more bending length in machine direction as compared to cross-laid fabrics. More fibre orientation in machine direction and high compactness of parallel-laid structures are responsible for this. However, the bending length in cross-direction is more for cross-laid structures as compared to parallel-laid structures because the predominant arrangement of fibres in machine direction makes their bending relatively easier in cross direction. For cross-laid webs, the bending length in machine direction is less than that in the cross direction. This is because of the fact that more fibres are oriented in cross direction, which increases the flexural rigidity and thus the bending length in cross direction. Parallel-laid fabrics have lower values of air permeability and thermal resistance than cross-laid fabrics because the arrangement of fibres in parallel-laid fabrics makes the fabric structure more compact so that it holds less air and offers more resistance to the flow of air. In another observation, air permeability of random-laid fabrics is found to be higher than that of cross-laid fabric because of the larger number of pores in random-laid fabrics.

### 2.1.4 Web Weight per Unit Area

Normally, a thicker and looser structure is obtained if the web weight is significantly increased without altering the needling program. This is because more fibres are able to evade the needling action. Naturally,
if the punch density and needle penetration are increased, stronger structures are produced from greater web weights since more fibres are located within the fabric. After a certain weight, there is a decline in the properties because of the greater fibre breakage, since the thicker web provides more resistance to needling passage. Thus, an increase in web weight does not guarantee an improvement in fabric properties. The choice of web weight is determined by thickness, strength and resilience required for different applications. In a study, it was observed that with an increase in basis weight, the tenacity initially increases and then either the rate of increase slows down or the tenacity decreases (Fig. 3), whereas the initial modulus increases (Fig. 4). This might be attributed to the fact that the tenacity of nonwoven fabric increases with the interlocking of fibres at a constant needling density and depth of needle penetration and thereafter the tenacity is reduced with increased web weight at constant needling parameters due to non-interlocking of fibres. Up to an optimum weight for a given depth of needle penetration, the contribution to tenacity by the increased number of fibres in the vertical peg is able to outweigh the reduction in tenacity caused by the increased fibre breakage. Beyond this optimum weight, the fibre breakage is probably excessive and results in drop in tenacity.

In general, fabric density increases with the increase in fabric weight per unit area. Firstly, due to the consequent increase in fabric thickness, both the effective distance of barb penetration and the effective number of barbs penetrating the web become higher, leading to greater fibre entanglement. Secondly, the heavy weight web provides a higher frictional resistance to the movement of punched fibres and thus increases the forces impacting the fabrics. At the other extreme, a very light web, which contains only two or three layers of card web, would provide almost no frictional resistance and would not consolidate appreciably on needling. Thermal insulation of fabric increases with the increase in basis weight of fabric due to the consequent increase in fabric thickness. However, warmth to weight ratio decreases with the increase in fabric weight per unit area. This is because of the more consolidation of heavier webs, leading to lower increase in thermal resistance value in relation to the increase in weight per unit area of the fabric.

Further, as the basis weight increases, there is drop in air permeability. The increase in fabric weight, besides increasing the number of fibres present, also increases the density of the fabric. The increase in density decreases the diameter of channels in the fabric, subsequently presenting a higher resistance to the flow of air. Further, the increase in thickness of the fabric also attributes to increase in airflow resistance. The relationship between air permeability and weight per unit area can be established using the following equation:

$$P_a = \frac{K_1}{W} + K_2$$
where $P_a$ is the air permeability; $W$, the weight per unit area; and $K_1$ and $K_2$, the constants for needle-punched fabrics ($K_1 = 1.75 \times 10^4$ and $K_2 = -6.6$).

To study the effect of fabric and fibre properties on fabric air resistance, following equation is derived using stepwise multiple regression:

$$r = 15.73 + 141.1m - 0.012 \frac{h^3}{(1-h)^2} + 29034 \frac{t}{d}$$

where, $r$ is the air resistance (Nsm$^{-3}$); $m$, the weight per unit area of the fabric (kg/m$^2$); $h$, the porosity of the fabric; $d$, the fibre fineness (dtex); and $t$, the thickness of fabric (m).

Using the above empirical equation, the fabric can be designed according to required air permeability. In another work, the artificial neural network (ANN) and empirical models have been developed to predict the air permeability of jute-polypropylene needle-punched fabrics with varying blend ratio, fabric weight and needling density.

Breaking elongation of the fabric decreases with the increase in fabric weight. The initial decrease is attributed to the better compactness of fibres causing reduced slippage and thereafter the decrease may be attributed to the fibre breakage which reduces fibre length and hence fibre-to-fibre cohesion. The increase in web weight also leads to increase in abrasion resistance and bursting strength and decrease in compressional resiliency of fabric.

