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IMPACT OF PCI PROCESS ON PHYSICAL PROPERTIES OF REINFORCEMENT MATERIALS

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DISSERTAÇÃO DE MESTRADO APRESENTADA
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Impact of PCI process on physical properties of reinforcement materials

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Magda Lopes Dias

Developed within the course of dissertation

Held in

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Abstract

The tire is a very complex composite that started as a piece of rubber and has been developed through the years. Nowadays, reinforcement materials are considered the backbone of a tire, allowing a better stability, and ensuring well-functioning and safety to the drivers. Reinforcement materials consist of steel, polyamides, polyesters, rayon, aramids, and hybrids of these cords. In the carcass and cap-ply of the tires, only textile cords are used. Polyesters and polyamides are the most applied ones due to their viscoelastic properties and lower price. However, these polymers are known for their shrinkage when submitted to high temperatures, leading to defected tires. When tires are inserted in the curing mold, the temperature increases up to 150 – 180 ºC and, during the following cooling step, if no counter force is applied, the textile cords will shrink. To prevent this behaviour, the Post Cure Inflation (PCI) process is applied in the cooling of the tires. Currently, this process is only dependent on the curing cycle – usually takes up to two curing cycles – and is independent of the type of materials in the tire.

This project was performed at Continental AG in Hannover in partnership with Faculdade de Engenharia da Universidade do Porto (FEUP). The main goal was to study the behaviour of the textile cords in the curing and PCI processes by developing a testing procedure at lab scale and create a Mathematical Model that enables to obtain the optimum conditions for the PCI process for different materials.

From the tests performed, it was seen that one of the most important parameters to control is the temperature at which the tires are released from the PCI. The Mathematical Model obtained was relevant for the company as a starting point to control and optimize the process. By doing the fine tuning of the PCI process, the materials in the tires will be more stable and consequently a better performance of the tire in service can be anticipated.

Keywords: Tire, reinforcement materials, textile cords, Post Cure Inflation

Resumo

O pneu é um compósito complexo que começou como um mero pedaço de borracha e que tem sido desenvolvido ao longo dos anos. Atualmente, os materiais de reforço são uma parte importante do pneu, atuam como o suporto principal permitindo uma melhor estabilidade e garantindo um bom funcionamento e segurança dos condutores. Os materiais de reforço consistem em aço, poliamidas, poliésteres, rayon, aramida e híbridos destas fibras. Na carcaça e no cap-ply dos pneus só são usadas cordas têxteis. Os poliésteres e as poliamidas são as cordas mais utilizadas devido às suas propriedades viscoelásticas e ao seu baixo custo. No entanto, estes polímeros são conhecidos pelo seu encolhimento quando são submetidos a elevadas temperaturas, levando a defeitos nos pneus. Quando os pneus são introduzidos no Molde de Cura, a temperatura tende a atingir valores entre 150 e 180 ºC e, durante o passo seguinte de arrefecimento, se nenhuma força for aplicada para contrariar esta tendência, as fibras tenderão a encolher. De maneira a prevenir este comportamento, o processo de Inflação Pós Cura (PCI) é aplicado no arrefecimento dos pneus. Atualmente, este processo depende apenas do ciclo de cura – normalmente dura cerca de um tempo correspondente a dois ciclos de cura – e é independente dos materiais que constituem o pneu.

Este projeto foi desenvolvido na Continental AG em Hanôver em parceria com a Faculdade de Engenharia da Universidade do Porto (FEUP). O principal objetivo foi estudar o comportamento das cordas têxteis nos processos de cura e PCI e desenvolver o procedimento de teste que simula à escala laboratorial estes mesmos processos. Finalmente, um Modelo Matemático foi criado que permite obter as condições ótimas de funcionamento do processo de PCI para materiais diferentes.

A partir dos testes realizados, verificou-se que o parâmetro do processo mais importante de controlar é a temperatura a que os pneus são libertados do PCI. O Modelo Matemático obtido foi relevante para a empresa como um ponto de partida para controlar e otimizar o processo. A possibilidade de ajustar o processo de PCI permitirá obter materiais de pneus mais estáveis e consequentemente poder-se-á antecipar pneus com uma melhor performance durante o serviço.

Palavras-chave: Pneu, materiais de reforço, cordões têxteis, Inflação Pós Cura

Declaration

I hereby declare, under word of honour, that this work is original and that all non-original contributions is indicated and due reference is given to the author and source

Magda Lopes Dias

Porto, 18 de Outubro de 2021

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Notation and Glossary

T_g	Glass Transition Temperature	℃

List of Acronyms

AG	Aktiengesellschaft (Corporation)
dtex	Decitex
PCI	Post Cure Inflation
FEM	Finite Element Model
N	Newton
PA	Aliphatic Polyamides
PET	Polyethylene terephthalate
tpm	Turns per meter
RT	Room Temperature
T_D	Total dtex
T_F	Twist Factor
T_L	Twist Level

1 Introduction

1.1 Framing and presentation of the work

The pneumatic tire is an integral part of automotive transportation that influences the overall performance of a vehicle. A single tire has a harmonious structure of over 20 compounds which work together to give optimum service. Among these, reinforcement materials are a large and extremely relevant proportion of the tire. They are usually embedded in rubber compounds (matrix) as the filled material, forming composite materials that gather the desirable properties that single constituents could not achieve alone. They provide a highly attractive combination of stiffness, toughness with light weight and corrosion resistance properties. For those reasons, these materials are the focus of innumerous studies.[1], [2]

In a tire, reinforcement materials can be found either in the body plies, cap-plies, bead cores and belt plies. Different applications require different reinforcement materials that enhance different properties. Bead cores and belt plies are usually reinforced with steel cords while body plies and cap-plies are reinforced with textile cords such as polyamides, polyester, rayon, and aramid. Body plies give the strength to contain the air pressure and provide for sidewall impact resistance. Cap-ply is used in higher speed rated tires and restricts expansion from centrifugal forces during high-speed operation. Therefore, the most ideal properties for these textile cords are dimensional stability and no long-term growth. [2]

Polyamides and polyesters are the most widely utilized textile reinforcements due to their low cost in comparation with rayon and aramid. Although they are known for their high-strength, due to thermoplastic properties, these two cords tend to shrink a substantial amount axially upon heating. During the curing process of a tire, these cords are subjected to high temperatures and when there is no counter pressure to maintain the cords stretched after being released from the mold, as they are still above the materials' glass transition temperature (T_g), these cords are free to shrink, impacting the tire uniformity, tire sizing and flatspotting during tire service. [2]

Post Cure Inflation (PCI) has been commonly used to prevent textile cords from shrinking while tires are cooling down after being released from the curing press. A controlled and tailor-made PCI process is fundamental to achieve a stable tire geometry and characteristics during service conditions. As a consequence, the present project has three focus: gain understanding of textile cords' physical properties and their interaction with the PCI process, develop and optimize the testing procedure which simulates at lab scale the production PCI process, and create a mathematical model that enables defining the optimum PCI process conditions in function of the reinforcement materials composing the tire.

1.2 Presentation of the company

Continental AG is a world's leading automotive manufacturing company that offers solutions for vehicles, machines, traffic and transportation, being best known for the production of tires. Founded in 1871 in Hannover, Germany, as a stock corporation, "Continental – Caoutchouc und Gutte-Percha Compagnie" started by producing soft rubber products, rubberized fabrics and solid tires for carriages and bicycles. Nowadays, the company ranks among the top 5 automotive suppliers worldwide of brake systems, instrumentation, systems and components for powertrains and chassis, vehicle electronics, infotainment solutions and technical elastomers. [3]–[5]

1.3 Contribution of the author to the work

This project starts based on tests previously done at Continental AG. This project has successfully developed an accurate testing procedure where some parameters were already optimized, and others still needed to be changed.

The behaviour of different cords in the testing procedure that simulated the curing and PCI process was studied and a Mathematical Model that indicates the optimum PCI conditions was obtained. This model comes as an awareness to something that the company started realizing – the PCI process can and should be controlled depending on the materials that compose the tire in order to optimize time and performance of tires.

1.4 Organization of the dissertation

This thesis is organized in 7 chapters as follows:

1. *Introduction* frames the relevance of this project on the company's knowledge, gives an initial insight into the work developed at the company and introduces de company where the work took place.
2. *Context and State of Art* describes all the needed knowledge so far regarding tires, reinforcement materials, textile cords and Post Cure Inflation process.
3. *Materials and Experimental Facility* reports the used materials, the developed experimental simulation as well as the equipment used to test the materials.
4. *Results and Discussion* display the results and its analysis.
5. *Conclusion* summarizes the main outcomes of this study and its contribution to the company.
6. *Assessment of the Work Done* synthesizes the accomplished objectives, provides a critical analysis of the work develops and provides information for future development.

7. *References* catalogue all the sources referred throughout the work.

2 Context and State of the art

2.1 Pneumatic Tire

A pneumatic tire is a highly engineered structural composite that blends a unique mix of chemistry, physics and engineering. It provides the only interface between the vehicle and the highway, carries the vehicle road, transmits engine power and guarantees the road surface friction to drive, brake and guide the vehicle, and absorbs road shocks and irregularities under a wide variety of operating conditions, providing a vibration-free motion on the road. [2], [6]

Figure 1 illustrates the major section of a passenger radial car tire where all layers of the tire are depicted. Table 1 describes the function of each layer of a tire.

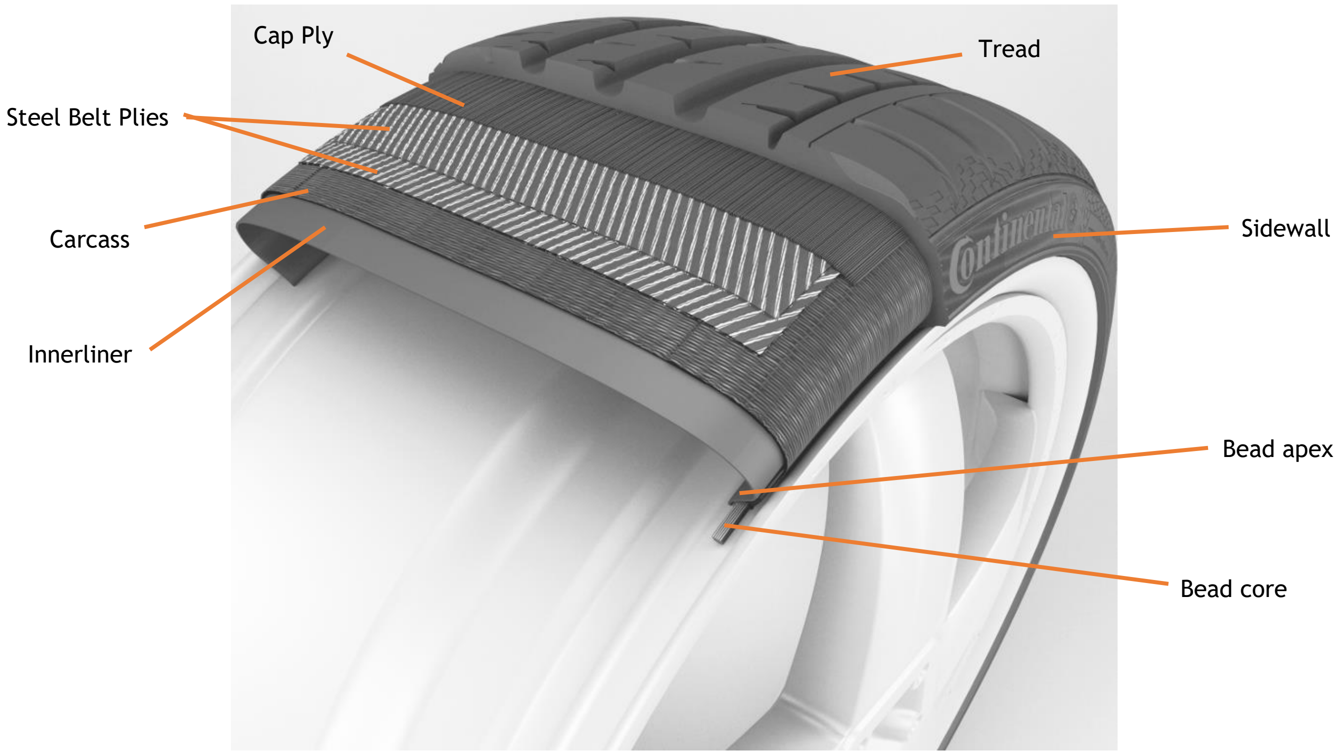


Figure 1 – Radial tire cross-section (adapted from [3]*)*

Table 1 – Function of the main components of a passenger car tire (adapted from [3])

	Components	Function
Tread	Tread	Promotes good road grip and enables water expulsion.
	Cap ply	Avoids tire growth during tire service. Enables high speed.
	Steel cord belt ply	Provides rigidity in the tire by restricting expansion, stabilizing the tread area and provide impact resistance.
Casing	Textile cord ply (carcass)	Layer of textile that controls the internal pressure of the tire and maintains its shape.
	Innerliner	Improves air retention by lowering permeation outwards through the tire.
	Sidewall	Protect the body plies from abrasion, impact, and flex fatigue.
Tire bead	Bead apex	Promotes directional stability, steering and performance.
	Bead core	Ensures firm tire seating on the rim.

2.2 Reinforcement Materials

2.2.1 Cord Materials

Tires are reinforced by layers of relatively inextensible cords – tire cord and bead wire – that provide strength and stability to the sidewall and tread, hold the air pressure, carry the load, and restrict deformation and growth of the tire during use. To this end cord materials must have high stiffness, resistance to repeated flexing and high strength-to-weight ratio. There are five major fibers that make up the currently reinforcement materials usage – rayon, nylon, polyester, aramid, and steel. [7] [8]

Polyethylene terephthalate (PET) tire cords are synthetic, long chain polymers produced mainly by condensation polymerization of terephthalic acid and ethylene glycol, being known as part of the polyester family. The most common usage is in radial body ply (carcass). PET advantages rely on high strength, good durability and high modulus combined with moderate to low shrinkage. However, PET is not as heat resistant as nylon or rayon. [2] [8]

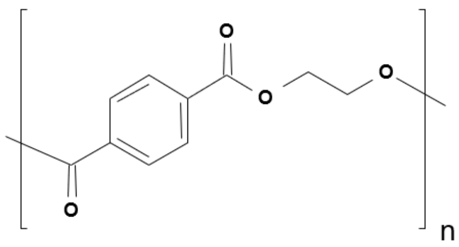
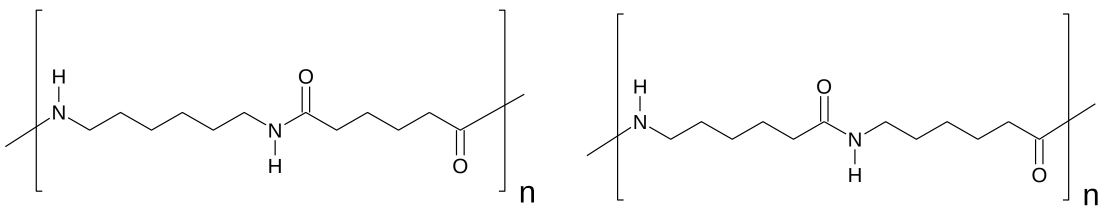


Figure 2 – Molecular structure of Polyethylene terephthalate [8]

Polyamides (PA) can be classified based on the length by PA-*x* or PA-*xy* where *x* and *y* represent the number of carbon atoms of the dicarboxylic acid between nitrogen atoms. Two varieties are used in tire cords – PA 6 (polycaprolactam) and PA 6.6 (polyhexamethyleneadipamide). These PAs carry a good combination of tensile strength, flexibility, and abrasion resistance. Despite both materials present similar properties, PA 6 is less expensive, more sensitive to moisture and subject to loss in tensile strength if moisture is present at tire curing temperatures. Its low modulus and low glass transition temperature make it unacceptable as a belt material. In addition to its typical shrinkage behaviour upon heating, PA is preferred in uses requiring carcass toughness, bruise and impact resistance, high strength, and low heat generation. In these applications, nylon has the major contribution in cap-ply. [2] [8]



a) PA 6.6 b) PA 6

Figure 3 – Molecular structure of PA 6.6 and PA 6 [8]

Aramid is a synthetic, wholly aromatic polyamide. It is 2 to 3 times stronger than polyester and nylon, has low elongation and its most outstanding physical property is high tensile stiffness. However, its relatively high cost has slowed adoption as a general radial belt material. Aramid is particularly suited where weight is important, such as in the belts of radial aircraft tires or in overlay plies from premium high-speed tires. [2]

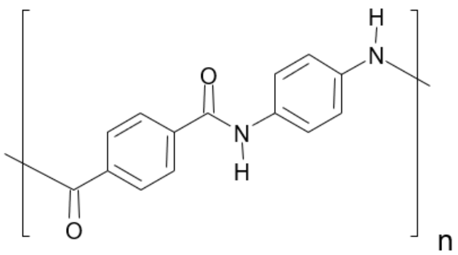


Figure 4 – Molecular structure of Aramid [8]

Rayon is a body ply cord or belt reinforcement made by regenerating cellulose. The very low shrinkage due to its high crystalline degree, high-modulus, good-adhesion properties of rayon make it an excellent choice for use in passenger tires. However, besides its high sensitivity to moisture, rayon has lost market share to polyester due to higher cost and environmental concerns with production facilities. [2]

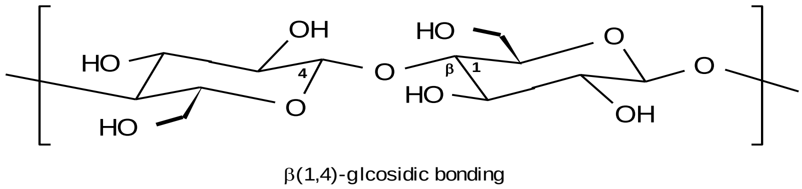


Figure 5 – Molecular structure of Rayon [8]

Steel cord is a carbon steel wire coated with brass that has been drawn, plated, twisted, and wound into multiple-filament bundles. It is most used in radial belts and in single-ply carcasses for large radial tires due to its high strength and stiffness. [2]

In the present work, only textile reinforcements – all except steel – will be approached.

2.2.1.1 Hybrid Cords

In addition to pure cords made of yarns of the same fiber type, hybrid cords are used nowadays as well. Hybrid cords combine more than one type of reinforcement polymers within a common cord, giving a chance to achieve new reinforcing materials with better performance than using conventional fibers. The hybrid cords offer incomparable properties in terms of high strength, good fatigue resistance, a versatile field to modify modulus, elongation and shrinkage of the cords, and weight with the economic advantage to satisfy the growing demands of the tire industry. [9] [10]

In the present work, the hybrid cords studied are made of aramid and PA 6.6 yarns. The mechanical properties of these hybrid cords are determined by the property boundaries of both materials. A variety of hybrid cord properties can be engineered by adjusting the aramid or nylon content and twist levels within the property boundaries of aramid and nylon 66 synthetic yarns. The benefit of the hybrid cord is the flexibility to engineer the cord properties by finding optimum combinations depending on the requirements of the application. [10]

In Figure 6 the force-elongation curves for the four different types of textile cords are represented. These curves were obtained in the lab to be further compared with the cords after undergoing the testing procedure. It can be verified the low elongation at break at a high specific force for the case of hybrid cord of aramid and nylon, while the nylon cords present the highest elongation at break and lowest modulus.

