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FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

INFLUENCE OF THE TEST SPEED ON THE FORCE *VS*. ELONGATION CURVES OF REINFORCEMENT MATERIALS

MASTER'S THESIS

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DISSERTAÇÃO DE MESTRADO APRESENTADA
À FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO EM
ÁREA CIENTÍFICA

Mestrado Integrado em Engenharia Química

Influence of the test speed on the Force vs. Elongation curves of reinforcement materials

Master's Thesis

by

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Performed at

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Departamento de Engenharia Química

July 2015

Acknowledgements

Over the past five months an extensive work has been developed and it together with the daily challenges have tested my intellectual and also my personal strength. The fact that I've managed to achieve all my goals and to overcome all the challenges is due to the magnificent people who were always supporting and guiding me.

It was thanks to the constant presence and to the unconditional support of my mother and my family that it was possible for me to fulfil my work without major difficulties and it was thanks to the patience and willingness to always be on my side of Rui Lopes that the distance between Portugal and Germany was shortened every day. To all of you a huge thank you for believing in me, for giving me the chance to grab this opportunity and for every day show me your Love, Affection and *Saudade*. I'll be eternally grateful to you.

Thanks to Professor Adélio Mendes for the support and inspiring words that motivated me to strive to be successful in this project.

A special thanks to Dr. Thomas Kramer, Dr. Michael Schunack, Dr. Carole Justine and Eng. Thomas Felten first for giving me the opportunity to do this work and also for, since the first day, always be ready to help me, answer questions, provide guidance in my project and for the constructive criticism.

A big thanks to the department of Body & Compound Reinforcement Technology for the constant availability in any subject and for making me feel so well integrated.

Thanks to Andreas Maibohm and to the entire Laboratory of Reinforcement Materials for the great working atmosphere and for the support provided to me throughout all my tests.

Finally, thanks to Eng. Alexandre Gomes, Eng. Carla Pires and Eng. Diana Pinto from Continental – ITA, for giving me a good first contact with the company and for always be available and present throughout my stay in Germany.

To all of you… Thank you very much.

Abstract

The tyre is an object with a complex technical structure that besides having rubber in its composition also has materials such as textile and metal reinforcements. Cords of fibres like cotton, rayon, nylon, polyester (PET), fiberglass, and aramid have been found to be suitable for tyre reinforcement once they improve the mechanical properties of the rubber compound and give adequate functional properties to the tyre. However, it has been observed that when tyres are under service conditions, if they suffer an impact against a road element, in some cases the reinforcement cords break. The conditions and the way these cords break are essential to know for developing better and safer solutions for the next tyre generation.

The standard Force vs. Elongation tests measure the force required to promote a certain cord elongation over time at a certain speed, which can be considered a slow speed when compared to the speeds at which the tyre impacts occur. Therefore, the Force vs. Elongation curves obtained during the tests are not able to reproduce the behaviour of the reinforcement materials in a real impact situation. And in this context the need for studies at higher test speeds, which could provide essential information about the speed influence on the Force vs. Elongation curves, emerged and became the focus of this master thesis.

In this project it was studied the behaviour of reinforcement materials PET 1440 x 2 and Aramid 1680 x 2 under a wide range of test speeds, in two different machines. It was as well studied the influence of the testing clamps, the initial length of the cords, the testing machines operation mode and the twist level of the cords. All these elements have their own contribution to the tests and the understanding of how they influence the final results allowed a better comprehension of the cords behaviour.

With the very accurate experimental data collected it was possible to verify that, when the test speed imposed by the machines increased, the cords presented an earlier break and, thereby, lower breaking forces and shorter elongations at break. This speed influence was more significant on the Aramid cords. It was also identified a need to evaluate and change the standard design characteristics of the testing system, in order to develop a new test that could reproduce the cords behaviour under real conditions.

Resumo

O pneu é um objeto com uma estrutura técnica complexa que, para além de apresentar borracha na sua composição, detém materiais de reforço de origem têxtil e metálica. Cordas de fibras como algodão, rayon, nylon, poliéster (PET), fibra de vidro, e aramida foram reconhecidas como apropriadas para o reforço de pneus uma vez que melhoram as propriedades mecânicas do composto de borracha e fornecem ao pneu propriedades funcionais adequadas. Todavia, tem sido observado que quando os pneus se encontram em serviço, se eles sofrerem um impacto contra um elemento da estrada, em alguns casos as cordas quebram. Conhecer as condições e o modo como as cordas quebram é essencial para o desenvolvimento de soluções melhores e mais seguras para a próxima geração de pneus.

Os testes padrão de Força vs. Alongamento medem a força necessária para promover um certo alongamento da corda ao longo do tempo a uma certa velocidade, a qual pode ser considerada como uma velocidade baixa quando comparada com as velocidades a que ocorrem os impactos dos pneus. Por isso, as curvas de Força vs. Alongamento obtidas durante os testes não são capazes de reproduzir o comportamento de materiais de reforço numa situação de impacto real. E foi neste contexto que surgiu a necessidade de realizar estudos a velocidades de teste mais elevadas, os quais fornecem informação essencial sobre a influência da velocidade sobre as curvas de Força vs. Alongamento, e estes tornaram-se o foco desta tese de mestrado.

Neste projeto foi estudado o comportamento dos materiais de reforço PET 1440 x 2 e Aramida 1680 x 2 numa vasta gama de velocidades de teste, em duas máquinas diferentes. Também foi estudada a influencia das garras de teste, o comprimento inicial das cordas, o modo de operação das máquinas de teste e o nível de torção das cordas. Todos estes elementos tem a sua própria contribuição nos testes e o entendimento de como eles influenciam os resultados finais permite uma melhor compreensão do comportamento das cordas.

Com os dados experimentais de grande precisão foi possível verificar que, quando a velocidade de teste imposta pelas máquinas aumentava, as cordas apresentavam uma quebra prematura e, assim, forças de quebra mais baixas e alongamentos de quebra mais curtos. Esta influência da velocidade foi mais significativa para as cordas de Aramida. Também foi identificada a necessidade de avaliar e mudar as características padrão do sistema de teste, com o objetivo de desenvolver um novo teste que seja capaz de reproduzir o comportamento das cordas quando sujeitas a condições reais.

Declaration

I declare, under honour commitment, that the present work is original and that every non-original contributions were properly referred by identifying their source.

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Notation and Glossary

α	Twist factor	$\text{tpm.}\sqrt{\frac{tex}{1000\text{ m}}}$
dtex	Decitex	g/10 000 m
BF	Breaking force	N
E@BF	Elongation at break	%

List of Acronyms

C-ITA	Continental-Indústria Têxtil do Ave, S.A.
PET	Polyethylene terephthalate
Ar	Aramid
ASTM	American Society for Testing and Materials

1 Introduction

1.1 Project presentation and framework

The wheel, which started as a simple structure in wood with a fixed axis, was one of the greatest inventions of the human history. Its wide field of applications and the amenities associated to its use arrived to simplify the daily life of many in the most different activities and sectors. Among them there is the automotive sector that owes its existence to the invention of the wheel and great part of its development to the evolutions that the wheel suffered [1].

The wheel has evolved from the basic need of decreasing friction while moving from a place A to a place B, to try to achieve the most different proprieties in order to satisfy the needs of the actual consumers. It was due to the automotive industry that the wheel wood structure found the need to be covered by materials that could protect it and, therefore, the concept of tyre was born. It was here that Continental found a way to grow up as a company and as a researcher and development entity that searches for the best compromises between the tyres proprieties and a design that looks forward to the safety and the continuous improvement [2].

Nowadays, the tyre is an object with a complex technical structure that presents not only rubber but also many others components, such as reinforcement materials, to provide to tyres their core characteristics. Tyres must provide safety, cushion, damping, assure good directional stability, and provide long-term service, with a great performance. Overall they must be able to transmit the longitudinal and lateral forces, while executing the typical driving manoeuvres in whatever place and weather the driver may face, ensuring a great and reliable adherence quality [3].

In order to achieve all that the costumers are expecting or even for trying to be one step ahead of competition, it is necessary to go further and to elaborate new laboratory tests to try to reproduce the real conditions under which the tyres are subjected in service.

When tyres are under service conditions, if its sidewall suffers an impact against any road elements, as curb stone edges, or obstacles it is important to understand the behaviour of the reinforcement materials at the speed that impact occurred. Once the standard Force vs. Elongation tests only analyse the impacts that cords can withstand at low speeds there is no real information to predict the speed at which the cords are more vulnerable, or even which impact forces can they support at such conditions. It was due to this lack of information that the studies of the impact of testing speed on Force vs. Elongation curves of reinforcement materials were required. To that effect, different test need to be designed to identify and provide more viable information about the reinforcement materials behaviour under these circumstances. With this knowledge it would be possible to realize new studies to improve the cords characteristics with the goal to provide a best reinforcement for tyres.

It was with the objective to answer to these needs that the present master thesis took place, in the R&D, Body Compound & Reinforcement Technology department, of Continental AG in partnership with the College of Engineering, University of Porto. The focus of these studies was in the behaviour of the reinforcement materials PET 1440 x 2 and Aramid 1680 x 2 under high speed testing.

1.2 Continental AG

The Continental Corporation, founded on 1871 in Hannover, Germany, is an automotive industry of worldwide renown that have been strengthening its brand in this sector and it consumers trust. Continental is divided in two big groups, the Automotive group that include the Chassis & Safety, Interior and Powertrain divisions; and the Rubber group that includes the Tyre and ContiTech divisions [4].

Continental is one of the five biggest tyres producers of the world and so it is possible to understand the great value that tyres have to this company [5]. And that is why its research and development activities, across the years, have been aiming towards Continental Tyres brand to represent the excellence in forces transmission and in trustful products, in whatever are the weather conditions, with the required efficiency [6].

1.3 Work goals and contributions

With the studies of the impact of the tests speed on Force vs. Elongation curves of reinforcement materials, it will be possible to verify and analyse the contribution of speed in the reinforcement materials response, in this case regarding to PET, polyethylene terephthalate, and Aramid cords. If it would be possible to formulate a theoretical expectation of the results and the results achieved were much different from it or if the speed has a great influence within the response of the materials then it must be considered the investment on the purchase of a specialized machine to perform Force vs. Elongation tests at the required speeds.

Note that it is the first time that these studies are being conducted within Continental, what gives to these works an experimental nature. Thereby, there is a need to know if any of these ideas/techniques are already being studied/applied in this or in others industries and, if yes, what are the contributes that we can get from them. It may also be needed, if any information could be found, a wide theoretical research for trying to predict results.

1.4 Thesis organization

This master thesis is organized in 6 chapters that are presented next:

Chapter 1.	**Introduction** gives some information about the company Continental AG and its principal product and introduces the objectives of this work.
Chapter 2.	**Stat of the art** presents some knowledge behind tyres and explains the basic concepts of its components. A main focus is given to the reinforcement materials and its properties.
Chapter 3.	**Procedure and technical description** explains the experiments conducted in order to achieve the goals of this thesis.
Chapter 4.	**Results and discussion** provide a profound analysis of the results achieved in the studies conducted.
Chapter 5.	**Conclusions** summarize the principal conclusions achieved in the present work.
Chapter 6.	**Project assessment** evaluates the level of achievement of the proposed objectives and provides suggestions to further studies.
References	Is a list of the references used throughout this master thesis.
Annexes	Provides additional information.

2 State of the art

2.1 Tyres

In our daily life the tyre appears as a vital and complex technical component that must fulfil a variety of functions [3].

It has evolved from the wheel that, for more than 5 000 years, has been reinvented due to the constant necessity to meet the current transportation needs [1, 3].

Looking to the wheels' use in a wide range of applications and the outcomes from its evolutions is it easy to understand why it is considered one of the greatest "inventions" in the human history [1, 11].

One of the biggest steps in the tire development was the discovery of vulcanization by Charles Goodyear, in 1839. It allowed, in less than 50 years, the invention of the pneumatic tyre by Robert W. Thomson and later, in 1888, with more success by John Boyd Dunlop [1, 8, 11].

The pneumatic, or air inflated, tyres use rubber and enclosed air to reduce vibration and improve traction. Therefore, they provide a more comfortable ride and enable automobiles to travel at higher speeds. They brought with them new standards of tyre performance [3, 11].

Nowadays, there are two types of pneumatic rubber tyres, the bias and radial ply. The first ones, which were the first to be invented and currently are the ones used with much less frequency, were named bias ply because the rubberized fabric cords run diagonally from one bead to the other. While the ply cords of radial tyres, which were first introduce in Europe in 1948, run perpendicular to the direction of travel, what means that they radiate at a 90° angle from the wheel rim, as it is possible to see from Figure 1 [3, 7, 11].

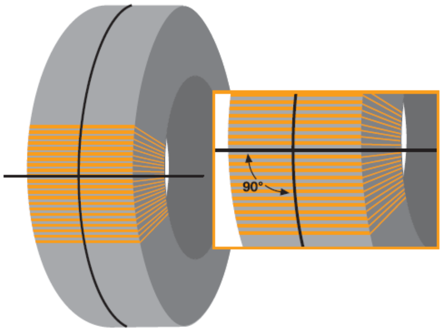


Figure 1 - Radial tyre (adapted from [3])

2.1.1 Functions

At the present, the tyres are expected to be capable to provide safety, cushion, damping, assure good directional stability, and provide long-term service while helping to economize fuel [3, 14].

Overall, they must provide a good interface between the vehicle and the road. For that they must transmit strong longitudinal and lateral forces during the complete driving experience to ensure optimal and reliable road holding quality. This must be possible in all weather and road conditions. [3].

2.1.2 Composition and Structure

A modern radial tyre in its composition contains diverse ingredients in varying amounts. These ingredients differ by tyre size and type (summer or winter tyre) but, in a general way, a tyre presents natural and synthetic rubber; fillers as carbon black and silica; reinforcing materials; plasticizers like oils and resins; chemicals for vulcanization as sulphur and zinc oxide; chemicals as antioxidants for counter environment effects and material fatigue [3, 7, 12].

All these materials are essential to a tyre due to its complex structure, which it is possible to recognize by the comprehension of the Figure 2. Then, following the numbers discriminated in the mentioned figure, the tyre components along with their functions and compositions will be explained [1, 3, 13, 15]:

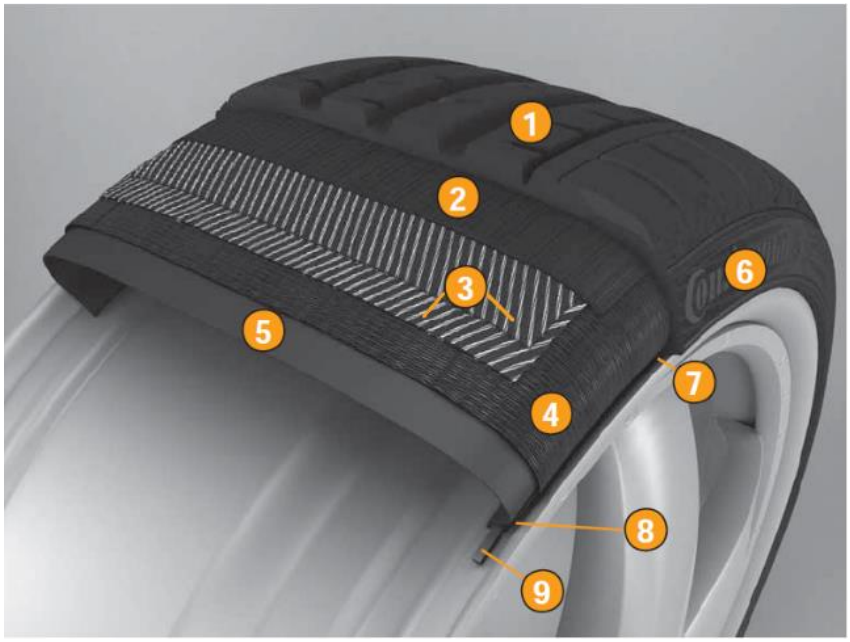


Figure 2 - Radial tire structure (adapted from [3])

1. Tread – the tyre component in contact with the road. It can be composed of multiple layers of rubber that give it a thickest structure. Its main purpose is to provide grip on all road surfaces, wear-resistance and directional stability, while being able to dissipate heat, reduce rolling resistance and damage to the casing.
2. Jointless cap plies – it consists of layer(s) of reinforcement textiles, embedded in rubber, in the circumferential direction of the tyre. Its primary function is to reduce the expansion in the crown under service conditions and to reduce the movement of the belt package. Thereby, this structure enhances high-speed suitability.
3. Belt plies – they are composed by high-tensile steel cords that are disposed in layers organized in reverse angles between each other. They promote shape retention, directional stability as well as better damage resistance and protection of the ply cords from road hazards. As result they help to reduce the rolling resistance and to increase the tyre’s mileage performance.
4. Carcass ply – one of the most important parts of a radial tyre, which is composed by textile reinforcement materials disposed in one or more layers directed in radial direction. The textile cord ply transmits forces from the road surface to the rim, surging to them as a linking structure. The carcass is also crucial in the control of the internal pressure and in the maintenance of the tyre‘s shape and, therefore, in its performance at high speeds and durability.
5. Inner liner – it is a sheet of rubber, with a high percentage of Butyl-rubber. It seals the air-filled inner chamber and acts as a tube in tubeless tyres.
6. Side wall – it is a flexible structure composed by rubber and its purpose is to protect the casing against direct mechanical load, external damage and environmental influences as UV-rays and Ozone. It also assists in the tread support and it stiffness can influence the bending and pressure forces transmission and, thereby, the driving behaviour.
7. Bead reinforcement – it comprises layers of reinforcement textiles that are attached, in the bead area, directly to the carcass. It aims to stiffen the sidewall and promote directional stability, precise steering response and tyre’s high speed durability.
8. Bead apex – it is the bead filler and is composed by synthetic rubber. It increases the stiffness in the sidewall and bead area, and therefore it enhances directional stability, gives steering precision and improves comfort.

9. Bead core – it is made of steel wire embedded in rubber and it’s used to ensure that the tyre sits firmly on the rim.

The recognition of each component composition and functions, together with the costumers’ requirements and the tyre producers need to excel in quality, helps to understand the difficulty behind the tyre design and the need to settle for a compromise between opposing features in such a complex product. Still the safety must be the absolute priority over all other design objectives [3, 7].

2.2 Reinforcement materials

Many elastomers present a weak structure to be used alone in some products. This means that most practical rubber products need reinforcement materials in order to improve the elastomer matrix [16].

It is possible to reinforce the elastomer matrix either with reinforcement fillers that are added to the matrix composition or some kind of cord that is added to the product assembly phases [16].

The principle behind the reinforcement fillers it is based on the improvement of the mechanical properties of the rubber compound, whereas the cord based components have the extra purpose to give adequate functional properties to the product [16].

From the information presented in the previous section, it was implicit that the uniformity is a prerequisite for a high-quality, high performance tyre and that the dimensional stability is one of the basic requirements of reinforcing material. Once tyres are a practical rubber product, and the rubber itself doesn’t have the structural stability required for proper handling vehicles, there is a need to use reinforcement materials [15].

The reinforcement materials used in tyres include steel cords and textile reinforcement materials, more precisely, rayon, polyester (PET), polyamide (Nylon) and aramid. Everyone of these materials present characteristic properties and they are used according to the type of tyre and to the specific needs of its components [1, 15].

2.3 Textile reinforcement materials

Along the years, due to the tyre performance demands, several materials have been found suitable for tyre reinforcement, being them: cotton, rayon, nylon, polyester, steel, fiberglass, and aramid [1]. Once the main focus of this work is on PET and aramid, this chapter will be targeting the textile reinforcement materials and, in particular, the ones just mentioned.

2.3.1 Fibres

From the time when fibres were collected from nature, and only used for clothing, till the present their value as a special type of material has been recognized. They are defined as “a textile raw material, generally characterized by flexibility, fineness and high ratio of length to thickness” by the textile institute [17].

The fibres consist of sequences of polymers that are macromolecules. The polymers consist of monomers, their basic units, linked together by covalent bonds [18].

One of the most important characteristics of polymers is their molecular arrangement. It is known that if the polymer molecules present areas of high orientation crystalline structures are formed, which present a longitudinal near to parallel alignment; on the other hand, if the polymers’ molecules present low orientation areas that leads to amorphous segment, and so they don’t present a defined orientation, as seen in Figure 3 [18].

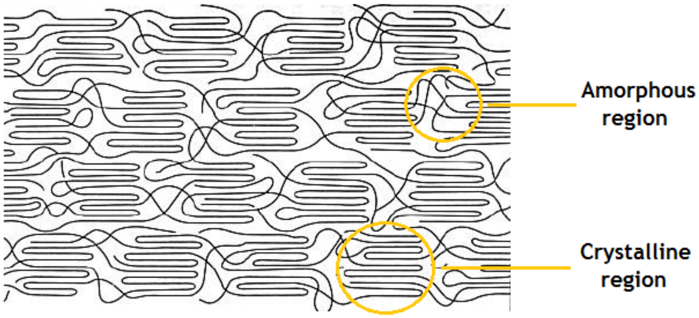


Figure 3 - Semi-crystalline polymer structure (adapted from [17])

Polymers with high orientation levels are characterized by high tensile strength, low elongation, and heat and chemical resistance, while the amorphous areas confer to the fibre characteristics such as flexibility, softness and comfortability [18].

Focusing on the fibres studied in this work, it is know that the polyethylene terephthalate, commonly known as PET, is a thermoplastic polymer with a semi-crystalline structure. One of the paths to its manufacture is the esterification of terephthalic acid (TPA) with ethylene glycol (EG) into the formation of PET monomers, bis-(2-hydroxyethyl) terephthalate (BHET), see Figure 4. Once each reaction component holds two functional groups, they continuously link up to form long chains. This chain reaction promotes the formation of a linear polymer, that does not branch, and it has the particularity to be reversible, what concedes to the polymer a very simple architecture. The PET final structure is significantly stable and so this polymer presents weak adhesion to other components, being needed a chemical activation to improve this feature. PET is also known for its stiffness, strength, water resistant and dimensional stability at high temperatures. Its cords are normally used as reinforcement in tyres carcass [16, 17, 20].

