Università degli studi di Messina

Dipartimento di Ingegneria

Tesi di Dottorato di ricerca in *“Ingegneria e Chimica dei Materiali e delle Costruzioni”*

XXX ciclo

“Biodegradable Polyesters Blends for biomedical applications. A Comprehensive Study on the Preparation and Characterization of Poly(lactide)/Poly(ε-caprolactone) Physical and Reactive Blends”

Dottorando:

Ing. Davide Nocita

Tutor :

Prof.ssa Annamaria Visco

Co-Tutor:

Dr. Sara Ronca

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Abstract

This PhD work has been intended first of all to find a new suitable class of materials to employ in the biomedical and environmental field.

Starting from literature reviews and the acknowledgment of the state of art in the field of biodegradable polyester blends, the attention was put on the reactive blending process, to obtain miscibility among two polymers of high commercial and academic interest for their specific and complementary properties, the Poly(lactide) (PLA) and the Poly(ε-caprolactone) (PCL).

PLA/PCL physical and reactive blends, with Ethyl Ester L-Lysine Triisocyanate as reactive agent, have been manufactured and analysed by means of several characterization methods.

It has been found that the reactive mixing conducted during the thermo-mechanical processing of blends, resulted for low LTI concentrations, into properly miscible systems, despite the evident immiscibility of the pure components in the molten state, confirmed by the large amount of literature in this regard.

High LTI concentration mixtures, showed a transition from a proper ductile thermoplastic, to a solid-like elastic dominant material, as shown by moduli build-up and frequency response rheological curves.

Furthermore, mechanical tests have shown how, at all LTI concentrations, the polymer ductility was maintained and, at the same time, a great increase in tensile resistance characteristics was noticed. These effects are apparently proportional with the reactive agent content.

Electronic microscopy, together with rheological analysis, underlined the appearing of a proper third phase, a densely cross-linked part resulting from the co-polyester-urethane structures, obtained by reactive mixing.

As a preliminary study, to underline the differences between a physical and a chemical method of emulsification, diblock PCL-b-PLA copolymers were also synthesised, used as additives and their effects evaluated.

The work has been conducted at the University of Messina, at the Department of Engineering, regarding the blends preparation and the mechanical, thermal, and surface characterization on processed samples. Jointly, at the Department of Materials of Loughborough University, have been instead studied the Rheological, morphological and chemical properties of the blends.

1. Introduction

1.1Biomaterials

The idea of a material to be used to substitute parts of the body, to give the chance to other parts to heal, or just to hold together edges of living tissues after an injury or a surgery, goes back to several centuries ago. Egyptians, Greeks, and then Romans doctors, used vegetal and animal fibres to suture wounds, and the first artificial prostheses were manufactured by wood, with outstanding results [1].

In a modern sense, a first definition of 'Biomaterial', has been proposed in 1974, during the *6th Annual International Biomaterials Symposium*: "*A Biomaterial is an inert substance, both for the organism and from the pharmacological point of view, designed to be implemented in a living system".*

Other definitions have also been given in years by scientific community, like during the *Consensus Development Conference on the Clinical Application of Biomaterials* in 1982 in Bethesda, or in 1986, in Chester, under the supervision of the *Biomaterials European Society* [2,3].

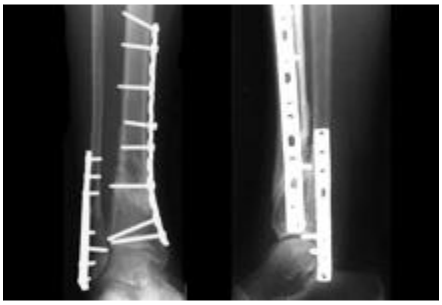

Fig. 1.1 Distal tibia bone fixation radiography. Credit : Ao Surgery Reference (https://www2.aofoundation.org/wps/portal/surgery)

Besides, the intent to rationalise and to define the terminology in detail, brought often to limitations and contradictions, because of the continuous and fast evolution in this research field.

For this reason, an operative and functional definition, is nowadays the most widely accepted one. It indicates Biomaterials as: *"Synthetic materials designed for a prolonged use in contact with biological systems, minimizing probable adverse reactions from the organism".*

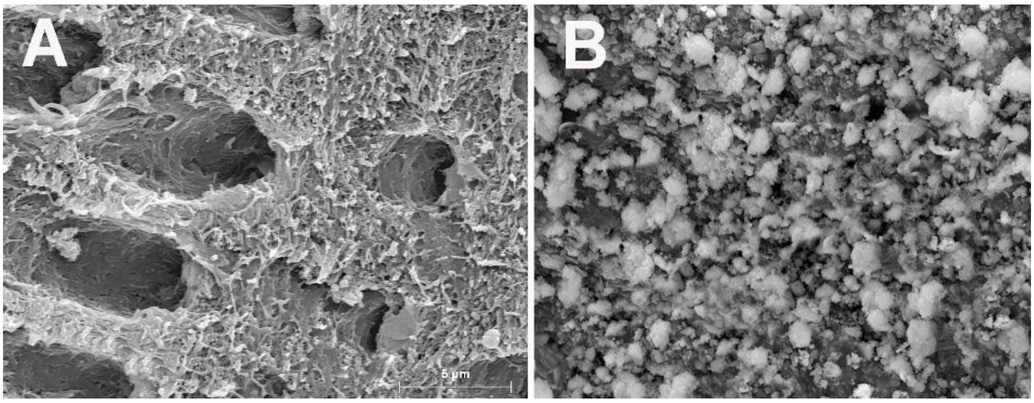

Fig. 1.2 A: Demineralized dentin with collagen fibres, degraded by the action of the dentinal proteolytic enzymes. B: Dentin treated with resin with fluoride-containing bioactive glass, which presents mineral precipitations – signs of remineralization [4].

A general classification of biomaterials can be made considering their chemical nature, one can then distinguish then between

- Metallic; Iron and not Iron based alloys or other more or less pure metals (Titanium)
- Ceramic; Metal oxides powders products or glasses
- Organic; Synthetic or natural macromolecules.

All of these classes, found and still find a widest applicative range, since many years, and industrial and academic efforts are being greatly put in this high interest research field.

Besides, this study was targeted on the science and technology concerning Biodegradable polyester blends, what follows, then, will be focused on polymeric materials characteristics.

1.2 Polymeric biomaterials

Polymeric materials, have found wide usage as biomaterials, for both their intrinsic properties and for their ability to resemble natural macromolecules. The main applications one should cite are :

- Regenerative medicine (Bones and soft tissues scaffolds and elastic supports)
- Drug delivery systems
- Prosthetics (Cardiology, Orthopaedics, Ophthalmology)

Most important advantages related to polymeric biomaterials use are:

- Great Biocompatibility
- Ability to get major modifications on their chemical composition, physical-mechanical properties and surface characteristics
- Low friction coefficients
- Easy processing and machinability even in complex geometries
- Ability to incorporate biomolecules or active compounds.

It is also worth mention that, one of the most important property of these materials is considered their ‘Bioactivity’, which is the ability to induce in the living tissue a specific biological activity. They are able to form direct interactions and biochemical bonds with a living tissue, that can cover freely the entire surface.

