

Design and Development of Denim Fabrics with Improved Strength and Impact Abrasion Resistance for Motorcyclist Clothing

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Abstract

This study aims to design and develop denim fabrics with enhanced mechanical and impact abrasion resistance performance using different materials, yarn types and fabric constructions. It was aimed to reach the standard impact abrasion resistance requirements of motorcycle protective clothing for Level 1 in high impact areas of the body (zones 1 and 2), such as hip and knee areas. The existence of cotton/Cordura® yarn in warp and T400 polyester yarn in the weft and the use of higher yarn densities increased the performance in tensile strength and impact abrasion resistance, compared to a classical cotton denim fabric. The use of coarser yarns and fabrics with a double weave construction increased impact abrasion resistance compared to single layer cloths. The double and backed cloth samples developed with cotton/Cordura® and Kevlar®/polyester yarns in their construction showed impact abrasion resistance times over 4 s and reached the "EN 13595-2:2002 Level 1 abrasion resistance" standard requirement.

Key words: denim fabric, Kevlar®, Cordura®, impact abrasion, strength, motorcyclist.

Introduction

Motorcycle clothing is designed to protect the motorcyclist against injuries during rides. In case a rider or pillion passenger falls from the motorcycle and slides along a tarmac surface, the motorcyclist clothing would be exposed to a high level of abrasion and impact [1-3]. Therefore the protective clothing has a main function of providing appropriate protection of the user by acting as an effective barrier between the user's skin and the road surface [4]. In this respect, attention should be paid to the fabric designs regarding the construction of fabrics and selection of materials to provide better abrasion and impact resistance.

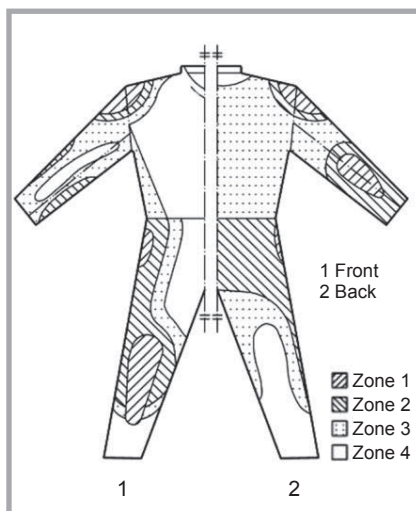


Figure 1. Zone positions on a motorcyclist's suit according to EN 13595[15].

The series of standards of EN 13595 assess the requirements, such as abrasion resistance or cut resistance, for motorcyclists' protective clothing [2]. According to EN 13595-2:2002 [5], for motorcycle protective clothing, the minimum abrasion resistance requirements (in seconds) of the material for use over high impact areas of the body (zones 1 and 2, representing hip and knee areas) are: 4.0 s for level 1 (low weight clothing and minor ergonomic limitations) and 7.0 s for level 2 (increased weight clothing and ergonomic constraints). The same standard also assesses abrasion resistance requirements for level 1, as 1.8 s in zone 3, and 1.0 s in zone 4, and for level 2, as 2.5 s in zone 3 and 1.5 s in zone 4 [1, 6, 7]. Figure 1 shows zone positions on a suit according to the standard [5].

Motorcycle clothing is made mainly of leather or textile materials. Leather provides mechanical strength but its breathability was reported to be insufficient [2]. Also coatings such as paraffin-wax, PU and PVC are applied onto heavy-weight cotton fabric to increase durability and reduce the coefficient of friction, thereby providing enhanced resistance to abrasion. However these coatings make the fabric heavy and stiff, thus obstructing wearer comfort [1, 8]. Therefore, as opposed to leather goods, recently, alternative high performance materials such as DuPont's Kevlar®, a high modulus para-aramid fiber, Invista's Cordura®, a high-tensile polyamide, ultra-high molecular weight polyethylene

and Lycra®, a polyurethane elastomer, have been utilised in fabrics used for protective motorcyclist clothing [1, 9]. For instance, tear and abrasion resistant Keprotec® fabric from Shoeller Textiles AG, Switzerland [10], have been widely used in premium brand motorcycling garments. Laminate and layered fabric constructions have also been employed in motorcycle apparel to enhance abrasion resistance [1].

