Abstract

KENNERLY, PAIGE. The Application of Hydroentangling to Enhance the Mechanical Properties of Woven Jacquards. (Under the direction of Dr. Behnam Pourdeyhimi.)

Hydroentangling is traditionally a nonwoven process of manufacturing fabrics through entangling loose webs of fiber using jets of water. This research proposes hydroentangling woven jacquard base fabrics using several speed and pressure combinations to mechanically enhance the structure. It also proposes to hydroentangle a loose web of fibers onto a woven jacquard fabric as a form of mechanically bonding the two structures. By bonding these fibers onto the woven fabric, the structure will be stabilized and mechanical properties will be enhanced. Control fabrics were compared to hydroentangled samples in order to select optimal hydroentangling processing parameters. The effects of these process parameters on fabric properties were studied. The mechanical properties of the woven fabrics before and after hydroentangling were also assessed.

One objective of this research is to determine if hydroentangling is a feasible means to overcome certain physical and mechanical shortcomings of jacquard woven fabrics. Test data indicates that certain aspects will be improved, while others may be negatively impacted by hydroentanlging. There are also critical energy points where any further enhancement in properties is diminished. The end use application of the fabric, as well as performance criteria will play a key role in determining if hydroentangling can be used as an alternate means of finishing a jacquard woven fabric, and will be unique to the specific company and production capabilities.

A second objective of this research is to determine if hydroentangling is a feasible means of bonding a single fiber carded web onto a base jacquard woven fabric. With the correct combination of base fabric construction and specific energy, bonding is possible. When energy is too high, the design will be jeopardized, while if energy is too low, adequate entanglement will not happen. Test data indicates that certain properties will be improved, while others may be negatively impacted by hydroentanlging. The end use application of the fabric, as well as performance criteria will play a key role in

determining if hydroentangling can be used as a feasible means of bonding a jacquard woven fabric with a carded web, and will be unique to the specific company and production capabilities.

The Application of Hydroentangling to Enhance the Mechanical Properties of Woven Jacquards

By
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Biography

Fayetteville, NC is the wonderful place was I was born and raised. I grew up playing all types of sports, including soccer and basketball, with my participation continuing through high school. Upon graduation from Pine Forest High School I attended North Carolina State University. I chose the College of Textiles to pursue a Bachelors of Science degree in Textile and Apparel Management. I graduated in May 2002 Magna Cum Laude. Throughout my undergraduate years I was highly involved in social and service fraternities and sororities, as well as the intramural sports program.

Upon graduation, I accepted a process improvement specialist job with Milliken and Co., working at the Hatch Plant in Columbus, NC. I was later promoted to advanced production leader at the Hatch Plant.

While working for Milliken and Co., I resided in Spartanburg, SC. I was highly active in the local Jaycees, and was awarded “Jaycee of the Year” for 2003. Throughout my years in the Jaycees I have chaired several charitable community activities, including an annual bachelor auction.

My parents, Bob and Molly Kennerly, are both retired and reside between North Myrtle Beach, SC and Fayetteville, NC. My father is retired from Firestone, and my mother as a school teacher. I have one sister, Charlotte, who lives in Zanesville, OH. She lives with her husband Tony, who is a military recruiter, and their son, William. William is 3, going on 15.

Upon the completion of my Masters Degree I will return to Spartanburg, SC, where I will work at the Auto Lamination Plant for Milliken and Co.

Acknowlegements

I am highly appreciative to my parent's for the support I always received concerning academics throughout grade school and during my undergraduate years at North Carolina State University. I can look back and am thankful that my parent's knew how important it was to excel at school and in life, and that they forced the issue with me whenever I offered resistance.

I am also very thankful to Milliken and Co. for the chance to return to North Carolina State University and receive my Masters Degree. The management at Milliken and Co. has been very supportive and accommodating in making success possible.

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1 Introduction

Hydroentangling is traditionally a nonwoven process of manufacturing fabrics through entangling loose webs of fiber using jets of water. This research proposes hydroentangling woven jacquard base fabrics using several speed and pressure combinations to mechanically enhance the structure. It also proposes to hydroentangle a loose web of fibers onto a woven jacquard fabric as a form of mechanically bonding the two structures. By bonding these fibers onto the woven fabric, the structure will be stabilized and mechanical properties will be enhanced. Control fabrics were compared to hydroentangled samples in order to select optimal hydroentangling processing parameters. The effects of these process parameters on fabric properties were also studied. The mechanical properties of the woven fabrics before and after hydroentangling were assessed.

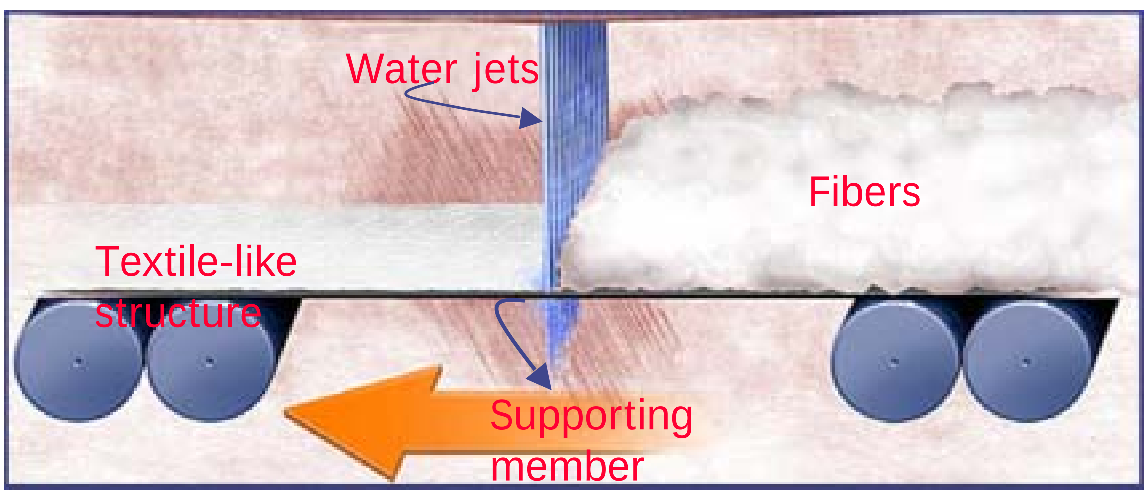
2 Literature Review

2.1 Hydroentangling

Hydroentangling, inspired from needle punching, is a process capable of bonding loose fibers into a uniform web. Fine, closely spaced high velocity jets of water are used to mechanically interlock fibers and fiber bundles to create fabrics. The energy is supplied by high-pressure streams of water in the form of columnar jets. The impact of the energy from the jets of water displaces each individual fiber and rearranges the fiber in respect to neighboring fibers. During displacement, fibers twist around one another, or interlock, due to frictional forces. The resultant fabric is a compressed and uniform web of entangled fibers.

Picture 1: Schematic of Hydroentangling Process

Source: NCRC presentation slides



Commonly used as a fabric formation technique, this thesis will set out to research the capabilities of using hydroentangling as a form of face finishing a woven jacquard structure, as well as to determine if it is a feasible means of bonding the woven jacquard structure to a single fiber carded web.

2.1.1 Hydroentangling Fundamentals

Three key factors in hydroentangling are water pressure, energy transfer, and the web support system. Insufficient energy transfer, or low pressure, will rearrange your fibers, but will not cause them to entangle with each other. It is important to note that for this research, the first manifold was always set lower than the remaining manifolds. This serves to pre-wet the fabric, and prepares the fabric for the subsequent blasts of high energy jet streams. Excess energy transfer, or high pressure, will produce weak areas in your fabric, as well as display no uniform areas. The web support system is a wire mesh belt carrying your web through the process. Surface characteristics of the mesh belt play a key role in determining properties and aesthetics in final fabric.

There is a wide diversity of vacuum levels and air flow associated with various types of hydroentangling. For the original manifold over belt configuration, it is critical to remove all standing water from the surface of the fiber web. Standing water would be disrupted when struck by the following orifice jets, causing a defect known as “chicken tracks”.

The micro-porous drum systems have very low open area, usually in the range of 3%. (TAM 589-I, Bonding Fundamentals Lecture Notes) This caused the vacuum to hold the web to the drum. This low open area and air flow caused the majority of the process water to splash off the surface of the drum and cascade down the web and drum. The reward for this change in entangling system is a significant improvement in energy efficiency and development of fabric properties at much lower energy inputs. The process water must be collected and reintroduced to the entangling system.

Water circulation and contamination is one key issue in hydroentangling. Every time the water jet strikes a web of fibers, contamination is created. This contamination could be fiber particles, fiber contamination, as with cotton, fiber finish and/or erosion. These contaminations should be completely removed to prevent orifice clogging and erosion. A clogged orifice will create a streak in the fabric that subsequent passes may not erase. Streaks are inherent with the hydroentangling process but are considered defects for most applications. The intention of the hydroentangled fabric manufacturers is to minimize streaking to a level acceptable for the end use. (TAM 589-I, Bonding Fundamentals Lecture Notes)

2.1.2 Advantages of Hydroentangling

This research chose to explore new hydroentangling capabilities due to the technologies numerous advantages. Advantages of hydroentangled nonwovens include reduced fiber breakage, which results in less fiber fall-out in the finished product. This attribute is important in numerous applications such as medical, filtration and clean room products. The fibers in the fabric are in effect washed during processing, where the fiber producer's finish can be removed. Chemicals and additives can be added during this wet operation as well. These fabrics offer excellent adhesion for coating or lamination. Another advantage is that fibers of various types can be intimately blended in the process, or two or more webs can be combined.

Common advantages found in end use products include:

- High bulk and coverage provided at low weights
- Wide range of fabric patterns and surface effects
- Simulation of drape and hand found in knits
- Strength can be varied through degree of entanglement
- Increased dimensional stability and
- Receptivity to dyes and finishes
- Fabrics can be combined through Spunlacing

2.1.3 Disadvantages of Hydroentangling

With all the advantages, there are some downsides to this technology. The disadvantages of hydroentangling led to a low growth period in the 1970's and 1980's. Large capital and technological investments were required. Production lines installed cost well over $20 million. (Holliday, 10) The slow speeds and production problems of some of these made it difficult to find markets where a profit could be made. In addition, it took significant experience and know-how to produce consistent quality fabrics.

Disadvantages of this process in one end use application can be an advantage in another. As an example, the elongation, distortion, or lack of stability in certain fabrics may cause baggy knees in a pair of pants. However, this characteristic of the fibers moving within the fabric also allow it to be molded or formed without rupturing or significant loss of strength.

Common limitations include:

- High capital and energy costs
- Technical technology and maintenance requirements
- Recoverability not sufficient compared to knits or wovens
- Problems in surface distortion and pilling
- Tensions must be monitored during wet and dry processing
- Foaming finished fibers may not be used
- Composite fabrics incur high costs

2.2 Hydroentangled Fabric Market

Benefits of hydroentangled materials, including softness, durability, and a similarity to traditional textiles has won it a preferred spot in many key end use markets. The overall market is receiving a huge boost from the explosion of the wipes market. Other applications range from medical garments, substrates for artificial leather, and apparel linings. (Wubbe, 6) This boom is leading to new money being placed in research and development of hydroentangled fabrics.

BFF Nonwovens' Mr. Barrington tends to prefer the advantages of spunlaced material over air laid. "Spunlace traditionally makes a virtue of its purity, its handle, softness and general cloth-like properties, hence its suitability for wipes and medical applications. The air laid people talk a good fight but their market penetration does not commensurate with their publicity efforts. Newer technologies always over claim." (Wubbe, 6)

All manufacturers seem to agree that the future of spunlacing is bright, but new technologies and trends are definitely emerging onto the surface. "Producers are still going to be looking for less down time, less stops during a production run and high quality water," said Idrosistem's Mr. Trevisan. (Wubbe, 6)

The opportunity for product innovation with hydroentanglement is essentially unlimited. Raw materials, energy levels, and screen patterns all can be varied to achieve a host of end products tailored to specific customer needs. As better fundamental understanding evolve, fiber entangled products can be manufactured to replicate and replace many traditional textiles, in low end and disposable areas and in the higher end durables market.

A major opportunity exists in combination or composite products. The tissue/fiber barrier fabric currently produced by DuPont and Chicopee is an example of such a product, with current output estimated 40 million pounds a year. (White, 37)

The combined North American and Western European volume of water jet entangled nonwovens rose from about 45,000 tons in 1988 to about 110,000 tons by 1992. (White, 37) North America will continue to account for the majority of the volume, but the European market will grow at a faster rate. The largest North American market will continue to be surgical packs and gowns. However, this is a market sector where growth will be slow because of the time factor to achieve acceptance in such a critical area. It is currently estimated that 12% of the nonwovens produced in the world are made with spunlaced technology. (Bitz,45)

2.3 Hydroentangled Products

Wipes and towels for a variety of industrial, food service, consumer, medical and a number of smaller, specialized applications have started to make in-roads into these markets. A number of new variants of water jet entangled products made from a variety of precursor webs are expected to be directed towards the increasingly specialized wipe and towel applications sector. Medical sponges and dressings and closely related medical products will develop as the benefits associated with such products are both recognized and quantified in terms of real cost.

In a number of other disposable product categories it is also projected that considerable growth can be achieved, including in disposable sheets and pillow cases, table cloths and napkins and baby nursery products.

In the U.S. it is also predicted that spunlaced cover stock will achieve some significance. As the threshold for successful entanglement is generally considered to be at the 20-25 grams sq. meter level, this may be more difficult to achieve than many consider. In Western Europe, major market growth of "conventional" spunlaced materials is expected in medical sponges and dressings, related medical products, wipes and towels, surgical packs and gowns, and disposable limited use textile replacement items.

Hydroentanglement technology is one of two major technology growth potential areas identified by most analysts working in the nonwovens sector, the other being melt blown. In terms of process economics, the cost of the fiber components in a precursor web is of major significance. The ability to utilize cellulose fibers, even if more sophisticated forms of cellulose pulp are chosen, is therefore of considerable economic benefit.

If this simple cost equation can be combined with other technological and performance benefits and the negative factors further minimized, there is no doubt that wet formed precursor webs with off-line entanglement, drawing on a wide range of precursor web technologies, could prove to be a most attractive manufacturing system. One of the key factors will be the ability to form, reel, and transport appropriate wet formed precursors.

Recent developments allowing the hydroentangling of structures based on "Kevlar" or "Nomex" indicate an important development. The use of high performance fibers in the precursor webs, possibly combined with other, less costly support fibers, will extend the use of this technology into the production of composite structures where the absence of a chemical binder is a positive cost advantage. Developments by DuPont in this field with the production of spunlaced Kevlar and Nomex aramid fibers are targeted at high performance specialty applications in the automotive, aircraft, and filtration markets.

Tradition textile company suppliers are also looking to benefit from the new boom in nonwovens. Needle supplier Groz-Beckert has registered the HyTec jet strip for spunlaced applications. With this strip, the company has enlarged its wide range of precision components for the textile industry to include another high-powered component. (Bitz, 67) The use of this strip guarantees production that is burr free, form-fit, with uniform jet geometries.

In durable applications, the production of composite structures based on different types of precursor webs, including glass, carbon and high performance organics, will be increasingly targeted at industrial filtration, and composite materials with high performance engineering requirements. With innovative technologies, and research into the future, it is clear that this technology is gearing up for a successful and profitable future in a wide variety of markets.

2.3.1 Product Differentiation

As nonwoven products continue to emerge and penetrate markets worldwide, the need for products with special properties unfolds. Finishing treatments that can bring commodity products specialized capabilities to withstand conditions of new application areas are key. Such treatments are necessary not only for fiber before web formation, but also to the web after manufacture. These processes will add value to developing and existing products.

Many finishes being added to nonwovens help that structure behave as a traditional textile, namely knitted or woven fabrics. Nonwovens can be produced in a more efficient manner with respect to time, money, and labor, so evolution in this area is a win win for manufacturer's and consumers.

Many emulsion suppliers have roots in the textile industry, so applying the knowledge learned is not a far stretch. The continued growth and proliferation of the nonwovens industry, as well as the decline of textiles in North America and Europe, has made nonwovens a top priority for many companies. "The trend is toward more topical finishes because they give more versatility and are easier to apply," says Mimi Carter, product manager of textile chemicals. (McIntyre, 56)

In a similar article written by Robert Lovegrove, he offers the following guidelines all raw material and roll good producers should know to avoid commoditization: 1) Do not underestimate the value of adhesives, 2) Understand the function and value of polymers, 3) Distinguish yourself with fiber and surface enhancements, 4) Think in terms of layers, 5) Add value by combining multiple polymers, adhesive and film technology.

2.4 Bonding

2.4.1 Hydroentangled Composites

Common applications of textiles in structural composites involve lamination. Several different layers are laminated in a sandwich structure, corrugated webs help impart stiffness and rigidity. Bonding techniques include chemical, adhesive, and stitch. These laminates do not have interlocking fibers between layers, so failure by delamination under impact, compression, and shear stress in common. The shapes produced with laminates are limited, costly, and inconsistent.

Interest lies in composites offering an alternative to these conventional laminates. There is also a need to produce advanced composites with enhanced inter-laminar strength, improved damage tolerance, and reduced manufacturing costs. Braiding and weaving are attractive, and produce complex net shaped structures for textile reinforcements. Fiber assemblies have also been seen for non-structural composite application, like in automotive.

One area not fully exploited for composite application is fiber assemblies, i.e. nonwovens. These nonwoven structures can be formed by bonding fibers through mechanical, thermal, chemical, or solvent means. Hydroentangling is one alternative method to these bonding methods.

European Disposables and Nonwovens Association define a nonwoven as a manufactured sheet, web, or batt of directionally or randomly oriented fibers bonded by friction and/or cohesion and/or adhesion.

Application areas of hydroentangled nonwoven fabrics cover from 20 to 500 g/m^2. Disposable medical products, which are breathable as well as protective from fluid and bacteria generally, comprise 60% of the total market. Household products and wipes comprise 20%, fusible textiles and textile interlinings hold 15%, and all others combined are 5%. (Acar, Harper, 106)

Fine water jets used during hydroentangling offer an alternative to needle punching, which is a highly mechanical process. Hydroentanglement is a suitable way of turning natural and synthetic fibers into fabrics, without damage or the need for any other binders.

Advantages of hydroentanglement over needlepunching include: 1) With water, fibers act as a plasticizer to reduce bending stiffness, flexural rigidity, and torsional rigidity of the fiber; 2) This allows the fibers to easily bend, twist, form loops, and entangle, all under less force; 3) High production speeds are achieved as complete hydroentangling lines are seen; 4) It also can be added to pre-existing web formation machinery.

Hydroentangled composites have potential to becoming the superior product over laminates. If laminated, the nonwoven will offer greater resistance to delamination due to the fibers entangled in all directions, improving cohesion. A further advantage is flexibility and compressibility for molding into different shapes. Hydroentangled fibers offer alternative method for producing composite fabrics with high energy absorbing properties. Fabrics with short staple fibers offer improvements in impact resistance.

In a similar article written by Scott Sullivan, appearing in *Nonwovens Industry* in early 1994, the use of hydroentangling as a form of bonding was explored. Several key members of the nonwoven community commented on the state of the industry, and the predicted future in spunlacing. In a statement made by Jon Schmidt, marketing coordinator for Fi-Tech Jon remarked that, "In addition to being used to consolidate webs, spunlacing is beginning to be used to laminate two nonwoven structures without the use of chemical binders." N. Taniguchi, manager & production control of Japan Vilene is reported to saying, "Spunlacing is certainly playing one of the important roles in our research and development of composite nonwoven fabrics." Keizo Ishibashi, with Unitika agrees. He says, "We are now focusing on composite nonwovens to meet a diversity of requirements, with 20% to 30% of our efforts aimed specifically at composites that utilize our spunlaced Cottoace cotton fabric."

Even with the growth of these markets, the cost of entry is realized early on. A spokesman for Dexter Nonwovens, a company servicing the medical industry with spunlaced fabric, has commented that, "Needlepunching with water is an easy to understand premise, but the machinery required (conveyor systems, water manifolds, water jets, filter equipment, and drying/vacuuming systems) are complex and expensive. It is clearly been very difficult for new competitors to enter the spunlace market."

Willi Hasselbrink, managing director-commercial, Freudenberg, has stated that, "The spunlace technology, in combination with advanced web formation systems, will have a significant role in continuing to substitute both conventional woven textiles further and other nonwoven technologies when they reach their limits."

2.4.2 Carpet tufting

One area where hydroentangling has proven a successful means of bonding a reinforcement material to the substrate is in the carpet industry. The common way of tufting carpets involves attaching a pile layer, through loop insertion, onto a carrier material. An example of a carrier material is a spunbonded or woven fabric, used for the primary backing. The surface may consist of velour or loops. The tufts are bonded in the primary backing by an adhesive coating, to give the structure required properties of utility and mechanical stress resistance. (Watzl) Attaching the tufts in position to the carrier layer is important for optimizing loop tear resistance and behavior of the carpet during testing.

A secondary backing may be used to add walking comfort, or a plush feel. This can either be a textile backing, or latex. The use of latex precoat has disadvantages during production and when recycling tufted carpet. (Watzl) Processing this latex leads to waste water and foul odor during recycling. Laminating remains the preferred means of sealing the secondary backing to the carpet, although high cost is one main characteristic of the process.

Needlepunching has been explored as an alternative to the expensive and highly chemical process of latex bonding, but severe damage to the carpet surface has been seen.

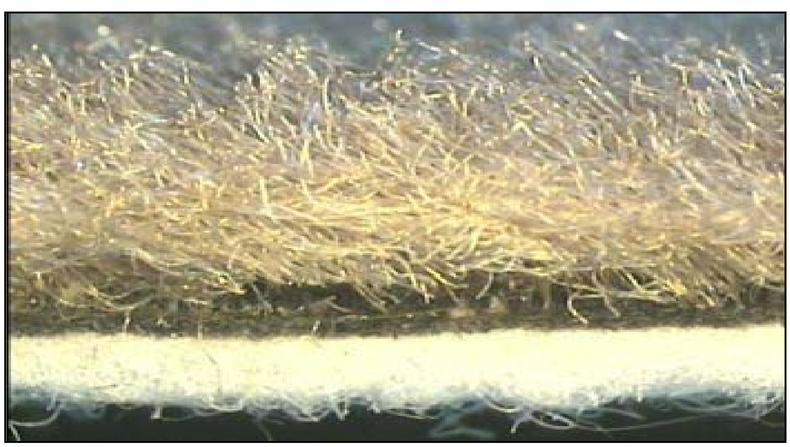
Applying a nonwoven web instead of the tufted backing does away with several ecologically harmful processing techniques. Spunlacing is one method of bonding the web of fibers onto the backing of the carpet, and does not disturb the pile layer. Thus, the carpet appearance is maintained. A carded web, unbonded or prebonded, is a suitable nonwoven material for this job. Fiber types consist of PES, PP, or PA.

Hydroentangling allows injection of fibers of the stabilizing web only so far into the backing of the primary material only so the materials are not visible on either side of the carpet.

The process was developed by Fleissner, and the company holds several patents on certain technologies. The patent describes the process covers stabilization of pile goods such as pile carpets, tufting carpets, plush and similar goods. It is suitable for fabrics with a face that can't be changed in the selling face, or reverse, but that the reverse is not stable at the beginning so the pile layer must be anchored in the back. This is done by inserting the pile layer into the primary carrier material. The reverse of the fabric length is provided with a backing to secure the pile layer, and the anchoring pile is only loosely retained. The backing is characterized by a nonwoven web attached on the reverse of the primary carrier retaining the pile fibers by hydroentanglement, as seen in Picture 2.

Picture 2: Latex Free reinforcement of Carpet Structure

Source: www.fleissner.com



A secondary step involves attaching the secondary backing to the web by another series of hydroentanglement. This step helps stabilize, but also adds comfort and plushness to the carpet. For optimum tear resistance, a mixture of thermoplastic or bicomponent fibers can be used as the backing material.

The success of this research has led to the question of weather or not this would work for other end-use applications. The research explained in this thesis shows that it can also be successful in the upholstery market, by hydroentangling a single fiber carded web onto the back of a greige woven jacquard structure.

2.5 Hydroenhancement

Fluid entanglement adds strength and integrity to a fibrous web, and the use of hydroenhancement, using spunlacing as a fabric finish, is most effective when yarn choices and fabric structures are modified to optimize properties.

Pattern screens may be used with fluid entanglement, and the design will be built into the fabric, also allowing nonwoven products to provide similar drape and hand to similar products made through weaving or knitting.

During the process of fabric hydroenhancement, surface fibers entwine to increase fabric coverage. Major benefits include: improved strength and abrasion resistance/fraying resistance, improved fabric coverage, softer hand and enhancement of under constructed fabrics, reduction of fabric tension, flatter fabric for easier cutting, cleaner fabric (more so with cotton or cotton blends), and a mercerized effect for cotton. (Mansfield)

A HydroENHANCER ™ system, offered by Textile Enhancements International, and developed in a partnership between Valmet Inc. and Zimmer Machinery Corp., subjects the fabric to small, high velocity jets of water in an attempt to bloom the fabric. This also intertwines the outer surface fibers within and between other fibers.

The system is a batch process offering multiple reciprocating devices. The process uses a pair of reversible, tension-controlled, driven fabric spools with the enhancement process placed between them. (Mansfield) There is a choice between three manifolds, two being programmed for active passes. These passes determine which side or sides are enhanced. Other water jet treatment systems are Fleissner's AquaTex, and Rieter's Perfojet offers JETlace 3000. Textile finishing is listed as an intended post-process step. (Pourdeyhimi, 3)

The U.S. Patent 5,136,761, issued on August 11, 1992, demonstrates clearly that hydroentanglement, when used as a finishing step, improves surface properties and the dimensional stability of fabrics. (Pourdeyhimi, 2) It has been observed that for 100% cotton jersey knits, hydroentanglement processes reduce damages brought about by abrasion by 50% or more, and fabric resists holes through 60,000 wash cycles. While choice in raw material also plays a role in final product properties, generally these materials are chosen for cost, making finishing steps necessary.

2.6 Intellectual Property

2.6.1 Improving physical and mechanical properties by hydroentanglement

U.S. Patent No. 60/529,490, filed on Dec. 15, 2003, by Dr. Behnam Pourdeyhimi for North Carolina State University, and relates to improving the physical and mechanical properties of fabrics by hydroentangling. This directly relates to the research conducted in this thesis. More specifically, this patent relates to methods for reducing pilling and improving abrasion resistance of pliable fabrics through using hydroentangling as a finishing process. Pills are small bunches or balls of interlaced fibers caused by small bundles of entangled fibers clinging to the cloth surface by one or more surface fibrils. Once the pills are subjected to physical stimulation (friction) they can form a fuzzy appearance to garments. This is an undesirable effect, lowering the commercial value of most fabrics.

This method involves a pillable fabric. A pillable fabric has a top surface, bottom surface, side edges, yarns which intersect at a crossover point to define interstitial open areas in the fabric, and fibrils extending from at least one of the top and bottom surfaces. The fabric may be comprised of woven or knitted fabric, and fibers may include cotton, polyester, nylon, or blends. The fabric is supported on a support member, which may be a belt, drum, or belt/drum combination. The support member may include a pattern of open areas to affect fluid passage.

At least one of the surfaces is exposed to the water jets, causing the fibrils to tangle in the interstitial open areas of the fabric. The process energy must be in the range of 4,000 to 5,000 KJoules/Kg of fabric using pressures of 200 bars or greater.

This method reduces the presence of fibrils on at least one fabric surface to an amount where pilling is less than 20% after 5,000 cycles of abrasion on a Martindale device according to ASTM D497 testing standard. The fibrils are also reduced to an amount where the remaining mass of the fabric is at least 80% to 90% after 50,000 cycles of abrasion on a Martindale device according to ASTM D4966 testing standard.

2.6.2 Reduction or elimination of pills

Several patents have been previously filed, all relating to the reduction or elimination of pills.

1. U.S. Patent No. 3,975,486 (Sekiqchi et al.) relates to a process for producing an antipilling acrylic fiber. This is accomplished during steps of coagulation; stretching and relaxing heat treatments are conducted under particular conditions.
2. U.S. Patent No. 4,205,037 (Fujimatsu) relates to acrylic synthetic fibers that are highly resistant to pilling, but have good dyeability. This is accomplished by specifying the composition of the acrylic polymer, the condition of the primary stretching step, the internal water content of water swollen gel fibers, and the conditions of the steps of drying (compacting, secondary stretching, and relaxing heat treatment).
3. U.S. Patent No. 6,051,034 (Caldwell) relates to a method for cellulosic towels where the composition comprising of an acidic agent, and an optionally fabric softener, is applied to a pillable cellulosic towel (face yarns). The towel is heated for time sufficient to effect a controlled degradation of the cellulosic fibers, reducing pills.

Prior antipilling techniques include methods which involve chemicals or process modifications. The need for an easier method leads to research where hydroentangling can be used as a finishing technique.

2.6.3 Improving Dimensional Stability

Various past efforts to improve the dimensional stability and physical properties of woven and knitted fabrics are illustrated in the following patents:

1. U.S. Patent 4,695,500 (Dryer et al.) relates to a loosely constructed knit or woven fabric that is dimensionally stabilized by causing staple length textile fibers to be entangled about the intersections of the yarns comprising the fabrics. The stabilized fabric is formed by covering one or both sides of the loosely constructed base fabric with a light web of staple length fibers, and subjecting the composite material to hydraulic entanglement while supported on a porous belt configured to direct and concentrate the staple length fibers at the intersections of the yarn comprising the base fabric.
2. U.S. Patent No. 5,136,761 (Sternlieb et al.) relates to an apparatus and method for enhancement of woven and knit fabrics through the use of dynamic fluids which entangle and bloom fabric yarn. The process includes a two stage enhancement process where the top and bottom sides of the fabric are supported and impacted with a fluid curtain of high pressure jet streams. The energy and use of the support members with open areas, aligned in offset relation to the process line, forms fabrics with uniform finish and improves qualities such as edge fray, drape, stability, abrasion, fabric weight, and thickness.
3. U.S. Patent No. 5,761,778 (Fleissner) relates to a method for hydrodynamic entanglement of fibers or a fiber web, composed of natural or synthetic fibers. Fibers of the web are entangled and compacted with one another by a number of water jets applied at high pressure, with a large number of water jets striking the fiber web not only in succession, but several times on alternate sides of the web for optimum twisting on the top and bottom of the structure.

4. U.S. Patent 6,557,223 (Greenway) relates to improvements in hydroenhancement efficiency through operating a manifold in relative movement to fabric transported under the manifold as to deliver a low energy to the fabric per pass in multiple passes. This process results in greater enhancement efficiency and reduction in wasted energy, and also improves fabric coverage and reduces shrinkage.

2.7 Nonwoven Trade

Although this research involves finishing a woven roll good using a typical nonwoven fabric formation technique, it is important to understand the growth of the nonwovens roll good market. This growth illustrates interest in nonwoven technology, and can lead to further research involving the use of historical fabric formation techniques in other areas, such as fabric finishing. It is no surprise that when most segments involved in the textile industry are reporting losses, nonwovens reports growth. Annual trade statistics compiled by the U.S. government are shown in Table 1.

Table 1: U.S. Trade of Nonwoven Roll Goods

Source: Mayberry; Franken, 18

	YEAR					**% change**
	2000	**2001**	**2002**	**2003**	**2004**	**2003-2004**
U.S. Exports (mil. Kg)	158.7	165.5	182.2	198.4	230.8	16.3
U.S. Imports (mil. Kg)	84.8	96.3	116	138	167.3	21.2

Data reveals that exports of nonwoven roll goods from the U.S. increased more than 16% during 2004, reaching a record 230 million kilograms, one kg = 2.2 pounds. (Mayberry; Franken, pg. 18) The Tariff Schedule code 5603 played a key role in the narrowing gap between exports and imports of nonwovens. In 1996 the U.S. government eliminated the duties on nonwoven roll goods entering the U.S. While imports have nearly doubled over the past four years, exports have grown 45%, a modest move when compared to imports.

Table 2 illustrates the estimated value of U.S. exports and imports for nonwoven roll goods. U.S. exports have steadily increased during the past four years, reaching more than $1 billion. Imports have seen steady growth, but only valued at 60% of the value of exports.

Table 2: Estimated value of Exports and Imports, Nonwoven Roll

Source: Mayberry; Franken, 18

FAS Value U.S. Exports (mil. $)					**General Customs Value (U.S. Imports (mil. $)**				
2000	**2001**	**2002**	**2003**	**2004**	**2000**	**2001**	**2002**	**2003**	**2004**
688.1	695.8	744.4	914.1	1027.3	362.4	374.1	432.4	543.3	630.1

Over half of U.S. exports remain in North America, with the amount shipped to Mexico and Canada increasing at a rate of 1.1%, but this number has been tapering off year after year. In 2002, 84% of U.S. exports of nonwoven roll goods were shipped to 10 countries, but this number dropped to 77% by 2004. (Mayberry; Franken, 18) The U.S. exports of nonwoven roll goods to North America are shown in Table 3.