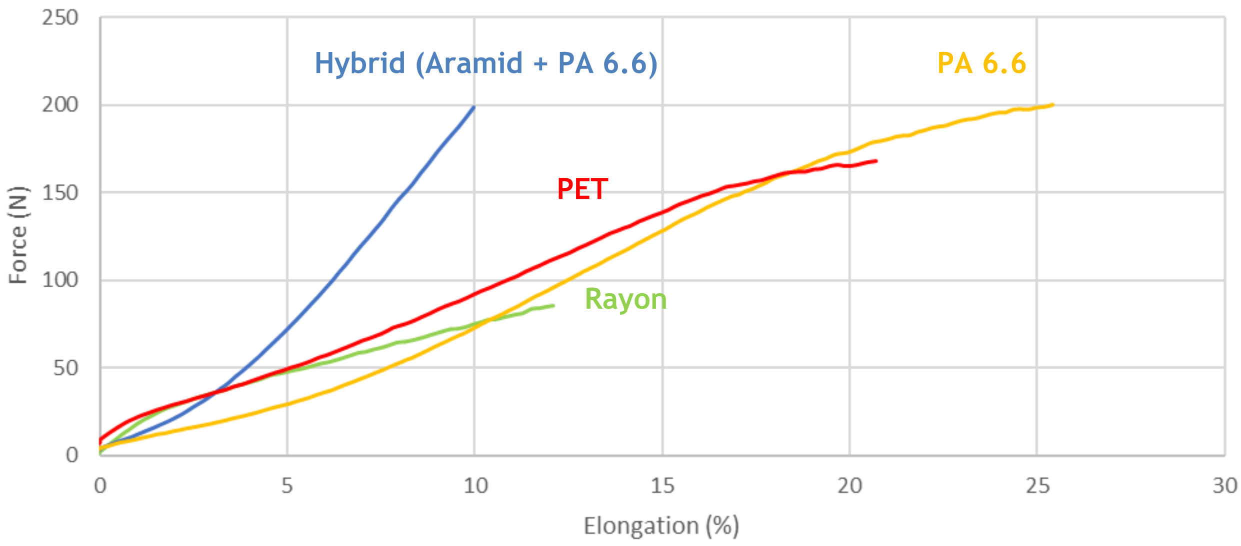


Figure 6 – Example of experimental results of Force-Elongation Curves of different textile cords.

2.2.2 Manufacture of textile reinforcements

For textiles to be used, they first need to be prepared and processed in order to build up structures designated as fabrics. First, the fiber is transformed into yarn during the spinning process. This process increases the strength and modulus and reduces elongation at break by increasing the polymer crystallinity and molecular orientation. Forcing polymers with amorphous zones to orientate in a certain direction will have repercussions in the shrinkage of the polymers in further stages. Secondly, during the twisting process, two or more yarns are twisted individually in the “Z” direction, resulting on a folded yarn. Afterwards, the folded yarns are back twisted in the “S” direction, resulting in the greige cord. Tire cords are usually balanced with equal twisted levels in yarns and cords. This step is then followed by the weaving process where the greige cord is transformed into greige fabric, which generally consists of two sets of cords interlaced – Wrap (cord that runs lengthwise to the machine) and Weft (cord that runs in right angle to wrap). Finally, during the dipping process, the greige fabric is dipped in a tank filled with a latex adhesive that allows to enhance the bond between the cord and rubber, and is dried in an oven. This treatment occurs under controlled conditions of time, temperature, and tension. This final tension is also a key factor on the shrinkage of a cord. The result should be a fabric with perfect conditions that allows good adhesion with the rubber and provides the necessary tensile requirements and thermal properties. [2] [8]

2.2.3 Cords Characterization

2.2.3.1 Textile terminology

The terminology used for defining tire cords comes from the textile industry. In Table 2 some important terminologies are summarized for a better understanding of the cords design and their characteristics.

Table 2 – Textile terminology (adapted from [2])

Terminology	Description
Filament	The smallest continuous element of a tire cord.
Yarn	Assembly of filaments plied together.
Cord	Two or more yarns plied and twisted together.
Decitex	The linear density in SI units, defined as the weight in grams of a length of 10,000 meters. Abbreviated as dtex.
Twist level (T_L)	The number of 360° turns per meter (tpm) of a yarn or cord.
Twist factor (T_F)	Represents the mathematical correlation between the twist level and the titer.
Cord Construction	Gives the information of how many yarns exist in the cord and how they are twisted. For example, a cord that has the construction x1x2 means that the cord has two yarns that first were twisted individually and then together.
Total dtex (T_D)	The total dtex of a cord is obtained by multiplying the linear density of a single cord by the total number of yarns present

Textile cords are identified by their code, linear density and construction. Thus, a cord represented as PA 6.6 1400x2 is a nylon 6.6 formed from two single yarns of 1400 dtex twisted together in opposite directions. The total dtex is obtained as follows

$$total\ dtex = 1400 \times 2 = 2800\ dtex \qquad (2.1)$$

2.2.4 Linear Density, Twist Level and Twist Factor

The linear density consists in the number of filaments present in the reinforcing material. Higher linear densities provide an increase in modulus and breaking force but induce consequently more weight and higher costs of the cord. Moreover, the increasing cord thickness leads to a higher shrinkage due to the increasing weight of material in unit length. [11] [12]

Cords with higher twist levels tend to have behaviour that resembles a “spring effect”. An increase in the twist levels puts extra stress on the yarn and cause to increase fiber-to-fiber friction, increasing the helix angle (α) between cord axis and filament axis, as demonstrated in Figure 7. For that reason, increasing twist levels lead to lower breaking forces, higher elongation at break and lower initial modulus. [11]–[13]

In this project, cords of the same fibre with different linear densities and twist levels were tested. In order to compare the properties of cords with different twist levels and linear densities, it is usual to calculate the twist factor. Equation 2.2 is used for such purpose. [11]

$$T_F = T_L \cdot \sqrt{\frac{T_D}{10{,}000}} \tag{2.2}$$

T_F, T_L and T_D represent twist factor, twist level and total decitex, respectively.

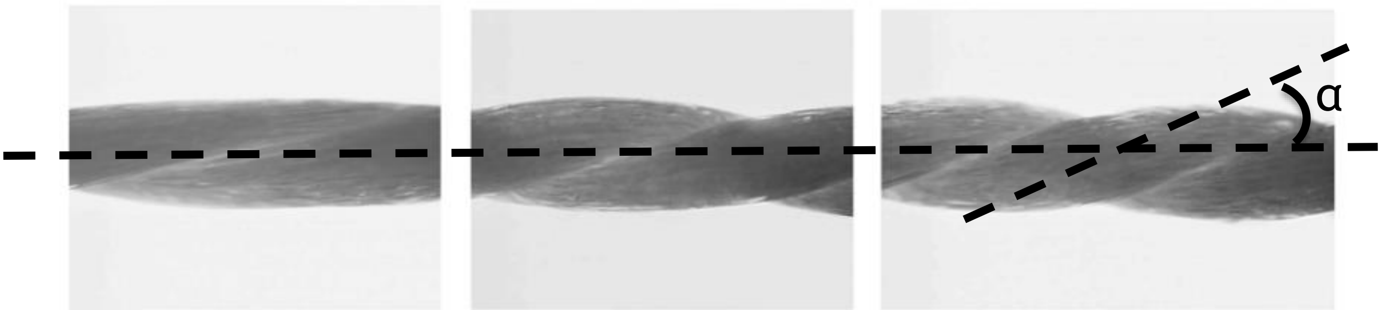


Figure 7 – Polyester cord with different twist levels (a) 200 tpm, (b) 350 tpm and (c) 470 tpm (adapted from [13])

2.2.5 Shrinkage and Shrinking Force

Crystallinity defines the degree of long-range order in a material, and strongly affects its properties. Polymers are often considered semi-crystalline, existing somewhere on a scale between amorphous and crystalline. This usually consists of small crystalline regions surrounded by regions of amorphous polymer and tie chains that belong to both phases. Figure 8 depicts, in a simplistic manner, the morphology of a PET fiber with all these regions. [14] [15]

Polymers are stretched during spinning and dipping process, forcing their amorphous molecule chains to orientate in a certain direction and “freeze” as such, increasing its modulus and strength. When submitted to temperatures above their glass transition temperature, the crystalline molecular structure of these polymers starts exhibiting a rubbery behaviour. These force-oriented amorphous sites will tend to shrink to their most stable entangled conformation leading to a smaller cord length. Textile cords such as polyamide and polyester show this effect, known as thermal shrinkage. [2]

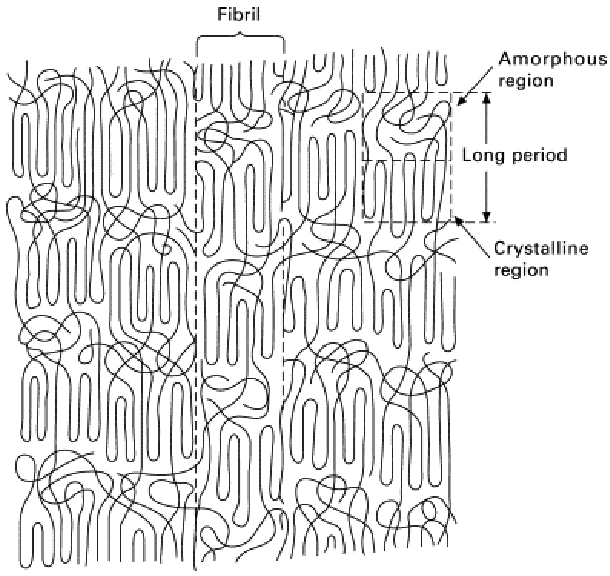


Figure 8 - Morphology of PET [15]

Associated with shrinkage, there is another important concept, the shrinking force. This force is the combination of pretension force and the force that is developed in the cords as a result of heating. Both these concepts are usually correlated with each other since the shrinking force also increases with increasing temperatures due to the polymers' shrinking characteristic. Nevertheless, this relation becomes invalid with the increasing twist factor due to the increase in the helix angle of the polymers. Several studies observed that, for nylon, while shrinkage increases with increasing twist factors, the shrinking force values decrease.[13]

2.3 Post Cure Inflation

2.3.1 Curing and Post Cure Inflation

One of the final manufacturing processes that a tire undergoes is curing (or vulcanization). Before this step, the rubber in the "green tire" – tire before curing – exhibits a viscous behaviour. The green tire is then mounted in a curing mold, where a bladder is blown up within a tire cavity to press the tire's outer surface tightly against the mold's inner walls while the tire is vulcanizing. During this step the tire is exposed to high temperature, causing a chemical reaction (vulcanization) to occur in the rubber compounds whereby the long polymer molecules become crosslinked together by sulfur or other curatives. The rubber compounds are transformed into strong, elastic materials in the cured tire. [16] [17]

After the curing cycle is finished, the tire is released from the curing mold. However, vulcanization of the rubber continues taking place at much lower rates as the tire cools down. The tire is under high temperatures and if no load is applied to counteract the polymers shrinking force, the viscoelastic cords in the hot tire are almost completely free to shrink. By shrinking, having an impact on the uniformity, tire sizing and flatspotting. A way to prevent these undesired situations is by immediately transferring the cured tire to a Post Cure Inflation (PCI) stand. The tire is fixed on a rim and an inner pressure is applied while the tire cools down. Due to the constraints by the inflation pressure, the cords are kept stretched and the tire dimension and shape remain relatively unchanged during the post-cure cooling process. In this manner, tires with desired uniformity in dimension and shape can be achieved. Figure 9 shows a typical tire PCI stand where two tires can be cooling down simultaneously. [17]–[19]

Nowadays the only controlled variables in the PCI are the inner pressure and the time that the tire stays inflated, corresponding approximately to two curing cycles. In truth, this process still has margin for improvement. Several studies demonstrated that PCI results are greatly dependent on the releasing temperature of the tires from the PCI stand. By controlling these variables, the optimum values that enhance the performance of PCI for different polymers can be obtained.

Figure 9 - Post Cure Inflation Stand

2.3.2 PCI influence on cords

The most prominent difference between tires with and without PCI are the tire dimension and shape. Tires without PCI usually have smaller section width and the tire is deformed due to differences in the degree of the polymers' shrinkage all over the tire. These tires are released from the curing mold at high temperatures and let to cool down with no load counteracting the shrinking force of the cords, undergoing a thermal shrinkage. Moreover, these tires exhibit dimensional growth with usage and become much squarer after exercising since the centrifugal force applied while the tire is rotating forces the cords to creep. [2], [18], [19]

In tires that are cooled down in PCI stands, the cords are stretched while temperature decreases, preventing cords from shrinking. When the tire reaches a temperature below the T_g, the amorphous regions of the polymers are totally frozen and the tire can be released from the PCI stand, cooling down to room temperature without constrains. These tires do not show considerable dimensional growth during service since the cords' properties were fixed already stretched. [18]

3 Materials and Experimental Procedure

This chapter describes the methodology followed, all the textile cords used and the developed testing procedure which simulates at lab scale the curing and PCI system. A scheme of the methodology followed is presented in Figure 10.

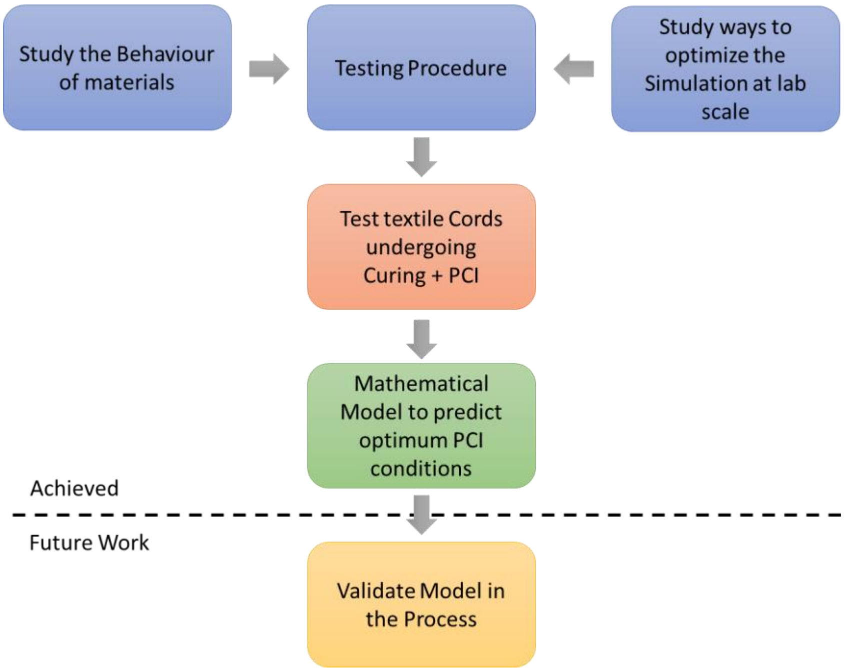


Figure 10 - Project development scheme

3.1 Textile Cords

The first goal of this thesis concerns the tire cords' physical properties and their interaction with the PCI process. To fulfil this goal, textile cords of different polymers with different cord constructions and twist factors were used. The cords and their specifications – code name, cord construction, twist factor, tire application - can be found in Table 3. Cords from two different types of tires were studied: tires for agricultural vehicles – Agro – and tires for passenger vehicles – PC. PA 2 and PA 3 have the same construction and twist factor. However, they differ in the mechanical properties. PA 3 is known as a “strong” nylon, since it has a higher material modulus when compared with PA 2.

For test conditions to be the same, all cords were previously conditioned and maintained in a standard atmosphere at 23 °C with a moisture content of 55% of relative humidity until tested.

Table 3 – Material Specification

Polymer	Denomination	Cord Construction	Twist factor	Tire Application
PA6.6	PA 1	1400x2	200	Carcass Agro
	PA 2	1400x2	150	Cap-ply PC
	PA 3	1400x2	150	Cap-ply PC
	PA 4	1880x2	200	Carcass Agro
	PA 5	940x2	150	Cap-ply PC
PET	PET 1	2200x2	200	Carcass PC
	PET 2	1440x2	200	Carcass PC
	PET 3	3440x2	200	Carcass PC
Rayon	R	1870x2	250	Carcass PC
Hybrid (Aramid + PA 6.6)	H	1680+1400	200	Cap-ply PC

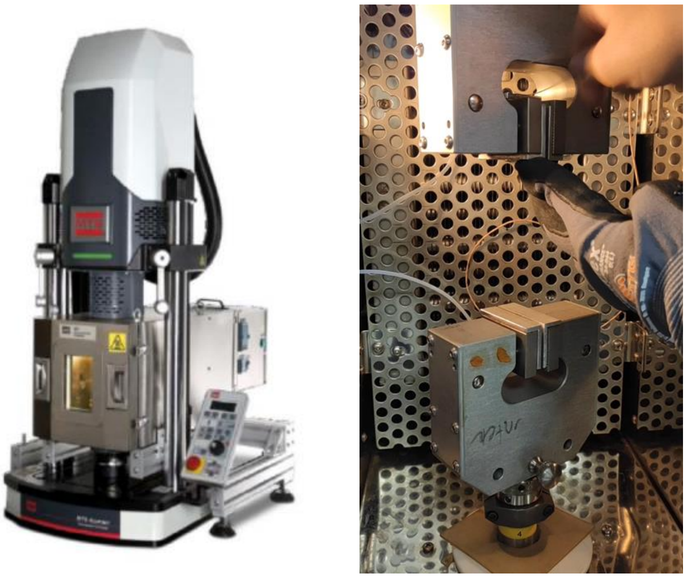
3.2 Experimental Simulation

The test procedure was developed based on previous attempts. Different process parameters were tested and optimized to shorten the overall test time.

3.2.1 Testing Procedure Development

The MTS Acumen™ 3 Test System that can be seen in Figure 11, connected to the MTS Flextest 40 Controller, was used for the testing procedure. It is equipped with a clamping system composed of pneumatic parallel clamps and the Mytron KPK 27 KH Climate chamber to control the temperature and the humidity. The software MultiPurpose Testware (MPT) and the MultiPurpose Elite (MPE) were used for the test procedure creation and for the data acquisition throughout the test.

Both testing procedures – with and without PCI – as well as all tensile tests were performed in the MTS.



(a) (b)

Figure 11 – (a) MTS Acumen^{TM} 3 Test System equipment [20] ; (b) Placing a cord inside the MTS.

3.2.1.1 Tensile Test

This test embodied the conditioning of the sample and the evaluation of the force when a increasing strain is applied in the cord. The tensile test was performed to virgin cords – cords that did not undergo any curing and PCI process – for two different room temperatures (23 °C and 60 °C) and to cords after the testing procedure with and without PCI.

