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I am submitting herewith a thesis written by Srinivasan Ranganathan entitled "Physical Characterization Of Thermally Point-Bonded Cotton/Polyester Nonwovens." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Textiles and Apparel.

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PHYSICAL CHARACTERIZATION OF THERMALLY POINT-BONDED COTTON/POLYESTER NONWOVENS

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ABSTRACT

The tensile and flexural properties of point-bonded cotton and polyester blended nonwoven fabrics were studied to examine the effects of binder level and processing factors. Fabrics were thermally stabilized by point-bond calendering. Four base-fiber/binder-fiber ratios were chosen. Three levels of bonding temperatures (408 °K, 422 °K, 436 °K) along with three levels of crush edge pressures (65, 130, 195 kN/m) were used to bond the webs. In an attempt to understand the heat transfer kinetics involved in thermal bonding, two bonding speeds (10 m/min, 20 m/min) were included.

The fabrics were characterized in terms of their specific stress, specific work of rupture and elongation at maximum stress (%), and flexural rigidity. The results indicated that fabrics stabilized using an embossed roll calender give tensile loading levels that were independent of crush edge pressures but increased significantly with embossed roll temperature. The effect of delivery speed of the fabric through the calender on the maximum levels of loading is significant in both the machine direction and cross direction. The strengths of the fabrics produced at the lower of the two delivery speeds are greater than those of, otherwise, comparable fabrics. The influence on strength from crush edge pressure or temperature becomes less pronounced at lower levels of binder.

SEM photomicrographs are used to show the extent of binder fiber melting and thus the degree of bonding throughout the total

thickness of the fabric at various processing conditions.

The anisotropic orientation of the structural elements within the fabric have a major effect on the strength of the nonwoven fabric when loaded in different directions. The fabric strength along the machine direction is, on the average, somewhat more than twice as great as the fabric strength along the cross direction. This is attributed to the machine direction orientation of the fibers, which is an inherent characteristic of the carded webs. This orientation, in turn, leads to greater number of load supporting fiber elements for machine direction loading.

Generally, elongation in the cross direction is slightly greater than the elongation in the machine direction. The results also showed that the stiffness of the fabric increases with the temperature as a result of more complete bonding at higher bonding temperatures and, consequently, a reduction in fiber element movement.

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CHAPTER I

INTRODUCTION AND OBJECTIVES

The growth of the nonwoven industry has been phenomenal in the recent years. These fabrics have gained wide acceptance in both industrial processes and in consumer goods. They range from filter fabrics to geotextiles and wipes to envelopes.

In 1986 alone, there was a reported growth of 7.4% by weight of nonwoven fabrics (1). This market is expected to grow more than 20% in the next five years (2). At least 6-7% annual growth for nonwoven roll good products has been predicted through the end of this decade. In 1976, only 10 million square yards of nonwoven penetrated Geotextile market; in 1981 the geotextile market consumed 120 million yards. Typical geotextiles/civil engineering end uses include road and area stabilisation, reinforcement of curved surfaces, erosion control and drainage. The growth of nonwoven businesses exceeds that of U.S. paper and textile industries and is comparable to that of any other fast growing businesses.

Nonwoven fabrics are generally classified as textile fabrics when which the main fiber material is a web of fibers or filaments. The fibers or filaments in the webs are held together by mechanical, thermal,chemical, or solvent means. These fabrics can be classified

either on the basis of bonding technology or on the basis of end use application. In the former, the fabrics are identified as needle punched, thermal bonded, spunbonded, spunlaced, adhesive bonded, meltblown, etc. Durable and disposable products is another way of classification. Geotextiles, apparel interlinings, roofing and carpet backings are some of the prominent durable nonwoven applications. Disposables are those that are discarded after single or limited use. These include filters, drapes, hospital gowns and surgical dressings.

Considering the wide variety of fabrics made from nonwovens, it is widely accepted that the key reason for nonwoven success is the ability to tailor the products to suit the requirements of the market. Floppy disc liners and tape recorder head cleaners are examples of nonwoven fabrics specially designed for a single end use. For these specific applications, no other product is known to do a more efficient job (2). The needs of the customers are fulfilled with specialized products on a price/performance basis. The ability to do so has emerged from the variety of fibers available and the structures that can be produced from them. To cite a few choices, we have natural or manmade, long or short length, micro or macro denier, high or low shrink, amorphous or crystalline, round or shaped cross section, single or bicomponent.

Apart from technological advantages, economic factors favor the increased use of nonwoven products. Lower cost and high performance webs can replace conventional products on a large

scale. These fabrics are engineered for specific types of end use performance. Finishing of nonwovens do contribute significantly in enhancing the market potential for nonwovens. Speciality products such as liquid repellant, flame retardent, soft, washables widened the range of applications of nonwoven fabrics.

The other factor to be recognised is that manufacturing costs of nonwoven goods are generally far lower than those of conventional woven and knitted goods due to reduced number of production stages and high production speeds. There are many processes in which the production rate of nonwovens is at least 80 times faster than that of woven and knitted goods. Apart from replacing the conventional fabrics, nonwovens have enabled many novel products to be developed where textiles had not found an earlier outlet.

The controlling features of nonwoven performance behavior are the choice of fiber production technology and the method of bonding. A striking similarity has been observed between the stress-strain properties of constituent fibers and the nonwovens made from those fibers. Length of the fiber, tenacity and surface properties of fiber are highly influential in the end use performance of the nonwoven fabric. This holds valid for almost all types of nonwoven fabrics. Systematic variation of fiber properties and processing conditions should render fabrics of intended structure and properties. This has been well realized in the case of thermal bonding.

Thermal bonding of nonwovens has become well established due its advantages such as reduced energy requirements, improved fabric properties, cleanliness and space savings (3). Growing use of thermal bonded products during the last few years in coverstock for diapers, sanitary napkins, hospital/medical products and interlining has been noticed.

It is expected that thermal bonding along with spunlaced stabilization will replace resin bonded fabrics for the most part, and growth of thermal bonding will be few percent (2). The general trend towards increases use of heat bonding continues, and it is partially attributed to the fact that it receives wider acceptance from the medical point of view of toxic and allergic concerns (1).

Vaughn (5) anticipates a high potential for the use of thermal bonded high loft structures. Particle loaded batts, apparel, furnishing and building insulation, roofing and geotextiles, and composite reinforecement are to be included in the thermal bonded high loft domain. Future growth potential is outstanding.

Calender bonding is one of the simplest and most versatile methods of Thermal bonding. Efforts have been made in the recent years to explore the possibilties of producing new fabrics and value added items from this process. Virtually all lofty thermoplastic staple fiber products, spun bonds, meltblowns, and combinations of these are canditates for value added enhancement through some form of thermal bonding application (5).

While successful production technologies for thermobonding are well established, the high speed categories are only suited to the production of lightweight materials (less than 70 grams/sq.m) since the rate of heat input is inadequte for medium and heavy weight materials. Current market developments in the nonwoven industry are in the field of semi-durable and durable nonwovens as opposed to disposable goods, for which the heavier weight products are required (5).

This could be offset by the proper selection of processing conditions since bonding process has been claimed to be critical in deciding the nature of the bond, and thus the properties of the fabric. Therefore it is essential that the relationships between processing conditions and the properties be identified clearly.

Cotton continues to dominate in the clothing market, and it is now working its way rapidly into nonwoven applications. In 1982 cotton consumption was 241 million pounds in the total fiber consumption of 1004 million pounds for nonwovens. It is estimated that the use of one ounce of cotton in every disposable diaper in the U. S. would require one million more bales of cotton a year (4). The properties of cotton such as comfort, absorbency, washability, biodegradability, resistance to certain chemicals or temperature are unmatched. Residential insulations made out of unbleached cotton and low melt polyester in a thermally bonded batt provides better "R" thermal values than fiber glass. More than ten companies are

currently processing cotton into high loft products (6). Holliday (6) attributes the lack of cotton use in the past to problems in bleached cotton processability and to a dirth of knowledge about how to process cotton from both web making and bonding standpoints.

This specific study was initiated to focus on the formation of staple fiber nonwoven fabrics through thermal calendering and to examine the interrelation between the performance bahavior of thermally bonded polyester/cotton nonwoven fabrics and the constituent base/binder fiber ratio and processing conditions.

The objectives of this study are:

1. Determination of tensile properties of cotton/polyester blended nonwoven fabrics that are thermally stabilized by thermal point bond calendering.
2. Evaluation of the influence of bonding temperature, pressure and bonding speed on the tensile behavior of nonwoven fabrics.
3. Investigation of the strength dependency of the fabric on the base-binder fiber ratio, and
4. Examination of the flexural characteristics of the nonwoven fabrics.

CHAPTER II

REVIEW OF LITERATURE

Nonwoven fabrics are essentially two-dimensional assemblage of textile type fibers held together by means of an additive or self bonding material, resulting in mechanically stable, self supporting, flexible, web-like structures. The properties of these structures are manifestantly dependent on the constituent fibers and the method of bonding them together. Furthermore, the properties of the binder and its distribution influence the characteristics of the fabric. In short, fiber properties, binder properties, processing factors and the method of bonding determine the behavior of the nonwoven structure. There has been research conducted in all these areas and this is reviewed with particular reference to thermal bonding.

I. FIBER PROPERTIES

The physical and mechanical properties of nonwoven fabrics produced by binding constituent fibers together are largely determined by the properties of the matrix fiber and the nature of their interaction in the fabric structure. Krcma (7) reports that the amount of fiber present in the fabric varies depending on the type of fabric, and is usually between 30 % and 100%. Fibers are chosen on

the basis of the fabric property/performance requirements and the method of manufacture.

Allan and Ingalls (8) have suggested that the use of helically crimped fibers improves the drapability of the fabric by virtue of the lateral flexibility of the fiber segments between bonding points. Fiber crimp affects, apart from drapability, the web properties such as air permeability, tenacity, density and bending resistance. The improvement in the flexibility of the fabric has been attributed to the actual increase in length of unbonded fiber segments (8).

Batra (9) postulates that the use of crimped fibers enhance the softness, extensibility, flexibility and drape of nonwoven fabrics. He further emphasizes the importance of modulus along the axial direction and the shear modulus in the cross sectional plane in the determination of stress-strain behavior of nonwovens. Cox (10) has demonstrated that initial stiffness and elastic modulus of the constituent fibers, together with their orientation distribution function, affect the initial stiffness and the elastic behavior of the fiber network structures, in which the fibers lie essentially straight for larger distances than the average distance between bonds. Therefore it is possible that the drapability of the nonwoven fabrics can be improved by the proper choice of the fiber parameters.

Cusick et al. (11) have noticed a striking similarity in the load-elongation behavior between bonded fabrics and their constituent fibers. This, in turn, suggests that the effect of the

fiber properties dominates over either the effect of the adhesive properties or the structural parameters. Similar views were expressed by Hearle and Newton (12) who found that the fiber network primarily determined the mechanical behavior.

Besso et al. (13) suggest that fiber tensile properties are frequently assumed to be the major contributor to most loading behavior. However, properties of the PET fabric and rayon random webs studied apparently suggest that only modulus and extension of the fibers translate into nonwoven properties. By contrast, tenacity of the fabric was essentially the same for webs with a given binder and, thus, did not reflect the real difference of strength between the base fibers. Surprisingly, the nonwovens made from the weaker fiber (rayon) were stronger with both binders.

Schroder and Korchan (14) found that fabric strength varies up to an optimum value as a function of fiber length. They suggested that the optimum value depends more on fiber crimp than on fiber fineness. One of these authors (15) also reports that the contributing effects of fiber length, crimp and binder distribution are still debatable.

Shimalla and Whitwell (16) claim that the length of the fiber affect the strength of the fabric since longer fibers provide more cross over points and hence, more, bonding sites. They also add that longer fibers should provide better anchoring of individual fibers and thus produce stronger fabrics.

Allan (17) suggests that a high degree of flexibility could be achieved by utilizing different types of cross sections available. He states that fabrics produced from triangular cross-section fibers will have more flexibility than that of fibers with circular cross sections(18).

Allan et al. (19) also illustrated that fiber stiffness is a direct function of its cross-sectional shape. The hexagonal arrangements of fibers are theoretically the most fabric-like, and a nonwoven with fibers approaching this geometry enjoys a wide commercial acceptance as a textile material. A triangular fiber has 28% more surface than a circular fiber for the same weight. The additional bonding area of triangular fiber provides the opportunity to strengthen the structure by increasing adhesion and emphasizing fiber breakage. Hollow fiber collapse is an additional mode of deformation hitherto unexploited in nonwoven design, although its importance has long been recognized in the performance of spring and summer wood fibers in paper making (18).

Batra (9) illustrates mathematically that the bending behavior of fibers exercise an important influence on the bending stiffness, compressive stiffness and the drape of nonwoven fabrics made from noncrimped fibers.

Besso et al. (13) report that the spin finishes applied to the fibers during fiber production might influence the bonding strength of the fiber/binder interface. Surface properties of fibers are important in both web preparation and also in subsequent bonding.

Moffett (19) showed that low-denier base fibers give stronger, softer and more flexible fabrics. Longer base fibers give greater strength, while shorter fibers improve flexibility slightly. Landoll and Hosfetter (20) report that crimp level, finishes and compaction are important in the web formation.

II. WEB PREPARATION

The web formation in the nonwoven manufacturing process is very important because the structural arrangement of fibers in the web influences the performance of the fabric. Barounig (21) reports that the web forming process influences the fiber orientation, web quality and output. There are two methods in which fibrous webs are formed. Dry forming is used in thermal bonding stabilization, while wet laid centers around paper and paper related nonwovens such as tissues.

Purdy (22) describes the characteristics of a satisfactory web. The web should have correct weight with minimal variation in this weight apparent, either along the length or across the width. Opening and blending is the initial process in web formation where the clumps of fibers are opened using the normal textile grade opener. Fibers of 25 denier or more are readily separated using a simple spiked lattice opener, but finer fibers need more severe treatment (23). The opening process essentially optimizes the contribution of

each fiber in the final product, recognizing that the distribution of the fibers depends upon the degree of opening and and the isolation of one fiber from another (24).

Blending is desirable for improving the homogeneity throughout the web structure. Different lengths of the same type are blended in an effort to combine strength and softness (25). On the other hand, thermoplastic binder fibers are blended with natural or other synthetic fibers at this stage.

In the mechanical web forming method, carding follows blending and individualises the fibers and removes smaller impurities. Furthermore each fiber is transported over the cylinder many times, and this improves the blending of fibers. Depending upon the method of deposition, either parallel or a cross laid web is obtained.

In parallel web formation, the primary web coming from cards are overlapped consecutively with each other using a special winding device. High production speeds are possible using tandem carding where several cards are operated in tandem manner. This method is widely used in the manufacture of light weight disposables (21). The fibers are oriented essentially in the machine direction and structural anisotropy results. One obtains very high tensile strength in the machine direction due to the orientation of the fibers in that direction. The strength ratio between MD and CD varies between 2:1 to 5:1. This drawback is partially overcome by incorporating cross-laid nonwovens.

In cross-laid web formation, oriented webs are laid down at or near alternating 45° angles on another oriented web on a conveyer running crosswise to the card. It is also possible to vary the working width of the card in this process. This process has been quite successful in the preparation of heavy weight webs (26). Tensile strength in the cross direction is improved to a considerable degree by the cross laid method and the strength in any direction is essentially constant.

In the case of aerodynamical web formation, fibers are randomly distributed in the web and so there is no clear directional orientation. Fiber webs with such an arrangement are referred to as random webs and material of this type are basically anisotropic. Parallel laid webs from a card exhibit a kind of anisotropy where there are two definite axes of symmetry in mechanical properties, and these two axes are perpendicular to each other.

The behavior of carded webs is explained on the basis of a fiber orientation distribution function and a curl factor, suggesting that these parameters play a key role in the performance of the webs (27). Patterson and Backer (28) report that the curl factor can be taken as unity, i.e, the effect of curl can be neglected. However, Hearle (29) later found that a crimp factor has to be included for a proper representation of the behavior. Hearle (29) also reports that fibers in the direction of deformation gives higher resistance than those lying across it. Kallme's (30) findings are similar to those of

Hearle, and he reports that the stress-strain properties are a function of their structural arrangement within the web.

Crimp, surface roughness,cross-sectional shape and staple length are reported to have an effect on the mechanical properties of webs. Crimp and staple length influence the fiber entanglement which is essential for adequate web adhesion. The fabric modulus is also affected by crimp and shape, whereas elongation is affected significantly by roughness, linear density, crimp and staple length (31).

Hertel and Lawson (32) report that the cross sectional area of the fiber affects the cohesion of the fibers in the web. The smaller, more circular fibers have greater surface area available for contact and, hence, a smaller load intensity. The orientation is also reported to have affected shear friction.

A typical thermal bonding line consists of three sections: an opening system, a multiple card system, and a calender. A bonding line with two openers allows blending of different fibers and independent feed to the card line for forming layered fabrics. The advantage of carded web is uniformity. The opening system must be able to separate fibers and form a uniform batt in order to feed the card evenly. A number of fiber characteristics are important especially crimp level, finish, and compaction. Each of these must be carefully controlled if the operator is to provide a uniform batt (20).

The web is formed by the card, similar to those used in cotton processing. In most operations, multiple cards are used to provide a continuous formation of several layers of web. This arrangement enables the cards to operate at peak efficiency, while the entire web forming line runs at high speeds. Typical pilot and commercial lines run at 90 to 180 m/min.

At those speeds, there can be considerable tension on the unconsolidated web, particularly at web transfer points. the cohesiveness of the web is governed primarily by crimp level and finish. High crimp provides good cohesiveness of the fibers in the web, but also makes the fiber more difficult to open (20).

Carding imparts a high level of machine direction orientation to the fibers, forming fabrics with a high degree of strength anisotropy. Improved cross direction strength and toughness can be obtained by inducing additional cross direction fiber orientation. This is achieved with randomizers, which buckle the web as it is doffed from the card, and by spreading the web prior to consolidation (25).

A lot of emphasis has been placed on the uniformity of the web since the quality of the fabric can be no better than that of web. Krull (33) suggests gravimetric feeding method for precision web control. The Vectroflo feeder, a computer controlled continuously weighing feeder, measures the exact weight of the condensed fiber lap as it is delivered to the carding machine. The feed roll speed is computed and controlled to ensure the desired output.

III. BONDING PHENOMENA - CHEMICAL

The satisfactory performance of a bonded fabric is largely influenced by the binder properties and its interaction with the fiber network. The strength of the fabric is a function of the strength of the interface.

Theories Of Interfacial Bonding

Many theories have been formulated to characterize the various bonding mechanisms but none of them has been considered to have universal applicability.