Table 3: U.S. Exports of Nonwoven Roll Goods to North America

Source: Mayberry; Franken, 20

	2000	**2001**	**2002**	**2003**	**2004**
Mexico (mil. Kg)	57.5	61.5	63.8	51.6	52.9
Canada (mil. Kg)	30	32.7	43.1	41	57.4
Combined % U.S. Total Exports	55.1	56.9	58.7	46.7	47.8

Looking at imports, 62 countries shipped nonwoven roll goods to the U.S. in 2004, many showing growth of more than 100% from 2003-2004. This data is shown in Table 4.

Table 4: U.S. Trade of Nonwoven Roll Goods

Source: Mayberry; Franken, 21

Top 10 Destinations for U.S. Exports: 2004			Top 10 Countries for importing to U.S.: 2004		
Country	Mil. Kg.	% change 2003-2004	Country	Mil. Kg.	% Change 2003 -2004
Canada	57.4	42	Israel	24.4	(1.0)
Mexico	52.9	2.5	Canada	19.6	6.6
U.K.	12.8	19.7	Mexico	15.8	103.2
Hong Kong	11.8	10.2	Germany	15.5	3.6
China	10.5	21.3	Italy	8.8	25.6
Honduras	7	22.4	Turkey	7.3	57.5
Japan	6.9	12.2	Finland	7.2	128.0
Germany	6.7	(14.1)	China	6.7	165.4
Thailand	6.6	8.8	Brazil	6.6	37.2
Belgium	6	6.9	U.K.	6.6	8.1

% Total Exports to Top 10 Countries					% Total Imports from Top 10 Countries				
2000	2001	2002	2003	2004	2000	2001	2002	2003	2004
80.1	80.6	83.6	78.1	77.4	82.2	84.3	80.4	76.4	70.8

2.8 Evaluating Mechanical Properties

One objective of this research is to determine what process parameters play a role in overall fabric properties, and how each parameter can be optimized to achieve specific properties. Previous research has been done that focuses on the role that energy transfer plays in a structure's overall mechanical properties.

E. Ghassemieh, M. Acar, and H.K. Versteeg, all from the School of Mechanical and Manufacturing Engineering at Loughborough University, have studied the effect of energy transfer while producing composite fabrics; composite fabrics have a growing application in areas of aerospace, transportation, and construction. Test samples consisted of five different webs with various density and fiber materials, as seen in Table 5.

Table 5: Web Properties

Sample	Material	Density (gsm)	Fiber orientation
1	Viscose/PET (70/30)	75	Parallel
2	Viscose/PET (70/30)	110	Parallel
3	Viscose/PET (70/30)	120	Cross-laid
4	PET	200	Cross-laid
5	Twaron	150	Cross-laid

Processing conditions for each of the five samples were as follows:

- Web 1: treated by three passes under the jet on each side at 5 m/min.

- Web 2: treated by four passes on first side, three passes on second side at 5 m/min.
- Web 3: treated by four passes on first side, three passes on second side at 10 m/min.
- Web 4: treated by two passes at constant pressure under water jet head. Machines speeds of 5, 10, 15, 20 m/min were tested.
- Web 5: Processed at pressures of 140, 160, 180, 200 (bar), and machine speeds of 10 and 30 m/min.

Fabric test procedures included 10 rectangular samples, 5 cm x 25 cm, taken from each fabric. Five were taken in the machine direction, and five were taken in the cross-direction. The EDENA standard tensile test was used to measure modulus and load at break for each sample. Fabric thickness was measured at 10 locations for each of the five samples, and an average was used in the results, shown in Table 6.

Table 6: Fabric Properties

Material	PET	Viscose	Twaron
Linear density (dtex)	1.6	1.7	1.7
Length (mm)	38	38	40
Tenacity (N/tex)	.47	.21	1.94
Bending modulus (kN/mm^2)	7.7	10	n/a
Modulus (kN/mm^2)	6.2	8.7	80
Wet Modulus (initial %)	100	2	n/a

The research concludes that the tensile strength of the fabrics increases to a maximum at a set critical pressure, and levels off as final water jet pressure is increased. The trends seen in magnitude of the critical pressure for webs made of PET, Viscose-PET, and Twaron fibers can be predicted from fiber properties, and the critical pressure increases with density. Parallel webs offer higher strength in the parallel direction than in the cross-direction, due to the fact that the jet energy for cross-laid webs is partly used to reorient the fibers back to a more parallel configuration. The research also conveys that pass speed does little to effect fabric properties if passed processed at critical pressure.

Maximum entanglement was achieved by setting the critical pressure on side one higher than that of side two. Strength properties as a function of specific energy consumption highlight the importance of optimizing your process to meet end use specifications and fiber property limitations.

2.9 Determining Structure-Process-Property Relationship

Similar research involving several fabrics made through hydroentangling is again used to show the importance of understanding how each process parameter plays a role in overall fabric performance.

In order to predict the mechanical performance of fabrics made through spunlacing, critical information on materials, the web, and the process are needed. Hydroentangling process parameters must be established, and it must be determined how these parameters affect the end use product. Optimal process parameters must be established, along with determining how each parameter determines key physical tests, such as tensile and tear strength.

The first paper in a series designed to explain such parameters, and the result to the final products were published by Dr. Behnam Pourdeyhimi and Amy Minton from the Nonwovens Cooperative Research Center at North Carolina State University, Mike Putnam of Benson, NC, and Han Seong Kim with the Department of Textile Engineering at Pusan National University in South Korea.

The materials used in the preliminary work consist of two sets: 10 fabrics prepared using nylon and polyester staple fiber, 3cm in length. Linear densities were 1.8 and 1.5 for both fibers. Webs, made by carding, were held constant with respect to web structure and density. Manifold settings were: 1) Treated on two sides with eight treatments top and bottom @ 100, 100, 300, 300, 300, 600, 600, 600 psi; 2) Series 1 was further treated on the alternate side (top @ 1200 psi and bottom @ 1200 psi); 3) Series 2 was further treated on the alternate side (top @ 1600 psi and bottom @ 3000 psi); 4) Series 3 was further treated on the alternate side (top @ 1000 psi and bottom @ 3600 psi; 5) Series 4 was further treated on the alternate side (top @ 1000 psi and bottom @ 3600 psi). All other process conditions were held constant, with the polyester fabrics being referred to from P1 to P5 and the nylon fabrics being referred to from N1 to N5.

N1 and P1 were processed at .31 KW/Kg; N2 and P2 were processed at .53 KW/Kg; N3 and P3 were processed at 1.10 KW/Kg; N4 and P4 were processed at 1.66 KW/Kg; and N5 and P5 were processed at 2.22 Kw/Kg. Energies are based on the Bernoulli equation, ignoring viscous losses within the system. With and manifold pressure of P_1, the jet velocity (V_1) is equal to $\sqrt{2}\ P_1/p$. p here is equal to 998.2 kg/m^{3,} which is the density at room temperature. P_1 is the pressure in Pa and V_1 holds the units of m/s.

Calculations of the energy transferred by the water jet is $\dot{E} = \prod/8\ pd^2\ C_2V^3$ where d equals the diameter of the orifice capillary in meters, and C_d is the discharge coefficient, while $\dot{E}$ is the energy rate in J/s. Specific energy is calculated with the formula: SE [J/ kg (fabric)] = $\dot{E}$/M where M is the mass flow rate of the fabric in Kg/s and can be calculated with M = sample width (m) x Basis width (kg/m^2) x belt speed (m/s). SE will be in Joules /kg fabric. All samples were formed on a 100 mesh belt at 120 feet/minute.

Structure and mechanical properties were tested for each sample prepared. The ODF was determined using the optical image analysis system. For each sample, 15 images are captured, each image representing the thickness ODF. Analysis is based on the Fast Fourier Transform of the image. This method has been proven to work well with noise, and results correlate mechanical and physical properties to earlier nonwoven samples.

Bending and tensile tests were conducted in order to determine directional mechanical properties. Each sample was cut at 18 degree intervals. The Cantilever method was used for bending measurements, while the Instron was used for tensile testing. Samples were 25.4 mm wide, and tested on a gage length of 101.6 mm. Tensile testing was performed at 100%/min extension rate. Five strips were tested at each angle. Cantilever results were used to determine bending rigidity, and this test was performed before tensile testing started. Fabric thickness was .5 grams/cm^2 for all webs.

The structure of each sample as well as the role the hydroentangling process plays on structural differences was monitored at several energy levels. The ODF did not appear to be statistically different for each polyester and nylon sample. This was determined using the chi-square test. Both ODF's have a MD dependent on both samples, which is 90 degrees. These results are typical for carded webs. The ODF was examined at each hydroentangling energy level to see if orientation is affected at each energy level. The ODF remained unchanged, and anisotropy rations were not different either. One note is that using an open form surface can lead to ODF changes locally, but this is not the case for closed surfaces.

Fabric thickness is .5 grams/cm_2 for all samples. Higher energy levels often result in higher levels of densification, leading to changes in fabric thickness. Results taken from the first energy level, .31, were not reportable. This is due to the openness of the structure, with very high loft, so results were not accurate. Another important note is thickness reduces with energy levels up to 1.6 KW/Kg, and then increase a little. This is due to the dimensional changes taking place in the fabric as the process approaches this energy level. These results hold true for both polyester and nylon.

Regarding the samples packing factor, the polyester samples reach the max faster than that of nylon, and nylon continues to densify at higher pressures.

Directional bending data shows that each sample was unaffected by process energy levels. In each case there is a peak, and then a decline. Bending rigidity follows the planar ODF trend no matter what the hydroentangling process energy. In the case of the P3 and N3 samples, these both show the highest bending rigidity results, followed by a decline.

Another important note is nylon appears to form a less stiff fabric than polyester. The nylon sample was less sensitive to energy levels used. Polyester peaks while additional energy levels lower the fabric stiffness. Fiber stiffness is one key indicator of fabric stiffness. Two factors in determining the fabric stiffness are fiber's modulus and diameter. This can be determined using the equation: $B = E/\prod d^4/64$. B is the bending rigidity, E is the modulus, and d is the fiber diameter. The nylon samples held a larger diameter than the polyester. Nylon fiber density is lower, while the denier is higher. The modulus of nylon is significantly lower than that of polyester, which causes a lower bending of the nylon fibers.

With an increase in specific energy, as it did in each sequence of the test series, the polyester samples have a gradual increase in tensile and stress modulus while approaching failure, then a decline. The nylon samples show an increase in tensile and stress modulus with a sudden change and a sharp decline. This shows that the nylon's tensile strength is more sensitive to changes in energy.

Directional tensile results are also captured and reported for all energy levels. An increase in tensile are followed up with a sharp decline after the critical energy level. The critical energy levels are the same for nylon and polyester, for both bending and tensile measurements.

The peak failure stresses, taken in the MD, show the average and standard deviations for both samples. Both the polyester and nylon samples have an increase in the tensile properties with energy. Polyester shows the higher of the two in strength, when compared at the same energy levels. Both samples peak at the critical energy point, and then show a rapid decline.

Peak failure strain in the MD show that the polyester samples have no trend as a function of energy. All samples convey a similar trend for strain to failure. Nylon shows an increasing trend with energy, but the variability in the data should be noted. Nylon also shows a higher strain to failure no matter the energy used to process. The two fibers entangle differently, and nylon continues to entangle with energy, longer than polyester.

The nylon samples have lower tensile strength, but pictures show more entangling when compared to the polyester samples. Nylon fibers unentangle, or slip away from each other, but polyester fibers break apart before unentangling can occur.

The first trials completed to help explain structure-process-property relationships in hydroentangled nonwovens include:

- Hydro energy has effect on mechanical properties
- Bending rigidity reaches a max point, then decreases with hydro energy
- Tensile failure stress reaches a max point, then declines with hydro energy
- Data was similar for polyester and nylon samples
- Basis weight is held constant with energy
- ODF remains constant with energy
- Fibers do not rearrange globally after pre-consolidation, and local rearrangement is more common with an open belt
- Peak performance can be correlated to dominant orientation
- Nylon appears to be more readily entangled than polyester because nylon has a lower bending rigidity and a lower glass transition, especially when wet

2.10 Jacquards

2.10.1 General Information

Jacquard weaving makes possible the raising of each warp thread independently of the others. This brings versatility to the weaving process, offering high levels of warp yarn control. Jacquard shedding makes possible the automatic production of unlimited varieties of pattern weaving. Major end-uses for the technology include napery, bedding, apparel, and upholstery.

2.10.2 Jacquard Market

Jacquard woven fabrics have long since been the preferred fabric for the upholstery end use market. In the upholstery market, 25% of retailers saw sales rise compared to July 2004 and 19% saw sales rise compared to August 2003. (Kidd, 16)

Jacquard woven fabrics are often described as the backbone of the home textile market. Home textiles are big business for many American based manufacturing companies. A list of the top fifteen by 2001 sales is listed in table 7 on the following page:

Table 7: Manufacturing Leaders in Home Textiles, 2001

Source: Home Textiles Today, 2002

Company	2001 Sales ($mil)	2000 Sales ($mil)	% Change
Springs Industries	1,801	1,801	0
Westpoint Stevens	1,752	1,883	-7
Pillowtex	1,114	1,423	-21.7
Mohawk Home	600	536	11.9
Dan River	482	450	7.1
Pacific Coast Feather	318	285	11.6
Croscill Home Fashions	315	302	4.3
Glenoit Corp.	252	237	6.3
Burlington Industries	249	293	-15
Hollander Home Fashions	203	211	-3.8
Maple Rugs	181	177	2.3
Franco Mfg.	180	153	17.6
Crown Crafts	177	310	-42.9
Louisville Bedding	177	173	2.3
CHF Corp.	124	116	6.9

In 1992, fabric produced for the United States upholstery market totaled 282 million square yards, with a value of $1.16 billion. (Fulmer, 76) The percentage (by volume) of upholstery fabrics used in 1992 can be seen in table 8 on the following page:

Table 8: Fabric for U.S. Upholstery Market, 1992

Source: American Textiles International, 1994

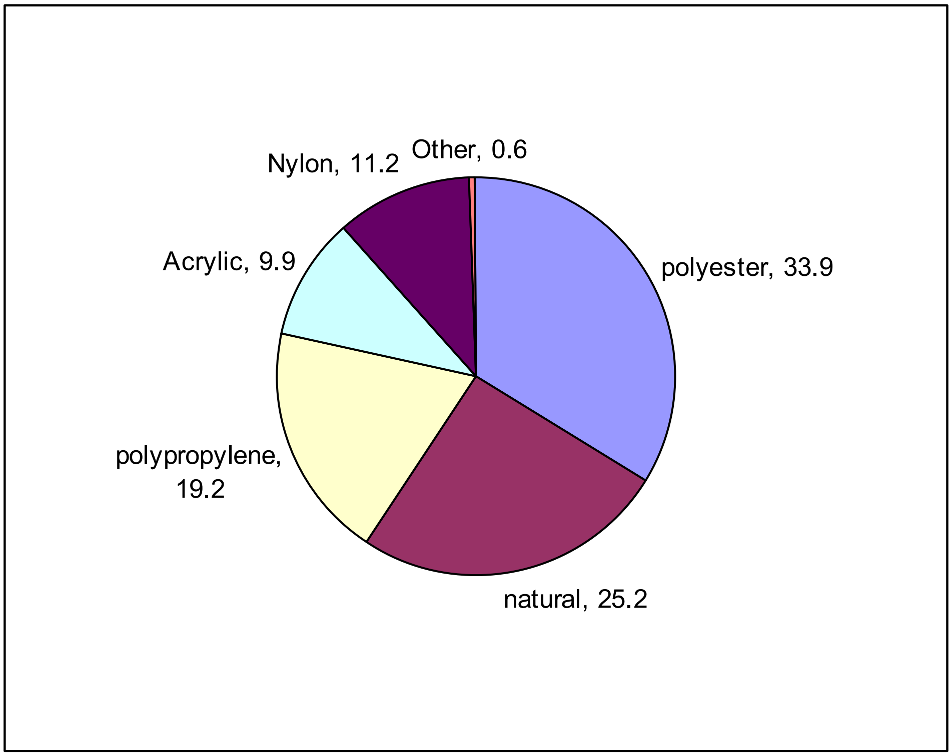
Fabric Type	Yards (Millions)	% of Total
Flocked Velvets	54	19.1
Woven Velvets	45	16
Dobby Weaves	45	16
Jacquard Weaves	70	24.8
Flat Knits	3	1.1
Cotton Prints	40	14.2
Tricot Knits	5	1.8
Raschel Knits	10	3.5
Tufted	10	3.5

Source: American Textiles International, 1994

As it may be noted, Jacquard woven fabrics command an astounding lead over any other type of fabrication process for producing jacquard upholstery. Fiber usage in these fabrics is graphically displayed in graph 1:

Graph 1: Fiber usage, residential and control upholstery, 1993

Source: American Textiles International, 1994



Polypropylene fibers, although not the biggest usage percentage in 1993, have gained in popularity. They are primarily used in nonwoven fabrics for furniture backing fabrics, woven fabrics for seating, wall coverings, mattress covers, panel cloths, knit fabrics, and tufted fabrics. Many of the physical properties required of upholstery fabrics are inherent in the fibers composing the substrates. The base fabrics used in this research are constructed using 100% polyester, both spun and filament.

To add even more stability for cutting and fitting, most upholstery fabrics are backed. Common backing mixes consist of latex, fillers, surfactants, crosslinkers, thickeners, and flame retardants. Upholstery fabrics see a great deal of abuse throughout their lifetimes, and these backcoaters help reinforce the fabric to withstand the abuse.

There are a number of polymers that have been used to offer a latex binder. Generic classifications can be identified as styrene-butadiene; acrylics, commonly the most popular; and vinyl acetate. Fillers extend the coating, add bulk and reduce the tack of the coating. Clay and calcium carbonate are popular fillers. If opacity is needed, titanium dioxide is used, and will improve UV stability. Surfactants are used on a case by case basis. Certain conditions dictate the use of surfactants. Some may be used as an emulsifier when incorporating an oil-based component in the mix. Others are good dispersing agents, and can keep various components dispersed and distributed. Some coating is applied as foam, so the surfactant is added as foaming agents to assist the mechanical foamer. Crosslinkers are used to improve the crosslinking and curing of the coating compound. Popular crosslinkers are ammonium chloride or p-toluene sulfonic acid. Thickeners are needed on non-foamed mediums. Two types are generally used, carboxylic acid and modified cellulose compounds. Flame Retardants are added by one of three methods: padding/spraying during finishing, including the chemical in the polymer during fiber manufacturing, or as component of backcoating mix.

3 Experimental Methods and Procedures

3.1 General Information

Three hydroentangling experiments consisting of multiple trials were conducted using four greige 100% polyester jacquard woven fabrics. They will be known as fabric A, B, C, and D. Fabric constructions are as follows:

Fabric A:

- 22 picks/inch
- Warp: 1-135-50 693 DB (filament)
- Fill: 10-2 100% polyester T54W Ring spun (3.30 TM)
- 350 gsm

Fabric B:

- 44 picks/inch
- Warp: 19/1 T-567 Air-Jet spun
- Fill: 2-150-68 56T DB (filament)
- 311 gsm

Fabric C:

- 59 picks/inch
- Warp: 19/1 T-56 Air-Jet spun
- Fill: 2-150-68 56T DB (filament)
- 348 gsm

Fabric D:

- 50 picks/inch
- Warp: 1-135-50 693 DB (filament)
- Fill: 10-2T54W Ring spun (3.30 TM)
- 635 gsm

The properties of all four of the greige jacquards were tested prior to hydroentangling. Properties tested were tensile strength, tear strength, abrasion resistance, air permeability, stiffness, pilling, ends and picks per inch, base weight, and fabric thickness. All tests are applicable to upholstery, the final end-use of the fabric.

All hydroentanglement and bonding trials took place using a Fleissner AquaJet Spunlacing System. The system is a five manifold belt and drum machine operated by the Nonwovens Cooperative Research Center located The Centennial Campus of North Carolina State University.

3.1.1 Experiment 1: Hydroentangling at slow conditions

The objective of experiment 1 is to determine if at slow conditions hydroentangling a greige woven jacquard is a feasible means to help the structure overcome current shortcomings in physical and mechanical testing. This will be determined by evaluating physical and mechanical properties before and after hydroentangling. Test results will be compared to determine if enhancement of the pre-hydroentangling samples has occurred.

The first experiment involved hydroentangling fabrics A, B, C, and D with the following variables:

- Speed: 10 meters/minute
- Pressure: 100 bar
- Passes: 1, 2, and 3 (one side only)

Passes reflect the number of manifolds. As previously mentioned, the hydroentangling equipment used for this research contains 5 manifolds. 1 pass reflects 5 manifolds, 2 passes reflects 10 manifolds, and 3 passes reflects 15 manifolds.

Again, the 100 mesh belt was constant throughout each trial.

The properties of all four fabrics were tested after pass 1, after pass 2, and after pass 3 in order to determine possible interactions between the number of passes through the AquaJet and final mechanical properties of the fabric. Properties tested were tensile strength, tear strength, abrasion resistance, air permeability, stiffness, pilling, end and picks/inch, base weight, and fabric thickness. These tests mirror the testing done to the fabrics before hydroentangling; again to determine what effect hydroentangling at a speed of 10 meter/minute at 100 bars of pressure, and for 1, 2, and 3 passes will have on the final product.

3.1.2 Experiment 2: Hydroentangling at Fast Conditions

The objective of experiment 2 is to determine if at fast conditions hydroentangling a greige woven jacquard is a feasible means to help the structure overcome current shortcomings in physical and mechanical testing. This will be determined by evaluating physical and mechanical properties before and after hydroentangling. Test results will be compared to determine if enhancement of the pre-hydroentangling samples has occurred.

The second experiment involved hydroentangling fabrics A, B, C, and D with the following variables:

- Speed: 50 meters/minute
- Pressure: 220 bar
- Passes: 1, 2, and 3 (one side only)

Passes reflect the number of manifolds. As previously mentioned, the hydroentangling equipment used for this research contains 5 manifolds. 1 pass reflects 5 manifolds, 2 passes reflects 10 manifolds, and 3 passes reflects 15 manifolds.

Again, the 100 mesh belt was constant throughout each trial.

The properties of all four fabrics were tested after pass 1, after pass 2, and after pass 3 in order to determine possible interactions between the number of passes through the AquaJet and final mechanical properties of the fabric. Properties tested include tensile strength, tear strength, abrasion resistance, air permeability, stiffness, pilling, end and picks/inch, base weight, and thickness. These tests mirror the testing done to the fabrics before hydroentangling; again to determine what effect hydroentangling at a speed of 50 meter/minute at 220 bars of pressure, and for 1, 2, and 3 passes will have on the final product.

3.1.3 Experiment 3: Bonding

The objective of Experiment 3 is to determine if bonding, through hydroentanlging, a single fiber carded web onto the back of a greige woven jacquard is a feasible means of reinforcing the structure. The bonding here will occur using the interlocking of fibers, not adhesives.

Fabrics A, B, C, and D were again used for these trials, along with a 50 gsm, 1 ½ x 1 ½ polyester carded web. The structures were bonded together using different pressures and speeds, with a 60 mesh belt used for each trial.

The initial designed experiment was compiled using the same speeds and pressures seen in Experiments 1 and 2: 10 meters/minute at 100 bar, and 50 meters/minute at 220 bar. However, once the trials began, it was evident that the initial pressures of 100 and 220 bars were much too high. In most cases, the backing was showing through onto the face of the fabric, making the distinct pattern lost. For this reason, all pressures were dropped substantially lower than with the previous trials, as well as the number of passes. It also became evident, due to the unique construction of each fabric, that using same pressure and pass parameters for each fabric were not suitable. In order to determine what would be feasible for each fabric type, a "hand sample" was first produced so the visual characteristics of the fabric could be observed. A hand sample is manually feeding into the hydroentangler a 1/2 yard piece of fabric, along with the backing through only the first 3 manifolds of the hydroentangler. The last 2 manifolds are disabled so that such a small sample may be processed. Since the feeding of the fabric into the hydroentangler is manual, 10 meters/minute is the fastest speed used for this set of trials.

The following process parameters were found to cause the 1 ½ x 1 ½ polyester carded web to show through to the face of the jacquard, jeopardizing the unique design characteristics:

Fabric B:

- Speed: 10 meters/minute
- Pressure: 220 bar
- Passes: One pass each side

OR

- Speed: 10 meters/minute
- Pressure: 220 bar
- Passes: 1 pass (back only)

OR

- Speed: 10 meters/minute
- Pressure: 100 bar
- Passes: 1 pass (back only)

It is important to note that the pressures shown are only for the first 3 manifolds, the last 2 were disabled. Also, testing was not done to the samples listed above, due to jeopardizing the design of the structure, also known as visual failure.

In some instances, the pressures were too low for bonding to occur between the greige woven jacquard and the 1 ½ x 1 ½ polyester carded web. The following process parameters illustrate such cases:

Fabric A:

- Speed: 10 meters/minute
- Pressure: 30 bar
- Passes: 1 pass each side

Fabric C:

- Speed: 10 meters/minute
- Pressure: 30, 25, 30 bar
- Passes: 2 passes (back only)

It is important to note that the pressures shown are only for the first 3 manifolds, the last 2 were disabled. Also, testing was not done to the samples listed above, due to unsuccessful bonding.

The following process parameters were found to bond the backing onto the fabric, while not jeopardizing the integrity of the distinct patterned construction:

Fabric A:

- Speed: 10 meters/minute
- Pressure: 30, 100, 100 bar
- Passes: 1 pass on each side

OR

- Speed: 10 meters/minute
- Pressure: 30, 30, 30 bar
- Passes: 1 pass on each side

OR

- Speed: 10 meters/minute
- Pressure: 30, 50, 100 bar

- Passes: 1 pass on each side

Fabric B:

- Speed: 10 meters/minute
- Pressure: 30, 50, 100 bar
- Passes: 1 pass on each side

OR

- Speed: 10 meters/minute
- Pressure: 30, 50, 30 bar
- Passes: 2 passes (back only)

OR

- Speed: 10 meters/minute
- Pressure: 100, 100, 100 bar
- Passes: 1 pass (back only)

Fabric C:

- Speed: 10 meters/minute
- Pressure: 30, 50, 100 bar
- Passes: 1 pass on each side

OR

- Speed: 10 meters/minute
- Pressure: 30,25,30 bar
- Passes: 2 passes (back only)

Fabric D:

- Speed: 10 meters/minute
- Pressure: 50, 100, 100 bar
- Passes: 1 pass on each side

OR

- Speed: 10 meters/minute
- Pressure: 30, 50, 100 bar

- Passes: 1 pass on each side

It is important to note that the pressures shown are only for the first 3 manifolds, the last 2 were disabled.

The properties of all four fabrics that successfully bonded to the polyester backing, as well as didn't jeopardize the integrity of the pattern, where tested in order to determine final mechanical properties of the end product. Properties tested include tensile strength, tear strength, abrasion resistance, air permeability, stiffness, pilling, end and picks/inch, base weight, and fabric thickness. These tests mirror the testing done to the fabrics before hydroentangling, and after experiments 1 and 2.

3.2 Test Methods

The following test methods were used when evaluating each sample:

1. Standard Test Method for Stiffness of Fabric - ASTM D 1388-96 (2002)
2. Standard Test Method for Air Permeability of Textile Fabrics - ASTM D 737-04
3. Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test) – ASTM D 5034-95 (2001)
4. Standard Test Method for Tearing Strength of Fabrics by Tongue (Single Rip) Procedure (Constant-Rate-of-Extension Tensile Testing Machine) – ASTM D 2261-96 (2002)
5. Standard Test Method for Abrasion Resistance of Textile Fabrics (Martindale Abrasion Tester Method) – ASMT D 4966-98 (2004)
6. Standard Test Method for Thickness of Textile Materials – ASTM D 1777-96 (2002)
7. Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Random Tumble Pilling Tester – ASTM D 3512-05
8. Standard Test Method for Abrasion Resistance of Textile Fabrics (Inflated Diaphragm Apparatus) – ASTM D 3888-99

3.2.1 Stiffness of Fabrics

Stiffness of each hydroentangled and bonded sample, as well as the control, was determined using ASTM D1388-96 (2002). The Cantilever test was employed, using a Drape-Flex Stiffness Tester, which involves bending of the fabric under its own mass. The test specimen is slid at a specified rate in a direction parallel to its long dimension, until its leading edge projects from the edge of a horizontal surface. The length of the overhang is measured when the tip of the specimen is depressed under its own mass to the point where the line joining the top to the edge of the platform makes a 41.5˚ angle with the horizontal. From this measured length, the bending length and flexural rigidity are calculated.

3.2.2 Air Permeability of Textile Fabrics

Air Permeability of each sample, as well as the control, was determined using ASTM D737-04.

The rate of air flow passing perpendicularly through a known area of fabric is adjusted to obtain a prescribed air pressure differential between the two fabric surfaces. From this rate of air flow, the air permeability of the fabric is determined.

3.2.3 Tensile Strength

Tensile strength of each sample, as well as the control, was determined using ASTM D5034-95 (2001). The tests were performed on a MTS Sintech 10/G, with a 2000 lb. load cell, 3 inch gauge length, at a speed of 12 inches/minute. Software used to compile test data was Testworks 4.0.

A 100 mm wide specimen is mounted centrally in clamps of a tensile testing machine and a force applied until the specimen breaks. Values for the breaking forces and the elongation of the test specimen are obtained given.

3.2.4 Tear Strength

Tear strength of each sample, as well as the control, was determined using ASTM D2261-96 (2002). The tests were performed on an Instron, model # 4400R, using a 50kg load cell, 75mm gauge length, at a speed of 50 mm/minute. Software used to compile test data was Testworks 4.0.

A rectangular specimen, cut in the center of a short edge to form a two-tongued specimen, in which one tongue of the specimen is gripped in the upper jaw and the other tongue is gripped in the lower jaw of a tensile testing machine is used. The separation of the jaws is continuously increased to apply a force to propagate the tear. At the same time, the force developed is recorded. The force to continue the tear is calculated.

3.2.5 Abrasion Resistance

Two methods of measuring abrasion resistance were employed for hydroentangled and bonded samples, as well as the control fabrics.

3.2.5.1Martindale Abrasion Method

Abrasion resistance of several hydroentangled and bonded samples, as well as all control samples was determined using ASTM D4966-98(2004). The tests were performed on a Nu-Martindale Abrasion and Pilling Tester machine, with 6 chambers at a load of 12 kPa.

Abrasion resistance is measured by subjecting the specimen to a rubbing motion in the form of a geometric figure, that is, a straight line, which becomes a gradually widening ellipse, until it forms another straight line in the opposite direction and traces the same figure again under known conditions of pressure and abrasive action. The abradent fabric is a plain weave, crossbred, worsted wool sample. Resistance to abrasion is evaluated by measuring change in appearance. Each test specimen was subjected to 6,000 cycles. Selections of specimens were further subjected to 30,600 cycles.

3.2.5.2 Inflated Diaphragm Method

Abrasion resistance of each hydroentangled sample, as well as the control samples was determined using ASTM D3886-99. The tests were performed on an Inflated Diaphragm machine.

A specimen is abraded by rubbing either unidirectional or multidirectional, against an abradent having specified surface characteristics. A specimen is held in a fixed position and supported by an inflated diaphragm which is held under constant pressure. A specimen is abraded by rubbing against an abradent having specified surface characteristics. The resistance to abrasion is determined using a visual assessment of the specimen surface after a specified number of cycles.

3.3 Fabric Thickness

Thickness of each samples, as well as the control samples, was determined using ASTM D1777-96(2002). A Thwing-Albert electronic thickness tester, model # 89-II-V was used.

A specimen is placed on the base of a thickness gage and a weighted presser foot is lowered. The displacement between the base and the presser foot is measured as the thickness of the specimen.

3.4 Pilling Resistance

Each hydroentangled sample's pill rating, as well as the control samples, was determined using ASTM D3512-05. A six chamber Atlas Tumble Pilling Tester was used. Do to the nature of the cotton sliver used; the bonded samples were not evaluated. Several tests were performed, but the cotton sliver immediately attaches to the carded polyester, leaving little room for surface interaction.