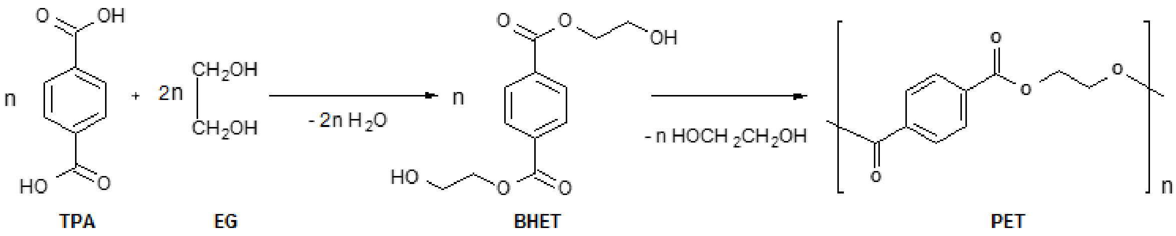


Figure 4 - Production of PET (adapted from [17, 21])

Regarding to aramid, its name comes as a shorter way to refer to "aromatic polyamide". It is a man-made fibre with a high crystal orientation and a distinctive gold colour, which is produced by the polymerization of terephthalic acid and p-phenyldiamine, see Figure 5. The aramid's molecules are characterized by relatively rigid polymer chains, which are linked by strong hydrogen bonds. These bonds are capable to transfer in a very efficient way mechanical stress. Due to this features aramid fibres present an excellent dimensional stability, high strength, good resistance to abrasion, flexing and stretching, and also to organic solvents and heat. Overall, aramid fibres are more expensive than traditional tyre reinforcement materials, but they are the only materials suitable for extreme high-performance tyres and thus they are used, for example, as reinforcement in the tyres' bead [22, 23, 24].

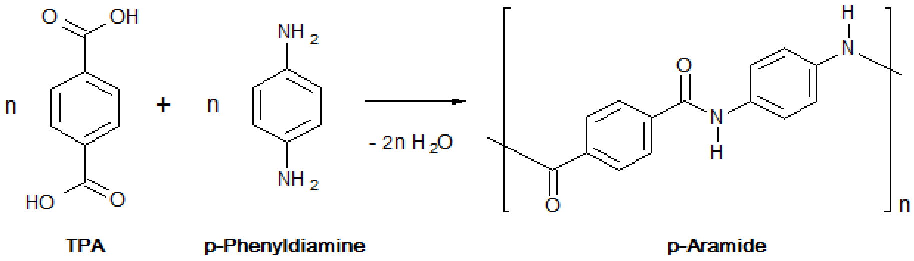


Figure 5 - Production of Aramid (adapted from [21])

2.3.2 From Filaments to Fabrics

The textile fibres in order to be useful as reinforcement materials need adequate strength and stability. By submitting the fibres to the spinning, twisting, weaving or knitting and dipping processes it was possible to assemble strong, self-locking sheets from these materials and thus meet the reinforcement materials requirements [17].

All the referred processes make part of the fabric manufacturing. It starts with the manufacture of the filaments, which are fibres with an immense length, using extrusion processes. Sequentially comes the twist process that firstly allows the formation of yarns, which are defined as filaments laid together with a substantial length, and later the greige cord assemble, being cords a structure composed by two or more yarns twisted together. Finally, disposing the cords in a coherent form it is possible by weaving to produce cord fabrics. All these structures are presented in Figure 6 [21, 25].

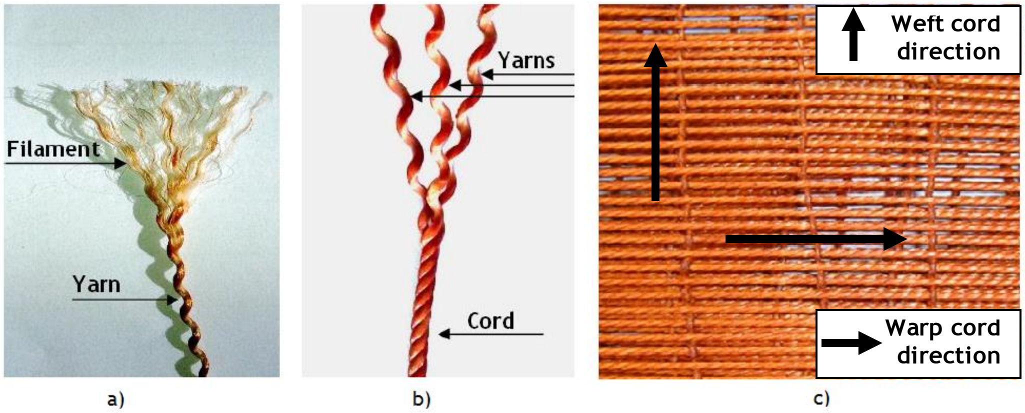


Figure 6 - Fibre and fabric structures (a), b) adapted from [26], c) adapted from [27])

Due to the lack of adhesion properties from the fibres to the rubber the dipping process appears as a crucial chemical and physical step in the activation of the fabrics. It is only after the dipping phase that their fibres are able to develop bonds with rubber and the fabric manufacture is considered finished [25]. The dipping process is also recognized as a tuning phase that allows to achieve the final properties of the materials.

2.3.3 Twist influence on cords behaviour

With the twist process the filaments are more firmly held together and the resultant cords more compact, which provides a greater resistance to damage from abrasion, and the fatigue resistance of yarns is improved. As it has been referred before, the cords are constructed by a twist process that is preceded by the yarns twist, these two twist steps present opposite directions. To differentiate the twist directions the term S–direction is used if the material turns clockwise, from top to bottom, and, if the material is turning in counter clockwise, the term used is Z-direction, see Figure 7 [1, 7, 19].

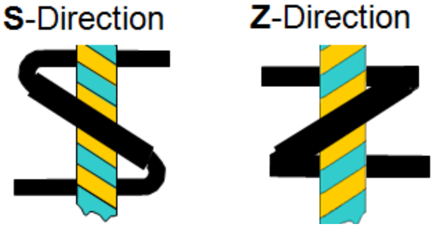


Figure 7 - Twist direction (adapted from [21])

Another important feature from the twist process is the twist level of the cords, see Figure 8. And it can be defined as a number of turns per meter and measured using the twist factor, α (Annex 1) [21].

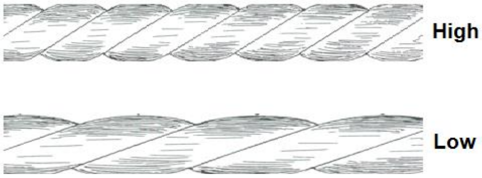


Figure 8 - Twist level (adapted from [21])

For each material there is an optimal twist level that provides the best mechanical properties to the cords, as it is shown in the Figure 9. After that value, as the twist level increases, the greatest is the effect of stresses on the cord due to the increase of the helix angle. Thereby, the force in the direction of the yarn axis increases and causes, overall, a lower breaking force (BF) of the cord, what is shown in the Figure 9 [1, 28].

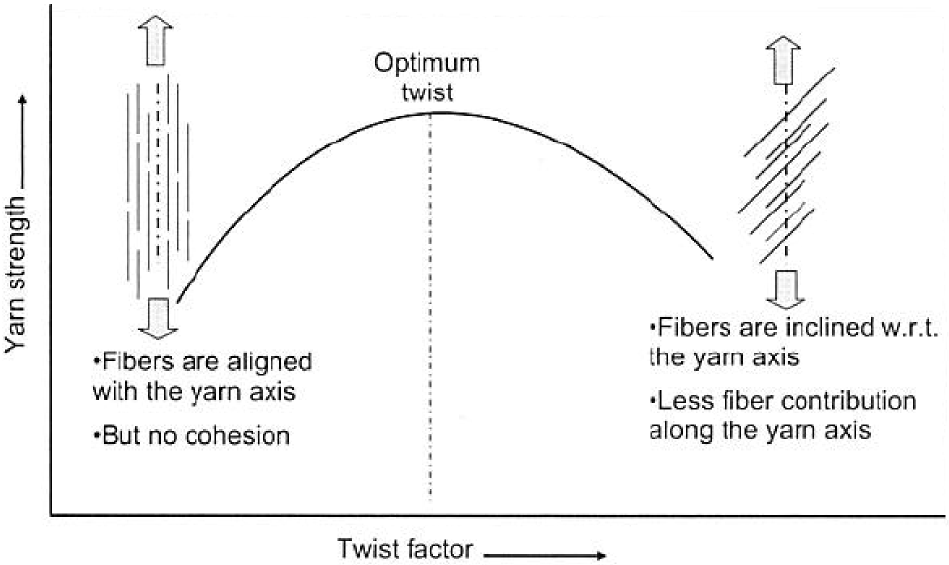


Figure 9 - Twist level, discontinuous fibres (adapted from [28])

2.3.4 Force vs. Elongation curves

Generally, the curves of Force vs. Elongation allow identifying the kind of material used in the cords construction. Every material presents a different behaviour when subjected to driving forces and so their curves, and their modulus, are unique. It can happen that the same material may present some deviations in their Force vs. Elongation curves according to the kind of clamp that is used to test them, to the dipping process conditions and even to the store conditions. But overall it is impossible to confound, for example, the curves from PET cords with the curves from Aramid cords. The Figure 10 presents the typical curves shapes of several dipped cords, with the following constructions: PET 1440 x 2, Aramid 1670 x 2, Rayon 1840 x 2 and PA6.6 1400 x 2.

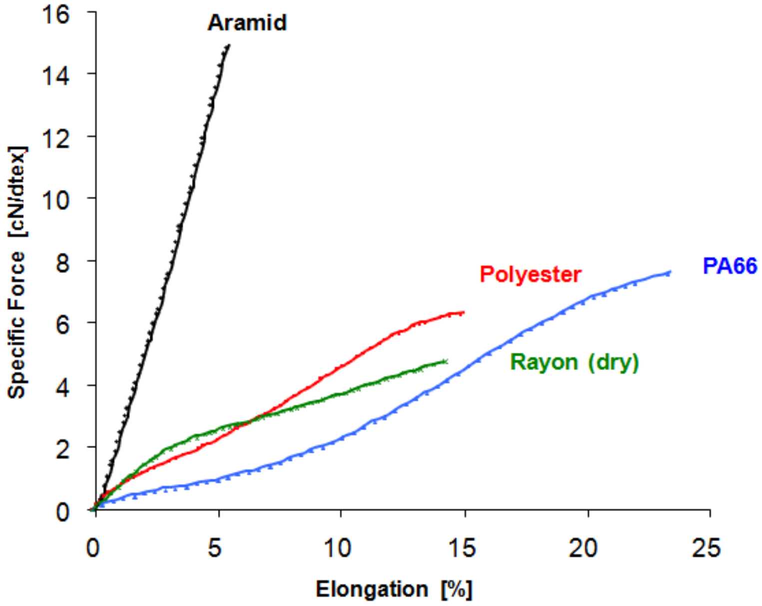


Figure 10 - Force vs. Elongation curves of dipped cords (adapted from [21])

The cords constructions, shown in the previous paragraph, include information about the linear density of the yarns, *dtex*, and the number of yarns used in the cord construction. For example, for the PET 1440 x 2: the "1440" represents the yarns *dtex*, in grams per 10 000 meters, and the "x 2" informs that it was constructed by twisting two yarns.

As clarification title, the cords' modulus is a property from the material that represents its resistance to deformation. It is expressed as the ratio of force to elongation or, in other words, as the curve slope at a certain elongation [25]. Looking to the Figure 10, e.g., it is possible to conclude that Aramid presents a higher modulus than Polyester what results in a higher breaking force but, at the same time, a shorter elongation is achieved.

3 Procedure and technical description

In order to achieve the purpose of this thesis an intensive study of the influence of testing speed on the Force vs. Elongation curves of PET and Aramid was carried out.

Due to the testing conditions provided by the company facilities it was needed to understand the influence of several variables in the tests performed in order to be able to fully comprehend the real effect of testing speed.

3.1 Equipment

To perform the tests there were available two different machines with different characteristics but capable to perform the same kind of tests:

1. Zwick Machine (standard machine to perform the Force vs. Elongation tests)

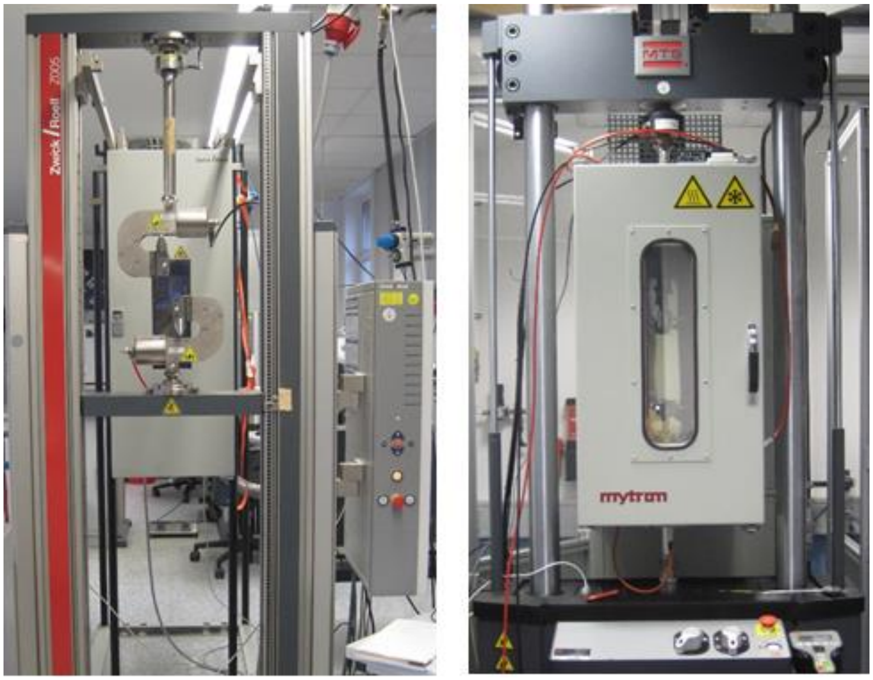
This testing machine, see Figure 11, is designed for demanding testing situations and is suitable for applications from all fields, including research projects. It allows test speeds from 0.00005 to 3000 mm/min that are independent of test load and, according to the testing needs, the use of a climate chamber is possible [29]. The load cell, or in other words the transducer that generate an electrical signal with a magnitude directly proportional to the force measured, used has a 2.5 kN capacity.

2. MTS Machine

The MTS machine, see Figure 11, is a high-force servohydraulic test system that is intended to deliver a full spectrum of tests, including the simple strength testing [30]. A servo system is a control system that measures its output and forces it to follow a command signal [31]. The MTS machine allows test speeds up to about 1150 mm/s. The load cell, due to lack of other load cells appropriated to this machine, used has a 15 kN capacity. The MTS machine used was provided with a climate chamber.

In order to simplify the machine presentations, in the future, the Zwick machine will be named as “Zwick” and the MTS machine as “MTS”.

When performing the tests the choice of clamps has a crucial place in the testing quality. To every material exist an appropriated clamp to test it and, more importantly, to grab correctly the cord. These hold action can be provided by pneumatic tension systems or by manual mechanical action. The clamps used in this work are presented next:



a) b)

Figure 11 - Zwick machine a) and MTS machine b)

1. PET standard clamps

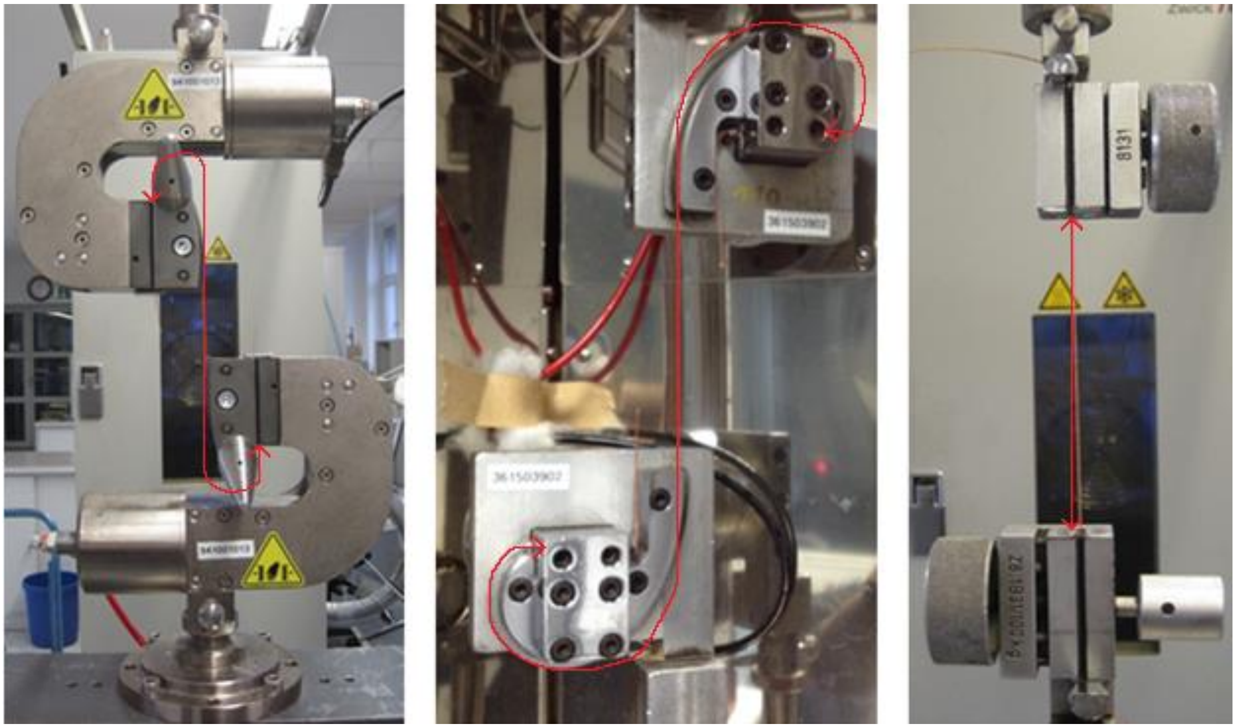
These clamps, as seen in Figure 12 a), present big dimensions and a considerable weight. Their rounded shape allows to decrease the friction in the PET cords' during the tests. They are controlled by pneumatic systems and the total length of cord that they allow to test is shown in red in the Figure 12.

2. Aramid standard clamps

The clamps seen in Figure 12 b) also present big dimensions and a high weight. Again, their rounded shape allows decreasing the friction in the Aramid cords' while they are tested. These clamps are controlled by pneumatic systems and the total length of cord that they allow to test is shown in red in the Figure 12.

3. Parallel clamps

The parallel clamps (Figure 12 c)) are small objects with a light weight. These clamps have a straight surface in their edges what promotes a worst quality of tests because this kind of surface leads to more friction in the areas where the cords are held promoting an earlier break. These clamps are controlled by manual mechanical action and the total length of cord that they allow to test is shown in red in the Figure 12.



a) b) c)

Figure 12 - PET and Aramid standard clamps, respectively a) and b), and c) parallel clamps

Again to simplify the data exposure the clamps will be named, considering the order in which they are presented in the Figure 12, as Std PET, Std Ar and Parallel clamps.

3.2 Material tested

The material supplied to the tests as well as their characteristics are presented in the Table 1:

Table 1 - Material supplied to the tests

Fibre	**Structure**	**Yarn construction, direction Z [tpm]**	**Cord construction, direction S [tpm]**	***dtex***	**Material designation in this work**
PET	Fabric cords	380	370	1440 x 2	PET.1
	Cord	350	340	1440 x 2	PET.2
		365	355		PET.3
		395	385		PET.4
		410	400		PET.5
Aramid	Fabric cords	330	330	1680 x 2	Ar

3.3 Design of experiments

Knowing the testing boundaries and the materials available, the design of the experiments were limited by the fact that the Std PET and Std Ar clamps, normally used on the Zwick, were too big, too heavy and pretty difficult to adapt in the MTS. Thereby, the first studies realized on the Zwick, concerning only to PET.1, had the objective to comprehend the influence of the clamps during the testing process. Thus the Std PET and Parallel clamps where used.

After, in order to try to understand the influence of the length of the cords tested, this thinking that the area of impact when a sidewall shocks against a road obstacle should be really small, different start positions, S.P., between the clamps where selected and tested using only PET.1, on both machines, using the Std PET and Parallel clamps.

As the Zwick only allows speeds up to 3000 mm/min the following speeds, presented in the Table 2, were tested.

Table 2 - Speeds tested in the Zwick

Test Speed	mm/min	100	300	400	700	1000	1300	1600	1900	2200	2500	2800	3000
	mm/s	1.67	5.00	6.67	11.67	16.67	21.67	26.67	31.67	36.67	41.67	46.67	50.0
Studied speeds			x			x		x					x

The “Studied speeds” are the speeds that will be presented in majority in the next chapter due to their relevance to the objective of this project, and because the other speeds, after previous analysis, don’t contribute in a large scale to the final comprehension of the test speed influence.

Stepping to the MTS, with material PET.1 and using the Parallel clamps some of the previous speeds where tested and higher speeds where achieved, being them the ones shown in Table 3, which allowed to conclude the desired test speed influence studies.

Table 3 – Speeds tested in the MTS

Test Speed	mm/min	100	300	700	1600	2500	3000	6900	13800
	mm/s	1.67	5	11.67	26.67	41.67	50	115	230
Test Speed	mm/min	20700	27600	34500	41400	48300	55200	62100	69000
	mm/s	345	460	575	690	805	920	1035	1150

After that some start positions tests were also performed, an attempt to test the cords using the Std PET clamps on the MTS was made, and the studies around PET.1 were concluded.

To compare two materials with pretty different modulus and levels of crystallinity, in the case of this work PET and Aramid, speed influence studies were performed with the Std Ar, with the material Ar, on the both machines. The speeds tested were presented in Table 4:

Table 4 - Speeds tested in the MTS, Aramid studies

Test Speed	mm/min	150	300	700	1000	1600	2500	3000
	mm/s	2.5	5	11.67	16.67	26.67	41.67	50
Test Speed	mm/min	6900	13800	20700	27600	34500	51780	69000
	mm/s	115	230	345	460	575	863	1150

In the Zwick the speeds tested were the ones shown in the Table 2 as “Studied Speeds”.

An important note is that this testing speeds presented in the Tables 2 to 4 are related to the final test speeds that the machines achieve, which are the speeds that the machines were programmed to reach, and not to the test speeds observed during the complete tests. This because an initial phase of acceleration is needed before the desired test speed is reached.

Due to the comparison of the results from the machines A and B a new study around PET was performed. Thus, some test with the material PET.1 were carried out in different Zwick machines available at Continental, and lately using the materials PET.2 to PET.5 the twist level relevance together with the machines A and B influence was tested. For that the Std PET clamps were used, in all the tests, on the machines A and B. The test speeds carried out on the other Zwick machines were defined according to the machines specifications and the need to be able to compare them.

3.4 Technical procedure

To perform the Force *vs.* Elongation tests, where the force required to promote a certain cord elongation is being measured, several rules described on the ASTM D885 were followed [32]:

1. The material must be stored, for at least one day, at the operation conditions, which are Temperature = 23 °C and Humidity = 55 %.
2. The S.P., the test speed and the material specific pre-load (e.g. to overcome the cord creases, which are an outcome of the fabric construction), to be applied on the beginning of the tests, should be set up in the machine controller’s interface.