Traditionally denim has a warp-faced twill fabric construction made from indigo dyed cotton warp yarns and undyed weft yarns made from cotton, polyester, and elastane yarns [11]. Durable denim motorcycle riding jeans have been referred to as protective denim [9]. Their manufacturers use different constructions in the garments such as plain and twill woven protective liners and single jersey, double jersey, rib and loop knitted protective liners. Protective lined denim garments comprise woven and knitted internal reinforcements or protective linings in the seat, hip and knee areas made nylon, polyester, para-aramid, ultra-high molecular weight polyethylene and Vectran®. Cordura® denim as outer fabric along with a polycotton lining and polyamide protective layer has also been used [12-14]. Another end-use of protective denim trousers for chainsaw operators was also reported, where a denim outer fabric with inner layers made from Kevlar®, ultra-high molecular weight polyethylene and ballistic nylon was employed [6].

Table 1. Fabric parameters of the reference and designed samples.

Fabric samples	Fabric type	Warp count & yarn type	Weft count & yarn type	Warp density, Ends/cm	Weft density, Picks/cm	Reed no.	Reeded width, cm	Weight, g/m ²
1	Single cloth	Ne 10/1 Cotton/ Cordura®	330 dtex T400 Polyester	35	22	75/4	168	331
2	Single cloth	Ne 10/1 Cotton/ Cordura®	9/1 Ne Cotton	30	19	75/4	168	334
3	Single cloth	Ne 10/1 Cotton/ Cordura®	Ne 10/1 Cotton / Cordura®	34	20	75/4	168	337
4	Single cloth	Ne 10/1 Cotton/ Cordura®	Ne 16/1 Cotton / 78dtex Elastane	32	22	75/4	168	309
5	Single cloth	Ne 6.4/1 Cotton/ Cordura®	9/1 Ne Cotton	26	20	56/4	168	415
6	Double cloth	Ne 6.4/1 Cotton/ Cordura®	450 dtex T400 Polyester	22	30	56/4	168	445
7	Double cloth	Ne 10/1 Cotton/ Cordura®	Ne 10/1 Cotton/ Cordura®	42	32	80/5	45	578
8	Double cloth	Ne 6.4/1 Cotton/ Cordura®	Ne 6.4/1 Cotton / Cordura®	39	16	80/5	45	771
9	Double cloth	Ne 6.4/1 Cotton/ Cordura®	Ne 5.2 (4 plied) Kevlar®/Polyester	40	23	80/5	45	745
10	Backing fabric	Ne 5.4 (3 plied) Kevlar®	Ne 2.5 (4 plied) Kevlar®	12	18	110/1	32	704
Reference (control)	Single cloth	Ne 10/1 Cotton	10/1 Cotton / 78 dtex Elastane	34	20	75/4	175	420

Considering the very limited studies available, and the growing industrial interest, this study will contribute to the current literature in the field of designing of denim fabrics for protective motorcyclists' clothing. Commercial protective denim garments mostly comprise protective linings in single layer denim garments to provide sufficient impact abrasion resistance. However, in this study, double cloth denim constructions were also studied to improve the impact abrasion resistance time. Nevertheless this study aims to design and develop denim fabrics with enhanced mechanical and impact abrasion resistance using different materials, yarn types and single and double layered fabric constructions. The fabric samples produced are then evaluated to determine which design constitutes better protection with respect to the mechanical strength and impact abrasion resistance. It was aimed to reach the standard impact abrasion resistance requirements of motorcycle protective clothing for level 1 [5] in high impact areas of the body (zones 1 and 2), such as hip and knee areas. According to the "EN 13595-2:2002 level 1 abrasion resistance" standard, the abrasion resistance in time to a hole is 4.0 s for level 1 in high impact areas of the body.