Some disadvantages are instead represented by :

- Release of potentially dangerous compounds (monomers, catalysts, additives)
- Ease of water and biomolecules absorption
- Relatively low mechanical properties for some applications

Many efforts on solving these known problems are nowadays being put by industry and academic research, since the high applicative potential of polymers in biological field.

The main distinction that can be made between polymeric biomaterials, is based on their ability to biodegrade in the substrate with which they are in contact.

They can then be basically divided into absorbable or not absorbable polymers, having different properties and applications, but both of high commercial and scientific interest.

1.2.1 Non absorbable polymers and their applications

As shown in table 1.1, many examples of non biodegradable and non absorbable synthetic polymers can be cited to underline their importance in biomedical field.

Table 1.1 Main synthetic non absorbable polymers

Synthetic non absorbable polymer	Applications
Fluorinated polymers	*Vascular Joints, Catheters*
Acrylic polymers	*Housings for extracorporeal therapeutic systems, maxilla-facial prostheses, bone cements, contact lenses, catheters*
Poly(acetals)	*Cardiac valves*
Poly(amides) PA	*Sutures*
Poly(carbonates) PC	*Housings for extracorporeal therapeutic systems*
Poly(esters)	*Vascular joints, soft tissue replacement, angioplasty balloons*
Poly(ether-ketones)	*Cardiac valves, artificial cardiac structures, special bone prostheses*
Poly(imides)	*Cardiac valves, artificial cardiac structures*
Poly(olefins)	*Sutures, catheters, artificial cardiac structures, tubing, joint replacement*
Poly(styrene) PS	*Scaffolds*
Poly(sulfones)	*Cardiac valves, artificial cardiac structures*
Poly(urethanes) PU	*Catheters, artificial cardiac structures, tissue adhesives, tubing*
Poly(vinyl-chloride) PVC	*Tubing, blood vessels*
Silicone rubbers	*Tubing, cardiac valves, catheters, soft tissue replacement*

Polyolefins, polyesters, halogenated polymers, are just some of the many kinds of plastic materials successfully used since many years, as a valid support in medicine and biological research field.

It would be worth mentioning in detail about all of these materials, but for brevity and historical interest reasons, just a brief discussion about the most relevant between them will be given.

1.2.1.1 *Ultra High Molecular Weight Polyethylene (UHMWPE)*

UHMWPE is one of the most used Polymeric biomaterials, because of its well known properties, i.e. mechanical strength on compressive loads, excellent toughness, wear resistance, chemical inertia, good wave transmission and electrical insulation [5,6].

It is an highly linear homopolymer, composed by chains, usually from 2 to $6*10^6$ g/mol of polyethylene ($[CH_2]_n$), obtained by polymerization of ethylene gases by Ziegler-Natta catalysts, usually titanium based. The reaction is conducted under pressure up to 6 bars, at 66-80° C

The mechanical behaviour of UHMWPE is related to its average molecular weight, which is routinely inferred from intrinsic viscosity measurements, since it cannot be evaluated by conventional methods like Gel permeation chromatography.

Its unprecedented molecular weight, brings it to an highest viscosity in the molten state, which does not let this polyolefin to be processed with usual methods. A sintering method, at high pressures and temperatures, is then required to obtain manufactured parts.

In most of the cases, this issue, brings to fusion defects evident in the solid state, which are often related to poorer physical characteristics, against the potentiality of this polymer [7].

Fig. 1.3 Examples of UHMWPE Joint Replacement parts [8].

The requirements for medical grade UHMWPE powders, in terms of catalysts residuals and calcium or ash contents, are specified in ASTM standard F648 and ISO standard 5834-1.

Highly superficially cross-linked UHMWPE it is one of the essential materials used in joint arthroplasty (Fig. 1.3), where it promotes ease of movements as opposite to the metal components, which usually play the role of the load bearing parts. It is the most chosen material to manufacture acetabular cups, tibial and patellar components.

Besides, despite the low friction coefficient, and the good resistance to the rolling and sliding actions between the polymeric and metallic components, it is considered for obvious reasons the weakest part of the joint.

Many authors and work have indeed been targeted to obtain further improvements on its adhesion and abrasion resistance, since it represents one the most important concerns in joint replacement [7].

The actual most successful strategy in improving the wear resistance of this polyolefin seems to consist in using carbon nanofillers to obtain nanostructured composites with a UHMWPE matrix, proving to show specific wear rate improvements up to ca 80% [6,9]

New research frontiers concerning UHMWPE based materials are directed towards the development of low viscosity and easy solid state processability systems, obtained by synthesising a 'Disentangled' grade of polyethylene, or towards improved physical characteristics nanocomposites, with specific optical properties. [10,11]

1.2.1.2 *Acrylic resins*

Acrylic resins, thermoplastic or thermoset, represent a wide range of medical application polymers. Most of the polymers of this category are the result of the polymerization of Methyl-Methacrylate.

Thermoplastic Poly(methyl-methacrylate), used since the 40's as a polymeric biomaterial, proved to be a great support in medicine since then. Meeting some of the toughest device requirements for processing, clarity, sterilization, functionality and regulatory compliance, this resin successfully finds application for : Dialysis and blood therapy systems, IV line components, Fluid control valves, Filter housings, Respiratory canisters, Suction devices, In vitro diagnostic systems (Fig. 1.4). [Plexiglas.com]

Fig. 1.4 Acrylic resin matrix medical devices, image courtesy of www.plexiglas.com

For some specific applications, this resin can also be obtained as a thermoset system. A solid power of PMMA particles with benzoyl peroxide (BPO) as a radical initiator and some fillers, can be mixed with a liquid phase composed by a solution of MMA monomer (95%), N,N-dimethyl-4-toluidine (DMT) as activator. The exothermic reaction occurring, brings to highly cross-linked acrylic structures, used as fixation systems in orthopaedics since several years.

Bone cements are indeed polymeric pastes used in orthopaedics to fix damaged bones or to bridge prostheses to the bone tissue, i.e. in joint replacement in which they represent an essential element, since they can are placed in free spaces between the prosthesis and the bone, acting like elastic zones. Usual fillers are represented by radio-opaque compounds like barium sulphate. Furthermore, the matrix can be commonly added with antibiotics, with the aim of supporting against infections after surgeries and joint replacement procedures. [12]

1.2.2 ***Absorbable polymers and their applications***

Technology of absorbable/biodegradable polymers, has evolved in two independent areas, one related to the natural macromolecules study, and the other to the synthetic polymers advances.

Natural polymers are basically represented by biomacromolecules like Poly(saccharides) or Poly(peptides), but Polyesters obtained by bacterial synthesis like Poly(hydroxy-alkanoates) legitimately belongs to this category too.

Carbohydrates chains of Chitosan and Hyaluronic acid (Fig. 1.5), have successfully been used in medicine as simple and effective drug delivery systems, being able to influence the release rate, or cross-linked water-swellable systems in surgical replacements [13].