3.2.1.2 Test Procedure without PCI

The first testing procedure included the curing process and the cooling step without PCI. A conditioned cord was clamped in the machine. The considered room temperature was 60 °C. When the test begins, the temperature starts to increase and the cord is stretched 1% or 3% depending if it is a carcass or cap-ply cord, respectively. Once the temperature in the chamber reaches the 150 °C corresponding to the curing temperature and stabilizes, it remains that way for 5 minutes. The curing process is said as being strain controlled because throughout the entire process the cord is kept stretched with the same displacement. Once the curing cycle is over, to simulate the tire being released from the curing mold, the force applied in the cord is removed and the chamber cools down to room temperature. Once the final temperature is stabilized, the time stops running and the tensile test is performed on the cord. The software takes the data related with the time, temperature and humidity in the chamber as well as displacement and force applied in the cord. Figures 12 and 13 show the typical given curves for temperature and displacement and for force applied in the cord and displacement for PA 6.6, respectively.

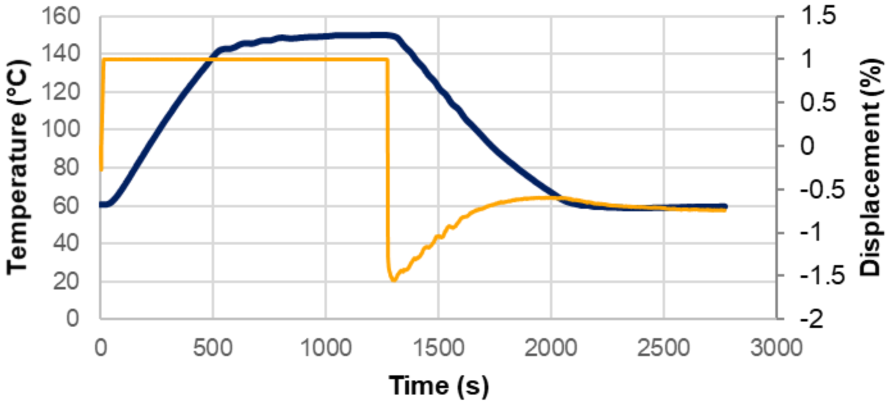


Figure 12 - Typical plot for temperature (blue line) and displacement (yellow line) in function of time for a test procedure without PCI for PA 6.6

In Figure 13 it can be seen that in the first 500 seconds of the curing step, when the cord is stretched and the temperature starts to increase, the applied force to keep the cord stretch also increases to counteract the increase of the cord's shrinking force with the temperature.

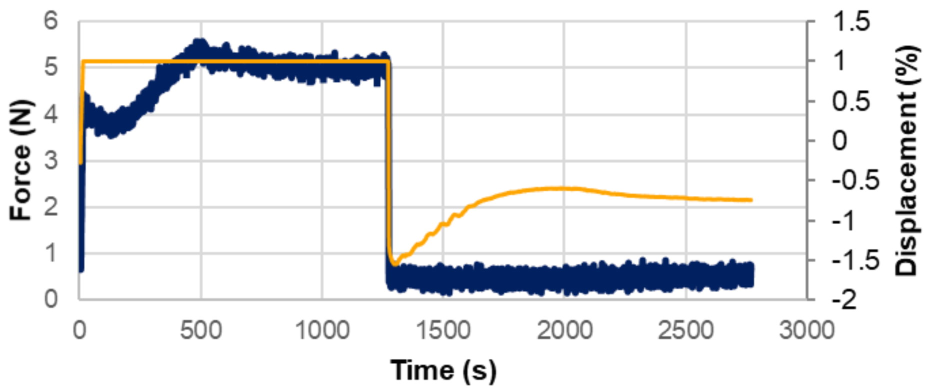


Figure 13 - Typical plot for force (blue line) and displacement (yellow line) in function of time for a test procedure without PCI for PA 6.6

3.2.1.3 Test Procedure with PCI

The final testing procedure included the curing and PCI processes. The curing step is the same as the testing procedure without PCI. To simulate the tire being released from the curing mold and inserted in the PCI stand, the force applied in the cord is removed during 30 seconds while the temperature is still 150 °C. Then, a load of 10 N is applied to stretch the cord and the temperature in the chamber starts to decrease, simulating the cooling down of the cords with PCI. Once the temperature in the chamber reaches a specific temperature, the force is removed and the cord cools down freely. When the temperature of the chamber stabilizes at the room temperature, the time stops running and the tensile test is performed to the cord. In the same way as without PCI, Figures 14 and 15 show the typical obtained curves for temperature and displacement and force and displacement in function of the temperature for PA 6.6, respectively.

The PCI step is said to be force-controlled, since a fixed pressure is applied. This inner pressure is equivalent to the force per each individual cord. Usually, a force of 2.03 bar or 4 bar is used depending on the type of tire application – if it is for a normal passenger car or for a racing car, or depending on the curing temperature, for example. By knowing the applied inner pressure, a Finite Element Model (FEM) simulation was used to estimate the actual force per cord in the carcass and cap-ply components. The results can be seen in Chapter 4.

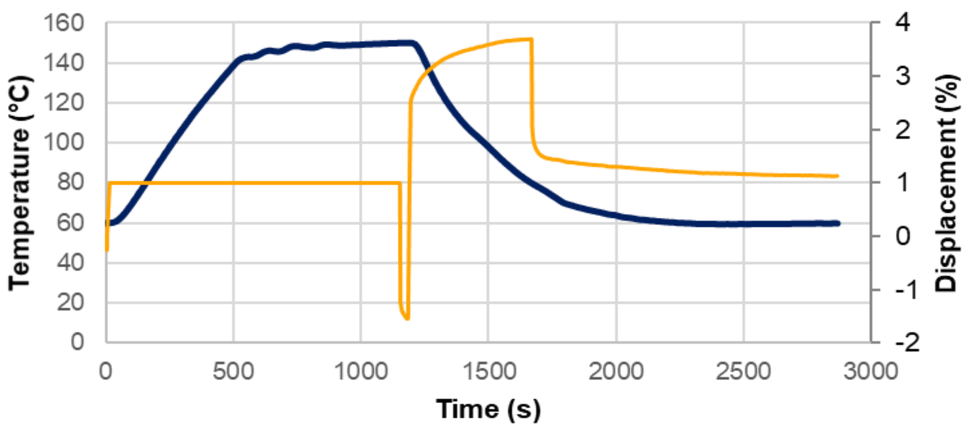


Figure 14 - Typical plot for temperature (blue line) and displacement (yellow line) in function of time for a test procedure with PCI for PA 6.6

Lastly, in both plots one can notice that, by looking at the displacement curve, the cord exhibits creeping during the PCI step. This is due to the fact that the temperature in the chamber is decreasing and so is the shrinking force. The applied fixed force during PCI is greater than the shrinking force leading to creeping of the cord.

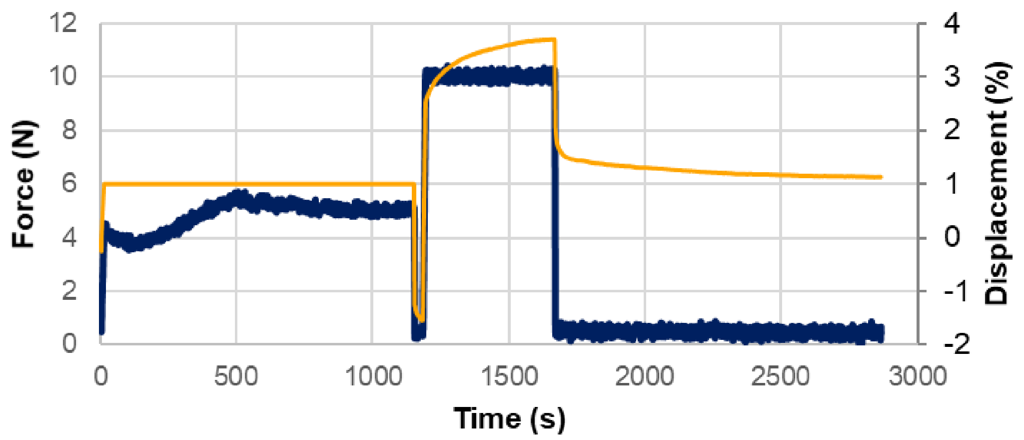


Figure 15 . Typical plot for force (blue line) and displacement (yellow line) in function of time for a test procedure with PCI for PA 6.6

3.2.2 Testing Procedure Optimization

By the time this thesis project started, the tests that were being performed in the MTS were taking 60 minutes to be completed. Moreover, they would consist of two steps. The first would be the curing step and the second simulated a tire cooled down with a fixed value for the strain – no waiting time in between. It was seen that the curing step is strain controlled and the PCI step is force controlled. The force per each individual cord during the PCI process for carcass and cap-ply cords was estimated with a FEM model simulation and the graphs can be found in Annex A. For a tire containing the textile cords from Table 4 in its composition, the maximum cord load observed on carcass cords for a PCI inner pressure of 2.03 and 4 bar was of 3.5 N and 4.5 N, respectively. By increasing the inner pressure in approximately 50% the change in the force was not significant. The same can be observed for cap-ply cords where the maximum cord load increased from 19 N to 21 N. For that reason, the values considered for the PCI force on carcass and cap ply cords were of 4 and 20 N, respectively.

Table 4 – Composition of a specific tire.

Tire application	Polymer	Cord Construction
Carcass	PET	2200x2
Cap-ply	PA 6.6	1400x2

It can be seen that the force for different PCI inner pressures is kept constant for carcass and cap-ply cords. For that reason, a standard force of 10 N was chosen to allow the comparison of cords with same polymers and different applications.

There was a limitation of the MTS regarding the maximum temperature it could reach, and that value was of 160 ºC. By testing the cords for a curing temperature of 150 and 160 ºC the results were similar. For that reason, the 150 ºC was chosen to be the curing temperature, enabling the time of the test to be reduce since the MTS would take less time to stabilize in a lower temperature.

Lastly, different room temperatures (RM) were tested – 23, 40 and 60 ºC – to verify if it would be possible to increase the RM and so decrease the test time. The chosen RM was of 60 ºC since below that temperature the results for PA 6.6 would be constant since the temperature is below the PA's T_g.

4 Results and Discussion

After submitting all cords to the experimental procedure, the obtained results were organized and discussed. The Design of Experiments can be found in Appendix A. The sub-chapters were organized first focusing on the results regarding the process parameters followed by results for different material constructions.

4.1 Influence of Process Parameters

In this sub-chapter the main goal was to evaluate the effect of the variation of the process parameters in the tested cords – if there is any effect on the final displacement and on the modulus and consequently on the stiffness of the cords. Three parameters were assessed: PCI release temperature, curing strain and PCI force.

4.1.1 PCI Release Temperature

PCI release temperature is the temperature at which the tire is released from the PCI stand. For the testing procedure, it is represented as the temperature during the cooling phase at which the force is removed from the cord.

To assess the behaviour of tire cords for different release temperatures, all cords were studied. Starting by PA 6.6, Figure 16 simulates the behaviour of the cord length undergoing curing and PCI process, displaying the curves of displacement in function of time for PA 3 released from the PCI at four different temperatures – 150, 120, 80 and 60 °C. The curves obtained for PET and for the hybrid are similar and can be found on the Appendix B. Figure 17 depicts the Force-Elongation curves for virgin cords at room temperature and for cords undergoing the testing procedure.

In Figure 16 it can be observe that cords released from the PCI process at higher temperatures will shrink more. The shrinkage of a cord is directly proportional to the impact on the cord's displacement. For that reason, cords released at higher temperatures will have a higher impact between the final displacement and the previous one. In contrast, cords released at lower temperatures will shrink less. Moreover, having into account that PA's T_g value is approximately 60 °C, the closer the release temperatures is to the material's T_g, the smaller the impact observed in the final displacement compared with the previous displacement.

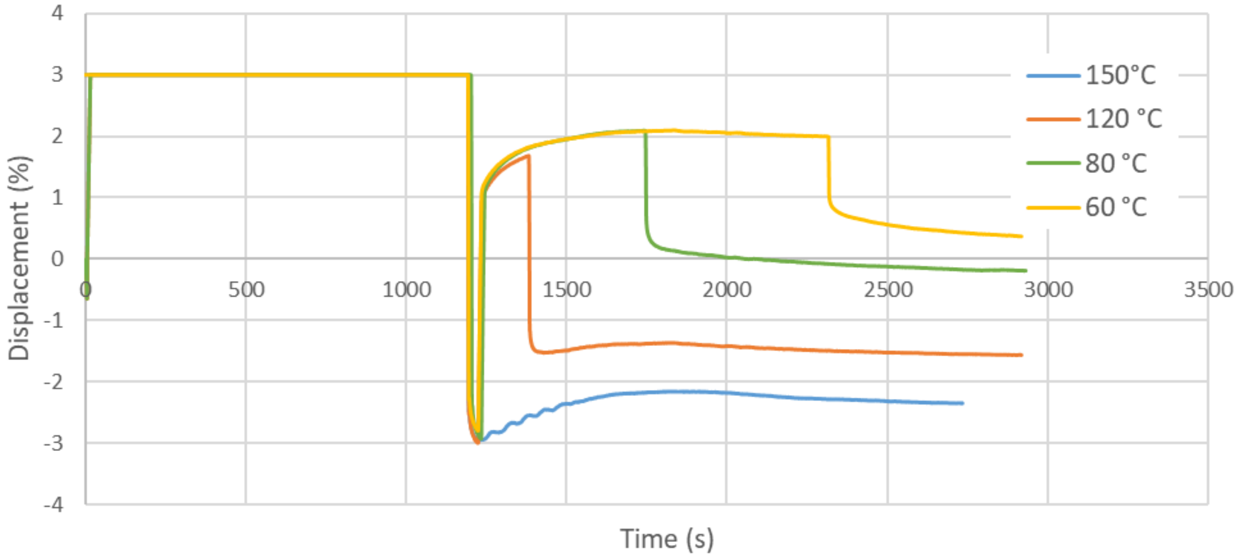


Figure 16 - Displacement in function of time for PA 3 cords that did not undergo PCI (released at 150 °C) and cords undergoing PCI released at different temperatures (120, 80 and 60 °C).

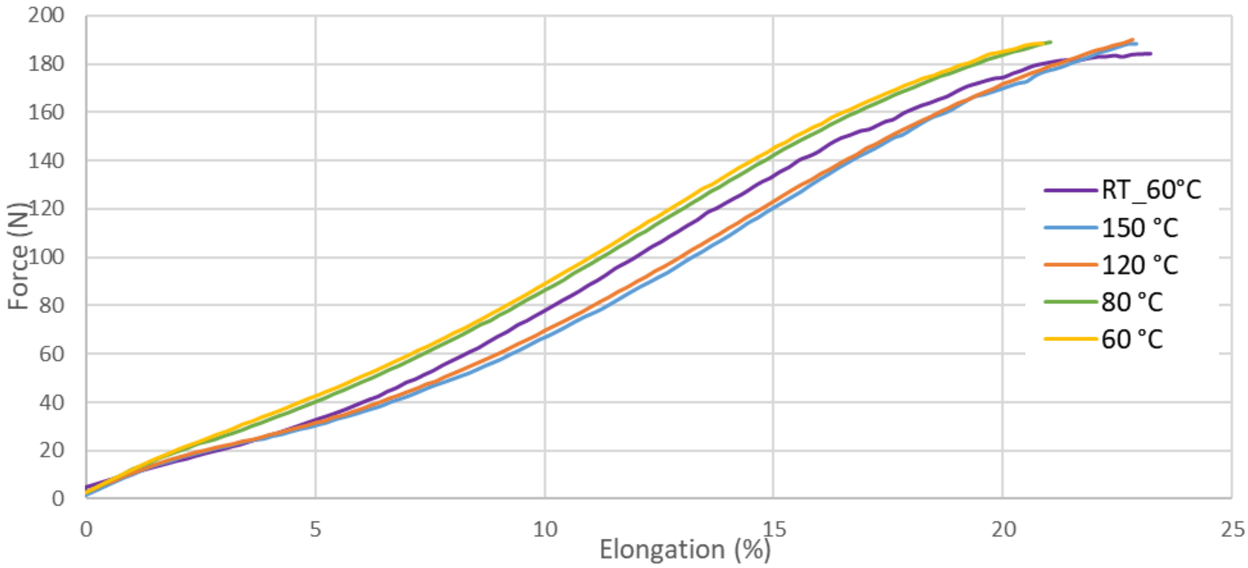


Figure 17 - Force-Elongation curves for virgin PA 3 cords at room temperature (RT) and for PA 3 cords not submitted to PCI (cords released at 150 °C) and undergoing PCI released at different temperatures (120, 80 and 60 °C).

In Figure 17 it is noticed that comparing with the curve for a virgin cord, cords undergoing only the curing process will see a decay in their material modulus. The same is applied to cords that also undergo the PCI process but are released earlier, at high temperatures. On the other hand, cords that undergo PCI process and are released at temperatures closer to the material's T_g might observe an increase on the material modulus. It is implied that the PCI process conditions can be adjusted to obtain textile cords with improved properties, if desired. The PCI release temperature not only affects the final displacement of the textile cords, it also influences the material modulus.

To have a general overview of the textile cords' behaviour for different release temperatures, the final displacements - obtained from curves like the one in Figure 16 – were plotted in function of the different release temperatures as it can be seen in Figure 18. PA cords have a linear behaviour regarding the final displacement for different PCI release temperatures, meaning that a cord's shrinkage is directly proportional to the temperature. Through this regression it can be noticed that, for PA 3, to obtain the target final displacement of 0 %, the cord should be release at 76 °C. A displacement of 0 % implies that the cord after curing press and PCI treatment has the same length as the cord before treatment. This situation is ideal so that the cords keep the same properties throughout all the processes.

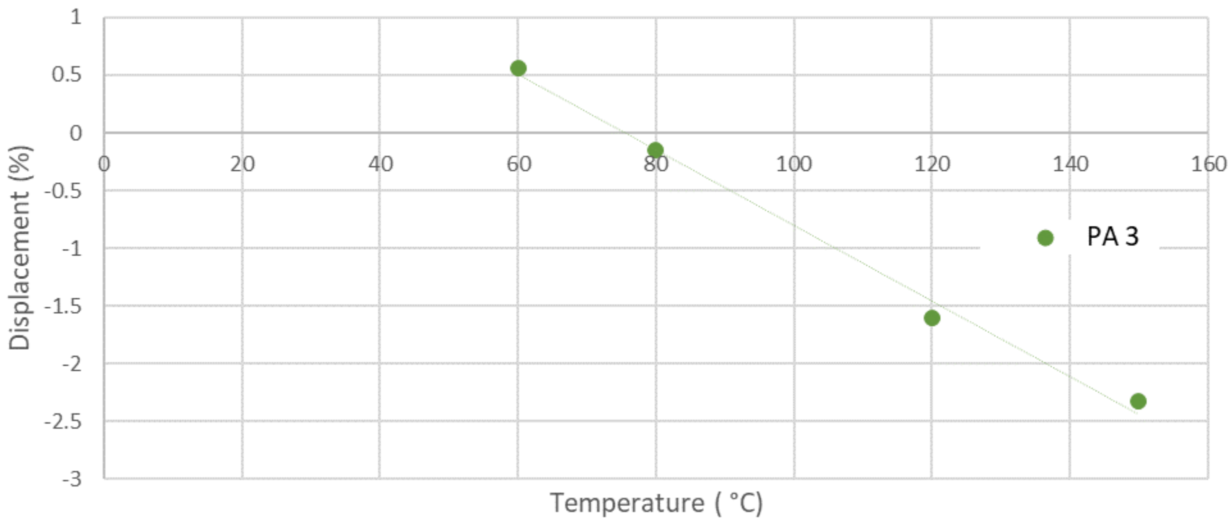


Figure 18 - Final displacement as a function of the PCI release Temperature for PA 3.