Pilling and other changes in surface appearance, such as fuzzing, that occur in normal wear are simulated on a laboratory testing machine. Pills are caused to form on fabric by a random tumble action produced by tumbling specimens in a cylindrical test chamber lined with a mildly abrasive material. To form pills with appearance and structure that resemble those produced by actual wear, small amounts of short-length gray cotton fiber are added to each test chamber with the specimens. The degree of fabric pilling is evaluated by comparison of the tested specimens with visual standards. The observed resistance to pilling is reported using the following rating scale:

5- No pilling

4- Slight pilling

3- Moderate pilling

2- Severe pilling

1-very severe pilling

4 Results and Discussion

4.1 General Information

Data analysis was done using the SAS software JMP, version 6.0. Using the software, two different data analysis were performed on the data. The first analysis is a one way analysis of variance (ANOVA). A one way analysis of variance is defined in the JMP tutorial as the attribution and test that part of the total variability in a response is due to the difference in mean responses among the factor groups. The analysis of variance technique computes the mean within each group and the sum of squared distances from each point to the group mean. These sums of squares are totaled to form an overall estimate of the variation unaccounted for by grouping the response. The total response variation less this residual determines the amount of variation explained by the analysis of variance model.

The second analysis performed on the data is a multiple comparison method known as Dunnett's Test. Fit Y by X, meaning a comparison between a selected input with a selected output produces the standard analysis of variance and optionally offers the Dunnett's comparison test. The Dunnett's test measures whether means are different from the mean of a control group, in this case, the pre-hydroentangled sample. It visually displays whether the means of each data set are statistically different from the mean of the control sample.

For each chart or figure an ID will be given. The first letter of the ID corresponds with fabric construction, followed by a hyphen. Following the hyphen the number corresponds to the number of passes (1, 2 or 3), while the letter corresponds to the condition type. The letter S means slow conditions of 10 meters/minute and 100 bar of pressure. The letter F means fast conditions of 50 meters/minute and 220 bar of pressure.

4.2 Specific Energy

A widely acceptable definition of specific energy is the thermodynamic energy per unit mass of an object. In the case of this research, specific energy relates to the amount of energy that is exposed to the fabric, and is a direct function of the speed at which the belt travels, the pressure applied by the water jets, and the number of passes each fabric takes through the hydroentangling unit. The following equations determine the specific energy for a given experiment:

1) Power = W = ½ $\dot{m}\,\overline{V}^2$(j/s)
2) $\dot{m}_{real} = \rho A C_d \overline{V}$
3) $W = \frac{1}{2}\rho A C_d \overline{V}^3$
4)

$$SE = \frac{\sum_{i=1}^{N} W_i}{\dot{M}} \frac{[kJ/s]}{[kg/s]} = \frac{N \times W}{\dot{M}}$$

N = Number of Jets

$\dot{M} = Fabric\,Mass\,Flowrate\,(kg/s)$

Where:

C_d = Discharge Coefficient

ρ = Water density (kg/m^3)

$\overline{V}$ = Mean velocity of jet (m/s)

4.2.1 Specific Energy of Hydroentangled Samples

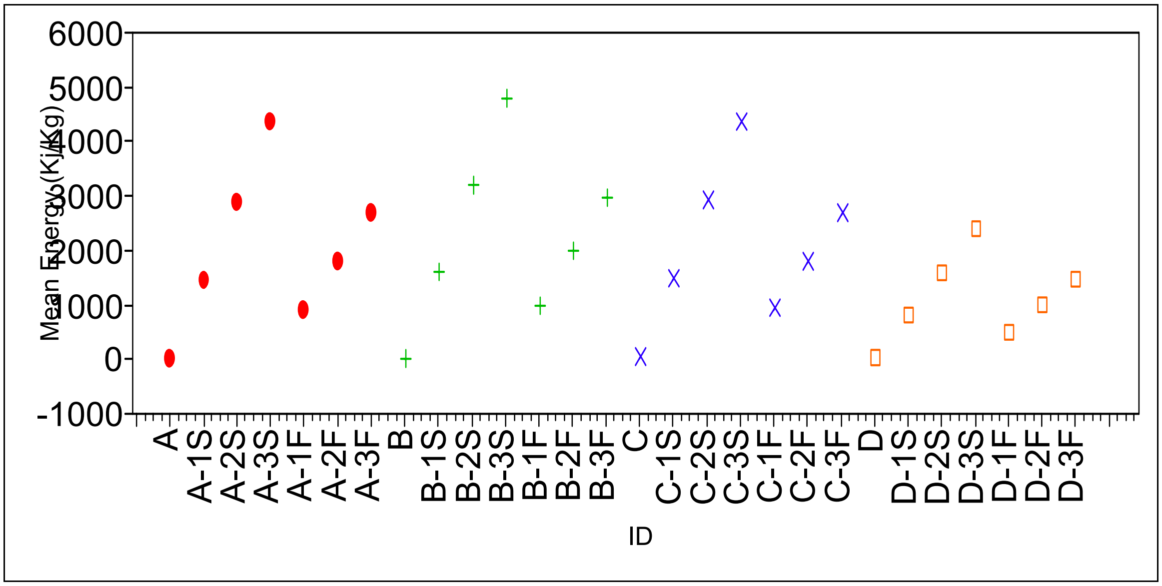


Figure 1: Specific Energy by ID

Figure 1 compares the specific energy for each hydroentangled sample. For each fabric construction, the control value with a specific energy equaling 0 is displayed. In each case, the slow conditions obtained the larger specific energy values, when compared to the fast conditions of the same fabric construction. This conveys the importance of dwell time during the hydroentanglement process. Although the fast conditions see higher bars of pressure, the decreased belt speed produce higher specific energy levels at the slower process conditions. Construction B offers the larger specific energy values in each condition, followed by C, A, and then construction D

4.2.2 Specific Energy of Bonded Samples

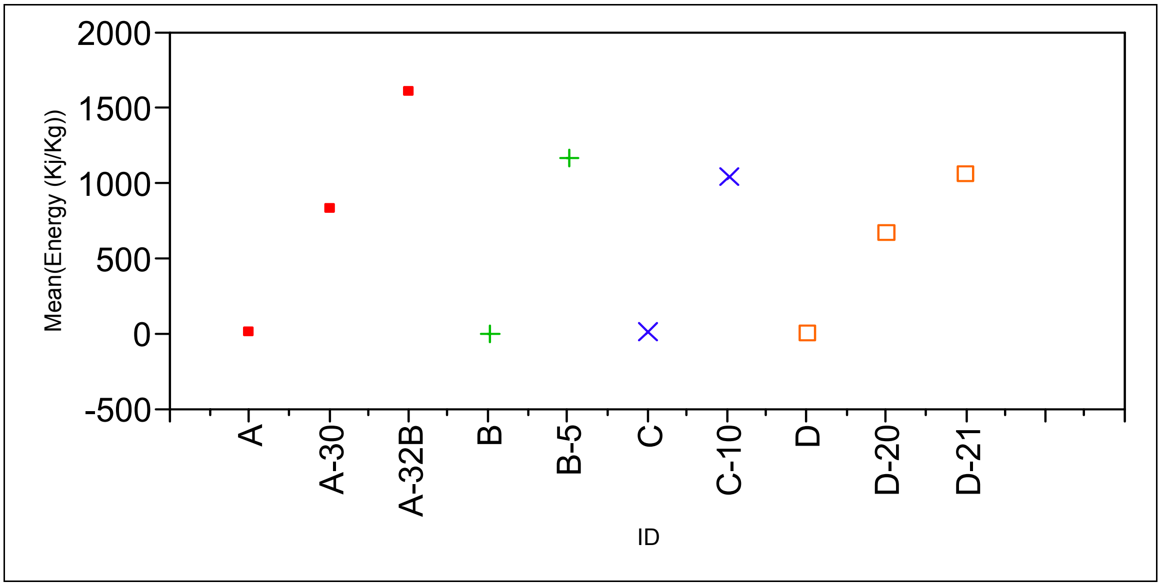


Figure 2: Specific Energy by Bonded Sample

Figure 2 compares the specific energy for each bonded sample. For each fabric construction, the control value with a specific energy equaling 0 is displayed. A speed of 10 meters/minute was held constant for each trial, and pressure conditions are similar, but not identical for each construction type.

4.3 Hydroentangled Samples

4.3.1 Fabric A

4.3.1.1Weight

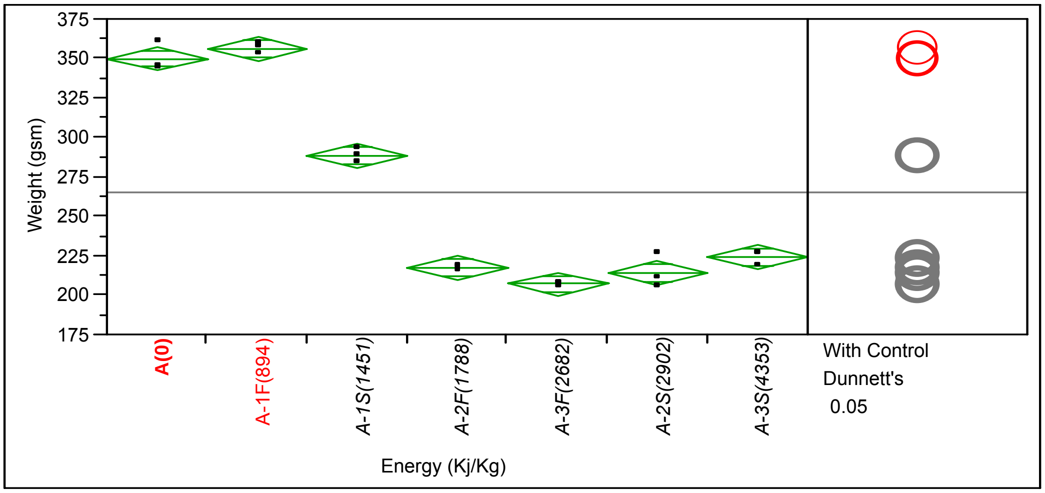


Figure 3: One way analysis of Weight by Energy

Figure 3 depicts an ANOVA analysis of weight by energy. Weight decreases as energy increases. The mean weight of sample at the lowest energy level, 894 Kj/Kg, is not statistically different from the mean weight of the control. The mean weights of all other samples are statistically different from the mean weight of the control. Once the energy level reaches 1788 Kj/Kg, there is no statistical difference in the weights of the samples.

4.3.1.2Picks per Inch

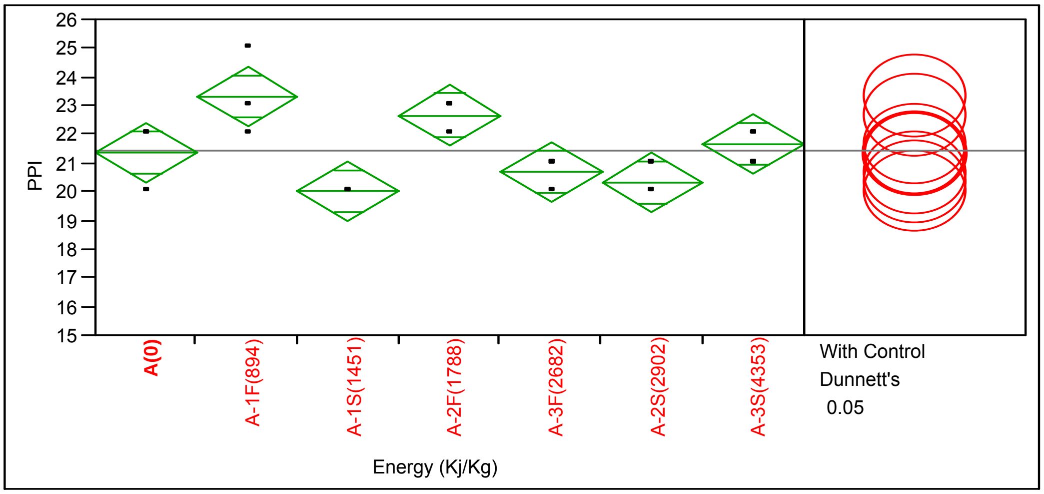


Figure 4: One way Analysis of Picks per Inch by Energy

Figure 4 depicts an ANOVA analysis of picks per inch by weight. The Dunnett's test conveys that none of the samples are statistically different from the control sample. Picks per inch does not change as energy increases. Process conditions used for these trials do not cause pick yarns to displace significantly.

4.3.1.3Ends per Inch

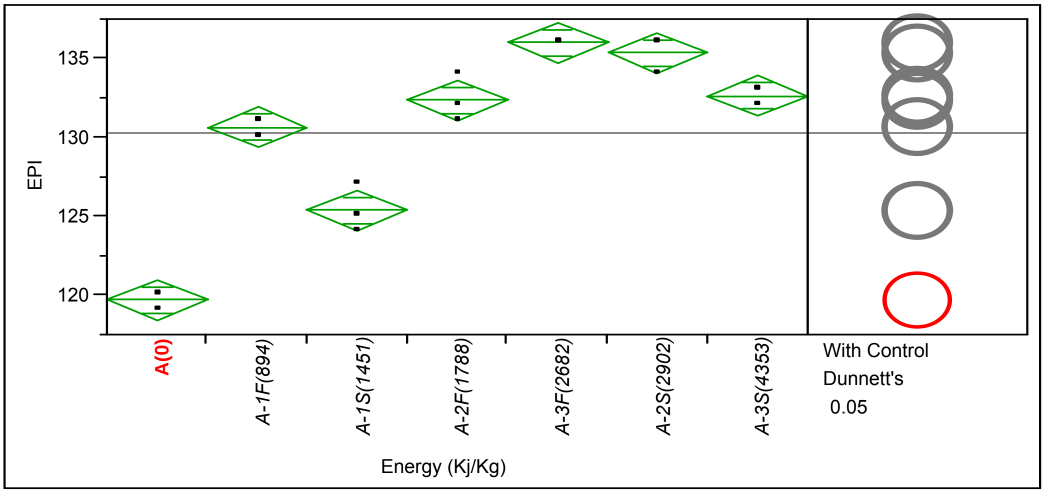


Figure 5: One way analysis of Ends per Inch by Energy

Figure 5 depicts an ANOVA analysis of ends per inch by weight. The Dunnett's test conveys that each sample is statistically different than the control sample. For each process condition the ends per inch increased when compared to the sample. As the sample passes through the hydroentangler, loose fibers are displaced and entangled, causing the construction to tighten up in area of loose fiber placement. Therefore, an increase in picks per inch for every condition type when compared to the control is expected.

4.3.1.4 Stiffness

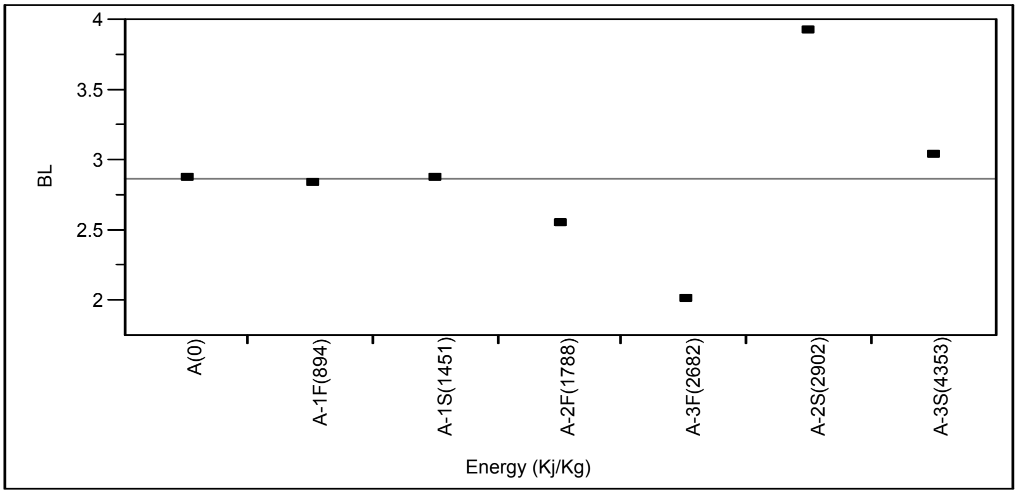


Figure 6: Plot of Bending Length by Energy

Figure 6 displays a plot of bending length for fabric A by increasing energy levels. There is little change as energy increase from 0 until energy approaches 1788 Kj/Kg. Here bending length begins to decrease, meaning a less stiff fabric. Once energy approaches over 2900 Kj/Kg, the bending length takes a sharp increase, meaning a much more stiff fabric is the result of high processing energy.

4.3.1.5Tensile Strength

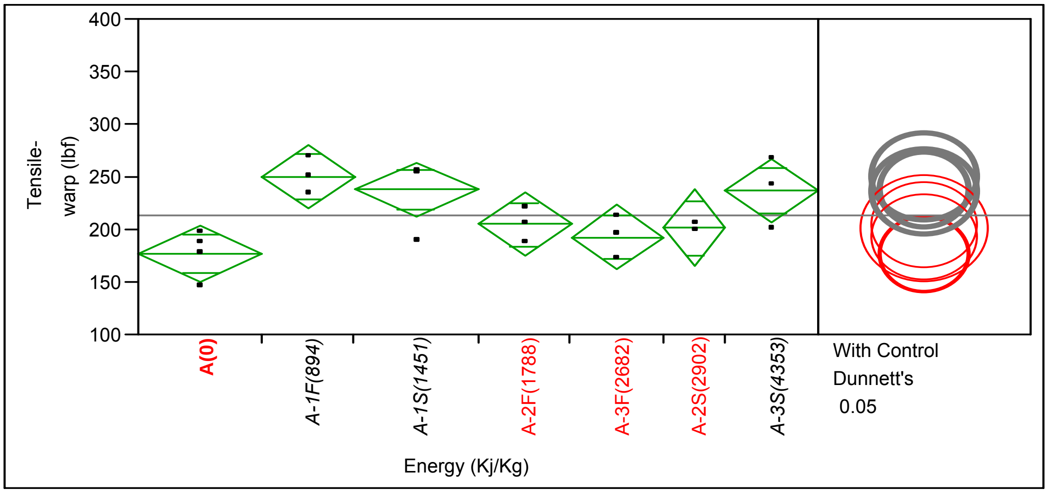


Figure 7: One way analysis of Tensile Strength (warp) by Energy

Figure 7, above, depicts an ANOVA analysis of tensile strength in the warp direction by energy. There is a slight increase in strength in the warp direction for each processed sample when compared to the control sample. This can be explained by the slight increase in ends per inch as shown previously in Figure 5. Figure 8, shown on the next page shows an ANOVA analysis of tensile strength in the filling direction by energy. Picks per inch was not significantly changed by processing as shown earlier in Figure 4. An increase in tensile strength is seen with the lower energy levels, but as energy approaches 1788 Kj/Kg and beyond, tensile strength in the filling direction is not improved over the control sample. At higher energy levels the construction begins to compact, which leads to a restriction on yarn mobility. This will cause a reduction in tensile strength of the fabric.

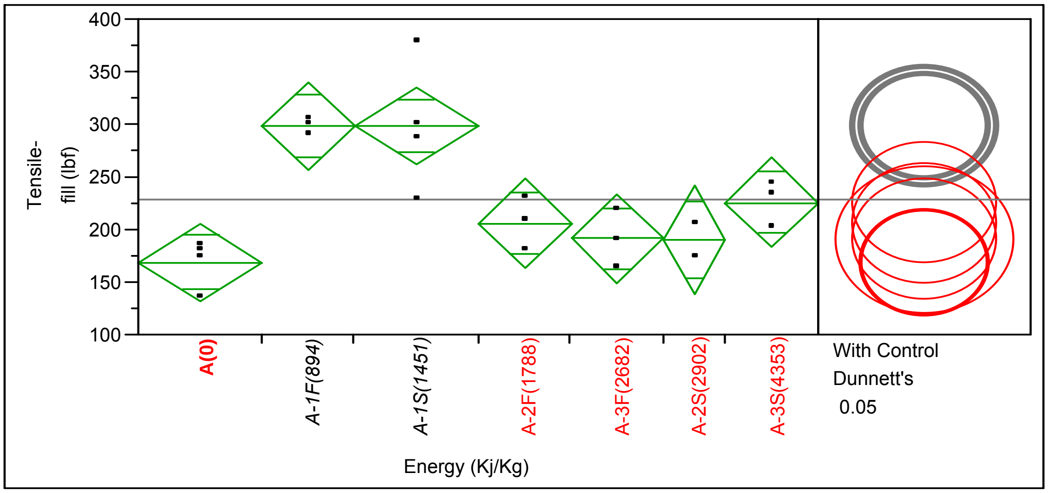


Figure 8: One way analysis of Tensile Strength (fill) by Energy

4.3.1.6 Tear Strength

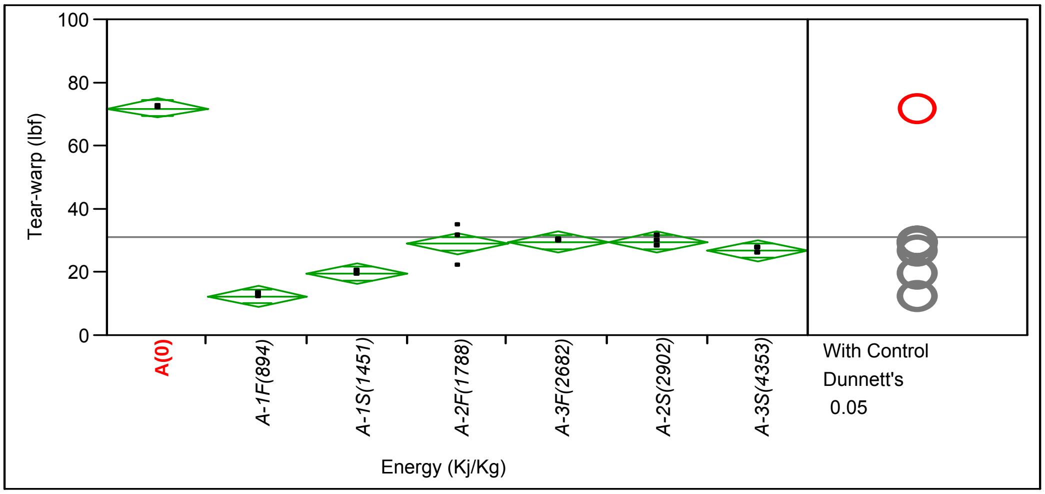


Figure 9: One way analysis of Tear Strength (warp) by Energy

Figure 9, shown above, is an ANOVA analysis of tear strength in the warp direction by energy. Figure 10, shown on the next page is an ANOVA analysis of tear strength in the filling direction by energy. In both cases, all samples mean tear strength values are statistically lower than the mean value of the control sample. Tear Strength values in the filling direction are higher than those in the warp direction. The reduction in tear strength is caused by the tightening of the structure during hydroentanglement. Yarn mobility is decreased as the structure moves from a loose to tighter state, jeopardizing tear strength.

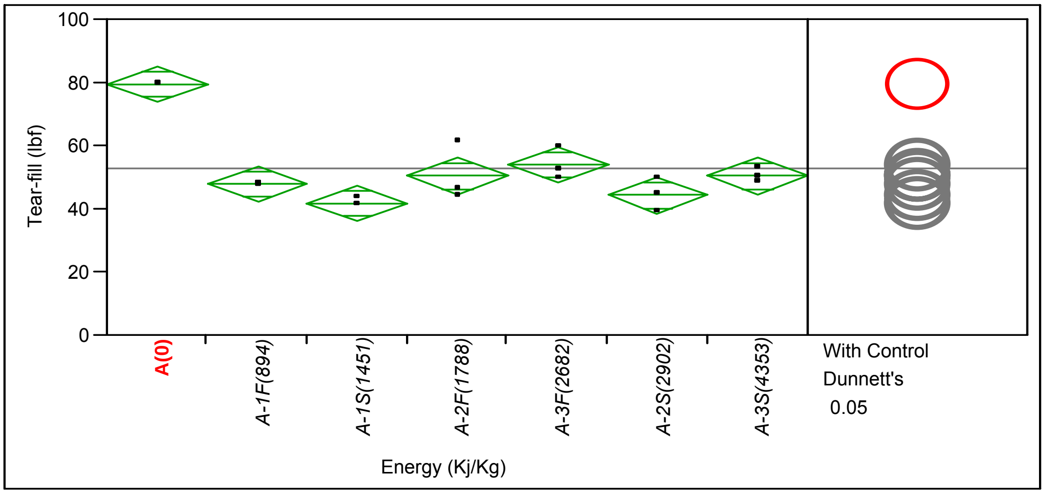


Figure 10: One way analysis of Tear Strength (fill) by Energy

4.3.1.7 Pilling

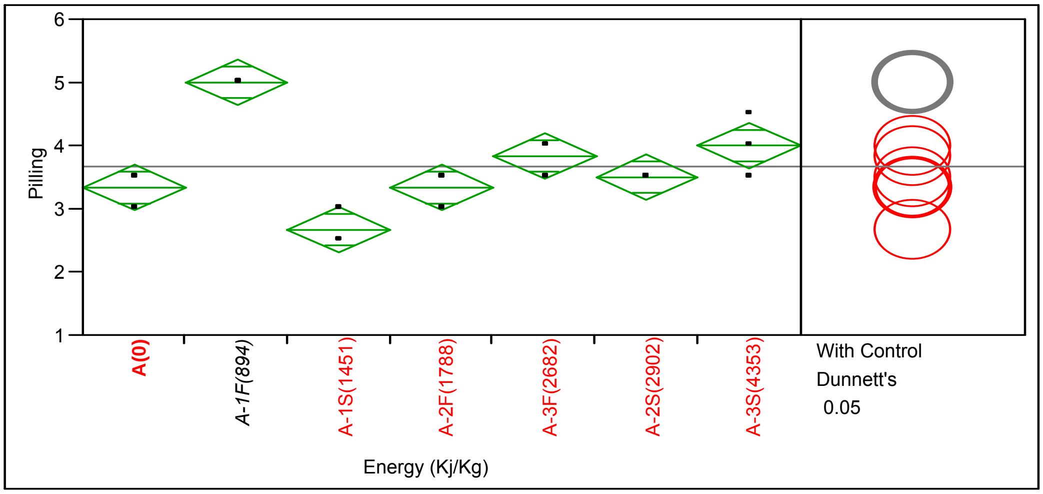


Figure 11: One way analysis of Pilling by Energy

Figure 11 depicts an ANOVA analysis of pilling rating by energy. All samples except the lowest energy level, 894 Kj/Kg, offer ratings that are not statistically different than that of the control. The lowest energy level maintains the highest overall pilling rating of all trial samples and the control. . Sample A-1F, with a rating of 5 is the only sample where the degree of pilling was considerably improved by hydroentangling the sample.

4.3.1.8 Air Permeability

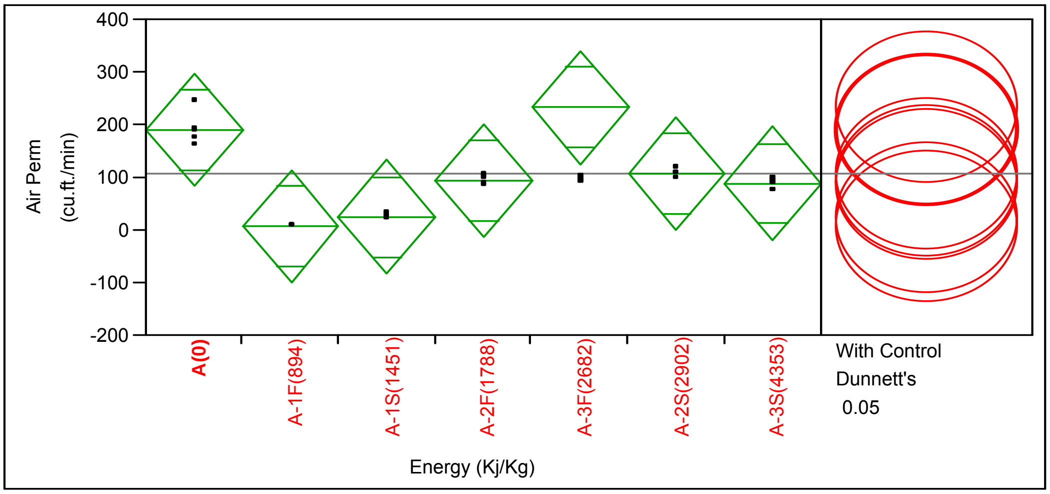


Figure 12: One way analysis of Air Permeability by Energy

Figure 12 depicts an ANOVA analysis of air permeability by energy. As the Dunnett's test shows, all mean values of air permeability are statistically the same as the control value. Air Permeability was not improved as energy levels increased. The average of all samples is around 100, significantly lower than the average of the control sample, slightly under 200. It has been shown that the construction of the fabric has changed, but Figure 26 demonstrates that porosity has not been affected.

4.3.1.9 Thickness

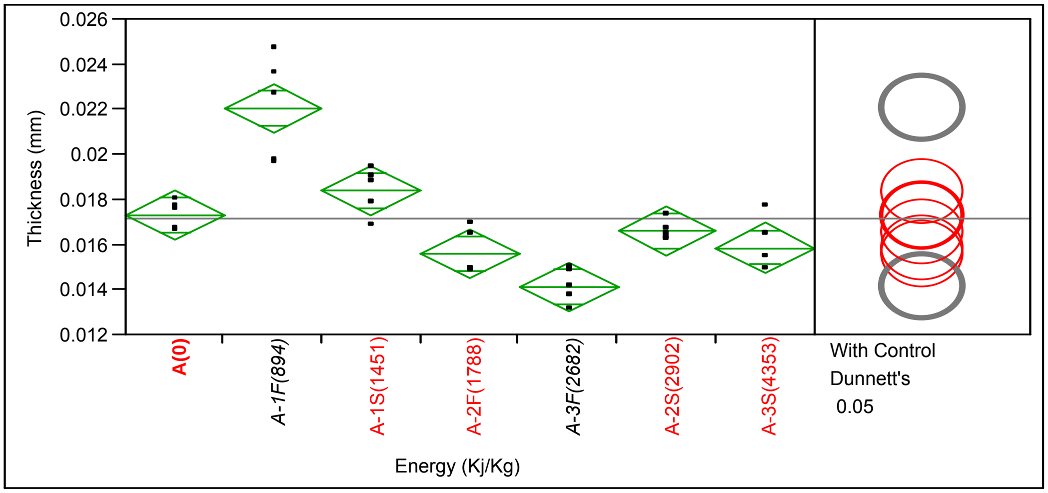


Figure 13: One way analysis of Thickness by Energy

Figure 13 depicts an ANOVA analysis of fabric thickness by energy. Two samples, A-1F and A-3F, have a mean thickness value statistically different than the mean thickness value of the control sample. In the case of A-1F, the mean value has increased, while A-3F, the mean value has decreased. The raised patterns of the jacquard fabrics chosen for the trials may be a factor in the overall outcome of the thickness measurements.

4.3.2 Fabric B

4.3.2.1Weight

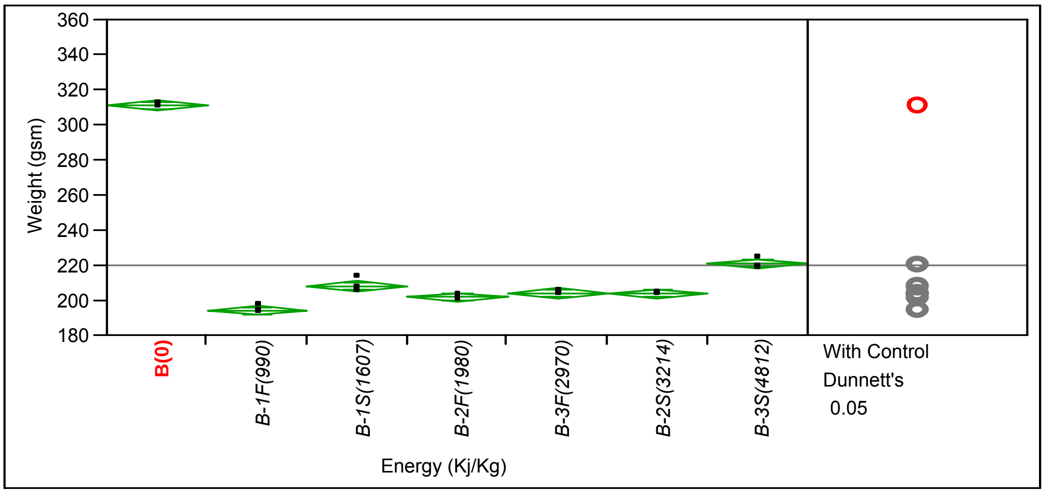


Figure 14: One way analysis of Weight by Energy

Figure 14 is an ANOVA analysis of fabric weight by energy. The Dunnett's test shows that all samples have a significantly different mean weight than the control sample. All samples have a significantly lower weight than the control. The test also shows us, that as energy increases, there is not a significant difference in the mean weights of each sample.