3. The tests are performed by the pull of the cords, due to the dislocation of the lower clamp until the cords break, see Figure 13.
4. Every test should be repeated from five to ten times and if the cords break on the clamps edges the results shouldn't be considered.
5. The data collected, see example on Annex 1, should be normalized by the testing time and its average obtained according to the calculations provided on the Annex 1.

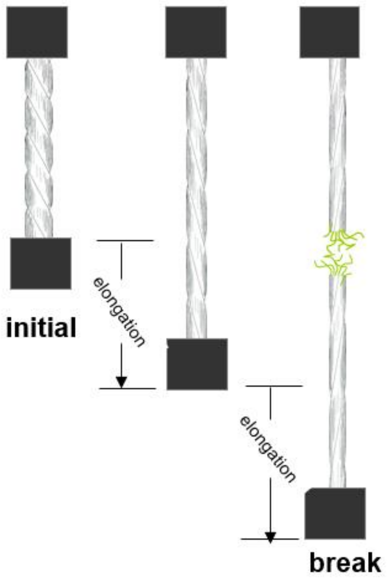


Figure 13 - Force vs. Elongation test (adapted from [21])

4 Results and discussion

In this chapter a profound discussion of the results achieved in the studies conducted will be realized. The influence of the clamps, length of the cords, machines and twist level will be analysed, and the main focus of the work will be the evaluation of the test speed influence on the Force *vs*. Elongation curves.

4.1 Studies of the clamps' influence

As said before, a study around the Std PET and Parallel clamps, while conducting the tests on the Zwick, was developed. In this study the behaviour of samples of PET.1 was analysed, considering a S.P. of 250 mm and the "Studied Speeds" previously referred.

The results of this study are presented in the Figures 15 to 17 but before step into their discussion the analysis of the Figure 14 is crucial. The Figure 14 exhibit the standard Force *vs*. Elongation curve for PET, Figure 14, where it is possible to recognize three stages. The first one corresponds to the cord structure response that is dominated by inter-fibre friction due to yarn bending. The second stage corresponds to the linear elastic response of the material where the yarns are straightened in the direction of application of the load. And the stage three is characterized by the yarn extension that is an outcome from the decrease of the cord crimp and consequent rise of the magnitude of the loading [28, 33].

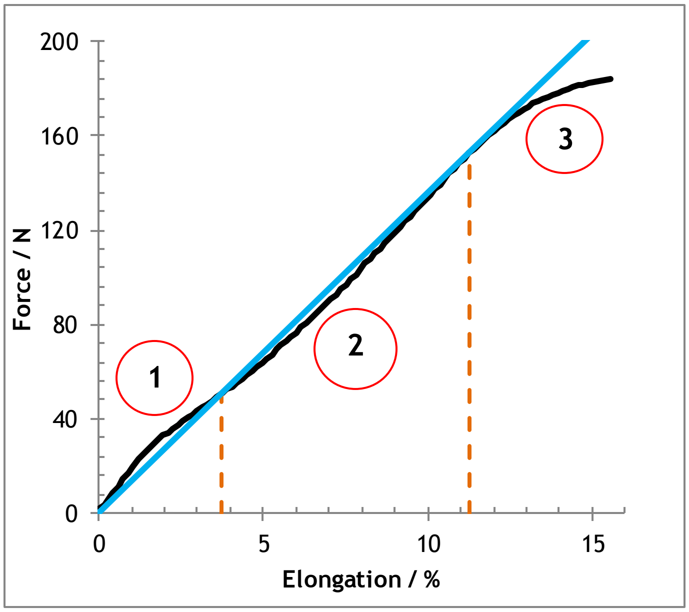


Figure 14 - Standard Breaking Force vs. Elongation curve of PET

Comparing the curves in the Figure 15, and having the knowledge from the previous paragraph, it is possible to conclude that the clamps have a great influence in the stages 2 and 3 of the PET samples. After a similar stage 1, the cords tested with the Parallel Clamps reveal a lower modulus on the stage 2 and break before being able to achieve the stage 3, while the cords tested with the Std PET clamps show a normal behaviour. These different behaviours result from the clamps geometry.

As it is possible to see in the Figure 12, chapter 3, whereas the Std PET clamps present a long section with a polish area and shaped curve, which provide support to the cords and, as an hypothesis, enables that only a shorter length of the sample is subjected to the load and to straightening actions. The Parallel clamps don't provide any kind of support and, therefore, the grabbing system has a greater influence on the cords behaviour.

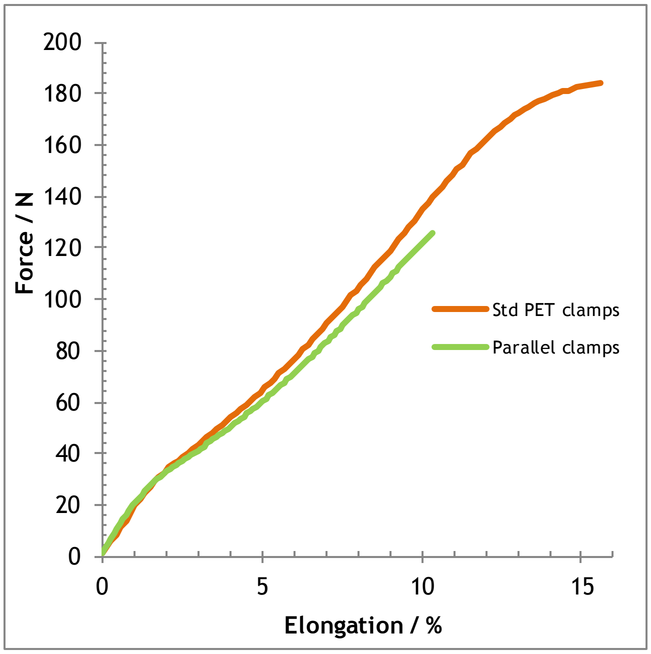


Figure 15 - Force vs. Elongation, PET.1, test speed of 5 mm/s, clamps comparison

Also, as the Parallel clamps grabbing system is provided by manual mechanical action the force and thus the friction put on the edges of the samples varies from test to test. Overall, the force needed to grab the cords with this grabbing system is up to five times greater than with system used with the Std PET clamps.

Thereby, it can be hypothesized that the lower modulus on the stage 2, Figure 15 – Parallel clamps, can be a result of the absence of the said long section that provides support to the cords during the pull. This section allows the cords to be straightened over time without high friction on the cords edges and, therefore, there is no direct influence of the grabbing system.

As this section is not present in the Parallels clamps, once the cords start to be straightened this process happens in the hole length of the sample and this twist action leads to high levels of friction in the cords edges, area where the filaments of the cord start to get damaged over the test time, what promotes earlier breaks.

Looking to the Figures 16 and 17, based on the previous explanations, it is possible to understand the great difference between the elongations at break and breaking forces achieved on the tests performed with the two clamps and the same speeds.

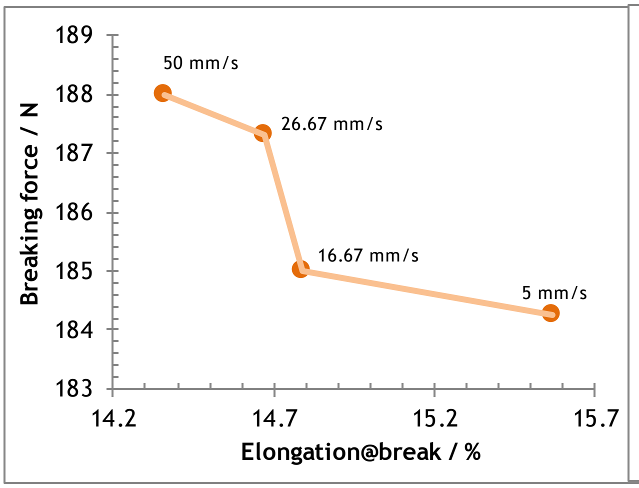


Figure 16 - BF vs. E@BF, PET.1, Std PET clamps

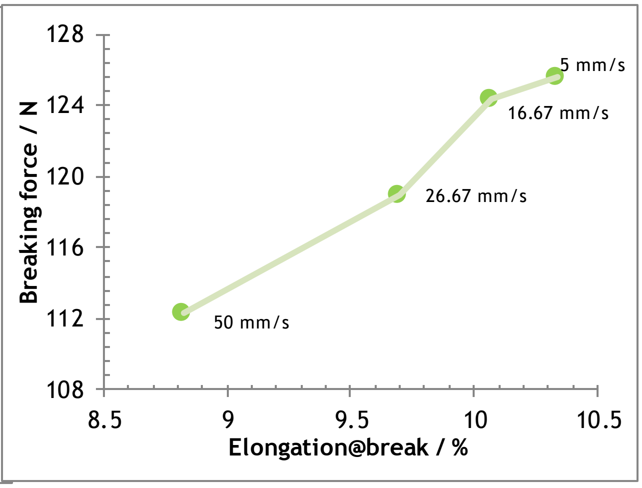


Figure 17 - BF vs. E@BF, PET.1, Parallel clamps

The results observed in the Figure 16 show a loss of elongation at break (*E@BF*) but an increasing of the breaking force with the increasing of the speed. Overall it was observed an increasing of the modulus of the Force *vs.* Elongation curves on the stage 2 and a shorter stage 3 with the increasing speed, Figure 18. With the support of the Figure 19 it was possible to notice that with the increasing of the speed there is needed less time to let the cords get the same level of elongation, what leads to higher instantaneous speeds, and, knowing the modulus in the Figure 18, to subject them to higher forces. Thus, it is possible to hypothesize that if the material is subjected to higher speeds shorter elongation are achieved as a result of a lack of time to the material get completely straight. Therefore, it keeps a certain level of twist that is able to support higher forces than cords with yarns completely straight, Figure 9, and which explain the behaviour seen in the Figure 16 and 18.

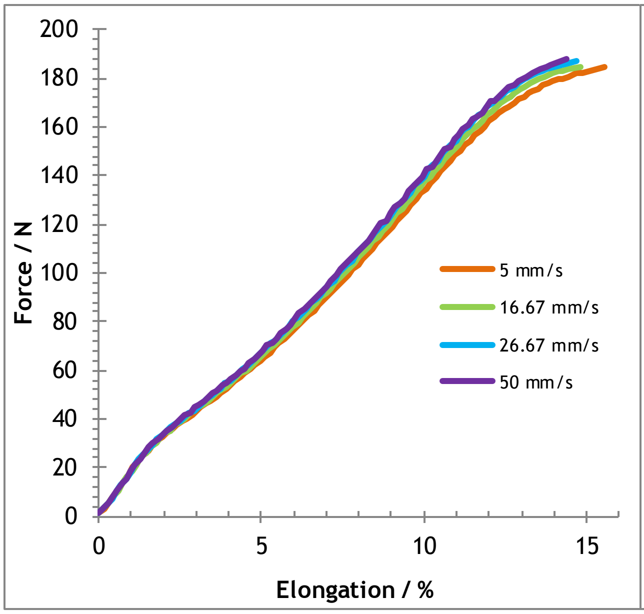


Figure 18 - Force vs. Elongation, PET.1, Std PET clamps

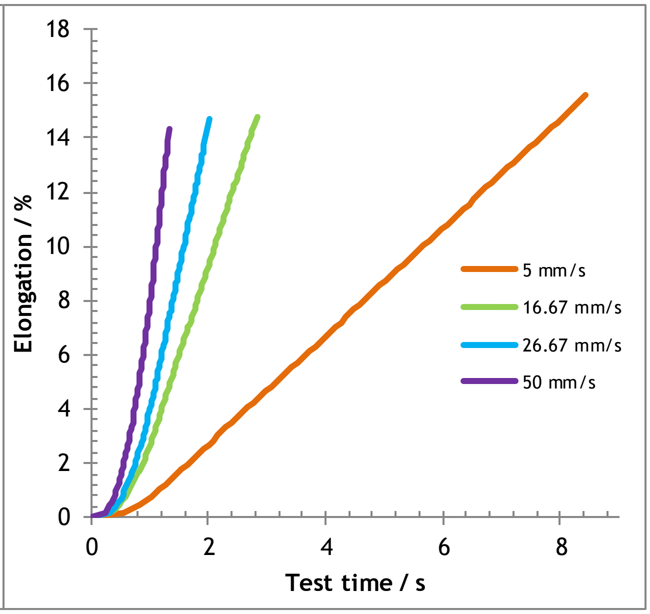


Figure 19 - Elongation vs. Test time, PET.1, Std PET clamps

Focusing on the Figure 17, the behaviours referred in the previous paragraph were also seen in these tests, Figures 20 and 21, but, due to the instability that the Parallel clamps provide to the samples, with the increasing of the speeds the cord edges suffer higher levels of stress and, thereby, the breaking forces and elongations at break achieved are much lower than the expected standard values, already considering its tolerable deviations.

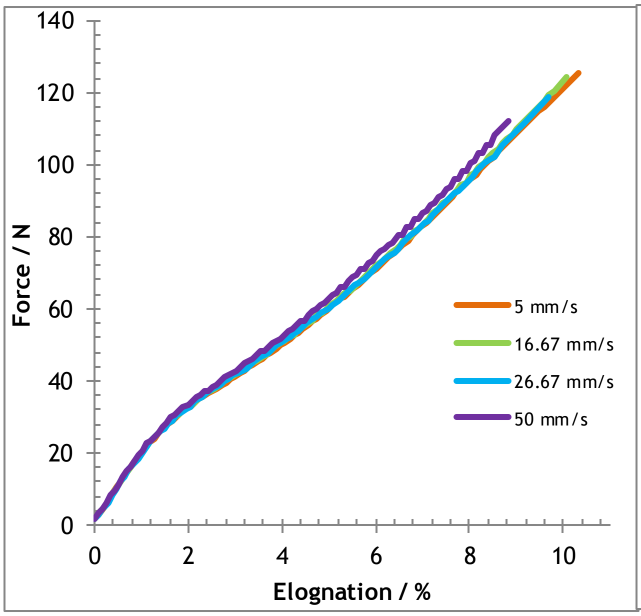


Figure 20 - Force vs. Elongation, PET.1, Parallel clamps

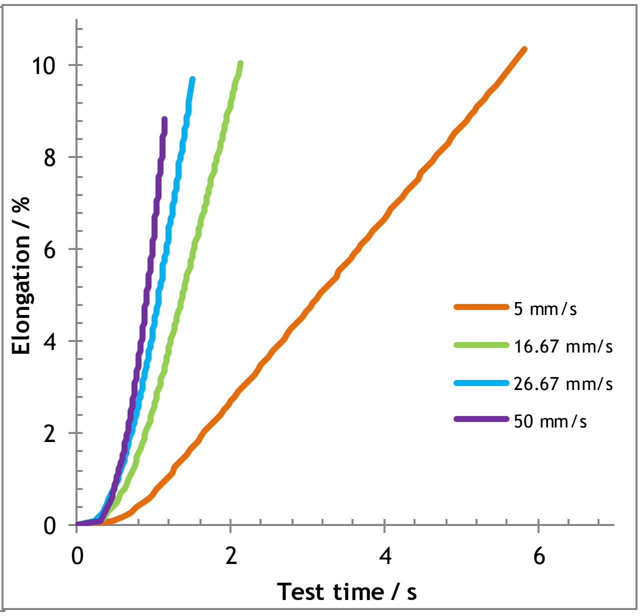


Figure 21 - Elongation vs. Test time, PET.1, Parallel clamps

These results show the huge influence that the clamps have on the test and explain the preference to use the Std PET clamps. On the other hand it is possible that the Parallel clamps, due to the absence of support areas to the cords, may present better results when the real behaviour of the tyres is studied.

4.2 Studies of the cords length influence

The total length of cord possible to be tested corresponds to the total distance between the claws in the clamps, see Figures 12 a), b) and c), and this distance is selected in the controllers interface by defining the clamps S.P.. The S.P. can be considered an important factor during the test performance as this distance can represent the real length of cord that is affected during an impact in a tyre sidewall. These studies were conducted on the Zwick machine.

4.2.1 Std PET clamps

Using the Std PET clamps to test PET.1 samples on the Zwick, due to the dimensions of the clamps, the S.P. allowed to be selected were 250, 325 and 400 mm. The studies of the influence of the S.P. on the Force *vs.* Elongation curves are displayed in the Figures 22 and 23.

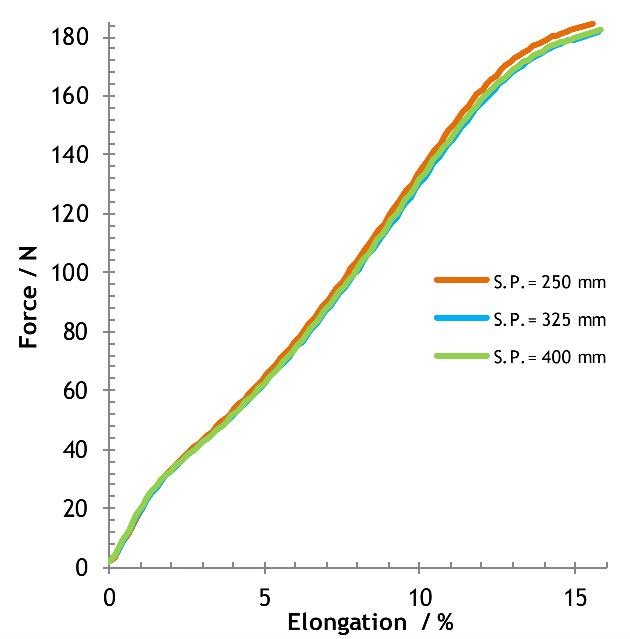


Figure 22- Force vs. Elongation, PET.1, test speed of 5 mm/s

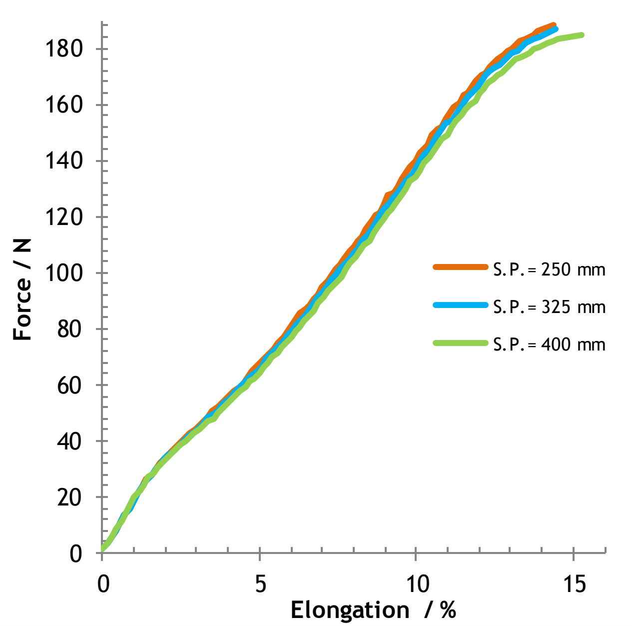


Figure 23 - Force vs. Elongation, PET.1, test speed of 50 mm/s

By the analysis of the Figure 22, standard test speed, it is possible to notice that with the increasing of the S.P. there is a decrease in the curves modulus on the stage 2 of the cord response, which is even clearer in the stage 3. With the increasing of the test speed the same modulus behaviour as a function of the S.P. variation is observed but, as seen in the Figure 23, the results from the S.P.= 400 mm present a greater deviation in terms of force and elongation when compared to the other curves in the Figure 22 and 23. To better understand these results the Figures 24 and 25 are next exhibited.

Observing the breaking forces in the Figure 24 it is visible that they increase with the speed and that the tests of the S.P.= 250 mm are the ones that obtained higher values of breaking forces. Looking to the Figure 25 and relating its results with the ones from the Figure 24 it can be concluded that the higher is the breaking force the shorter is the elongation achieved. In the both charts the S.P.= 400 mm presents an irregular behaviour when compared to the results from the others S.P..

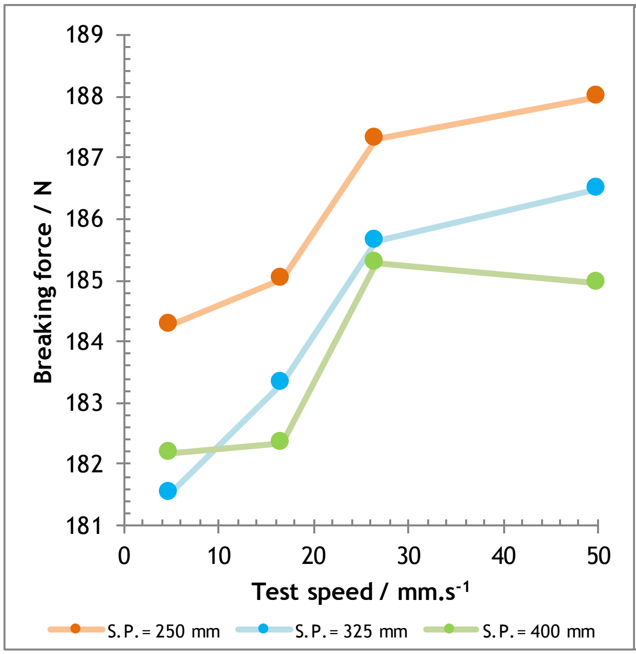


Figure 24 - BF vs. Test Time, PET.1

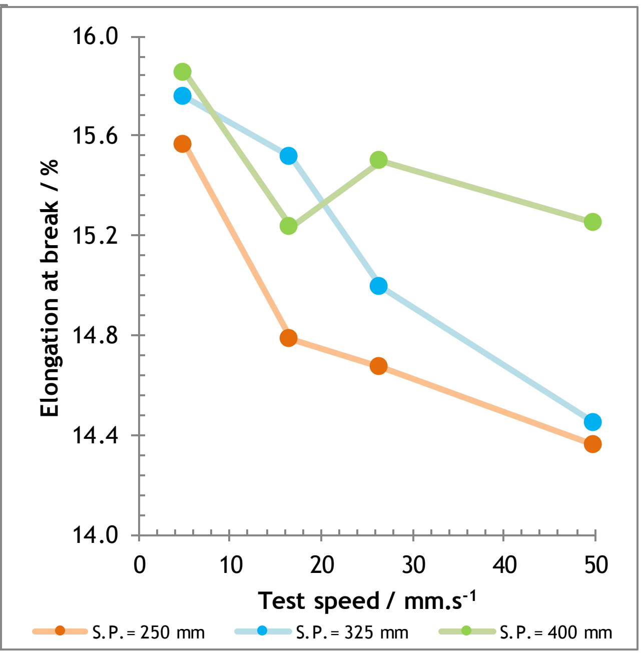


Figure 25 - E@BF vs. Test Time, PET.1

To understand the influence of the cord length on the test speeds the Figures 26 and 27 are presented. In them it is possible to see the evolution of the elongation with the time. Knowing that the curves slope correspond to the speed it is visible that for a value of time, e.g. time = 5 seconds Figure 26, the highest speed is for the test with a S.P. of 250 mm and the slowest is for the S.P. of 400 mm. The same kind of behaviour is seen in the Figure 27 but, looking closely to the both charts, as the speed is increased ten times the curves obtained in the Figure 27 present the exact same shape, but with a greater slope, that is visible in the first four seconds of the curves in the Figure 26. This means that the cords in the Figure 27 suffer the same kind of speed evolution that the cords in the Figure 26 suffered in their initial response stages but in half of the time, i.e. less than two seconds. Overall, longer S.P. implies longer test times that allow the cords to achieve longer elongations.