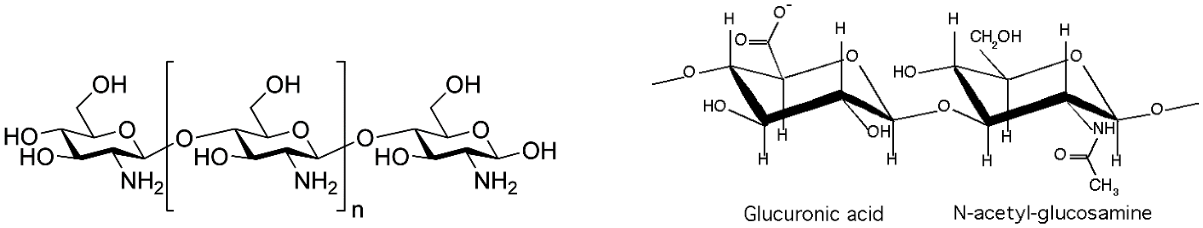

Fig. 1.5 A, Chitosan structure; B, Hyaluronic acid structure

Besides, among all these biomaterials, aliphatic polyesters represent probably the most known and used category of biodegradable polymers, since their wide and well tailorable range of properties, and their industrial and technological interest.

1.2.2.1 *Absorbable Aliphatic polyesters*

Aliphatic polyesters are, together with some polycarbonates, polyanhydrides, and poly(amino acids), the most well-known synthetic hydrolysable polymers. As discussed above, some biodegradable polymers belonging to this category can be synthesized or produced by bacteria and cyanobacteria. [14]

Since their peculiar characteristics, in terms of bio-compatibility, mechanical and thermal properties, bio-activity, aliphatic polyester are probably the most used ones among absorbable polymers.

Table 1.2 Absorbable polyesters

Absorbable polyesters	Applications
Poly(lactide) PLA	*Drug delivery, bone regeneration, scaffolds*
Poly(ε-caprolactone) PCL	*Drug delivery, sutures, scaffolds*
Poly(glycolide) PGA	*Sutures, tissue engineering*
Poly(3-hydroxybutyrate) PHB	*Drug delivery, tissue engineering, medical packaging*
Poly(3-hydroxyvalerate) PHV	*Drug delivery, tissue engineering, medical packaging*
Poly(butylene succinate) PBS	*Drug delivery, bone regeneration, medical instruments*
Poly(butylene succinate-co-butylene adipate) PBSA	*Drug delivery, bone regeneration*
Poly(dioxanone) PDS	*Sutures*

Later on, Poly(lactide) and Poly(ε-caprolactone) and absorbable polyesters peculiar properties will be described in detail, since they represent the main components of the blend presented in this work. Instead, a brief description of some of the most important others absorbable polyesters, will follow.

Poly(glycolide) or Polyglycolic acid (PGA), which chemical structure is shown in Fig. 1.6, is the simplest linear, thermoplastic aliphatic polyester. PGA and its copolymers have been used since many years, as a material for the manufacturing of absorbable sutures and as synthetic polymers for tissue engineering applications. It is a very stiff (E ~ 7 GPa for fibres), tough, crystalline polymer with a melting temperature of ~ 225 °C and a glass transition temperature, Tg, of 36 °C. Despite its limited possibilities of use in drug delivery systems, mainly because of its low solubility and high melting point, it has excellent fibre-forming properties. It has successfully been used as a suture material, even for its fast biodegradation rates in living tissues, of the order of one month[14,15].

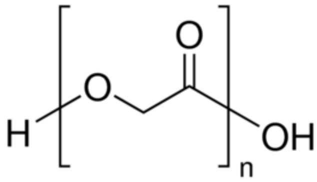

Fig. 1.6 Poly(glycolide) chemical structure

Polybutylene succinate (PBS) (Fig. 1.7) is a biodegradable, synthetic polyester, similar in physical properties to PE. It exhibits moderate stiffness (~ 480 MPa) and melting temperature (110 °C), quite high ductility, crystallinity and density (1,26 g/cm^3). It can be prepared as a linear polymer (similar to HDPE) or with specific number of long chain branches (similar to LDPE).

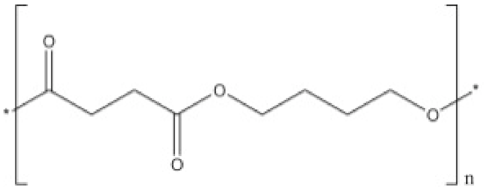

Fig. 1.7 Poly(butylene succinate) chemical structure

It finds application in medicine as a promising material for bone and cartilage repair, and for medical instruments as a main blend component [16].

Poly(3-Hydroxyalkanoates) like PH3B or PHV (Fig. 1.8), are common example of proper biopolymers, considered promising materials for biomedical applications because they are biodegradable, non-toxic and biocompatible. They are obtained naturally by bacterial activity (i.e. Ralstonia eutropha) and since their high biocompatibility they have played an important role in the treatment of disease and the improvement of health care.

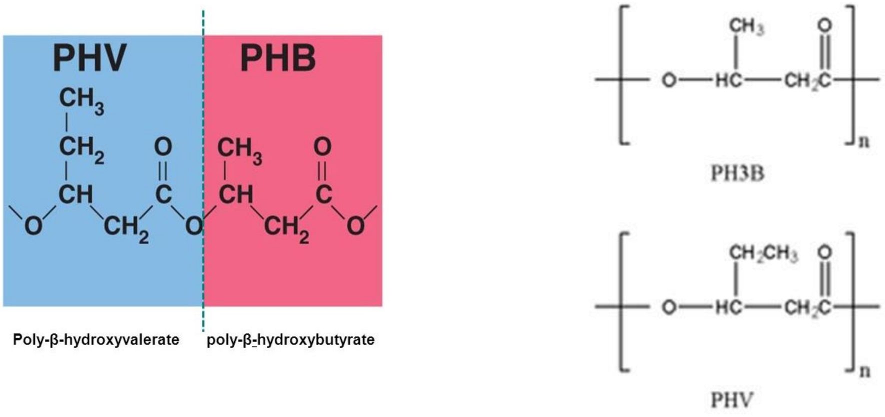

Fig. 1.8 Poly(hydroxy valerate) and Poly(hydroxyl butyrate) chemical structure

The physical and material properties of PHAs are significantly influenced by their monomer composition and chemical structure. Some short alkyl side chains PHA may exhibit too rigid and brittle behaviour, lacking the superior mechanical properties required for biomedical applications. In contrast, longer side chains may be elastomeric but show very low mechanical strength. Therefore, for medical packaging materials, tissue engineering, and other specific applications, the physical and mechanical properties of these microbial bio-polyesters might need to be diversified and improved. Many effort have been, and are indeed being put to improve the physical-chemical properties of these tailorable natural polyesters.

Tissue engineering field, found great usefulness from these polymers concerning subcutaneous tissue, cardiovascular system, nerve tissue engineering, gastrointestinal system, bone tissue and cartilage tissue-tendon and ligaments tissue engineering.[17]

1.2.3 Absorbable devices

The biodegradable and absorbable polymers discussed above found in years wide applicative field in medicine. Their ability to dissolve in living tissues is considered the key property for all their applications, since the degradation rates are known, and they allow to tailor the physical characteristics trends in time, and the release rate of eventual additives.

1.2.3.1 Absorbable Sutures

They are commonly used for internal or deep structures, when the later removal should be avoided. Monofilament or braided threads can be manufactured from PGA (Fig. 1.9) (commercially named *Vicryl* or *Dexon*), PDS, and PCL copolymers. There can then be many choices regarding the degradation time and the mechanical properties.