Bickermann (34) suggests that mechanical bonding can be achieved by bulk penetration of one phase into the pores of the other, to form the bickermann interlocking.

Owens (35) in his adsorption theory, states that secondary forces are sufficiently strong for good bonding provided adequate molecular contact is achieved in the distance over which these forces operate. The maximum free energy of adhesion is effective over a range of only 1 Å and then it is reduced as the inverse fourth power of distance.

According to diffusion theory (36), the chain ends in a polymer melt should have the ability to exhibit micro-brownian motions. There should be sufficient time for chain entanglements to occur which will provide strength at the interface when the bulk of the polymers is heated above their flow temperatures.

Low self adhesion, which is generally observed both with polar polymers and with materials in which the molecules are perpendicularly oriented with respect to the plane of contact, would be consistent with the diffusion theory (37). The attainable bond strength is limited by the nature of the bonding forces and compatibility of adhesives with the substrate (38). The effective area of bonding is governed by the wettability of substrate by the adhesive. Furthermore, kinetics of the wetting process are influenced by the viscosity of the binder in the fluid state.

Selection Of a Binder

Shimalla and Whitwell (39) list the requirements of an efficient adhesive bonding. They report that the presence of a weak boundary layer on the substrate is an undesirable feature. The surface tension of the adhesive should be less than that of the critical surface tension of the substrate. Extensive interfacial contacts must be formed by choice of bonding conditions. The adhesive must be set to maintain the interfacial contacts, frozen stresses must be prevented and a weak boundary layer must be eliminated.

Coke (40) reports that an ideal binder system should have strength approaching that of the fiber. Also binder location, high specific adhesion to fiber, elastic recovery or the ability of the fabric to return to its original shape after it has been stretched by a small amount are some desirable binder charecteristics. Resistance

to sunlight, good dimensional stability, freedom from discoloration and good crease resistance, crease recovery and resilience are important for good fabric characterestics.

Bozzacco (41) found that the best fabrics were produced when the binder fiber and the base fiber were chemically similar. He further claims that the fabrics produced by thermoplastic fiber bonding have broad applications in the manufacture of ribbons, tapes, decorative fabrics and filter fabrics.

Meazey (42) expressed a similar view and also adds low cost, easy application and minimal curing conditions as commercial necessities. Bozzacco (41) lists the factors to be considered in the choice of binder for nonwoven fabrics:

1. Limitation of processing equipment.
2. End use requirements.
3. Fiber blend to be used.
4. Cost and economy of binder.
5. Mechanical stability, particle size, and other latex and binder properties.
6. Types of adhesion and sealability.
7. Degree of firmness or softness imparted to the fabric.
8. Migratory behavior of blends.
9. Stability to ultraviolet light and heat, abrasion, solvent and water.

Binder Properties

The adhesive bonding phenomenon between thermoplastic fibers depends on the structure, polarity, tack temperature, bonding temperature, and stress concentration (16, 39). The strength of the adhesive joints is a function of intermolecular forces between the two sets of molecules,distance between the molecules, wetting efficiency and the internal stresses that arises during changes of state of the adhesive (43).

Temperature and application time play important role in the determination of adhesive and cohesive properties. Krcma (7) reports that a temperature above the glass transition is the most favorable condition for good adhesion properties. Wetting of the bonded surface by the binder is a key factor in measuring bond effectiveness. Binder fibers will not wet the surface until they have reached a viscous liquid state and the rheological properties of the polymer are altered in favor of good bonding (7).

Hearle and Newton (44) assumed that the mechanical properties of nonwovens are primarily determined by the fiber network, with the binder playing only a minor role. However, later works showed that the binder material interacted with the fiber network and contributed significantly to the stress-strain behavior of the whole assembly. Model experiments with single bonded fibers exhibited a phenomena in which the failure occur either by rupture of the fiber or slippage at the fiber-binder interface.

Miche's experiments involving various types of binders led to the empirical equation connecting binder modulus and fabric modulus (45):

$$E_f = 700\, E_b / (1+16\, E_b)$$

where E_f = fabric modulus

E_b = binder modulus

The significance of this equation, according to Miche, is that at lower binder modulus where 16 E_b is small compared with unity fabric modulus becomes proportional to binder modulus being given by 700 E_b. At higher binder modulus, the term 16 E_b begins to dominate and the fabric modulus then tends toward the constant value 700/16 approximately 45 g/tex.

Hearle et al. (46) found a proportionality between fabric modulus and the square root of the binder modulus which held good only over a very narrow range.

Hearle (44) reports that, in a fabric where there is a low binder content (20%), there is a change in the nature of the deformation and the rupture is caused primarily by a breakdown in the bonding. Load-Elongation curves also indicate that there is a progressive tendency for less slippage to occur as the binder content is increased. Miche studied the mechanical properties of viscose random laid fabrics which had been saturation bonded with a variety

of binder latices. He observed that the strength of the fabric increases proportionally in proportion to the amount of the binder.

Moser (47) found that the fabric strength became insensitive to the level of binder at higher levels, and he attributed this behavior to an already effective bonding at intermediate levels of binder. He also observed that the bending length, i.e., flexural rigidity, was virtually independent of binder concentration. In contrast, Miche (45) found that the effect of binder level on fabric stiffness varies with different types of binders.

Hearle and Newton (48) in another work, studied the influence of binder on the tensile properties of nonwoven fabrics. Their findings indicated that the fabric modulus decreased as the binder becomes more elastic, and the decrease was more pronounced at higher levels of binder content.

They observed a complex pattern of relationship between the breaking strength and binder properties. At very low levels of binder content, the effect of changes in the binder properties on rupture strength was not significant, and this was attributed to the fact that the binder content was too low to produce a stable fabric. Though the amount of binder appears to be the dominant consideration for base fiber stabilization, it is to be recognized that the stiffer binder fiber does not produce a stronger fabric. The authors observed that the possible failure mechanism was through either bond slippage or fiber breakage.

Fabric strength is highly dependent on the amount of binder and there is a high correlation between fabric strength and the cohesive strength of the binder material (49). Besso et al. (13), in their studies of contributions of fibers to nonwovens properties, drew some different conclusions. In contrast to the previous findings that the tensile properties of the binder on the nonwoven tensile properties is usually considered to be minimal, they reported that fiber/binder interface forces are assumed to be the weak link in the assembly. In particular, this interfacial phenomenon limited the strength of the network. The experiments indicated a direct translation of binder strength to nonwoven strength. It also appears, from the experimental results, that cohesive binder strength is the overriding factor in determining nonwoven strength.

The other interesting observation is that the tensile strength increased with increase in add-on level but reached a plateau above approximately 45 % add-on. Tensile failure of the nonwoven in the plateau region was first thought to be due to fiber breakage; however, the authors found no fiber breakage, suggesting that either deposition of binder at the add-on levels of the plateau occurs along the non-load bearing fiber surfaces, or the cohesive strength of the binder now exceeds the adhesive strength of the binder/fiber interface (13). Rigdahl and DeRuvo (50) showed that immersion of a dry formed network structure in an organic solution of poly(vinyl acetate) is a very effective binding technique with regard to strength improvement. The change in mechanical properties is,

however, affected by the degree of interaction between the solvent used and the cellulosic material. It is plausible that strength of the network is determined by the strength of fiber-polymer-fiber bonds. It is, however, not clear whether the bond breakage is of a cohesive nature, i.e the polymer film ruptures, or of the adhesive kind (failure along the interface). The authors believe that spraying a water based latex on the web (which is a commercial process) is of no benefit to the product since it can cause an initial breakdown of the network structure by the fact that water interacts strongly with the cellulose.

In an ideal case, the distribution of the binder in the web is macroscopically homogeneous and microscopically agglomerated as discrete beads at the tie points. This ideal situation is rarely found because of the interfacial phenomenon and the question arises as to what extent interfacial properties affect the behavior of nonwovens (13).

External agents, such as wetting agents, added to the binder solution tend to accumulate at phase boundaries and, thus, are expected to influence the adhesive strength of the binder/fiber interface. The results show that the addition of wetting agent decreases the tenacity, modulus and increases elongation (13).

Surface active agents play a major role in determining the failure mode of a nonwoven. They may affect the tenacity not only by decreasing the cohesive strength of the binder or by making the binder distribution less load bearing, but also by changing the

cohesive failure into adhesive failure. Hence, the choice of the appropriate surfactants becomes critical either in the surfactant composition used in preparing the binder or in any eventual surfactant additive used to obtain the needed rapid wetting out of the web at high production speeds.

IV.THERMAL BONDING FIBERS AND BONDING OF BLENDS

The thermal bonding process has been described as the method in which the web containing the bonding fiber is heated to the melting point of the bonding fibers. The bonding fibers melt and the melt collects preferentially at the inter-fiber contact points of non-melting carrier fibers and links these together. Cooling causes the molten components to solidify, thereby providing the nonwoven with a secure bond (7).

Web consolidation is normally obtained by thermal calendering, although through air bonding and ultrasonic bonding can be used. The delivery speed in ultrasonic bonding is slow, but does yield a soft hand. Through air bonding can be done more rapidly but this method heats the entire fabric, and in general does not result in good softness. Thermal calendering is fast, and with engraved rolls, can result in superior softness on at least one side of the fabric (20).

It has been confirmed that to get mechanical properties the fibers involved in bonding must keep their fiber characteristics continuous through the bond area and must not be destroyed by complete melting. The bonding fibers then contribute to bonding and matrix load carrying capacity.

It has been shown that thermal bonding mostly comes from the polymer flowing under the mechanical action of the embossed roll at a certain temperature below the melting temperature range (51).

Thermal bonding is notable for its simplicity and advantages such as low energy requirements,no water evaporation, no curing of the binder, no exhaust air problems, no solvent vapor or other gases released, lower capital expenditure costs, and higher production speeds. In addition, this process produces nonwovens charecterized by high bulk and softness, high porosity and absorbency, no melt clogging of nonwoven pores, nonwovens made from a single polymer, no problems associated with food,chemical filtration or skin tolerability (52).

Thermal Bonding Fibers

One of the factors that can be attributed to the success of thermal bonding has been the range and variety of custom tailored fibers available for bonding. There are essentially three types of bonding fibers: (52)

Adhesive fibers

Bicomponent fibers,

and

Melt adhesive fibers.

Adhesive fibers are unstretched amorphous polymer fibers. On reaching a temperature of barely 100° C, these fibers soften superficially to become tacky and capable of forming a bond. But calendering is needed over the entire surface to achieve this. Because the web needs to contain a high proportion of adhesive fibers and it becomes boardy and assumes a paper like texture. It is, hence, of limited commercial use (52).

The bicomponent fiber overcomes some of the previous problems of single component fibers and is usually produced as a core/sheath fiber, where the core of the fiber comprises a polymer with a higher melting point than the sheath. The core component acts as the carrier element of the nonwoven.

The sheath, which consists of a polymer with a lower melting point, bonds the fibers. The drawback, however, resides in this very structure, which prevents the melt component from accumulating at the contact points of the carrier fibers. Bicomponent fibers are generally higher in cost than unicomponent fibers and are restricted in bonding temperature range (53). Because resulting individual bonds are relatively weak, a greater density of bonding points are required.

Melt adhesive fibers are suitable for a much wider usage. In principle, any thermoplastic fiber with a melting range of 100 to

200 °C can be employed as a melt adhesive. However, a disparity between the chemical structure of the carrier and the bonding fiber will generally mean mechanically weaker adhesive bonds. These unicomponent fibers often lose their structural identity upon bonding. The formed bonds generally have a high level of adhesive mass associated with each bond compared to those from bicomponent fibers (54). The specific type of bond formed is dependent on several factors including fiber chemistry, fiber morphology,processing factors, linear density and staple length.

Nakao (55) studied the relationship between bond strength and crystallinity of high polymers such as polyethylene, poly(ethylene terepthalate), and nylon. He suggests that when crystalline polymers are used as hot melt adhesives, the factors to be considered are the weak boundary layer, surface morphology, overall crystallinity, density, melting point, crystallizing point, tacticity and so on. In addition, for amorphous polymers, the following should be considered: surface geometry, surface free energy, visco-elastic behavior, cross linking, molecular weight, and so on (55).

Polyester Binder Fibers

PET is not suitable as a hot melt adhesive. The reason is that on cooling from melt, PET turns into a brittle white powder like product. This is due to the rapid growth of crystals in random directions. This problem, however, does not arise when PET is used as a bonding fiber.

Polyester fiber adhesives may be classified in one of three basic categories(47):

A binder fiber which melts at a lower temperature,

A moldable binder fiber which softens at lower temperature,

or a self-bonding fiber.

Binder Fibers: These low temperature melting fibers are typically blended with regular molding matrix fibers in concentrations varying between 5% - 50%. These binder fibers will adhere to a number of different substrates including polyester,nylon, rayon,cotton, other cellulosics, acrylics, modacrylics, vinyl, metals and others. There are two kinds of binder fibers, namely unicomponent and bicomponent.

Moldable Binder Fibers: A Moldable binder fiber, usually amorphous PET, will have a fairly high melting point; however, the softening point will be considerably lower. If the fiber is exposed to temperatures above the softening point while under compression, a satisfactory bond can result. The main difference between a standard binder fiber and moldable binder fiber is the higher pressure or intimate contact required with the moldable binder fiber (54).

Self-Bonding Fibers: These polyester fibers with a mid-range melting temperature are capable of functioning simultaneously as a

matrix and binder in nonwoven fabrics bonded with an engraved roll. These fibers are able to do this because they soften and become tacky at temperatures well below their melting point. The benefit of a fiber that bonds so far below its melting point is that, even within the bonding points, there is fiber integrity. This integrity translates to high bond strength and in turn to high fabric strength.

Various amorphous polymers are obtained by the copolycondensation of different acids and alcohols, which are commercially available as polymer adhesives. It was found that high bond strength was obtained by quenching PET from melt, turning PET into an amorphous state. It was concluded that the tensile strength decreases with the development of PET spherulites, with the result that tensile strength increased about 10 times by rapid cooling compared with slow cooling (56). Joints formed between rayon and vinyon fibers and between polyester and copolyester fibers in staple nonwovens are of the improper adhesive types, i.e, failure occurs at a weak boundary layer in the bond interface.

Effect Of Binder Concentration

Shimalla and Whitwell (39) studied the effects of binder concentration and bonding pressure. To attain high strength in adhesive bonded nonwovens, appreciable bonding is generally required. Relative fiber movement is restricted as free fiber lengths between individual bonds are decreased; the rigidity of the network increases with the increased density of bonds within the fabric.

Introduction of low melting fibers in a web constitutes a form of selective bonding, providing an opportunity to increase the number of bonds and to decrease free fiber length between bonds. Increases to 25 % binder concentration and increases in bonding pressure then maximize tenacity, elongation, and initial modulus in the regions under investigation.

Binder concentration and bonding temperature are found to be primary variables controlling the failure mechanism of the nonwovens (16). At higher binding concentrations, i.e, 50%, the sum of the bond strengths due to physical entrapment by binder along the length of the base fiber appears sufficient to induce base fiber rupture (16).

At medium bonding temperatures well below the melting of the base fibers and at low binder concentrations, interfacial failure of the bonds and subsequent disentanglement and slippage of the base fibers is the probable cause of failure. True cohesive failures were observed only at very high bonding temperatures. Brushwood (57) investigated the effect of heating on cotton. He reports that excessive heating of cotton could possibly cause some visible discoloration, lower fiber strengths and elongations through changes in chemical properties of the fiber. The adverse effects associated with heating were more pronounced on fibers with lower micronaire and high noncellulose contents compared to fibers with higher micronaire, low noncellulose content.

Mechanical processing also damages cotton, particularly when performed at low fiber moisture levels. If a reasonable amount of moisture regain is allowed with moderately heated cottons, permanent damage by mechanical working is much less severe. Differential dye studies have suggested that structural changes in cotton may occur with increasing heating temperature.

Effect Of Temperature

Muller (58) studied the mechanical properties of nonwoven fabrics bonded at different temperatures. Higher bonding temperatures generally improve individual bond strength but can be detrimental to fiber strength. Excessively high temperatures or low temperature are not of any practical interest due to increasing stiffness or lowering strength, respectively.

The surface of the bonding fibers melt at the established points and so affect a bond between the fibers. In order to retain desirable properties of the nonwoven such as 'hand', it is necessary to adjust the surface temperature so that the fibers themselves remain below the melting point in the areas between the raised points of the engraving. The range between the temperature at which a bond between the fibers is affected and the temperature at which full melting of the fiber takes place is about 12 -15 °C in the case of polyester and about 5 °C with polypropylene.

An increase in roller surface temperature generally brings about an improvement in nonwoven strength. This improvement can

be achieved only up to a certain maximum value, after which strength declines. A change in production rate also changes the contact time available for heat transfer. Compensation must be made for such a change in contact time. It has already been shown that compensation can be affected by adjusting nip pressure (58).

Imachi (59) has reported that best bonding between different thermoplastic polymers occur when the lower melting point polymer melts while the other remains intact. This is to say that the thermal bondable polyester should have maximum bond strength at its melting point. However, this does not take into account other factors such as melt flow viscosity, rate of crystallization and variation with temperature and pressure.

Gibson and McGill (60) also studied the effect of calender temperature on the properties of bonded fabric. They expected that, at a fixed bonding pressure, there must be an optimal temperature-time history which gives maximum bonding strength. Contact time is determined by production line speed, so temperature is the other logical variable. The authors also list polymer related variables that would affect the properties of calendar bonded nonwovens through adhesion mechanism involoving molecular weight, melting point, viscosity, and surface tension. The fiber morphology, which is intimately connected with the physical properties, is certainly a major factor in the determination of nonwoven properties.

Goraffa et al. (61) found that fibers with higher elongation-to-break give stronger nonwoven fabrics. The authors report a dramatic

difference in MD and CD strengths due to anisotropy caused by carding. Their conclusion is that there are essentially three ways in which a nonwoven fabric can fail when stretched:

1. adhesive failure can occur between the fibers in the bond site,
2. individual fiber failure either near the attachment point to the bond site or somewhere in the fiber between two bonding sites,

and

3. fracture of the bond site itself.

As bonding temperature increases, the authors speculate that the failure mechanism changes from one of loss of interfacial adhesion in the bonding sites to one of cohesive failure.

Wei et al. (62) found that shrinkage of the fabric begins at a temperature below 150 °C, probably because of molecular chain relaxation of amorphous regions; however, at higher temperatures (greater than 150 °C) shrinkage occurs abruptly and very steeply for fibers coinciding with the melting of small and imperfect crystals. The amount of disorientation of the amorphous chains will depend on the bonding temperature. The higher the bonding temperature, the higher would be the shrinkage. Compared with the shrinkage in the machine direction, the low shrinkage in the cross direction is solely a consequence of low fiber orientation in the web in this direction, an inherent factor in carded webs.