Methods

All experiments were carried out at 65% RH and 21 °C.

Tensile and tear strength tests

The tensile and tear strength of the single cloth fabric samples were measured according to ISO 13934-1:2013 [15] and ISO 4674-1:2003 [16] standards, respectively, using a James H. Heal-Titan

strength tester (England). These measurements were performed to determine the performance of different yarn types used to produce the samples. A test speed of 100 mm/min was used. Five different measurements were taken in both the warp and weft directions and the average values calculated. Tear strength values are reported as the tear strength of warp and weft yarns in the results section.

Impact abrasion resistance test

Both single and double cloth samples were tested for impact abrasion resistance by SATRA Technologies (UK) according to EN 13595-2:2002 [5]. This test is practically applied to double cloths and backed fabrics. However, in order to compare their performance, both single and double cloth samples were tested in this study.

A test sample mounted on a holder was dropped from a specified height onto a moving 60 grit abrasive belt with a fixed speed of 8 m/s. Two fine electric copper wires were positioned along the outer and inner surface of the sample. An electronic timer started when the first wire was cut upon contact with the belt. When the sample was abraded through and perforated, the second wire was cut, stopping the timer, and the abrasion resistance time (in seconds) was recorded as the time taken to perforate the specimen. Impact abrasion resistance tests were performed on the samples in the warp, weft and S and Z diagonal directions. The impact abrasion resistance time reported is the average of three measurements in the warp, weft and cross directions. A more prolonged time to perforate the specimen implies better performance of the test material.

Results and discussions

Production of fabric samples

75/25 cotton/Cordura® (T420 Nylon 6.6) blended warp yarns in two different linear densities of 59 tex and 92 tex were used. Invista's Cordura® was selected due to its high abrasion resistance [1, 9] *Table 1* shows fabric parameters of the single and double layered samples designed and produced. Approximately 2 meters of each sample was produced. For the production of fabric samples 1-6, warp yarns were rope dyed and sized prior to weaving. Fabric samples were woven with a 3/1 twill design on a Picanol Optimax industrial rapier weaving machine (Pinacol, Belgium) at a running speed of 550 rpm. After weaving, the fabric samples were exposed to a basic finishing process where the sizing on the fabric was partially removed. These fabrics were then tested for the impact abrasion resistance time. Since their impact abrasion resistance time values failed to reach the standard requirement, double cloth samples were designed and produced, and these fabrics were then tested.

To obtain fabric samples with increased thickness and weight, samples 7, 8 and 9 were produced in a double cloth construction using a 3/1 twill weave design. Due to the limited availability of an industrial weaving machine, double cloth samples were produced on an automated CCI Tech SL8900 Evergreen, Taiwan, sample weaving machine. Prior to weaving, warp yarns were sized with a sample sizing machine, Kaji Seisakusho KS-7 Unisizer, Singapore, using chemical based Kozalinsize 2205 cold sizing. Then warping was performed using a CCI Tech SW550, Taiwan, mini warper. The warp length of beams were approximately 2 meters for each sample.

Sample 10 was produced as a backing fabric using specially designed plied Kevlar® yarns as an alternative to a Kevlar® single jersey knitted backing fabric used as local reinforcement in protective denim clothing. Sample 10 and a Kevlar® single jersey knitted fabric were used to back single layered samples 5 and 6 during impact abrasion resistance tests. These samples will be referred to as “Sample 5 & Knitted Kevlar”, “Sample 5 & 10” and “Sample 6 & Knitted Kevlar” in the results section. The reference or control sample is selected as a classical denim fabric made from 100% cotton in the warp and cotton/elastane in the weft.