Main specifics for a suture thread are required, like: toughness, tensile strength, knot resistance, cross sectional regularity, slipping ability. A well balanced set of properties, allows the operator to avoid ischemic, septic or dehiscent phenomena on the wound to be sutured. It is worth mention also that the material choice, must be always considering the specific part to deal with, because of the substantial differences among the various kind of tissues. [18,19]

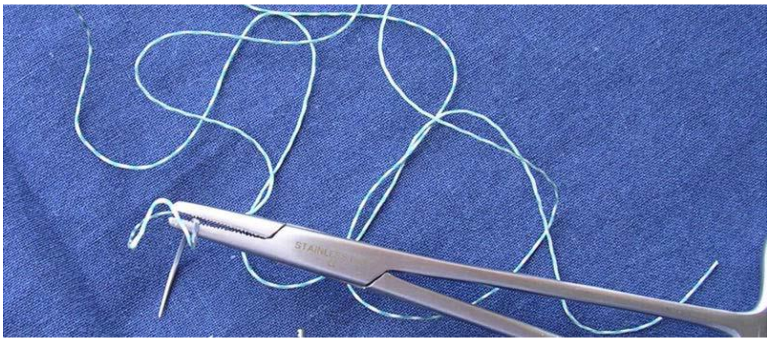

Fig. 1.9 Dexon (PGA) suture thread

1.2.3.2 Tissue engineering scaffolds

A scaffold or three-dimensional (3-D) construct, represented in Fig. 1.10, provides the necessary support for cells to proliferate and maintain their differentiated function, and its architecture defines the ultimate anatomic shape of the new tissue.

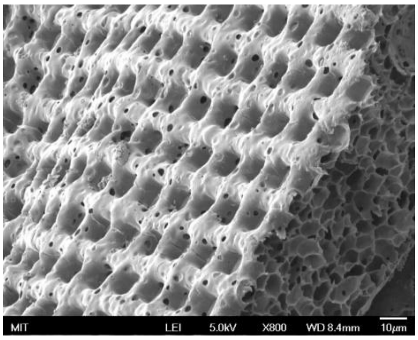

Fig. 1.10 SEM image of a porous polyester scaffold obtained with phase inversion process of polymers with micro patterning. Credit : The Koch Institute Public Galleries (https://ki-galleries.mit.edu/2016/hyder-2)

Many of the cited polymers can be used to manufacture these systems. PGA, PLA, PCL, Poly(orthoesters), Poly(anhydrides), and natural macromolecules like collagen or chitosan, represent the wide selection of materials suitable for this application.

Besides, a polymer scaffold material has to be chosen that will degrade and resorb at a controlled rate at the same time as the specific tissue cells seeded into the 3-D construct attach, spread and increase in quantity (number of cells/per void volume) as well as in quality. This is obviously related to the kind of tissue that has to be regenerated.

The following properties are defined as desirable for a scaffold :

- Interconnecting pores of appropriate scale to favour tissue integration and vascularisation.
- Manufactured from material with controlled biodegradability or bioresorbability.
- Appropriate surface chemistry to favour cellular attachment, differentiation and proliferation.
- Adequate mechanical properties to match the intended site of use and handling.
- Not inducing any adverse response.
- Ease of fabrication into a variety of shapes and sizes.

Most of the efforts nowadays put into this research subject, are focused on the surface properties and modifications of polyesters scaffolds, or on the synthesis of tailored macromolecular systems for the manufacturing of highly reliable and biocompatible systems[20,21,22].

1.2.3.3 Drug delivery systems

New drug delivery technology is concerned with the systematic release of a pharmaceutical agent to maintain a therapeutic level of the drug in the body for a sustained period of time. It is know that, traditionally, to administer the entire dose of drug in one portion, can result in high, sometimes close to toxic, plasma concentrations of drug. The actual therapeutic effect is, indeed, achieved not simply by administration of the drug but instead by maintaining a long-term appropriate plasma concentration, and by providing the drug only where and when it is needed.

This may be achieved by incorporating the therapeutic agent into a degradable and resorbable polymeric vehicle, releasing the agent continuously as the matrix erodes in time. The material degradation rate can then be considered a key factor to govern the drug release kinetics, improving the therapeutic value of the cure.

Drug delivery systems, developed in time since almost half a century, are various and include : diffusion-controlled membranes, osmotic pumps, resorbable devices, hydrogels, ion-exchange materials, polymeric pro-drugs, and slowly dissolving matrices[16,23].

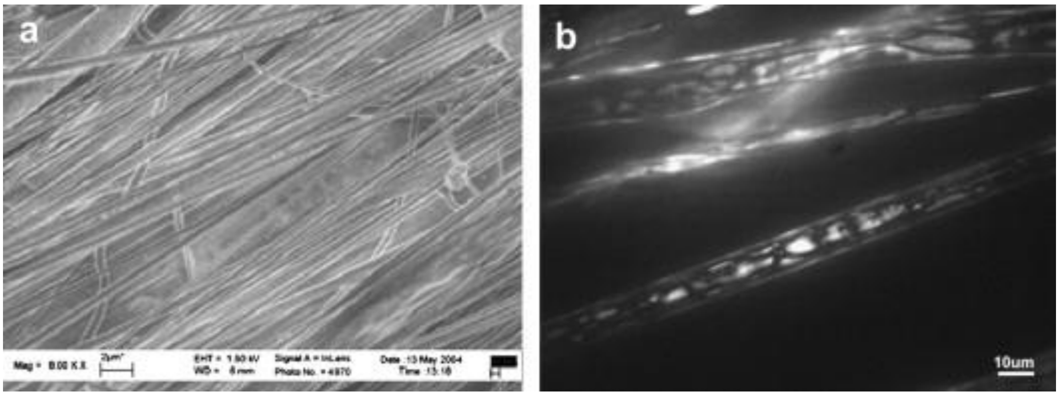

Fig. 1.11 (a) Aligned BSA encapsulated PCLEEP fibres electrospun at 1 mL/h. (b) Fluorescein isothiocyanate-conjugated bovine encapsulated electrospun fibres of PCLEEP. [24]

Specific chemical and well tailored physical properties, biocompatibility, purity, and reproducibility, are considered the most important characteristics of a proper drug delivery system, that should be also maintained within all of the scaled-up manufacturing process, the packaging, and storage phases of the device[16].

Aliphatic degradable polyesters like PLA, PCL, PGA, Polysaccharides like Chitosan, or Polypeptides like Collagen have been and still are the most used matrices in this research field.

Recently, many efforts have been put by academic and industrial research to obtain new polymer systems, having the desired mechanical and physicochemical properties for specific clinical applications. Methods of tailoring polymers for drug delivery, include engineering the molecular architecture, copolymerization, and homopolymer blending.

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2. Polymers blends: characteristics and processing methods

2.1 Polymers blends

A polymer blend, generally speaking, is a mixture between two or more polymers, manufactured with the intent of obtaining a specific material with different physical or chemical characteristics. Mechanical strength, chemical resistance and optical characteristics are just some of the properties that can be tailored with a well-balanced mixture. Blending has also then gained popularity as an easy and not costing method of developing polymeric materials with versatility for many commercial applications. [1] Ca. 36 wt% of the total polymer use in industries and research is nowadays constituted by polymer blends. Their extensive use, can be understood citing the following material-related benefits:

- Providing materials with full set of desired properties at the lowest price.
- Extending the engineering resins’ performance.
- Improving specific properties.
- Offering the means for industrial and/or municipal plastics waste recycling.