Focusing on the data obtained for PET 1 in Figure 19, there is a sudden change of the curve's slope close to 80 °C. This is due to the fact that the T_g of PET is also close to 80 °C. Below this temperature, the chains of the polymers in the textile cords are "frozen" and will not shrink. It can then be antecipated that cooling a tire in the PCI stand to a temperature equal or below the material'sT_g leads to a positive impact on the material properties and stability and, as consequence, a more uniform tire performance.

From the literature and chapter 2, it is known that rayon has a high degree of crystallinity for a polymer and is known for not having a thermal shrinkage. Figures 20 and 21 depict the curves for rayon. Releasing cords from PCI at different temperatures does not have an impact on the final displacement of Rayon cords. The same can be observed regarding the modulus of the materials. These results confirm what is in the literature. For this reason, is recommended for tires with textile cords made of Rayon not to undergo the PCI step since there will be no shrinkage from rayon's side.

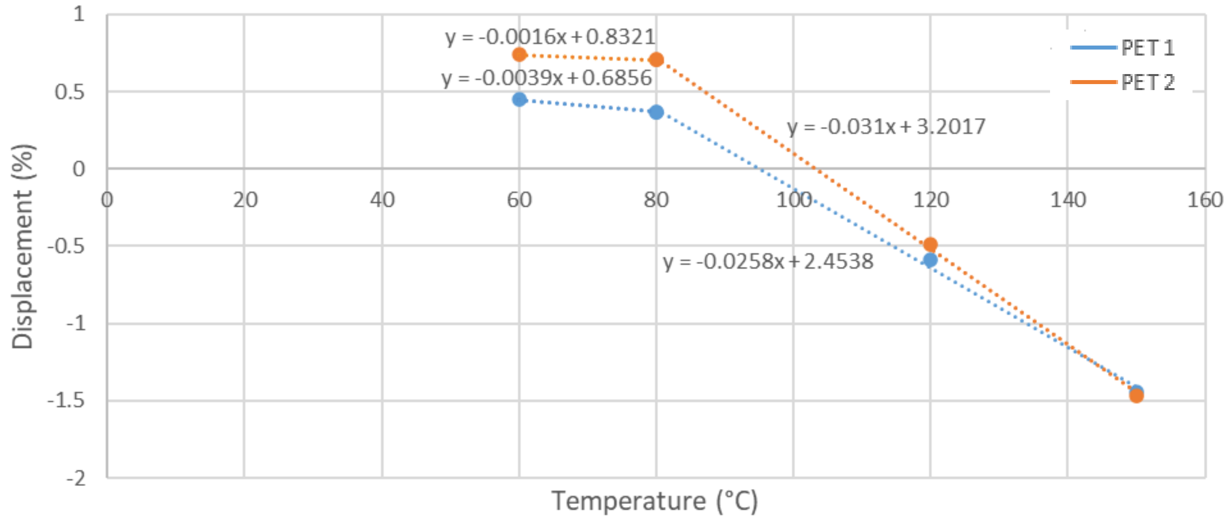


Figure 19 - Final displacement in function of the PCI release Temperature for PET 1.

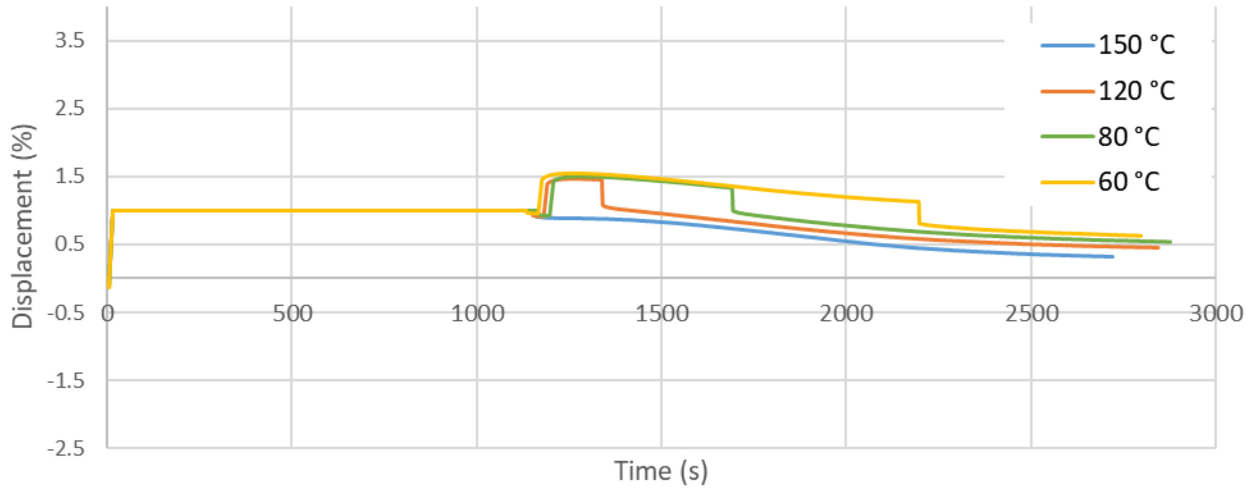


Figure 20 - Displacement as a function of time for R 1 cords that did not undergo PCI (released at 150 °C) and cords undergoing PCI released at different temperatures (120, 80 and 60 °C).

In Figure 22 the displacements as function of the different PCI release temperature are plotted for different fibres and the different slopes can be compared. The curve for rayon has a slope of approximately 0, which emphasizes the fact that Rayon does not shrink. On the other hand, PA 6.6 has the highest slope, so these textile cords have highest thermal shrinkage and shrinking force.

In what concerns the hybrid, the behaviour visualized resembles PA 6.6 but with lower shrinkage. This PA and aramid combination will lead to a stronger cap-ply cord with lower shrinkage, combining the properties of both polymers to obtain a cord with an even better performance.

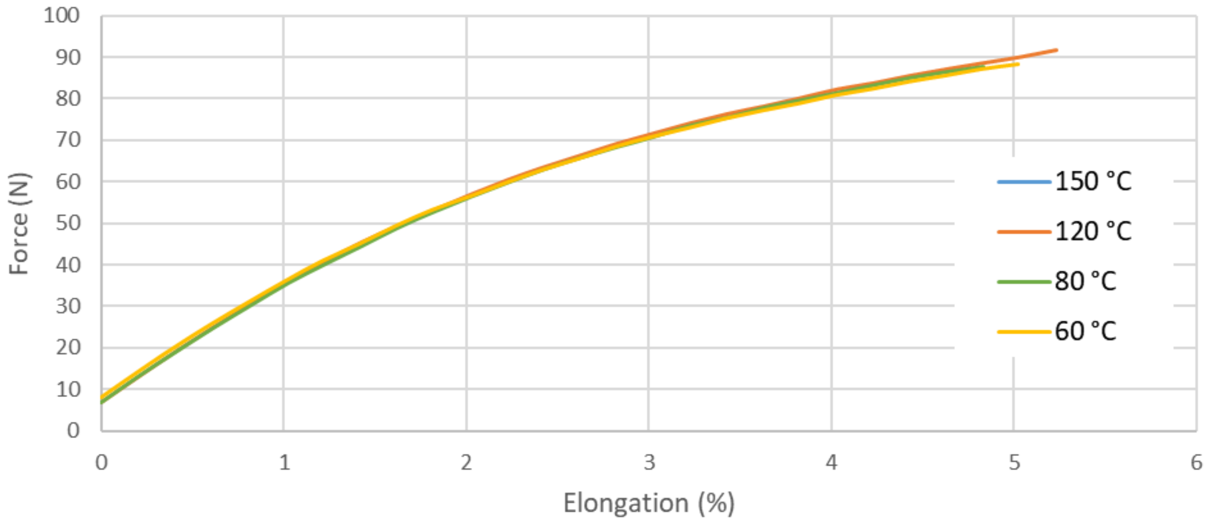


Figure 21 - Force-Elongation curves for virgin R 1 cords not submitted to PCI (cords released at 150 °C) and undergoing PCI released at different temperatures (120, 80 and 60 °C).

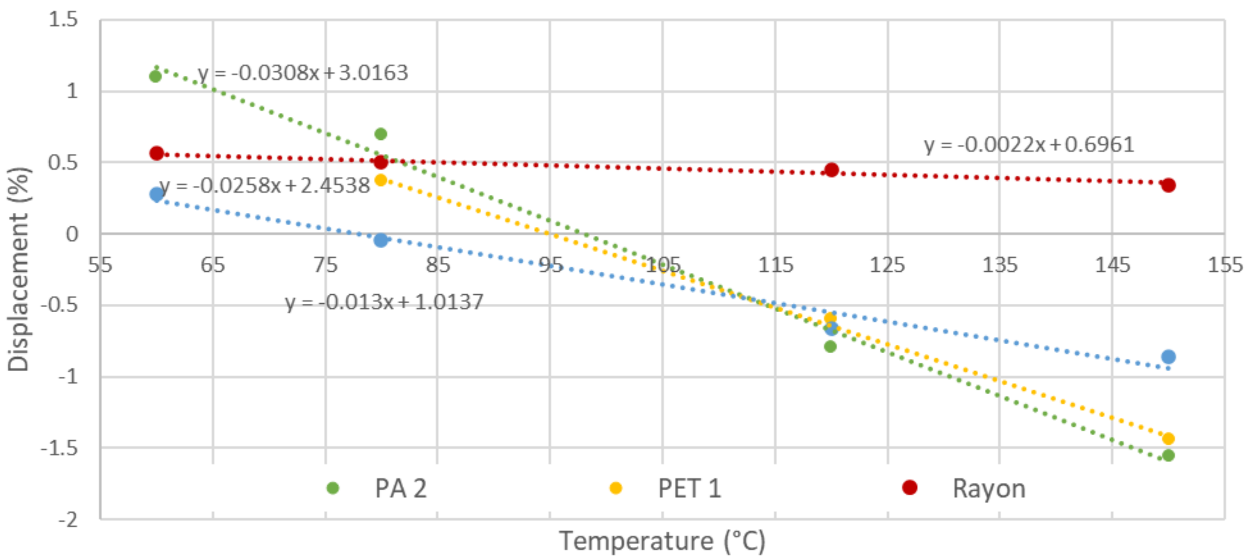


Figure 22 – Comparation of final displacement as a function of the PCI release temperature curves for different polymers – PA, PET, Rayon and Hybrid.

From this subchapter, the points to focus are that for PA, PET and hybrid the temperature at which the cords are released from the PCI rim can have a major impact in the properties of these materials. If the release temperature is close to the material's T_g, the impact is lower. For rayon there is no significant impact observed since it does not shrink.

4.1.2 Curing strain

In Chapter 3 the usual curing strain felt by a cord was referred and it depends on the location of the cord in the tire - 1% or 3% for carcass and cap-ply cords, respectively.

Figures 23 depicts the curves of the displacement in function of time for PA 1 released at 120 °C, a typical carcass cord. Even though two different curing strains were applied, the final displacement and the material modulus are similar for both cases. In the Appendix C, Figure 45 shows that even if PA 1 is released at a lower temperature (80 °C) and undergoes two different curing strains, the result is the same. The same can be said for the modulus of the material as seen in Figure 24. It can be inferred that the curing strain has no influence on the final displacement and stiffness of textile cords.

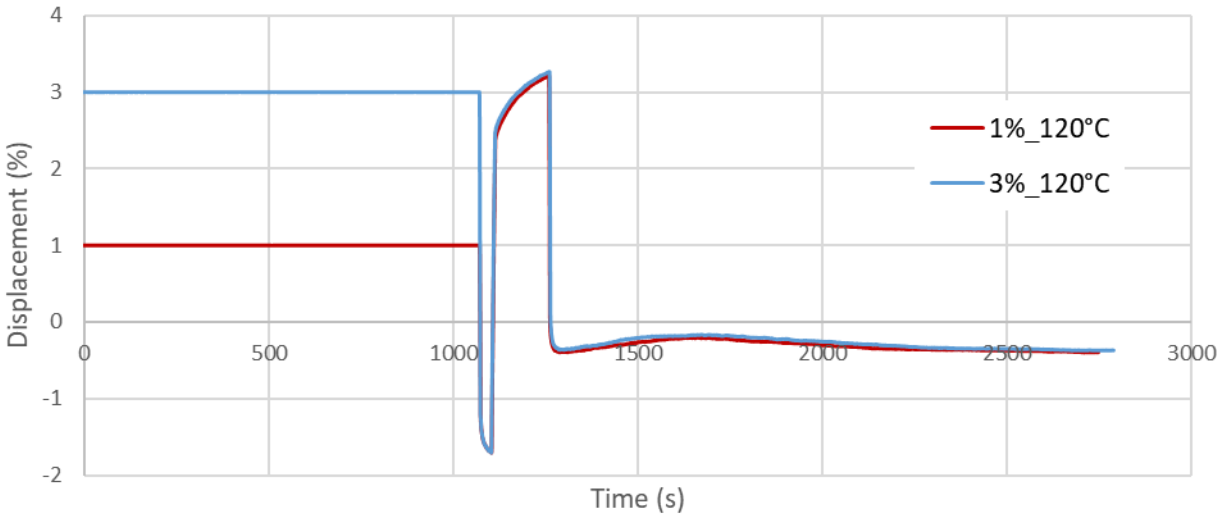


Figure 23 - Displacement in function of time for PA 1 released from PCI at 120 °C undergoing two different curing strains: 1% (red curve) and 3% (blue curve).

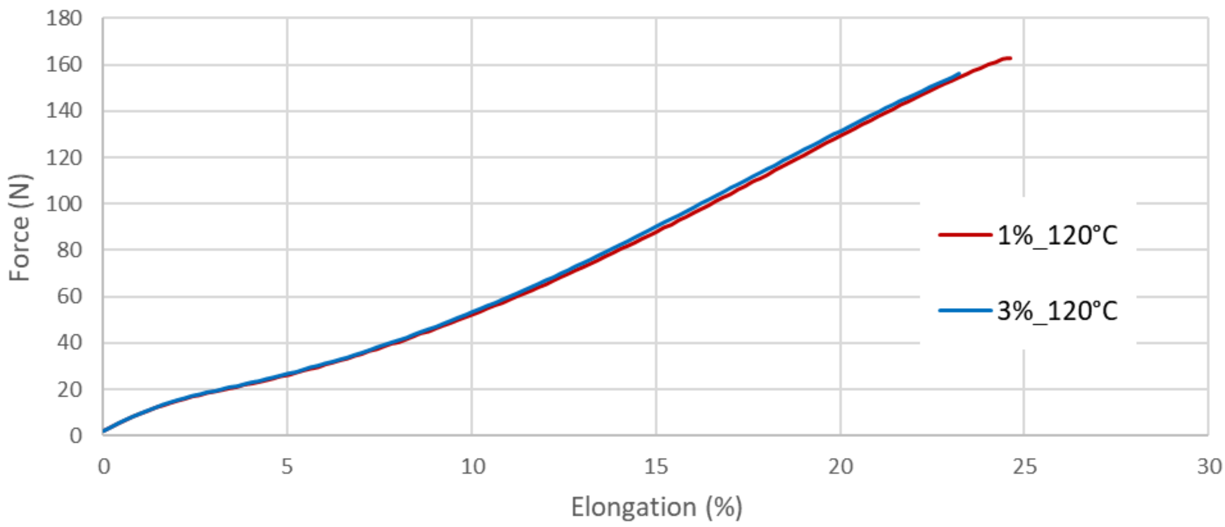


Figure 24 - Force-Elongation curves for PA 1 released from PCI at 120 °C undergoing two different curing strains: 1% (red curve) and 3% (blue curve).

4.1.3 PCI Force

The force applied during PCI was varied to study its effect on different textile cords. Figure 25 plots the displacement as a function of time for PA 2 released at 80 °C. In Figure 26, the Force-Elongation curve for the same material is displayed. By changing the PCI force, one can see that the final displacement is independent of the PCI force as well as the Force-Elongation curve – the modulus is kept constant. The same can be verified for nylon cords released at higher temperatures, as it can be seen in the Appendix D.

The same study was conducted for PET 1. In Figure 27 can be observed that, when released at 120 °C, cords that undergo a PCI force of 10 and 20 N have the same final displacement and stiffness. However, cords that undergo a lower PCI force of 4 N – the FEM simulation value obtained for carcass cords - will be less stretched during PCI and, when released, will shrink less, showing a lower impact on the final displacement. This result was expected since the force applied in the PCI is lower than the force during curing for this case, as it can be seen in Figure 48 on Appendix D. Despite this difference, all these cords will have a similar modulus as seen in Figure 28. Cords undergoing higher PCI forces compensate the stretch – and consequent increase of strength - with higher shrinking values due to the fact that these cords are released from the PCI stand at higher temperatures.

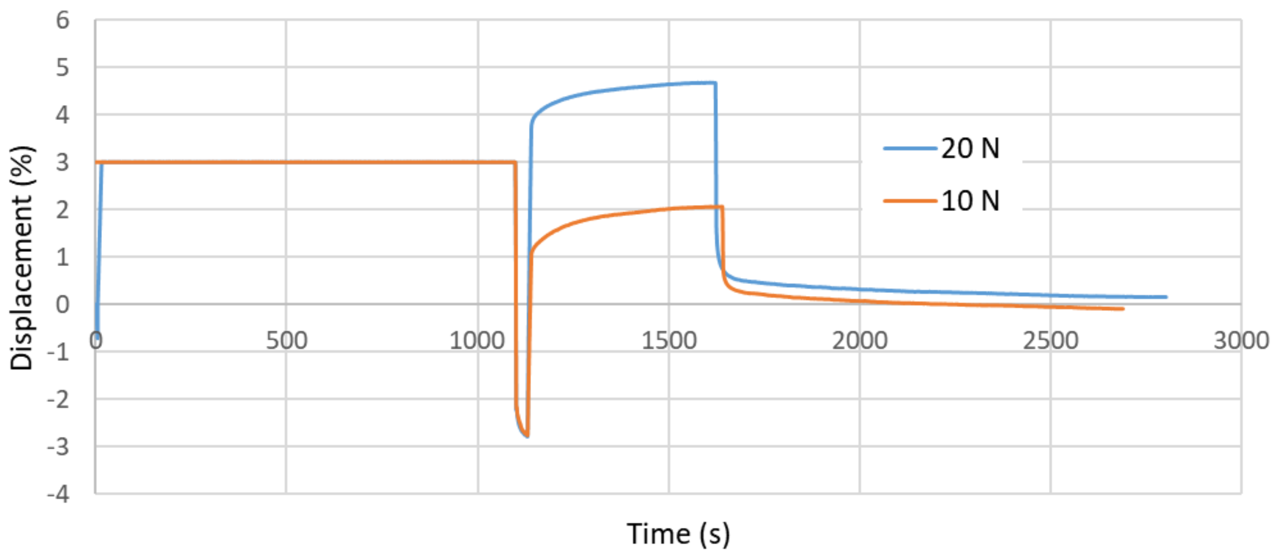


Figure 25 - Displacement in function of time for PA 2 released from PCI at 80 °C undergoing two different PCI forces: 20 N (blue curve) and 10 N (orange curve).