Since there was limited opportunity to work with different reed numbers on a industrial weaving machine, reed numbers of 75 and 56 were selected for warp yarns of 59 tex and 92 tex, respectively, to produce samples 1-6. However, different weft yarns and weft densities were used to obtain different denim fabric constructions. As a result of using different weft yarn types with the same reed number, different warp densities were obtained. In the same manner as for single cloth samples, warp yarn counts of 59 tex and 92 tex were used for weaving double cloth samples 7 and 8, where the same yarns were used as filling as well. For double cloth sample 9, the weft yarn type (plied Kevlar®/Polyester) and density were changed. For sample 10, specially designed plied Kevlar® yarns were used in both the warp and weft. An AGTEKS DirecTwist twisting machine (Turkey) was employed to produce the filling yarn (made from 37 x 2 tex staple Kevlar® twisted with two 17 tex polyester filaments) in Sample 9 and the warp (made from 20 x 2 tex staple Kevlar® covered with 17 tex filament Kevlar®) and weft yarns (made from 37 x 2 tex staple Kevlar® twisted with two 20 tex staple Kevlar® yarns) in Sample 10 (see *Table 1*).

Tensile and tear strength

Figures 2 and *3* show the mean of the maximum tensile strength, and mean extension results for single cloth samples 1-6 and the reference sample in the warp and weft directions, respectively.

In the warp direction, compared to the reference fabric, improvement levels of 10.5%, 3%, 6%, 9.6%, 6.7% and 10% in tensile strength were obtained for samples 1 to 6, respectively (*Figure 2*). The mean maximum tensile strength values of samples 1 to 4, with 59 tex cotton/

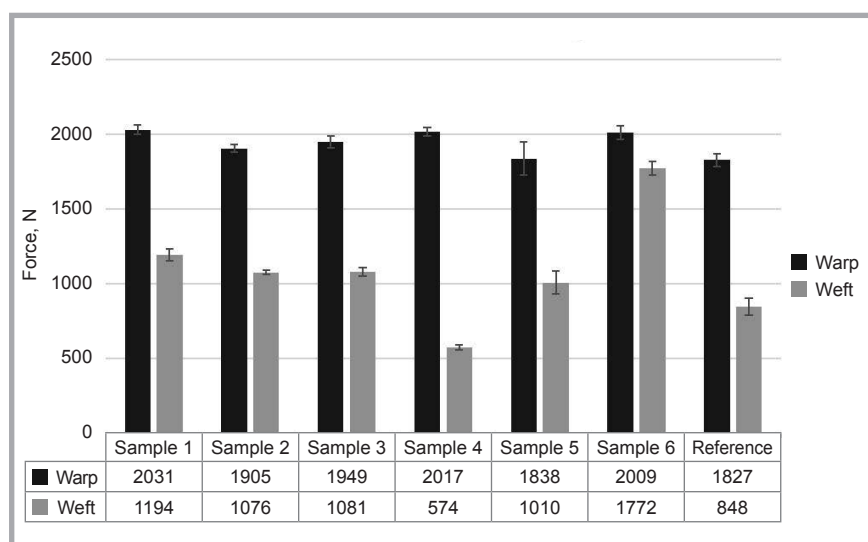


Figure 2. Mean of maximum tensile strength in warp and weft directions.