During the thermal bonding process, significant morphological changes can be expected to occur in the bonding regions. The physical properties of thermally bonded fabrics are a manifestation of the characteristics of bonding regions. The fabric tenacity, breaking elongation and the energy-to-rupture are strongly affected by the bonding temperature (62).

The less oriented amorphous regions and lamellar crystalline structure promote the fusion in Herculon™ T-151 polypropylene fibers and stronger bonds. On the other hand, microfibrillar structure in Herculon™ T-123 polypropylene fibers having relatively higher birefringence inhibit the fusion between fibers in thermal bonding processes. At higher temperatures, a large part of the fiber melts, thus creating conditions that are conducive to the formation of polymer films and greater coverage of fibers. This results in increasing bond area and, consequently, a decrease the length of bonds between fibers. Hence, flexibility also decreases.

The forces developed in the fibers during heating result from the release of internal strains frozen in during spinning and drawing process. These forces are reported to increase initially with an increase in temperature and then decrease due to relaxation phenomena. As the temperature approaches the melting point, the last of the frozen strains are relieved in the formation of deformation of the filament (63).

Barish (64) showed that as isotactic polypropylene crystallizes from the melt, a completely spherulitic polymer may

generate internal stresses sufficient to cause actual cracking and fracture of spherulitic boundaries. If one considers a nonwoven system in which a low-melting binder fiber is bonded to a high-melting base fiber, the volume contraction of the binder fiber may be somewhat restrained near the interface by the less flexible base-fiber substrate. Thus, frozen stresses developing at or near the fiber-fiber interface during thermal bonding could play a major role in bond strength.

Mukhopadyay et al. (65) report a loop bonding test for the determination of bonding strength. This test has been used in the University of Manchester built flexible thermo mechanical analyser (FTMA). Two interlinked loops, attached to upper and lower jaws of a tensile tester are held together at a chosen tension and temperature for a selected time in order to make a bond. One arm of each loop is cut after the bond is formed and the strength of the bond is determined with the FTMA in the tensile test mode.

The mechanism of bonding may not be a primary function of the surface energy or chemical composition or even crystal morphology, but rather it may be influenced principally by the surface topography. It is suggested that a prealignment of polymer chains occurs in suitably sized cracks or channels in the surface (66). The temperature,tension and time can, thereby, dramatically influence the nucleating activity of a surface resulting in varying bond strengths for the different samples under otherwise identical conditions.

Jaffe (67) studied the thermal behavior of polypropylene fibers at different spin-line stress levels. He attributed differences to the fact that the sample produced under low spin-line stress conditions contained spherulitic crystalline regions, whereas the high-stress fiber contained row nucleated structures. This suggests that the fibers with good thermal bonding performance have skin structures containing more disordered and small crystals. Thus, major melting of different sized and disordered crystals may occur on the surface at temperatures of 10 °C or more below the actual melting of the perfect and ordered crystals of polypropylene fibers.

Jaffe also found that as melt time increased, crystallization slows down. This means that the rate of recrystallization slows down with respect to time, and thereby the bond strength approaches a steady state value. Increased tension may accelerate stress induced crystallization and a higher bond strength would be achieved at higher tension levels.

Effect Of Moisture

Mukophadyay et al. (68) examined the moisture wicking effect on the bonding process, by which fibers were soaked in water and then processed. It was expected that in addition to physical parameters such as pressure, temperature and time, bond strength would be affected by variables such as water present in the material along with previous structural and thermal histories of the materials. The results of the study have shown that the presence of

water in the material can influence the thermobonding mechanism. If the effective thermobonding mechanism is a skin/core structural phenomenon, then water with its plasticising may have an important role. In this mechanism, good bond strength is achieved when the skin of the fibers melt to form the bond, leaving the core undisturbed. As polypropylene does not have any significant moisture regain, water on the surface may help the skin material to flow better at a lower temperature. This results in the formation of a good bond, while the core is unaffected at that lower temperature. Thus, the optimum bond temperature is lowered when the fiber matrix has been soaked in water.

Effect Of Pressure:

According to Muller (58), the pressure in the roller nip has two functions:

1. improvement of contact heat transfer from the rollers to the web, and
2. joining the molten fiber surfaces together.

At the bonding point, the bonding fiber structure no longer exists. A reduction in pressure would, first of all, cut down heat transfer, thereby reducing the availability of the heat required for melting. Secondly, it would impair the quality of bond between the molten fiber surfaces. A further increase of the pressure beyond the optimum reduces strength in both directions. Excessive roller nip pressure prevents the ideal flow of the fiber into the bonding points.

Effect of Time During Bonding

Increased bonding time is a result of an increase in the interval of contact. Longer times result in heat setting (stress relaxation under fixed length), which imparts a degree of dimensional stability against shrinkage. It is sensitive to the temperature of the heat setting operation. Once the interfacial temperature at the center of the web corresponds to the minimum bonding temperature, bond formation occurs, and is essentially complete throughout. Little further change will be effected provided bonding occurs rapidly. Longer times simply lead to an increase in stiffness without corresponding additional strength (16, 39).

Cooling Rate and Binder Recrystallization

Relatively rapid quenching reduces spherulitic crystal sizes and prevents migration of low molecular weight fractions to form a weak boundary layer. Adhesion is improved and a more flexible network results. With binders which do not crystalize readily, properties are virtually unaffected by changes in cooling rate or cyclic bonding (16).

Rebenfield, et al. (69) reported that an increase in the quench rate reduces the time for such processes as melting, cooling and recrystallization, and eventually leads to frozen stresses which may weaken the bond.

V. PROPERTIES OF NONWOVENS

The mechanical behavior of nonwoven fabrics is largely determined by fiber properties, the orientation and distribution of fibers in the web, the bonding mechanism and the finishing treatments (16). Fiber selection is based on their contribution to final properties of fabric in terms of strength, elongation, thermal properties and dimensional stability. Fiber geometry plays a key role in the deformation mode of the fabric. Binder choice and bonding conditions affect the contribution of binder towards the mechanical properties of fabric.

One of the major differences between woven and nonwoven fabrics of today is the characterestically greater rigidity of nonwovens (46).

Achieving adequate drape and ideal hand without sacrificing strength of fabrics has been a major problem with adhesive bonded nonwovens (70). The properties of both woven and nonwoven fabrics are determined by a complex interaction between fiber properties, structural geometry, and in the case of nonwovens, bond properties. Although these interactions are not completely understood, the low bending rigidity of the nonwoven fabrics can be attributed, for the most part, to the bonding together of the individual fibers by the binder used in the manufacture of nonwoven fabrics (71).

Winchester and Whitwell (72) defined three types of nonwovens on the basis of their stress-strain behavior. Type I

nonwovens, obtained from poorly bonded webs, exhibited low modulus, low tenacity, and high elongation. The fabrics in this category were flexible and bulky. Type II nonwovens, from moderately bonded webs showed increased modulus and tenacity and reduced elongation. Type III nonwovens were strongly bonded fabrics which exhibited high modulus and tenacity with low elongation.

Miche et al. (73) investigated the stress-strain charecteristics and fabric drape of latex bonded viscose rayon and nylon nonwovens. The latex level on the fabric influenced the number and thickness of binder joints between fibers. The acceptable drape of the test nonwovens was achieved at a binder level that was incompatible with adequate strength. Mohammed and paek (70) found that the nonwovens with the high binder level of approximately 65% add-on displayed the highest strength but had a somewhat stiffer hand, while those with 25% add-on were bulky and soft in hand.

Freeston and Platt (82) studied the bending behavior of nonwoven fabrics, and concluded that bending rigidity is more closely approximated by a unit cell model that assumes no freedom of relative fiber motion than by the same unit cell model with complete freedom of relative fiber motion. The binder used gives them tensile strength but prevents the relative fiber motion during bending so essential to good flexibility.

On the basis of the results, the authors (71) suggest three methods of improving the bending behavior of nonwovens. In the first, the fibers must have freedom of movement between the two

surfaces. Secondly the fibers should be bonded only at the mid-plane. Finally, increasing distance between the bonding points and using fibers with improved mechanical properties should enhance the flexural charecteristics without the risk of loss in strength.

Rupture Mechanisms

There are three principal ways reported in the litrerature in which fabric might lose integrity (16, 39). They are:

1. fiber deterioration and eventual failure before adhesive or cohesive forces are affected,
2. over stressing of adhesive bonds, and
3. deterioration of cohesive forces.

Troesch and Hoffmann (74) suggest that the mechanical behavior of nonwovens is determined primarily by the fiber and the binder. In addition, quantitative binder/fiber ratio is a key factor that affects the performance of the fabric. They also report that inhomogeniety in blending is detrimental to uniform stabilization of the fabric throughout.

In an effort to assess the relative importance of fiber strength and bonding strength (includes both binder strength and the strength of the bond between binder and fiber), Michie (65) studied the fabric strength at different gauge lengths. It was noticed that at lower binder content, the strength-gauge length plot was linear down to approximately 4 cm jaw separation. Subsequent decrease in jaw

span length results in a rapid rise in strength. This strength rise becomes less pronounced as the binder content increases.

At zero or approximately zero jaw separation the strength should be independent of binder content. With nylon fabrics, this condition is realized, but with the viscose fabrics there is a significant increase in strength in passing from 9% to 42% binder. This may be due to a difference in structure in the fabric with very high binder content. As the extent of binder is increased there must inevitably come a stage where a continuous matrix of binder is formed, which would be expected to add significantly to the fabric strength (75).

The rapid increase of strength below a limiting jaw span may be taken as a diagnostic of bonding weakness. Hearle (76) reported that surface deformations in fibers, which would affect bonding strength can occur due to the relief of strain frozen in during processing.

Treiber (77) suggested a method for studying the dynamic web behavior. He modified the specimen stage of a SEM and took stepwise pictures. He observed that with low load or saturation bonded webs, deformation starts over large area and the loaded segments begin to arrange themselves in the direction of the force.In soft webs with plastic elastic binders, the failure of the material is usually produced by rupture of the binder. The failure of the material is rather complex and is characterized by partial delamination and fiber segment orientation in the direction of the stress. A gradual

rupture and destruction of the bonding junctions follows along with fiber orientation, and is coupled with some plasticizing phenomena. Bond failure starts at a relatively early stage of the deformation process and increases progressively during rupture.

In more rigid materials having a more brittle binder and strong adhesion, both fiber rupture and failure at binder cross-links occur,depending on the orientation of the fiber segments in the direction of tension.

In print bonded materials, the rupture of the web occurs in the nonprinted area, primarily by fibers slipping after the few anchoring points of these fibers in the printed area have been broken. The printed area survives with only small deformation and bond destruction from the stress. With thermoplastic embossed materials, the breaks occur partly in the central area of the embossed square and partly in the transition zone between embossed areas (78).

Imachi (59) studied the effect of bonding temperature near the melting point on the interfacial bonding strength, and the relation between the strength and the binding temperature in PE/Nylon and PP/PE. He reports that the failure mode was interfacial. PE is considered to have the lowest strength among those polymers used in his experiment. Hence, if the failure mode is not interfacial, the failure has to occur in the PE layer and the observed peel strength, should depend on the strength of PE. Accordingly, the peel strength corresponds to interfacial bond strength.

He also reports that the interfacial bonding strength has a maximum at the bonding strength in the vicinity of the melting point of the adherend and is reduced when the bonding temperature is increased above it. The mechanism has yet to be sufficiently explained.

The force needed to separate the attached components is dependent on stress concentration, the boundary layer and molecular forces across an interface, the viscosity, and the filming properties of the adhesive (79).

Deakyne et al. (30) studied the effect of quench rate during thermal bonding of heterogenous web systems. They noticed an increase in the strength with increasing quench rate, and a maxima that is reached as the draw ratio increases. He attributes this behavior to reduction in crystallite sizes and large flaws between the crystals, tending to produce stronger bonds throughout the assemblies. When the crystallisation process is completed in a very short time, the stress concentrations are frozen into structures. Competing processes apparently exist as the quench rates are increased. First crystals are refined in size,with voids and flaws throughout the mass greatly reduced. As the rate further increases, reduction in flaws diminish, but the remaining points of stress concentration have little time to relax, and the frozen stresses begin to weaken the structure.

Attempts are made to improve the mechanical properties of nonwovens without the risk of losing much drapability. Structures

such as embossed pattern bonded allow some degree of fiber movement between the bonding points, and this gives improved flexibility. However, it leads to a weak link at the interface of bonded and non-bonded regions. One possibility would be to improve the interfacial strength by the proper choice of processing parameters, and fiber surface structures, so that there would be an even distribution of the load among the fabric loading elements.

CHAPTER III

EXPERIMENTAL METHODS

The purpose of this study was to determine the tensile and flexural properties of cotton and polyester blended nonwoven fabrics that had been thermally stabilized by point-bond calendering. The properties of the fabric were expected to depend on the base fiber-binder fiber ratio as well as on processing factors. Therefore, the ratios and processing conditions were varied to study their influence on the properties of the fabric. The effect of these parameters has been characterized in terms of specific stress, elongation-at-break, specific work-of-rupture and bending rigidity. The properties were studied in both machine and cross directions.

I. FIBER IDENTIFICATION AND PROPERTIES

The base fiber used in all these studies was cotton, supplied by Cotton, Inc. It is a scoured and bleached commodity cotton, and had a reported moisture content of 5.2 %, a micronaire value of 5.4, and an upper half mean fiber length of 24.4 mm (0.96 inch). This scoured cotton is known to provide an excellent bonding surface to the polyester thermal bonding fiber.

The binder fibers used in this study were Kodel™ 438 polyester staple supplied by Eastman Chemical products, Inc. This fiber was produced from copolymers which melt and/or flow at temperatures substantially below those of conventional polyester polymer. When heated to a fluid state, these thermoplastic fibers normally contract into nodules around the cotton fiber with which they are in contact and the integrity of the binder fiber is lost. At high crush edge pressures, the melt undergoes forced flow into available interstices or away from the compression fields. The polymer is partially crystalline, with a low glass transition temperature and it has an extremely low melt flow viscosity with excellent flow properties (Table. 1). Between the softening and the

TABLE 1

KODEL™ 438 BINDER FIBER PROPERTIES

Characteristic	Value
Linear Density	3.5 denier
Staple Length	1.5 inches
Hot Air Shrinkage At 353 °K	2.0%
Melting Point	403 °K
Glass Transition Temperature	288 °K
Flow Point	388 °K

melting temperatures, the fiber swells as a result of molecular chain relaxation and becomes sufficiently tacky to provide some bonding with other binder fibers and with the base fiber.

II. WEB PREPARATION

Carding of fibers, and subsequent bonding of webs were all carried out on machinery available at the Textile Processing Laboratory of the University of Tennessee.

Opening

The fibers were opened separately using a laboratory opener-blender constructed in-house. This machine consists of a conical chamber in which four rows of toothed beater blades are positioned at right angles to each other on a centrally located rotating shaft. This beater blade system, when in motion, allows the projecting teeth to move between two rows of axially offset projections of similar geometries mounted to the conical chamber walls, thereby producing an opening/blending effect. Tufts of fibers are fed in at the smaller end of the chamber and are carried by centrifugal forces toward the larger end as they are opened by their dynamic interaction between the rotating and fixed blades. The cotton and the polyester staple fibers are fed into the opener-blender separately and the actual blending is initiated by hand just prior to carding.

Carding

The final uniform blending of cotton/polyester is completed on a Hollingsworth card, which is a modified granular card with the conventional flats installed at the licker-end of the machine. Only a partial card width is used, following procedures established by the USDA for 50 gram national regional variety tests (26). This procedure results in 18.5 cm wide, 1.5 m long carded laps of 26 layers of web using specially constructed collecting drums attached to the card. The multi-web collection system produces a well-blended sample through its many doublings. This sets the standard fiber configuration of the thermally bonded fabrics.

III. THERMAL BONDING

The thermal bonding unit is a Ramisch Kleiniwefers 600 mm (23.6-inch) width five-roll calender capable of providing smooth or point bonding. This unit is very versatile, and the temperatures of the pattern roll and its complimentary smooth roll can be controlled separately and over a wide range. The embossed roll has a diamond pattern, covering approximately 25% of the surface area. Both rolls are stainless steel, and it is possible to have a wide range of crush edge pressures.

IV. EXPERIMENTAL PARAMETERS

The experimental plan called for the examination of calender roll nip pressure and calender roll temperature on the tensile and flexural properties of four blend ratios by weight of cotton and a thermal binding fiber. Three crush edge pressures along the nip of the calender roll pair of 65, 130 and 195 kN/m were selected along with embossed roll temperatures of 408 °K (275 °F), 422 °K (300 °F), and 436 °K (325 °F). The contacting smooth roll temperature was fixed at 394 °K (250 °F) slightly below the melting temperature of the thermal binding fiber in order to prevent melting of the polyester throughout the nonwoven. the experimental design is shown in the Table 2.

Transient Heat transfer from the calender roll into the cotton/polyester blended sample establish the mechanical properties of the thermally bonded fabrics. In order to study this kinetic effect, two speeds were chosen at 10 and 20 m/min. The blend ratios of cotton/Kodel-438 polyester were 50/50, 65/35, 75/25, and 85/15 with the intent that the cotton content be maximized.

Fiber Testing

Crystallinity measurements: In order to measure the degree of crystallinity of the bonding fibers, Differential Scanning Calorimetry (DSC) was used and it works on the principles of

differential heat absorption in which a reference sample and the sample for which the crystallinity to be measured are heated by separately controlled heating elements.

The power to each heater is continuously adjusted in response to any thermal effects in the sample so as to maintain sample and reference at identical temperatures. The differential power required to achieve this condition is recorded as the ordinate on an X-Y recorder, with the programmed thermal scanning rate of the system as abscissa.

TABLE 2.

EXPERIMENTAL DESIGN

Parameter	Description			
Fiber	Cotton		Kodel 438	
Blend Ratio (C/P)	50/50	65/35	75/25	85/15
Fabric Weight (g/m^2)	160			
Temperature (°K)				
Embossed Roll	408	422	436	
Smooth Roll	394			
Crush Edge Pressure (kN/m)	65	130	195	
Feed Roll Speed (m/min)	10	20		

The calculation of the degree of crystallinity involves the measurement of the area under the melting peak. This is done above a somewhat arbitrariry base line. Then, if

ΔH_f = heat required to transform 1 gram of pure crystal to one gram of purely amorphous material,

then

% crystallinity = $\Delta H_f / \Delta H_f^\circ$.