4.3.2.2Picks per Inch

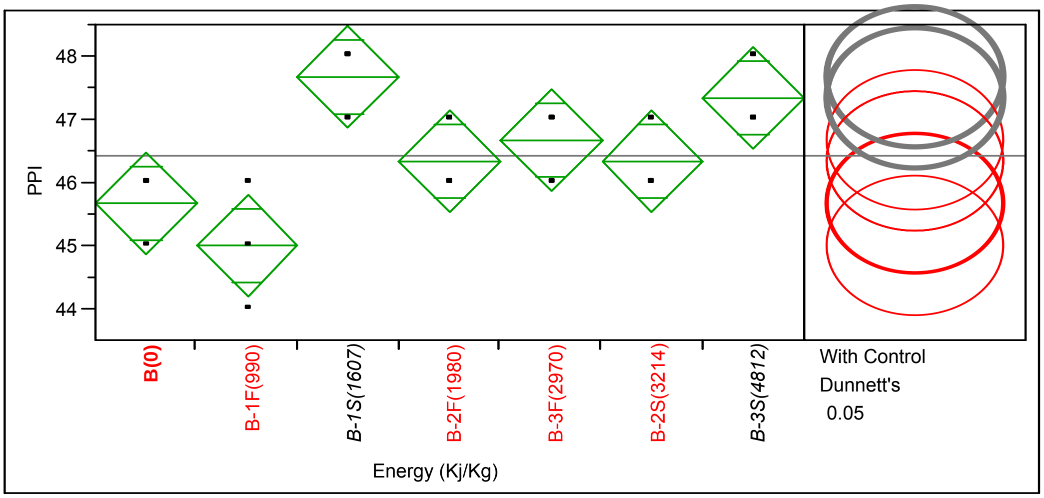


Figure 15: One way analysis of Picks per Inch by Energy

Figure 15 is the ANOVA analysis of picks per inch by energy. After surpassing the initial specific energy of 990 Kj/Kg, there is an increase on picks per inch when compared to the control sample. The process conditions through the hydroentangler caused the structure to compress; causing an increase in picks per inch overall, but as energy increases, there is not a significant difference in picks per inch.

4.3.2.3Ends per Inch

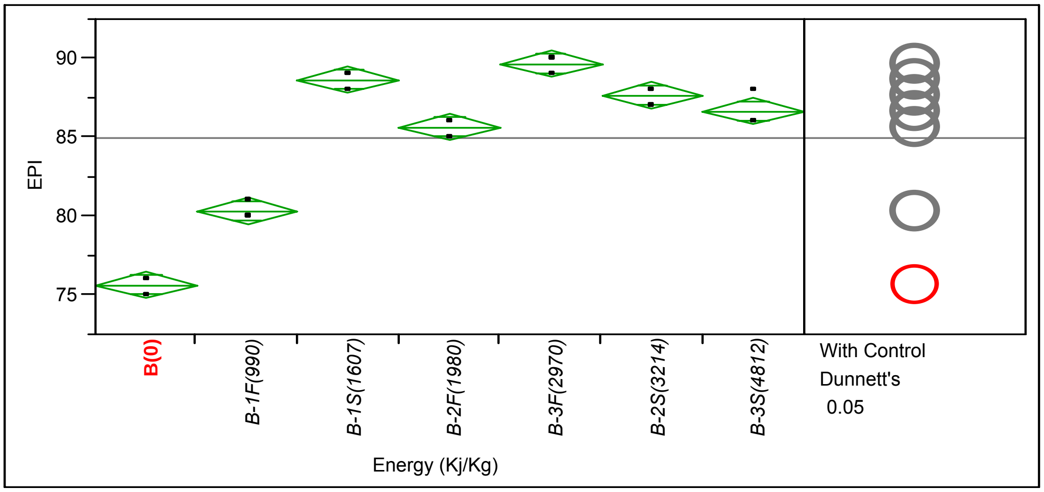


Figure 16: One way analysis of Ends per Inch by Energy

Figure 16 is the ANOVA analysis of ends per inch by energy. The Dunnett's test shows that all samples have a statistically different mean end count per inch as compared to the control sample. In each case, the ends per inch have increased over the initial control count. As energy approaches and exceeds 1607 Kj/Kg, there is not a significant difference in mean end count per inch.

4.3.2.4Stiffness

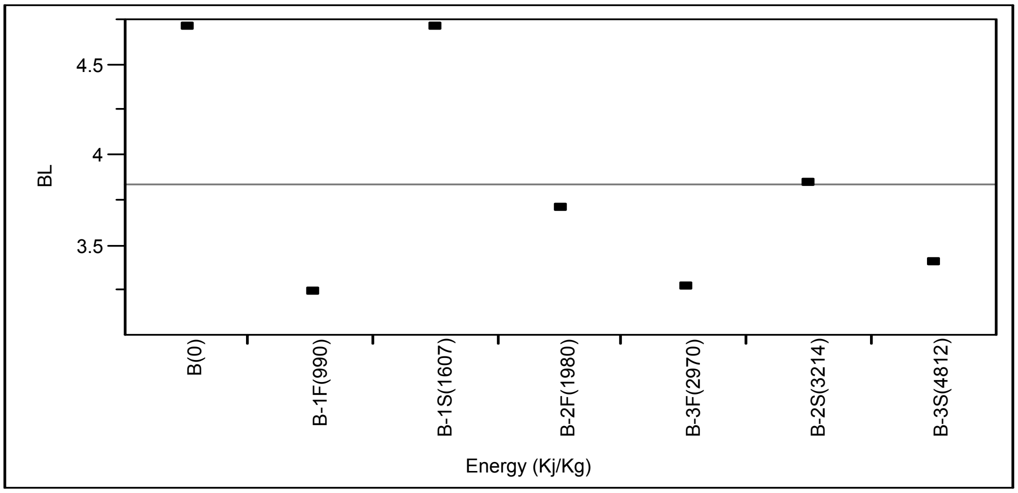


Figure 17: Plot of Bending Length by Energy

Figure 17 shows the plot of bending length by energy for fabric construction B. In general, when compared to the bending length of the control sample, all trial samples had much lower bending length values. This means that the trial samples were less stiff than the control sample that did not see the hydroentangling process.

4.3.2.5Tensile Strength

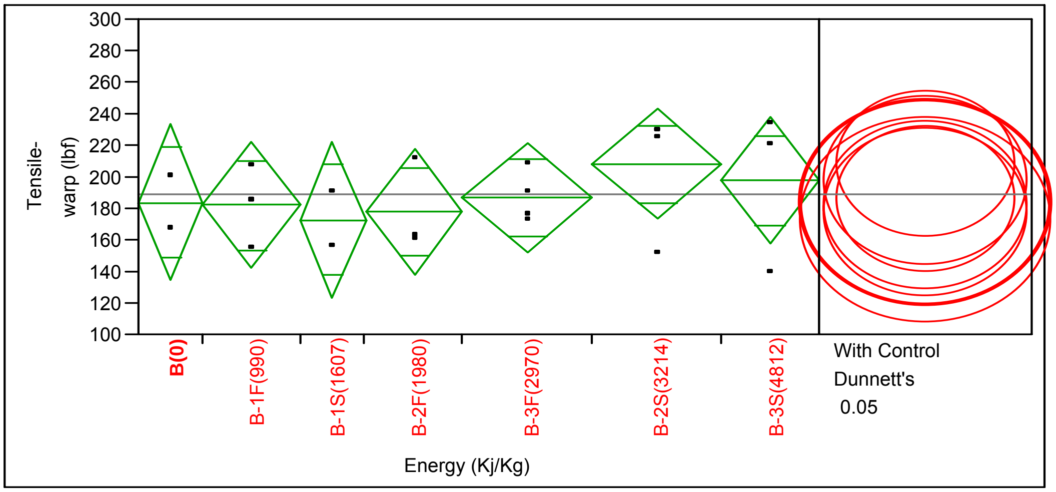


Figure 18: One way analysis of Tensile Strength (warp) by Energy

Figure 18 shows the ANOVA analysis of tensile strength in the warp direction by energy. All trial samples have a mean tensile strength value in the warp direction that is statistically the same as the control sample. Looking at Figure 19, the ANOVA analysis of tensile strength in the filling direction by energy is shown. Again, the Dunnett's test shows that there is no significant difference in the mean tensile strength values for each trial sample when compared to the control sample. In both warp and fill directions, there is not a significant change as energy increases.

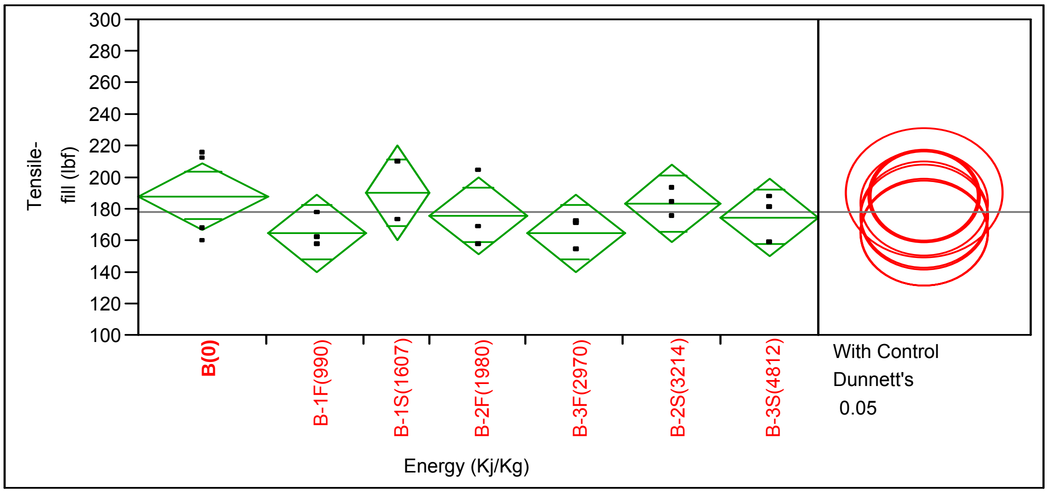


Figure 19: One way analysis of Tensile Strength (fill) by Energy

4.3.2.6Tear Strength

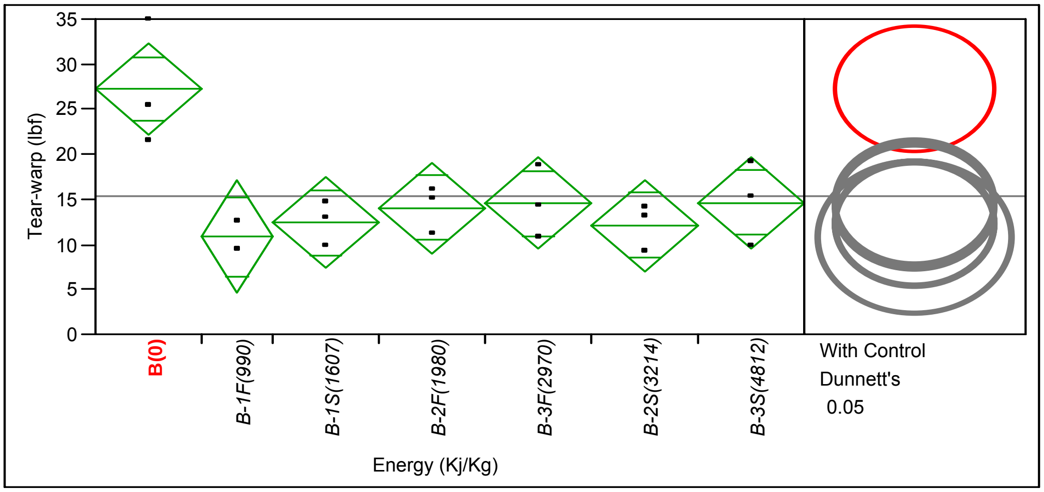


Figure 20: One way analysis of Tear Strength (warp) by Energy

Figure 20 shows the ANOVA analysis of tear strength in the warp direction by energy. In each case, the trial samples have a significantly lower tear strength in the warp direction when compared to the control sample. There is only a slight change as energy increases. Figure 21 displays the ANOVA analysis of tear strength in the filling direction by energy. Again, the trial samples have significantly lower tear strength in the filling direction as compared to the control sample. There is no significant difference as energy increases among the trial samples. As surface fibers entangle during the hydroentangling process, yarn mobility is reduced, thus compromising tear strength values.

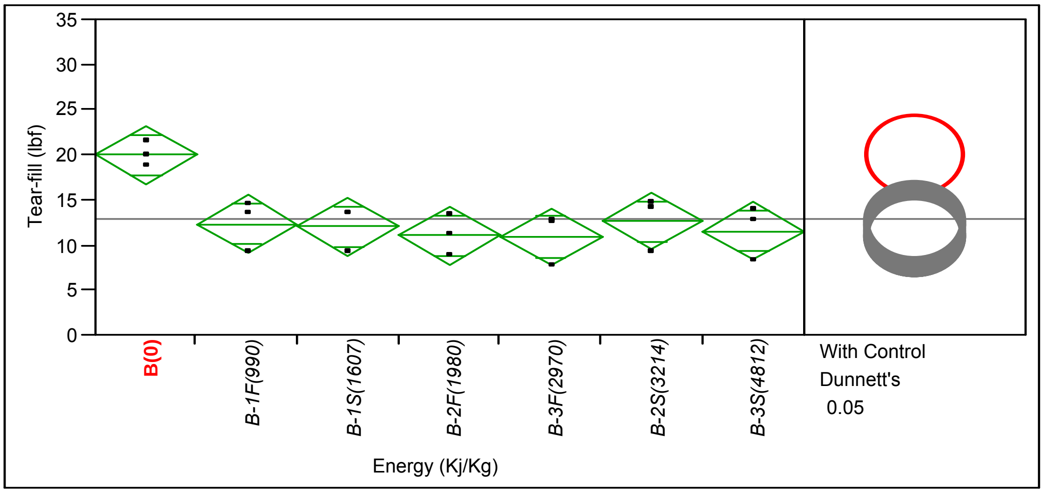


Figure 21: One way analysis of Tear Strength (fill) by Energy

4.3.2.7Pilling

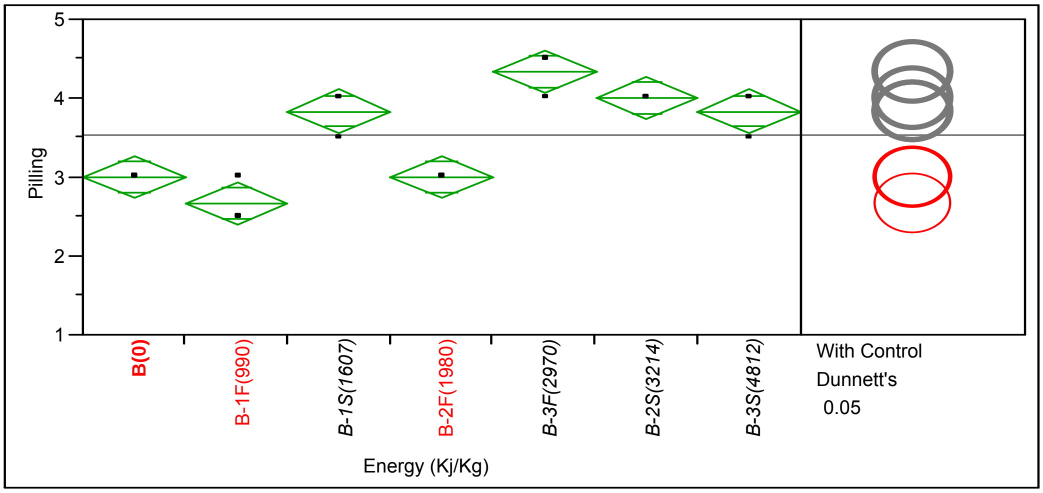


Figure 22: One way analysis of Pilling by Energy

Figure 22 displays the ANOVA analysis of the pilling rating by energy for fabric B. Both the first and second pass samples at the fast conditions have ratings that are statistically the same as the control. For all other samples, ratings were improved when compared to the control sample rating of 3.

4.3.2.8 Air Permeability

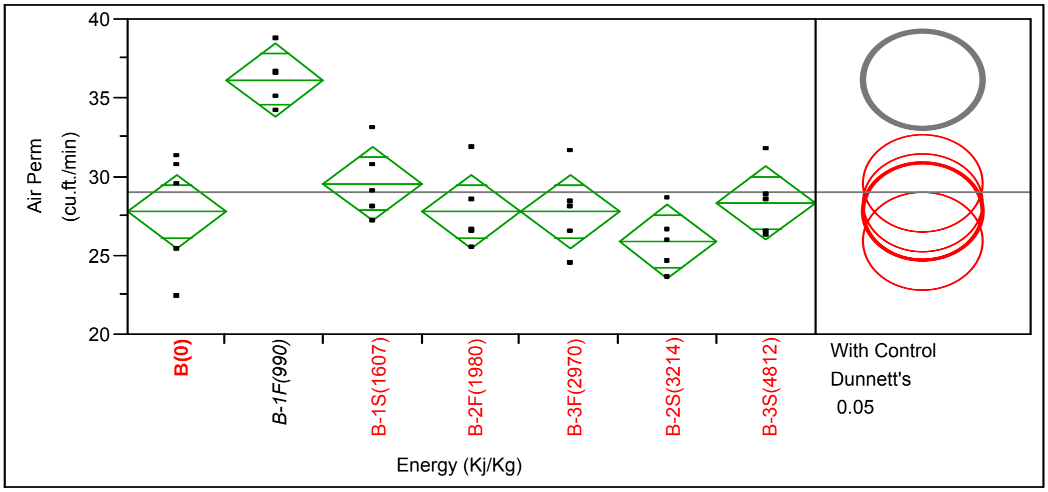


Figure 23: One way analysis of Air Permeability by Energy

Figure 23 shows the ANOVA analysis of air permeability by energy. The initial energy level, 990 Kj/Kg, showed an increase in air permeability values. All others had mean air permeability values that were not statistically different than the control. Although the structure was compressed, this did not have an effect on air permeability.

4.3.2.9Thickness

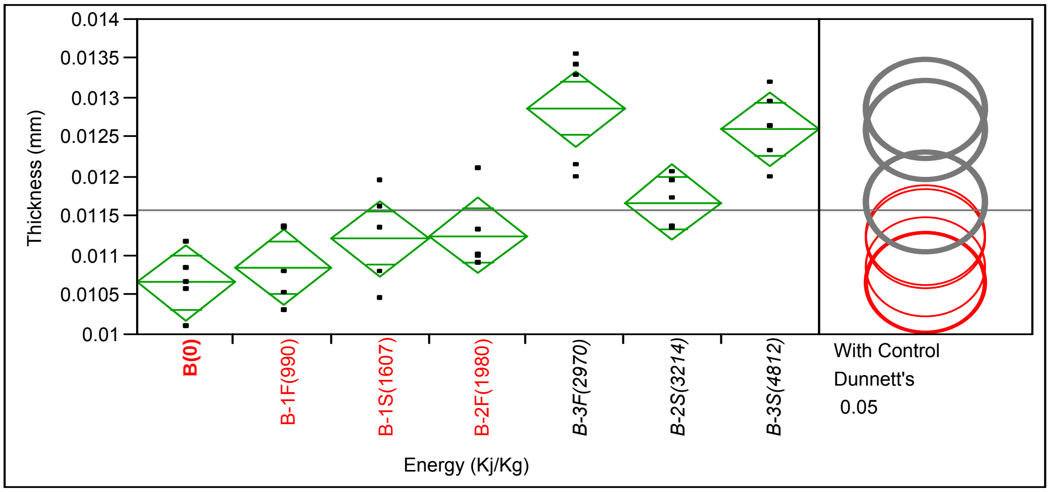


Figure 24: One way analysis of Thickness by Energy

Figure 24 shows the ANOVA analysis of fabric B's thickness by energy. The Dunnett's test shows that as energy levels remain below 2000 Kj/Kg, there is no statistical difference in fabric thickness when compared to the control. As energy levels exceed 2000 Kj/Kg, fabric thickness becomes statistically higher than the control sample.

4.3.3 Fabric C

4.3.3.1Weight

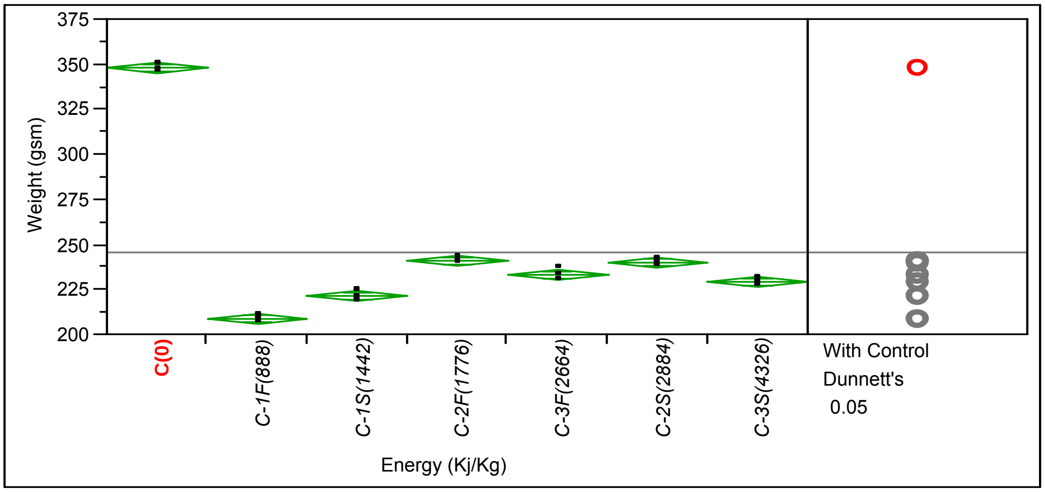


Figure 25: One way analysis of Weight by Energy

Figure 25 shows the ANOVA analysis of fabric C's weight by energy. In all instances the weight of all trial samples was statistically lower than the control. As energy approaches and exceeds 1770 Kj/Kg, there is not a significant difference in the mean weight of the samples.

4.3.3.2 Picks per Inch

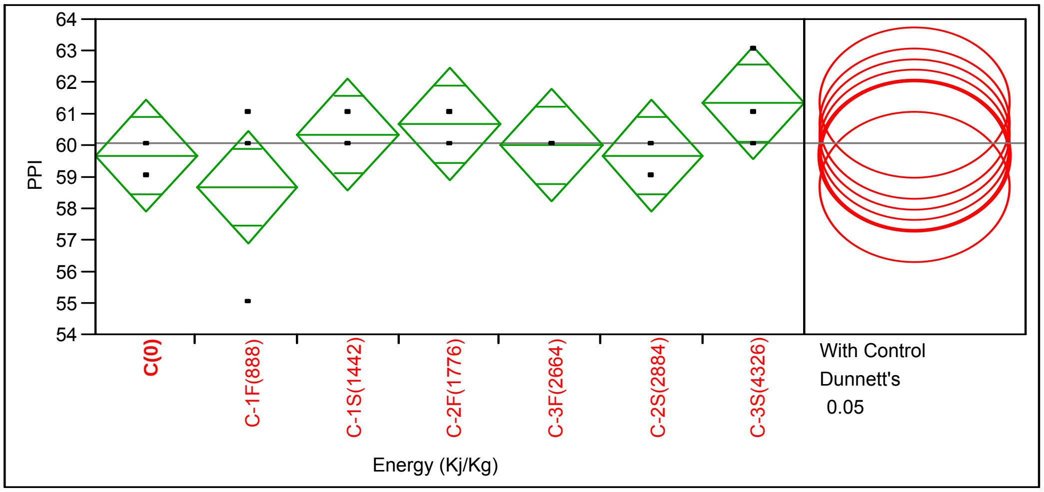


Figure 26: One way analysis of Picks per Inch by Energy

Figure 26 shows the ANOVA of picks per inch by energy. For each trial sample, there is no significant difference in the mean picks per inch count when compared to the control sample. While some compression is evident, the increase in energy did not statistically change the picks per inch of the woven jacquard fabric.

4.3.3.3Ends per Inch

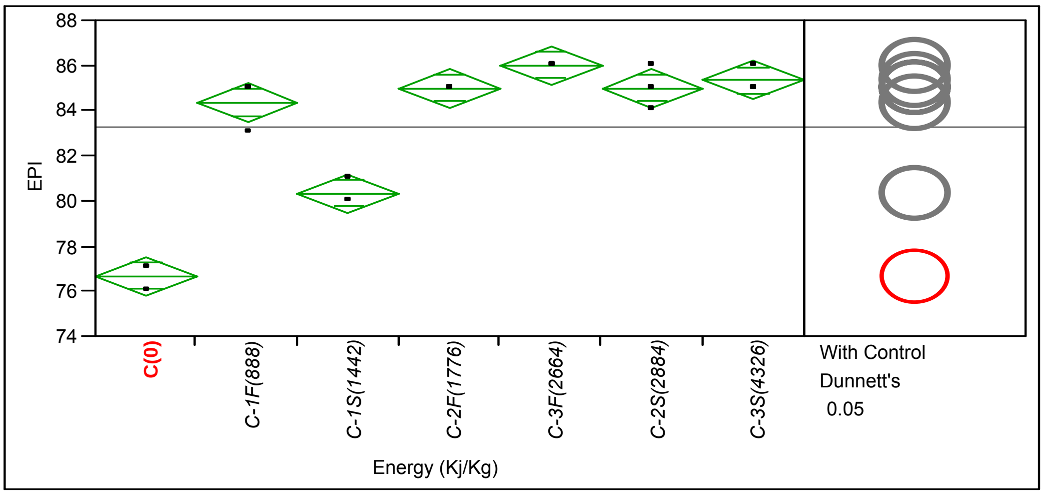


Figure 27: One way analysis of Ends per Inch by Energy

Figure 27 shows the ANOVA analysis of ends per inch by energy. In each instance, when compared to the control fabric, the mean ends per inch count for each trial sample is statistically higher. Once energy approaches and exceeds 1776 Kj/Kg, there is no significant change in ends per inch.

4.3.3.4Stiffness

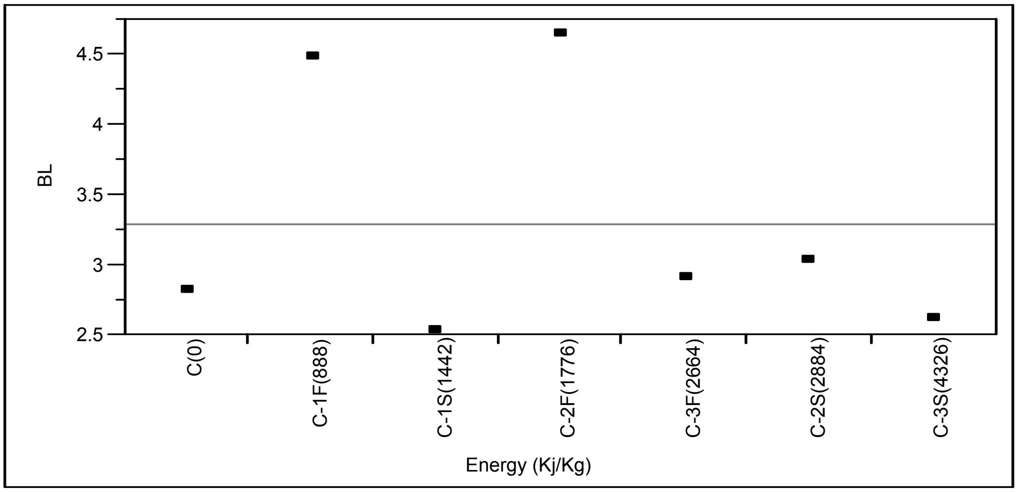


Figure 28: Plot of Bending Length by Energy

Figure 28 shows the plot of the bending length of fabric C by increasing energy level. In general, there was no significant difference in the bending lengths of the control sample when compared to the hydroentangled samples. There were two instances when the bending length increased, at the initial energy level of 888 Kj/Kg, and again at 1776 Kj/Kg. Overall, increasing energy level during the process does not cause entangled fibers to become stiff enough to have a great impact on bending length.

4.3.3.5 Tensile Strength

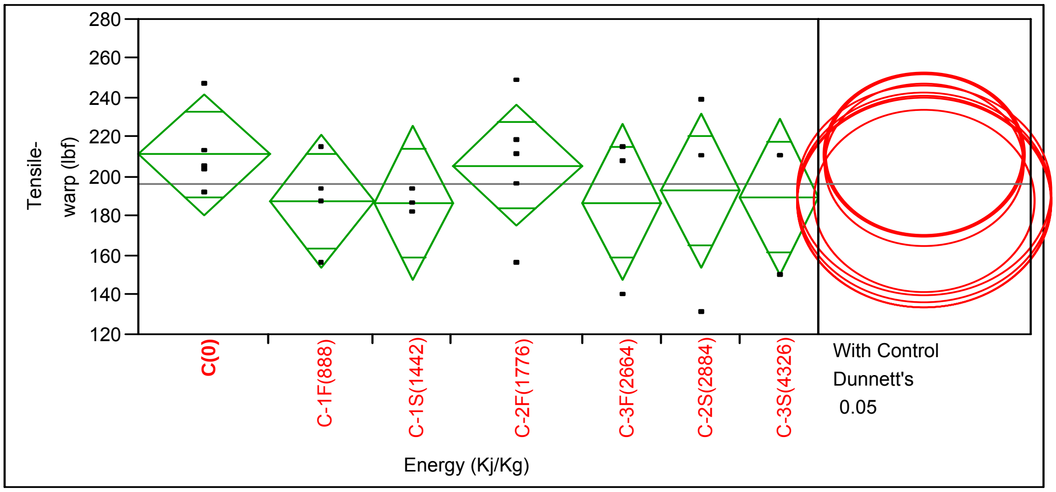


Figure 29: One way analysis of Tensile Strength (warp) by Energy

Figure 29 shows the ANOVA analysis of tensile strength in the warp direction by energy. The Dunnett's test shows that there is no statistical difference in the mean tensile strength values in the warp direction when compared to the control sample. Figure 30, displays the same trend. An increasing energy level does not statistically change the tensile strength of the trial samples, when compared to the control samples, in either the warp or filling direction.

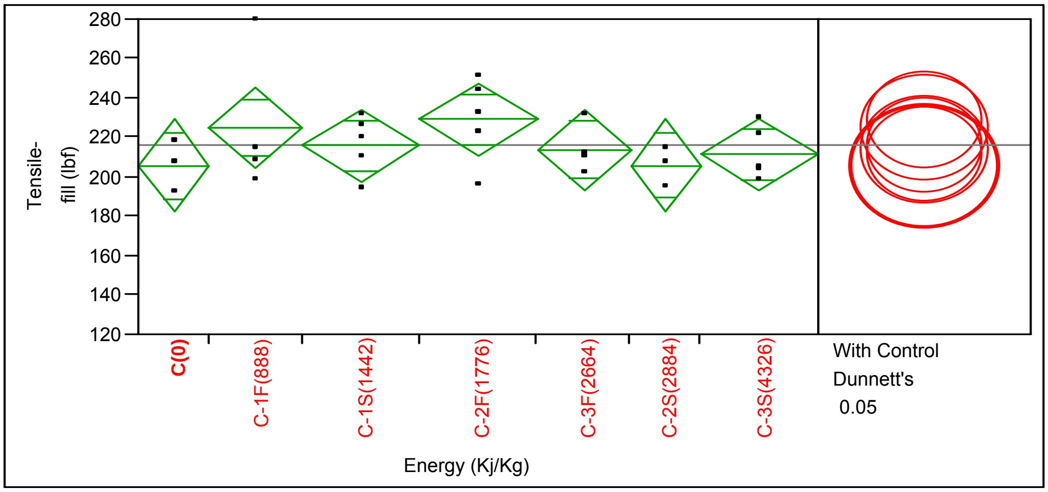


Figure 30: One way analysis of Tensile Strength (fill) by Energy

4.3.3.6 Tear Strength

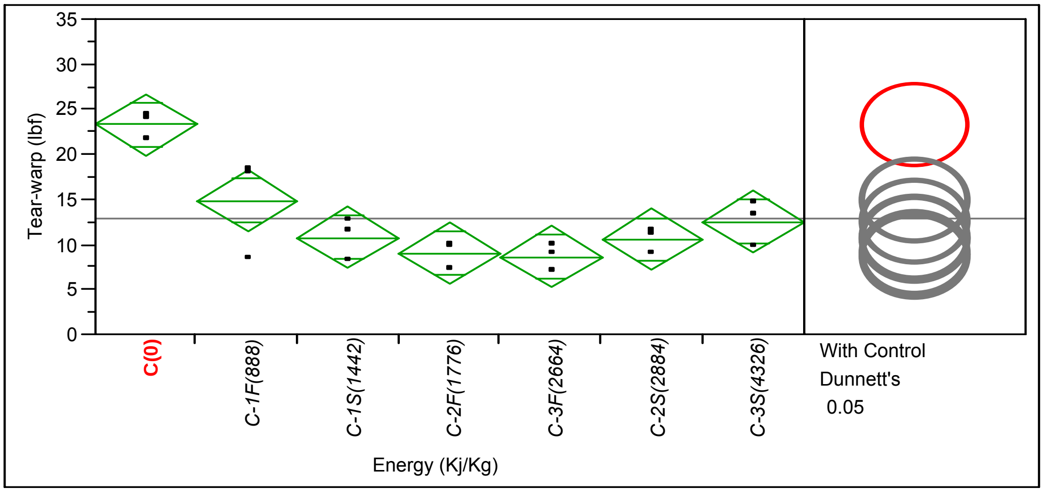


Figure 31: One way analysis of Tear Strength (warp) by Energy

Figure 31 shows the ANOVA analysis of tear strength in the warp direction by energy. The Dunnett's test shows that the control sample has a mean tear strength value in the warp direction statistically higher than the trial samples. As energy approaches 2000 Kj/Kg, tear strength in the warp direction declines, but does not significantly change after exceeding this energy level. Figure 32, shown below is the ANOVA analysis for tear strength in the filling direction by energy for the sample fabric. The lowest energy ranges, between 888 – 1442 Kj/Kg do not show a statistical difference in mean tear strength values in the filing direction as compared to the control fabric. As energy approaches 1776 Kj/Kg, tear strength values in the filling direction are statistically lower than the control value. Once exceeding 1776 Kj/Kg there is not a significant difference in tear strength values in the filling direction.