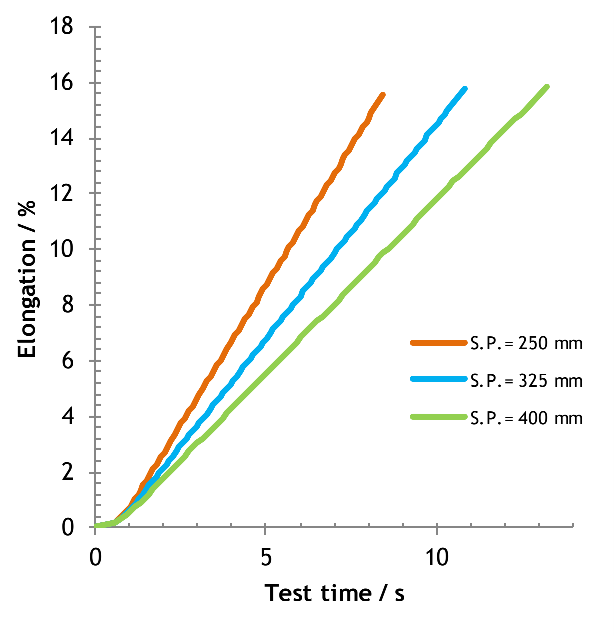


Figure 26 - Elongation vs. Test time, PET.1, test speed of 5 mm/s

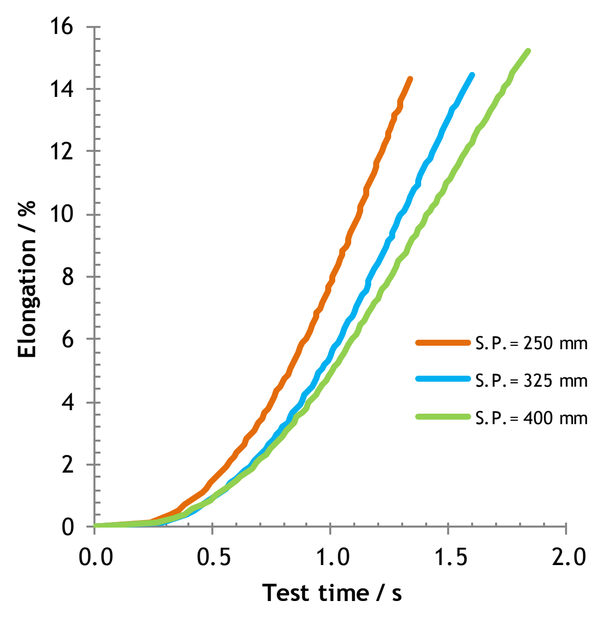


Figure 27 - Elongation vs. Test time, PET.1, speed of 50 mm/s

In general the variation of the instantaneous speeds together with the clamps influences, studied in the previous chapter, provide the results analysed in the Figure 22 to 25. In the particular case of the S.P. = 400 mm the long length between the clamps and the occurrence of small vibrations on the test system, due to the test speeds, could be reflected as vibrations that are propagated as waves along the samples during the test time. These events can be seen as noise in the data achieved and can explain the irregular evolution of values obtained with this S.P. when compared to the other two S.P..

4.2.2 Parallel clamps

As it has been seen in the chapter 4.1 the curves of Force *vs.* Elongation from the samples tested with the Parallel clamps have different modulus and present shorter elongations when compared to the curves obtained with the Std PET clamps. Thereby, the Figures 28 and 29 don't present an unexpected content in terms of curve shape.

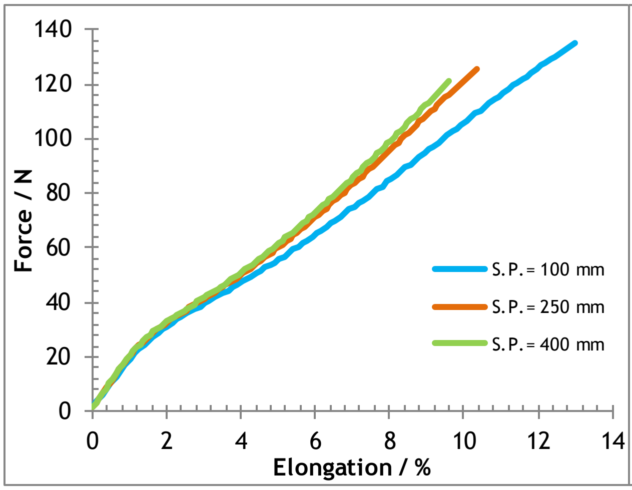


Figure 28 - Force vs. Elongation, PET.1, test speed of 5 mm/s

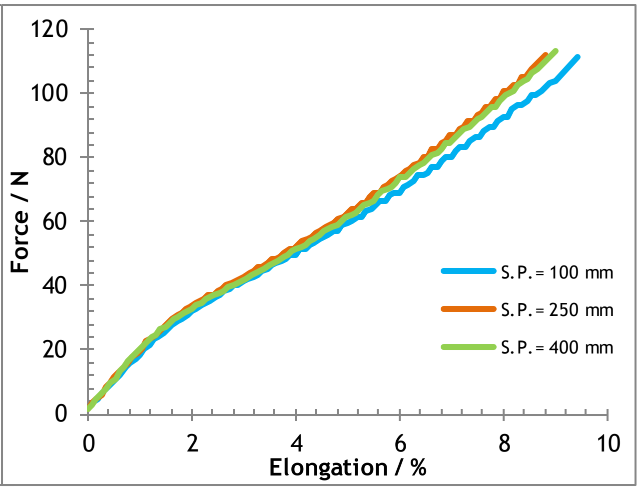


Figure 29 - Force vs. Elongation, PET.1, test speed of 50 mm/s

Evaluating the S.P. influence in the both charts an opposite behaviour is noticeable when comparing these results with the ones in the Figures 22 and 23, chapter 4.2.1. In the Figures 22 the shorter is the S.P. the higher are the breaking forces and the elongations achieved. In the Figure 23 the curves of the S.P. of 250 and 400 mm present a similar behaviour when again the S.P.= 400 mm presents the curve (stage 2) with the lowest modulus.

The same is visible in the Figures 30 and 31 where the results of the S.P. of 250 and 400 mm in general present close behaviours and the results of the S.P.= 100 mm have a deviated response, which is more visible in the case of the standard test speed.

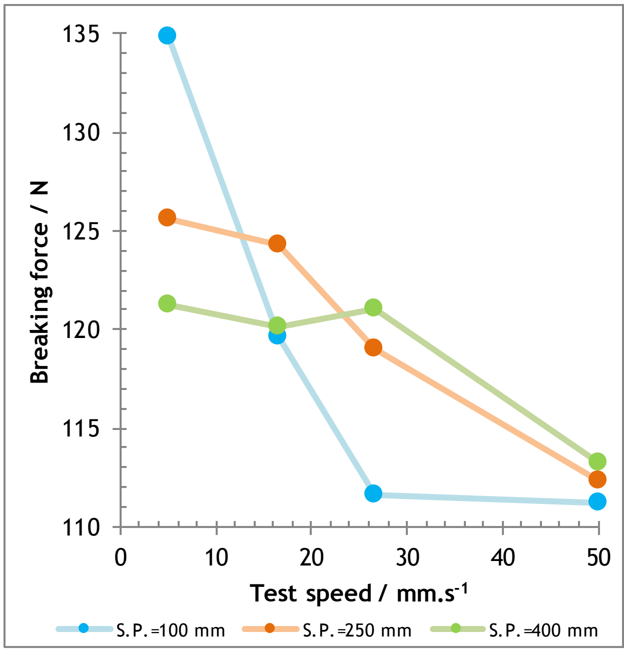


Figure 30 - BF vs. Test speed, PET.1

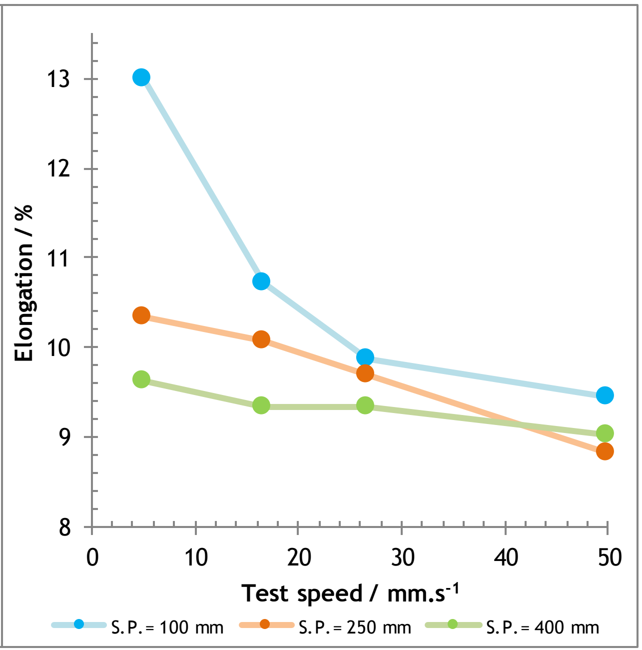


Figure 31 - E@BF vs. Test speed, PET.1

To explain these results an analysis of the Figures 32 and 33 is made. In the Figure 32 the curves that correspond to the S.P. of 250 and 400 present the exact same behaviour (see Figure 72 Annex 2) as seen in the Figure 26, chapter 4.2.1, but an earlier break and the curve of the S.P.= 100 mm shows the expected behaviour in terms of breaking force, when thinking in the analysis of the S.P. influence in the instantaneous speed, made in the just mentioned chapter, but a longer elongation is achieved. In the Figure 33 the same kind of results are shown but in this case there is not such a great similarity between the curves of the S.P. of 250 mm of this Figure and the one in the Figure 27, chapter 4.2.1., as this curve get closer to the curve of the S.P.= 400 mm (see Figure 73 Annex 2).

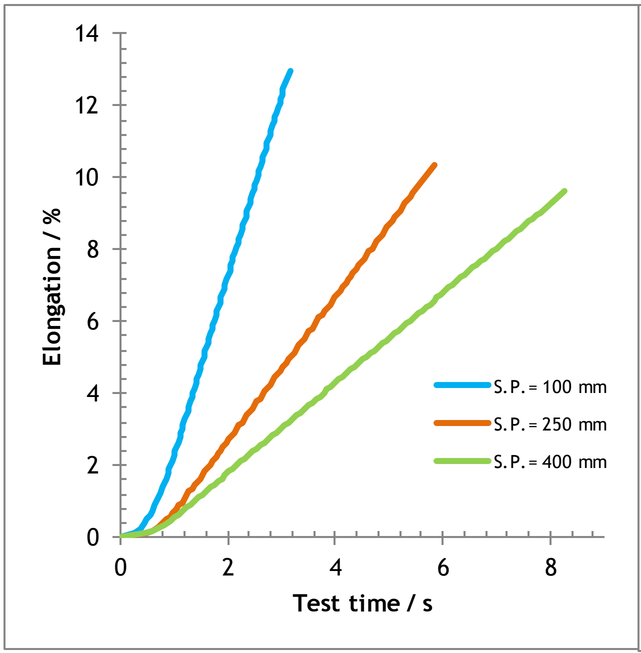


Figure 32 - Elongation vs. Test time of PET.1, speed of 5 mm/s

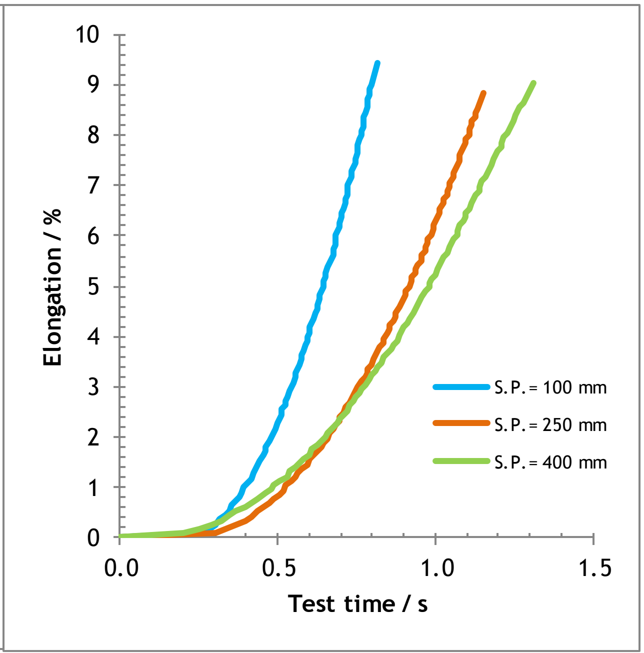


Figure 33 - Elongation vs. Test time of PET.1, speed of 50 mm/s

It can be hypothesized that the Parallel clamps' features, as said in the chapter 4.1, are the ones that lead to the referred shorter elongations achieved and to the irregularity seen in the breaking forces, Figures 30 and 31. The different results obtained to the S.P. of 100 mm can be hypothesized as an outcome of the greater stability that the shorter initial cord length provide to the test system. As said before shorter S.P. reflect less noise and, therefore, better results are achieved.

At last, the greater stability of the elongations at break results, when compared with the values seen in the chapter 4.2.1, is an outcome of the break of the cords on the mentioned curve response stage 2, which normally suffers some variations in its modulus due to the studied variables but these variations are not as significant as the ones visible in the curve response stage 3.

The important facts to retain from this chapter are that the test time decreases with shorter S.P. what promotes shorter elongations at break, and that better results, in terms of noise, are achieved to shorter S.P..

4.3 Studies of the test speed influence

These test speed studies were made on the MTS machine using as testing material PET.1, which was tested with the Parallel clamps due to the characteristic of the machine, and Ar that was tested with the Std Ar clamps because of the material properties.

To understand the influence of the test speed in the curves of Force *vs.* Elongation of the just mentioned materials the results achieved will be presented in the next sections, starting with the analysis of the results from PET.1, passing to Aramid and finishing with a comparison between the two materials.

4.3.1 PET.1, Parallel clamps, S.P.= 250 mm, MTS

Using the Parallel clamps spaced from one another by 250 mm, the PET.1 was tested in the MTS machine using the speeds tabulated in the Table 3, chapter 3. The curves of Force *vs.* Elongation, which shape is close to the ones seen when using the Std PET clamps in the Zwick machine, obtained to these test are presented in the Figure 34.

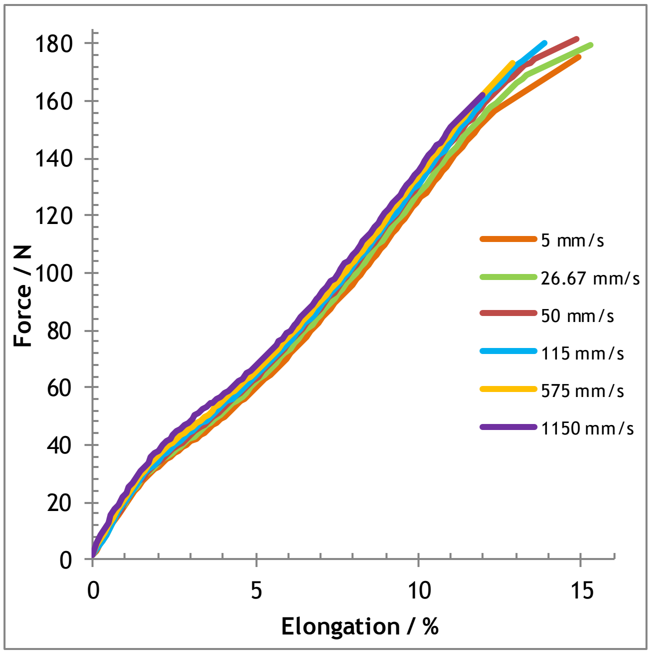


Figure 34 - F vs E, PET.1, S.P.= 250mm

To make the visualization easier of the speed influence in the curves of Force vs. Elongation, in the Figure 34 are only represented 6 of the 16 speeds tested mentioned on the Table 3. Thus it is possible to observe that, considering the stage 2 of response of the Force *vs.* Elongation curve, with the speed there is an increasing of the curve modulus and it is visible a great influence of the test speed in the breaking forces and elongations at break (Figure 74, Annex 2). There is visible a variation of around 20 newton and 3 % of cord elongation between the higher and lower values achieved.

To clarify and explain the results observed in the previous chart the Figures 35 and 36 are next exhibited.

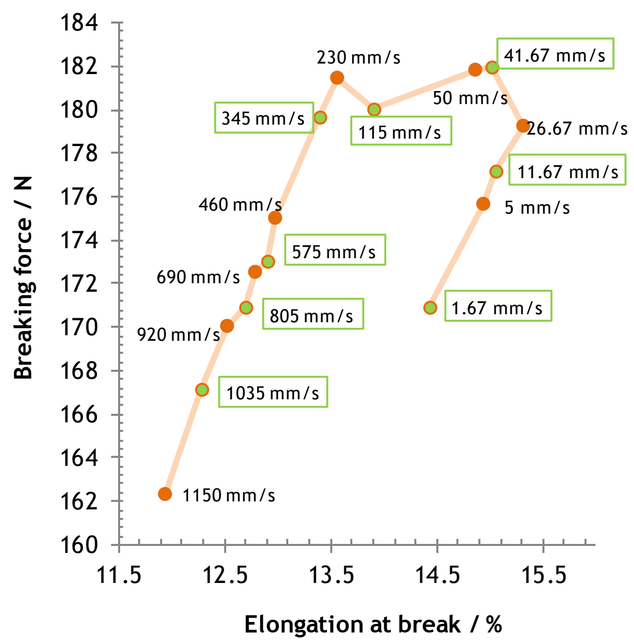


Figure 35 - BF vs. E@BF, PET.1, S.P.=250 mm

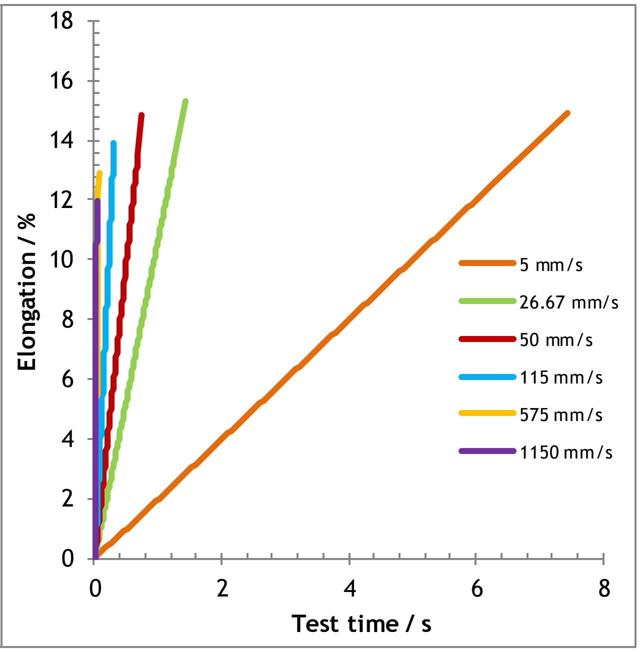


Figure 36 - Elongation vs. Test Time, PET.1, S.P.=250 mm

Analysing the Figure 35 it is possible to notice that the breaking force increases till the speed of 41.67 mm/s where it achieves its highest value, from that speed till the 230 mm/s there is a fluctuation of values and lately the breaking force start to decrease until it achieves its lowest value at 1150 mm/s.

In the Figure 36 the Elongation *vs.* Test time results shows that, with the increasing of the test speeds, less time is needed to achieve the same level of elongation and, therefore, the instantaneous speeds observed are greater. Thus, the results observed in the Figure 36 are consistent with the ones seen in the chapters 4.1 and, thereby, the hypothesis related with the levels of twist achieved by the cords at the end of the tests can be used to explain the results seen in the Figures 34 and 35.

Before explaining the evolution of the breaking forces and the elongations at break it is important to take into account that these tests were performed with the Parallel clamps in the MTS. This machine has a different kind of operation and a load cell with a lower level of sensitivity, this when compared with the Zwick machine and its load cell, thus new factor are influencing the collected data. Thereby, it can be hypothesized that the variations of less than 1 % seen in the elongations at break, achieved to speeds up to 26.67 mm/s, can be an outcome of the low precision of the data acquisition system considering the range of elongations in study. And the fluctuations on the breaking force seen for the speeds between 41.67 mm/s and 230 mm/s can be caused by the clamps grabbing system or by the low precision of the load cell to the range of forces in work. It can also be hypothesized that to lower speeds, as the material is subjected to load forces for a longer period and twist actions in a greater extension, the grabbing system of the clamps will have a greater influence on the results achieved than in the results that are reached at higher speeds. And overall the shape of the curves obtained in the Figure 34 can be the result of the sum of all the pointed factors.

Considering the just mentioned hypothesis it can be supposed that, without the referred factors, the PET.1 until speeds up to 115 mm/s would present a behaviour close to the ones seen in the Figures 16 or 17 and 18 or 20, chapter 4.1, depending in the type of influence that the machine operation could have on the results collected.

To speeds higher than 115 mm/s it can be hypothesized, as in the chapter 4.1, that as the instantaneous speed increases less time is given to the material to get straightened and, therefore, lower levels of elongation are achieve. Thus, considering the content seen in the Figure 9, chapter 2, the level of twist that the cords keep to the speeds tested is not the optimum what leads to lower values of breaking force. To prove this theory several cords with different levels of twist could be tested at every required speed to evaluate if an optimum level of twist, or close to it, is achieved in the cases studied.

4.3.2 PET.1, Parallel clamps, S.P.= 100 vs 250 mm, MTS

The studies made in the chapter 4.2 are only for relatively slow tests speeds. Thereby, as the MTS allows studying speeds 23 times greater than the ones analyzed in the Zwick tests, the PET.1 was also tested using a S.P. of 100 mm and the test speeds presented in the Table 3, chapter 3. The comparison between these results and the results analyzed in the previous section, which were obtain by tests performed under the same conditions but with a S.P.= 250 mm, are presented in the Figures 37 to 40.