DSC curve obtained for the Kodel 438 thermal bonding fiber is given in the Appendix (Figure A.1).

Fabric Testing: Nonwoven fabric strength properties and flexural characteristics were measured using American Society for Testing and Materials (80) standard textile testing procedures. All samples were conditioned at 65 % relative humidity and 70 °F as recommended in ASTM procedures.

Fabric strength and elongation-at-break were measured by means of the standard 4-inch (10.2 cm) gauge length tensile test, using procedures described in ASTM Method D1682-64. The results of five specimens taken from each of five bonded samples were averaged. Tensile tests were carried out in both the machine and cross directions of the fabrics. The chart speed and cross head speed

were set at 5 inches/min, thereby establishing the appropriate conversion factors.

The load-elongation curves obtained from the Instron tester provide breaking strength, elongation-at-maximum load, and total energy-to-rupture of the specimen.

The fabric tensile properties are calculated in the normalized units of specific stress (N-M/Kg) as follows:

$$\text{Specific stress} = \frac{\text{tensile strength X 9.8 X 39.37}}{\text{specific weight}}$$

$$\frac{\text{(Kgf/in) X (m/sec}^2\text{) X (in/m)}}{\text{(Kgm/m)}}$$

Specific work of rupture was calculated to characterize the energy expended in the total failure of the fabric when placed under tensile load. It is calculated as follows:

$$\text{Specific work of rupture} = \frac{\text{work of rupture}}{\text{mass/length X gauge length}}$$

$$\text{work of rupture} = \frac{\text{\# in the integrator X full scale load X 9.8 X 5 X (1/39.37)}}{\text{Kgf X (m/sec}^2\text{) X in X (m/in)}}$$

Elongation at break was calculated as follows:

$$\text{Elongation at break (\%)} = \frac{\text{gauge length (in)}}{\text{elongation (inches)}} \text{ X } 100$$

Fabric flexural rigidity, which refers to the bending resistance of the fabric, is measured according to ASTM testing method D 1368-64 using the Electric Cantilever Bending apparatus. Specimen size was 1 inch X 6 inch and five readings were taken from each set of samples. Four measurements were made on each specimen, with the embossed surface first up and then turned over.

From the mean length of overhang, the bending length and flexural rigidity were calculated following the relationships:

Bending Length, $C = O / 2$

where O - the length of the overhang in cm,

and

Flexural Rigidity, $G = W \times (O/2)^3$

where W = weight/unit area (mg/cm^2)

CHAPTER IV

RESULTS AND DISCUSSION

In an effort to understand the bonding behavior of cotton/polyester blends and the effect of processing variables, the tensile and flexural properties have been studied and summarized. To reiterate, three fabrics were produced at three different temperatures, three different pressures and two different speeds. Four different levels of base fiber-binder fiber ratios were used to determine the effect of binder content level. The results of tensile and flexural measurements are given in the tabular form.

The results show that within any blend ratio and at a chosen delivery speed, crush edge pressure is not a controlling factor, either in the machine direction or in the cross direction within the range of pressures used. This was a surprising result in light of the significant role that nip pressure contributed to the strength of the smooth roll calendered fabrics reported (81). It has been reported that the pressure has the effect of the spreading the thermoplastic binder through the structure, so that the binder will be more effectively utilized (16, 39, 58). However, in all these cases smooth rolls were used in contrast to the embossed roll calendering of the present study. Although the average force along the nip of the calendering rolls was calculated in an identical way, the actual pressures at points of pattern contact are substantially higher than

that of paired smooth steel rolls. It is quite plausible that the range of pressures chosen in this study does not influence the properties due to already existing high pressure at the embossed area. Also steel on steel at the nip of the feed rolls of the Ramisch raises the contact pressure relative to that which would be expected from the steel on rubber condition in the smooth roll calendering.

I. EFFECT OF DELIVERY SPEED

The specific stress values of the cotton/kodel 438 nonwovens are summarized in Tables 3-6. The first number in the pair corresponds to the fabric produced at 10 m/min, and the second one corresponds to the fabric produced at 20 m/min. The effect of delivery speed of the fabric through the calender on the levels of loading failure is significant for both the machine direction and the cross direction measurements as shown in figure 1. The effect of increasing bonding time has been reported to increase the extent of fiber-fiber contact due to improved wetting (16, 39). Longer bonding times cause heat setting which, in turn, imparts a degree of stability against shrinkage (16, 39). The results show that the strengths of fabrics calendered at the lower of the two delivery speeds are greater than those of similar blends and processing parameters produced at the higher rate. A higher degree of melting

TABLE 3

SPECIFIC STRESS (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 50/50 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	8553	11355	10463	3371	3976	4364
	5914	8582	8570	2829	3381	3466
130	8375	10618	11521	3522	3704	4906
	5886	7594	8639	2745	3459	3590
195	8435	10883	10720	3433	3692	4164
	5234	7918	7996	2624	3462	3251

TABLE 4

SPECIFIC STRESS (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 65/35 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	6056	8827	8220	3036	3112	3168
	5860	6025	6137	2966	3001	2935
130	11288	8965	6636	4743	2963	2918
	7547	7210	7395	3565	3327	3310
195	6205	8774	6617	3048	2887	3060
	6501	5686	6079	1938	3916	1972

TABLE 5

SPECIFIC STRESS (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 75/25 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	6089	7745	10336	3468	3899	3858
	5333	6589	9023	2675	3651	2763
130	5927	7892	10613	3233	3979	3836
	5420	7022	8319	2729	3654	3497
195	5608	7319	10670	3100	3962	3393
	5378	7122	8489	2892	3764	4049

TABLE 6

SPECIFIC STRESS (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 85/15 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	5228	6424	8324	2824	3062	3364
	2146	2966	3231	630	873	1121
130	4659	6520	6043	2653	2838	2554
	3827	3897	3636	1174	1384	1131
195	5305	6419	7234	2737	3182	3733
	3730	3846	3979	1256	1459	1495

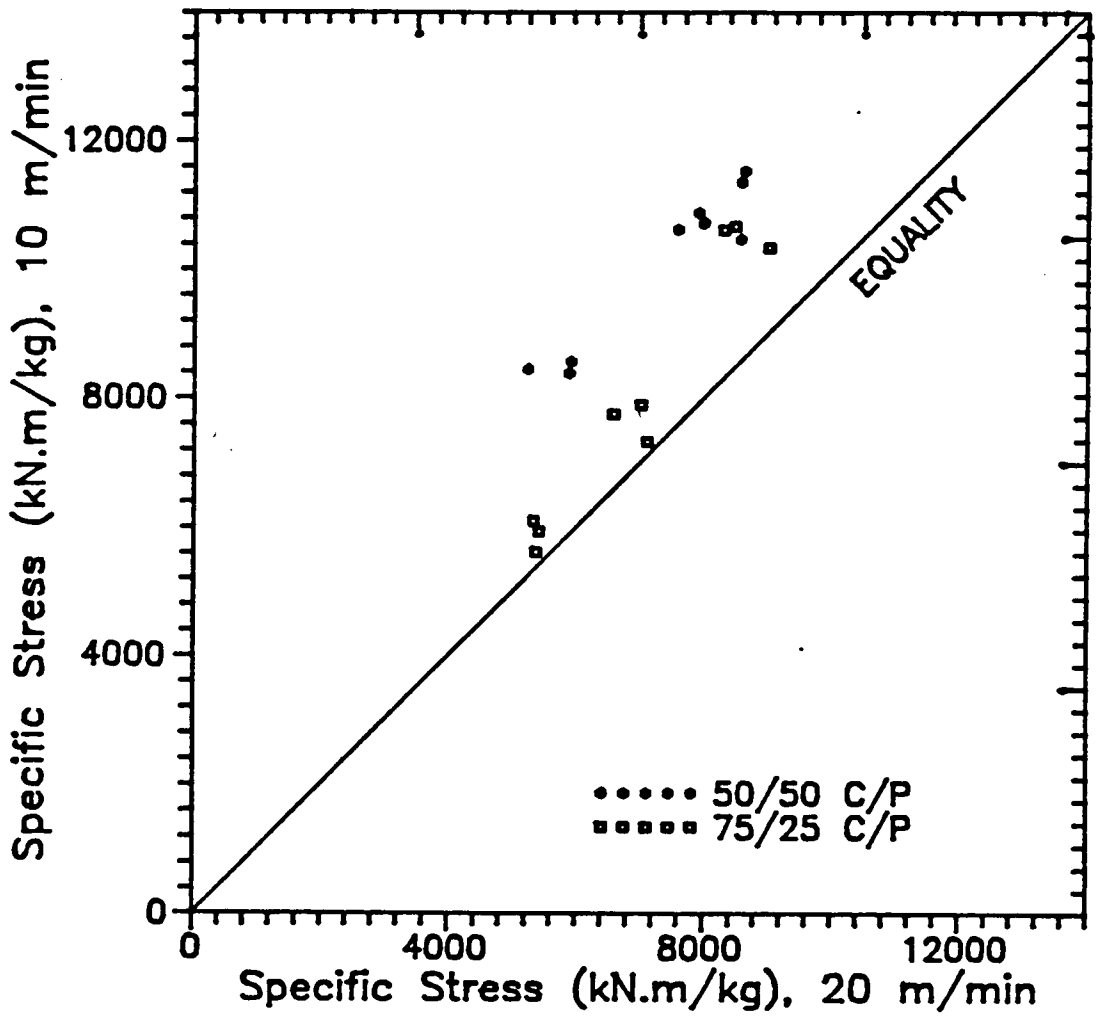


Figure 1. Comparison of Machine Direction (MD) tensile strengths of two Cotton/Polyester blend levels of fabrics calendered at two delivery speeds (10 and 20 m/min).

is observed at lower bonding speeds and enhanced spreading of the binder fibers is achieved.

The delivery speed has greater effect on breaking load when the percentage of binder fiber is large. As the percentage of the binder fiber is reduced, strength becomes less dependent on delivery speed as shown by the tendency of the 75/25 C/P specific stress data to move toward the line of equality. This is attributed to the reduced heat transfer to the thermal bonding fiber at increased speed of delivery, to differences in specific heats of two fiber types, and to their differing heat conductivities.

As this percentage of binder fiber increases, the polymer does not melt as completely throughout the layers in the nip region at high delivery rates and the strength of the fabric is substantially reduced. SEM pictures showed that the number of partially melted and non melted fibers are larger in number at the higher binder content fabric produced at higher speed. The binder does not appear to have absorbed the heat necessary to completely melt the binder fiber in the vicinity of the raised embossed pattern. The effect is easily observed when comparing strengths along machine and cross directions respectively. Machine direction refers to the direction of processing through both card and calender, whereas cross direction is that direction perpendicular to processing. Both calender delivery speeds are included in the plotted data where they are all grouped together, indicating that the speed of calendering does not affect the ratio of strength in the two directions (Figure. 2). This is not

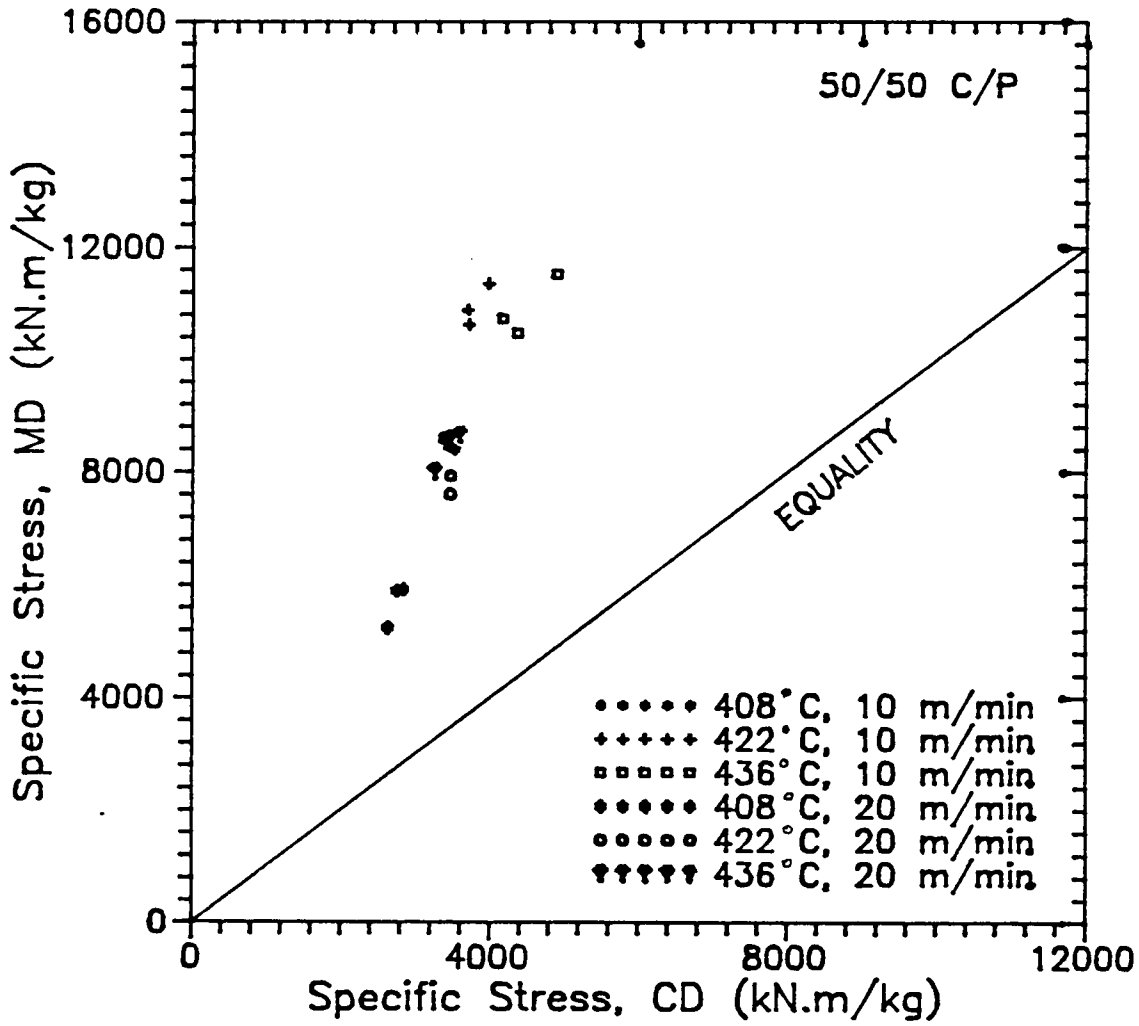


Figure 2. Comparison of MD and CD tensile srengths on 50/50 cotton/polyester nonwovens.

surprising since the orientation of the fibers is unaffected by processing speed.

The 75/25 C/P specific stresses (Figure. 3) at the lowest temperatures appear to lie slightly to the right of the 50/50 C/P results. The presence of different amounts of polyester fibers during carding could account for the slight displacement. The variability in the data is not so large as to demonstrate clearly that the fabric strengh along the MD is, on the average, somewhat more than twice as great as the fabric strength along the cross direction. Typically, light weight parallel-laid nonwovens have MD/CD strength ratios of 5/1 to 10/1.

II. EFFECT OF TEMPERATURE

The temperature plays a crucial role in establishing the loading behavior of the fabric. There is a significant effect generated by the embossed roll temperature, where an increase in temperature results in major increases in fabric strength. It has been reported that the temperature strongly influences the type and distribution of bonds(16, 39). Higher bonding temperatures have been found in these studies to produce stiffer, stronger fabrics because of the increased penetration of the binder. At higher temperatures, the binder fiber is able to exhibit more of its fluid nature and incorporate more base fibers into the bonded network (10, 32).

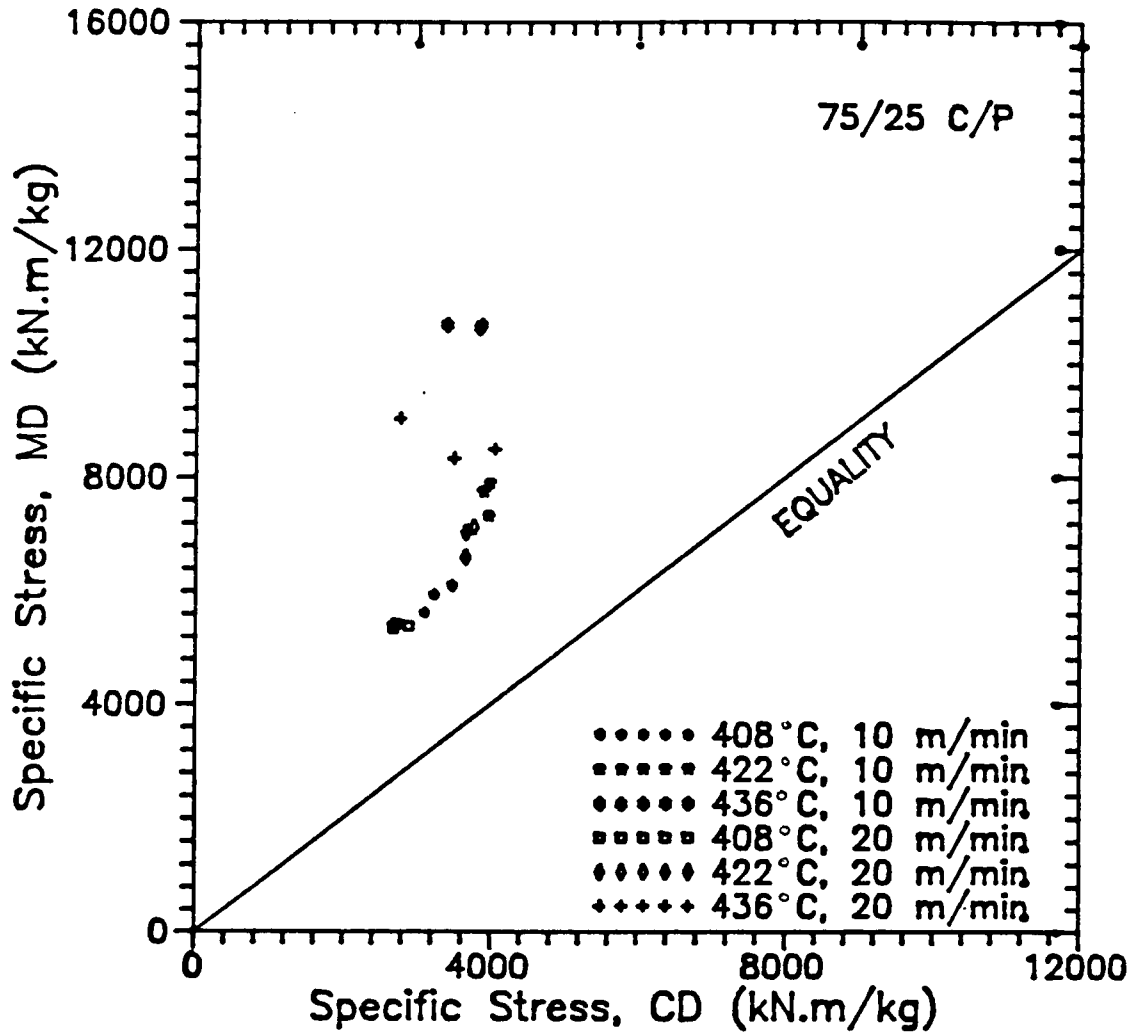


Figure 3. Comparison of MD and CD tensile strengths on 75/25 cotton/polyester nonwovens.