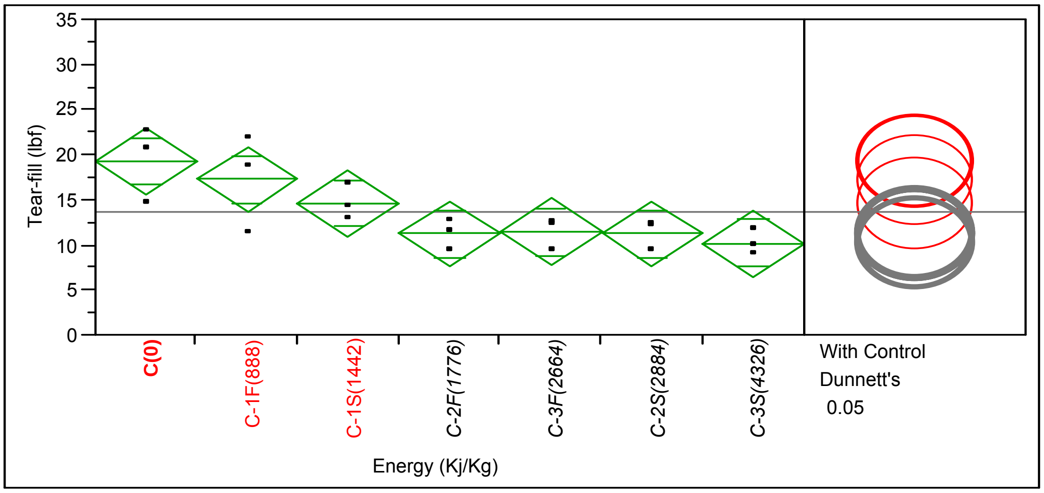


Figure 32: One way analysis of Tear Strength (fill) by Energy

4.3.3.7Pilling

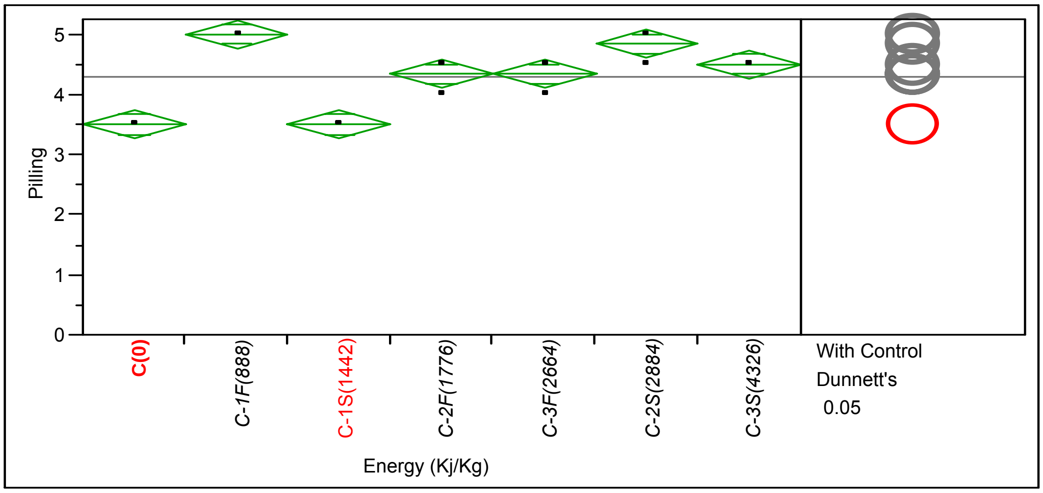


Figure 33: One way analysis of Pilling by Energy

Figure 33 shows the ANOVA analysis of the pilling ratings by energy for fabric C. In general, pill ratings were improved by hydroentanglement, although as energy levels exceed 1776 Kj/Kg, there is no significant difference in mean pill ratings among the trial samples.

4.3.3.8 Air Permeability

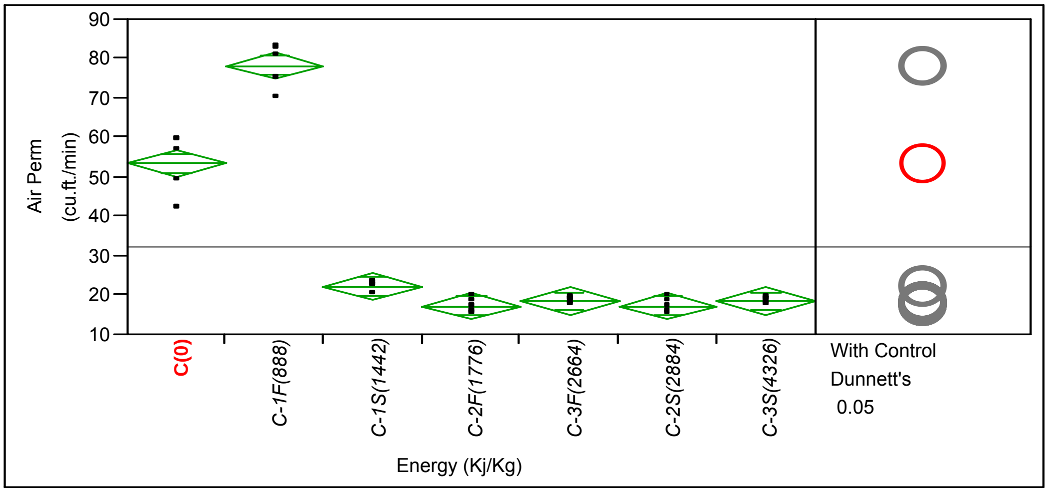


Figure 34: One way analysis of Air Permeability by Energy

Figure 34 shows the ANOVA analysis of air permeability by energy for fabric C. All trial samples have mean air permeability values that are significantly different than the control fabric. The lowest energy level has a statistically higher air permeability mean, while all others trial samples have statistically lower mean air permeability values. In general, hydroentanglement statistically lowered the air permeability for fabric C. As energy approaches and exceeds 1442 Kj/Kg, there is no statistical difference in mean air permeability values amongst the trial samples.

4.3.3.9Thickness

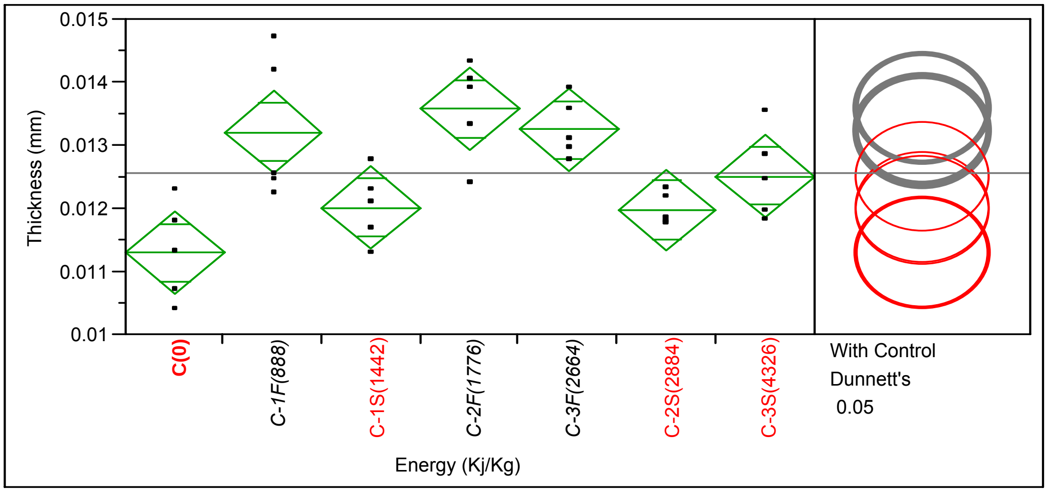


Figure 35: One way analysis of Thickness by Energy

Figure 35 shows the ANOVA analysis of thickness of the fabric C by energy. There is no noticeable trend here. This can be attributed to the raised and lowered patterns noted in the fabric's jacquard weave construction.

4.3.4 Fabric D

4.3.4.1Weight

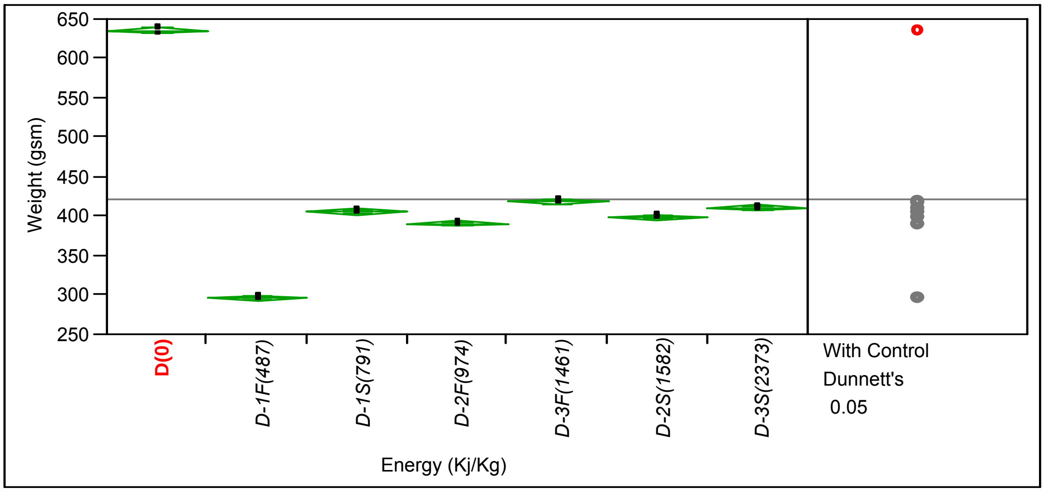


Figure 36: One way analysis of Weight by Energy

Figure 36 shows the ANOVA analysis of fabric D's weight by energy. In all instances the weight of all trial samples was statistically lower than the control. As energy approaches and exceeds 791 Kj/Kg, there is not a significant difference in the mean weight of the samples.

4.3.4.2Picks per Inch

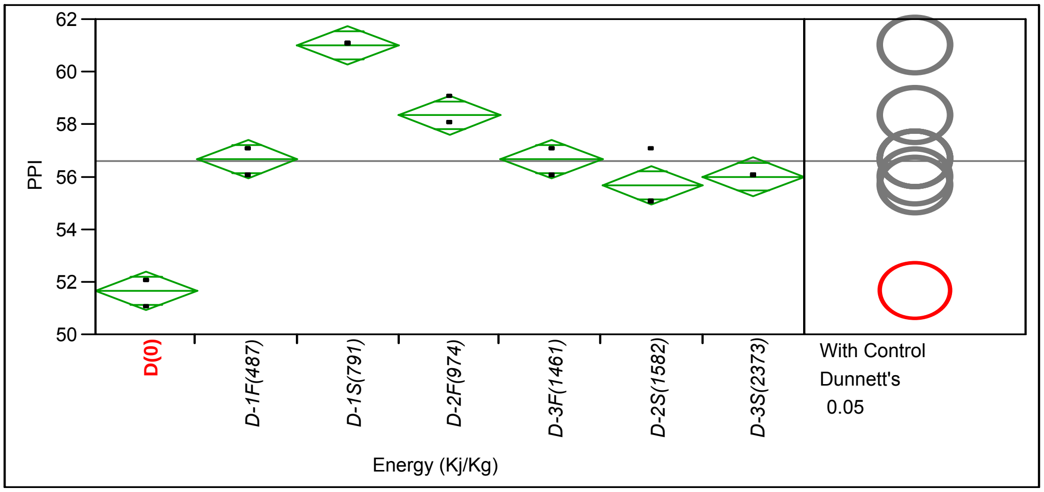


Figure 37: One way analysis of Picks per Inch by Energy

Figure 37 shows the ANOVA analysis of picks per inch by energy. All trial samples have a mean picks per inch count statistically higher than the control. Once the energy level reaches 1461 Kj/Kg, there is not a significant difference in mean picks per inch amongst the trial samples.

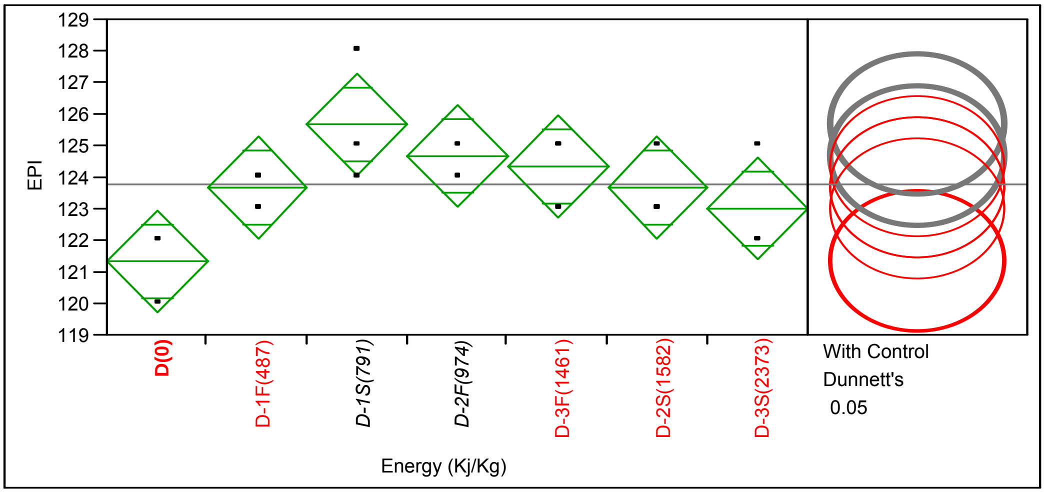


Figure 38: One way analysis of Ends per Inch by Energy

Figure 38 displays the ANOVA analysis of ends per inch by energy. In general, when compared to the control sample, mean ends per inch counts were slightly higher, but not statistically different.

4.3.4.3 Stiffness

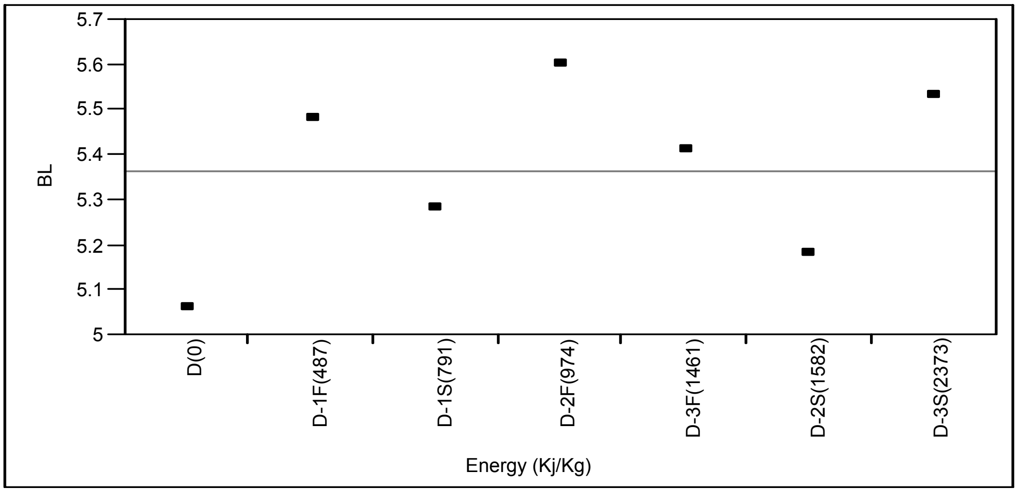


Figure 39: Plot of Bending Length by Energy

Figure 39 shows the plot of bending length for fabric D by increasing energy levels. In every instance, the bending length of the trial samples was higher than the control sample. Increasing bending lengths mean a stiffer fabric. The process of hydroentangling has caused surface fibers to entangle amongst each other and embedded fibers, causing a stiffer fabric.

4.3.4.4Tensile Strength

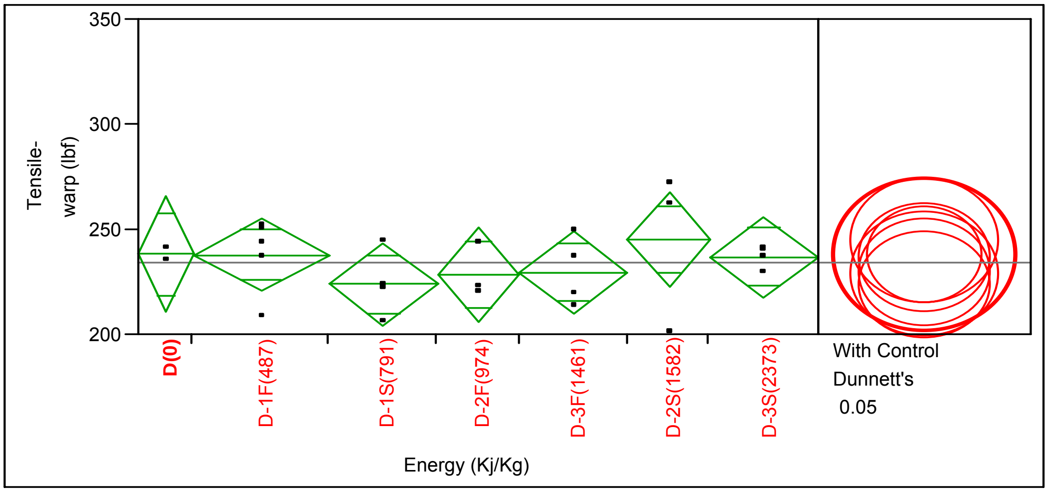


Figure 40: One way analysis of Tensile Strength (warp) by Energy

Figure 40 shows the ANOVA analysis of tensile strength in the warp direction by energy. For each trial sample, the mean value of tensile strength in the warp direction is not statistically different from the control value. Figure 41 displays the ANOVA analysis of tensile strength in the filling direction by energy. There are two samples where the mean tensile strength value in the filling direction was statistically lower than the control value; in all other cases the values were not statistically different.

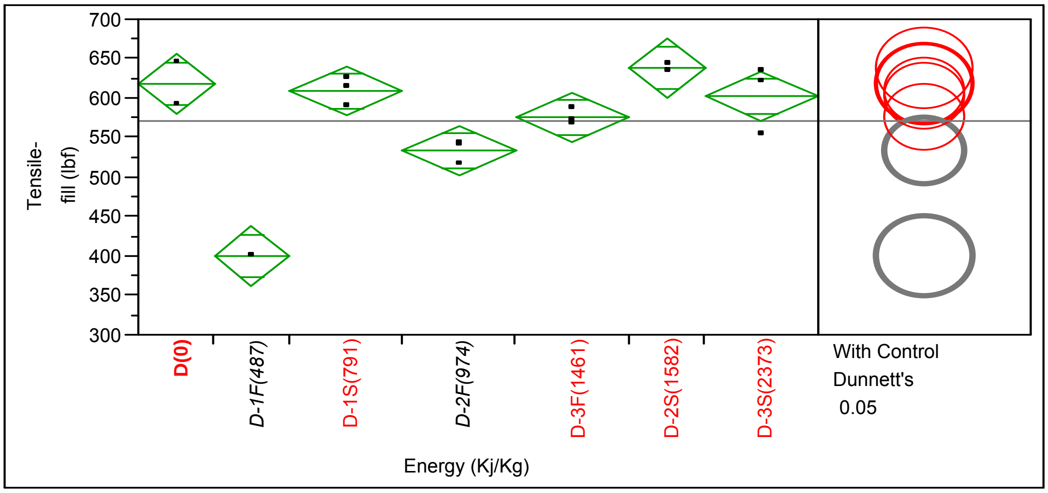


Figure 41: One way analysis of Tensile Strength (fill) by Energy

4.3.4.5Tear Strength

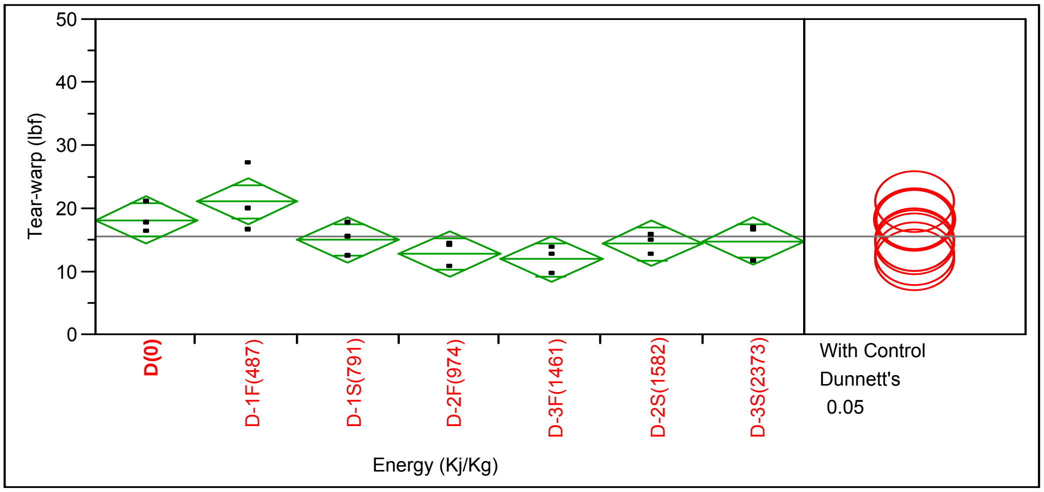


Figure 42: One way analysis of Tear Strength (warp) by Energy

Figure 42 shows the ANOVA analysis of tear strength in the warp direction by energy. In each case, the mean values of the trial samples are not statistically different from the control value. Figure 43 is the ANOVA analysis of the tear strength in the filling direction by energy. In each instance, the mean values for the trial samples were statistically lower than the control value. As energy approaches and exceeds 974 Kj/Kg, there is no significant difference in the mean values of tear strength in the filling direction amongst the trial samples.

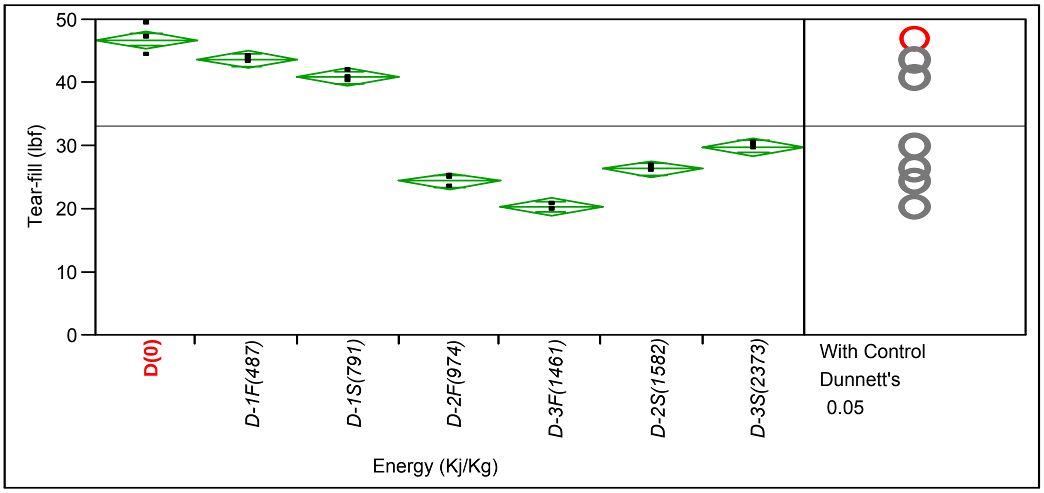


Figure 43: One way analysis of Tear Strength (fill) by Energy

4.3.4.6Pilling

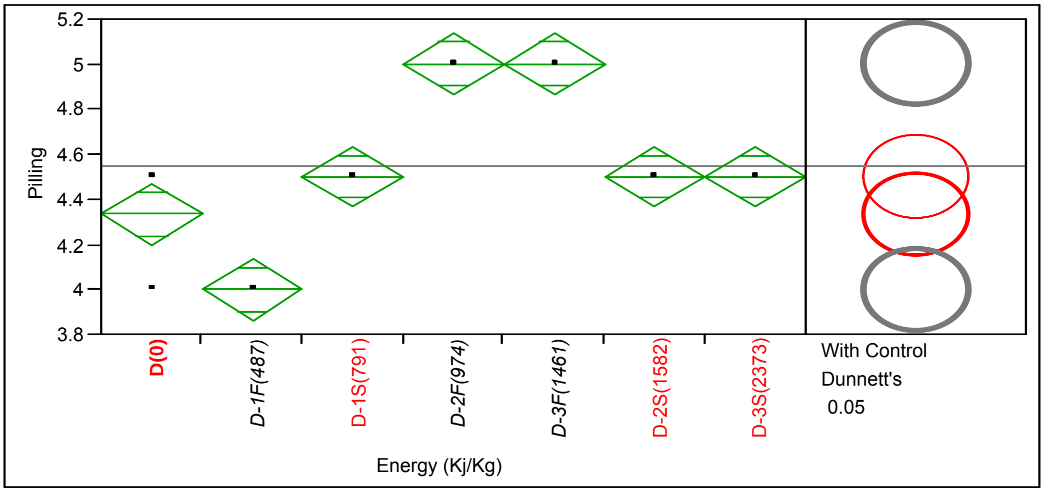


Figure 44: One way analysis of Pilling by Energy

Figure 44 shows the ANOVA analysis of the pilling ratings by energy level for fabric D. Fabric D started at almost perfect to begin with, with a mean value above 4. The lowest energy level, 487 Kj/Kg was the only sample to do statistically worse than the control. Several other samples were not statistically different, while others were statistically better.

4.3.4.7 Air Permeability

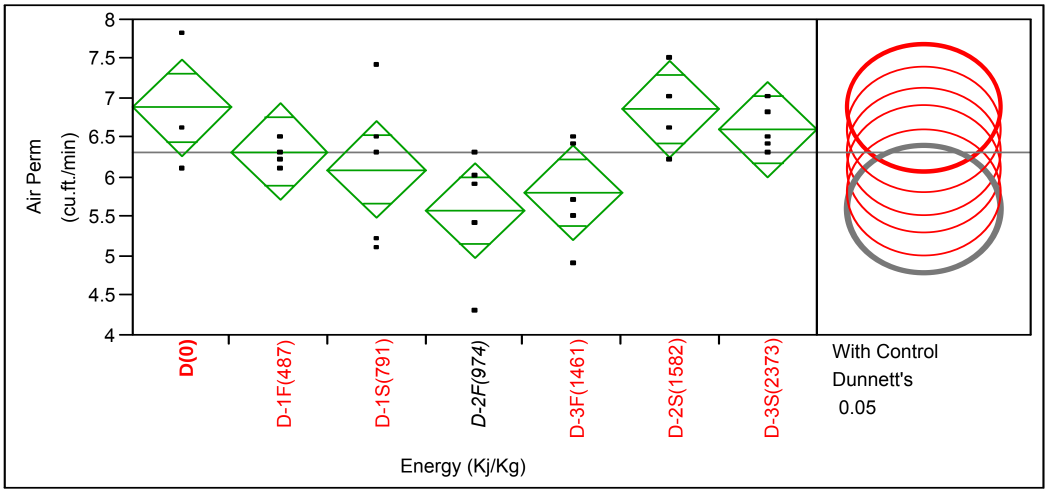


Figure 45: One way analysis of Air Permeability by Energy

Figure 45 displays the ANOVA analysis of air permeability by energy for fabric D. There is one sample, energy level 974 Kj/Kg, that is statistically different from the control, but in general air permeability values were not affected by hydroentangling.

4.3.4.8 Thickness

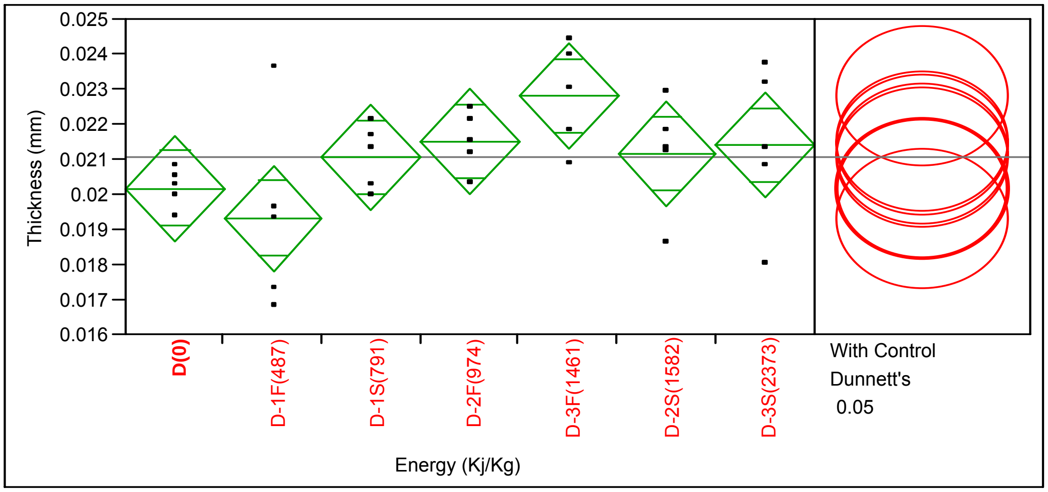


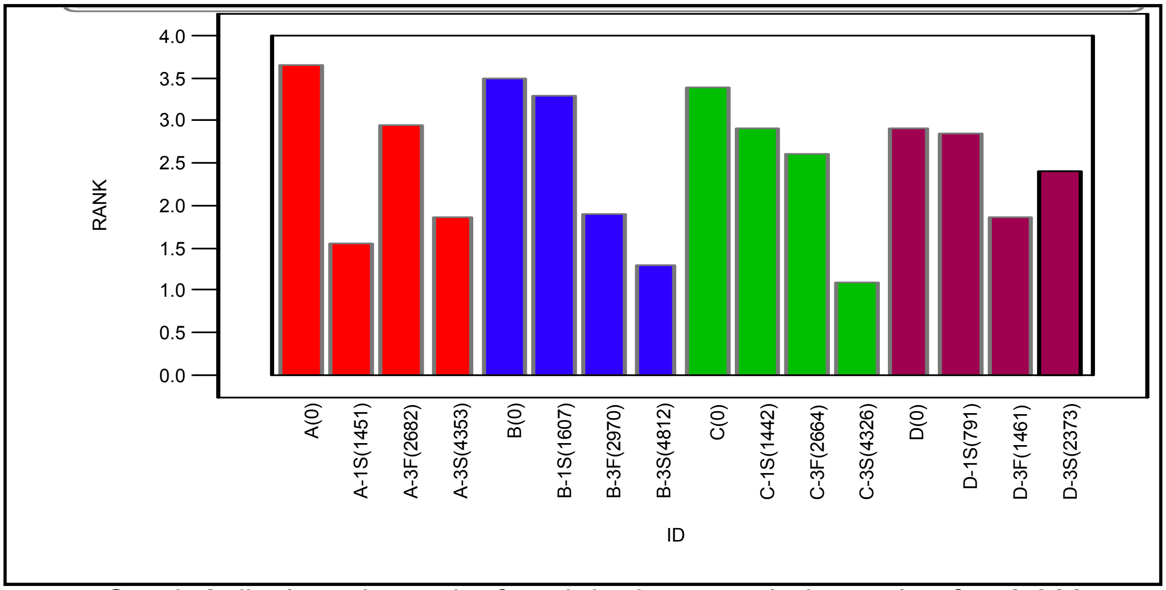
Figure 46: One way analysis of Thickness by Energy

Figure 46 shows the ANOVA analysis of thickness by energy for fabric D. The mean values for fabric thickness are not statistically different from the control value. Fabric thickness was not affected by hydroentanglement for fabric construction D.