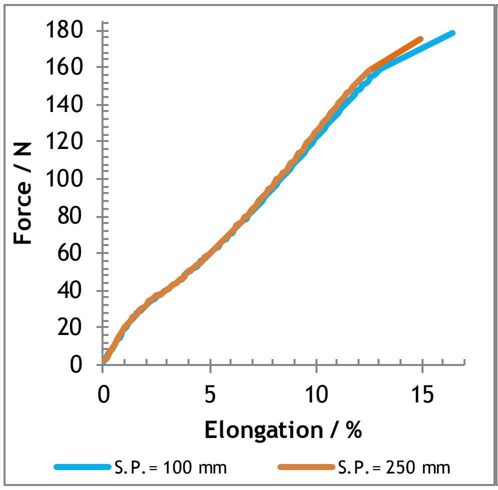


Figure 37 - Force vs. Elongation, PET.1, speed of 5 mm/s

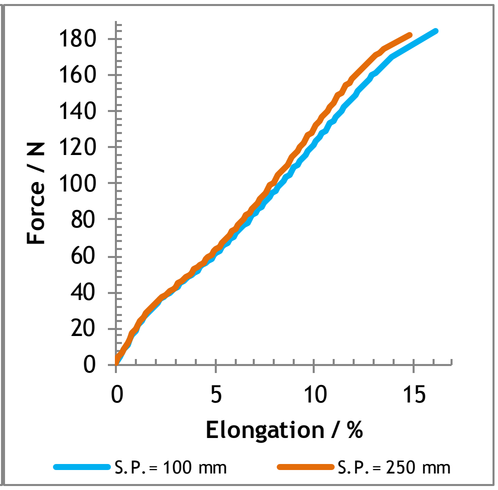


Figure 38 - Force vs. Elongation, PET.1, speed of 50 mm/s

As it is possible to see in the Figures 37 and 38 to the speeds of 5 and 50 mm/s the results present a mixed behaviour as the curve shape is the one normally achieved to the Std PET clamps, as it has been noticed in the previous chapter, and the S.P.= 100 mm provide the results with higher values of breaking forces and elongation at break. These results can be explained by the arguments, presented in the Section 4.2, concerning to the stability that shorter S.P. provide to the test system.

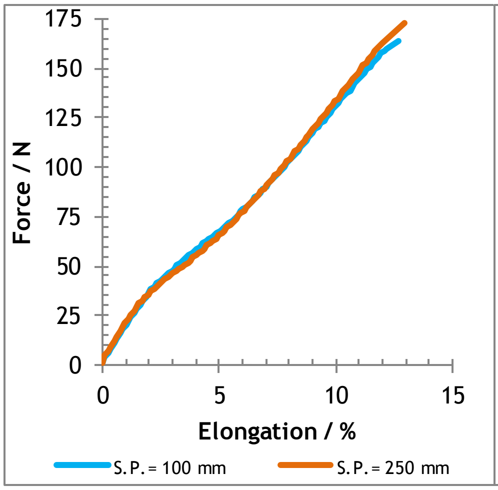


Figure 39 - Force vs. Elongation, PET.1, speed of 575 mm/s

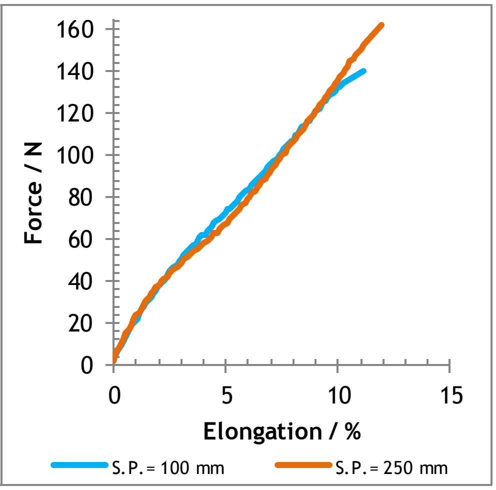


Figure 40 - Force vs. Elongation, PET.1, speed of 1150 mm/s

Analysing the curves of Force *vs.* Elongation shown in the Figures 39 and 40 it can be hypothesized that, when high speeds are tested, the influence of the instantaneous speed on the material behaviour, content already explained in previous chapters, overlap the stability that the shorter S.P. provides to it. This happens because the test times observed with the S.P.= 100 mm will be shorter than to one with a S.P. of 250 mm (see Annex 2 Figures 75 and

76), what leads the cords with a shorter initial length to present lower breaking forces and shorter elongations at break, and overall different material responses during tests. Thereby, the higher is the test speed the more visible are the differences between the curves responses from the two S.P..

To present the evolution of the Breaking Force *vs.* Elongations of the two S.P., with the test speed, the Figure 41 is next presented.

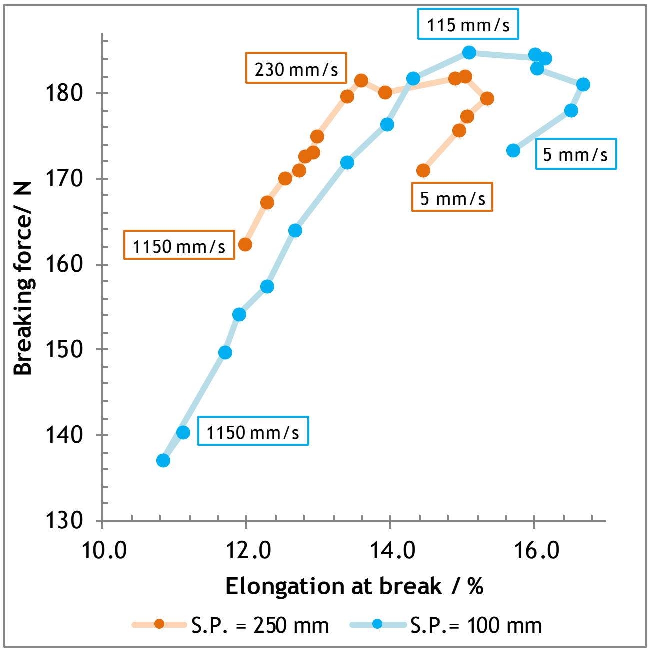


Figure 41 - BF vs. E@BF, PET.1, S.P. comparison

Only the lowest, one intermediate, and the highest speeds tested were labelled in the Figure 41 in order to indicate the direction of the speed evolution in the chart and at the same time to allow a better focus on the results.

By comparing the two curves it is possible to conclude that, to relatively low speeds, the results prove the theory that a S.P. of 100 mm provides a better stability to the test system. This because the initial evolution of the breaking force is, comparatively with the results from the S.P.= 250 mm, more regular and the values of elongation achieved are higher.

When the breaking forces start to decrease, a big discrepancy between the results from the two S.P. is observed and, thus, the analysis of the Figures 39 and 40 is supported. This proves that the teste speed, or in other words the instantaneous speed (when considering a same level of elongation), has a great influence in the cords responses.

4.3.3 Aramid, Std Ar clamps, S.P.= 250 mm, MTS

Regarding to Aramid the full study of the test speed influence in the curve of Force *vs.* Elongation of this material was performed with the Std Ar clamps, in the MTS machine, testing the speeds tabulated in the Table 4. Some of the curves of Force *vs.* Elongation obtained during the studies are presented in the Figures 42.

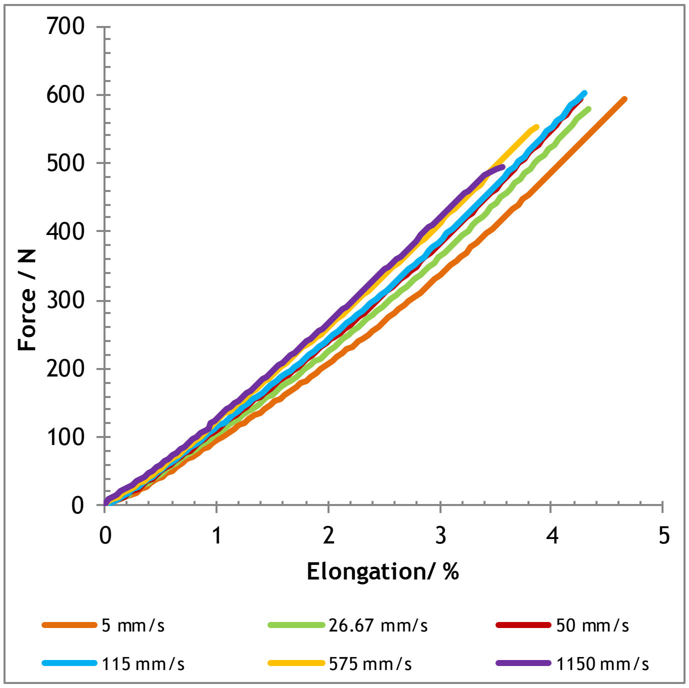


Figure 42 - Force vs. Elongation, Aramid

By the analysis of the Figure 42 it is possible to notice that with the increasing of the speed the curves modulus increases and, thereby, the curves slope gets close to linear. It is also visible that to high speeds the last stage of the Force *vs.* Elongation curve presents an irregular shape.

The first observation of the Figure 42 can be explained by the already mentioned hypothesis that says that with the increase of the instantaneous speed the samples are able to achieve higher levels of elongations earlier and, therefore, as the test time present a much shorter duration, see Figure 44, it is possible to suppose that the cords maintain certain levels of twist. The highest is the test speed the higher is the level of twist that the cords keep what, considering the content of the Figure 9, leads to lower breaking forces, as these levels of twist probably are not the optimum to, a material with a high level of crystallization as Aramid, support each speed tested. The Figure 43 supports the relation between the low elongation at break and low breaking forces achieved when the material is subjected to high speeds.

The second observation of the Figure 42 can be explained by the fact that with the high test speeds it is possible to observe not only the cords behaviour but also the filaments behaviour. This irregular curved shape at the end of the Force *vs.* Elongation curves it is a normal outcome from the break of the cord filaments at the end of the tests. Usually it is not possible to see because there is no enough data recorded, as the recording system stops when the cord breaks, but with a higher test speed more events are possible to be registered.

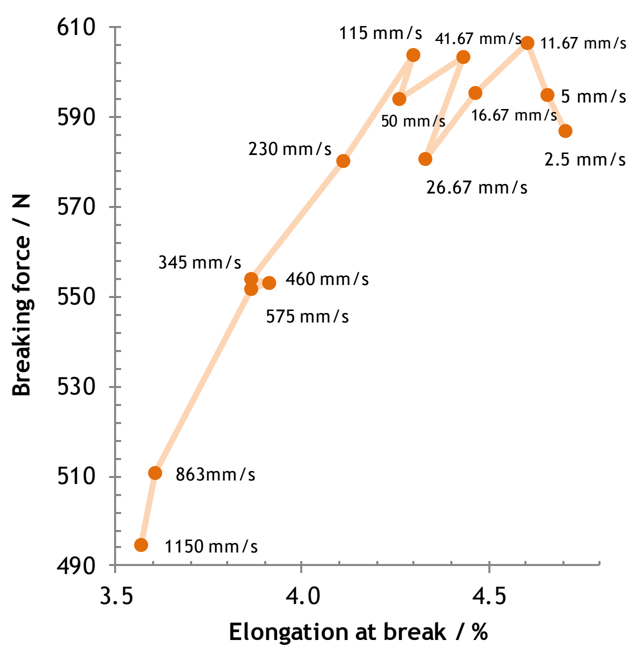


Figure 43 - BF vs. E@BF, Aramid, S.P.= 250 mm

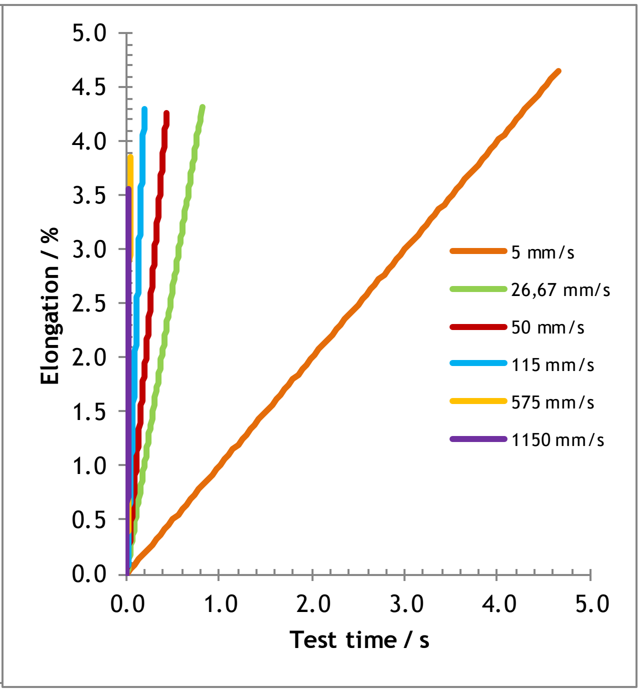


Figure 44 - Elongation vs. Test time, Aramid, S.P.= 250 mm

Looking to the Figures 43 and 44 it is noticeable that until the speed of 115 mm/s there is not a regular evolution of the cords elongation at break and breaking forces. In general, this variation in the cords response with the test speed can be hypothesized as a result of the machine characteristic and mode of operation and also as a variable response of the material according to the test speed and the different levels of twist maintained by the cords, which must be furthered studied to be better understood.

An interesting point to be noticed is that the elongation at break lost from the lowest to the highest speed is lower than 1.5 %, but to previous stages of the material response the loss of elongation is even lower, Figure 77 Annex 2. While there is a loss of around 111 newton between the higher and lower values achieved to the BF.

4.3.4 PET vs Aramid, S.P.= 250 mm, MTS

To compare the influence of the test speed in two materials with different modulus and crystalline structures, such as PET and Aramid, the Figures 44 to 46 are exhibited in this section.

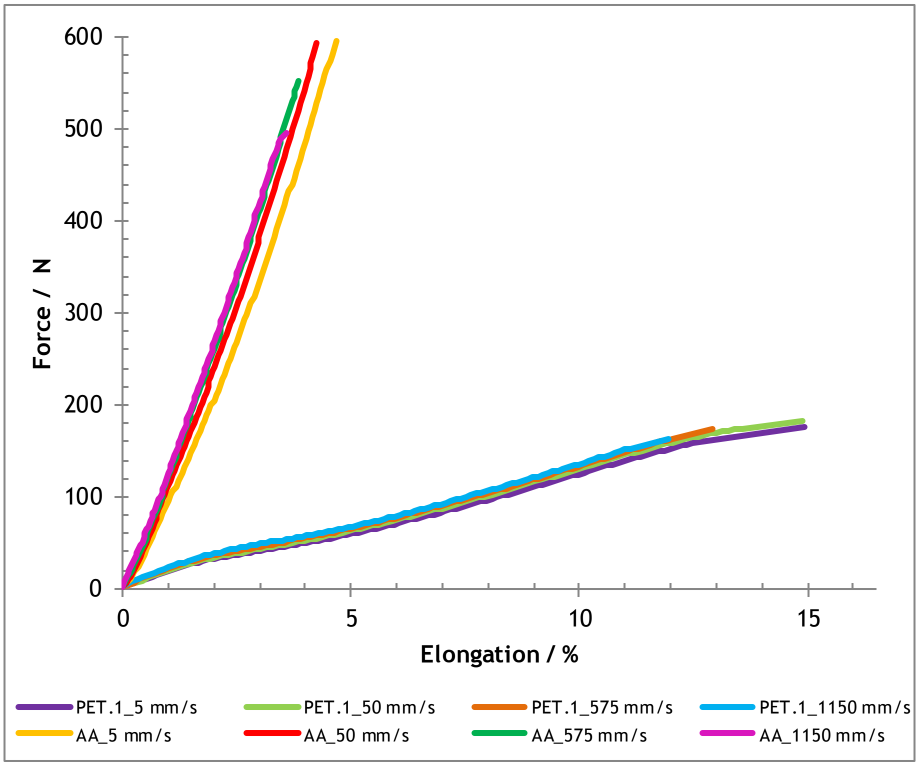


Figure 45 - Force vs. Elongation, PET.1 vs. Aramid, S.P.= 250mm

The Figure 45 is presented to highlight, despite of the test speed, the higher elongations and lower forces supported by the PET, due to its semi-crystalline structure, and the Aramid crystalline structure that allows the material to support higher forces but to be strained for a shorter elongation.

To compare the influence of the test speed on the both materials, Figures 45 and 46, a normalization of the values of the breaking forces and of the elongation at break was made. To perform these normalizations the values of breaking force and elongation at break used were the ones obtained to the speed of 5 mm/s to each material.

Overall, looking to the Figures 45 and 46, it is possible to verify that the test speed has a greater influence on the Aramid behaviour in terms of breaking force, loss of about 111 N to Aramid and 20 N to PET, while in terms of elongation of break the test speed influence is close between the two materials, even though it is still more visible to the Aramid cords.

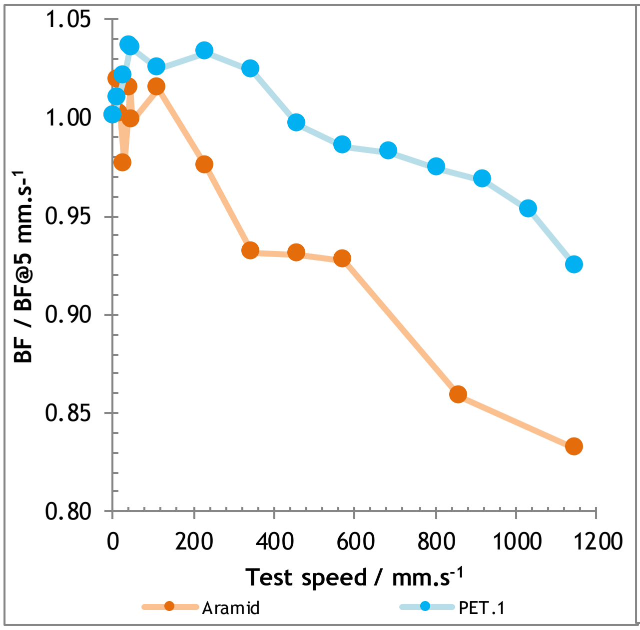


Figure 46 - Normalized values of BF, PET.1 vs. Aramid

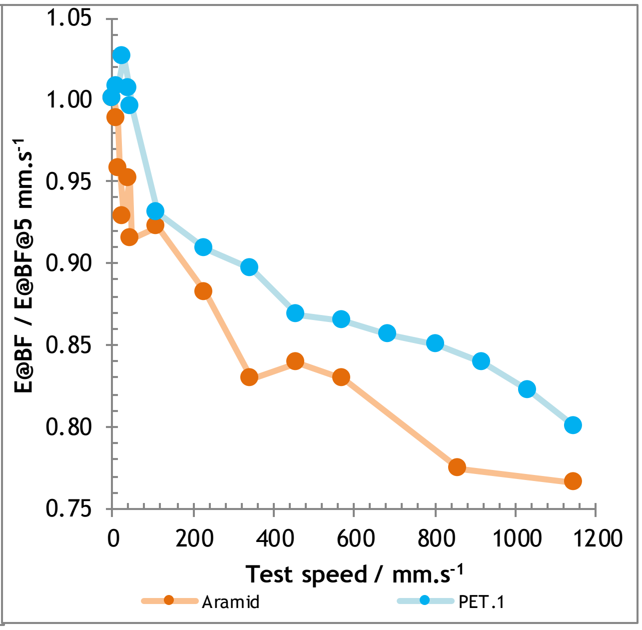


Figure 47 - Normalized values of E@BF, PET.1 vs. Aramid

The cause of this greater influence of the test speed on Aramid must be better studied. Although, it could be hypothesized that the Aramid's crystalline structure when compared to the PET structure could be more susceptible to twist changes, once it normally supports lower levels of elongation the greater difficulty to straight the cords could present a huge influence on the material behaviour. In other words, as Aramid presents a high level of crystallinity if it is elongated it will break soon because it will get more brittle and the material won't be able to respond to high speeds. In other hand, PET with its amorphous structure may dampen the speed influence.

4.4 Studies of the influence of the machines on the results achieved

If the results from the previous chapters are compared it is be possible to notice that, even though the same kind of clamps has been used when testing the same speeds under the same room operation conditions, there is a deviation in the modulus, force and elongation values obtained in every tests. Therefore, this chapter will be used to show these differences between the values and to try to understand what could be the reason that is causing these variations.

4.4.1 Zwick *vs.* MTS: analysis of the results obtained with the same clamps

The first step to compare the two machines is to verify how noticeable the differences between the results obtained with both of them are. Thus, using the results obtained for three different speeds the Figures 48 to 56 exhibit the deviations observed between the same kinds of test performed in the two machines.

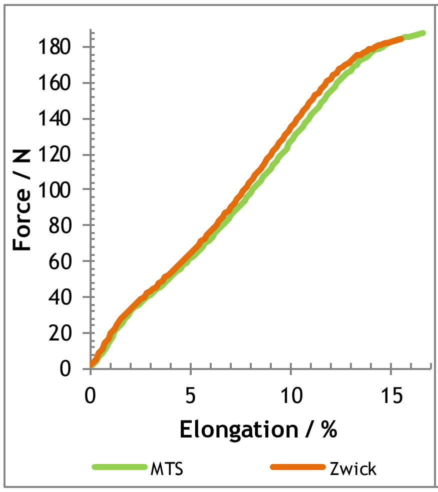


Figure 48 - Force vs. Elongation, speed of 5 mm/s, Std PET clamps

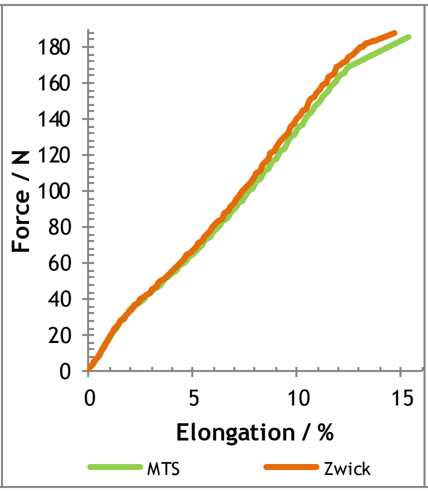


Figure 49 - Force vs. Elongation, speed of 26.67mm/s, Std PET clamps

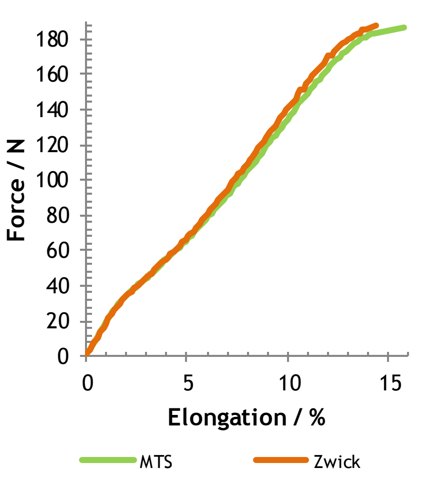


Figure 50 - Force vs. Elongation, speed of 50 mm/s, Std PET clamps

Observing the Figures 48 to 50, the major differences between the results obtained with the Std PET clamps are on the curve modulus, regarding to its step 2 in the MTS results, which are lower to every speed tested and the elongation levels at break are higher, about 1 to 2 %.