Generally, increases in the temperatures improve individual bond strength but can be detrimental to base fiber strength.

Fabric strength has been reported to pass through a maximum as temperature is increased. Excessively high and low temperatures are not preferable since they may lead to high stiffness or low strength. Morphological structure also changes with temperature above softening point. Molecular orientational changes in the morphology during exposure to elevated temperatures have been found to influence the bonding properties (16). Similar results were observed in the case of thermal point bonding of cotton/polyester nonwovens.

A change in temperature from 408 °K to 436 °K doubles the specific stress. The results obtained on the 50/50 blend are somewhat more complex, although the general increase in strength with increase in bonding temperature is observed. The delivery speed of the nonwoven through the calender does affect the fabric strength levels. A delivery speed of 20 m/min produces a significant loss in strength compared to strengths of fabrics produced at 10 m/min at the lowest bonding temperature. The same occurs at the two highest temperatures, although there is less effect of temperature on the fabrics within either delivery speed grouping.

The general trends of increasing fabric strength with temperature can be further illustrated with the four blends calendered at the fixed delivery speed of 10 m/min (Figure 4). The observation that nip roll pressure does not affect strength allows

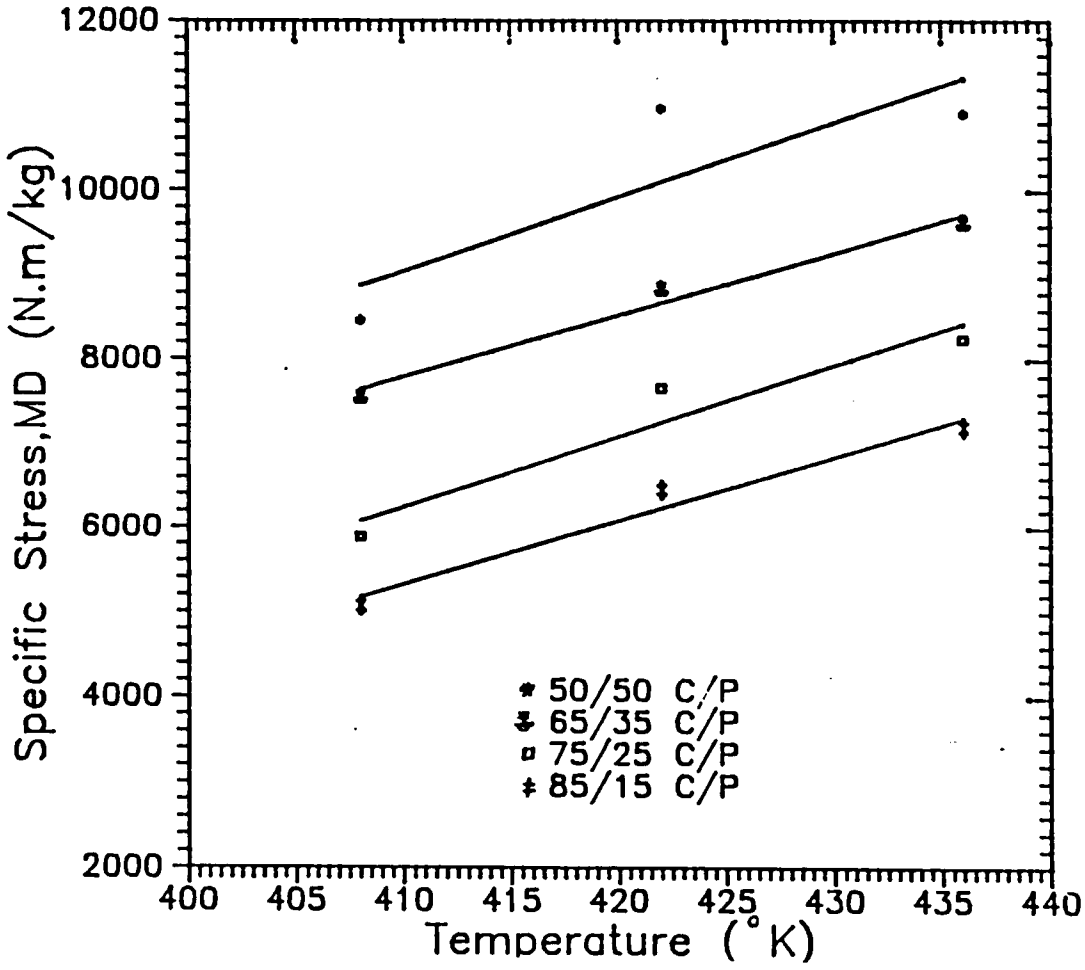


Figure 4. The effect of Pattern roll temperature and blend ratio on tensile strength.

one to average the data across crush edge pressures. Each of the three values characterizes each of the three temperatures. A smooth curve is drawn visually through the three data points of each blend family to represent blend family trends. Two results are immediately obvious, the first being that strength level generally increases with temperature and that the increase is significant. Secondly, the fabric strength values decrease with increasing cotton content. The strength of the 85/15 C/P blend is approximately one-half that of a 50/50 blend of cotton/polyester. The reasons for both of these trends may be attributed to several factors.

It has already been indicated that there is a dynamics of heat transfer that contributes to the extent to which the thermal binding fiber undergoes melting. The strength of the carded web is, when calendered, sensitive to the delivery speed through the calender. The area of embossed contact certainly remains unchanged and the only effect lies in the time of proximity of the fibrous material to the heated region between rolls. Both rolls of the calender are heated, of course, and heat is transferred into the nonwoven from both the surfaces of the fabric. The smooth roll temperature (394 °K) lies below the melting temperature (403 °K) of the polyester binder and only aids in the rate by which sufficient heat is passed into the fibrous material to the Kodel 438 copolymer. The degree of melting throughout the total thickness of the fabric largely determines the fabric strength. Additionally, the extent to which melting is complete increases with embossed roll temperature. Hence, strength

increases with increased embossed roll temperature as observed. SEM photographs of fabrics produced at two different temperatures show that there is a relatively high degree of melting across the section of the bonded web at the higher temperatures and at the feed speed of 10 m/min.

III. EFFECT OF BLEND RATIO

Binder concentration affects the flexural rigidity as well as the strength characteristics of a nonwoven fabric. At higher binder concentration, an increase in binder content causes an increase in the strength.

The decrease in fabric strength with changing blend ratio is not quite so obvious, because at least two factors are involved. The first of these is fiber load bearing behavior and the second is the quantity of the polymer contributing to bonding at the points of embossing.

In staple nonwovens of low binder content, bonding increases the average effective length of the fibers. Bonding of the fibers together has also been reported to change the effective distribution of fiber lengths in the web.

In the study of smooth roll calendering of the same fiber blends, it was observed that the cotton fibers did not fail during loading, but that tensile failure occured as a result of the fibers

pulling away from the encapsulating polymer melt. A minimum force is required to accomplish this and the ultimate fabric loading will involve the total number of load supporting fibers, be they cotton or polyester. Consider the two extreme blends of 50/50 C/P and 85/15 C/P. The linear density of the binder fiber is approximately twice that of the cotton. Thus, the total length of the combined fiber is 1.5 times the length of the cotton alone. If this latter length is denoted L_0 then the combined length is 1.5 L_0. In contrast, the total length of fiber in the 85/15 blend will calculate to $1.8L_0$, an increase of supporting fiber of 20 %. From the reasoning above, this would imply a strength of the 85/15 to exceed that of the 50/50 blend fabric by 20%. This, obviously, is not the situation. The directions are, in fact reversed.

The other factor that controls strength is the amount of polymer contributing to each area of embossing and this, too, depends on the blend ratio. For a 50/50 C/P blend by weight, the amount of co-polymer equals the cellulose by weight at each embossed point. As the blend ratio is changed to 85/15 C/P by weight, the amount of binding polymer is reduced by 70 %. Furthermore, if the amount of polymer directly determines the ultimate strength of the bonds of the encapsulated support fibers, then the strength would be expected to drop by nearly 70 % as the fabric blend is changed from a 50/50 ratio to an 85/15 ratio. This is, indeed the direction of the strength loss observed in the data although the strength loss is not so drastic. But when this argument

is combined with that of the fiber load bearing behavior, the losses are quite reasonable. Therefore, the opposite effects produced by the increased number of fiber support elements and the decreased quantity of binder fiber as the blend ratio is varied from 50/50 toward 85/15 accounts reasonably well for the fabric strength behavior. This, combined with the dynamics of the heat transfer, gives a more complete picture of the tensile properties of pattern roll calendering of cotton/kodel-438 nonwovens.

The response of elongation to either machine or cross directions on the fabrics is perhaps as expected. The elongation values measured at the maximum stress are listed in Tables 7-10. Overall, the elongation in the cross-direction is slightly greater than the elongation in the machine direction, with a few exceptions. Most of the data lies beneath the line of equality (Figure 5), suggesting that the initial orientation distribution fibers undergoes a distinct re-orienatation before tensile failure occurs. The ratios of elongations in the two directions is rather independent of blend ratio, with perhaps the exceptions where the processing temperatures have been highest. There is possibly a branching at the higher elongations, although there is not a clear separation. At the highest temperature, the 75/25 C/P blend fabrics show greater elongations in the machine direction than they do in the cross-direction. This was the more common observation in smooth roll calendering and was attributed to the greater number of load supporting fiber elements for machine-direction loading, generating

TABLE 7

ELONGATION (%) AT MAXIMUM STRESS OF COTTON/KODEL 438 NONWOVENS OF 50/50 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	13	20	19	18	22	30
	12	24	19	13	21	23
130	13	19	19	18	22	25
	15	18	13	19	24	22
165	12	19	19	17	25	26
	11	15	18	13	19	24

TABLE 8

ELONGATION (%) AT MAXIMUM STRESS OF COTTON/KODEL 438 NONWOVENS OF 65/35 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	24	18	24	29	32	29
	11	11	11	14	13	14
130	23	16	24	27	31	24
	17	16	12	16	15	14
195	24	18	22	22	25	23
	14	13	14	16	15	16

TABLE 9

ELONGATION (%) AT MAXIMUM STRESS OF COTTON/KODEL 438 NONWOVENS OF 75/25 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	7	16	22	9	13	26
	5	20	18	8	12	13
130	6	11	22	9	12	25
	6	9	22	8	12	13
195	6	9	19	9	13	17
	5	11	20	8	12	20

TABLE 10

ELONGATION (%) AT MAXIMUM STRESS OF COTTON/KODEL 438 NONWOVENS OF 85/15 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	8	12	16	10	10	13
	7	7	5	7	8	7
130	15	19	23	11	13	13
	7	7	7	8	10	8
195	8	23	22	9	9	10
	8	12	8	8	10	11

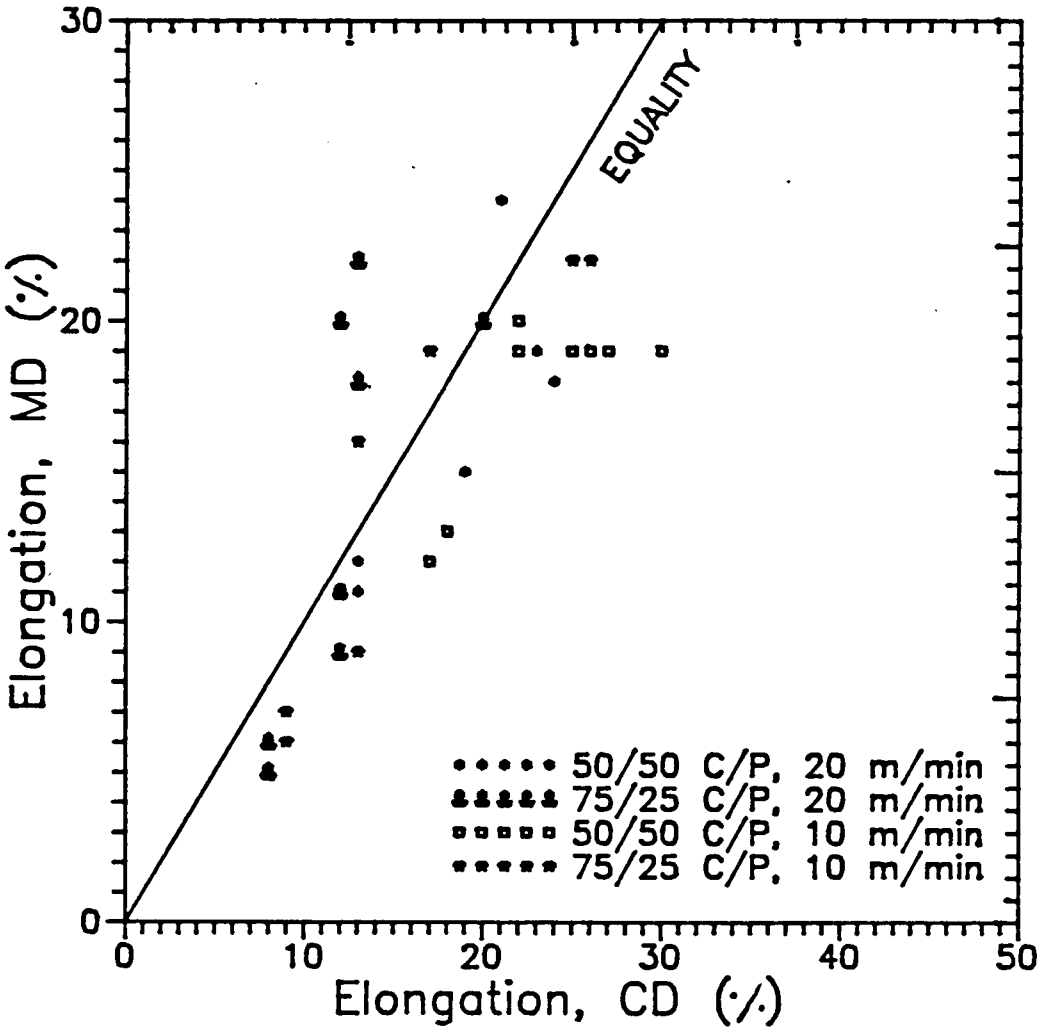


Figure 5. The effect of direction (MD versus CD) on the extensibility properties of 50/50 and 75/25 C/P blended fabrics.

a lower load per fiber (81). It is possible that the lower content of polyester in the 75/25 C/P would result in enhanced bonding between available polyester fibers and produce an effect on loading different from the 50/50 blend fabrics.

The fabrics consisting of a 75/25 C/P blend ratio have lower elongations than those of a 50/50 blend ratio and there is little effect of calender delivery speed on those elongations. The percentage of polymer binder at the embossed points has been seen to be the major factor in the fabric strength. This result has been reflected over into extension to failure where a reduction in the polymer holding the matrix fiber lowers the ability of fibers to realign prior to the failure of the fabric. The distribution of data near the line of equality would suggest that fiber orientation is a small factor toward setting extension behavior.

Energy-to-rupture is a property that characterizes the total energy expended in the failure of the fabric when placed under tensile load. It, of course, includes the energy that has been required to reach maximum loading at which specific stress and elongation have been determined. Additionally, it represents the energy that has gone into the total fiber breakage and bond failure, as well as unrecoverable elastic losses. Results of the energy-to-rupture measurements are reported in Tables 11-14. In the case of this study, it is concluded that the prime contributor to fabric failure has been bond failure and that the matrix fibers remain essentially intact. The results (Fig. 6) of the total energies involved

TABLE 11

SPECIFIC ENERGY-TO-RUPTURE (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 50/50 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	879	1863	1654	536	746	1168
	664	1815	1503	375	773	862
130	904	1660	1815	612	703	1244
	633	1246	1579	361	634	773
195	872	1666	1772	580	843	972
	578	1219	1390	325	575	727

TABLE 12

SPECIFIC ENERGY-TO-RUPTURE (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 65/35 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	2319	1289	2342	1142	923	1262
	579	577	564	324	306	329
130	2166	1233	2450	1219	804	1336
	1263	1114	1153	479	500	449
195	2299	1389	2307	1100	663	1183
	815	846	779	337	296	337

TABLE 13

SPECIFIC ENERGY-TO-RUPTURE (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 75/25 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	413	1362	1897	296	522	932
	317	1296	1463	235	470	496
130	391	1118	1942	269	483	927
	378	1376	1704	201	519	477
195	370	1002	1700	248	504	720
	352	1113	1628	251	476	578

TABLE 14

SPECIFIC ENERGY-TO-RUPTURE (N.M/KG) OF COTTON/KODEL 438 NONWOVENS OF 85/15 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	714	803	947	475	368	419
	134	225	232	57	83	107
130	1430	1219	1226	477	443	379
	256	288	254	104	131	101
195	963	1325	1239	3886	516	460
	691	966	869	337	373	409