By transporting fibres from the horizontal to the vertical plane in a carded web, needles cause a mechanically interlocked fabric. The manner of this transfer is of interest together with the forces generated on needles during punching and the resultant effect of needle wear. It is found that some fibre extension occurs during reorientation along with the slippage, which allows fibre movement. Studies on viscoso webs show that the punching force is representative of the fibre pick up. The punching force starts declining at high needle penetrations due to the fibre breakage and is higher at the front of the needle board than at the back. The forces generated through needling are the result of stiffness of fibres, number of fibres within each tuft, depth of needle penetration and coefficient of friction between fibres and steel. By the application of suitable fibre finish, it is possible to minimize friction between fibre and steel and to change intrafibre friction. This greatly assists in reducing needling forces and fibre damage.

### 2.1.5 Effect of Reinforcing Material

Incorporation of a scrim, which is a light weight, open weave and coarse fabric, into the centre of web provides additional strength. Higher fabric density in case of fabrics having reinforcing material is due to the presence of woven structure, which helps in better locking of fibres and less bouncing back of fibres during consolidation. Thermal insulation decreases in the presence of reinforcing material because better entanglement of fibres causes the thickness of fabric to reduce. It is observed that the presence of scrim causes reduction in air permeability of nonwoven fabrics again due to the better consolidation of fibre with the presence of scrim, which itself resists air flow. The use of reinforcing material causes higher tenacity at break, abrasion resistance and bursting strength, and lower breaking elongation.

Further, the type of reinforcing material and its position in the web also affect the fabric properties. In a study on jute floor covering, it was observed that the air permeability is greater when an open construction of the reinforcing material is used. Further, air permeability is higher when the reinforcing material is used at the centre of the web than at the base. Since more number of barbs pierce through the reinforcing fabric when placed at the centre of the web than at the base for a given depth of needle penetration, the fabric is subjected to greater damage by the action of needles, which, in turn, leads to higher air permeability.

### 2.2 Effect of Machine Variables

The most important machine variables are depth of needle penetration and needle punch density; others being the type of needle, barb size and number of passages. For a given needle, the fibre movement through the web depends on the depth of needle penetration and the degree of entanglements depends on the needle punch density. The effect of needling appears to create ‘pegs’ in the fabric, these pegs comprise vertical fibres surrounded by horizontal fibres. The horizontal fibres are either by-passed by all the needles or are the connecting parts of fibres between the pegs. The pegs are created by the needles, and their size depends on the original web thickness, amount of needle penetration, and needling density. The pegs influence bulk and mechanical properties of needle-punched fabric.

#### 2.2.1 Depth of Needle Penetration

Depth of needle penetration is usually defined as the distance by which the needle point passes below
the top surface of the loom bedplate. If the distance of separation of the loom plates is subtracted from the sum of the barb penetration and the distance of the first barb from the needle point, the depth of needle penetration is obtained. Here, barb penetration means distance of the first needle barb below the under surface of the stripper plate when the needle board is at its bottom most position (Fig. 5). Barb penetration \(b\) can be expressed by the following equation:

\[
b = (t + d) - y
\]

where \(b\) is the barb penetration; \(t\), the distance between two loom plates; \(d\), the needle penetration through the bed plate; and \(y\), the distance of first barb from the needle end.

The effect of depth of needle penetration on the fabric structure depends on the number of barbs that pass into the web and the distance traveled by barbs through the web. The actual vertical distance where a particular fibre is transported by barbs depends upon the thickness of web, position of fibre in the web, position of barbs on the needle and depth of barb penetration.

During the needling process, the fabric gets stretched. This stretch may increase with the increase in amount of needle penetration. The needle penetration not only determines the amount of fibres being taken up by the needle barbs but also the extent of the movement of fibres. With higher needle penetration, the fabric becomes more stretched and needling is also more likely to cause fibre breakage. Fabrics made by the finer needles stretch less compared with those made using coarser needles. With coarse needles, more fibre breakage due to the large barbs causes more stretching. A decrease in fabric thickness with increased depth of penetration is also observed, which is due to the reorientation of fibres and the greater pressure exerted on fibres remaining in horizontal plane by the fibrous arcs between adjacent tufts as they are pulled further into the web. This will cause a compression of the web and a consequent increase in density. Depending on fibre orientation, the fabric made using finer needle causes less breakage owing to the smooth barbs. Two important barb quantities which affect fabric dimensional changes are the undercut angle and barb depth (Fig. 5).