Regarding to the Parallel clamps, Figures 51 to 53, a big difference between the results obtained is visible. While in the Zwick the cords break before achieving the curve stage 3, when the cords are tested in the MTS they break during the just mentioned curve response stage.

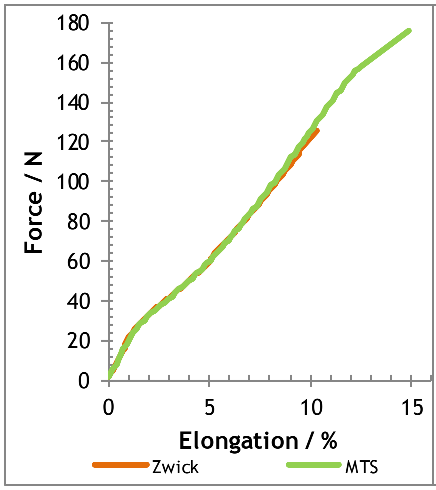


Figure 51 - Force vs. Elongation, speed of 5 mm/s, Parallel clamps

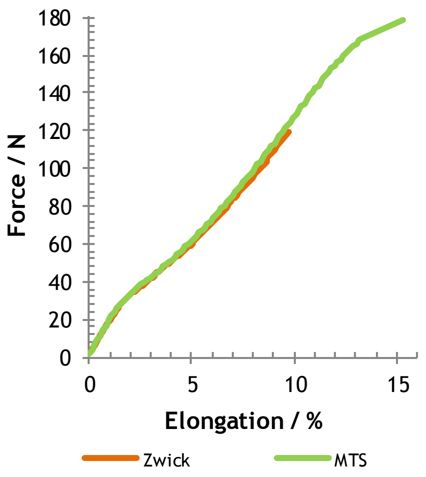


Figure 52 - Force vs. Elongation, speed of 26.67 mm/s, Parallel clamps

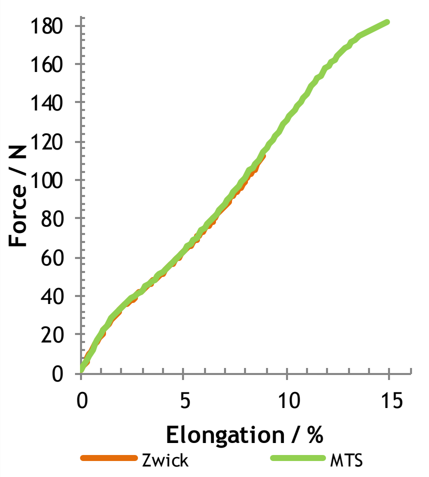


Figure 53 - Force vs. Elongation, speed of 50 mm/s, Parallel clamps

This allows the cords tested with the MTS machine to achieve the expected standard values of breaking force and elongation.

Observing the results from the Std Ar clamps, Figures 54 to 56, looking to the standard test speed of 2.5 mm/s used to test the Aramid cords no big differences are observed between the results achieved with the two machines. However, with the increasing of the speed a higher modulus stars to be visible to the results achieved with the MTS machine and at the same time higher levels of elongation and greater values of breaking force are reached. Thus the results from the MTS reveal a better answer from the Aramid cords to the test speeds.

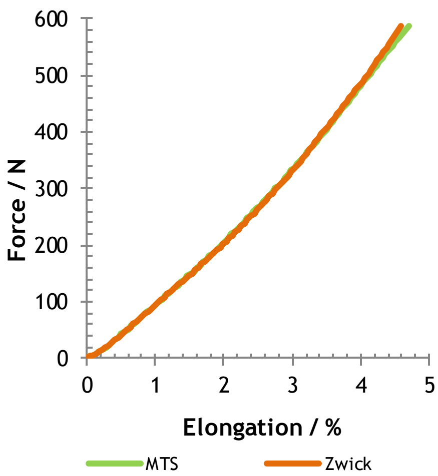


Figure 54 - Force vs. Elongation, speed of 5 mm/s,Std Ara clamps

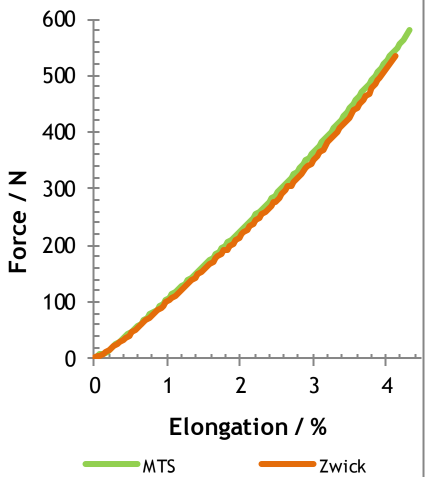


Figure 55 - Force vs. Elongation, speed of 26.67 mm/s, Std Ara clamps

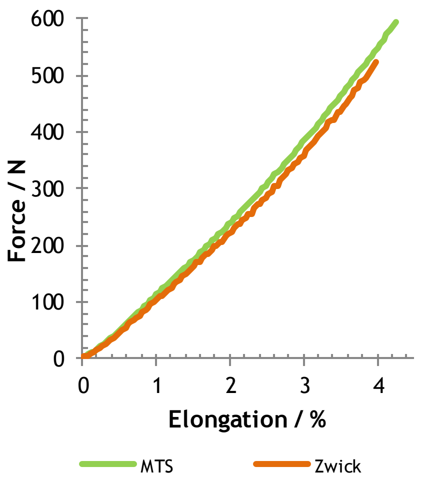


Figure 56 - Force vs. Elongation, speed of 50 mm/s, Std Ara clamps

Concerning to the complete results comparison it is possible to conclude that the MTS machine provides better results than the Zwick machine, but the cause to this fact is not known. Thereby, first it is needed to understand if there was any problem in the tests performed in the Zwick machine and after, if a negative answer is achieved, different hypothesis must be studied. In any case, the desired high test speeds are only achieved on the MTS.

4.4.2 Comparison between Zwick machines

To understand if any mistake was made during the tests or if the Zwick machine used had any failure in it system, some speeds were retested in two different Zwick machines. Due to the test speed limits that each one of them was able to execute, the test speeds retested were 5, 11.67 and 16.67 mm/s.

To differentiate the three Zwick machines used to perform these studies they will be named as ZM3 (Zwick machine used to perform all the studies), ZM1 (Zwick machine also available to perform tests in the Reinforcement laboratory) and ZMLou (Zwick machine used to perform studies at C-ITA).

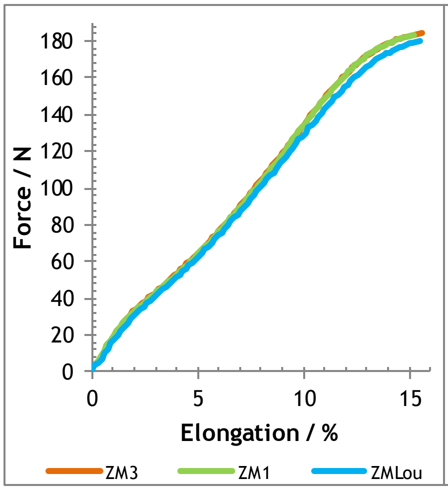


Figure 57 - Force vs. Elongation, speed of 5 mm/s, Std PET clamps

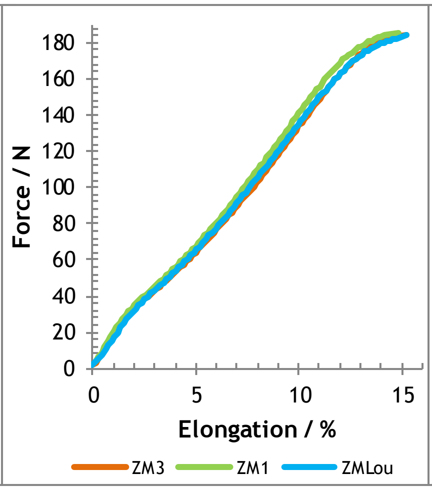


Figure 58 - Force vs. Elongation, speed of 11.67 mm/s, Std PET clamps

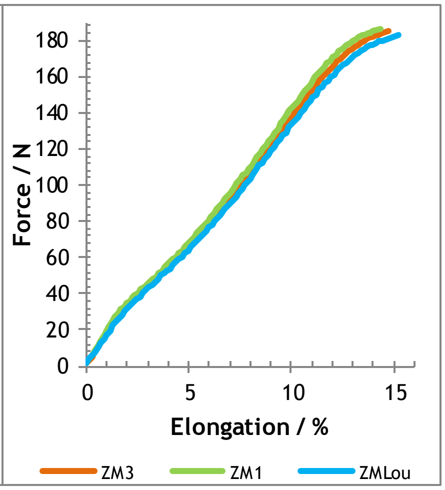


Figure 59 - Force vs. Elongation, speed of 16.67 mm/s, Std PET clamps

As it is possible to see from the Figures 57 to 59 the ZM3 has a close behaviour to the other two Zwick machines. Even though some deviations are verified they can be justified by the fact that they are three different machines with different features. Therefore, it can be concluded that there weren't any mistakes or failures during the tests performed with the ZM3. Thus it is needed to verify which other factors can be causing the different results obtained with the Zwick and MTS machines.

4.4.3 Comparison between the MTS and Zwick machines operation modes

By the time spent working with the machines and the analysis of their results the major difference noticed between the MTS and Zwick operation mode was in terms of the test speed evolution over time.

Looking to the Figure 60, which results were obtained using a S.P. of 250 mm and the Parallel clamps, knowing that the slope of the curves correspond to the Test speed (%/s) it is possible to conclude that, as the slopes from the two machines, to each speed, are really close to each other, the final test speed to which the cords are subjected is approximately the same.

It is also noticeable that with the increasing of the test speed the shorter is the time that the MTS needs to achieve the stipulated test speed when compared with the Zwick. And thereby the MTS provides higher instantaneous test speeds that, as mentioned before, can influence the material response.

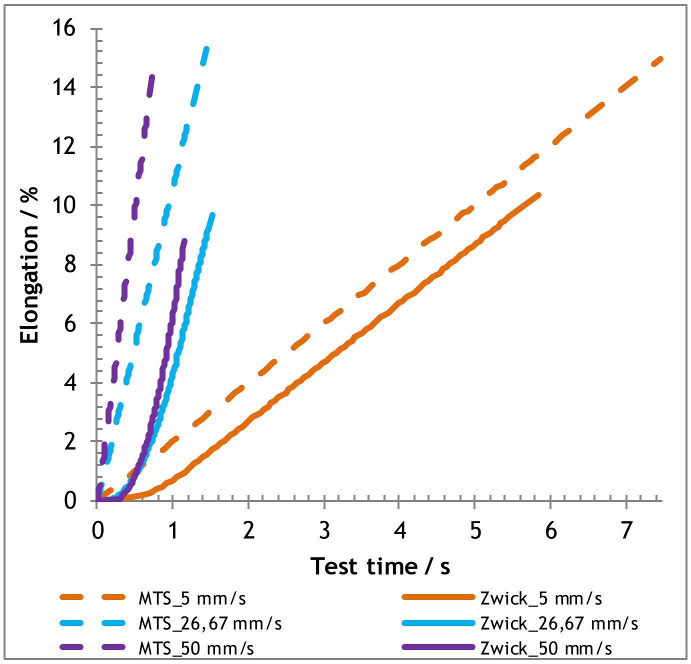


Figure 60 - Elongation vs. Test time, Aramid, S.P.= 250mm, Parallel clamps

The results presented are from the Parallel clamps but the results from the Std PET clamps present the same kind of variations. The only motive to choose the results from these clamps was to provide a better view of the results, that because the ones from the Std PET clamps presented a lot of noise due to the Std PET clamps weight and the average calculations performed.

The analysis just made is better illustrated in the Figures 61 to 63.

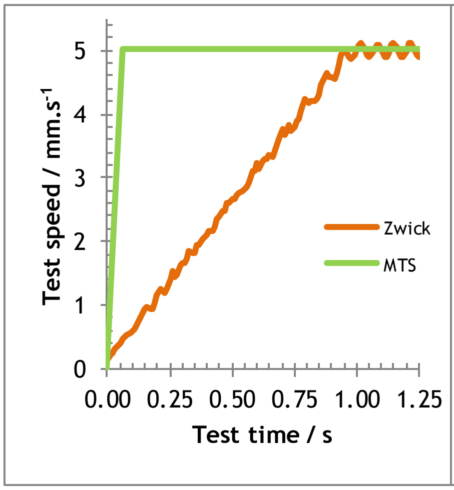


Figure 61- Test speed vs. Test time, speed of 5 mm/s, S.P.= 250 mm, Parallel clamps

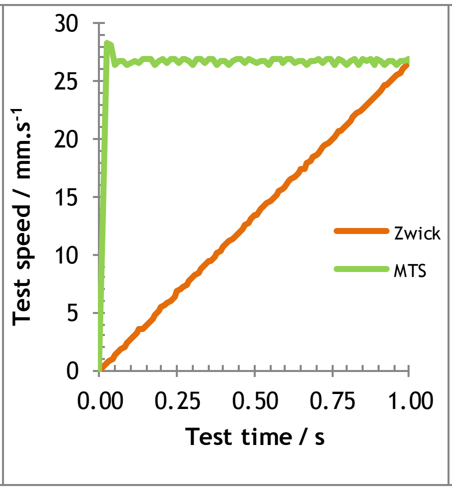


Figure 62 - Test speed vs. Test time, speed of 26.67 mm/s, S.P.= 250 mm, Parallel clamps

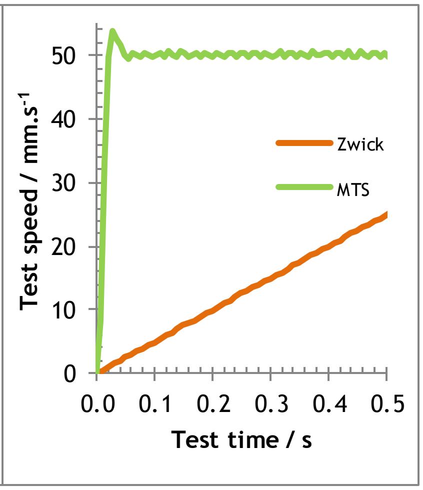


Figure 63 - Test speed vs. Test time, speed of 50 mm/s, S.P.= 250 mm, Parallel clamps

In the Figures 61 to 63 it is visible that the MTS achieves the test speed in periods of time as short as 0,1 seconds while the Zwick machine needs more than about 1 second to achieve one of the slowest speeds tested. This difference in the time needed to achieve the test speed, or in other words the acceleration observed during the tests, depends on the machine operation mode and thus, as the MTS is a pneumatic machine controlled by a servohydraulic system, it is expected that the MTS has lower times of response when compared with the Zwick, as it is observed.

Overall, the differences in the time that it takes to the machines to achieve the supposed test speed and therefore the instantaneous speeds, over time, can be hypothesized as the major factors that lead to the different results observed with the two machines.

Focusing on the tests time, results from the Std PET clamps, it was observed, Table 5, that the test times recorded with the MTS, when compared with the ones from the Zwick, are closer to the values of test time predicted with the theoretical formula 1.7 present in the Annex 1.

Table 5 - Comparison between the real and theoretical test times

Machine	Test speed [mm/s]	Test time [s]	Theoretical test time [s]	Machine	Test speed [mm/s]	Test time [s]	Theoretical test time [s]
Zwick	5	8.45	7.78	MTS	5	8.31	8.31
	26.67	2.03	1.38		26.67	1.44	1.44
	50	1.34	0.72		50	0.80	0.79

This reveals that the MTS machine has an operation mode closer to the theoretical expected, when considering the operation test speed and the cords elongation at break.

In terms of a real impact in a tyre sidewall during a tyre service it may be expected a time of impact of around 2 milliseconds and an elongation of the PET reinforcement cords of around 10 millimetres. In the tests performed with the MTS the values presented in the Table 5 were achieved. To better visualize these results the Figures 78 and 79, Annex 1, represent these values in a graphic way and allow comparing the results achieved with the MTS and the Zwick machines.

By the analysis of the time of impact and variation of cord length achieved for the speed of 1150 mm/s and S.P. of 100 mm, it can be concluded that with the MTS it was almost possible to achieve the values of a real impact. However, higher speeds must be tested to reproduce the cords response in the reality but for that a different machine should be used.

Table 6 - Values of time of impact and variation of cord length achieved in the MTS tests

S.P. [mm]	Test speed [mm/s]											
	5		26.67		50		115		575		1150	
	Time of impact [ms]	Δ Cord length [mm]	Time of impact [ms]	Δ Cord length [mm]	Time of impact [ms]	Δ Cord length [mm]	Time of impact [ms]	Δ Cord length [mm]	Time of impact [ms]	Δ Cord length [mm]	Time of impact [ms]	Δ Cord length [mm]
100	3293.9	41.2	605.3	40.0	328.1	40.3	138.1	37.7	29.8	31.6	18.7	27.7
250	7459.5	37.3	1437.8	38.3	749.2	37.2	308.5	34.8	64.5	32.3	34.7	29.9

Overall it can be concluded that, for the machines available at Continental, the MTS is the machine that can provide better results when the tests' objective is to reproduce the cord response in a real situation.

4.5 Influence of the twist level on the results achieved

The method selected to evaluate if the machine acceleration systems actually have an effect in the results achieved was based on the understanding of the cords twist level effect in the cords responses achieved with the MTS and Zwick machines.

Therefore, the Figures 64 to 69 introduce the studies about the influence of the twist level, cords constructions presented in the Table 1, in the results achieved with the two machines.

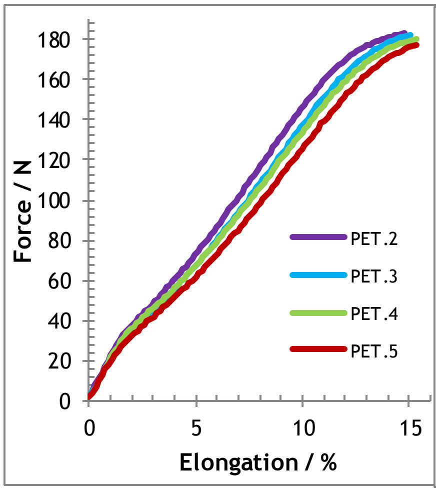


Figure 64 - Force vs. Elongation, speed of 5 mm/s, Zwick

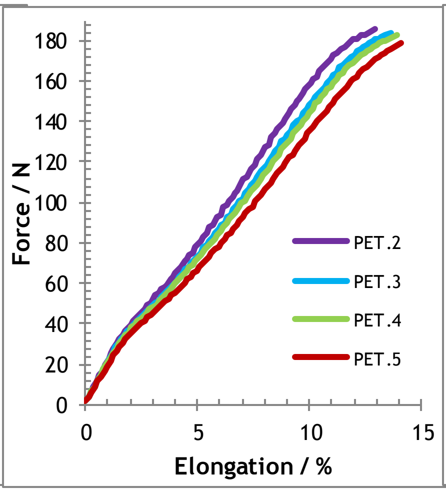


Figure 65 - Force vs. Elongation, speed of 26.67 mm/s, Zwick

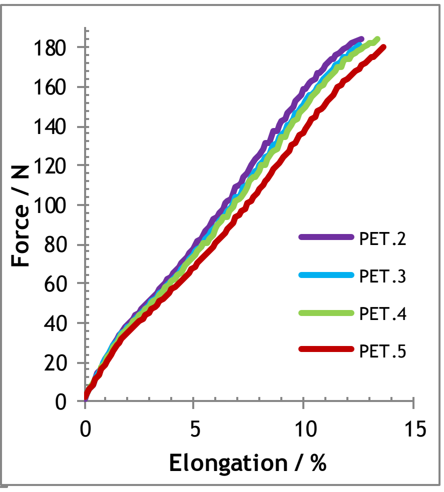


Figure 66 - Force vs. Elongation, speed of 50 mm/s, Zwick

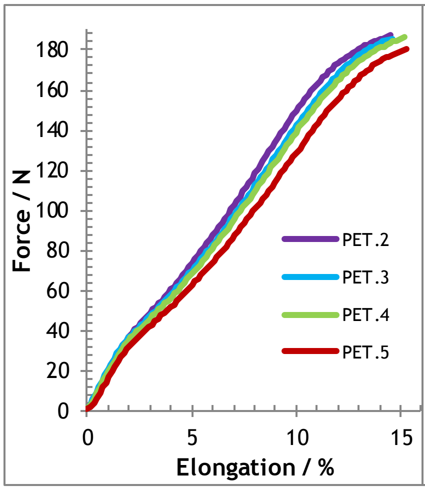


Figure 67 - Force vs. Elongation, speed of 5 mm/s, MTS

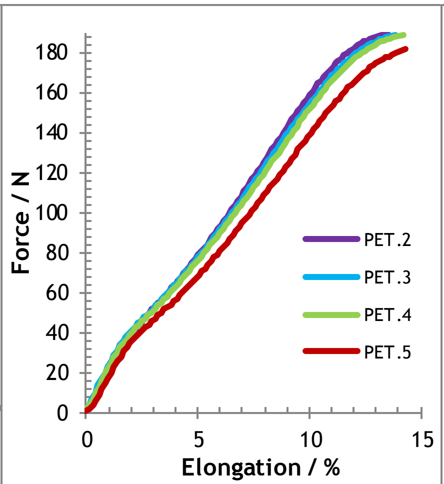


Figure 68 - Force vs. Elongation, speed of 26.67 mm/s, MTS

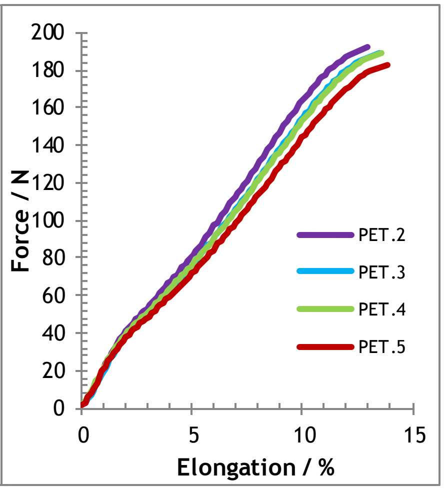


Figure 69 - Force vs. Elongation, speed of 50 mm/s, MTS

Analysing the results obtained it is visible that the higher is the twist level the longer are the elongations achieved, to each force, which confers to the curves of Force *vs.* Elongation a lower modulus. This happens because higher levels of twits enable higher structural elongation of the cords. In general the influence of the test speed is also evident as to increasing speeds a loss of elongation is observed. In terms of breaking force, from the lowest level of twist, 350 Z and 340 S (PET.2), to the higher level of twist, 410 Z and 400 S (PET.5), around 8 N are lost.