4.4 Abrasion

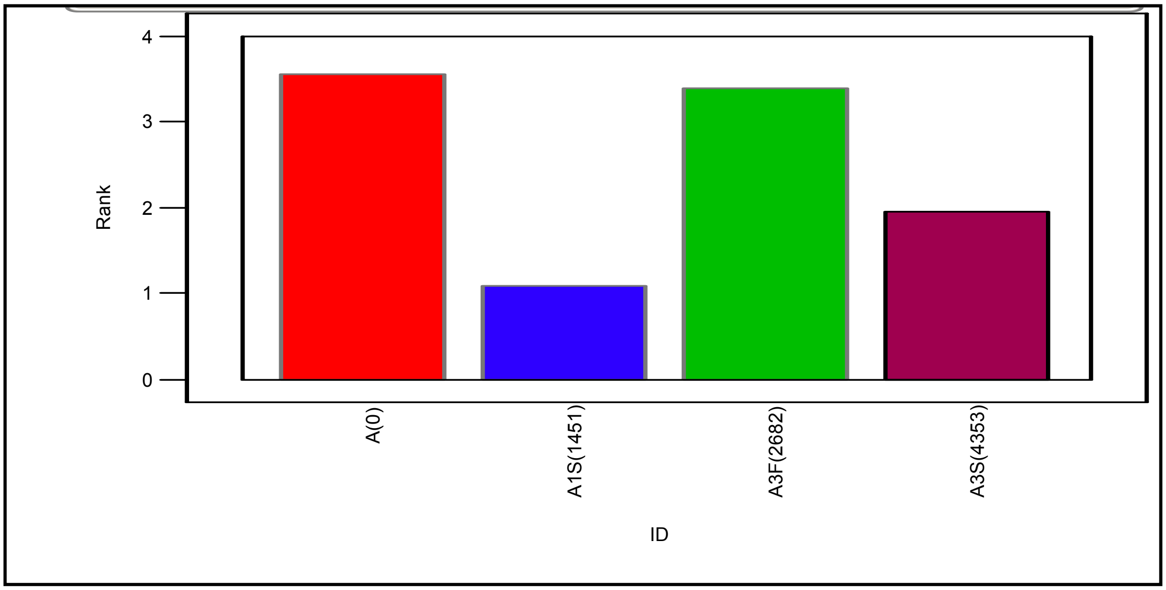
4.4.1 Hydroentangled Samples

Graph 2: Rank of Hydroentanlged Samples (6,000 cycles)



Graph 2 displays the rank of each hydroentangled sample after 6,000 cycles of abrasion. Twenty people were polled, and the above graph is the average rank for all responses. There were four samples shown for each fabric construction. Keeping each fabric construction separate, each sample was given a ranking from 1 to 4, 1 being the best, and 4 being the worst. In each case, the control sample held the highest rank, meaning it had the worst appearance. But for every case, except fabric A, the lowest energy sample was not far behind the control.

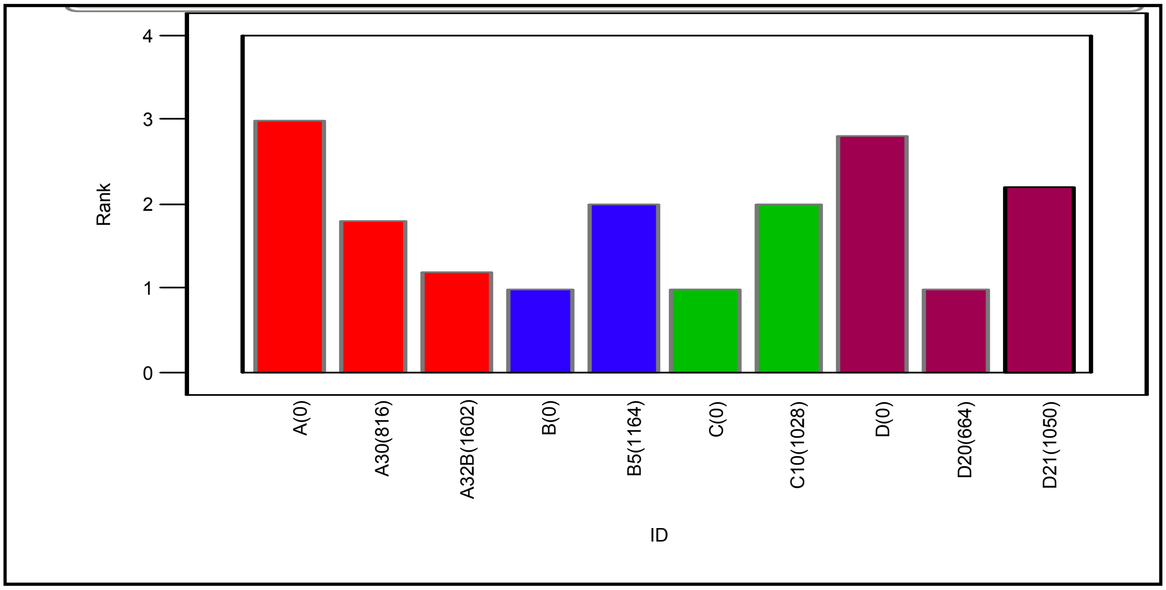
Graph 3: Rank of Hydroentangled Sample A (30,600 cycles)



Graph 3 displays the rank of several fabric A samples after undergoing 30,600 cycles of abrasion. The responses changed from the previous poll at 6,000 abrasion cycles. The control sample does not hold the highest rank, although it is a close second to A-3H. A-1L, which also did the best after 6,000 cycles, is again ranked as the best in overall appearance.

4.4.2 Bonded Samples

Graph 4: Rank of Bonded Samples (6,000 cycles)



Graph 4 shows the rank of the bonded samples after 6,000 cycles of abrasion. In the case of fabrics A and D, the control sample ranked the worst on appearance, while with fabrics B and C, the control was chosen as the better sample during the appearance evaluation.

4.5 Bonded Samples

4.5.1 Fabric A

4.5.1.1Weight

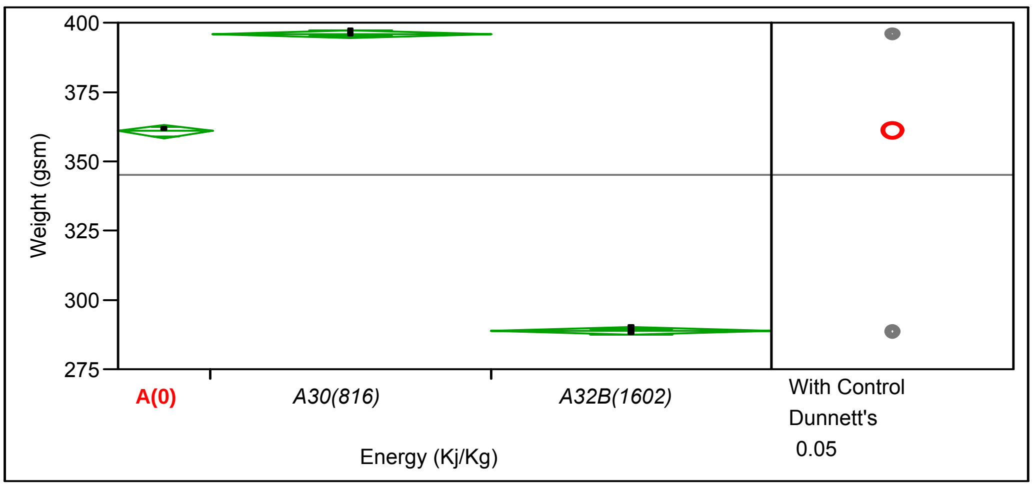


Figure 47: Construction A Bonded: Oneway analysis of Weight by Energy

Figure 47 is the ANOVA analysis of weight by energy for the bonded samples of fabric A. Weight is increased at the initial energy level, which is expected due to the presence of a 50 gsm carded web on the bonded samples that is not present on the control sample. Moving into a higher energy level, the sample has lost weight, meaning most of the carded web fibers have been washed away with the higher energy level process conditions. In each instance, the mean weight of the bonded samples was statistically different from the control sample.

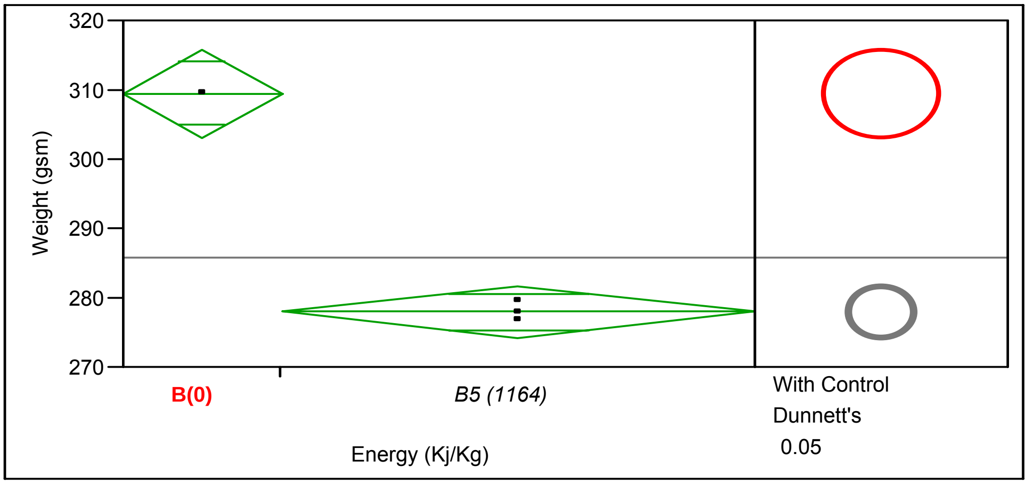


Figure 48: Construction B Bonded: Oneway analysis of Weight by Energy

Figure 48 is the ANOVA analysis of weight by energy for the bonded sample of fabric B. The presence of energy and the carded backing on the control sample has caused a mean weight that is statistically lower than the mean weight of the control sample.

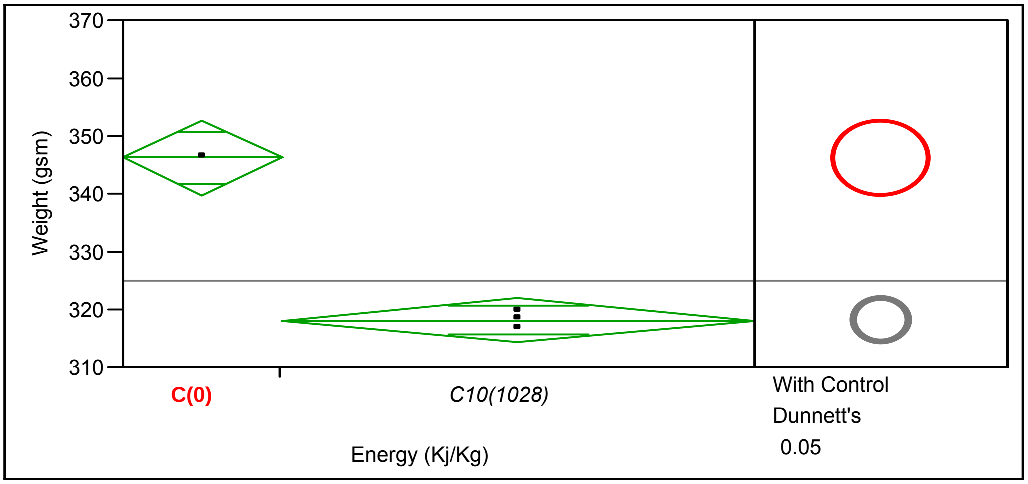


Figure 49: Construction C Bonded: Oneway analysis of Weight by Energy

Figure 49 is the ANOVA analysis of weight by energy for the bonded sample for fabric C. As energy is introduced to the control fabric, the mean weight of the sample is statistically lower. A reduction lower than 50 gsm, as seen here, means that base fibers were also washed away, along with backing fibers.

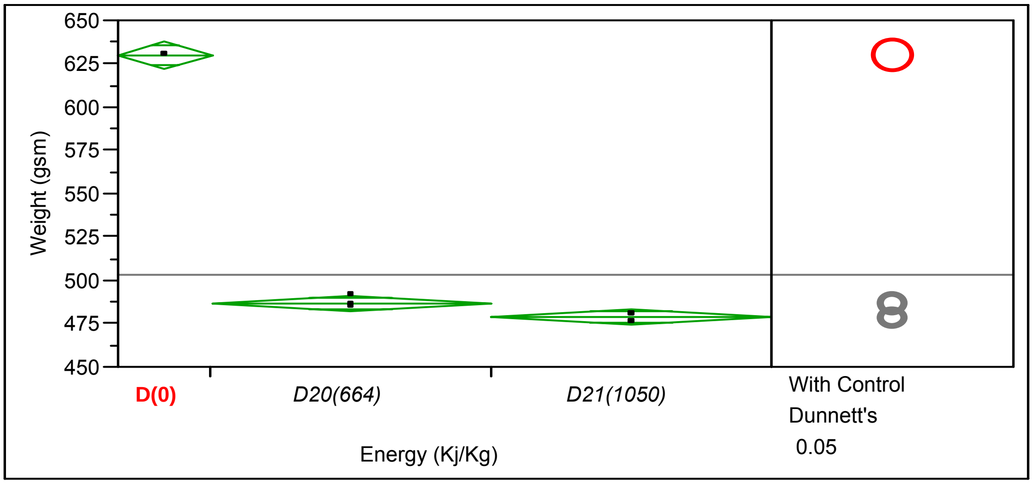


Figure 50: Construction D Bonded: Oneway analysis of Weight by Energy

Figure 50 displays the ANOVA analysis of weight by energy for the bonded samples of fabric D. In each instance, a presence of energy causes the sample to have a statistically lower mean weight as compared to the sample. However, as energy is increased there is no change in the mean weight of each sample.

4.5.1.2 Picks Per Inch

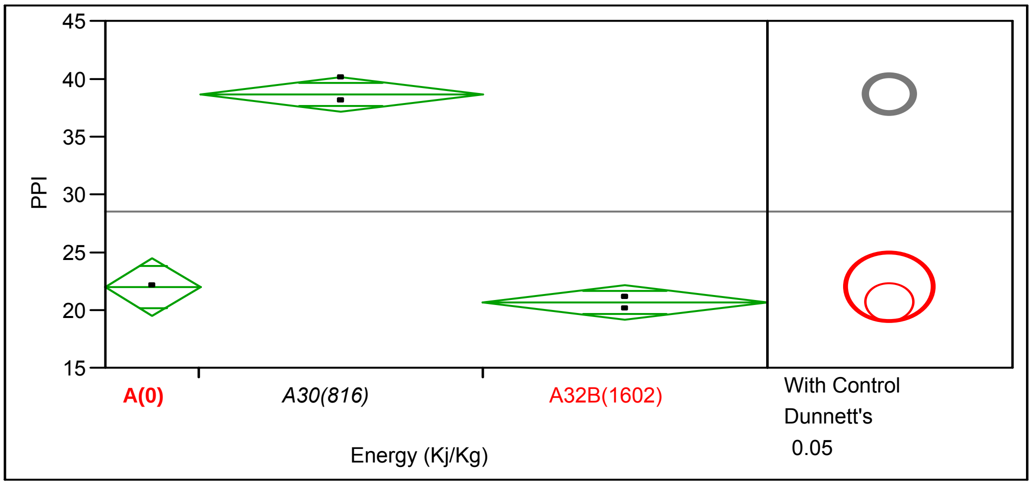


Figure 51: Oneway Analysis of Picks Per Inch by Energy

Figure 51 is the ANOVA analysis of picks per inch by increasing energy for fabric A bonded samples. The initial energy level has a picks per inch count statistically higher than the control, while the higher energy level's mean pick count is not statistically different from the control.

4.5.1.3 Ends Per Inch

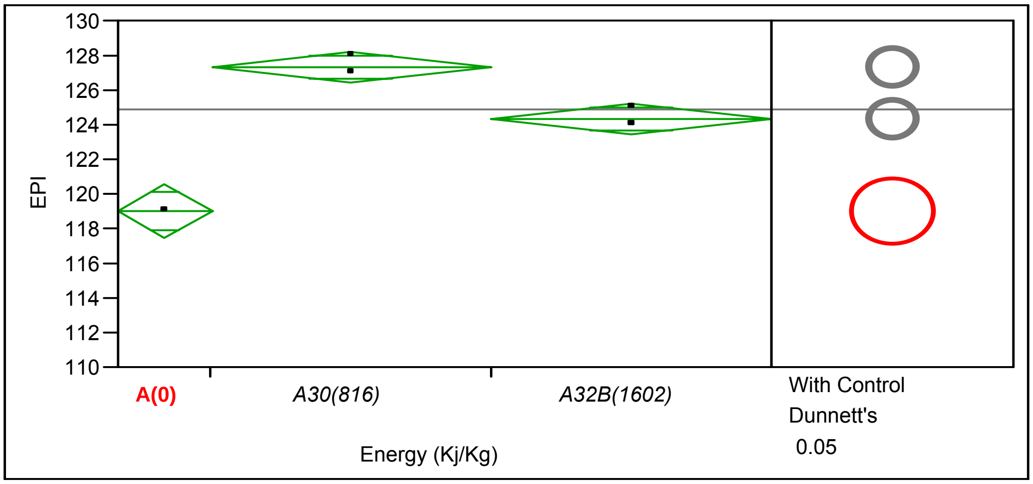


Figure 52: Oneway Analysis of Ends Per Inch by Energy

Figure 52 is the ANOVA analysis of ends per inch by energy level. Both of the bonded samples have a mean ends per inch count higher than the control sample.

4.5.1.4 Bending Length

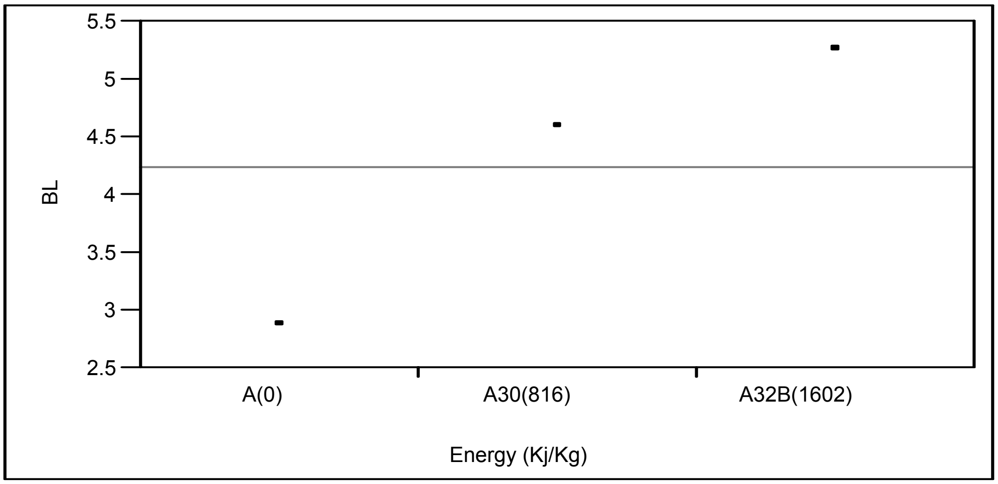


Figure 53: Plot of Bending Length by Energy

Figure 53 is a plot displaying the bending length by energy level. As energy levels increase, the fabrics have become stiffer, having a higher bending length.

4.5.1.5 Tensile Strength

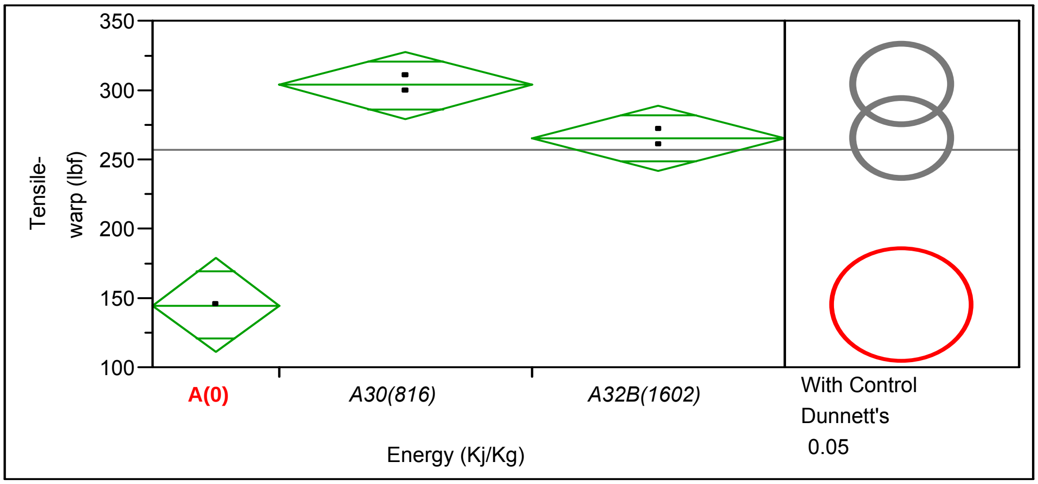


Figure 54: Oneway Analysis of Tensile Strength (warp) by Energy

Figure 54 is the ANOVA analysis of the tensile strength in the warp direction by energy level. Both bonded samples have a statistically higher tensile strength in the warp direction as compared to the control sample. As energy levels increase between samples, there is not a significant difference in tensile strength.

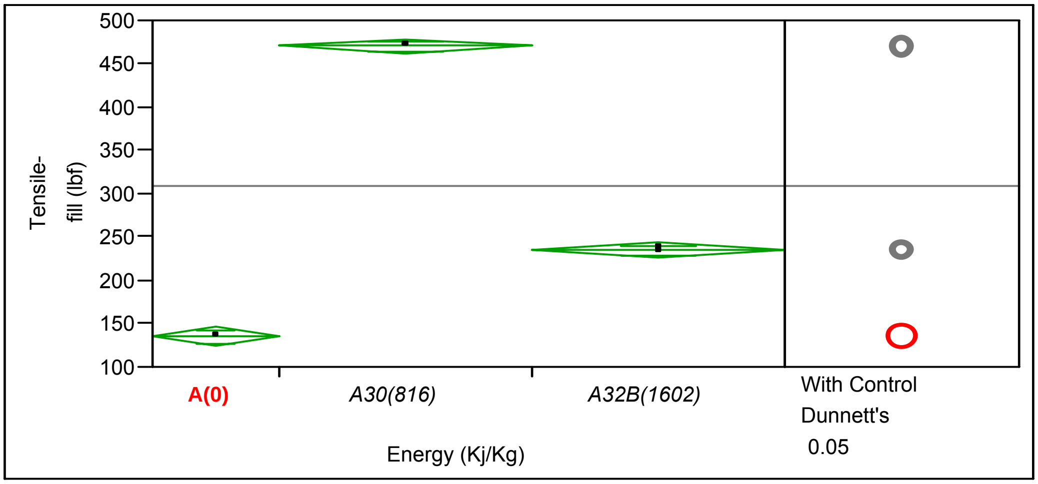


Figure 55: Oneway Analysis of Tensile Strength (fill) by Energy

Figure 55 is the ANOVA analysis of the tensile strength in the filling direction by energy level. Both samples have a statistically higher tensile strength in the filling direction as compared to the control sample. As energy levels increase between samples, there is a significant difference in tensile strength loss in the filling direction.

4.5.1.6 Tear Strength

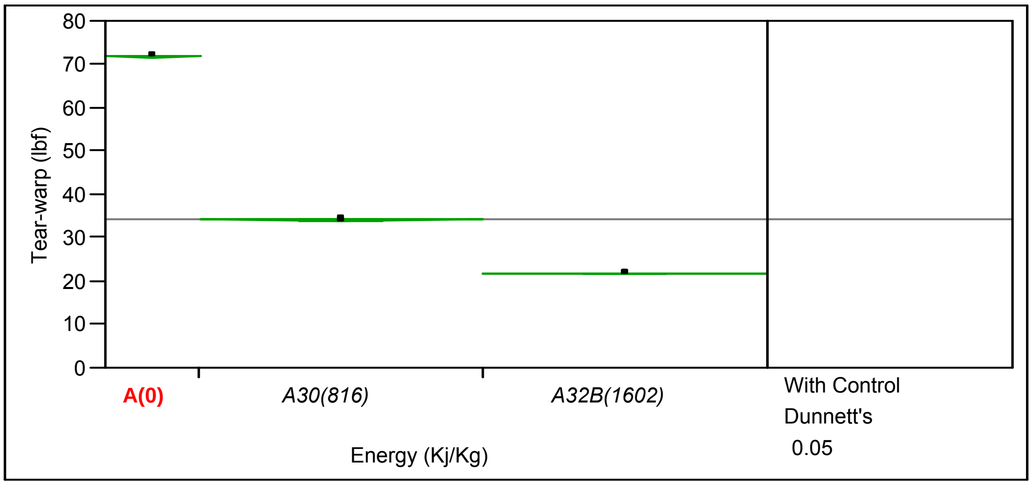


Figure 56: Oneway Analysis of Tear Strength (warp) by Energy

Figure 56 displays the ANOVA analysis of tear strength in the warp direction by increasing energy level. Both bonded samples have statistically lower tear strength values in the warp direction as compared to the control sample. As energy levels increase between the samples, the tear strength significantly decreases.

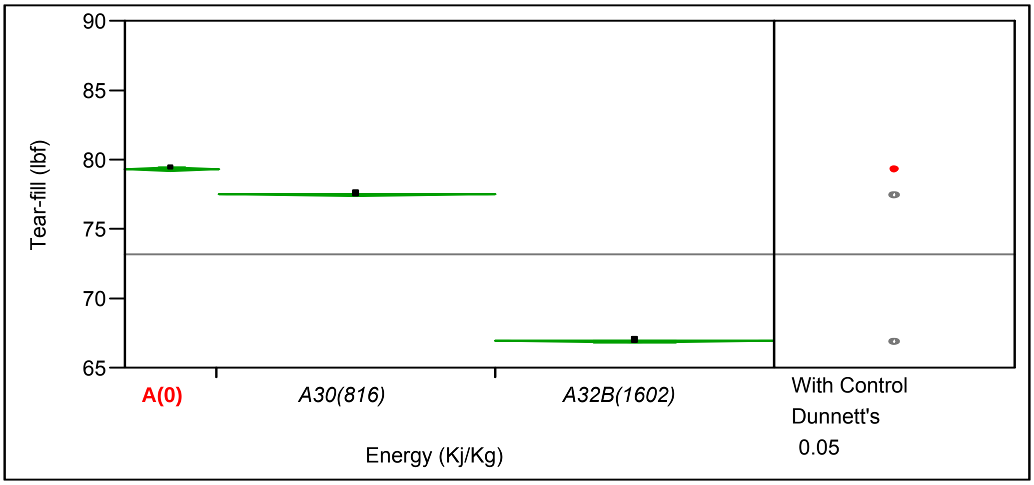


Figure 57: Oneway Analysis of Tear Strength (fill) by Energy

Figure 57 displays the ANOVA analysis of tear strength in the filling direction by energy. The bonded samples have statistically lower tear strength values in the filling direction as compared to the control sample. As energy levels increase between the samples, the tear strength significantly decreases.

4.5.1.7 Air Permeability

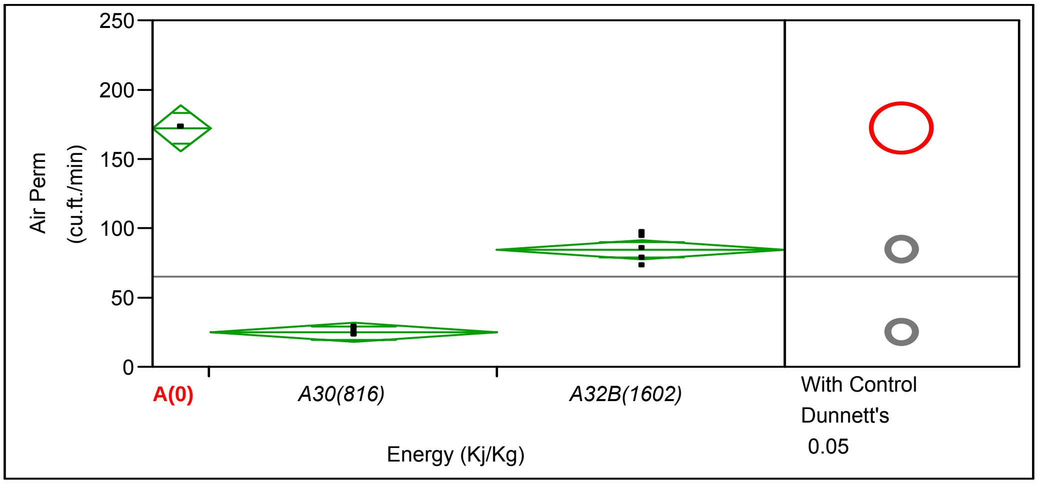


Figure 58: Oneway analysis of Air Permeability by Energy

Figure 58 shows the ANOVA analysis of air permeability by increasing energy level. The air permeability in the bonded samples is statistically lower than the values in the control sample. As energy increases between the samples, the air permeability also increases.

4.5.1.8 Thickness

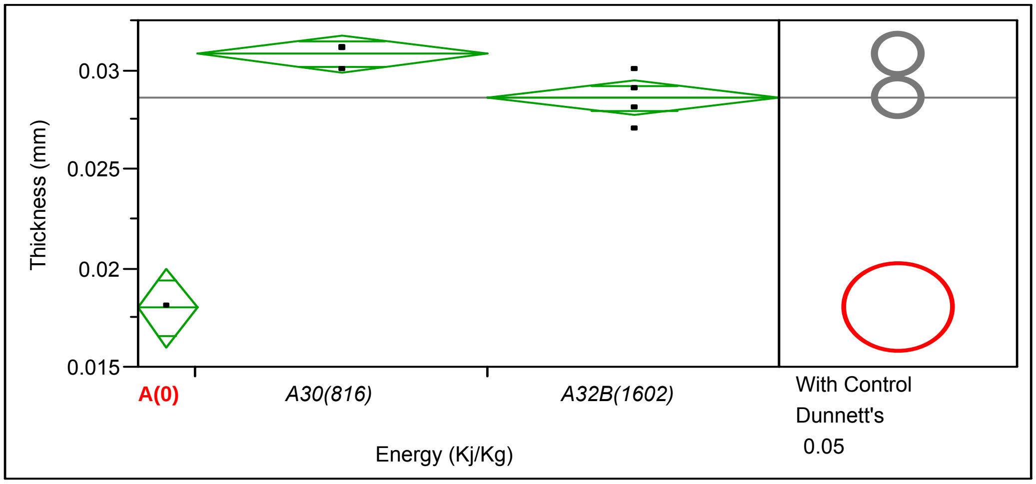


Figure 59: Oneway analysis of Thickness by Energy

Figure 59 shows the ANOVA analysis of thickness by energy. In both bonded samples, the mean thickness values are statistically higher than the mean thickness value of the control sample. There is no statistical difference in the mean thickness values between the bonded samples as energy increases.

4.5.2 Fabric B

4.5.2.1 Weight

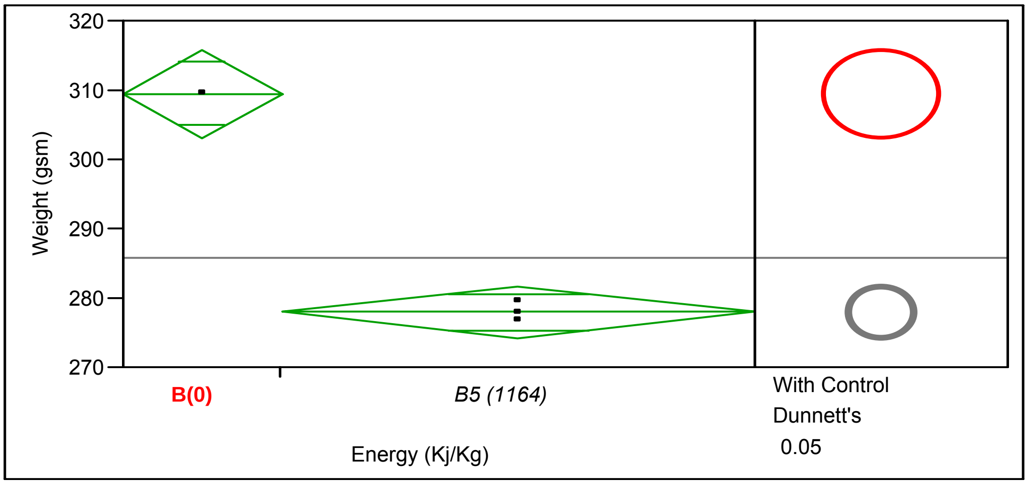


Figure 60: Oneway analysis of Weight by Energy

Figure 60 shows the ANOVA analysis of weight by increasing energy for fabric B. The bonded sample has a weight statistically lower than that of the control sample.