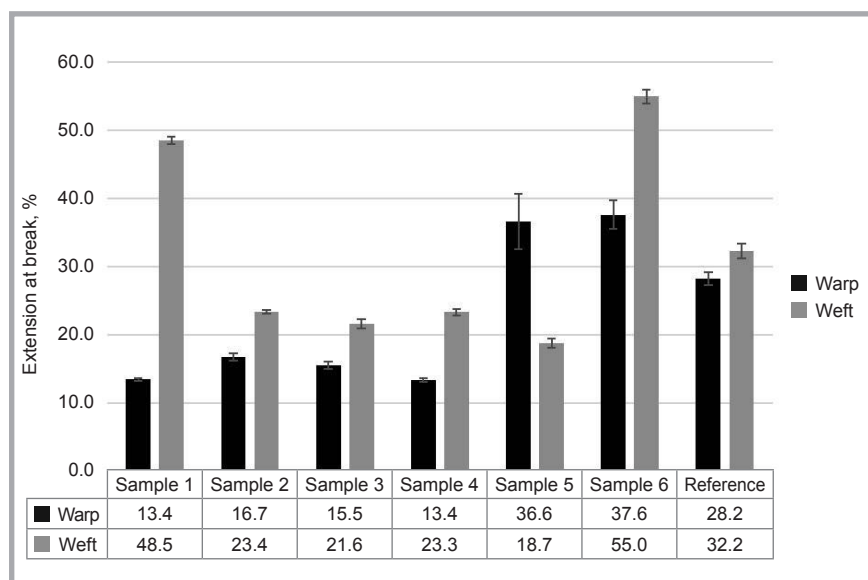


Figure 3. Mean extension at break for tensile strength test in warp and weft direction.

Cordura® warp yarns, were expected to be lower than those of samples 5 and 6, with thicker 92 tex cotton/Cordura® warp yarns. However, *Figure 2* shows that they have quite close values of tensile strength, explained by the difference in their warp yarn densities. Samples 5 and 6 have a lower end density compared to those of samples 1 to 4. Having less warp density expectedly decreased the tensile strength.

In the weft direction, compared with the reference fabric, a 36%, 20%, 23% and 19% increase in tensile strength were obtained for samples 1, 2, 3 and 5, respectively (*Figure 2*). On the other hand, a decline in tensile strength was observed at a level of 35% for sample 4, as compared to the reference. This re-

sult may be due to the fact that sample 4 has similar weft density; however, it comprises a thinner weft yarn (37 tex cotton/78 dtex elastane) compared to other samples. In sample 6, a significant improvement level of 104% in the tensile strength compared to the reference sample was obtained, which may be due the existence of T400 polyester filling yarn and almost 50% higher weft density compared to other samples.

Sample 6 showed the best performance for tensile strength among other samples, especially in the weft direction. Samples 1 and 6, both having T400 filament polyester filling, showed better performance in the weft direction than the rest of the samples i.e. 2-5. The higher tensile

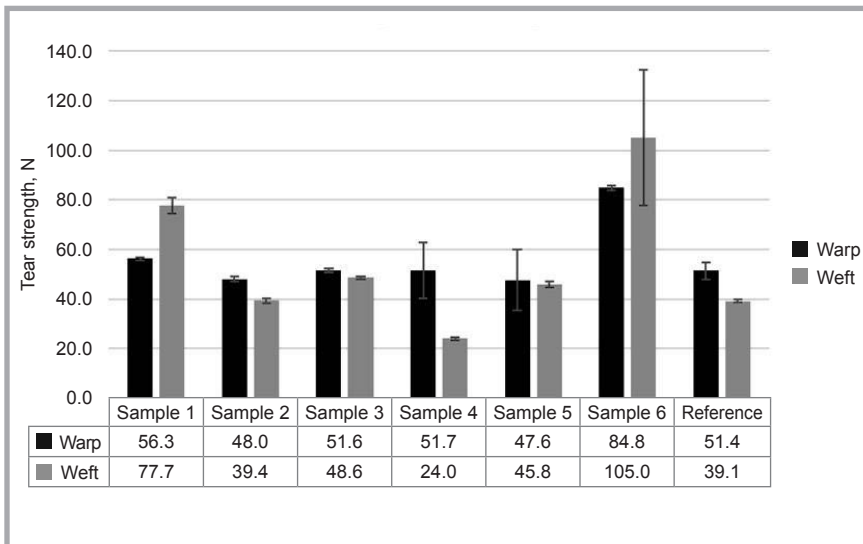


Figure 4. Average tear strength of warp and weft yarns.

strength of sample 6 than that of sample 1 was due to its weaving parameters, including yarn type and yarn density.

The extension under load values showed that samples 1-4 had lower extension values compared to the reference fabric (**Figure 3**).