All the benefits cited above, can be obtained when the alloying process results in a stable and reproducible set of properties. Thus, the morphology must either be stable, unchanged during the processing steps, or the changes must be known before. It is then clear then, how the alloying must make use of an appropriate dispersing method for polymeric materials (viz. mechanical mixing, solution blending). [2a]

Generally, polymer mixtures have to be distinguished between two categories, miscible and immiscible blends. In the first one can find for example compounds of PS [Poly(styrene)] and PPO [Poly(phenylene oxide)], in the second one blends of PP [Poly(propylene)] and PE [Poly(ethylene)]. Besides, as well known, even in the miscible blends it can be found phase separation, because of many parameters that have an effect during processing or formulation, like composition, molecular weight, temperature, pressure, etc. In a general sense then, the complete polymer/polymer miscibility does not exist, it is instead always limited to a more or less wide "miscibility window", a range of the independent variables listed above. [1,2a]

To achieve the knowledge of what is miscibility, it is usual to refer to its thermodynamic definition, which among many others results in the most precise. Generally, miscibility between the components of a blend is obtained when there are both the conditions expressed below:

$$\Delta G_m < 0; \qquad (2.1)$$

with

$$\Delta G_m = \Delta H_m - T\Delta S_m \qquad (2.2)$$

And $$\left(\frac{\partial^2(\Delta G_m)}{\partial \varphi_i^2}\right)_{T,P} > 0 \qquad (2.3)$$

Where:

- ΔG_m is the Gibbs energy of mixing
- φ is the composition and it is usually taken as the volume or weight fraction of one of the components
- ΔS_m is the entropy variation and is a measure of disorder or randomness, is always positive and, therefore, is favourable for mixing or miscibility especially for low molecular-weight solutions. It is noteworthy that for this kind of systems, since the configurational entropy amount is = 0, this variation has an overall minimum contribution on the equation.
- ΔH_m, the enthalpy of mixing, is the heat that is either consumed (endothermic) or generated (exothermic) during mixing. It is the most relevant contribution on the Gibbs equation. If the mixing is exothermic then the system is driven towards miscibility, and this happens only when specific and strong interactions between macromolecules occur. This kind of interactions are classically hydrogen bonding, dipole-dipole and ionic interactions [1].

Mixing two polymers usually results then in an immiscible system, characterized by a coarse, easy to alter morphology, and poor adhesion between the phases. These blends have large size domains of dispersed phase and poor adhesion between them. As a result, their performance is poor and irreproducible. In particular the impact strength, maximum strain at break, and the yield strength are affected. The irreproducibility originates from instability of morphology — blends' structure developed during the compounding step is unstable and irreproducible. To be able to solve these three problems (degree of dispersion, stability of morphology, and adhesion between the phases in solid state) one must learn about the region between the two phases in binary polymer blends, the interface or rather the interphase [2a].

Helfand and his co-authors provided the basic relations and a theoretical guidance to the properties of the interface in high molecular weight blends, as well as to their modification by incorporation of an emulsifying agent [2a,3].

According to this theory, most important properties of the interfacial region are: the interfacial thickness, Δl_∞, and the interfacial tension coefficient, ν_∞.

They are both related to the square root of the thermodynamic binary interaction parameter, χ_{AB}.

The interfacial thickness, Δl_∞, is directly proportional to χ_{AB} , whereas ν_∞ inversely, thus their product: $\Delta l_\infty * \nu_\infty$, is to be independent of thermodynamic interactions. This brings to understand how as a general tendency, there is a reciprocity between the interfacial tension coefficient and the interphase thickness.

It is also known by the Helfand's theory [3] that:

- The chain-ends of both polymers concentrate at the interface
- Any low molecular weight third component is forced by the thermodynamic forces to the interface
- The interfacial tension coefficient increases with molecular weight up to an asymptotic value [2b,3].

The interfacial properties are, as well known, among the most relevant factors that have an effect on the structure and morphology of immiscible blends.

Moreover, at high dilution, or at low flow rates the morphology of polymer blends is also controlled by three dimensionless microrheological parameters:

- The viscosity ratio $$\Lambda = \frac{\eta_A}{\eta_B} \qquad (2.4)$$

where η_A is the viscosity of the dispersed liquid and η_B that of the matrix;

- The capillarity number $$\kappa = \frac{\sigma_{AB}\, d}{v_{AB}} \qquad (2.5)$$

where σ_{AB}, d, and v_{AB} are respectively the shear stress, the average drop diameter and the relative interfacial tension

- The reduced time $$t^* = \frac{\dot{\gamma}}{\kappa} \qquad (2.6)$$

where $\dot{\gamma}$ is the shear rate [2b,4].

In particular, the dependence of the morphology on the viscosity ratio between the dispersed phase and the matrix has been deeply investigated by authors like Wu et al [5] and Hietaoja et al. [6]. They managed to estimate the relative influence of interfacial tension and viscosity ratio on phase morphology dimensions. The diameter of the dispersed particles at equilibrium is directly proportional to the interfacial tension and inversely proportional to the shear rate and the matrix viscosity for a given viscosity ratio. These expressions indicate that the finest dispersion can be obtained when the viscosity ratio is near unity, condition for which, generally a Co-continuous morphology can also be obtained.

Thus, it is evident how the interphase and rheological properties are the keys for the morphology development in polymer blends, which in turn is the checking factor for their performance about macroscopic properties.

Coarse unstable phases, driven by strong interfacial tension, exhibit poor mechanical and general macroscopic properties.

Many efforts have been put into the development of miscible blends of synthetic polymers of industrial interest. Blends of Acrylic, Styrenic, Vinylic polymers, Polyolefins, Elastomers, Rubbers, have been widely studied and characterized. They find space for many applications of commercial interest and are commonly used in industry. [2a] Their characteristics are anyway out of the aim of this thesis which will be instead targeted on polyester blends and their properties.

To obtain Bio-polymer blends, with specific properties for medical or environmental applications, is nowadays one of the most followed targets in polymer blends science and technology. As discussed in chapter 1, these materials can show many specific properties, like solubility in a biological medium, durability, chemical inertia with the environment. All of them are expression of the specific macromolecular chemical structure, which is often caused by the kind of source from where they are obtained. It is then clear, how obtaining a mixture between two of these polymers, can bring to a well-defined set of physical and mechanical properties, with the further advantages from all the other chemical characteristics that define that kind of polyesters.

2.2 blends processing

Blends can be processed in many ways, basically distinguished in thermo-mechanical methods, in which shear and temperature are applied to the mixture, and solution casting, in which a solvent is able to solvate all the and a stirring system brings the necessary motion to the macromolecular chains. They can both result in manufacturing a homogeneous mixture, and, as discussed later have their own advantages.

On an industrial scale, thermo-mechanical methods are always preferred for obvious reasons, but in research laboratories the solvent casting is still seen as a favourable alternative to study many kind of systems

2.2.1 Internal mixing

Internal mixing is often used as a laboratory scale, thermo-mechanical processing method. It is used to obtain thermoplastic polymers mixtures, or to blend plastics and rubbers with solid, liquid or gaseous additives. As described better later it represents one important method of processing for the reactive blending of many polymers and thermoplastics. There are many commercial kinds of mixers used for many kinds of polymeric materials calculated.