4.5.2.2 Picks Per Inch

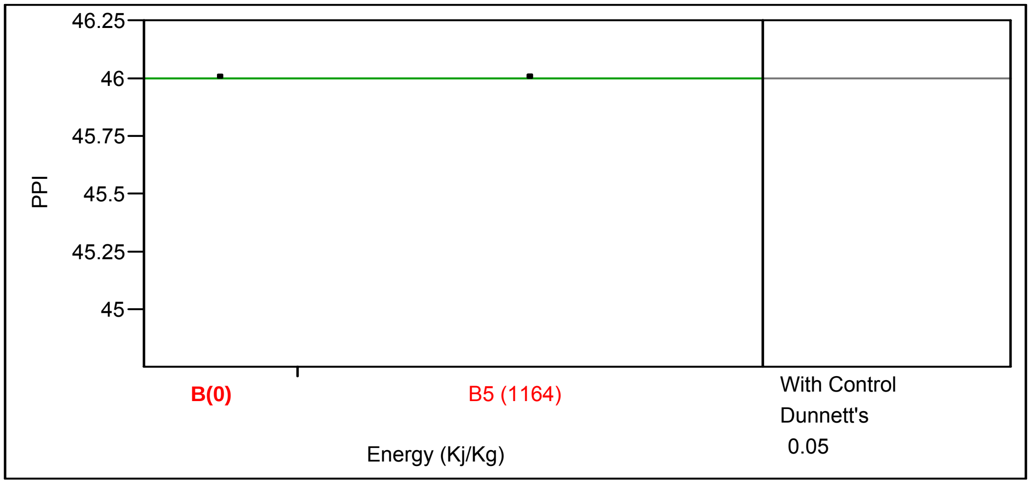


Figure 61: Oneway analysis of Picks Per Inch by Energy

Figure 61 shows the ANOVA analysis of the picks per inch by increasing energy level for fabric B. There is no change in picks per inch when comparing the bonded sample to the control sample.

4.5.2.3 Ends Per Inch

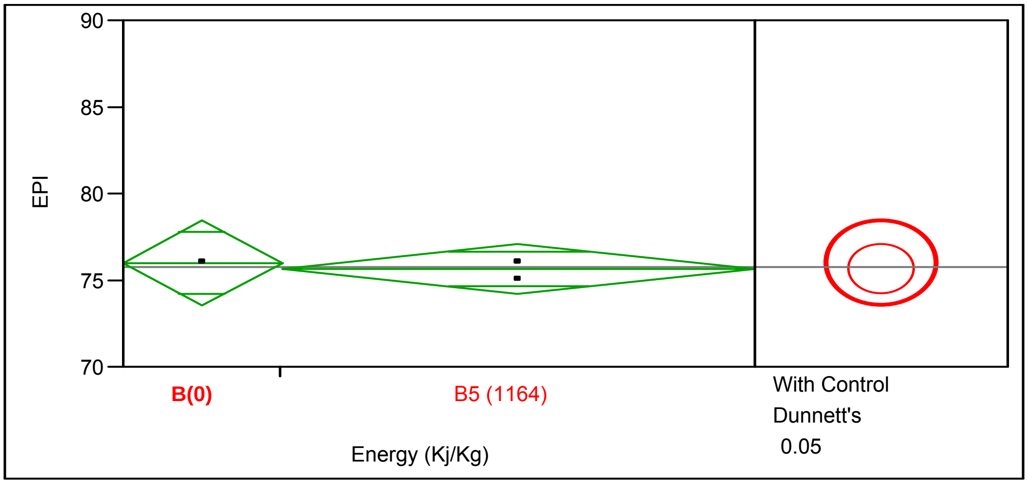


Figure 62: Oneway analysis of Ends Per Inch by Energy

Figure 62 shows the ANOVA analysis of the ends per inch by increasing energy level. There is no statistical difference in the mean ends per inch value between the bonded and the control sample.

4.5.2.4 Bending Length

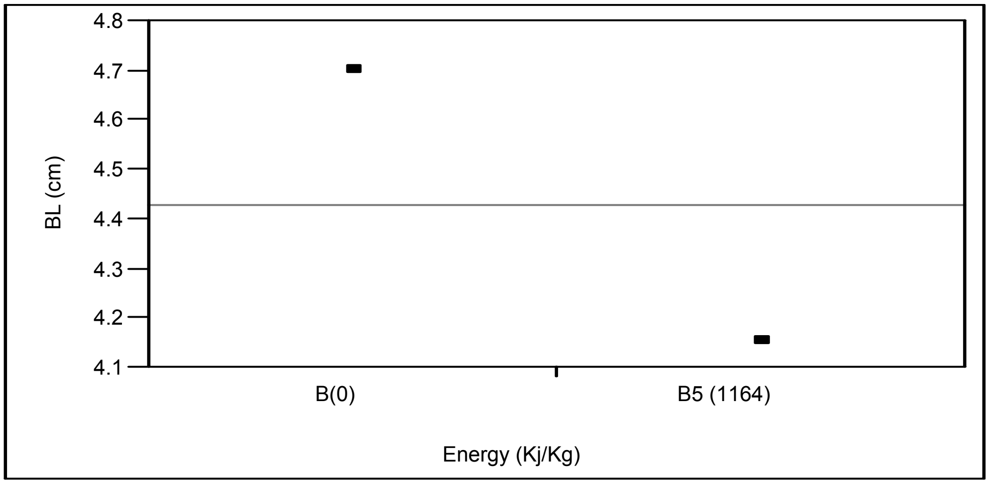


Figure 63: Plot of Bending Length by Energy

Figure 63 is a plot of bending length for the bonded and control sample. The bending length of the bonded sample is significantly lower than the control, meaning that the stiffness of the fabric is reduced when introducing a backing fabric to the structure.

4.5.2.5 Tensile Strength

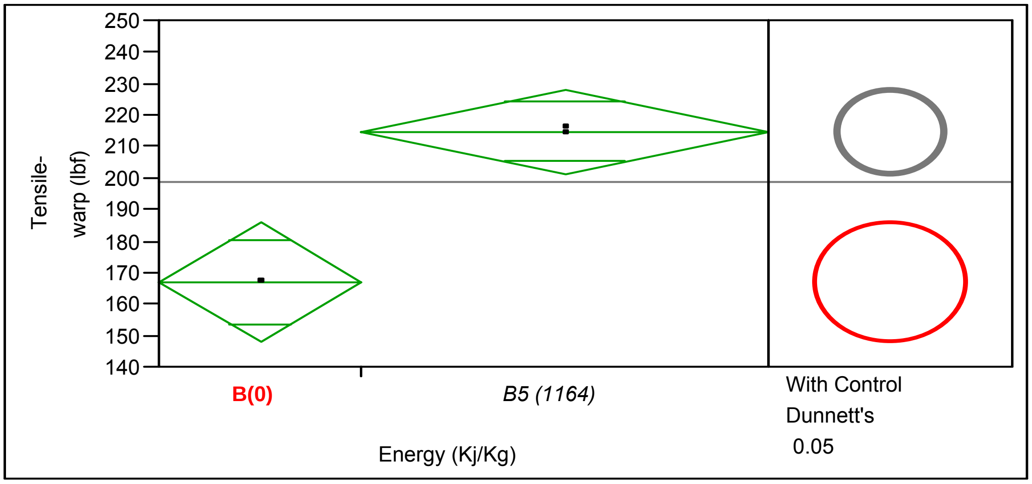


Figure 64: Oneway analysis of Tensile Strength (warp) by Energy

Figure 64 is the ANOVA analysis of tensile strength in the warp direction for the bonded and control sample. The tensile strength in the warp direction of the bonded sample is statistically higher than that of the control sample.

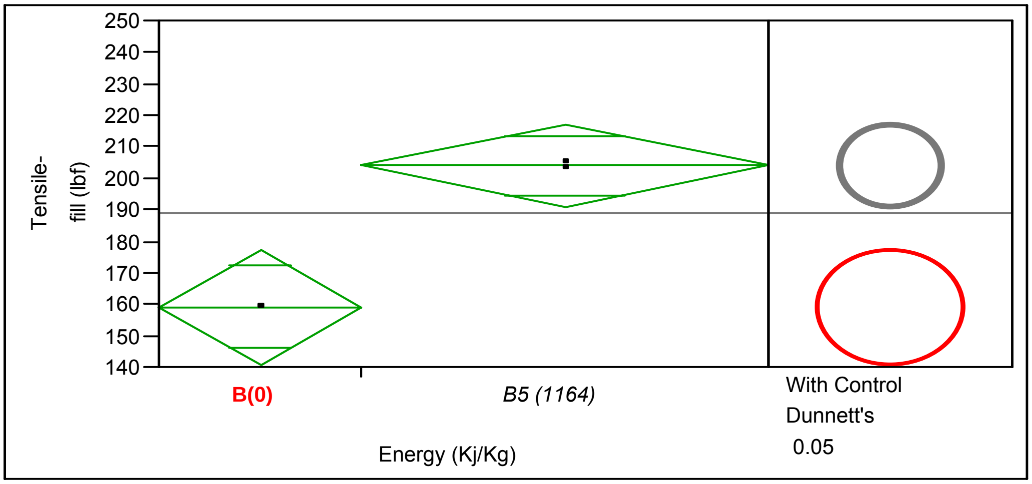


Figure 65: Oneway analysis of Tensile Strength (fill) by Energy

Figure 65 is the ANOVA analysis of tensile strength in the filling direction for the bonded and control sample. The tensile strength in the filling direction of the bonded sample is statistically higher than that of the control sample.

4.5.2.6 Tear Strength

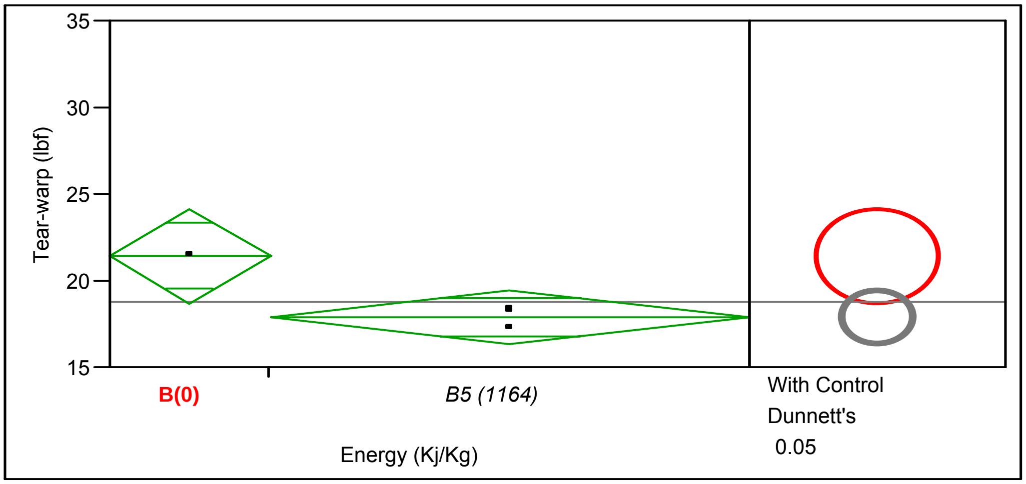


Figure 66: Oneway analysis of Tear Strength (warp) by Energy

Figure 66 is the ANOVA analysis of tear strength in the warp direction for the bonded and control sample. The tear strength in the warp direction of the bonded sample is statistically lower than that of the control sample.

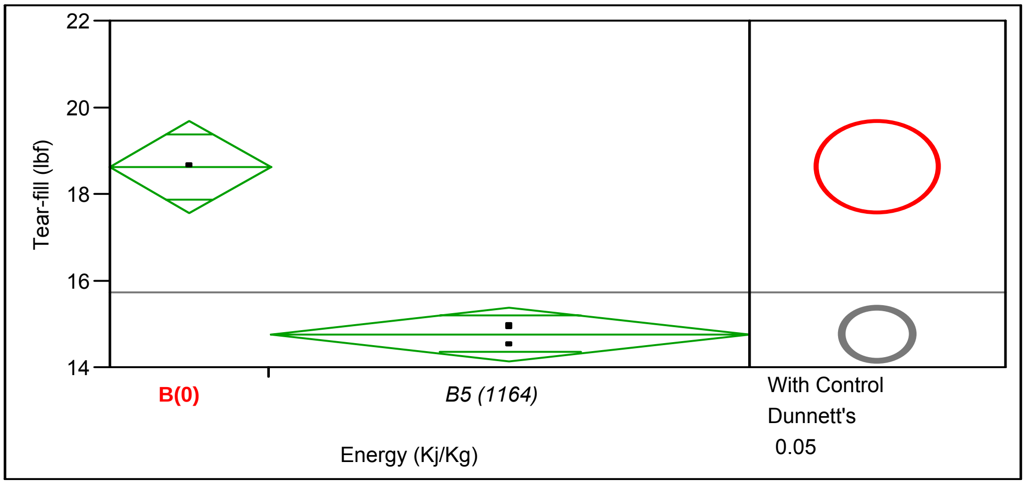


Figure 67: Oneway analysis of Tear Strength (fill) by Energy

Figure 67 is the ANOVA analysis of tear strength in the filling direction for the bonded and control sample. The tear strength in the filling direction of the bonded sample is statistically lower than that of the control sample.

4.5.2.7 Air Permeability

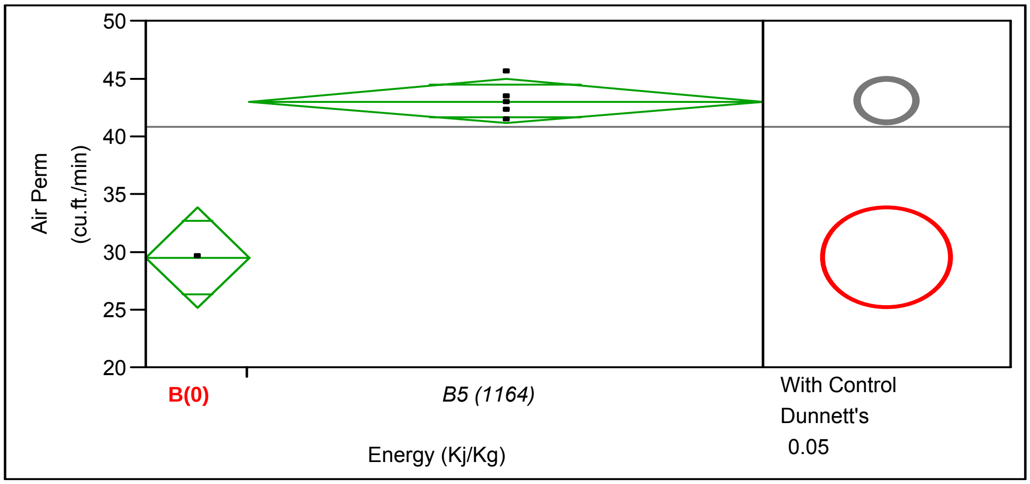


Figure 68: Oneway analysis of Air Permeability by Energy

Figure 68 is the ANOVA analysis of air permeability for the bonded and control sample. The air permeability of the bonded sample is statistically higher than that of the control sample.

4.5.2.8 Thickness

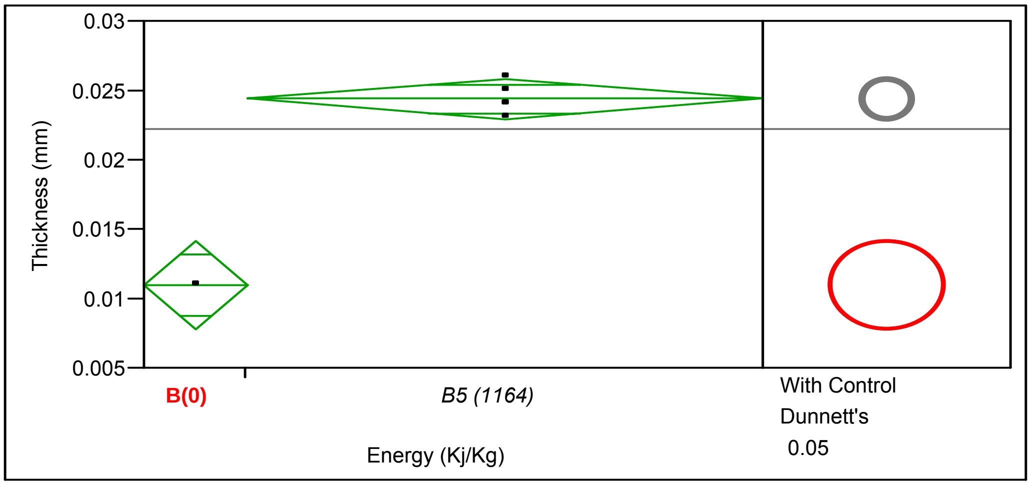


Figure 69: Oneway analysis of Thickness by Energy

Figure 69 is the ANOVA analysis of thickness for the bonded and control sample. The thickness of the bonded sample is statistically higher than that of the control sample. This is due to the presence of the 50 gsm web entangled onto the back of the base structure.

4.5.3 Fabric C

4.5.3.1 Weight

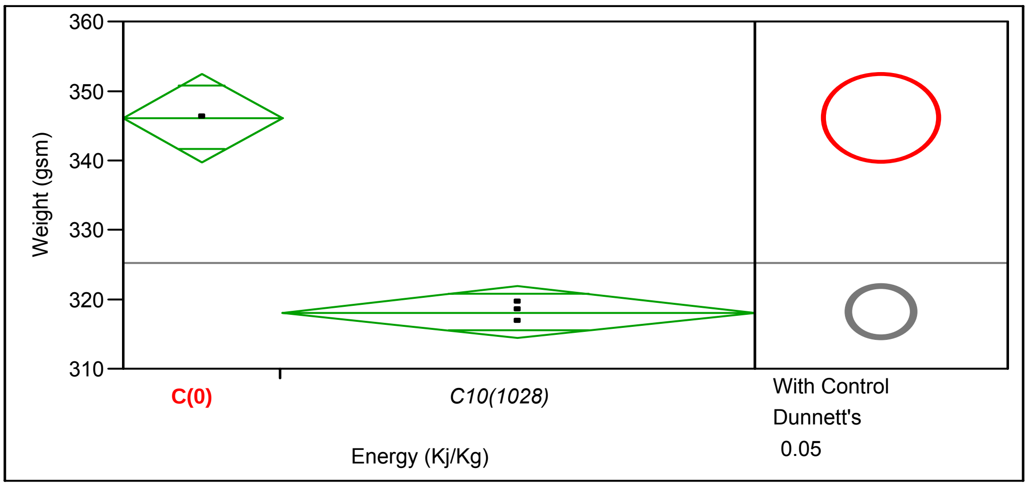


Figure 70: Oneway analysis of Weight by Energy

Figure 70 is the ANOVA analysis of weight by energy for the bonded and control sample for fabric C. The weight of the bonded sample is statistically lower than the weight of the control sample.

4.5.3.2 Picks Per Inch

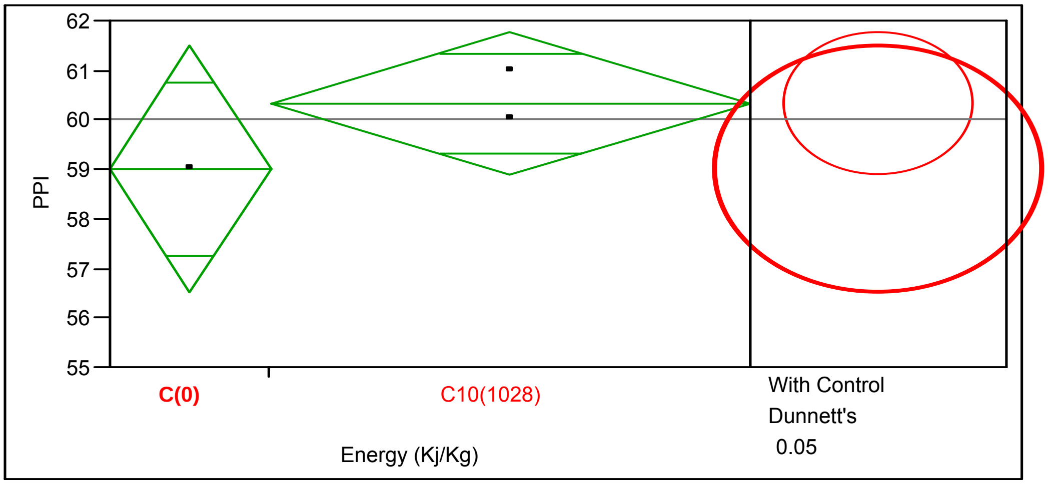


Figure 71: Oneway analysis of Picks Per Inch by Energy

Figure 71 is the ANOVA analysis of picks per inch for the bonded and control sample. There is no statistical difference in the mean picks per inch value of the bonded and control sample.

4.5.3.3 Ends Per Inch

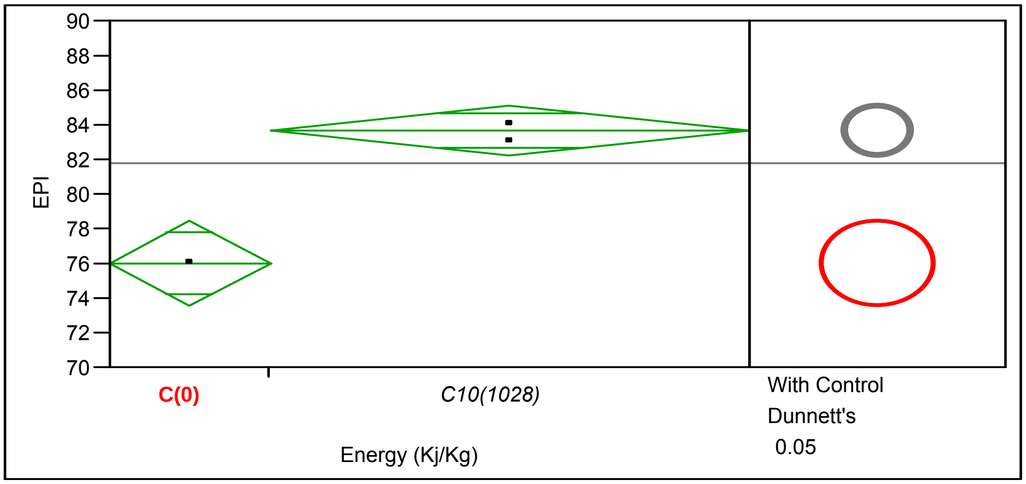


Figure 72: Oneway analysis of Ends Per Inch by Energy

Figure 72 is the ANOVA analysis of ends per inch for the bonded and control sample for fabric C. The mean ends per inch value for the bonded sample is statistically higher than that of the control sample.

4.5.3.4 Bending Length

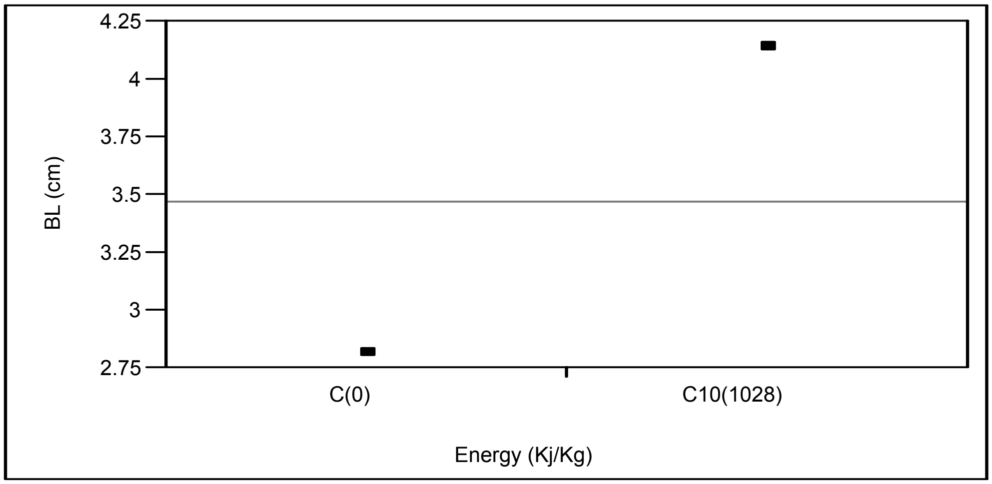


Figure 73: Plot of Bending Length by Energy

Figure 73 is a plot of bending length for the bonded and control sample. The bending length of the bonded sample is significantly higher than that of the control sample. The presence of a backing as well as the introduction of energy has caused a stiffer fabric.

4.5.3.5 Tensile Strength

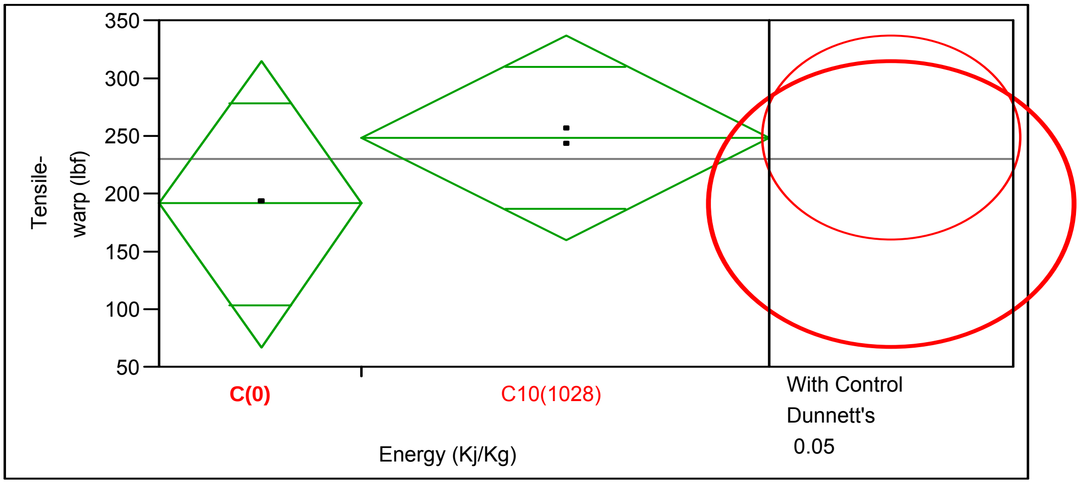


Figure 74: Oneway analysis of Tear Strength (warp) by Energy

Figure 74 is the ANOVA analysis of tear strength in the warp direction for the bonded and control sample. There is no statistical difference in the tear strength of the bonded sample when compared to the control sample.

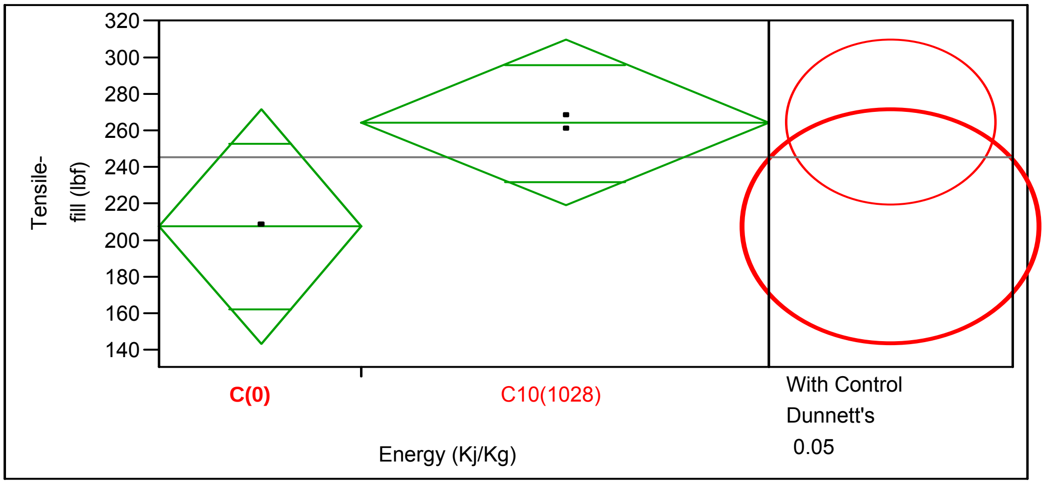


Figure 75: Oneway analysis of Tensile Strength (fill) by Energy

Figure 75 is the ANOVA analysis of tear strength in the filling direction for the bonded and control sample. As with the case in the warp direction, in the filling direction there is no statistical difference in the tensile strength of the bonded sample when compared to the control sample.

4.5.3.6 Tear Strength

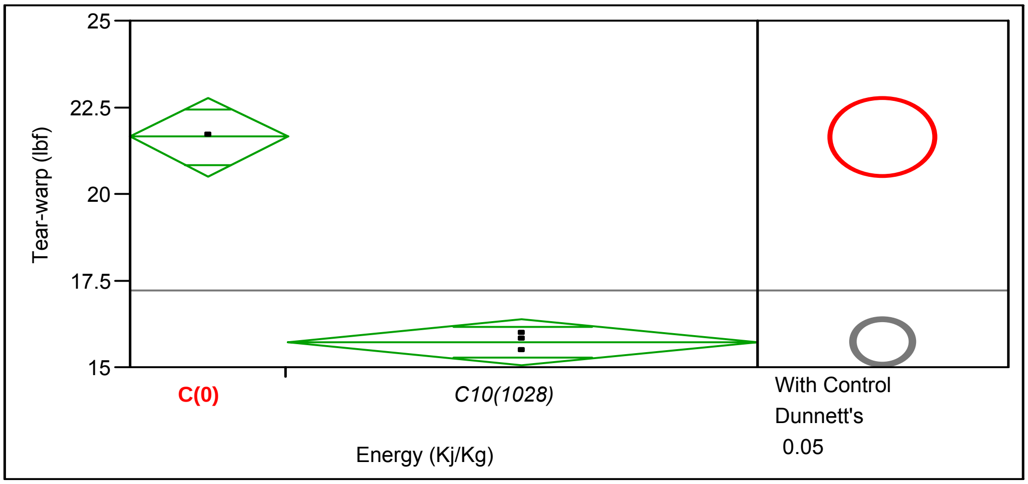


Figure 76: Oneway analysis of Tear Strength (warp) by Energy

Figure 76 is the ANOVA analysis of tear strength in the warp direction for the bonded and control sample. The bonded sample has statistically lower tear strength in the warp direction when compared to the control sample.

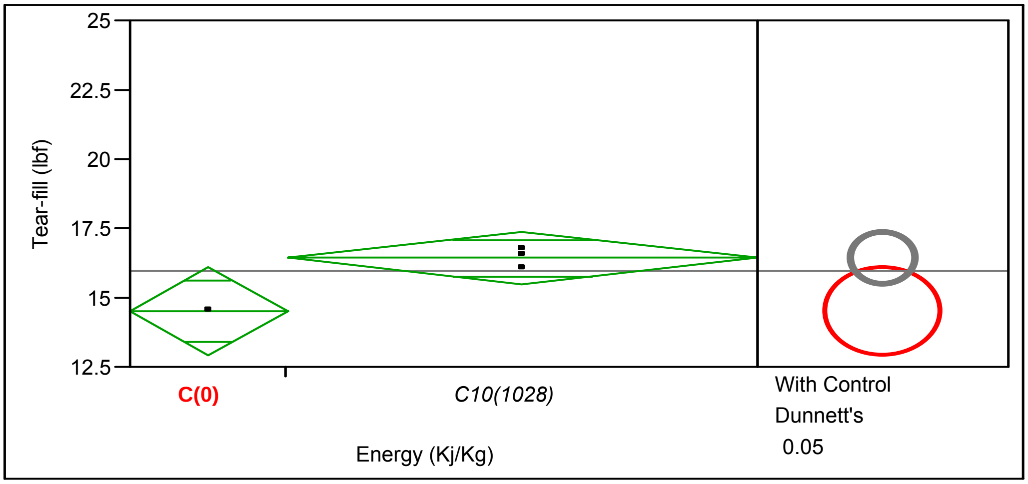


Figure 77: Oneway analysis of Tear Strength (fill) by Energy

Figure 77 is the ANOVA analysis of tear strength in the filling direction for the bonded and control sample. The bonded sample has statistically higher tear strength in the filling direction when compared to the control sample.