The decrease in extension values in the warp direction compared to the reference fabric was 52%, 41%, 45% and 52% for samples 1-4, respectively, which may be due to the presence of cotton/Cordura® yarn in the composition of the fabric.

Samples 5 and 6 showed an increase in extension values of 30% and 33% in the warp direction, respectively, compared to the reference sample. This may be explained by the use of coarser cotton/Cordura® warp yarn of 92 tex in samples 5 and 6, as compared to the reference sample with 59 tex cotton warp yarn. Coarser yarn has a higher number of fibers in its cross section and the exploitation of more fibers in the yarn cross section, hence more resistance to friction, resulting in higher extension rates.

In the weft direction, as compared to the reference fabric, decrease rates of 27%, 33%, 28% and 42% in extension values were observed for samples 2-5, while increase rates of 50% and 70% were observed for samples 1 and 6. An explanation for this observation is the existence of T400 polyester filling yarns in samples 1 and 6, leading to higher extension in the weft direction. Sample 6 showed approximately more than 100% higher extension rates than other samples (2-5).

Among all the samples, sample 6, with coarse cotton/Cordura® yarn (92 tex) in the warp and 450 dtex T400 polyester in the weft, showed the highest performance with maximum tensile strength and maximum extension under a load in both the warp and weft directions.

Figure 4 shows the average tear strength values of warp and weft yarns in the fabric samples. The tear strength of warp yarns in sample 6 is almost 60% higher than that of samples 1-5 and the reference fabric. The low warp density in sample 6 and slippage and grouping of warp yarns over T400 polyester weft yarns before tearing and their resistance against the tearing force together yielded a higher tear resistance.

Even though the same warp yarns were used in samples 5 and 6, T400 polyester yarn was used as filling in sample 6, whereas, 66 tex staple cotton weft yarn was used in sample 5. Warp yarns in sample 6 could easily slip over T400 polyester weft yarns, group together and increase resistance against the load, while in sample 5 warp yarns were not able to slip over staple cotton weft yarns as much, which resulted in lower tear resistance compared to sample 6.

The tear strength of weft yarns of samples 1 and 6 were 98% and 169% higher than that of the reference fabric, respectively, which is due to the presence of T400 polyester filling yarns in these samples. Sample 4 showed a decrease in tear strength at a rate of 38% compared to the reference sample, which is due to its fine yarn count. Overall sample 6 showed the best performance.

Impact abrasion resistance

As seen in **Figure 5**, woven single layered fabric samples 1-6 showed impact abrasion resistance below 1 s and failed to reach the “EN 13595-2:2002 Level 1 abrasion resistance” standard, which is between 4 and 7 seconds for use over high impact areas of the body (zones 1 and 2) [7]. The use of Cordura/cotton yarns in single denim fabrics yielded similar resistance times to that of denim alone and did not provide a sufficient increase in the impact abrasion resistance times. As none of the single layers passed the abrasion resistance test, it was decided to test double layer and backed samples.

Double cloth sample 9 and sample 5 backed with sample 10, which is referred to as “5&10” in **Figure 5**, showed abrasion resistance times over 4 s and performed far better than the rest of the samples.

Sample 8 has a double cloth construction with 92 tex cotton/Cordura® in the warp and 28 x 4 tex (4 plied) Kevlar®/polyester in the weft. This sample reached the impact abrasion resistance requirement for level 1 in zones 3 and 4, covering the majority of the motorcyclist clothing. Samples 8 and 9 both have cotton/Cordura® in the warp; however, sample 9 performed better due to the existence of Kevlar®/polyester yarn in the weft. Sample 9 reached the abrasion resistance requirement for level 1 in zones 1, 2, 3 and 4.

Samples 7 and 8 have to be reinforced to reach the abrasion resistance requirements for level 1 in zones 1 and 2. Sample 7, with 59 tex cotton/Cordura® in the warp and weft, met the standard requirement for level 1 only in zone 4 by resisting for 1.33 s against impact abrasion. Sample 8, with 92 tex cotton/Cordura® in the warp and weft, met the standard requirement for level 1 in zones 3 and 4 with 2.37 seconds.