In other hand comparing the results of each twist level in the two machines, to the three speeds presented, see Figures 80 to 91 Annex 2, it is possible to observe that the bigger deviations in the results are in terms breaking forces that are higher to the tests performed in MTS, while to each force the values of elongations are usually lower. Especially in the curves stage 3 of response, it is observed that the Zwick results present lower modulus.

It may be hypothesized that these constant differences of response, especially in the curves stage 3, could be an outcome of the different kind of initial accelerations and of the different test times that the cords are subjected to when tested in the two machines. It was expected that to greater levels of twist the initial acceleration of the MTS would lead to major differences in the results when compared to the ones obtained with the Zwick. However, it wasn't observed and, therefore, further studies are required to determine if the mentioned factors together with the clamps and speeds influences may lead to the differences seen in the Figures 80 to 91.

The observed twist influence, Figures 64 to 69, can in part be used to prove the hypothesis (better explained in the previous chapters) that with different instantaneous speeds the cords maintain different levels of twist because: considering the cords with the same construction, when the test speed increases, and thereby the instantaneous speeds, the cords start to present lowers levels of elongation to each force. Therefore, it can be concluded that these data show evidences that, as a whole, prove some of the hypothesis assumptions.

To understand how the twist level influence evolves with the test speed further studies are needed and only with their results it will be possible to understand the mechanical behaviour of the cords and the main reasons to the results obtained in this work.

5 Conclusions

In this thesis the influence of design characteristics of the testing system, namely the clamps, length of the cords, machines operation mode and twist level was studied, as well as the influence of the test speed on the Force *vs.* Elongation curves of reinforcement materials, being this last subject the main focus of the work.

Regarding the clamps it was concluded that they have a huge influence on the results mainly due to their physical features and to the support that they may or not provide to the cords during the tests. The greater stability provided by the Std PET clamps explain the preference to use them in the laboratory tests but, on the other hand, it is possible that the Parallel clamps, due to their simpler structure, may present better results when the real behaviour of the cords in tyres is concern.

In relation to the initial length of the cords it was concluded that the shorter it is the shorter is the test time which promotes shorter elongations at break.

Analysing the influence of the test speed, regarding to PET cords, it was observed that with the increase of the test speed the Force *vs.* Elongation curve modulus increased. However, it was concluded that a greater influence of the test speed was visible in the breaking forces and elongations at break as it was verified a loss of around 20 newton and 3 % of cord elongation between the higher and lower values achieved. Concerning to Aramid cords, it was possible to observe that increasing the speed the Force *vs.* Elongation curves modulus increases, getting the curve slope close to linear. But then again the greater influence of the test speed was visible in the breaking forces and elongations at break, as it was verified a loss of cord elongation of around 1.5 % and a loss of force of around 111 newton, between the higher and lower values achieved. Thereby, it was concluded that the test speed has a greater influence in the last stages of the curve of Force *vs.* Elongation and in the response of materials with higher levels of crystallization.

Regarding to the influence of the twist level on the results achieved it was verified that the higher is the twist level the longer are the elongations achieved, which gives to the curves of Force *vs.* Elongation a lower modulus. Thereby, it was concluded that the twist level when conjugated with the test speed has an important role in the cords response.

6 Project assessment

6.1 Accomplished objectives

The main objective of this thesis was to study the influence of the test speed on the Force *vs.* Elongation curves for the reinforcement materials PET 1440 x 2 and Aramid 1680 x 2. Knowing the different features of the MTS and Zwick machines it was also needed to study the influence of the operation mode of the two testing machines, identify and understand the big differences between the clamps used to perform the tests, evaluate the influence of the initial length of the samples and finally to recognize the influence of the cords twist level in the several studies executed.

All this studies were performed and with their results it was possible to accomplish the main objective of this work.

6.2 Limitations and future work

The major limitations of this project were in terms of lack of knowledge of the mechanical behaviour of the cords during the tests. As it was needed to perform the tests at high speeds with some adaptations, this taking into account the standard Force *vs.* Elongation tests, a lot of questions emerged in terms of how the cords are straightened and how is the distribution of forces along the cords for each kind of clamps, during the test time. This because it was observed a great influence of the clamps on the results achieved but, as there wasn’t any factual knowledge that could explain such discrepancy of results, a lot of questions still open concerning to the mechanical behaviour of the cords in each case.

To answer to these new questions, future studies of the mechanical behaviour of the cords when tested with the different clamps could be performed. In these, e.g., a photo/video observation of the cords, in their full length, could be performed. The same kind of observation could be done to better understand the influence of the operation mode of the two testing machines in the results achieved and to evaluate which kind of acceleration would provide more realistic results.

In the future, a laboratory test could also be tried to reproduce in a more detailed way the impacts that the cords suffer during tyre service. For that, several studies are needed to be done in order to have knowledge about the temperature and humidity levels, more likely, at the cords breaking point, and to be able to define an initial cord length, S.P., that would comply with the real length of reinforcement material affected during a tyre impact. With these new parameters it would be possible to conduct laboratory tests whose results would be more likely to reproduce the Force *vs.* Elongation curves of tyres' cords.

Finally, it can also be recommended to study the dependency of cord twist level on testing speed.

6.3 Final Assessment

This project was a great and challenging academic opportunity due to the fact that it was the first time that these studies were conducted and thereby step by step it was always needed a critical point of view on the work.

On a personal and professional level the opportunity to work within an experienced multinational team was a great experience that was exceptionally enriching and stimulating.

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Annex 1

1.1. Twist factor

The twist factor can be calculated using the next formula:

$$\alpha = \frac{T}{m}\sqrt{\frac{tex}{1000}} \tag{1.1}$$

Where *T* represents turns, *m* represent meters and *tex* represent the linear density of the yarns in grams per 1000 meters.

1.2. Data treatment

Test time:

In order to compare the several results obtained for the different test speeds and different machines it was necessary to normalize the collected data.

For that it was necessary to observe the values of force collected and identify when the pre-load was achieved. Only after this point it could be considered that the test of Force *vs.* Elongation had begun and, therefore, the test time should start here. Thus to the time elapsing since the start of the operation of the machine, recorded in the collected data to each sample tested, should be subtracted the time recorded when the pre-load was achieved.

Only the data points that come after the normalized test time (test time = 0 s), including this point, should be considered in the results analysis and comparison.

Average calculations [34]:

To each test that had been performed, e.g. PET tested with the Parallel clamps at a speed of 50 mm/s, at least five samples were tested. This means that to evaluate the results achieved to each test, it was necessary to perform an average calculation.

At the same time it was defined that 100 points were enough to describe the results, i.e. the curve described by this number of points was capable to represent well the up to ≈ 60 000 points recorded during the tests. What raised the need to condensate the results.

In order to answer to these two needs an already existing Excel document was used. It allowed to, choosing two of the three variables recorded (force, elongation and time), obtain the average of the results in a condensate form.

The mathematical content in this Excel document was able to, using the pair of values measured to each sample, reduce the number of points by performing interpolations (with a defined step interval) between the data points, see Figure 70 and formula 1.2 to 1.4.

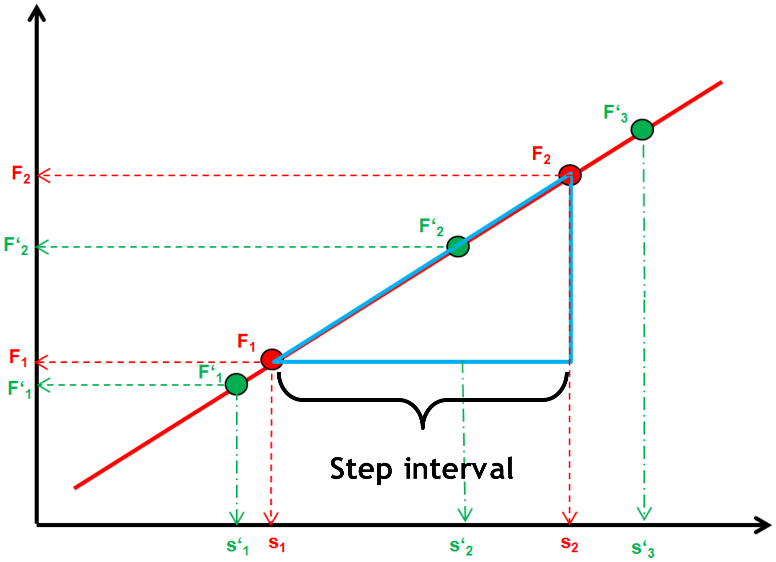

Figure 70 - Interpolation of the desired step interval between data points (adapted from [34])

$$\frac{F_2 - F_1}{s_2 - s_1} = \frac{F_2' - F_1}{s_2' - s_1} \tag{1.2}$$

$$\frac{F_2 - F_1}{s_2 - s_1} = \frac{F_2' - F_1'}{s_2' - s_1'} \tag{1.3}$$

Subtracting the formulas 1.2 and 1.3 it is and solving in order to F_1 it is possible to reach the next formula:

$$F_1 = F_2' - \frac{F_2' - F_1'}{s_2' - s_1'}(s_2' - s_1) \tag{1.4}$$

In the Figure 70 the points at green correspond to the recorded data and the red points to the interpolated values with the defined step interval. With the interpolated points a new curve of data is established.

As with the previous mathematical process all the new curves present the same step interval, which means that all them are defined, e.g. considering a curve of Force *vs.* Elongation, to the same elongation values, to obtain the average curve it is only needed to calculate the average between all the forces.

An inconvenient from this process is that as the measurements of each sample achieve different number of points, sometimes, this difference can be too large (what means that the curve obtained to one sample will be much longer/shorter than the curve obtained to another sample, i.e. there is a lack of point to calculate the average) which leads to the extrapolation of values between the curves edges, see Figure 71 and formulas 1.5 to 1.6. The outcomes of these extrapolations are the long straight sections observed in the last stages of the curves, seen all along the master thesis content as e.g. in Figure 37 chapter 4.3.2.

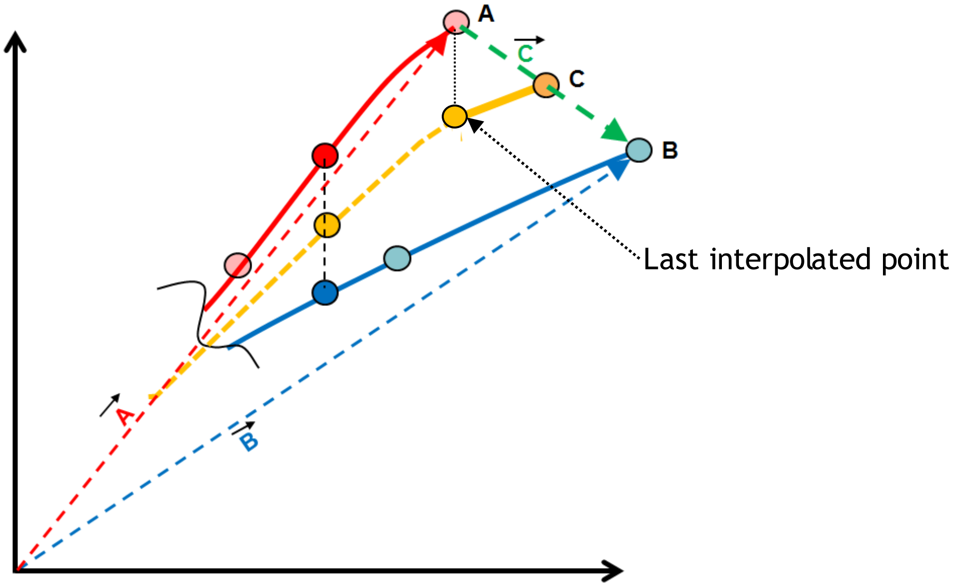

Figure 71- Calculation by extrapolation of end-points of the curves (adapted from [34])

In the Figure 71 given the points A (s_A,F_A) and B (s_B,F_B), last values from each curve, it is possible to calculate the values of the position of the point C (s_C,F_C), last value of the average curve. After defining the vectors $\vec{A} = \binom{s_A}{F_A}$, $\vec{B} = \binom{s_B}{F_B}$ and $\vec{C} = \binom{s_c}{F_c}$ it is known that:

$$\vec{C} = \vec{B} - \vec{A} \qquad (1.5)$$

To extrapolate the point C it is considered that it is located half way between the points A and B and thereby:

$$\frac{1}{2}\vec{C} = \frac{1}{2}\left(\vec{B} - \vec{A}\right) \Rightarrow \mathrm{C}\ (s_c, F_c) = \mathrm{C}\left(\left(\frac{1}{2}(s_B + s_A)\right), \left(\frac{1}{2}(F_B + F_A)\right)\right) \qquad (1.6)$$

At the end a connection between the last interpolated point and the extrapolated point C is made and thus the long straight section appears. The length of this section depends on the difference between the lengths of the remaining curves.

1.3. Theoretical test time

The theoretical test time can be calculated using the next formula:

$$test\ time\ (s) = \frac{test\ speed\left(\frac{mm}{s}\right)}{elongation\ at\ break\ (mm)} \tag{1.7}$$

1.4. Note: Zwick noise

As a note it is important to refer that to relative high speeds the final results from the Zwick machine present more noise than the ones achieved with the MTS. This is an outcome from the low data acquisition that the Zwick system provides, e.g. to the speed of 50 mm/s only 100 to 150 point are recorded. These numbers of points are not the optimums to perform the Average calculations and, therefore, the final results can present a lot of irregularities, i.e. noise.

Annex 2

2.1. Cord length studies, Parallel clamps

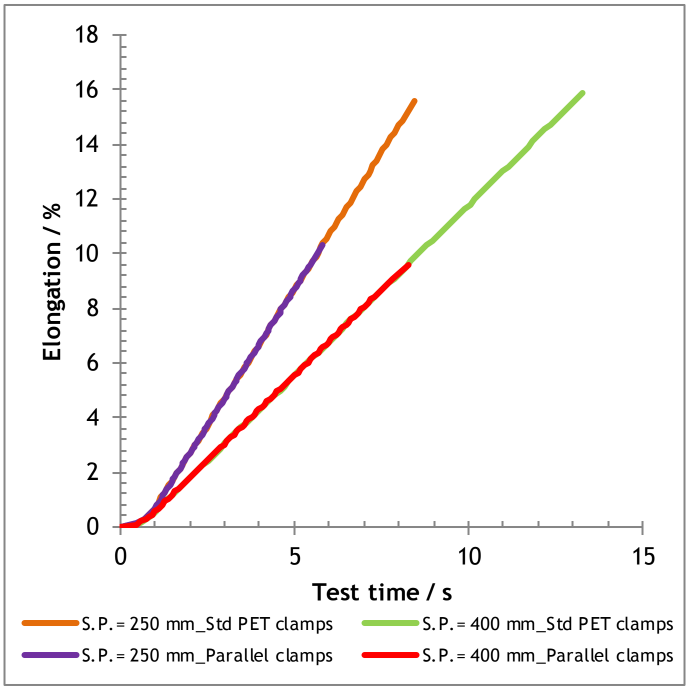

Figure 72 - Comparison of results obtained with the Std PET and Parallel clamps, speed of 5 mm/s

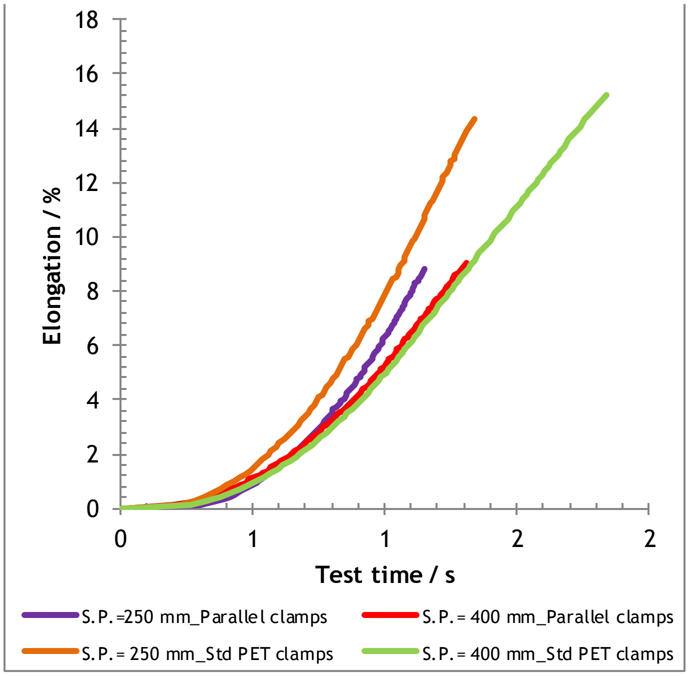

Figure 73 - Comparison of results obtained with the Std PET and Parallel clamps, speed of 50 mm/s

2.2. Test speed influence

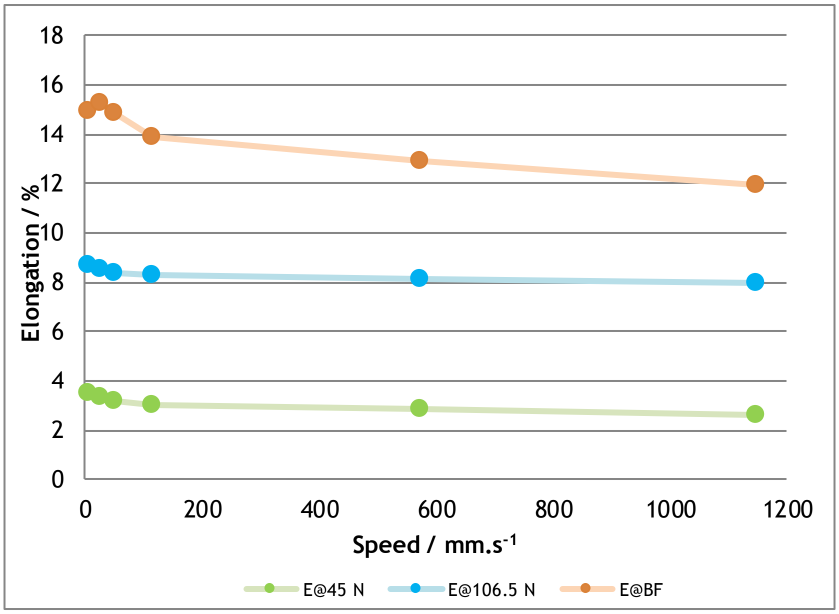

Figure 74 - E@Test Force, PET.1, MTS, S.P.= 250mm, Parallel clamps

In this Figure it is possible to see that the major variations in the elongation, as a function of the speed, are seen only in the Elongation at Break, supporting the idea that the test speed has a more noticeable influence in the stage 3 (see Figure 14, Chapter 4.1) of the curve of Force vs. Elongation.

It is important to note that the speeds are presented as equal to all the cases studied as a way to compare the data, it doesn't mean that at the time that the specific load (e.g. 45 N) was achieved the machine had already reached the programmed test speed.

2.3. Test speed and cord length influence

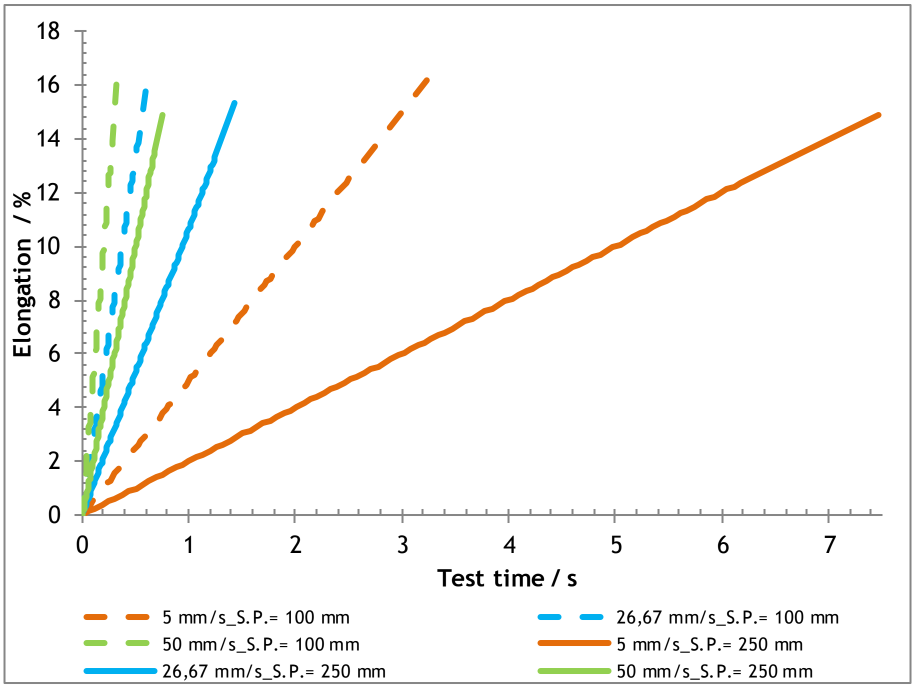

Figure 75- Elongation vs. Test time, PET.1, MTS, Parallel clamps, S.P. comparison, lower speeds

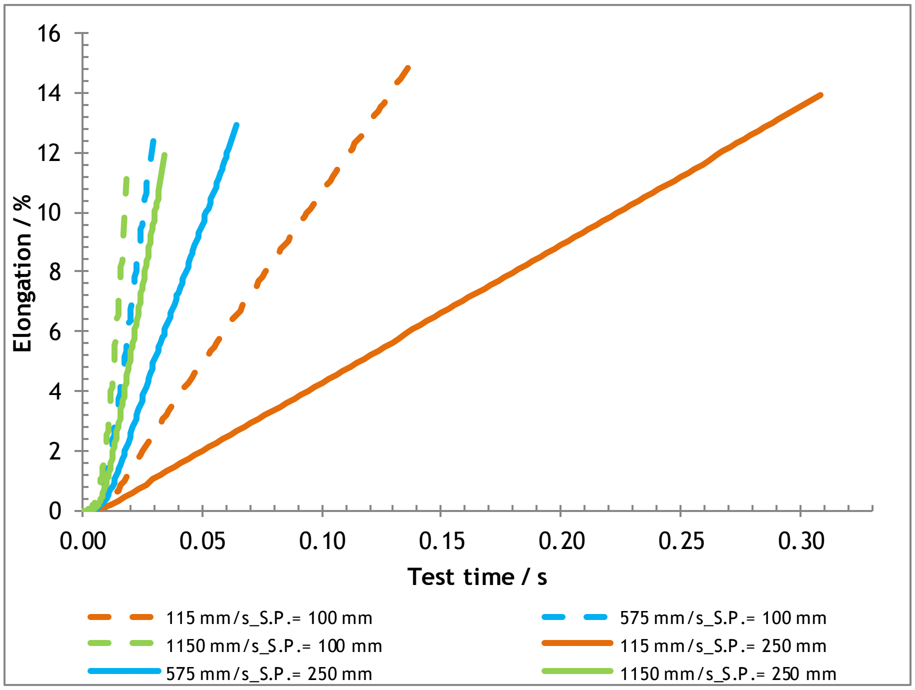

Figure 76 - Elongation vs. Test time, PET.1, MTS, Parallel clamps, S.P. comparison, higher speeds