Fig.2.1 A Brabender Plastoraph EC, Credit: Brabender GmbH & Co KG (www.brabender.com)

Machines used for this purpose, also called batch mixers, are schematically made by an asynchronous motor used to move two compounding blocks, the rotors, spinning, usually in a counter-rotating way, in a processing chamber of fixed volume. Chamber walls are heated by thermal-resistances, and processing temperature is constantly checked by a thermocouples system. A gearbox and an electronic system, are also embedded to set the rotors speed, to keep it constant and to regulate and estimate the stresses on the compound inside the chamber. Torque values on the rotors, as an index of viscosity of the system, and of the shear rate on the mixture, can be read by a transducer, installed in the external part of the gearbox. When necessary, for example when a chemical reaction is driven during the processing, a climatic system to keep compounds in an inert environment can be used. The chamber can then be isolated from the atmosphere and an inlet valve let an inert gaseous compound be the mixing environment.

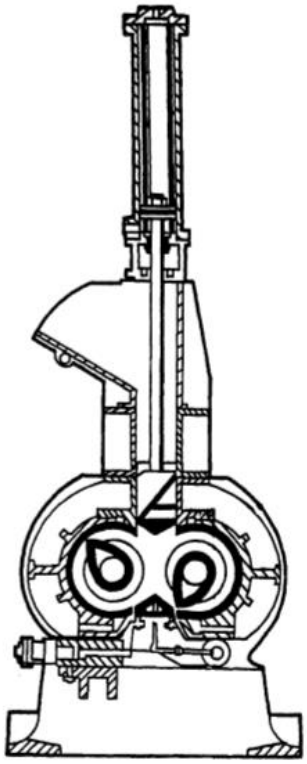

Fig. 2.2, cross sectional view of a batch mixer, [7]

Parameters that can be set are basically temperature on the chamber walls, rotors speed and time of mixing, for an easy use of the machine. Furthermore, rotors geometrical profiles, are designed to result similar to the mixing blocks of modular screws working in extruders. As also discussed later, the aim of this design is to apply the correct shear flow to the mixture. Those systems basically are then, on a laboratory scale, a processing method for materials with conditions similar to those in the mixing zone of a twin screw extruder.

Those systems prove to be useful on a laboratory scale because of their versatility, the dispersion performance, and also because the amount of materials used is always limited to grams. In an extruder with the same degree of mixing instead, to make it perform as it should, and since it is a strictly continuous method of compounding, one has to use amounts of material that can be in the order of kilograms.

It is possible with this easy and commonly used method, to obtain thermoplastic compounds brought to miscibility with the help of useful additives. Ternary blends, reactive mixtures or materials with specific chemical properties can be obtained by mixing the polymeric phases of the blend with other components chosen for the purpose materials.

Many studies have also investigated on the flow motion in batch mixers, and highlighted the machines performance and effects of processing parameters on various rubbers and plastics.

2.2.2 Twin screw extrusion

Twin screw Extrusion is a widely used industrial processing method for manufacturing thermoplastic polymeric compounds in the shape of profiles, from pellets or powders. They prove to be particularly useful in polymer blending, because of the conditions on materials that can be obtained in this kind of continuous method of mixing.

In a one screw extruder, or kneader, the transport mechanism is based on friction between the polymer and the walls of the channel, this makes these types of machines working on the frictional forces at the wall and on then on the properties of the material processed. In most commercial extruders the flights of one screw stick in the channel of the other screw. Because of this, the polymer cannot rotate with the screw, irrespective of the rheological characteristics of the material. This indicates the most important advantage of many twin-screw extruders: the transport action works on the characteristics of the material to a much lesser degree than in the kneaders.

Various types of twin screw extruders are commercially available and they differ widely in their operating principles and function, they have then a wide range of abilities for distributive and dispersive mixing and hence in their application areas.

Fig. 2.3, Intermeshing co-rotating compounder, Credit: Krauss Maffei Berstorff (http://www.kraussmaffeiberstorff.com)

The first main distinction is made between intermeshing and non intermeshing extruders, each of which may be divided on the basis of the direction of the rotation of the screws into co-rotating or counter-rotating. Each kind of extruder finds its application in polymer blending, from tangential or non-intermeshing counter-roating machines, used generally for rubbers compounding, to intermeshing corotating extruders used widely in manufacturing reactive blends. [7] [12]

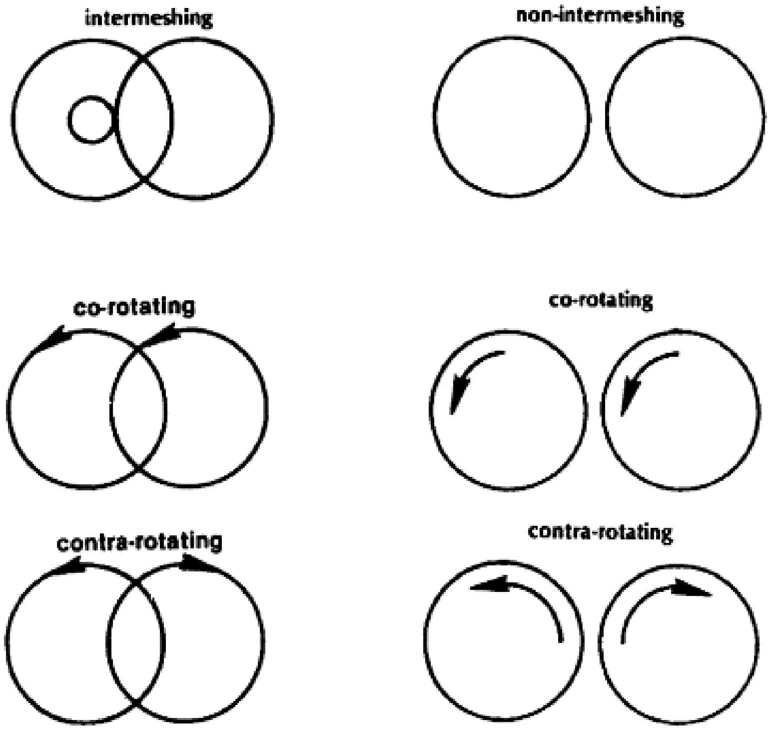

Fig. 2.4 Schematic representation of Twin Screw Extruders Types [7]

In blends compounding the most used kind of extruders are the counter-rotating and co-rotating intermeshing machines.

Counter-rotating systems allow narrower residence times for compounding, with lower overall shear stress distribution, and this can give an advantage in processing easily degradable mixtures, like PVC or colour-concentrate preparations.

The co-rotation of the screw drives instead, towards more homogenization and dispersion, blocking the droplet coalescence, because material is transferred back and forth between the screws, for this reason is the most used method used for polymer blends.

Most twin screw extruders can be assembled using the building block principle, which involves the use of screw elements of different lengths/pitches and special kneading elements of various widths available as blocks that are interchangeable. This makes it possible to design the every processing section exactly as required for obtaining optimum processing conditions.[12]

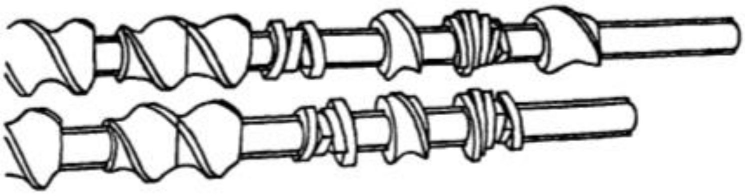

Fig.2.5, Example of design of screws kneading building blocks in compounding

If a twin-screw extruder is stopped and opened, several zones can be distinguished. Generally they can be categorized into six main parts or zones:

Table 2.1, Extruder partitioning (atozplastics.com)

Intake or solid transport Zone	for introducing the material into the extruder.
Zone	for heating the material and therefore the material and achieve partial or total mixing.
Venting Zone	for removing the volatiles and moisture.
Mixing Zone	for ensuring proper mixing.
Vacuum Zone	for completely removing the volatiles and moisture to the required levels.
Metering Zone	for building up the required pressure at the die.