Samples 7 and 8 both have double weave constructions. However, sample 7 comprises thinner 59 tex cotton/Cordura® yarns both in the warp and weft, while sample 8 has thicker 92 tex cotton/Cordura® yarns in both directions. Sample 8 showed 78% higher abrasion resistance than sample 7, implying that coarser yarns improve resistance against impact abrasion.

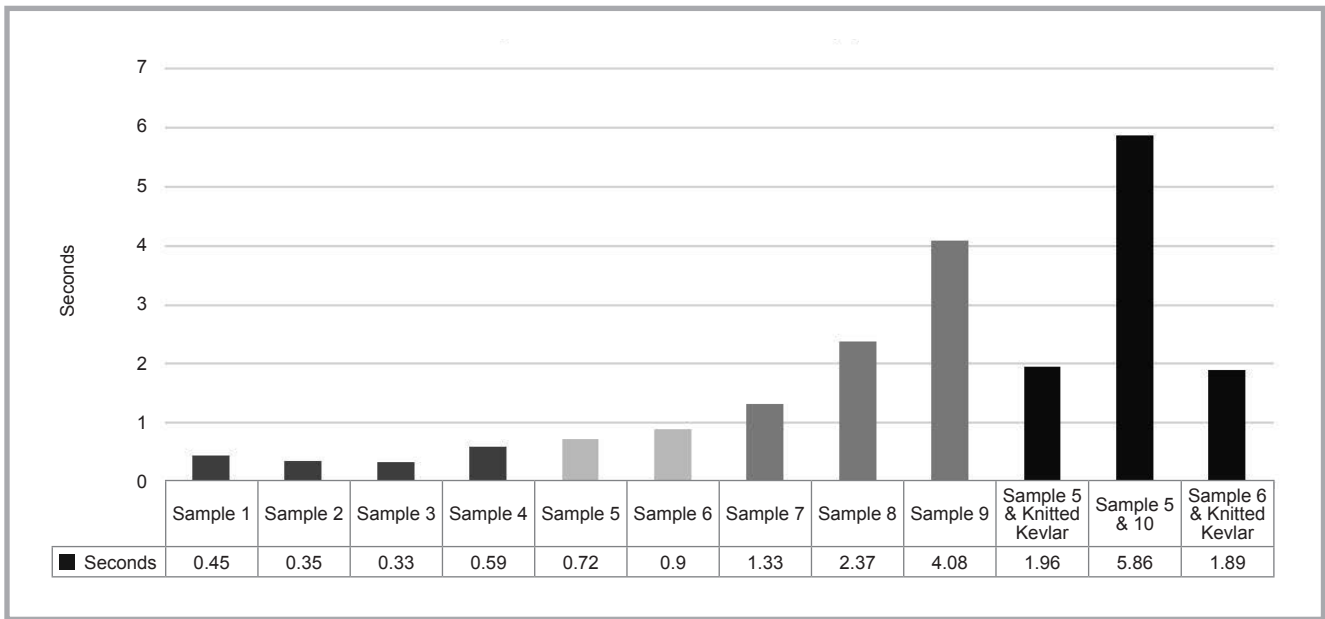


Figure 5. Impact abrasion resistance times for single layer, double cloth and backed samples.

Sample “5 & 10” showed the highest performance by resisting for 5.86 s against impact abrasion. Sample 5 has a single layer construction with 92 tex cotton/Cordura® in the warp and 66 tex cotton in the weft. Sample 10, which is the Kevlar® backing fabric, comprises 36 x 3 tex (three plied) Kevlar® in the warp and 59 x 4 tex (4 plied) staple Kevlar® in the weft. When sample 10 was used to back sample 5, it increased the impact abrasion resistance of sample 5 from 0.72 to 5.86 s, which corresponds to an improvement level of 713%. This shows that woven backing sample 10 may be used as a reinforcement fabric in high impact zones 1 and 2 for level 1.