2.4. Aramid, Std Ar clamps, 250 mm

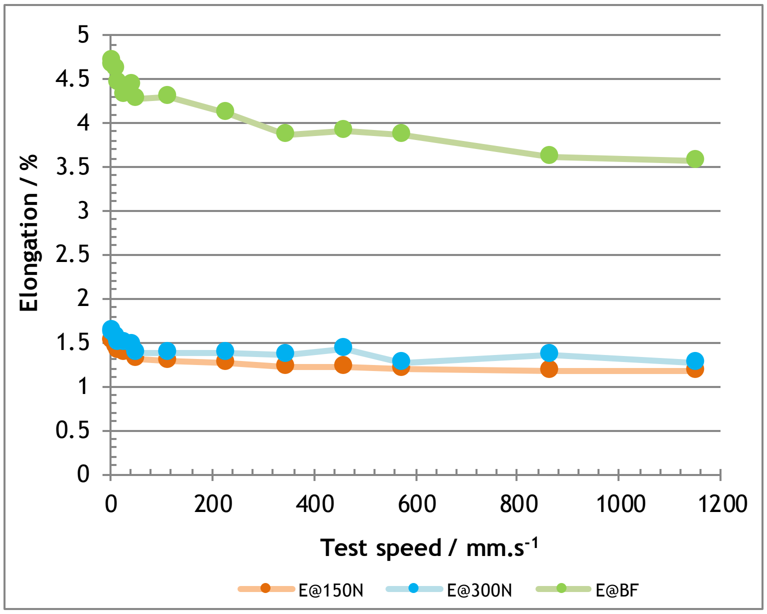

Figure 77 - E@Test Force, Aramid, MTS, S.P.= 250 mm, Std Ar clamps

2.5. Machine influence

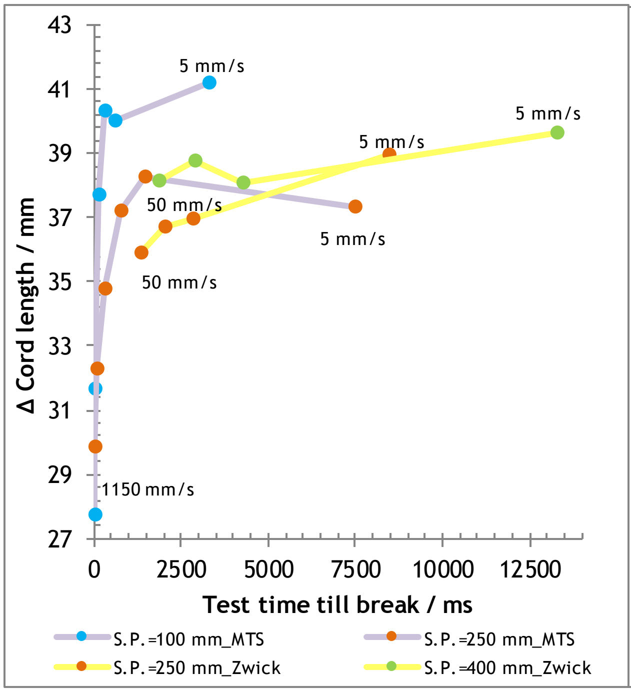

Figure 78 - Variation of cord length vs. Time till break, parallel clamps, PET.1

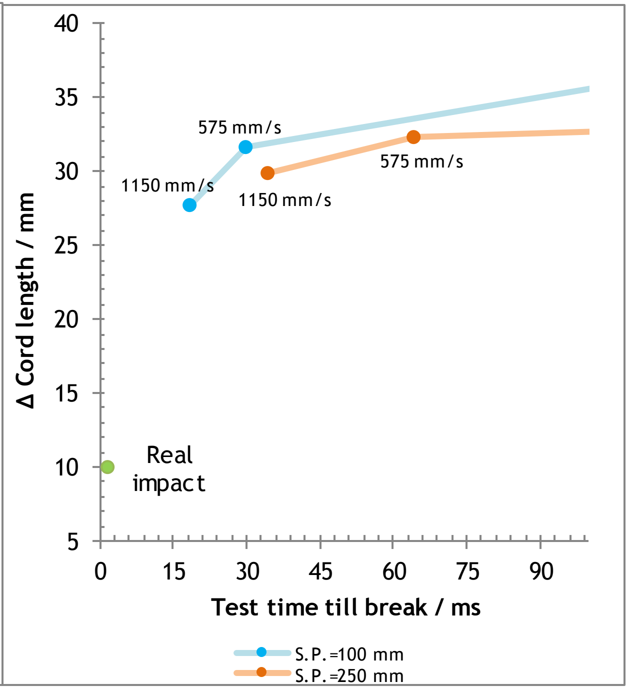

Figure 79 - Variation of cord length vs. Time till break, parallel clamps, MTS, PET.1

2.6. Cord twist influence, Std PET clamps, S.P.= 250 mm

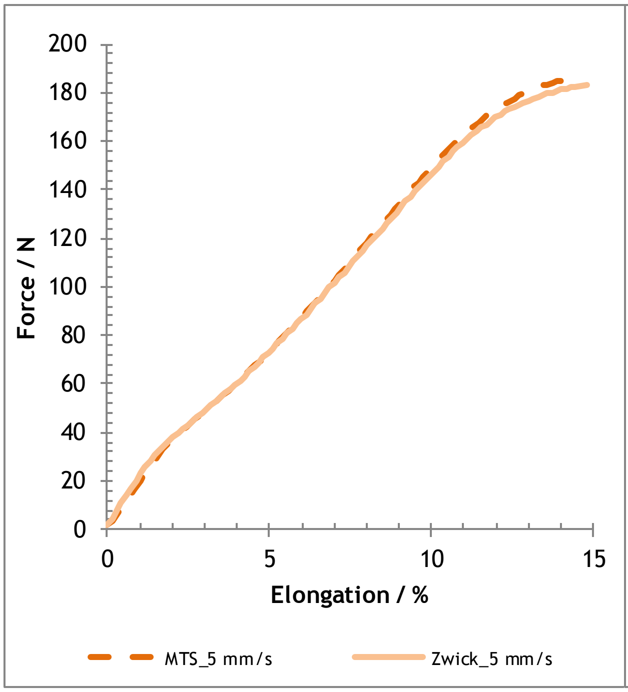

Figure 80 - Force vs. Elongation, cord construction 350 Z and 340 S

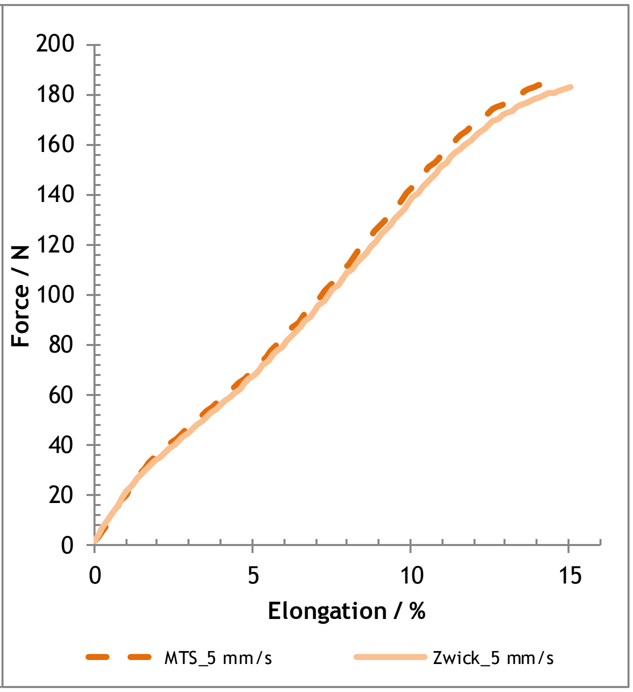

Figure 81- Force vs. Elongation, cord construction 365 Z and 355 S

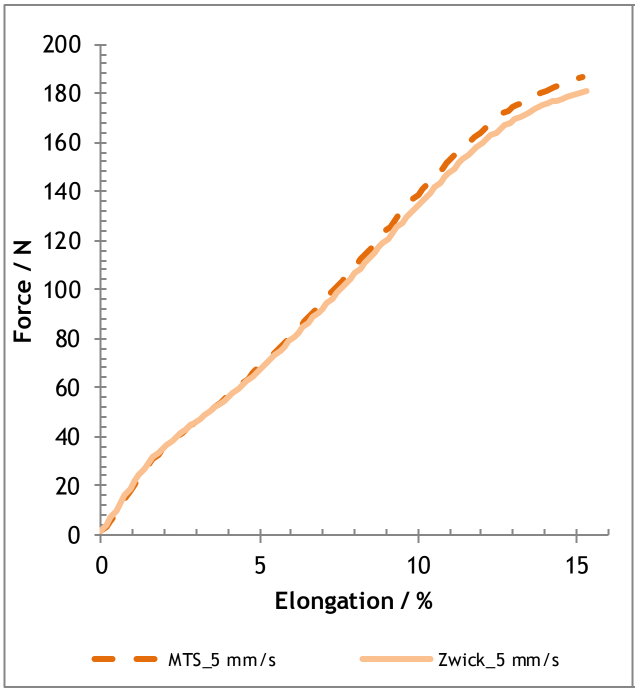

Figure 82 - Force vs. Elongation, cord construction 395 Z and 385 S

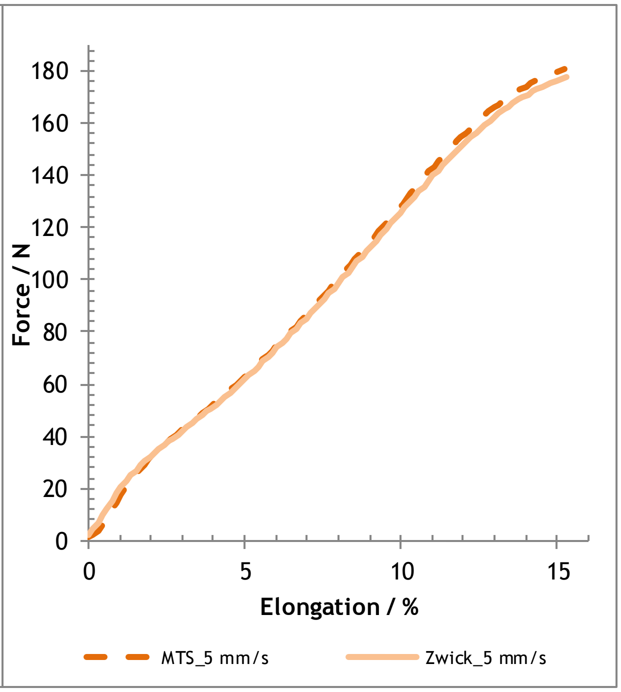

Figure 83- Force vs. Elongation, cord construction 410 Z and 400 S

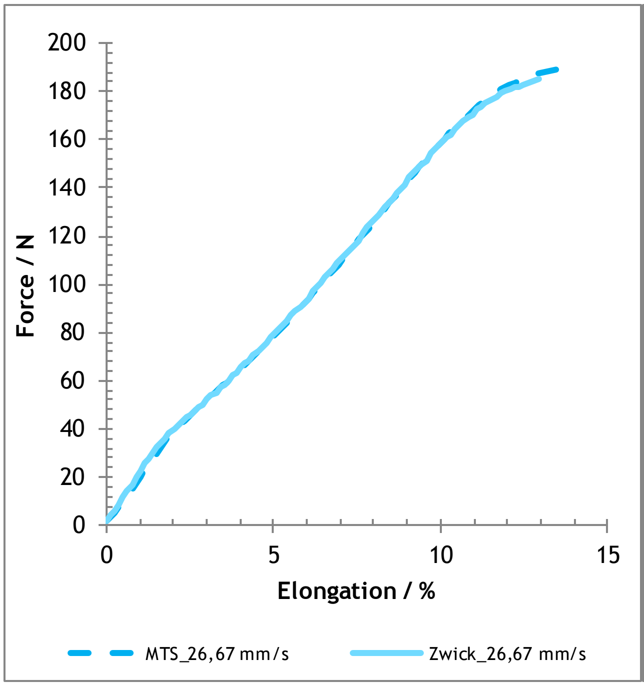

Figure 84 - Force vs. Elongation, cord construction 350 Z and 340 S

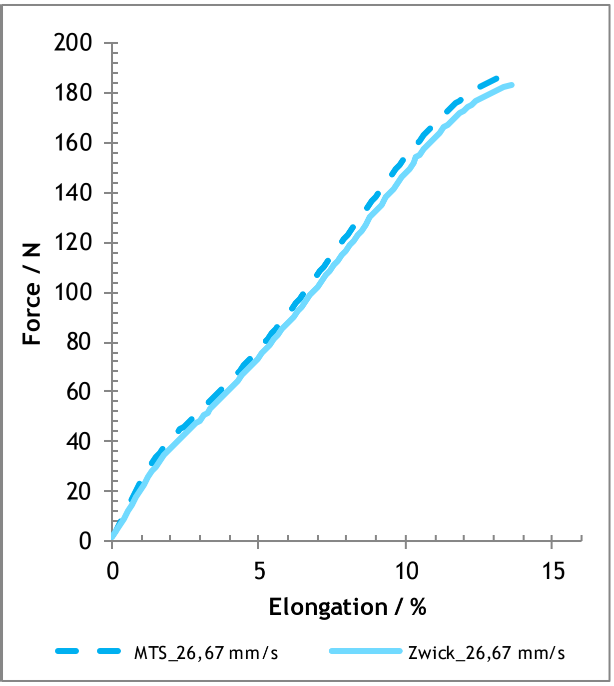

Figure 85 - Force vs. Elongation, cord construction 365 Z and 355 S

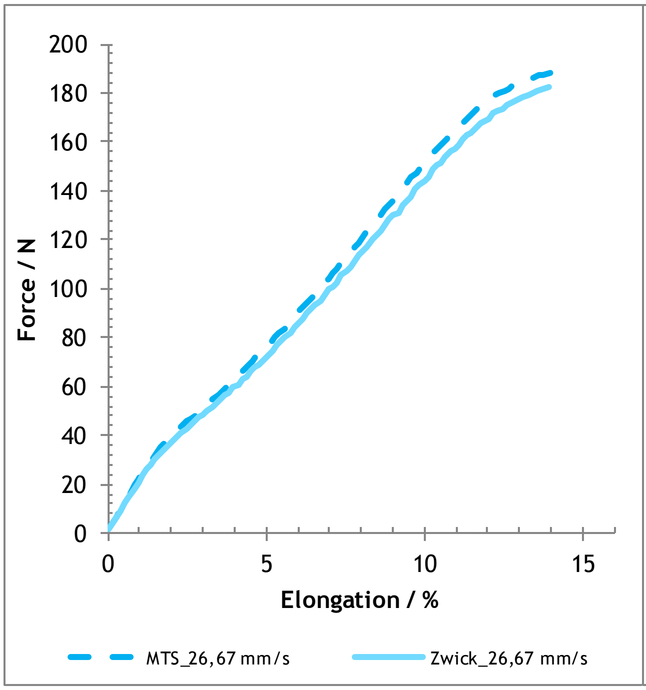

Figure 86 - Force vs. Elongation, cord construction 395 Z and 385 S

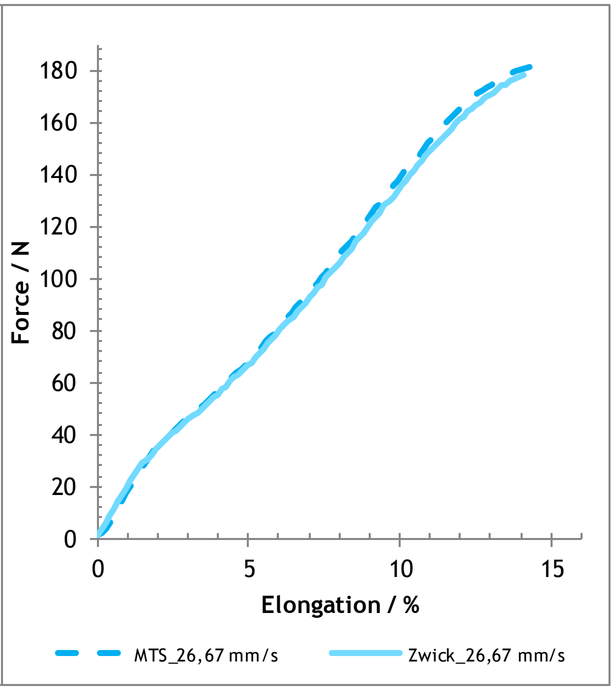

Figure 87 - Force vs. Elongation, cord construction 410 Z and 400 S

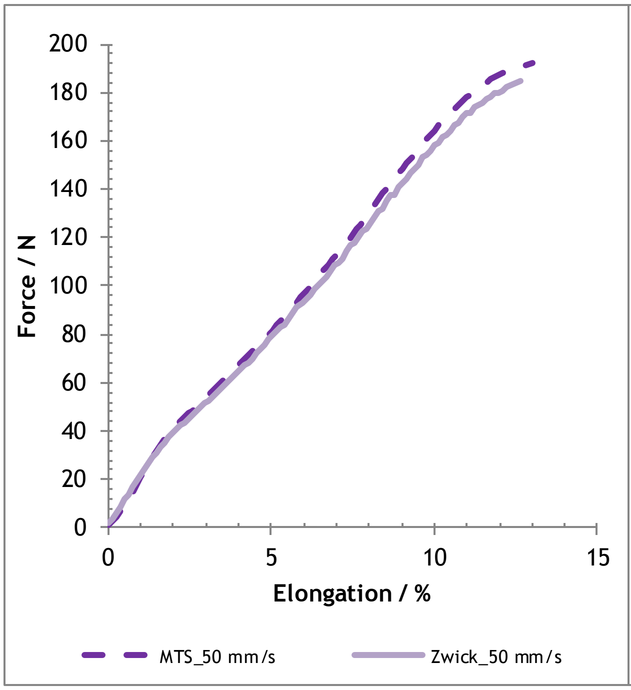

Figure 88 - Force vs. Elongation, cord construction 350 Z and 340 S

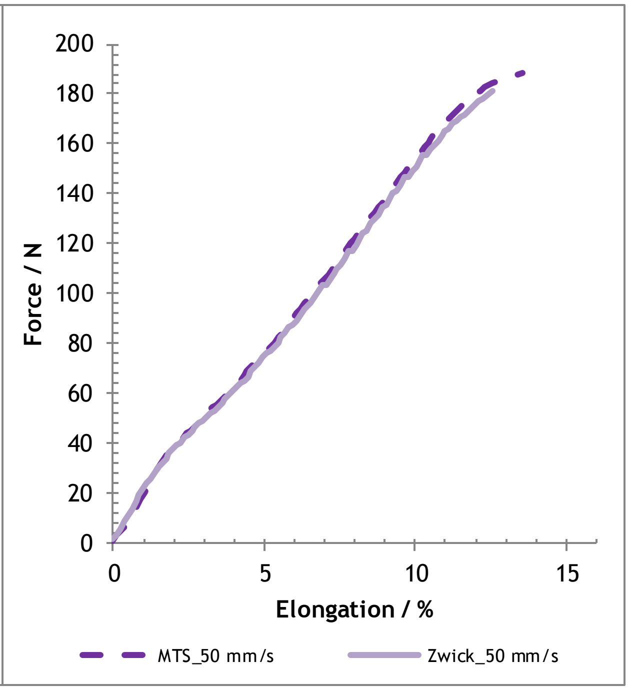

Figure 89 - Force vs. Elongation, cord construction 365 Z and 355 S

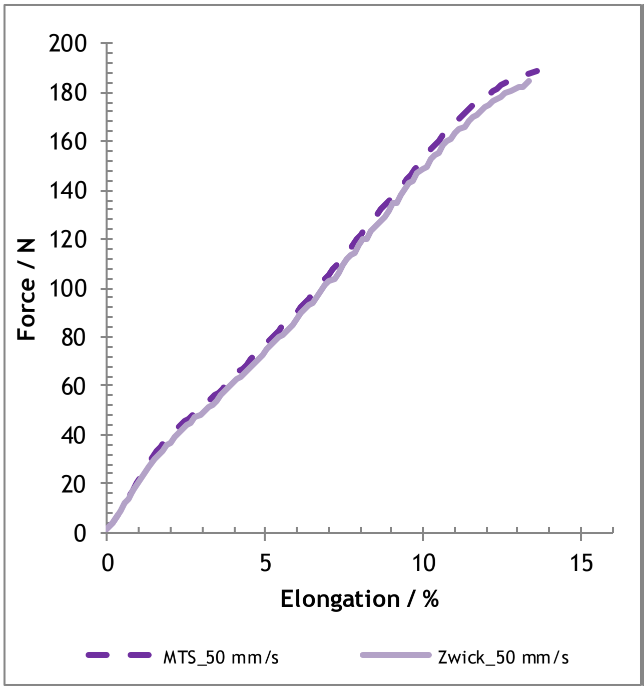

Figure 90 - Force vs. Elongation, cord construction 395 Z and 385 S

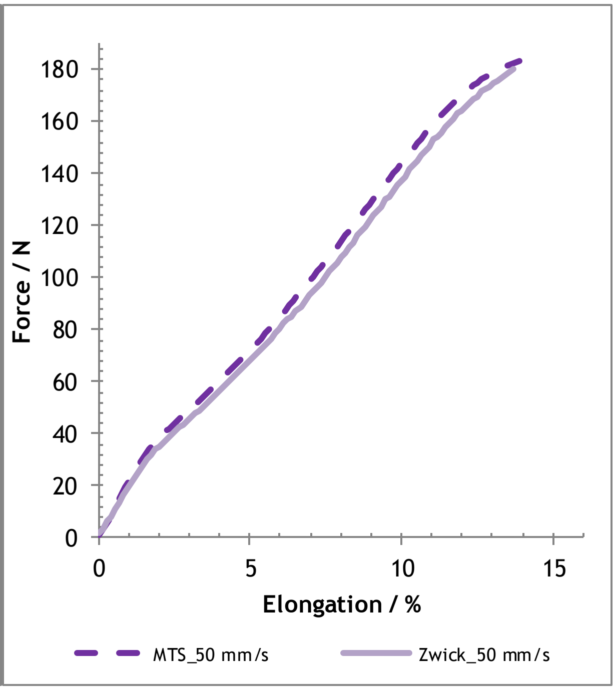

Figure 91 - Force vs. Elongation, cord construction 410 Z and 400 S