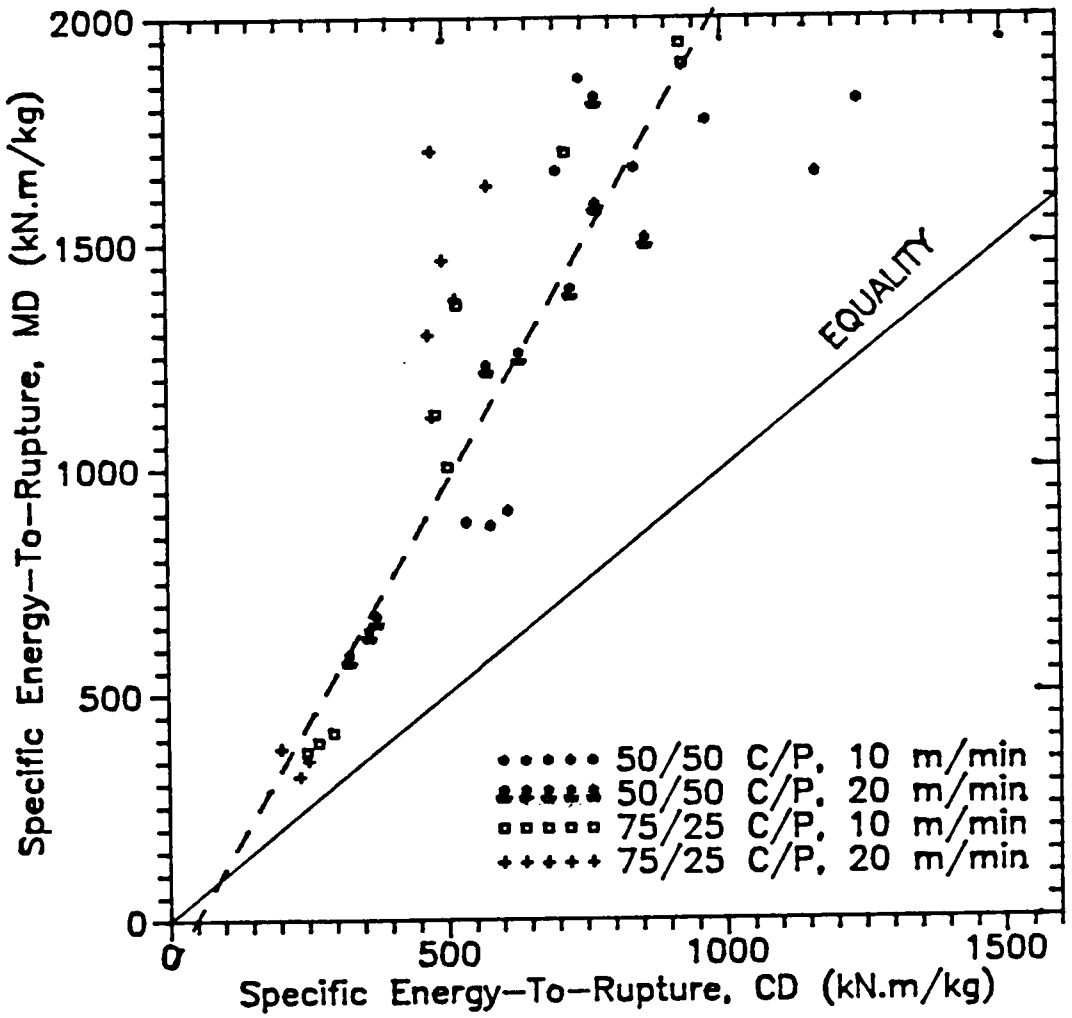


Figure 6. The effect of direction (MD versus CD) on the energy-to-rupture properties of 50/50 and 75/25 C/P blended fabrics.

in fabric rupture show an asymmetry in the two directions of loading. The energy to rupture of the fabric is significantly greater in the machine direction. This is to be expected because of the similar asymmetry in specific stress (Fig. 2), while moderated by the small reverse effect in elongation.

The cause for the asymmetry may also be argued from the standpoint of bonds from calendering and from the number of individual load bearing fibers intersecting an imaginary line across the width of the test strip. The number of load bearing fibers is reduced for cross-direction tensile tests in comparison to the machine direction because of the asymmetric distribution in.fiber orientation generated by the carding process. Since the cumulative energy involved is directly proportional to the number of fibers separated from the bonds and to the total number of bonds per fiber that must be broken, the energy should be proportionately reduced in the cross-direction from that observed in the machine-direction. The ratio of energy-to-rupture in the machine-direction to the energy-to-rupture in the cross-direction is approximately 2:1. This would predict a failure of twice as many bonds in the machine-direction compared to the number that failed in the cross-direction.

Fabric stiffness is represented in terms of flexural rigidity. Flexural rigidity measurements are reported in Tables 15-16. The results demonstrate that the fiber orientation asymmetry within the fabric, the blend ratio, the processing parameters, the thermal treatment, and the embossing roll all significantly control the

TABLE 15

FLEXURAL RIGIDITY (G.CM) OF COTTON/KODEL 438
NONWOVENS OF 50/50 BLEND RATIO

Pressure (KN/M)	Temperature (°K)					
	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	1270	3720	3616	1300	1110	912
	1270	3370	3853	1400	1140	1114
	1710	2100	3340	470	640	788
	3000	2500	2590	810	790	1461
130	1390	2100	3423	580	750	1689
	1540	2700	3677	130	910	1539
	1700	1850	2802	780	530	670
	2800	2310	2590	170	750	1194
195	1830	2400	3259	530	630	919
	3100	2500	2680	110	780	1194
	1680	2700	2455	580	920	788
	2800	2500	2455	1490	1230	1182

TABLE 16

FLEXURAL RIGIDITY (G.CM) OF COTTON/KODEL 438
NONWOVENS OF 75/25 BLEND RATIO

	Temperature (°K)					
Pressure (KN/m)	408	422	436	408	422	436
	Machine Direction			Cross direction		
65	1610	2900	2441	600	700	974
	5700	4500	4257	3700	2400	1880
	1900	2600	2579	960	840	955
	3000	3300	5092	2400	2700	1768
130	2450	3100	3784	730	715	1144
	5300	5400	5317	2900	2600	2056
	2310	2300	3183	2960	817	1056
	3810	3800	5203	3460	2430	1938
195	2900	700	2796	860	660	785
	5500	2400	4831	2820	2100	1801
	2370	3100	2947	920	750	1190
	4250	4400	4767	2500	3020	1938

flexural behavior. First it is observed that the stiffness of the fabric is greater in the machine direction than it is in the cross direction. This difference is close to a factor of two, indicating that the effective number of fibers that undergo bending is greater by a factor of two for machine direction flexure. This factor of two has risen in the previous context of specific strength, where it was used to interpret the tensile loading differences in the two directions. So this result of fabric stiffness is not unexpected.

Fabrics of a 75/25 C/P blend appear to be stiffer than fabrics comprised of a lower cotton content, especially in this case where bending is in a direction to give a convex embossed surface (Figure 7). Figure 8 represents the opposite case where bending produces a concave embossed surface. The differences are not so distinct under this latter condition, where both blends cover the same range. The total range of the latter, however, is much less than the former situation. In both cases, the stiffness increases with increasing temperature. This is a result of more complete bonding.

The effect of bend curvature of a fabric on its stiffness is further shown by graphing the flexural rigidity of one configuration against that obtained by bending of the fabric in the opposite sense (Figure 9). There is a depth asymmetry in bonding and fiber geometry profiles within the fabric caused by a pair of calendering rolls, one of which has an embossed surface and the other which has a smooth surface. Embossing produces a cavity in the fabric, with the bonding region at the bottom of cavity and in the near neighbourhood of the

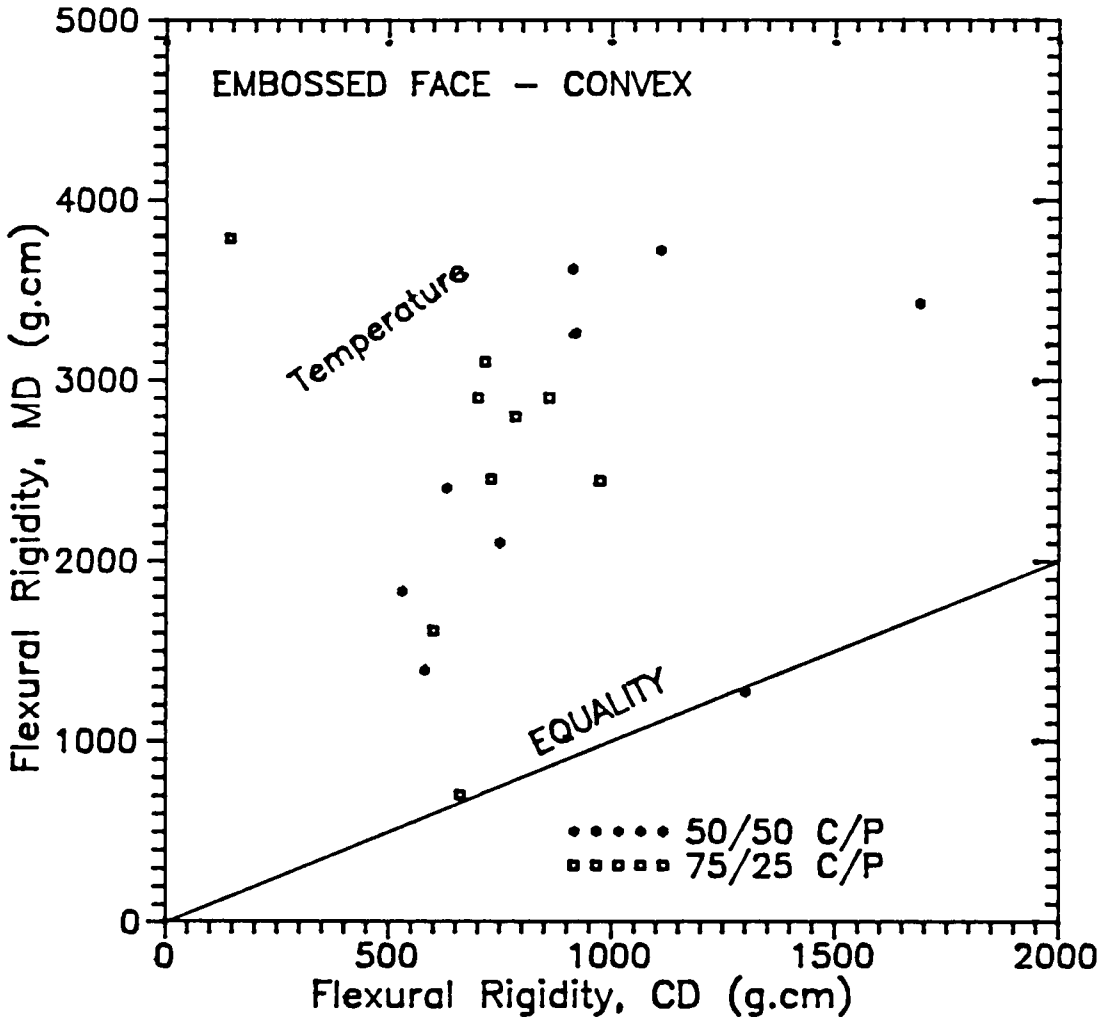


Figure 7. Comparison of fabric stiffness in machine and cross direction (embossed surface up and convex) at 10 m/min delivery speed.

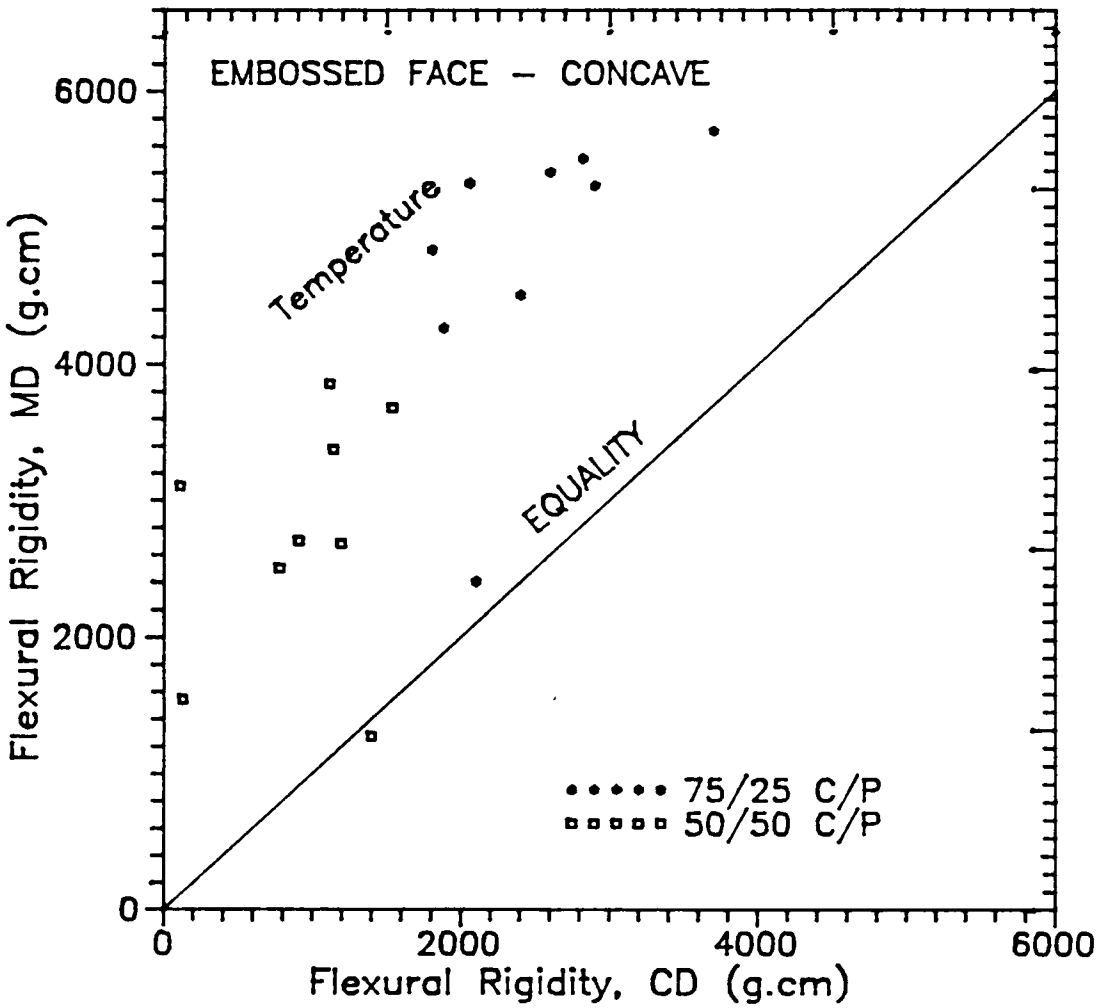


Figure 8. Comparison of fabric stiffness in machine and cross direction (embossed surface down and concave) at 10 m/min delivery speed.

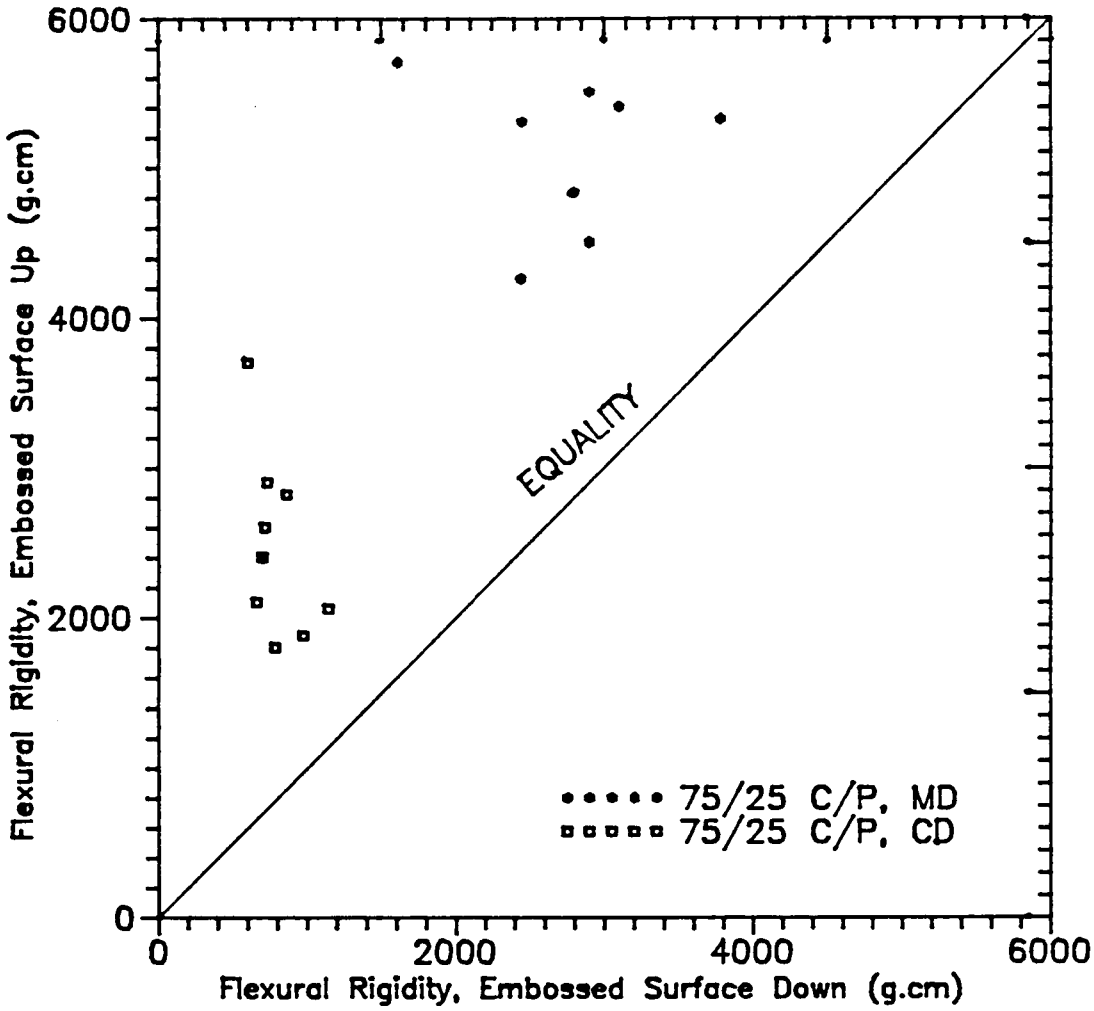


Figure 9. The effect of direction of flexure on fabric stiffness.

fabric surface in contact with the smooth roll. Thus the fabric has a dimple-like pattern which is prominent on the embossed surface. There is a smaller dimple-like pattern on the back surface which is apparently produced as the fibers readjust following passage through the nip region. The flexural rigidity is almost always greater when bending results in a convex embossed surface. This is explained by reasoning that the fibrous mass is more easily distorted on a small scale by compression rather than by extending fibers.

The tensile and flexural properties of thermally bonded nonwovens are dependent on both the processing factors as well as on the binder content. The interaction between these two factors generally accounts for the variations in the performance behavior of these fabrics. For instance, higher temperatures lead to stiffer fabrics as the result of better bonding. At a given temperature, binder concentration plays an important role since the bending behavior of the fabric is directly related to the bending behavior of the constituent fibers and the bonding characterization.