Each zone works functionally by the screws design set, which has to be adapted to the specific kind of compound.

Apart from obvious reasons like the specific design of screw building blocks, the chamber length and geometry, and the overall technological degree of these industrial compounding systems, it has been confirmed by many authors and works, characterizing materials obtained by several methods of mixing, that Twin screw extruders can yield mixtures with a greater degree of dispersion than those produced by any kneader or batch mixer. [7]

Because of the amounts of necessary components for the mixing, it remains anyway the most valuable processing method, but just on greater scales of manufacturing.

2.2.3 Solvent casting

Developed as a method to obtain very thin plastic films since the last century, highly technologically improved solvent (solution) casting, is today used for the production of engineering plastics, optical and medical applications and sheet forming for the electronic field.

Solvent casting can be used as mixing method on a laboratory scale to obtain soluble polymers mixtures. It allows the use of additives, and from a technological point of view, one of the main advantages in blending with this method is represented by the lowest thermo-mechanical degradation among all the processing technologies.

For the raw materials of the dope making process there are some obvious prerequisites:

- The polymer must be soluble in a volatile solvent or water.
- A stable solution with a reasonable minimum solid content and viscosity should be formed.
- Formation of a homogeneous film and release from the casting support must be possible.

There almost no lower limit on the amounts of materials used with this process, on a laboratory scale, and this represents one of the main advantages when expensive, or rare compounds need to be preliminarily analysed.

The solvent choice is very important because of the chemical interaction effects on the mixture, like its viscosity, its dilution entropy, and then the crystallization rates of the components.

The Dope preparation is obtained by carefully dosing the components, selecting a correct stirrer and a paddle. Special attention should be also given to the dope degassing when required, and to the filtration process [14].

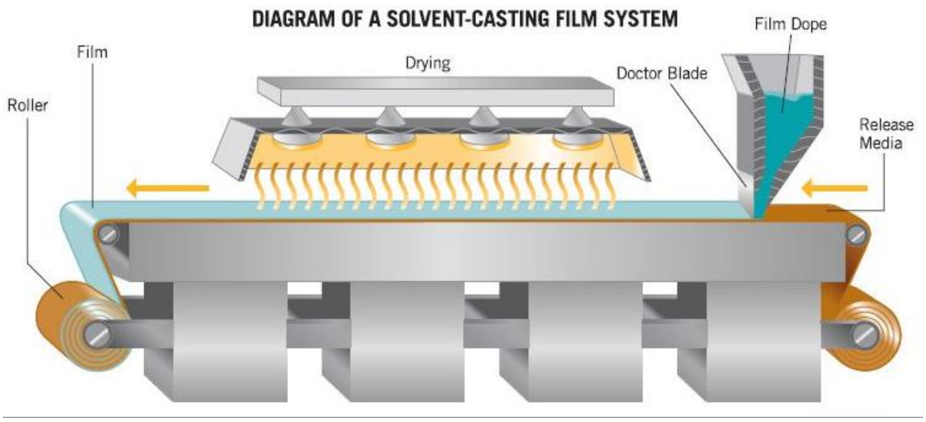

Fig. 2.5 Schematics of Solvent Casting process

The only big disadvantage related to this technique is about its implementation on a large industrial scale, when the solvents to be used can be dangerous for the environment or human health, or are rare products of the chemical industry

2.3 Emulsifying and dispersion in blends

Since dispersion is a key parameter in polymer blending, as discussed above, many methods of obtaining properly dispersed phases have been studied and applied by research and industry.

The additives for miscibility effect on the drop size and the interfacial tension, V_{AB}, follows the same behaviour as the emulsion drop size reduction upon addition of a surfactant. This behaviour is usually described as the “titration curve” that characterizes the surfactant efficiency. The shape of the titration curve depends on the type of emulsifier and the emulsification process, e.g., mixing time and equipment. A similar behaviour is to be expected for polymer blends upon addition of an additive [2b].

Emulsification is then a key factor to obtain dispersed phases when the mixture is immiscible because of the thermodynamic aspects discussed above.

Emulsifying agents can be represented mainly by physically interacting compounds, i.e. copolymers of various chemical structure, or by reactive agents, playing their role by acting 'in situ' during processing, with the formation of structures, capable to greatly improve miscibility.

These methods concern then the effects on the interfacial area and interaction between the phases, of what can be set or added during the thermo-mechanical processing of polymeric mixtures.

An important distinction then, should be made, from physical to chemical methods of emulsification.

Physical methods can be distinguished basically on the effect of thermo-mechanical processing parameters and physical additives used in the mixture like copolymers of opportune chemical structure.

Chemical methods are instead basically about chemical reactions driven 'in situ', capable to give compounds that can act as emulsifiers.

2.3.1 Effect of processing parameters on dispersion and properties

As reported in literature, parameters of processing like temperature, shear rate and geometry of mixing machines can have an effect on dispersion, and other properties of blends.

If the components are thermodynamically immiscible, as discussed above, there is phase separation: the minor component appears as dispersed droplets in a matrix of the major component. A dispersive mixing can then reduce the droplets size of the disperse phase. Because of the interfacial forces, this type of mixing is obtainable just with high shear forces in the system [12].

Furthermore, according to some authors studying on the processing parameters effect on the blends structure, the solidifying dynamics and morphological distribution of components, is the major aspect in defining the mechanical properties, despite the blending technology used, if the correct shear stress is applied to the material [15,16].

2.3.2 Physical agents

Ternary blends that comprise two immiscible polymers and a copolymer are of a particular interest. They not only represent an ideal model for studying miscibility of polymer blends, but they have also found direct commercial applications.

The chemical structure plays an important role in the emulsification ability of copolymers. Many block or graft copolymers can be used for the purpose, with segments identical to those of the homopolymers or, alternatively, the blocks could be chemically different but miscible each with different homopolymers.

Morphological analyses, showed that di-block copolymers, usually have a higher interfacial activity than triblock or graft copolymers. It is possible that because of steric restrictions at the interface, graft and tri-block copolymers, tend to form micelles in the homopolymeric phases. This adds to the complexity of the system morphology, bringing the copolymer to a harder way to exhibit its effect [2b].

The di-block copolymers more readily interact with the two homopolymeric phases, forming appropriate entanglements that result in reduction of the interfacial tension coefficient, and enhanced interfacial adhesion in the solid state, as confirmed by measuring the mechanical properties.

As reported by Ajji [2b] an expression for the minimum copolymer agent amount required to saturate the interface, w_m, has been developed by Paul and Newman [17]:

$$w_m = 3\emptyset M_w/(RaN_{Av}) \qquad (2.7)$$

Where $\emptyset$ is the volume fraction of the dispersed phase, M_w is the interfacial agent molecular weight, R is the radius of the dispersed drop, a is the specific cross-sectional area of the copolymer macromolecule and N_{av} is the Avogadro number.