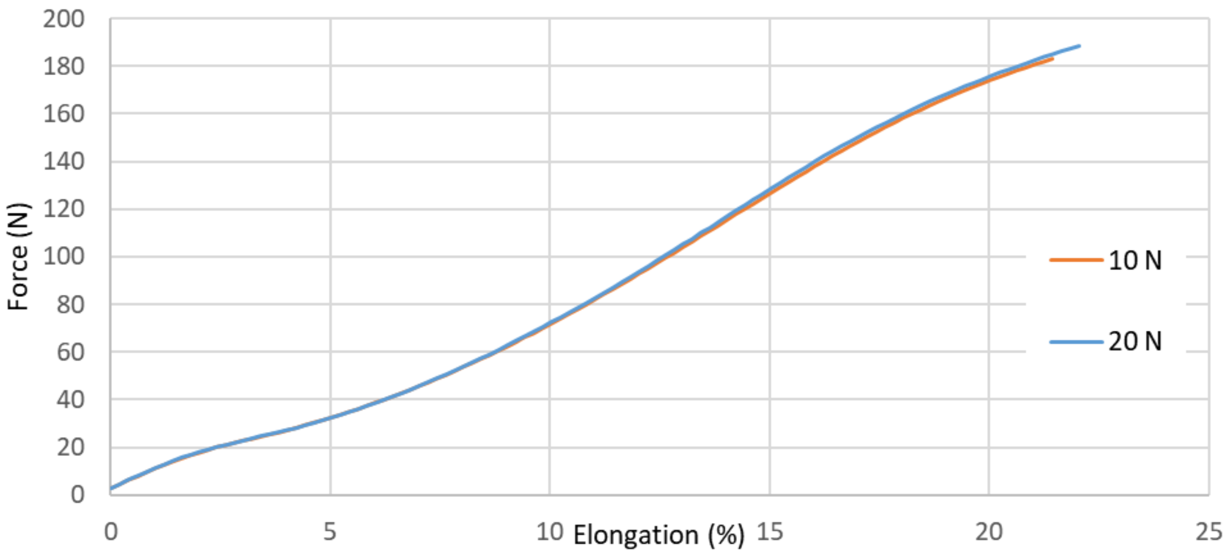


Figure 26 - Force – Elongation curve for PA 2 released from PCI at 80 °C undergoing two different PCI forces: 20 N (blue curve) and 10 N (orange curve).

The same study was performed to PET 1 cords that were released from the PCI process at 80 °C and the obtained result differs from the previous one. In Figure 29, it can be noticed that cords submitted to higher PCI forces will have a higher impact in the final displacement. Moreover, this impact is lower than in cords released at higher temperatures. Since these cords are being released at a temperature closer to the material T_g, the polymer chains have lower mobility and will shrink less. Furthermore, Figure 30 shows that cords undergoing higher PCI forces will show an increase in their material modulus since they are being stretched and will not shrink that much.

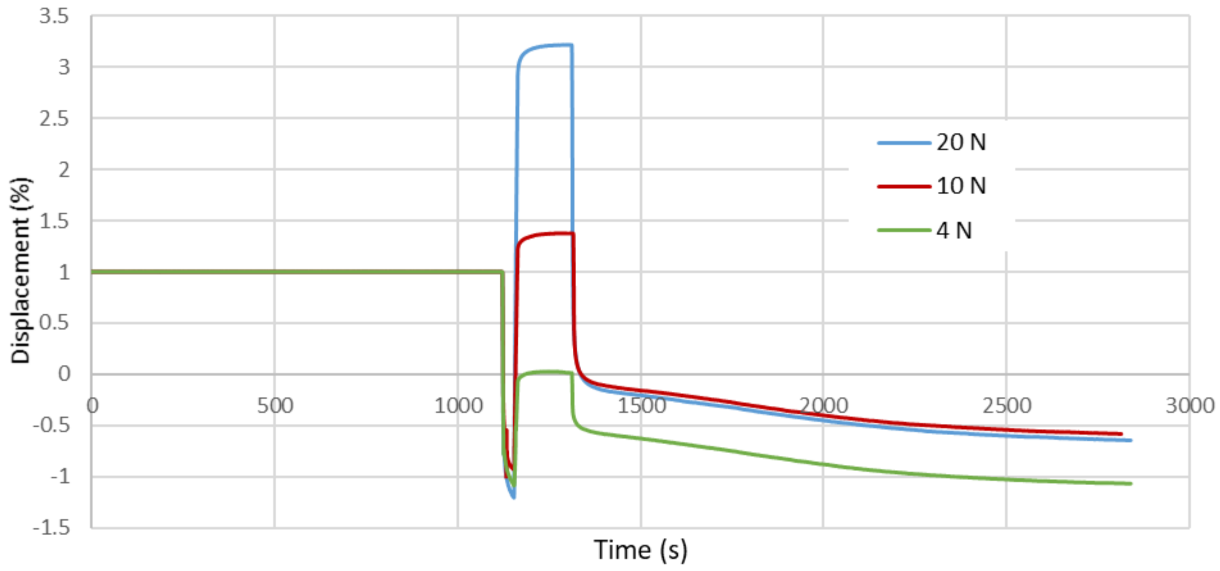


Figure 27 - Displacement in function of time for PET 1 released from PCI at 120 °C undergoing three different PCI forces: 20 N (blue curve), 10 N (red curve) and 4 N (green curve).

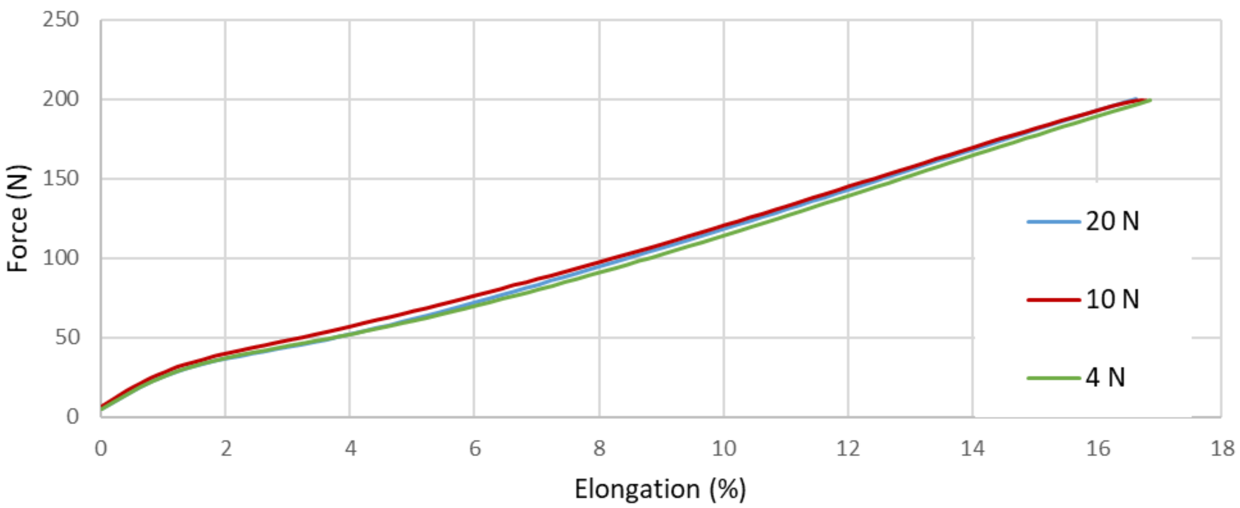


Figure 28 - Force – Elongation curve for PET 1 released from PCI at 120 °C undergoing three different PCI forces: 20 N (blue curve), 10 N (red curve) and 4 N (green curve).

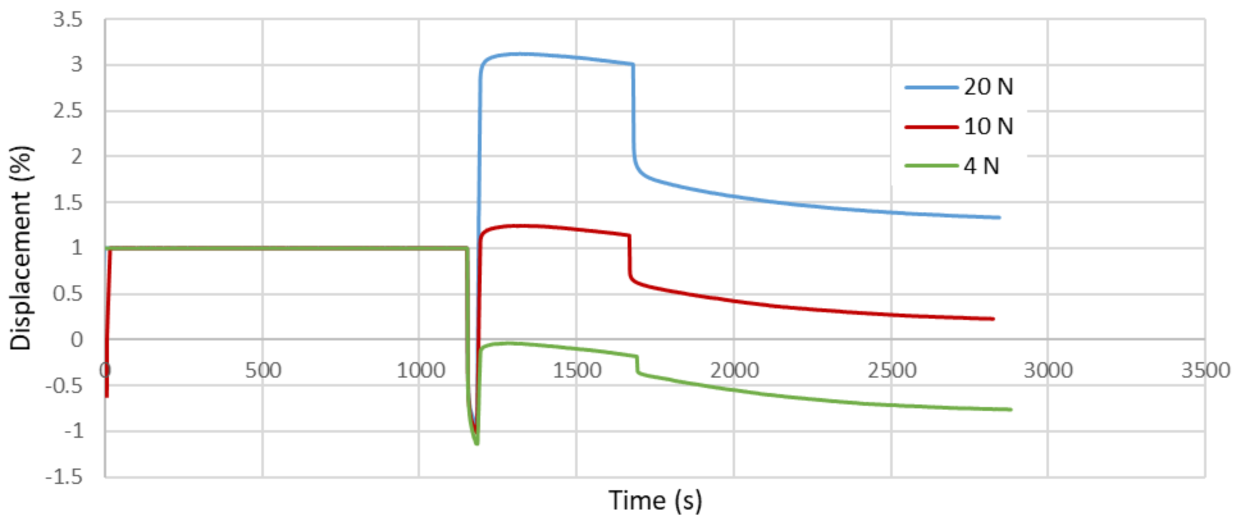


Figure 29 - Displacement in function of time for PET 1 released from PCI at 80 °C undergoing three different PCI forces: 20 N (blue curve), 10 N (red curve) and 4 N (green curve).

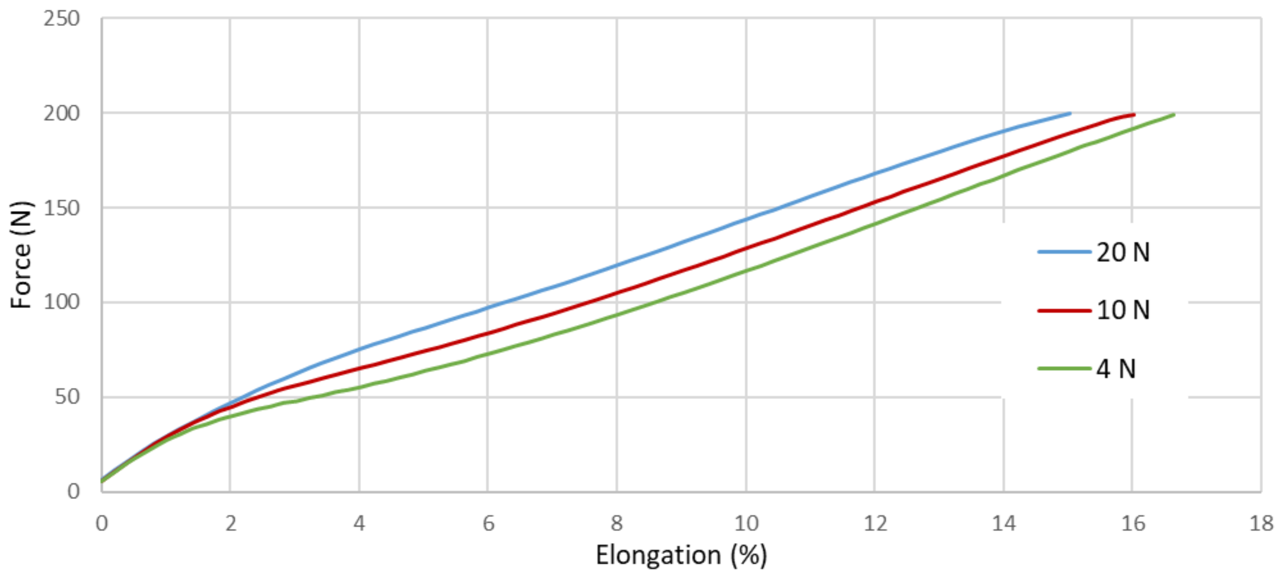


Figure 30 - Force - Elongation curve for PET 1 released from PCI at 80 °C undergoing three different PCI forces: 20 N (blue curve), 10 N (red curve) and 4 N (green curve).

Finally, different PCI forces were applied to the rayon and the results can be seen in Figures 31 and 32. As foreseen, rayon cords released at 80 °C will have no change in the PCI force from 10 to 4 N, leading to the same final displacement and material modulus. The same results were obtained when increasing the PCI release temperature.

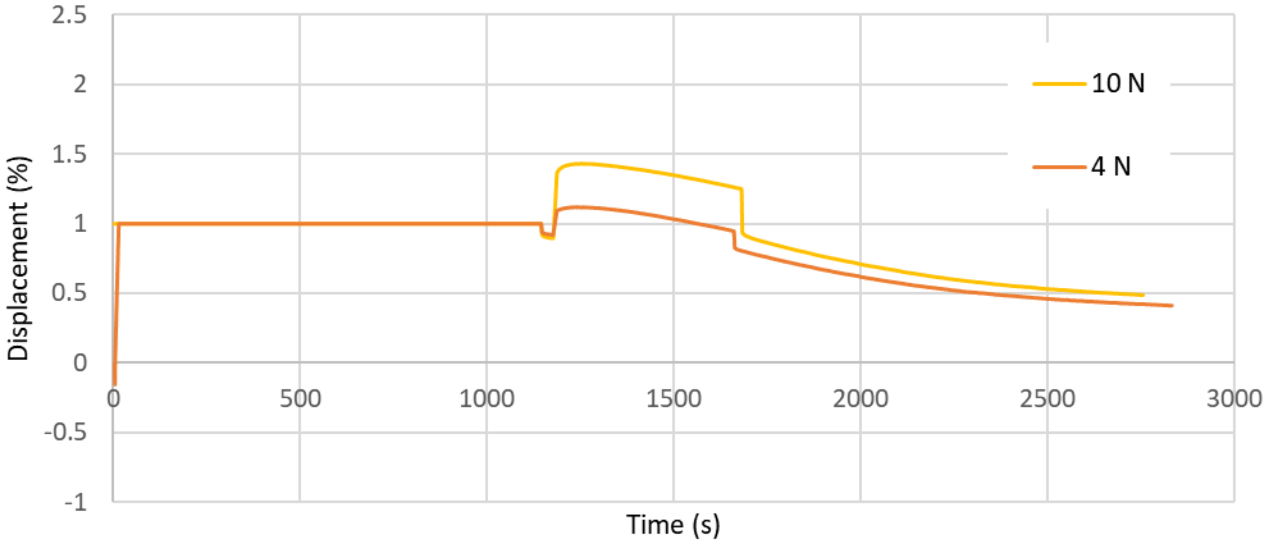


Figure 31 - Displacement in function of time for R 1 released from PCI at 80 °C undergoing two different PCI forces: 10 N (yellow curve) and 4 N (orange curve).

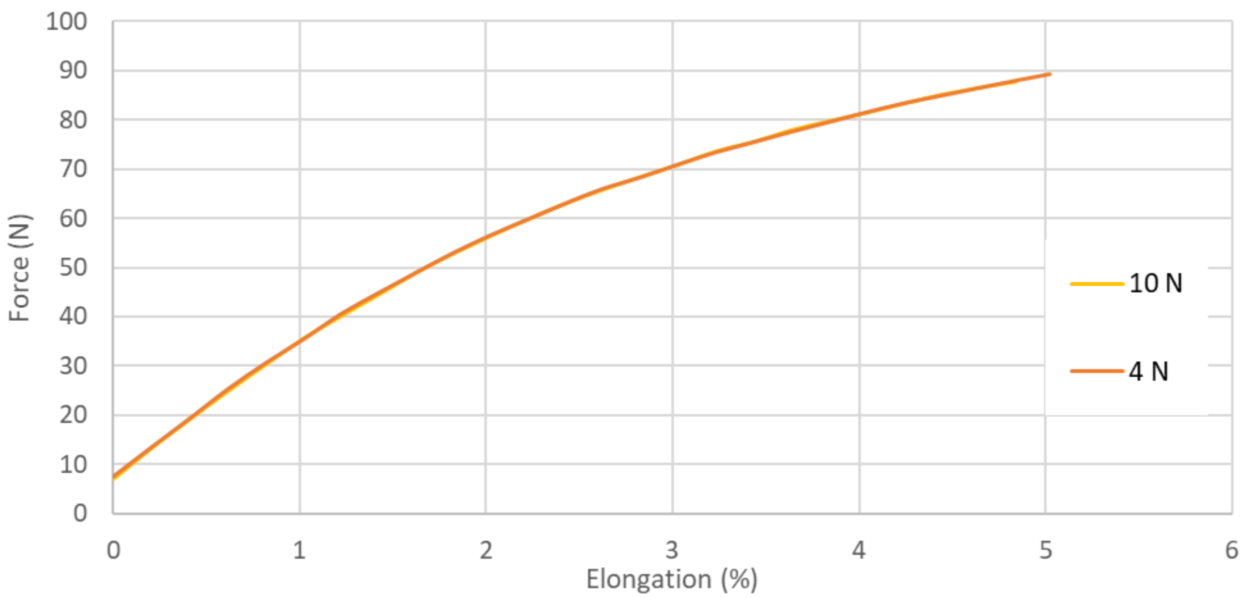


Figure 32 - Force – Elongation curve for R 1 released from PCI at 80 °C undergoing two different PCI forces: 10 N (yellow curve) and 4 N (orange curve).

4.2 Influence of Material type

After evaluating the process parameters, the materials' characteristics were the main focus. The effect of cords with different linear densities and twist factors on the final displacement and PCI release temperatures were studied.

4.2.1 Linear density

PA 2 and PA 4 are PA cords with equal twist factors of 150 and different linear densities of 1400 and 940 dtex, respectively. PA 2 is the cord with higher linear density, known as the thicker cord.

Figure 33 plots the curves of the displacement in function of time for PA 2 and PA 4 – cords undergoing curing and PCI processes. During the PCI step, PA 2 shows a lower creeping behaviour when compared with PA 4. This indicates that it has a higher shrinking force counteracting the PCI force. Higher shrinking force usually – but not always – means higher thermal shrinkage. For both cords to achieve the 0 % final displacement, having into account that the thicker cord has a higher shrinkage, it has to be released later at lower temperatures when compared with a cord that has a lower linear density. This can be observed in Figure 34, where the final displacement was plotted in function of the release temperatures, the optimum release temperature is obtained when the curve for each cord intercepts the x axis, so those temperatures are of 98 ºC and 106 ºC for PA 2 and PA 4, respectively. In this graph, both PAs show a linear behaviour and have similar slopes. The same conclusions were obtained when comparing PA 1 and PA 5 and PA 3 and PA 4 and can be found on Appendix E.