There is large variety of needles which are different in size and shape. Most commonly used needle is a triangular needle with nine barbs on three-sided working area. General needle shape and dimensions have become fairly standard but barb design is the area in which most developments are taking place. Universal use of long standing chiseled barb onto the apices of a triangular blade section is constantly being threatened by more advanced shaped barbs. Further, the nine-barb needle is not always necessary for producing maximum fabric tenacity, which can be achieved using fewer barbs at higher depth of penetration. Thick webs may need nine-barb needles to provide the necessary compaction for the production of a usable fabric, and thus the web weight should be considered before selecting the number of barbs on a needle for a particular purpose. It is observed that the needle itself plays some role in causing fibre reorientation, since it has been found that even using needles without barbs increases the strength of fabric as they are pushed through the web. Compared to vertical needle punching, oblique needling results in better strengthening of the fibrous web since the needles penetrate through a longer path and there is more thorough entanglement of the fibres. Fabrics produced by double-sided oblique needling have greater tenacity, lower breaking extension and higher density with lower air permeability than fabrics produced by single-sided perpendicular punching. Needle punching of the web in longitudinal direction and with hot needles are also claimed.
With a low needle penetration, the punched loops do not protrude from the bottom surface of fabric. However, when the needle penetration is large, fibre tufts are punched out below the fabric surface. Fabric density increases with the increase in needle penetration, because the increased needle penetration leads to an increased number of barbs penetrating the web and causes the web to become more consolidated, resulting in high density. It is observed that the heat transfer coefficient increases with the increase in fabric density. Further, as the depth of needle penetration increases, the thermal resistance of fabric decreases.

Air permeability decreases with the increase in needle penetration, since a consequent increase in compactness of fabrics offers more resistance to air flow. But at much higher levels of needle penetration, the air permeability of the fabric increases due to the greater number of fibre breakage and increase in size of pegs.

In another observation, the interaction effect of fabric weight and needle penetration on air permeability is observed. Air permeability decreases with the increase in needle penetration at a higher level of fabric weight, but at a lower level of fabric weight, the permeability first decreases and then increases. Due to the interaction between needling density and needle penetration, the permeability decreases with the increase in later parameter at lower value of needle density, but it increases and then decreases at higher level of needle density.

Fig. 4 shows that as the depth of penetration is increased, the initial modulus of fabric increases because the more number of fibres get reoriented into the vertical structure. These larger vertical tufts resist fibre movement during initial fabric extension, which results in higher load and consequently higher initial modulus. Tenacity of the needle-punched fabric first increases on increasing the needle penetrations and then decreases sharply. The number of fibres in a vertical unit increases with the increase in depth of needle penetration and leads to better entanglement and consolidation of the structure, which provides a higher fabric strength. After certain level of needle penetration, the decrease in tenacity is observed due to the occurrence of fibre breakage, leading to damage of the fabric structure.

On increasing the needle depth, the bending length initially increases up to a certain extent and then decreases. At less needle depth, since the fibres are not to be pulled so much into the vertical structure, lower bending length is obtained. Higher needling density restricts fibre mobility during bending and this, in turn, results in higher bending length. An excessive needle depth and/or needling density results in severe fibre breakage, which leads to poor stiffness.

Figs 6 and 7 show the effect of depth of needle penetration and needle density on the compressibility and recovery of 6 denier cross-laid hollow polyester needle-punched fabrics.
It is observed that as the depth of needle penetration increases, the compressibility decreases but recovery increases at all stages of punch density. This is due to the higher entanglement and web consolidation as the depth of penetration increases.

2.2.2 Needle Punch Density

The needling density affects the compactness of fibres in the web structure as a result of repeated penetration of punching needles. The specific number of punches per square centimeter is the product of machine strokes per centimeter of web advance and the number of needles per centimeter of working width. The punch density (the number of punches per unit area) is calculated using the following relationship:

\[ P_d = \frac{S \times N}{A_d} \]

where \( P_d \) is the punch density (punches/cm\(^2\)); \( S \), the number of strokes/min; \( N \), the number of needles/cm working width of the loom; \( A_d \), the amount of advance/min (cm).

It is known that in a needle punching machine, the needles follow repeatedly the same points of pre-needled batt/fabric by the movement of needle board. This creates a patterning appearance called tracking on the fabric. When a fabric achieves same punch density by higher number of passes (by decreasing the strokes/min), the chances of tracking formation minimize, because the chances of superimposition of the points selected by the rows of needles are less. Thus, the needle density will be well distributed with higher number of passes. However, the higher passes also lead to heavy breakage of fibres, since the fibres of the compact fabric experience severe needling force.

An increase in amount of needling decreases the fabric weight produced from a particular web weight. The decrease in fabric weight is due to the drafting and spreading of fibres during punching, which increase with the amount of needling. This reduction in fabric weight may be partly due to the increase in length because of the drafting action, as the web is dragged through the needling zone between the bedplate and the stripper plate. It is partially due to the recovery of fibres pulled down by the needles into the holes in the bedplate. When the needles are withdrawn, they will tend to pull the fibres up again and the recovery forces will lead to the spreading of web. The percentage reduction decreases with the increase in weight, probably because the heavy weight webs develop a higher frictional resistance to spreading.