The three dimensional plots (Figure 11-13) summarize the effect of interaction of processing factors and base-binder fiber ratio. In any case, the processing parameters strongly affect the nature of the bonding between the fibers. The bonding in these fabrics is achieved primarily through the adhesive forces acting between base and binder. The physical entanglement of the base fibers arising out of the fiber nature and carding is another

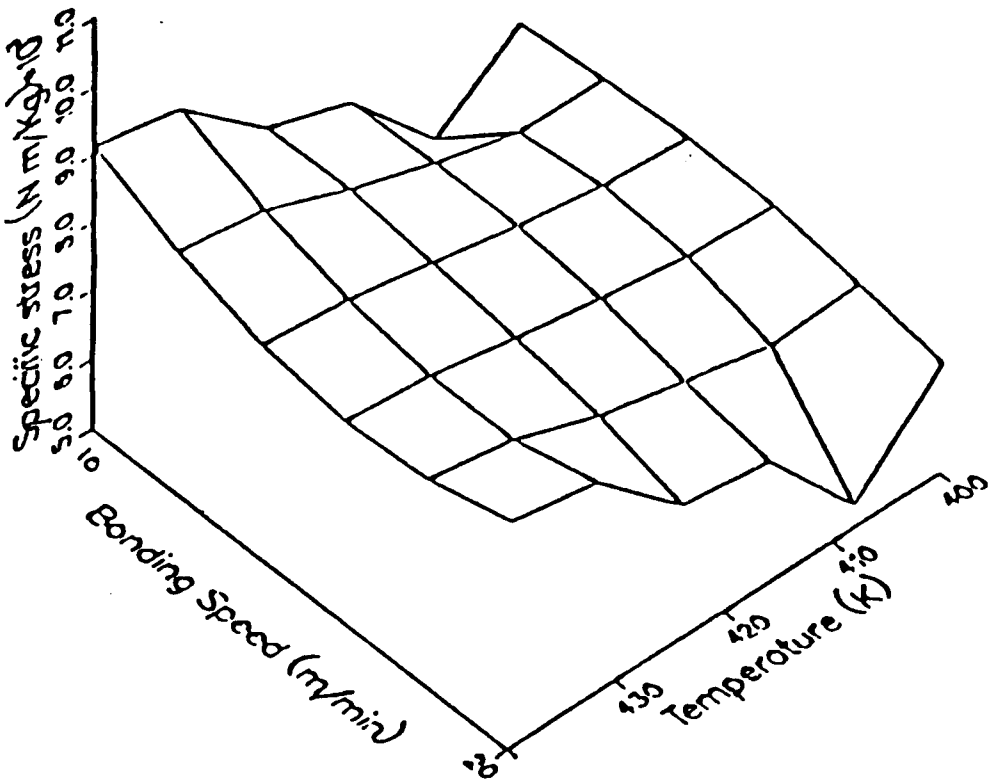


Figure 10. The effect of bonding speed and embossed roll temperature on fabric strength (specific stress).

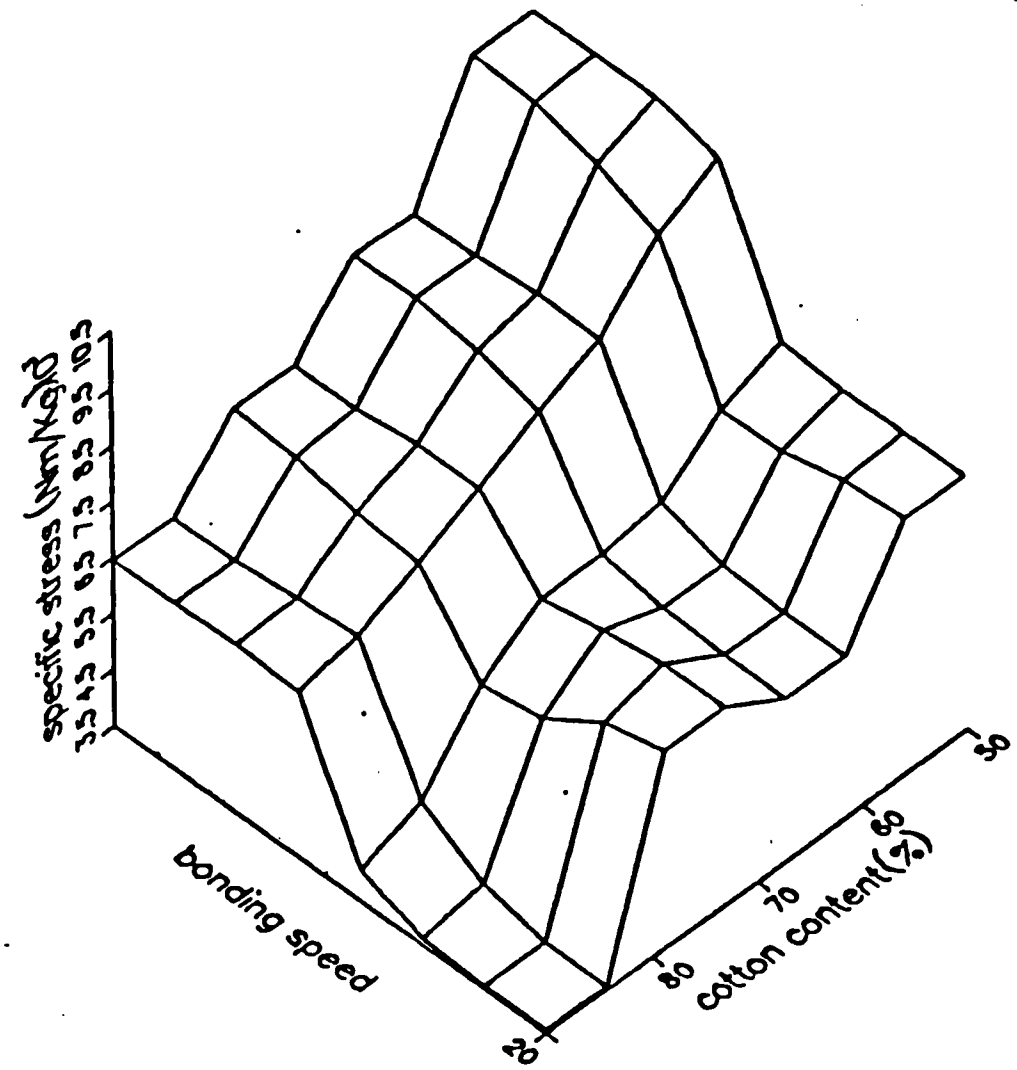


Figure 11. The effect of bonding speed and blend ratio on fabric strength (specific stress).

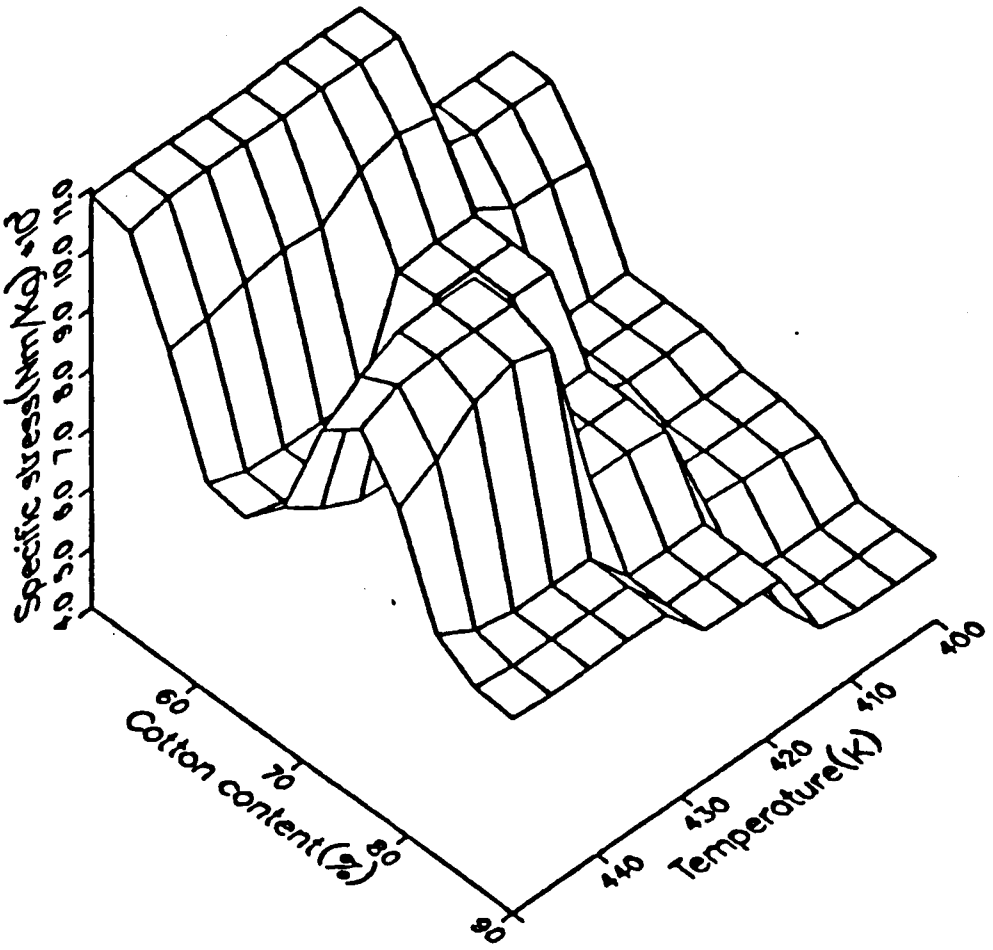


Figure 12. The effect of embossed roll temperature and C/P blend ratio on fabric strength (specific stress).

contributing factor to the bond strength. The adhesive strength at the crossover points is certainly less than the fiber strength, and therefore, the likelihood of fiber rupture is low. The rupture mechanism can be either interfacial failure in which slippage occurs or the binder may rupture. In thermal bonding, stresses are introduced at the interfaces due to binder solidification/ recrystallization. In the point bonded structure, the binder fibers are well distributed due to carding process and well spread around among the base fibers due to the application of heat and pressure. This reduces the possibilities of binder rupture and leaves the interfacial rupture or fiber slippage as the probable mode of failure. The interfacial properties can be improved through the proper choice of bonding conditions. The bonding history determines the structural attributes such as degree of crystallinity and spherulite size and the ultimate performance behavior.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to examine the tensile behavior of point bonded cotton/polyester nonwovens. Three different temperatures, three different crush edge pressures and two delivery speeds were used in this study to understand the effect of processing factors. Also four different base-binder fiber ratios were used to determine the influence of binder content.

The physical and mechanical properties studied included specific stress, specific work-of-rupture, elongation-at-break (%) and flexural rigidity.

The results demonstrated that nip roll pressures in the range of 65-195 kN/m did not influence the tensile behavior of the fabrics. This may not have been the case had the range been between 0-65 KN/m. The crush edge pressure has the effect of spreading the thermoplastic binder fiber and increasing the contact area for heat transfer as demonstrated previously in the smooth roll calender. However, the actual pressure is quite high at points of contact in the pattern roll calender. Therefore, the range of pressures does not show any significant effect.

Calender roll temperatures had a major effect on the properties as did the delivery speed through the calender. Roll temperatures and delivery speeds both influence the heat transfer into the fabric and,

thereby; influence the degree of melting of thermal binding fiber in the bonding region. The increase of temperature from 408 °K to 436 °K on the embossed roll significantly increases the fabric's specific stress. The SEM pictures show the higher degree of melting and spreading of the binder fibers at higher temperatures. This leads to better bonding characteristics and load bearing behavior.

Fast delivery speed reduces the extent of melt and, thereby, reduces the bonding of the matrix fiber consisting of cotton and unaltered polyester. Both fibers contribute as load bearing elements in the fabric. The strength becomes less dependent on the delivery speed at the lower levels of binder content since complete melting of binder fiber occurs irrespective of delivery speed. The failure of the fabric appears to result from shearing of the encapsulating or melted polymer rather than through fiber breakage.

The results also showed that the fabric strength increases with increasing level of binder content. The ability of the fabric to elongate under load is tied also to the thermal conditions of processing, with a minor influence from fiber orientation distribution function. Fiber orientation also affects the stiffness of the fabric, along with the depth profile produced by embossed calendering. Increase in temperature leads to an increase in the stiffness of the fabric. The differences of stiffness resulting from opposing modes of flexure in the fabric are attributed to compression versus expansion behavior of the fibrous materials.

The results of this study call for a detailed study in the area of morphological changes in the binder fibers with bonding temperatures and speed. The surface morphology of binder fibers may be an influencing factor in the adhesion mechanism between binder and base fibers.

Development of a testing technique and instrument to study the adhesive nature of the bond will be very useful in the selection of binder type and binder content. This would also lead to a better understanding of the rupture mechanism under tensile loading.

Another viable area would be to study the heat transfer kinetics during thermal bonding. The amount of heat passing through the fibrous web as a function of temperature, time and pressure can be useful in optimising the processing parameters for different fibers.

LIST OF REFERENCES

1. Smith, P., Textile Horizons, 4, 27-35 (1988).

2. Holliday, T., Industrial Fabric Products Review/Buyers Guide 1, 3 (1983).

3. "Special Report: Thermal bonding" Textile World, 12 (81) .

4. "Cotton the King" Nonwoven Industry, 1, 8 (1988).

5. Vaughn, E. A., Nonwoven Industry, 4, 24 (1987).

6. Holliday, T., "The cotton flower is blooming" Nonwoven Industry,12 (1988).

7. Krcma, R., Manual of Nonwovens, Manchester, England. Textile Trade Press, 1971.

8. Allan G. G., C.W. Ingalls, Cellulose Chemistry and Technology, 10, 801 (1976).

9. Batra, S. K., On Properties of Fibers as Structural Elements in Nonwovens, Proceedings of the Tenth Technical Symposium, INDA, New York, Nov. 1982.

10. Cox, C. S., British Journal of Applied Physics, 3, 72 (1952).

11. Cusick, G. E., J. W. S. Hearle, R. I. C. Miche, R. H. Peters, and P. J.Stevenson, Journal of the Textile Institute, 54, 52-74 (1963).

12. Hearle J.W.S., A. Newton, Textile Research Journal, 38, 343-351 (1968).

13. Besso, M. M., G. E. Gillberg, D. E. Stuetz, Textile Research Journal, 52(9), 587 - 592 (1982).

14. Schroder, S. K. N. Korchan Textiltechnik, 28, 636 (1978).

15. Korchan, N., Tech. Text., 22, 123 (1979).

16. Shimalla C. S., J. C. Whitwell, Textile Research Journal 46, 513- 518 (1976).

17. Allan, G. G., "Binder-Fiber Interactions in Nonwovens" Theory Design of Wood and fiber Composite Materials B. A. Jayne Ed., pp 299-326, ch. 12, 1972

18. Treiber. E., Tappi, 61(4), 87-90 (1978).

19. Moffett, R., Nonwoven Fabrics: New Bonding Techniques, Modern Textiles, 37, 62- 65 (1956).

20. Landoll, L. M., B.J. Hosfetter, "Polypropylene fibers and Textiles IV" Plastics and Rubber Institute, Manchester (1984).

21. Barounig. J., Modern Nonwovens Technology, D. T. Ward, Eds., Nonwovens Report(Texpress), Manchester., 1977.

22. Purdy, A. T., Developments in Nonwoven Fabrics, Textile Progress, 12(4) Scott Brothers, London, 1983.

23. Bayer, J., "Long Fiber Air-Laid Processes and Structure", Nonwovens Workshop, The University of Tennessee, Knoxville, 1987.

24. Harvey, B., D. E. Wood Nonwovens '71. Peter Lennox-Kerr Eds. The Textile Trade Press, Manchester, England 1971. pp 33-61.

25. Drelich, A., "Nonwoven Textile Fabrics" Encyclopedia of Chemical Technology., Vol.16, John Wiley & Sons, Inc. 1981.

26. Landstreet, C. B., P. R. Ewald and H. Hutchens, Textile research Journal, "The 50-gram Spinning Test: Its development and Use in Cotton-Quality Evaluation," 32, 665-669 (1962).

27. Trott, D. W., and F. L. Scardino, Textile Research Journal, 39, 1041 -1037 (1969).

28. Petterson, D. R., S. Backer, Textile Research Journal , 30, 704- 711 (1960).

29. Hearle, J. W. S., V. Oznaslav, Journal of the Textile Institute, 70, 439 - 451 (1979).

30. Kallmes, O. J., Theory and Design of Wood and Fiber Composite Materials, B. A. Jayne,ed., New York: Syracuse University Press, pp. 177 - 196, 1972.

31. Scardino, F. L., W. J. Lyons, Textile Research Journal, 40, 559 - 570 (1970).

32. Hertel, K. L., and R. Lawson, Journal of the Textile Institute, 70, 439- 451 (1979).

33. Krull, M. J., "Gravimetric feeding - A means to precision web control" G. E. Cusick, Eds., UMIST, Manchester, 1980.

34. Bickermann, R., The Science of Adhesive Joints, Academic Press, New York, 1968.

35. Owens, D.R., 'Estimation of Surface Free Energy of Polymers, Journal of Applied Polymer Science, 13, 1741-1747 (1969).

36. Voyutskii, S.S, and Vakula V.L., The role of diffusion phenomena in polymer- to- polymer Adhesion, Journal of Applied Polymer Science, 7, 475 - 491 (1963).

37. Iyengar, Y., and Erickson D. E., Role of Adhesive - substrate Compatibility in Adhesion. Journal of Applied Polymer Science, 11, 2311 - 2324, 1967.

38. Schonhorn H., Frisch, H.L and Kwei T.K Kinetics of Wetting of surfaces by Polymer Melts, Journal of Applied Physics, 37, 4967-4973 (1966).

39. Shimalla C. S and J.C. Whitwell, Textile Research Journal , 46, 513- 518, 1976.

40. Coke, C. E " Nonwoven fabrics" Chem. & Industry., 10 (1569 - 76), 1958.

41. "Nonwoven Fabrics", Handbook of Adhesives, Irving Skeist ed., NY: Reinhold Publishing 1963, 647 - 661, Ch. 58.

42. Meazey, A.E. " Binders used in bonded fabric production" proceedings of the Nonwovens '71 symposium, 63 - 71.

43. Alner, D.J., "Conference On the Aspects of Adhesion" Northampton College of Advanced Technology, University of London Press, 1968.