For PET, the obtained results are identical. In Figure 35, PET 1, when compared with PET 2, has a lower creeping behaviour during the PCI step, so its shrinking force and thermal shrinkage are higher. For that reason, this thicker cord has to be released at lower temperatures to obtain the same target final displacement of 0 %. On the other hand, it can also be said that cords with lower linear densities have a lower shrinkage and can be released at higher temperatures to obtain the final displacement of 0 %.

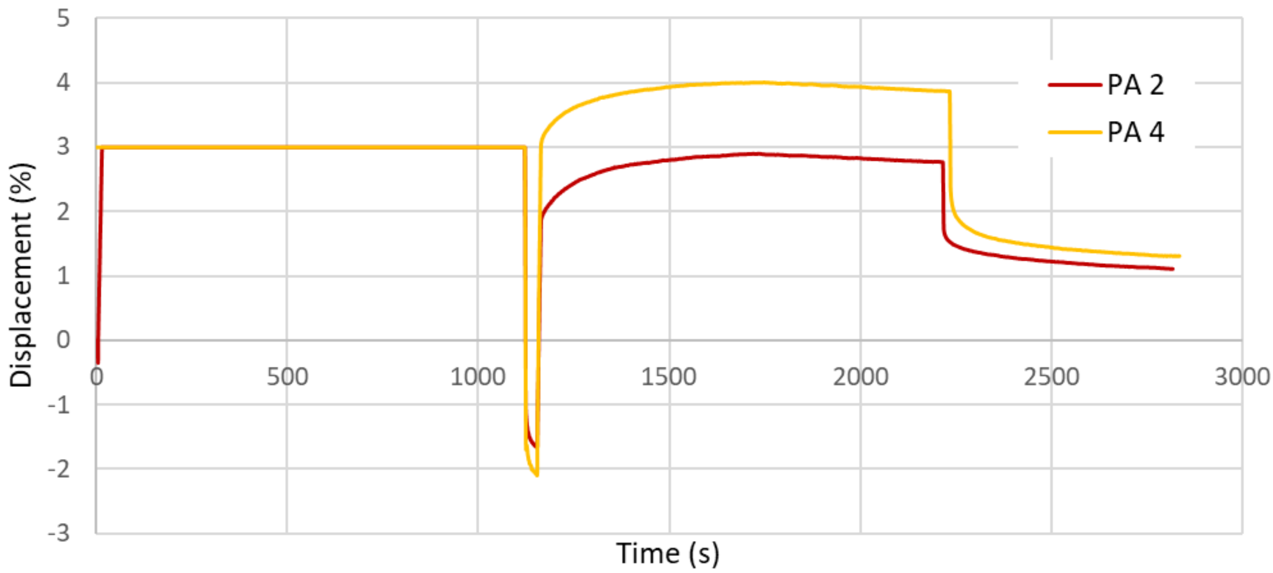


Figure 33 - Displacement in function of time for PA 4 (yellow line) and PA 2 (red line) released from PCI at 60 °C.

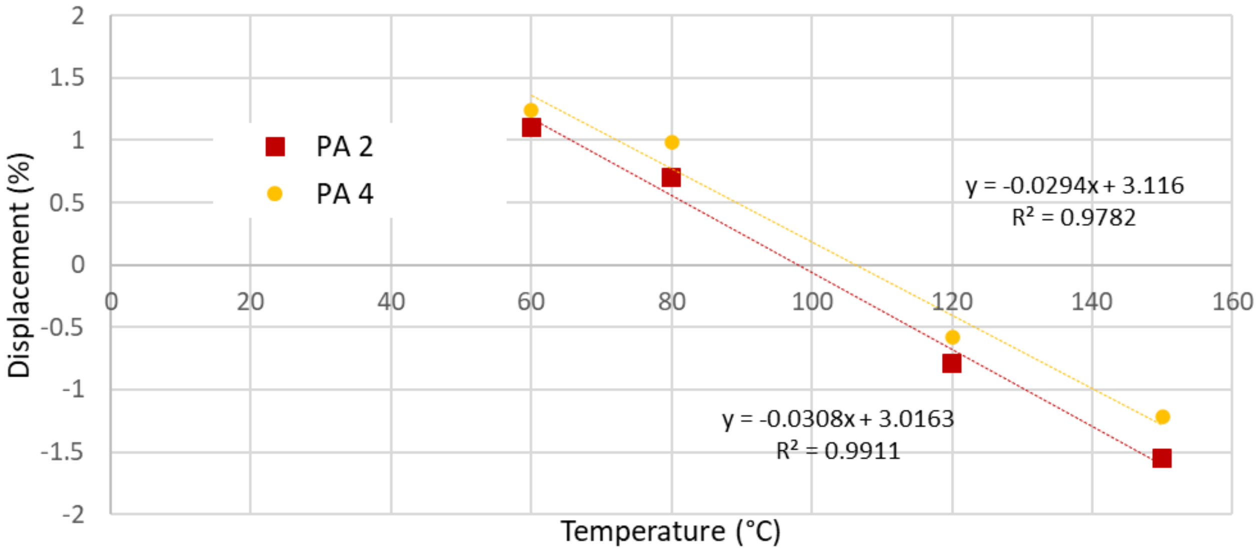


Figure 34 - Final displacement in function of the PCI release Temperature for PA 4 (yellow line) and PA 2 (red line).

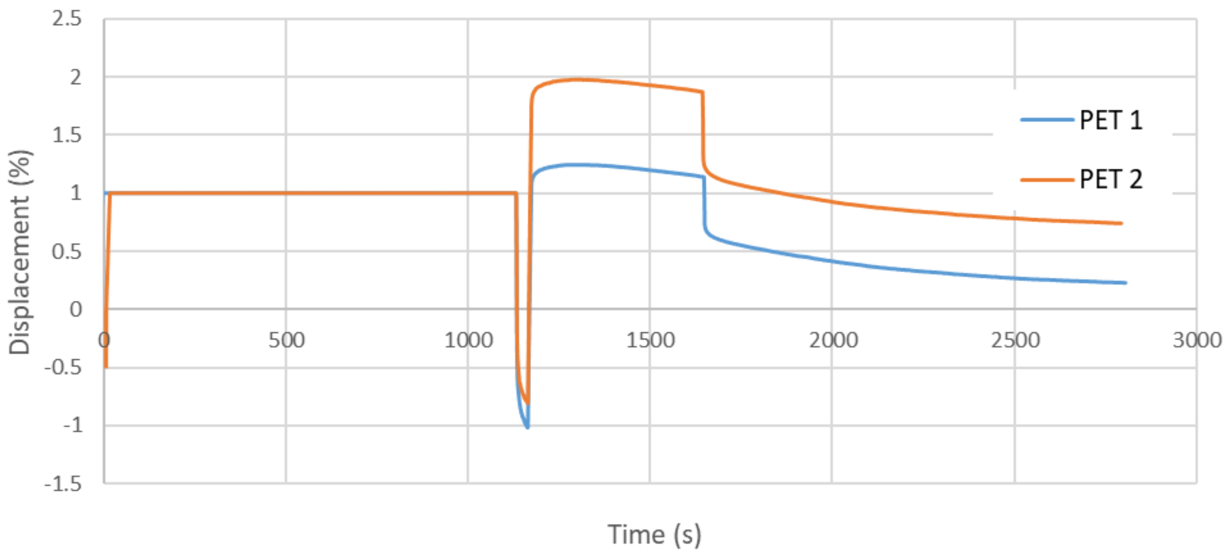


Figure 35 - Displacement in function of time for PET 1 (blue line) and PET 2 (orange line) released from PCI at 60 °C.

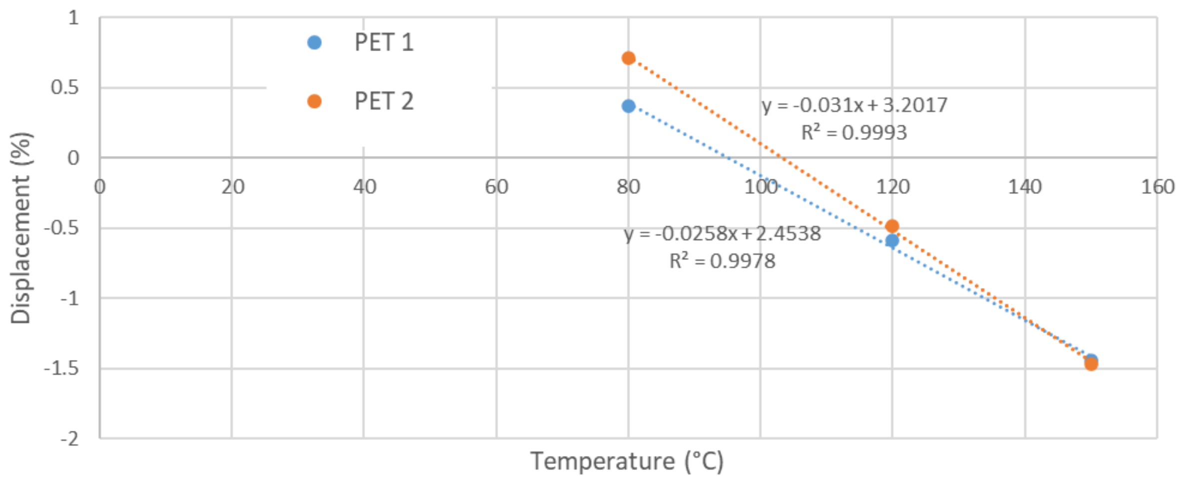


Figure 36 - Final displacement in function of the PCI release Temperature for PET 1 (blue line) and PET 2 (orange line).

4.2.2 Twist Factor

Following the same logic used for linear densities, PA 6.6 cords with different twist factors were also evaluated. PA 1 and PA 2 have a linear density of 1400 and twist factors of 200 and 150, respectively. From Figure 37 and similar as what was seen previously, PA 1 – the cord with highest twist factor – has a higher creeping behaviour. This indicates that the shrinking force that is counteracting the force during PCI is lower. As a result, this cord can be released at higher temperatures to obtain the final displacement of 0 % when compared with a cord that has a lower twist factor and a higher shrinking force. In Figure 38 this can be confirm by seeing that, to achieve the displacement of 0 %, PA 1 should be released at 120 ºC and PA 2 at 98 ºC, approximately. These results were not expected at first since, as seen in Chapter 2, higher twist factors lead to higher shrinkage. However, as it was also pointed in Chapter 2, there is an exception for PA, higher twist factors lead to higher shrinkage and lower shrinking forces.

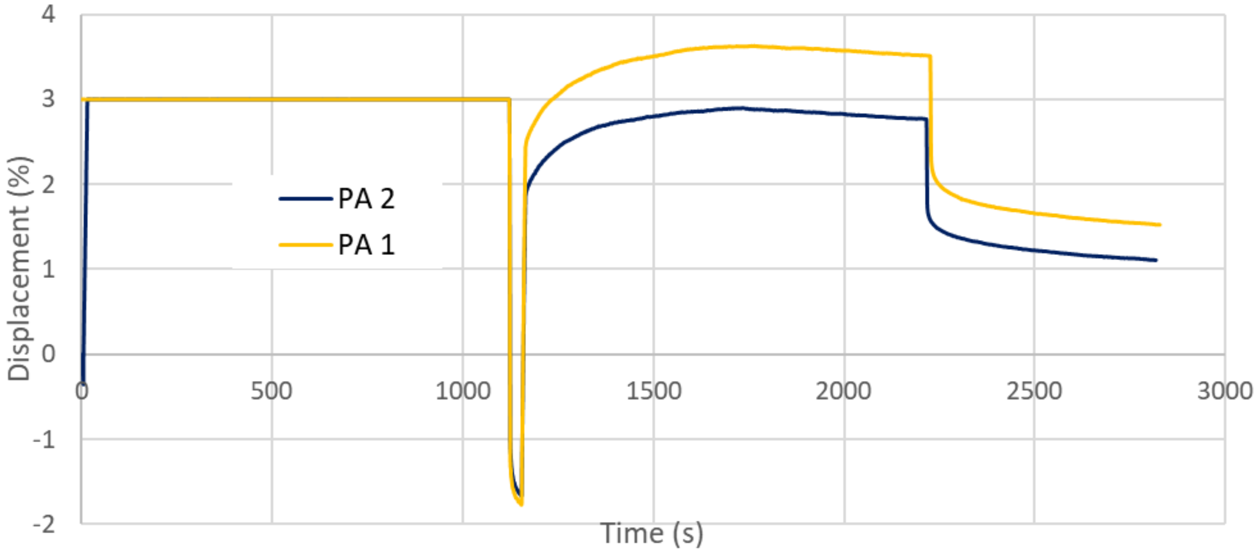


Figure 37 - Displacement in function of time for PA 1 (yellow line) and PA 2 (blue line) released from PCI at 60 °C.

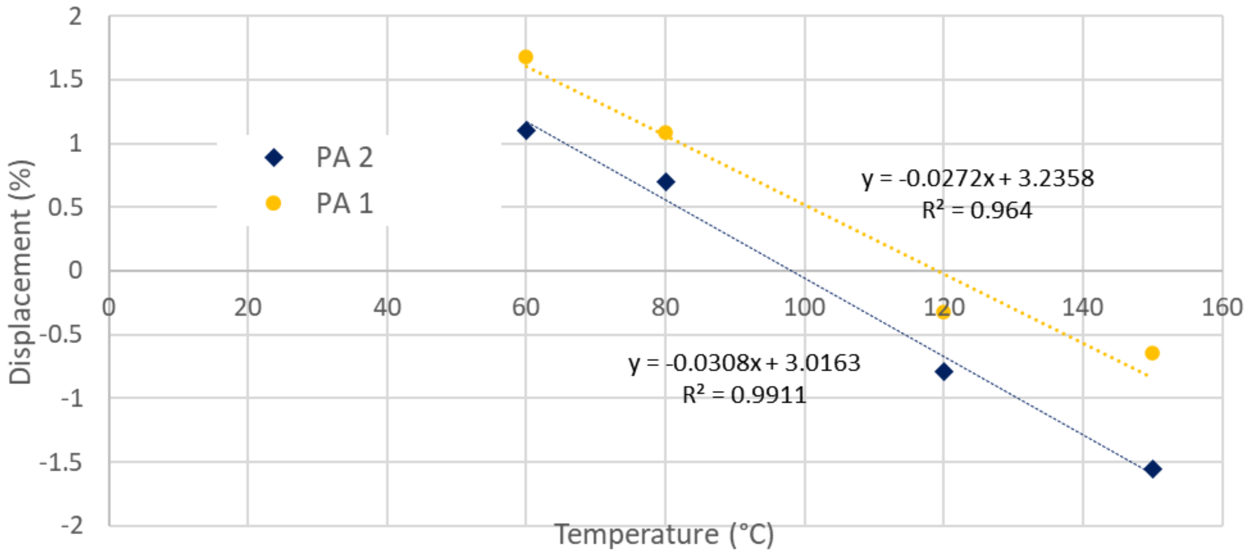


Figure 38 - Final displacement in function of the PCI release Temperature for PA 1 (yellow line) and PA 2 (blue line).

4.3 Development and implementation of Mathematical Models

After undergoing all tire manufacture processes, it is required that the length of a textile cord in the tire is kept the same, implying that the cords' properties do not change. This is verified when the cord is released from the PCI stand at a temperature that enables the final displacement to be of 0 %.

From the previous sub-chapters, it was noticed that cords show a linear behaviour when the final displacement is plotted in function of the different PCI release temperatures. Furthermore, the slope of these curves is similar. By intercepting the curve of each cord with the x axis – the final displacement is 0 % - it is possible to predict the optimum release temperature for the different cords. For that, two mathematical models were built – one for PA 6.6 and one for PET.

To obtain the model parameters, the least squares method was used. This method is a form of mathematical regression analysis used to derive estimates of the parameters which specify the line of best fit for a set of data. It assumes that the best fit curve has the minimal sum of deviations from a given set of data. Each point of data represents the relationship between a known independent variable and an unknown dependent one. [21] [22]

For PA 6.6, cords with different linear densities and twist factors were studied. The independent variables are the PCI release temperatures, the cords' linear density and twist factor. In a Microsoft Excel sheet with all these variables arranged in columns, a regression from the Analysis ToolPak was ran. The linear regression for PA 6.6 is structured as follows:

$$f = a + bx_1 + cx_2 + dx_3 \tag{4.1}$$

The dependent variable f stands for the final displacement and x_1, x_2 and x_3 are the independent variables linear density, twist factor and temperature, respectively. The coefficients *a*, *b*, *c* and *d* were obtained directly from the regression.

The mathematical model for PA 6.6 works by introducing the values of the total cord decitex – linear density of a single cord multiplied by the total number of yarns present – and the twist factor and a value for the optimum release temperature is obtained. The math behind this is straight forward: in Equation 4.1 the value for f is 0 and, by arranging the equation in function of the temperature, x_3, one obtains:

$$x_3 = \frac{a + bx_1 + cx_2}{d} \tag{4.2}$$

In addition, by introducing the current temperature at which the tire is being released from the PCI stand, the model infers what is the final cord length displacement and what is happening to the cord – if the fibre is creeping or shrinking. This is done by introducing the values of linear density, twist factor and the given release temperature in Equation 4.1 and the final displacement is computed. If this value differs by more than 10 % from the desired final displacement of 0 %, if this value is positive, it means that the fibre is creeping, and if it is negative the fibre is shrinking.

For PET, the mathematical model is used in the same way to obtain the same results, the only difference is that it doesn't depend on the textile cords' twist factor since all polyesters studied had the same value for the twist factor.

In practice, for the tire with specifications in Table 3, through the mathematical models it is possible to infer what should be the optimum PCI release temperatures for the different polymers and can be found in Table 5.

Table 5 – Optimum Release PCI Temperatures for PET and PA 6.6

Polymer	Cord Construction	Optimum Release Temperature (ºC)
PET	2200x2	97
PA 6.6	1400x2	95

Approximately, the PCI temperature is dependent of the curing cycle and, for a curing temperature of 150 ºC, it is defined in Equation 4.3.

$$PCI\ time = 1.3 \times Curing\ time \quad (4.3)$$

For this curing temperature, the curing time is usually of 23.5 minutes, so the PCI cycle would be of 30.6 minutes. The total time of the cycle (curing + PCI) would be approximately 54 minutes. By knowing how the temperature of the tire is decreasing during the cooling of a tire in the PCI – Annex B - the time at which it should be released from the PCI is obtained. Taking the temperatures obtained from the models, for an optimum release temperature of 95 ºC, the total time of the cycle would be of 41 minutes. The time reduction would be of 13 minutes.