4.5.3.7 Air Permeability

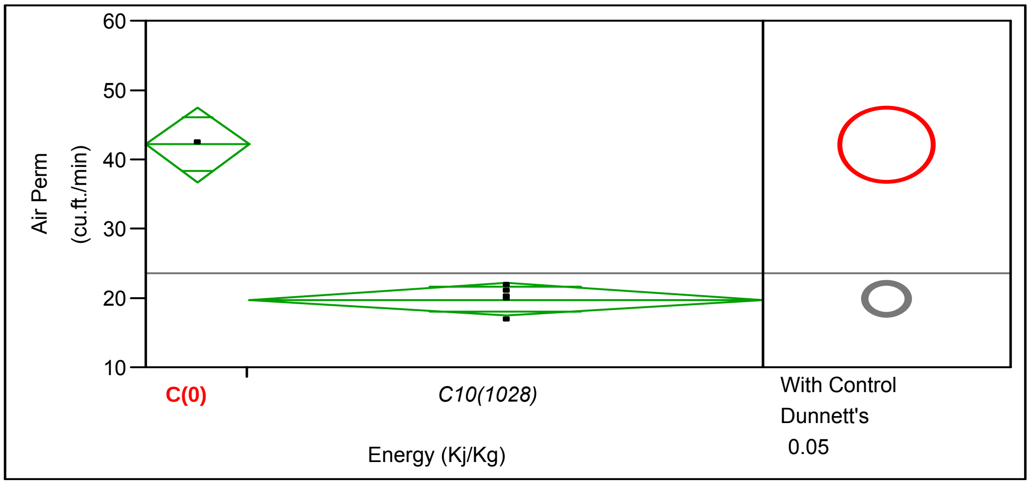


Figure 78: Oneway analysis of Air Permeability by Energy

Figure 78 in the ANOVA analysis of air permeability for the bonded and control sample. The air permeability in the bonded sample is statistically lower than that of the control sample. This can be caused by the presence of the 50 gsm carded web. It can have an adverse affect on the porosity of the structure.

4.5.3.8 Thickness

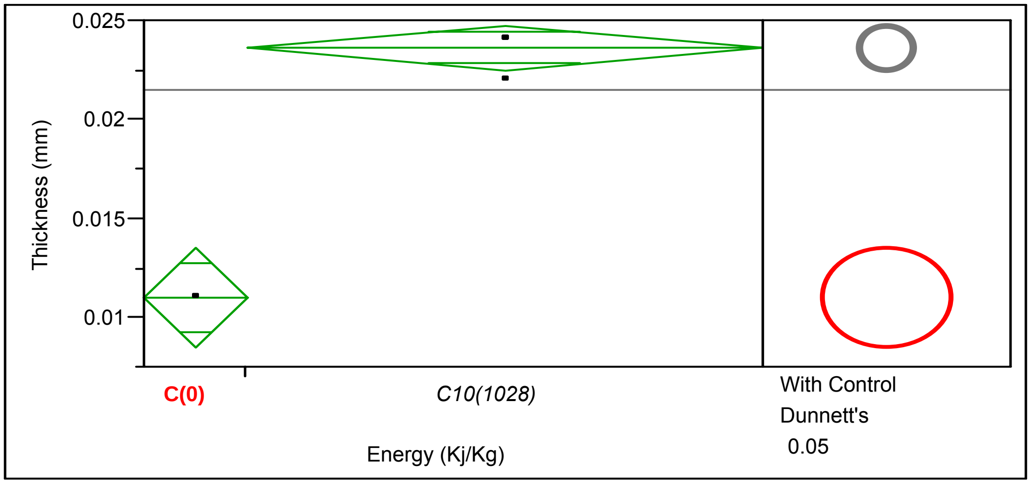


Figure 79: Oneway analysis of Thickness by Energy

Figure 79 is the ANOVA analysis of thickness for the bonded and control sample. The thickness of the bonded sample is statistically higher than that of the control.

4.5.4 Fabric D

4.5.4.1 Weight

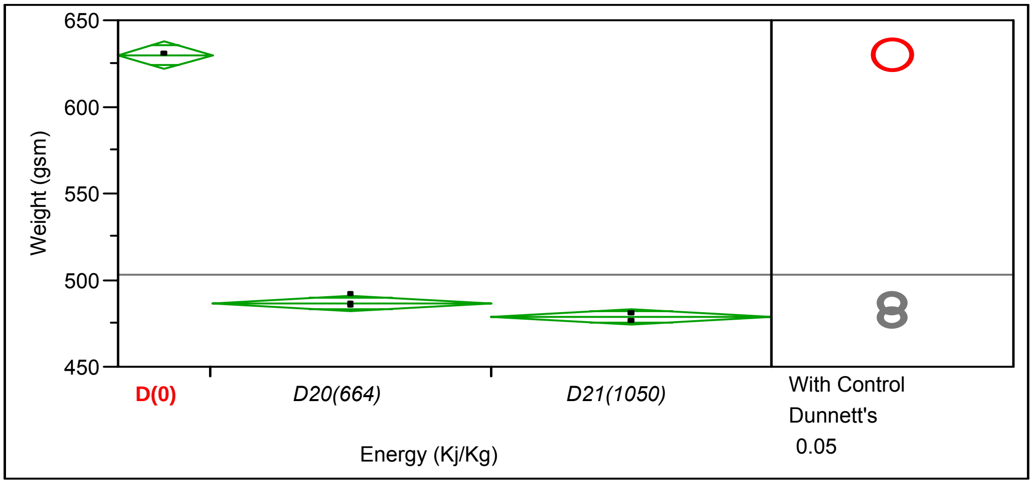


Figure 80: Oneway analysis of Weight by Energy

Figure 80 is the ANOVA analysis of weight by increasing energy for the two bonded samples and the control sample for fabric D. The weight of the bonded samples is statistically lower than that of the control sample. The difference in weight amongst the two bonded samples is insignificant.

4.5.4.2 Picks Per Inch

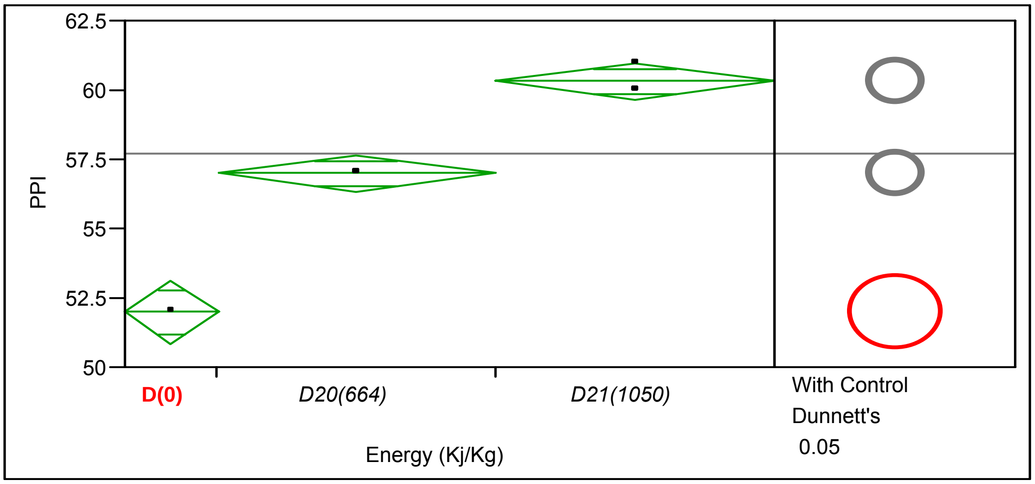


Figure 81: Oneway analysis of Picks Per Inch by Energy

Figure 81 is the ANOVA analysis of picks per inch by energy. The bonded samples have a statistically higher picks per inch count than the control sample. Also, the picks per inch count increases as energy increases.

4.5.4.3 Ends Per Inch

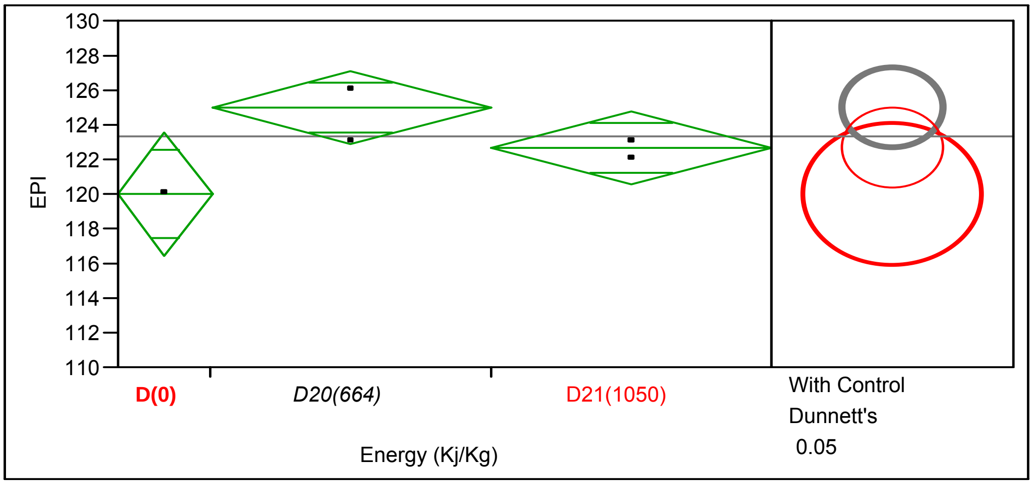


Figure 82: Oneway analysis of Ends Per Inch by Energy

Figure 82 is the ANOVA analysis of ends per inch by energy. The ends per inch at the initial energy level of 664 Kg/Kg is statistically higher than that of the control sample, while the ends per inch count at the higher 1050 Kj/Kg has no statistical difference in ends per inch when compared to the control. The difference in ends per inch between the bonded samples as energy increases is small.

4.5.4.4 Bending Length

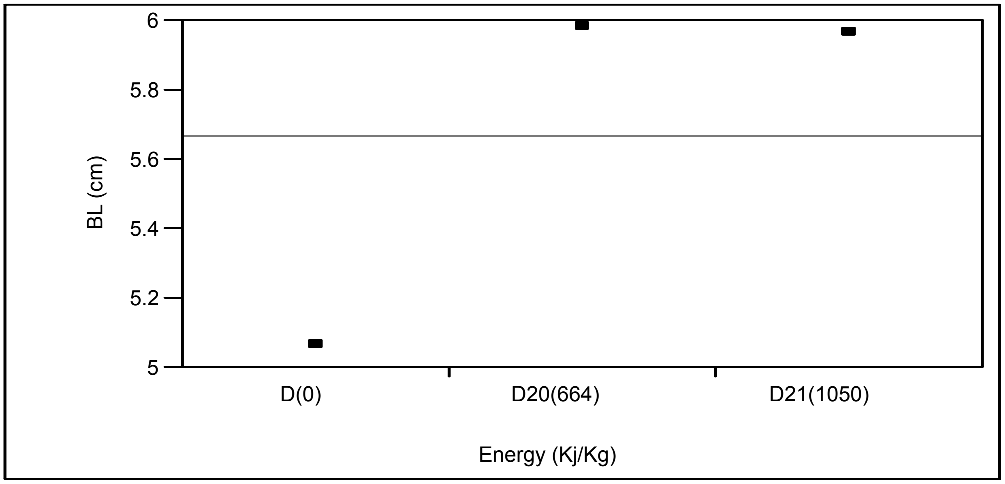


Figure 83: Plot of Bending Length by Energy

Figure 83 is a plot of bending length by energy level. The bending lengths of the bonded samples are higher than that of the control sample, meaning the structures are stiffer. The difference as energy is increased in bending length is small.

4.5.4.5 Tensile Strength

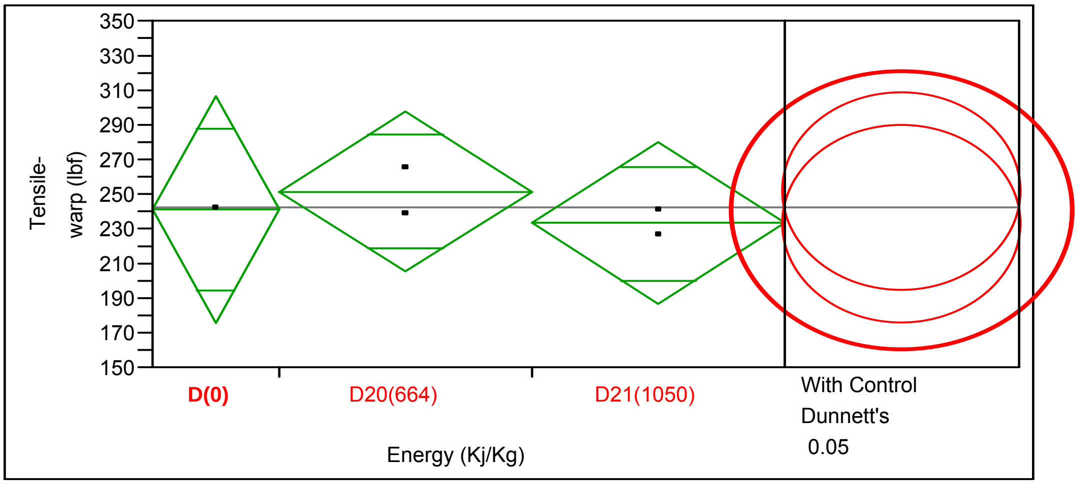


Figure 84: Oneway analysis of Tensile Strength (warp) by Energy

Figure 84 is the ANOVA analysis of tensile strength in the warp direction by energy. There is no statistical difference in tensile strength in the warp direction between the bonded and control samples.

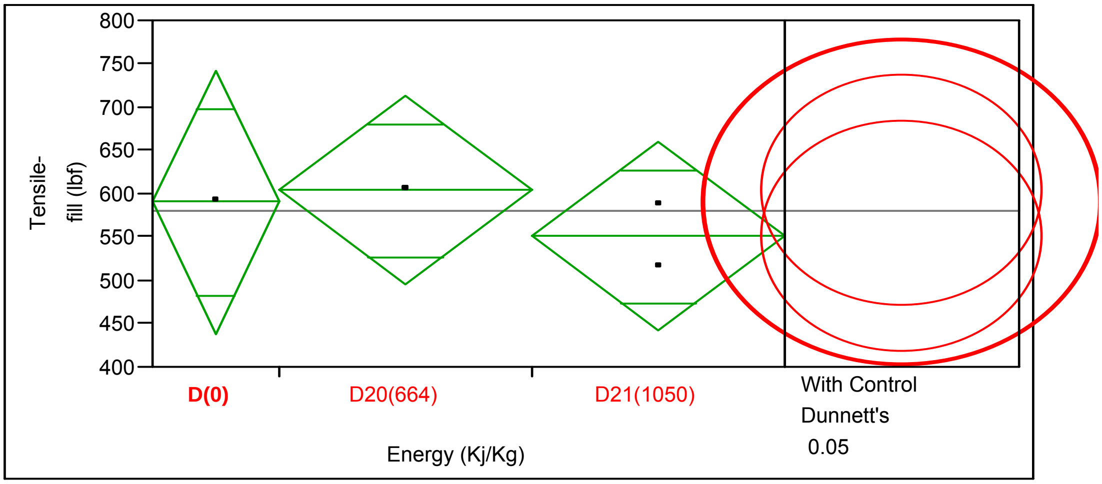


Figure 85: Oneway analysis of Tensile Strength (fill) by Energy

Figure 85 is the ANOVA analysis of tensile strength in the filling direction by energy. There is no statistical difference in tensile strength in the filling direction between the bonded and control samples.

4.5.4.6 Tear Strength

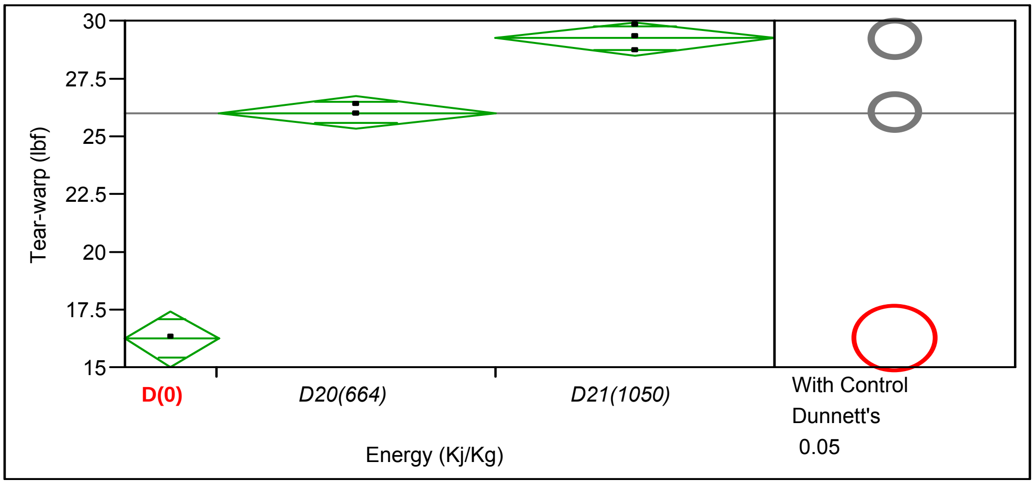


Figure 86: Oneway analysis of Tear Strength (warp) by Energy

Figure 86 is the ANOVA analysis of tear strength in the warp direction by energy. The tear strength in the warp direction for the bonded samples is statistically higher than that of the control sample. There is also an increase in tear strength as energy increases between the two bonded samples.

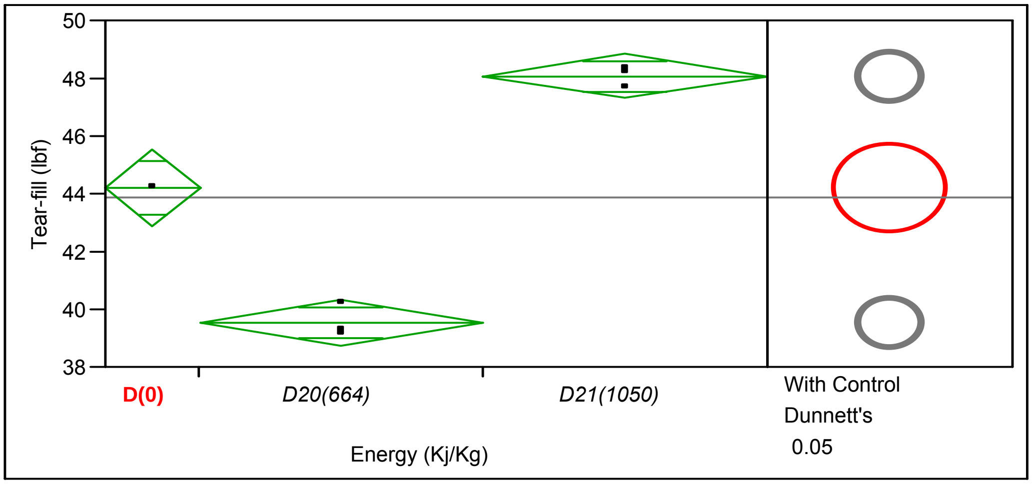


Figure 87: Oneway analysis of Tear Strength (fill) by Energy

Figure 87 is the ANOVA of tear strength in the filling direction by energy. The tear strength in the filling direction for the bonded samples is statistically different from the control sample. At the initial energy level of 664 Kj/Kg the tear strength in the filling direction is reduced as compared to the controls sample. As energy increases to 1050 Kj/Kg, tear strength in the filling direction is statistically higher than that of the control sample.

4.5.4.7 Air Permeability

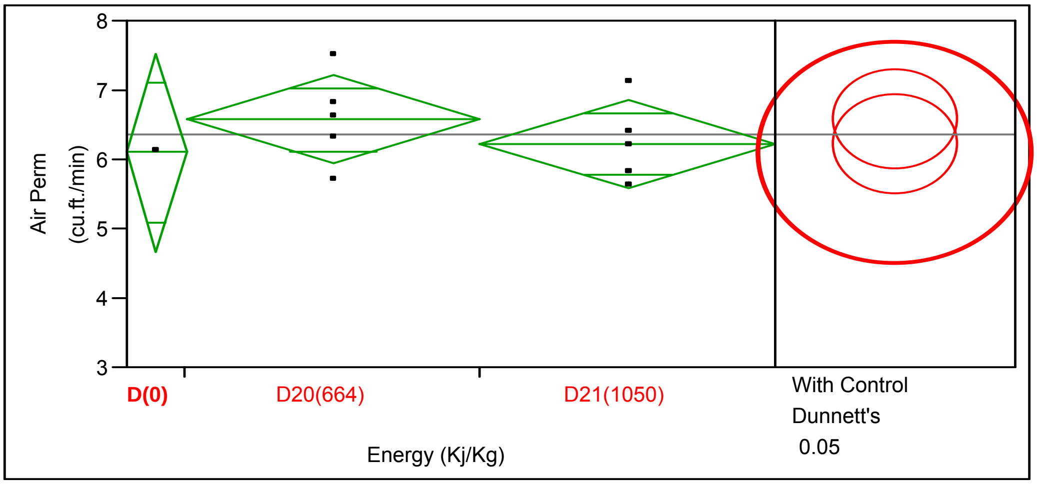


Figure 88: Oneway analysis of Air Permeability by Energy

Figure 88 is the ANOVA analysis of air permeability by energy. There is no statistical difference in the air permeability values of the bonded samples when compared to the control sample.

4.5.4.8 Thickness

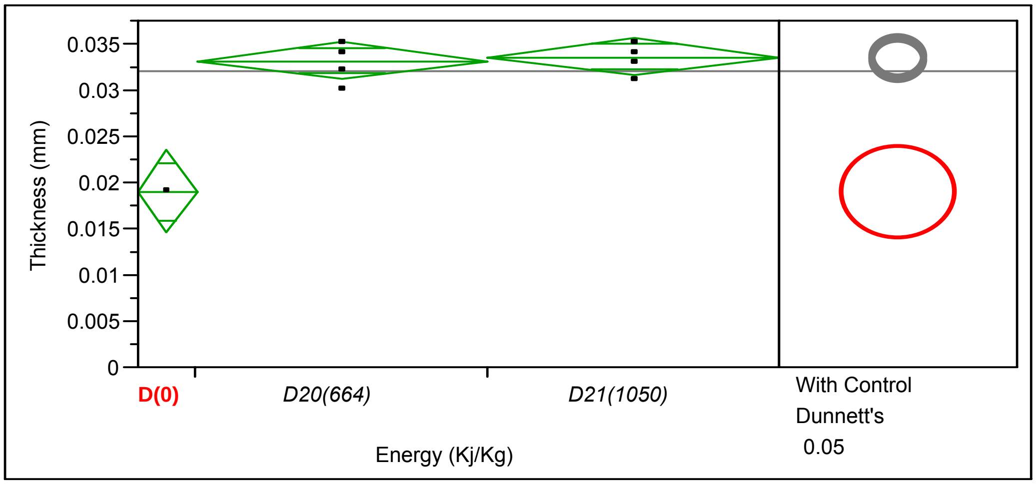


Figure 89: Oneway analysis of Thickness by Energy

Figure 89 is the ANOVA analysis of thickness by energy. The thickness values of the bonded samples are statistically higher than that of the control sample. There is little change in thickness between the two bonded samples as energy is increased.

5 Conclusions

5.1.1 Hydroentangled Samples

After review of specific energy values for each hydroentangled trials, the following conclusions were determined:

- Slow conditions, 10 m/min @ 100 bar, have larger specific energy values when compared to the same fabric construction and number of passes at fast conditions, 50 m/min @ 220 bar
- When comparing like warp and filling constructions (A and D; B and C), the fabric with the lower picks per inch count and base weight in gsm will maintain higher specific energy values for each trial.
- When comparing all four fabrics, those constructions with spun warp and filament filling constructions (B and C), have higher specific energy levels for each trial, compared to those constructions with filament warp and spun filling constructions (A and D).

After review of physical and mechanical testing data on all four fabric constructions, the following conclusions were determined:

- Mean base weight of the control sample is statistically higher than mean weight of each trial sample.
- For each fabric construction there is a critical point of energy where mean weight is not affected by an increase in energy.
- For fabrics A, B, and C mean picks per inch count for the control sample is not significantly different from the mean picks per inch count for the trial samples. Also, as energy increases there is no significant change in mean picks per inch count between each trial sample.

- For fabric D, mean picks per inch count for the control sample is statistically lower than the mean picks per inch count for each trial sample.
- For fabrics A, B, and C mean ends per inch count for the trial samples are statistically higher than the mean ends per inch count for the control sample. For fabric D there is also an increase in mean ends per inch count for the trial samples compared to the control samples, however not statistically higher.
- For each fabric construction there is a critical point of energy where mean ends per inch are not affected by an increase in energy.
- The mean tensile strength values for the control sample in the warp direction are not statistically different from the mean tensile strength in the warp direction for the trial samples.
- There is no statistical difference in the mean tensile strength values in the warp direction between trial samples as energy increases.
- The mean tensile strength values for the control sample in the filling direction are not statistically different from the mean tensile strength in the filling direction for the trial samples.
- There is no statistical difference in the mean tensile strength values in the filling direction between trial samples as energy increases.
- For fabrics A, C, and D, mean tensile strength values in the warp direction were slightly higher than mean tensile strength values in the filling direction. For fabric B, mean tensile strength values in the filling direction were slightly higher than the mean tensile strength values in the filling direction.
- For fabrics A, B, and C, mean tear strength values for the control sample in the warp direction are statistically higher than mean tear strength values in the warp direction for the trial samples. In each case, there is a critical point of energy where mean tear strength values in the warp direction are not affected by an increase in energy.

- For fabric D, there is no statistical difference in mean tear strength values between the control sample and the trial samples.
- The mean tear strength values for the control sample in the filling direction are statistically higher than the mean tear strength values in the filling direction for the trial samples. In each case, there is a critical point of energy where mean tear strength values in the filling direction are not affected by an increase in energy.
- Pill ratings were improved in the trial samples when compared to the control samples.
- Abrasion ratings were improved in the trial samples when compared to the control samples at 6,000 cycles.
- Abrasion ratings were not improved in the trial samples when compared to the control samples after 30,000 cycles.
- For fabrics A, B, and D, there is no statistical difference in mean air permeability values between the control sample and trial samples. For fabric C, the mean air permeability values in the control sample were statistically higher than the mean air permeability values in the trial samples.

The objective of this research is to determine if hydroentangling is a feasible means to overcome certain physical and mechanical shortcomings of jacquard woven fabrics. Test data indicates that certain aspects will be improved, while others may be negatively impacted by hydroentanlging. There are also critical energy points where any further enhancement in properties is diminished. The end use application of the fabric, as well as performance criteria will play a key role in determining if hydroentangling can be used as an alternate means of finishing a jacquard woven fabric, and will be unique to the specific company and production capabilities.

5.1.2 Bonded Samples

After review of specific energy values for each hydroentangled trials, the following conclusions were determined:

- Specific energy values must be high enough to cause the carded web backing material to entangle with the base fabric.
- Specific energy values must be low enough that the carded web backing material does not show through to the surface of the base fabric, jeopardizing the jacquard design.

After review of physical and mechanical testing data on all four fabric constructions, the following conclusions were determined:

- Weight is statistically affected by applying energy and a carded web onto a base fabric. In the lowest picks per inch construction, weight increased at initial energy levels. For all other instances, weight was statistically reduced in the bonded samples when compared to the control sample.
- The base weight of the control fabric, along with the energy level seen during processing has an affect on picks per inch in the bonded sample. Possible outcomes are an increase in picks per inch, no statistical difference, or decrease in picks per inch.
- An increase in ends per inch, or no statistical difference is the expected result of bonding a carded web onto a base fabric using hydroentangling.
- In general, bending length of the bonded sample will be statistically higher than that of the control sample.
- Tensile strength in the warp and filling direction for bonded samples can be expected to be statistically higher or show no statistical difference from the control sample.
- Tear strength in both the warp and filling direction are affected by applying energy and a carded web onto a base fabric. Depending on process

parameters, tear strength can either be increased or reduced, but a statistical change is expected.

- Abrasion resistance was positively affected by bonding for fabric constructions A and D, while negatively affected for fabrics B and C, at 6,000 cycles.
- The base weight of the control fabric, along with the energy level seen during processing has an affect on air permeability in the bonded sample. Possible outcomes are an increase in air permeability, no statistical difference, or decrease in air permeability.
- Thicknesses of the bonded samples are statistically higher than thickness of the control sample.

The objective of this research is to determine if hydroentangling is a feasible means of bonding a single fiber carded web onto a base jacquard woven fabric. With the correct combination of base fabric construction and specific energy, bonding is possible. When energy is too high, the design will be jeopardized, while if energy is too low, adequate entanglement will not happen. Test data indicates that certain properties will be improved, while others may be negatively impacted by hydroentanlging. The end use application of the fabric, as well as performance criteria will play a key role in determining if hydroentangling can be used as a feasible means of bonding a jacquard woven fabric with a carded web, and will be unique to the specific company and production capabilities.

Table 9: Summary Table of Results for Hydroentangled Samples

ID	Energy (Kj/Kg)	Weight (gsm)	PPI	EPI	Pill Rating	Tensile warp (lbf)	Tensile fill (lbf)	Tear warp (lbf)	Tear fill (lbf)	Air Perm (cu. ft/min)	Thickness (mm)
A	0	350	21	120	3.33	176	169	72	79	190	0.017
A-1S	1451	288	20	125	2.67	238	298	19	42	24	0.018
A-2S	2902	214	20	135	3.5	201	190	29	44	107	0.017
A-3S	4353	224	22	133	4	236	226	27	50	88	0.016
A-1F	894	356	23	131	5	250	298	12	48	6	0.022
A-2F	1788	217	23	132	3.33	204	205	29	50	94	0.016
A-3F	2682	207	21	136	3.83	192	191	30	54	91	0.014
B	0	311	46	76	3	184	188	27	20	28	0.011
B-1S	1607	208	48	89	3.83	173	190	12	12	30	0.011
B-2S	3214	204	46	88	4	208	183	12	13	26	0.012
B-3S	4812	221	47	87	3.83	198	175	15	12	28	0.013
B-1F	990	195	45	80	2.67	182	165	11	12	36	0.011
B-2F	1980	202	46	86	3	178	176	14	11	28	0.011
B-3F	2970	204	47	90	4.33	186	165	15	11	28	0.013
C	0	348	60	77	3.5	211	206	23	19	53	0.011
C-1S	1442	221	60	80	3.5	187	216	11	15	22	0.012
C-2S	2884	240	60	85	4.83	193	206	11	11	17	0.012
C-3S	4326	229	61	85	4.5	190	211	13	10	18	0.013
C-1F	888	209	59	84	5	187	225	15	17	78	0.013
C-2F	1776	241	61	85	4.33	206	229	9	11	17	0.014
C-3F	2664	233	60	86	4.33	187	214	9	11	18	0.013
D	0	635	52	121	4.33	238	672	18	47	7	0.020
D-1S	791	405	61	126	4.5	224	609	15	41	6	0.021
D-2S	1582	398	56	124	4.5	245	638	14	26	7	0.021
D-3S	2373	410	56	123	4.5	237	603	15	29	7	0.022
D-1F	487	296	57	124	4	238	401	21	44	6	0.018
D-2F	974	390	58	124	5	229	533	13	24	6	0.022
D-3F	1461	418	57	124	5	230	575	12	20	6	0.023

Table 9, shown above, displays the average value for each property tested by ID. Highlighted in red are the best and worst performances for each test. As stated earlier, the end-use for the fabric will point to the best process parameter for each fabric construction. For instance, if high tensile property is high on the priority list for fabric construction A, then A-2F, meaning two passes at 50 m/min at 220 bar, is the best process parameter. However, A-2F does not have the best tear resistance or pilling rating.

6 Recommendations for Future Work

This research focused on two key objectives key aspects: 1) Determining if hydroentangling is a feasible means of enhancing the properties of a jacquard woven fabric; 2) Determining if hydroentangling is a feasible means of bonding a single fiber carded web onto a jacquard woven base fabric as a form of stabilizing the structure. Results dealing with the first objective indicate that while certain properties are enhanced, it may be at the expense of others. The end use of the fabric, as well as manufacturing capabilities will determine if hydroentangling is feasible. Results dealing with the second objective show that at the right specific energy, the base structure can mechanically bond to the single fiber carded web. As a result of bonding the two structures, stability is enhanced in most cases.

This research offers a general understanding as to the capabilities of using hydroentangling in a capacity not traditionally seen. It would be beneficial to supplement the work started by looking at the following:

- How yarn properties affect mechanical properties of the structure after hydroentangling
- The use of blend constructions for the base fabric
- The use of blend constructions for the backing fabric for bonded experiments
- The affect on the dyeing process after hydroentanlging
- The outcome to other end use fabrics, such as automotive interior, subjected to the same experiments

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