44. Hearle, J. W. S and A. Newton Textile Research Journal, 38, 488 - 486 (1968).

45. Miche, R.I.C Textile Research Journal, 36, 501 - 505 (1966).

46. Hearle, J. W. S, Miche, R. I. C, A. Stevenson. Textile Research Journal, 34, 275 - 282 (1964).

47. Moser, V. J., American Dyestuff Manufacterer, 53, 38 (1964).

48. Hearle, J. W. S , and A. Newton, Textile Research Journal 491 (1967).

49. Tikhomirov V. B, Chupryminov O. I, and Ovchinnikova S. A Tech. Text Industry USSR, No. 5 22-25 (1969).

50. Rigdahl, M., and Alf DeRuvo "The effect of cellulose -solvent interaction on the mechanical properties of Bonded fiber structures", Journal of Applied Polymer Science, Vol. 29, 187-195 (1984).

51. Olivieri. P., M.Branchesi, T. Ricupero, Polypropylene Fibers and Textiles IV Plastics and Rubber Institute Manchester, pp 40/1 to 40/10 (1984).

52. Philip, P., Nonwovens World, 81 - 96 (1986).

53. Harris, F. O, Nonwoven Industry, 9-13, 12 (1982).

54. Urquart, J. L., Jr. "Polyester Adhesive Fibers" Nonwovens Workshop, The University of Tennessee, Knoxville, 1987.

55. Kazumune Nakao, Journal of Adhesion, 4, 45 - 102 (1972).

56. Hubbel, D. O., J.C. Whitwell, Textile Research Journal, 40, 521 (1970).

57. Brushwood, D.E., Textile Research Journal, 58, 309-317 (1988).

58. Muller, D. H., "Carding and Thermobonding of Nonwovens" Nonwovens Workshop, The University of Tennessee, Knoxville, 1988.

59. Imachi, A. "Effect of bonding temperature on the interfacial bonding strength of PE/PP and other polymers," Journal of Polymer Science Part C: Polymer Letters, 24, 537 - 540 (1988).

60. Gibson, P. E., and R..L. McGill, Proceedings of the 1987 TAPPI Nonwovens Conference, Apr. 1987.

61. Goraffa. A.A-M., J.P. Crane, Y. Iyengar and W.K.Kwok, "Polyester staple for Thermally bonded nonwovens. Proceedings of the 13th Annual tech. symposium of INDA, 246-266 (1985).

62. Wei, K. Y., T. L. Vigo, B. C. Goswami, Journal of Applied Polymer Science, 30, 1523-34 (1985).

63. Fraser, W. A, J. C. Whitwell, and Bernard Miller Textile Research Journal, 43, 123-128 (1973).

64. Barish, L. The study of cracking and fracturing of spherulitic isotactic polypropylene, J.A.P.Sc, 6, 617-623 (1962).

65. Mukhopadhyay, S.K., and P. W Foster, Polypropylene Fibers and Textiles IV Plastics and Rubber Institute Manchester, pp 42/1 to 42/7 (1984).

66. Huson M.G., McGill W. J, J. P. Sc., Polymer Chemistry Edition 22,No.11 Part2, 3571 - 80, 1984.

67. Jaffe, M., in Thermal Methods in Polymer Analysis, Shalaby S. W. Eds., Franklin Institute Press, Philadelphia, U S A,1977.

68. Mukophadyay, S. K., "Effect of Moisture on Thermal Bonding" Proceedings of the Sixteenth Technical Symposium, INDA, New York, May 1988.

69. Rebenfield, L., C. K. Deakyne, J. C. Whitwell, "The strength of interface bonds. " Proceedings of 1976 INDA Technical Symposium, 263 - 278 (1976).

70. Paek, S. L., and M.H. Mohammed, Textile Research Journal, 48, 281 - 286 (1978).

71. Miche, R. I. C., Textile Research Journal, 33, 458-471 (1973).

72. Winchester, S. C., and J. C. Whitwell. Textile Research Journal, 40, 458-471 (1970).

73. Miche, R.I.C., R.H. Peters and W. Taylor. Textile Research Journal , 3, 325-329 (1963).

74. Trosech, J., and G. Hoffmann, TAPPI , 59, 8 (1976)

75. Philip, P., Nonwovens World, 6, 26 (1978).

76. Hearle, J. W. S. Textile Institute and Industry, 5, 232 - 234 (1964)

77. Treiber. E, TAPPI, 18, 61 (1978).

78. Deakyne, C. F., L. Rebenfield and J C Whitwell. Textile Research Journal, 47, 491-494 (1977).

79. Vaughn E.A., and R. C. Brannon, "A Dynamic Study Of Relative Binder Effectiveness in Dry-Laid Polyester Nonwovens. " Proceedings of the 1976 INDA Technical Symposium., 81-92 (1976).

80. American Society for Testing and Materials, 1977 Annual Book of ASTM Standards, Part 24, American Society for Testing Materials, Philadelphia, 1977.

81. Duckett, K. E., and L. C. Wadsworth, proceedings of the 1987 TAPPI Nonwovens Conference, P.121, Apr. 1987.

82. Freeston, W. D., and M. M. Platt, Textile Research Journal, 35, 48-57 (1965).

APPENDIX

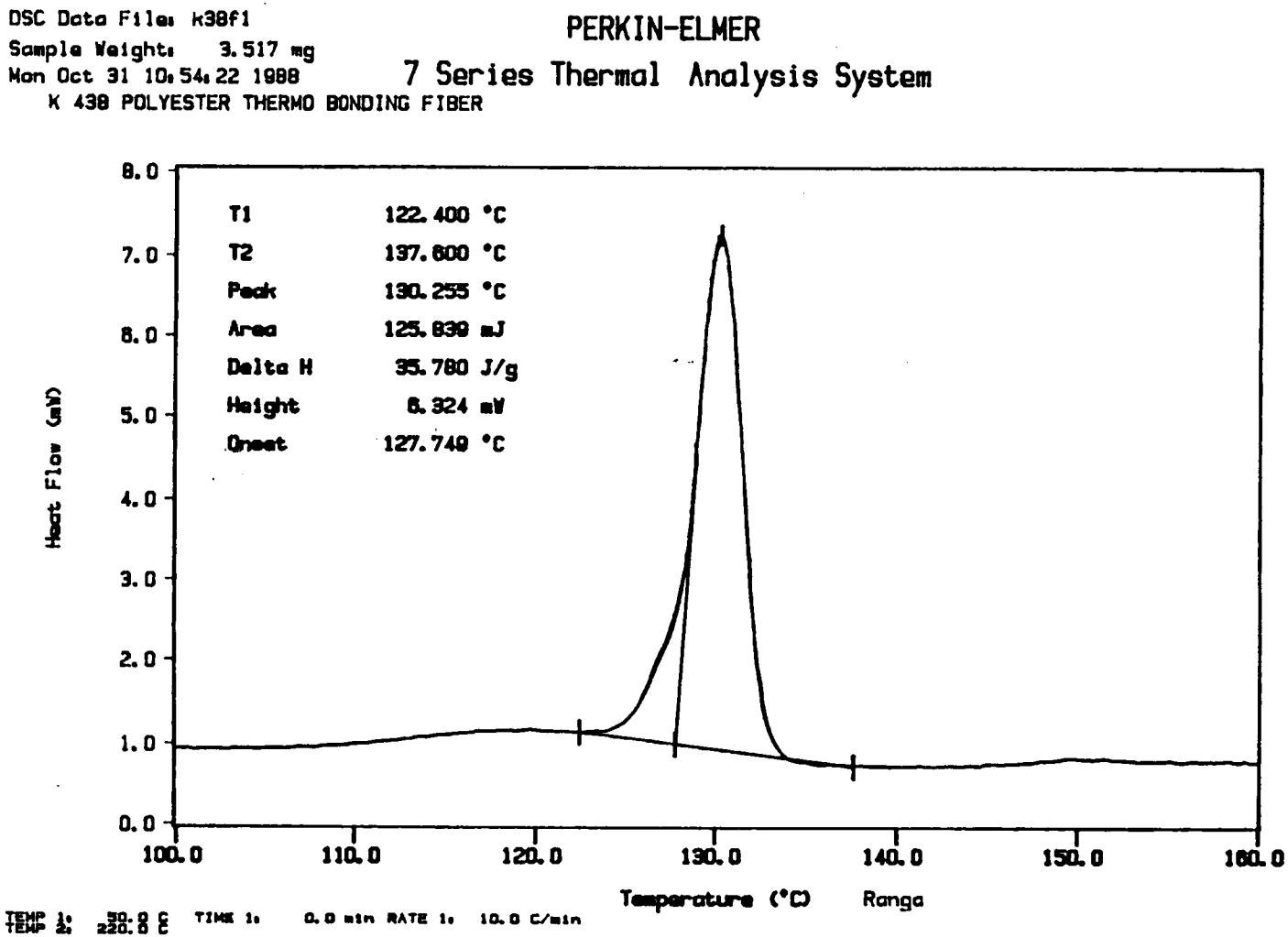
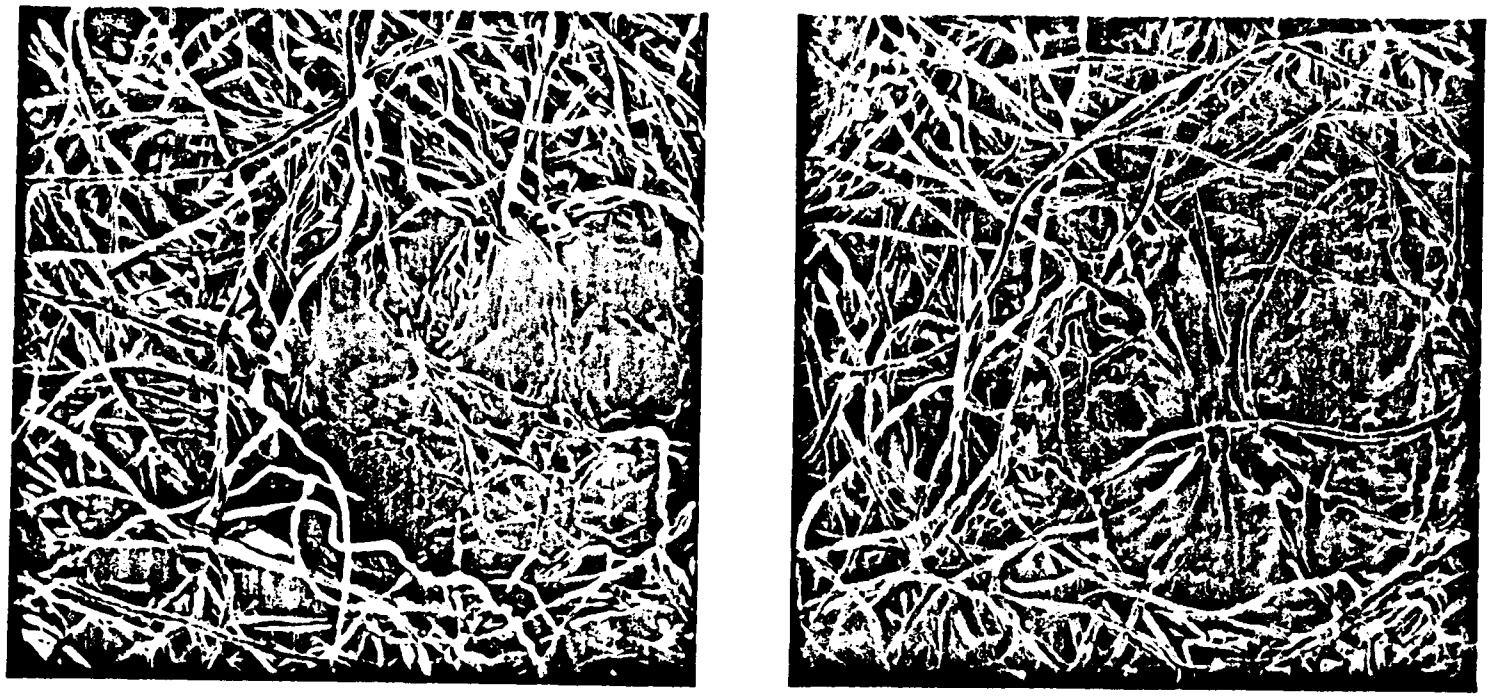


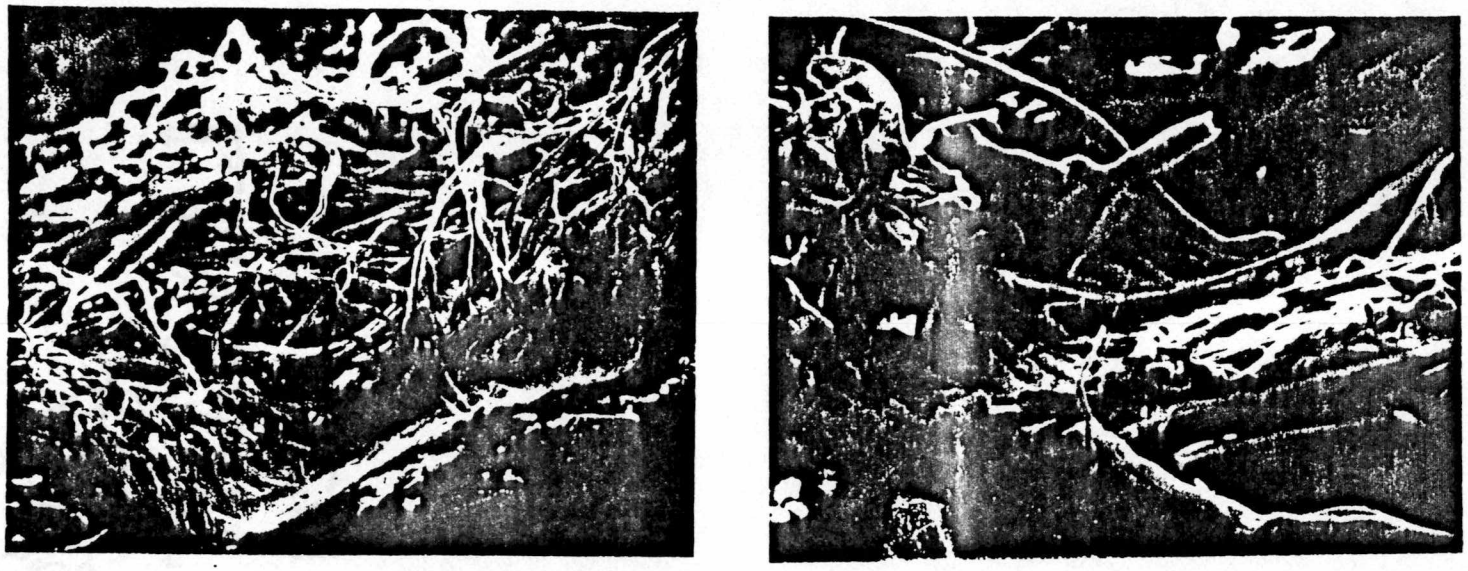
Figure A.1. D S C Analysis of the Kodel™ 438 Fiber



(i) At 275 °F (40x magnification)

(ii) At 325 °F (40x magnification)

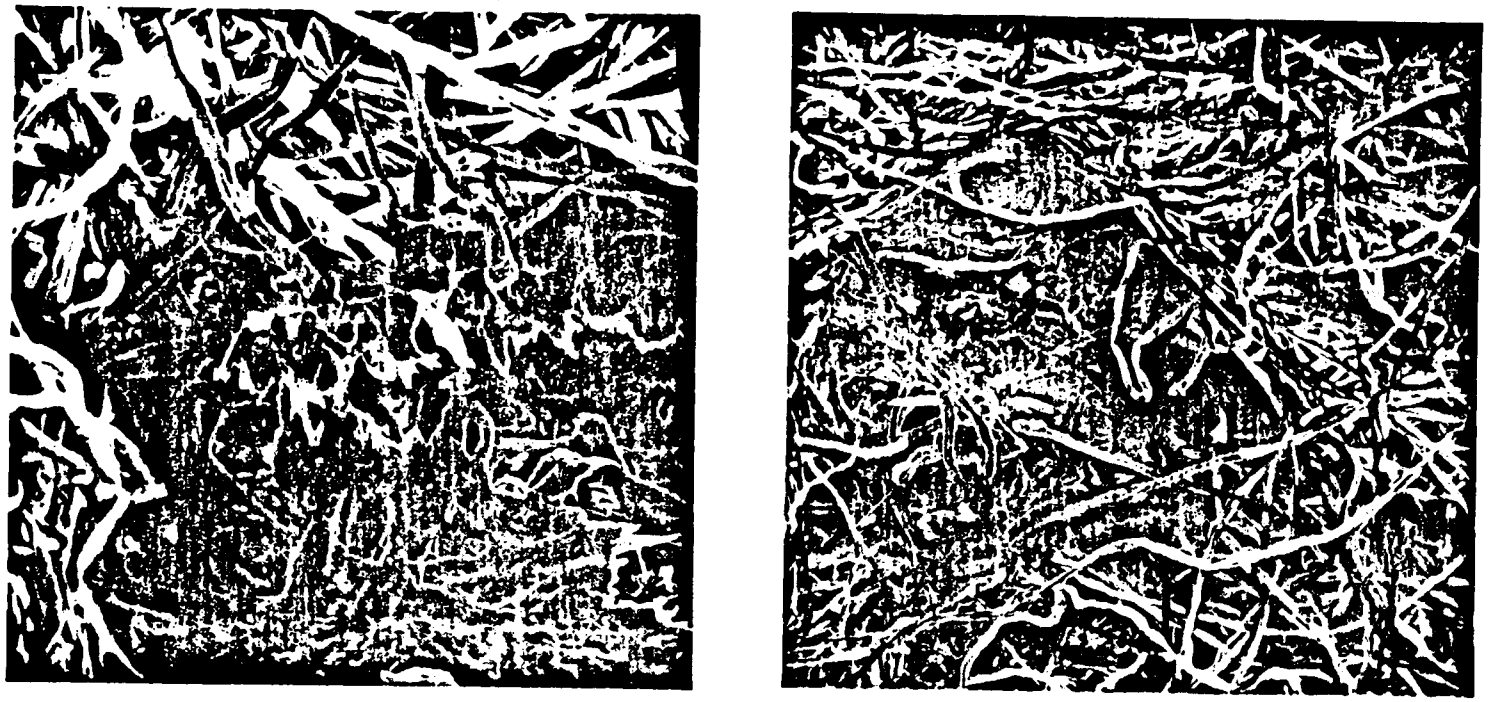
Figure A.2. SEM Photomicrographs of 50/50 C/P fabrics produced at differerent temperatures



(i) At 275 °F (40x magnification)

(ii) At 325 °F (100x magnification)

Figure A.3. SEM Photomicrographs of Cross-sections of 50/50 C/P fabrics produced at differerent temperatures



(i) At 275 °F (100x magnification)

(ii) At 325 °F (40x magnification)

Figure A.4. SEM Photomicrographs of 85/15 C/P fabrics produced at differerent temperatures

VITA

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