Although this model was not validated due to time constrains, some conclusions obtained throughout this project were verified in the process. PA cords were directly removed from tires after going through the entire tire manufacture process and were evaluated. Figure 39 depicts the normalized relation between the elongation of cords at 45 N when the tires are released from the curing mold at a temperature of 175 ºC and 150 ºC and no PCI process is applied afterwards and when the PCI process is applied. Focusing on tires released at 175 ºC, the difference in elongation at 45 N between using and not using the PCI process is of 14 %. Furthermore, for tires that don't undergo the PCI process, the difference in the cords' elongation at 45 N between tires released at 175 and 150 ºC is of 8%. For tires that undergo the

PCI process, the cords' elongation is lower for tires released at lower temperatures. Cords that have a lower elongation at 45 N have a higher modulus, meaning that these cords are stiffer. What can be retained is that the temperature at which the tires are released from the PCI process influences greatly the mechanical properties of the cords in the tire, as it was seen throughout this chapter. Despite the effect of the PCI force and the different material constructions in the tire, the main parameter to be controlled in the PCI process is the temperature since it influences all the other parameters and therefore the material properties in the tire.

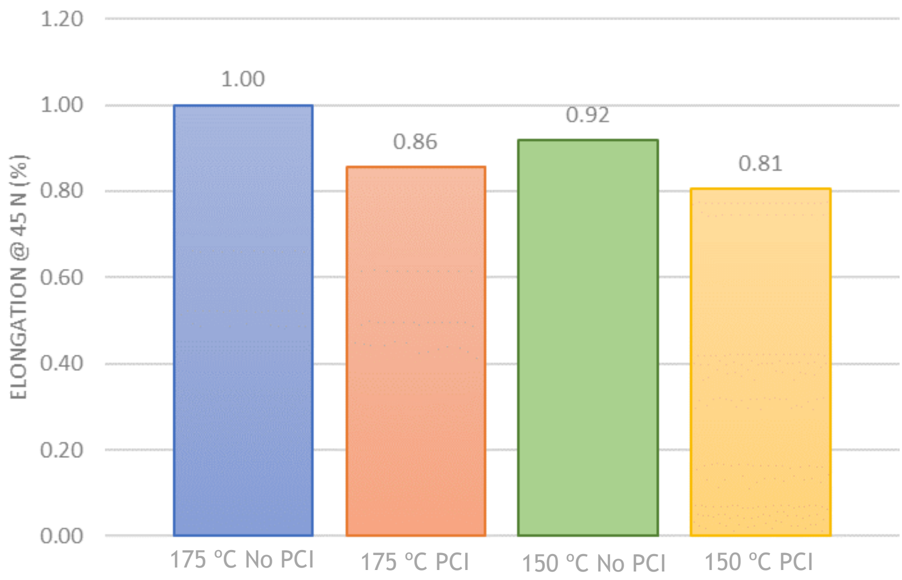


Figure 39 – Normalized elongation @ 45 N of cords obtained directly from tires released at different temperatures – 175 and 150 °C – subjected or not to the PCI process.

5 Conclusion

The present work was conducted to evaluate the impact of the Post Cure Inflation process on textile cords' physical properties by assessing different process parameters and cords of different polymers - PA 6.6, PET, Rayon, and a Hybrid of PA 6.6 and Aramid - with different constructions. For that, a testing procedure was developed and optimized to simulated at lab scale the curing and PCI process. The results were used to obtain a mathematical model that enables defining the optimum PCI process conditions for different reinforcement materials composing the tire.

The process parameters assessed were the temperature at which the tires are released from the PCI rim, the curing strain, and the PCI force. The shrinkage of a cord is directly proportional to the temperature. Thus, the temperature at which a tire is released from the PCI has a great impact on the cord's final displacement and modulus. Cords released at higher temperatures tend to shrink more, having a higher impact on the final displacement and a decrease on the modulus of the material, while cords released at temperatures closer to the material's T_g will not show a considerable shrinkage, having a lower impact on the final displacement and an increase of the material modulus. Furthermore, a linear behaviour between the final displacement and the release temperature was verified. This allowed to predict the optimum release temperature by calculating the temperature at which the final displacement is 0 %, so that the properties of the cords are not affected – the modulus of the material is kept constant. Moreover, comparing the curves for the different polymers, it was seen that Rayon does not shrink so no impact is observed when it is released at different temperatures. PA 6.6 has the highest shrinkage behaviour, followed by PET and hybrid materials.

Changing the curing strains had no impact on the final displacement of the cords, and the material modulus was kept constant. Moreover, regarding the PCI force, it was seen – for PET and predicted for PA 6.6 – that it has an impact on the final displacement and modulus of the material if the cords are released at temperatures closer to the material's T_g.

Regarding the cord itself, cords with higher linear density have a higher shrinkage than cords with lower linear density. To obtain the same final displacement of 0 %, the thicker cords of PA and PET should be released at lower temperatures. Following the same logic, PA cords with higher twist factor have a lower shrinkage than cords with lower twist factor and so can be released at higher temperatures.

Mathematical models were developed based on the linear behaviour of the cords towards the release temperatures and had into account the different cord constructions. The results allow to understand that the most important parameter to control is the PCI release temperature since it has the greater impact in the cords and the other parameters are affected by it. Despite not being yet validated in the actual process, these models were already important to raise the awareness of the fact that the PCI process is not yet optimum. It is our recommendation that the PCI process should be sensitive to the materials composing the tires.

To conclude, one of the main outcomes is that a fine tuning of the PCI process possible and is also a way to reduce the time of the process's cycle and increase the stability of the materials in the tires. By having a tailor-made PCI process, the Company will benefit of an optimized process to produce tires with better performance during usage and a significant reduction of uniformity, tire sizing and flatspotting.

6 Assessment of the work done

6.1 Objectives Achieved

The first goal to be achieved in this thesis was to develop and optimize a testing procedure that simulates at lab scale the curing and PCI process. After achieving similar results to the ones obtained in the actual process and being prevented by the MTS limitations from shortening the process steps even more, it was possible to then complete the second main goal related to gaining understanding of textile cords' physical properties and their interaction with the PCI process. All process parameters were studied for PA 6.6 and some of them for PET, the Hybrid and Rayon. That way was possible to confirm the predictions for the different cords and understand the behaviour for different parameters. Finally, two Mathematical Models were created for PA 6.6 and PET to enable defining the optimum PCI process conditions, the first one depending on the PCI release temperature, linear density, and twist factor, and the second one depending only on the PCI release temperature and linear density.

6.2 Limitations and Future Work

The MTS had two main limitations – the temperature in the chamber could go above 160 ºC and there was only a pair of grips that could be used. It is known that the curing temperature varies between 150 and 180 ºC and a difference of 30 ºC could have an impact on the overall time of the process. As future work, simulate the process at higher temperature would lead to even more accurate results and a more precise Mathematical Model.

There was a time limitation that did not allowed to validate the model in the process. That would consist in using the values obtained in the model for the optimum conditions in the process and verify if the results were in agreement with the ones obtained at lab scale. Naturally, to improve the models, the more polymers and characteristics tested the better.

Finally, it would be interesting to test a boarder range of temperatures, especially for PA. It could be verified that, at lower temperatures (closer to PA's T_g), the behaviour of PA would be similar to PET's.

6.3 Other Work Carried Out

When this project started, before developing the testing procedure, different cords of different materials were tested in the Reinforcement lab to have a practical idea and understand the concepts of the shrinkage behaviour, the shrinking force and the Force-Elongation curves.

6.4 Final Assessment

Academically, this project was challenging and deeply interesting. It was a very positive experience to develop a project that has an importance to the company and to gain know-how in the area of textile reinforcements.

Personally, this was an extremely enriching and rewarding experience to be part of a company like Continental and to develop skills such as adaptation, autonomy, communication, and versatility.

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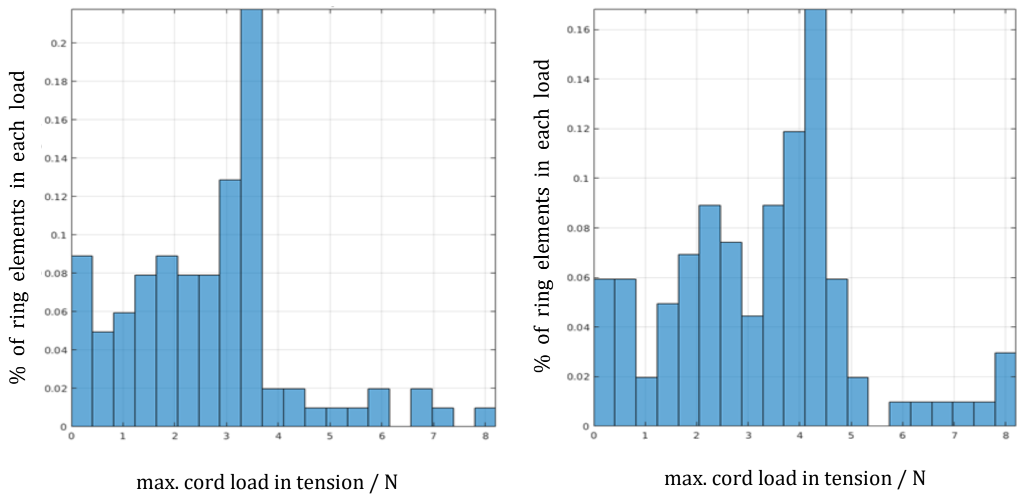
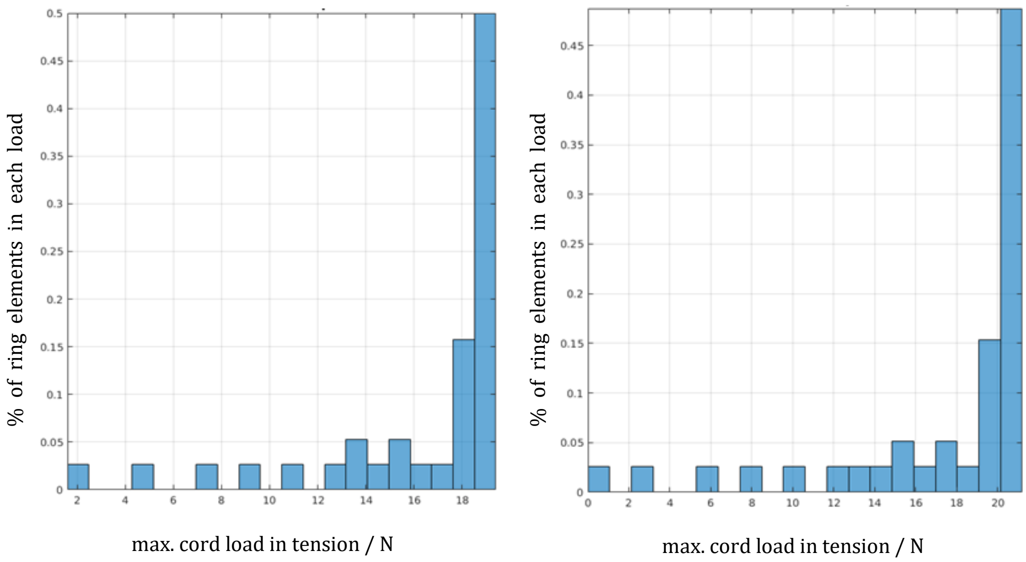
Annex A - FEM simulation PCI force



(a) (b)

Figure 40 - Percentage of ring elements in each load group for maximum cord load for carcass cords submitted to (a) 2.03 bar and (b) 4.0 bar



(a) (b)

Figure 41 - Percentage of ring elements in each load group for maximum cord load for cap-ply cords submitted to (a) 2.03 bar and (b) 4.0 bar

Annex B - Cooling of a tire in the PCI

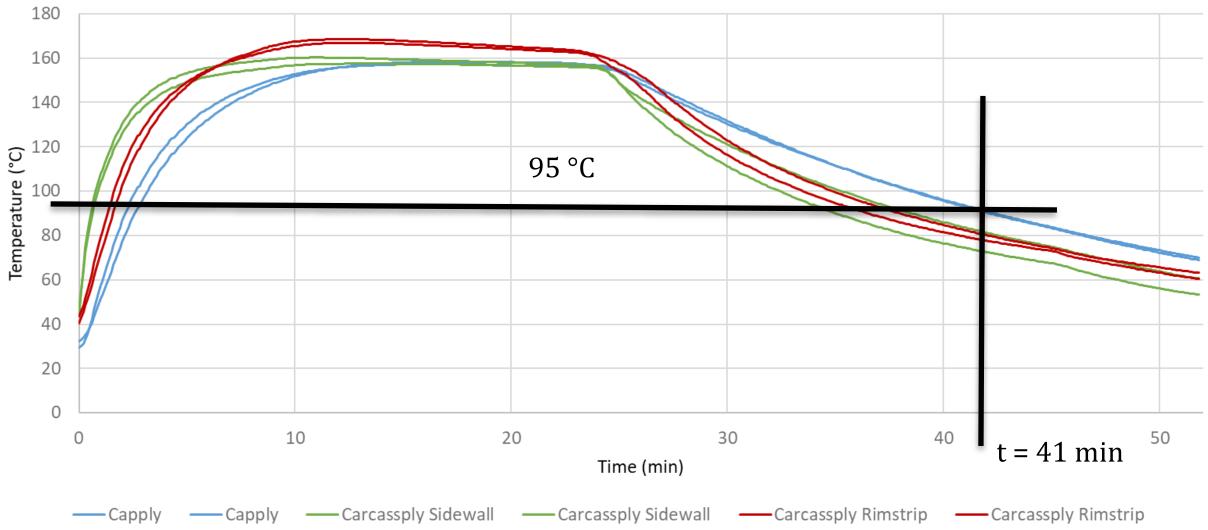


Figure 42 - Temperature (ºC) as a function of the time (min) of a tire during the curing and PCI process.

Appendix A – Design of Experiments

Table 6 – Design of Experiments

	Material	Cord construction	Twist factor	Curing Strain (%)	Force during PCI (N)	PCI Release Temperature (˚C)
PA6.6	PA 1	1400x2	200	1	10	150, 120, 80, 60
				3		
	PA 2	1400x2	150	3	20	120, 80
					10	150, 120, 80, 60
	PA 3	1400x2	150	3	10	120, 80
	PA 4	1880x2	200	1	10	150, 120, 80, 60
	PA 5	940x2	150	3	10	150, 120, 80, 60
PET	PET 1	2200x2	200	1	10	150, 120, 80, 60
					4	120, 80
	PET 2	1440x2	200	1	10	150, 120, 80, 60
	PET 3	3340x2	200	1	10	150, 120, 80, 60
Rayon	R	1840x2	250	1	10	120, 80
					4	150, 120, 80, 60
Hybrid	H	1680 + 1400 (aramid + PA6.6)	200	3	10	150, 120, 80, 60

Appendix B – Displacement vs Time behaviour for PET and Hybrid

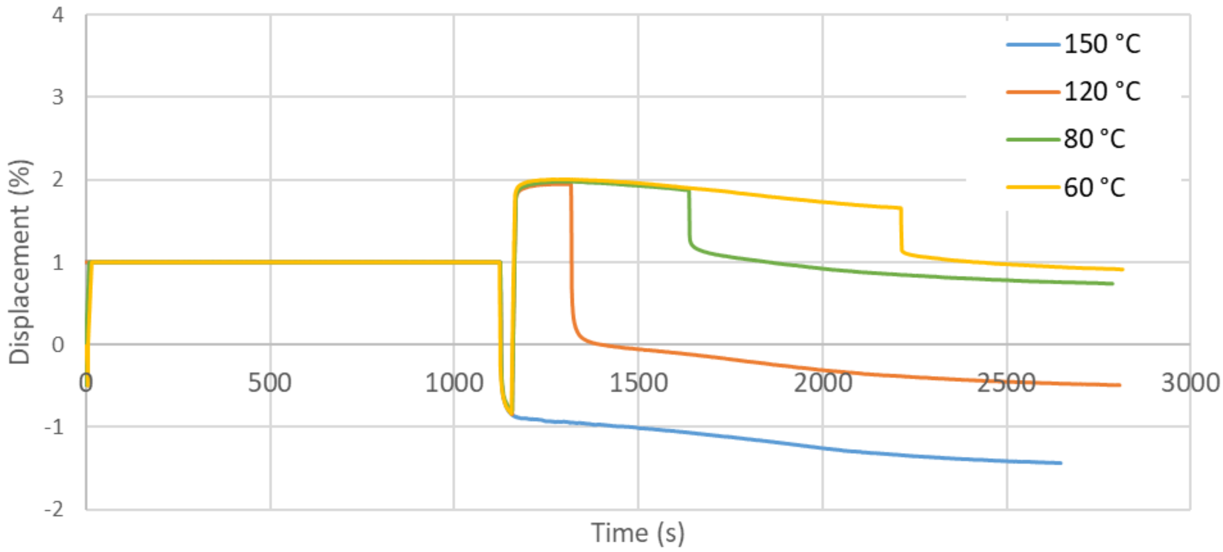


Figure 43 - Displacement in function of time for PET 2 cords that did not undergo PCI (released at 150 °C) and cords undergoing PCI released at different temperatures (120, 80 and 60 °C).

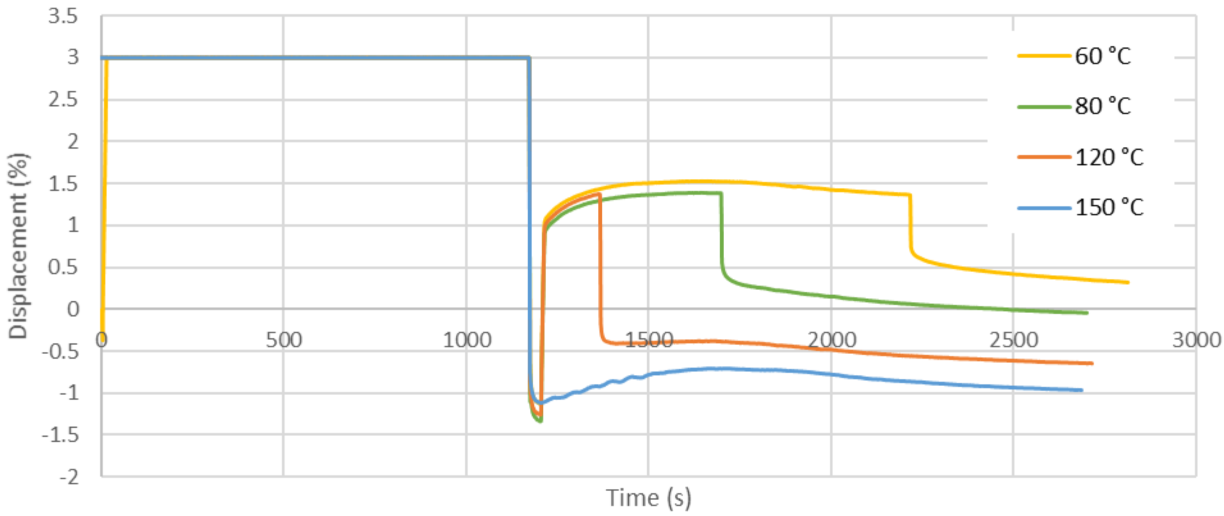


Figure 44 - Displacement in function of time for H cords that did not undergo PCI (released at 150 °C) and cords undergoing PCI released at different temperatures (120, 80 and 60 °C)

Appendix C - Curing strain

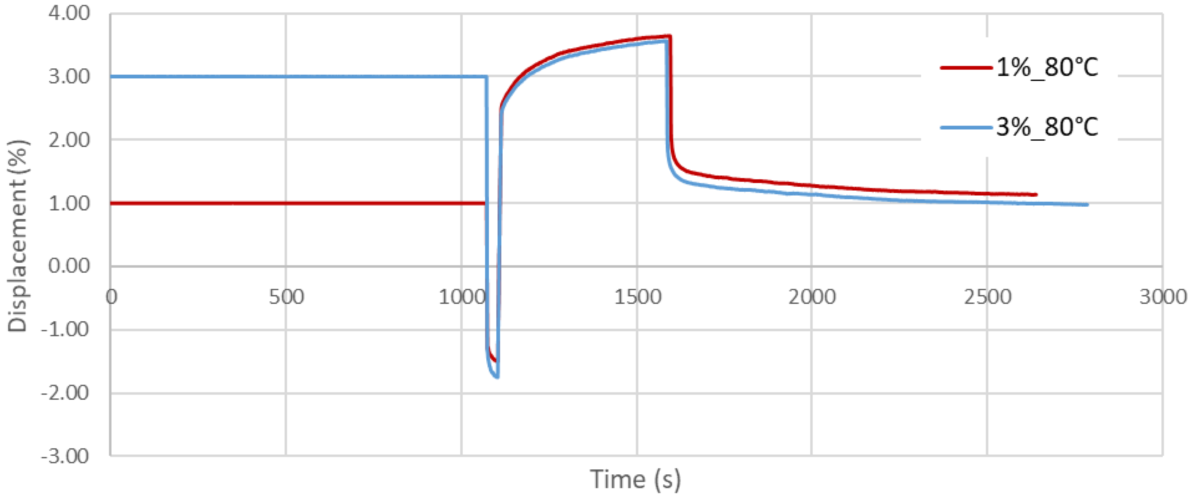


Figure 45 - Displacement in function of time for PA 1 released from PCI at 80 °C undergoing two different curing strains: 1% (red curve) and 3% (blue curve).