As the number of needle penetrations is increased, the thickness of fabric for the same basis weight decreases due to the increased fibre locking. This, in turn, resists the fibres to bounce back to their original position when the needle is withdrawn. In certain cases, thickness may start increasing on increasing the needling further, which is due to the reason that with the excessive number of needling density the fibres break and protrude on the surface of fabric, showing greater thickness. Moreover, the tendency of fibres to bounce back improves with the excessive needling density.

Fabric density increases with increased needling density but after certain amount of needling the fabric density falls. The rise in density with needling density is due to the better interlocking of fibres within the fabric. The fall in density with higher needling is attributed to the increased number of pegs and spreading of fabric. Heat insulation properties of the fabrics go down after an initial increase as the number of needle penetrations is increased. This is because the structure becomes more compact and therefore holds less air, which reduces the insulating properties. For the same reason as cited above, the heat transfer coefficient goes up as the number of needle penetrations is increased. Heat insulation properties of the needled fabrics are considerably better than the woven fabrics of the same weight.

Air permeability decreases with the increase in needling density within a limit because of the increasing entanglements between the fibres, but beyond that limit with the increase in needling density fibre damage occurs, which leads to holes in the fabric consequently increasing the air permeability. In a study on virgin polypropylene and jute blend, it was observed that with the increase in needle density, the air permeability increases at lower fabric weight but it decreases at higher fabric weight.

In an experiment by Hearle et al., the rate of loss in weight during the abrasion of woollen needled fabrics was measured and it was found that after an initial rapid rate of loss, there was a decrease in weight, which was prominent in heavily needled fabrics, followed by another period of rapid loss. As the number of penetration increases, the abrasion resistance increases linearly and the softness decreases. The fabrics with soft handling properties have poor abrasion properties and vice versa.
The stress-strain curves of needled fabrics are influenced by the amount of needling. The more highly needled fabric shows more coherence and strength. At first, the modulus, tenacity and breaking extension increase with the increase in amount of needling, but at high needling the modulus and tenacity begin to decrease. The initial increase is due to the increase in entanglement, while the fall must be due to tearing of web and breaking of fibres. Optimum needle punch density is likely to be different for different fabric weights with same depth of needle penetration.

In a further study, it is observed that apart from tenacity, initial modulus and breaking elongation, the fabric tensile and compressional recovery improve with the increase in needling density or depth of needle penetration. The bending length and bending modulus along the machine direction reduce on increasing the amount of needling density. This is because the fibres in the fabric might be broken due to the increased needling density. The reduction in fibre length might be responsible for the increase in flexibility of fabric, thereby reducing the fabric resistance to bending. This reduction in bending modulus with the increase in punch density is more pronounced in fabric having lower basis weight (Fig. 8). The fabric of higher basis weight shows an initial improvement in the bending modulus with the increase in needling density up to an optimum level and thereafter, the increase in needling density reduces the bending modulus. This may be due to the initial rise in compactness of fabric followed by fibre breakage.

3 Conclusions

Bulk and physical properties of needled fabric determine the suitability of fabric for its various applications. The above properties are influenced by the fibre properties, web characteristics, machine design parameters, machine variables and finishing operations. In general, the denser nonwoven fabric made from same raw material and web weight possesses lower air permeability, and higher strength and elongation. Greater consolidation in nonwoven fabric is usually achieved through higher needling density and needle penetration. Initial modulus and compressibility decrease but compressional recovery improves with the increase in depth of needle penetration. However, there is a limit beyond which properties of the fabric deteriorate with the increase in above machine variables. In the mechanical means of consolidation, spunlace technology (using hydroentangled jet) is found to be superior with regard to damage of fibres. A large variation in needle type and shape is possible with the variation in needling angle in the machine meant for improved fabric characteristics.

Usually, the higher fabric weight and presence of scrim improve the strength and abrasion resistance of fabric, provided the fabric is made with suitable needling parameters. Fibre orientation in the web is determined by the need of preferential/isotropic performance in the plane of fabric. Aerodynamic random-laid webs produce a more balanced structure with regard to fibre orientation distribution. Normally, longer and finer fibre leads to greater fabric strength, provided the fibre breakage is controlled. Hollow fibre fabric possesses higher bulk and tensile strength but lower abrasion resistance than circular and trilobal fibre fabrics.

Finishing techniques are opted in cases where dimensional stability (by heat setting), improved surface properties (by calandering, raising, coating and lamination) and much higher fabric strength (by chemical bonding) are required, particularly for nonwoven moulded automobile carpets, synthetic leather, needled carpets, wipes and mattress pads.

References