Knitted Kevlar® backing fabric increased the impact abrasion resistance of sample 5 from 0.72 to 1.89, yielding an improvement level of 170%. However, this improvement provided by the Kevlar® knitted fabric level is much lower than that provided by the Kevlar® woven backing fabric.

Additionally thicker yarns yielded an increase in resistance against impact abrasion. When single layer fabric samples were compared, samples 5 and 6, with 92 tex cotton/Cordura®, resisted for a more prolonged time than samples 1-4, with Ne 59 tex cotton/Cordura®. Moreover fabrics with a double weave construction showed increased performance against impact abrasion compared to single layer cloths.

Conclusions

In this study, denim fabrics were developed with enhanced mechanical and abrasion resistance using different materials, yarn types and fabric constructions. The fabric samples produced were then evaluated and compared with a classical cotton denim fabric, namely the reference fabric, to determine which design constitutes better protection with respect to the mechanical strength and impact abrasion resistance.

The results showed that both in the warp and weft directions, compared to the reference fabric, improvements in the tensile strength were obtained with the denim fabrics designed. The existence of coarse cotton/Cordura® yarn in the warp and T400 polyester yarn in the weft and the use of higher yarn densities increased the performance of the tensile strength. The low warp density and easy slippage and grouping of warp yarns over weft yarns before tearing and their resistance against the tearing force together yielded a higher tear resistance.

The use of cotton/Cordura® yarns in the warp and weft within the denim fabric construction provided improved abrasion resistance compared to the reference fabric. Thicker warp yarns in the fabric construction enhanced the abrasion resistance.

The woven single layered fabric samples showed impact abrasion resistance below 1 s and failed to reach the “EN

13595-2:2002 Level 1 abrasion resistance” standard, which is between 4 and 7 seconds for use over high impact areas of the body. Moreover fabrics with a double weave construction showed increased performance against impact abrasion compared to single layer cloths.

Double cloth sample 9 and single cloth sample 5 backed with Kevlar® woven fabric sample 10, which is referred as “5 & 10”, showed abrasion resistance times over 4 s and performed far better than the rest of the samples. Sample “5 & 10” showed the highest performance by resisting for 5.86 s against impact abrasion. When sample 10 was used to back sample 5, it increased the impact abrasion resistance of sample 5 from 0.72 s to 5.86 s, which corresponds to an improvement level of 713%. This shows that the woven backing sample designed may be used as a reinforcement fabric in high impact zones 1 and 2 for level 1. Knitted Kevlar® backing fabric increased the impact abrasion resistance of sample 5 from 0.72 to 1.89, yielding an improvement level of 170%. However, this improvement level provided by Kevlar® knitted fabric is much lower than that given by Kevlar® woven backing fabric. Sample 8, with a double cloth construction with 92 tex cotton/Cordura® in the warp and 28 x 4 tex (4 plied) Kevlar®/polyester in the weft, reached the impact abrasion resistance requirement for level 1 in zones 3 and 4, covering the majority of the motorcyclist clothing. For samples 8 and 9, both having cotton/Cordura®

in the warp, sample 9 performed better due to the existence of Kevlar®/polyester yarn in the weft. Sample 9 reached the abrasion resistance requirement for level 1 in zones 1, 2, 3 and 4.

Sample 7, with 59 tex cotton/Cordura® in the warp and weft, met the standard requirement for level 1 only in zone 4 by resisting for 1.33 s against impact abrasion. Sample 8, with coarser 92 tex cotton/Cordura® in the warp and weft met the standard requirement for level 1 in zones 3 and 4 with 2.37 seconds, implying that coarser yarns improved the resistance against impact abrasion.

The results of the current study will also provide an insight for the selection of fabrics for protective denim clothing utilised in other application areas such as workwear and sportswear. For the extension of this study, comfort properties of the fabrics designed will be examined.

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