Appendix D - PCI Force

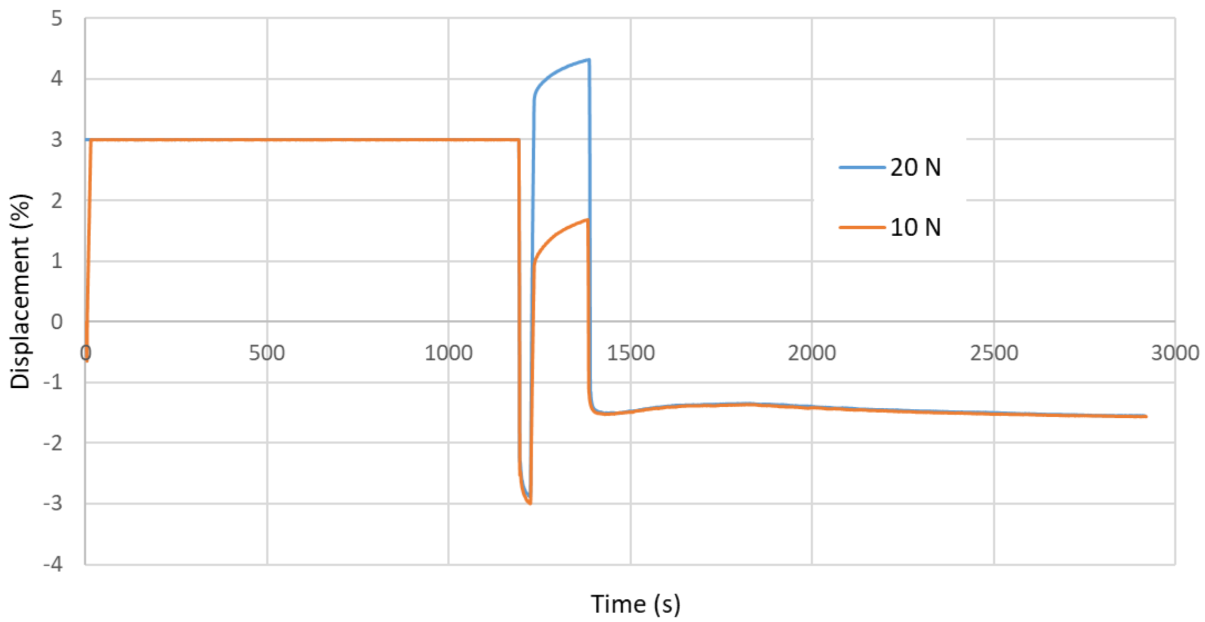


Figure 46 - Displacement in function of time for PA 2 released from PCI at 80 °C undergoing two different PCI forces: 20 N (orange curve) and 10 N (blue curve).

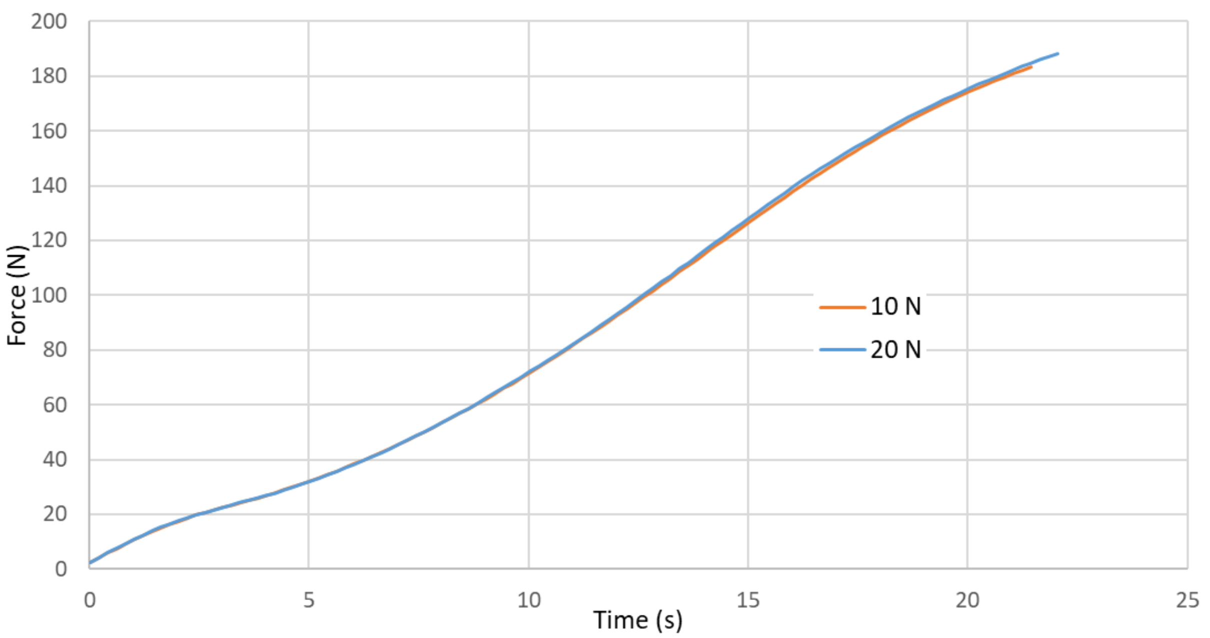


Figure 47 - Force – Elongation curve for PA 2 released from PCI at 80 °C undergoing two different PCI forces: 20 N (orange curve) and 10 N (blue curve).

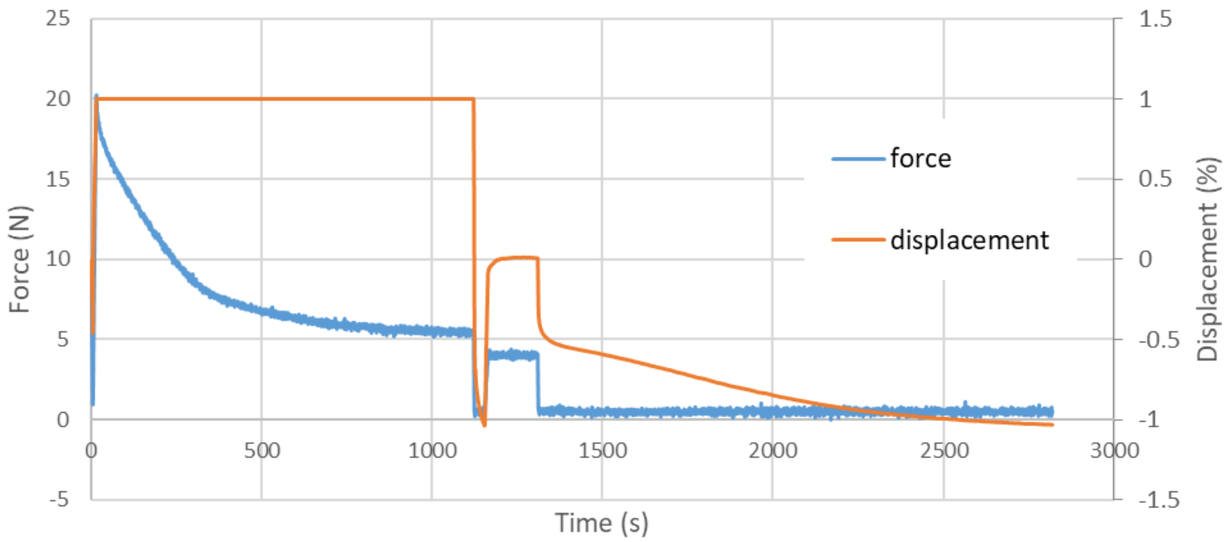


Figure 48 – Force (N) and Displacement (%) as a function of the Time (s) for a PET 1.

Appendix E - Linear densities

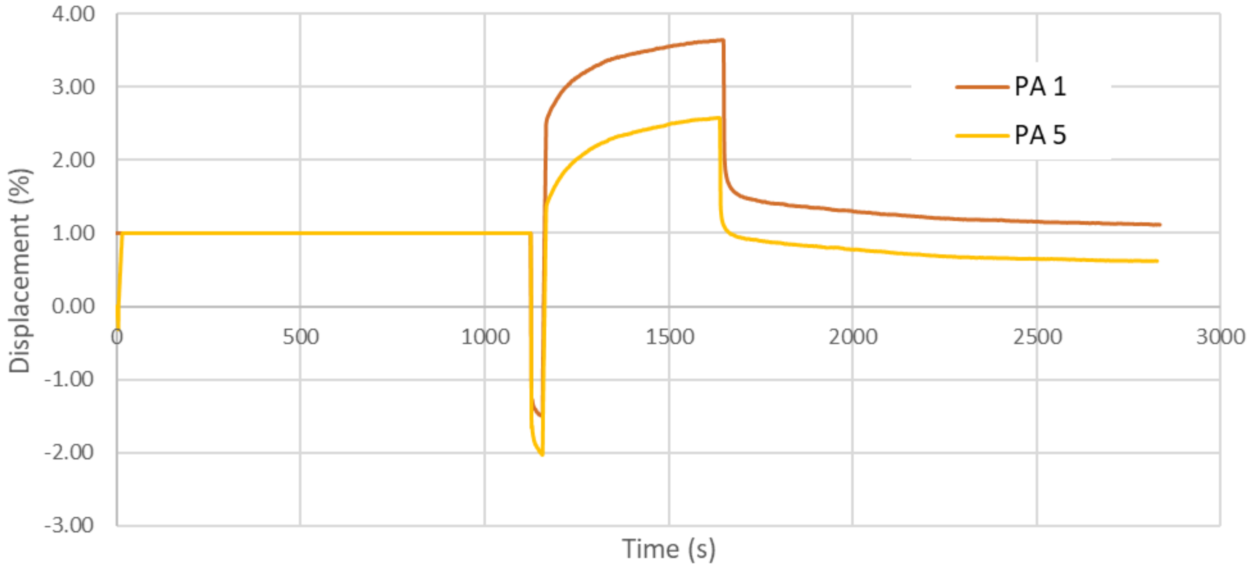


Figure 49 - Displacement in function of time for PA 1 (brown line) and PA 5 (yellow line) released from PCI at 80 °C.

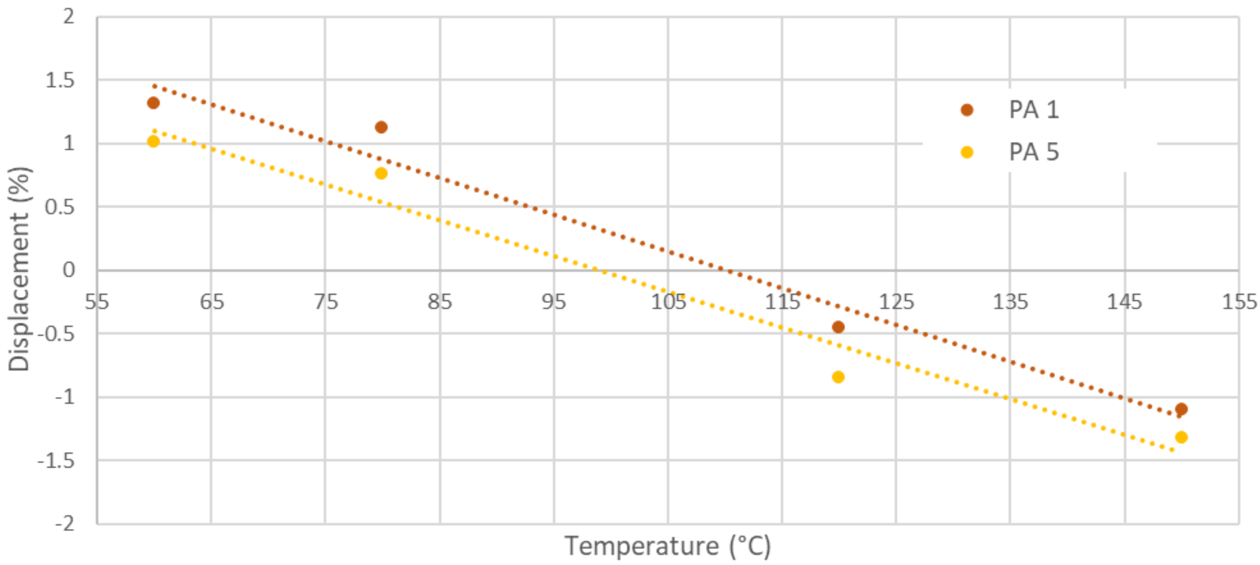


Figure 50 - Displacement in function of temperature for PA 1 (brown line) and PA 5 (yellow line).

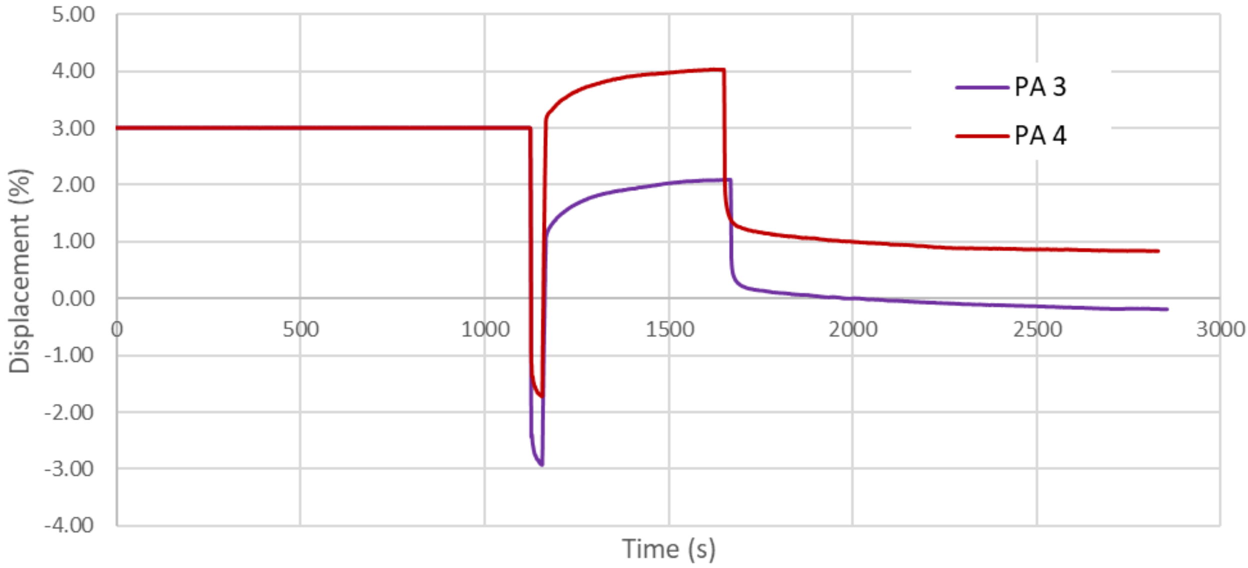


Figure 51 - Displacement in function of time for PA 3 (purple line) and PA 4 (red line) released from PCI at 80 °C.

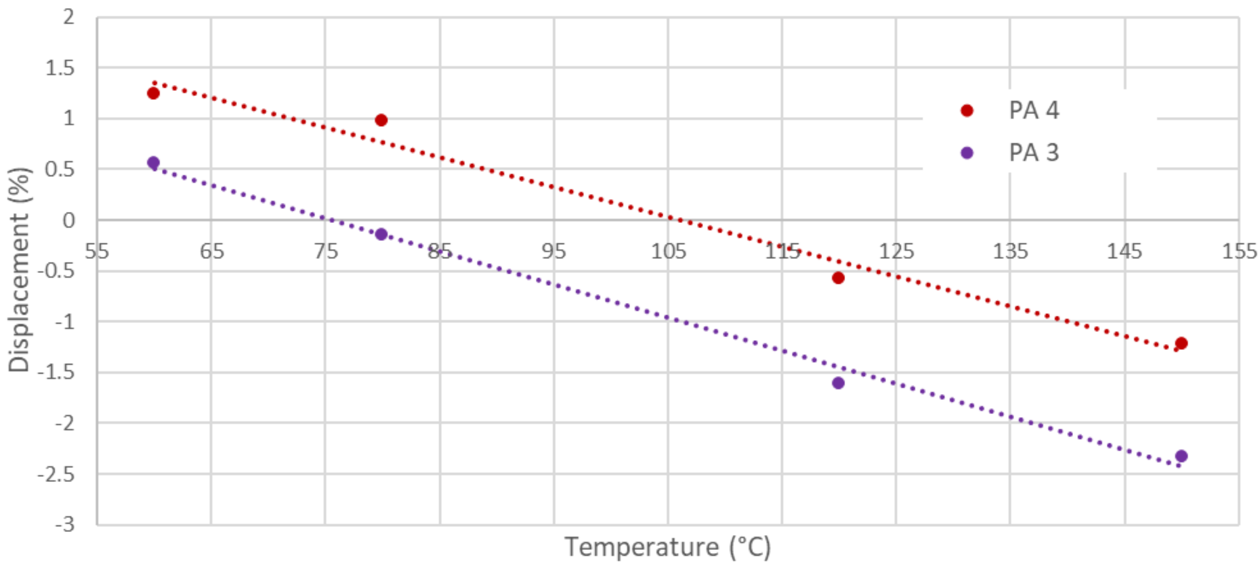


Figure 52 - Displacement in function of temperature for PA 3 (purple line) and PA 4 (red line).