The copolymers addition effects are strongly related to the interfacial tension between the phases. As discussed above, they can act as a proper surfactant in an immiscible solution. Thus, the idea of the critical micelle concentration, CMC, and the limiting value of the interfacial tension coefficient, v_{CMC}, can be applied to polymer blends. This suggests the possibility of otaining thermodynamically stable droplet condition, in which the minor phase drops, coated with an interfacial film of copolymer, are dispersed within the major phase polymer. This theory also predicts that larger are the repulsive interactions and/or higher is the molecular weight of copolymer, lower is the concentration for saturation of the interface. Once the concentration of added copolymer exceeds CMC the micelles can be obtained.

The results achievable by these physical additives for miscibility are of great technological and scientific interest. It is worth mention anyway, that the highest improvement obtained by these methods of emulsification, regards the variations on impact resistance, resilience and ductility of blends. When major changes in physical properties of different kind are to be obtained, chemical methods should be considered, for the application [2b].

2.3.3 Reactive blending

Reactive blending is a method to obtain compounds, with identical chemical structure of the main components of the mixture, by reactions between polymers and reactive agents. These compounds obtained during the thermo-mechanical processing stage of the blends, can be used as emulsifiers in immiscible polymer mixtures. A block, graft, or crosslinked copolymer of the two (or more) separate polymers in the blend, can be formed through covalent or ionic bond formation. In this manner, such a copolymer, obtained by a heterogeneous reaction taking place across a melt-phase boundary, can both promote optimum dispersed phase particle size formation during compounding and prevent phase coalescence of the dispersed phase during any subsequent high stress and/or heat treatment processes. Furthermore, when the reaction is driven by means of some multifunctional molecules, they can reach the cross-linked state and widen their extension as an actual third phase [13,18,19].

The compounds obtained can then decrease the interfacial tension and increase the physical-mechanical properties of the resulting material. It is then possible to directly obtain a miscible mixture or to use the compound to emulsify another blend of the same kind of components [13].

Reactive Mixing has at least two main advantages:

- First, the copolymer is automatically formed at the interface between the two immiscible polymers where is needed to stabilize morphology. In contrast, when an emulsifying copolymer is added as a separate entity to a polymer blend, it must first diffuse to the homopolymer-homopolymer interface to be effective to get morphology stabilization and a better interphase adhesion. Furthermore, the added copolymer may prefer to form micelles as a separate phase that is useless for compatibilization.
- A second great advantage of in situ copolymer formation is that the molecular weight of each of the two distinct polymeric segments in the copolymer is usually the same as that of the individual bulk polymer phase in which the segment must dissolve. This results in an optimum copolymer/bulk phase interaction to get maximum interfacial adhesion.

These reactive processes are run in single screw or twin screw extruders, or similar continuous or semi-continuous processing equipment, as well as in batch mixers [19, 20]. Furthermore, since the chemical processes are driven by using the reactive agent as an additive to the blend, during its processing, the machine used to mix the components can be seen as a reactor. So as in any other reactor, parameters like temperature, pressure, and here in particular the shear rate, are very important about the resulting blend.

In reactive extrusion, in particular, the mixing has to assure that the distance between the components is small enough that diffusion can provide complete dispersion within the time available or to assure stoichiometry within the reaction.

On this subject it is worth mentioning that dispersive mixing occurs mainly in the high shear zones of the machine [13], then, since the reaction kinetics at the processing temperatures are usually very fast, it is suggested to add the reactive agent within that extruder zone.

In conclusion, Reactive Mixing, is one of the most reliable and used methods to get miscibility in a polymer blend. Most of the research in this field is indeed targeted on industrial development and improvement of this technique, shown by the large number of patents on the subject.

A special mention is worth for the Cross-linking induced by reactive blending. As described better later, it was one of the most important subject of this thesis work.

It represents a way to obtain with this processing, not just miscibility among two polymeric phases, but it is also capable to form structures acting as a proper third phase with a very noticeable effect on all the physical-mechanical-chemical properties of the mixture [18].

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3. Biodegradable polyesters, physical and reactive blends

3.1 Biodegradable polyesters, characteristic properties and applications

In any application, the use of degradable polymers is dependent on the knowledge of the interaction of these materials with the environment. The type and the number of small molecules evolving from the materials govern this interaction. [1]

In particular, biodegradable polyesters have shown to have a wide range of applicability, because of their peculiar physical and chemical properties and their favourable interaction with many environments.

The ester bond, represented by a carbonyl and a following oxygen atom in the main backbone, has the characteristic to be highly hydrophilic, and then hydrolysable. The scission can then be obtained passively by chemical hydrolysis or actively by enzymatic reaction, where the latter is understandably the quicker. Furthermore, as shown in Fig 3.1. carboxylic end groups are formed during these macromolecular scissions, and this may enhance the rate of further hydrolysis. This mechanism is denoted “autocatalysis”.

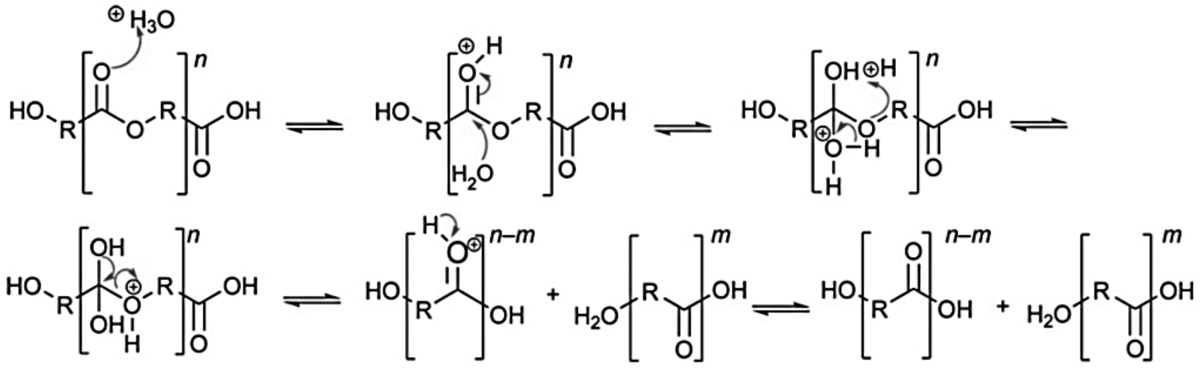


Fig.3.1 Example of Polyester Hydrolytic scission, acid catalysed, general reaction verse

The rates of biodegradation of polyesters are largely dependent upon the type of repetitive unit, composition, sequence length, molecular geometry, molecular weight, crystalline degree and structure, hydrophilicity, surface area, and additives.

Polyesters with a high tendency to crystallize and with long non-polar monomer structures, like poly (e-caprolactone), can show very low hydrolysation rates, that can require for complete degradation years of interaction. More amorphous, polar and generally lower molecular weight materials like PLA tends instead to complete degradation in much less.

The academic and industrial interest on the subject, starts from the increasing demand for renewable sources of polymeric materials, because of all well-known issues related to the petroleum industry, from the extraction to the processing of oil, and the necessity of a 'Bio' alternative to the most common synthetic polymers.

The applicability range of this polymers class is then nowadays very wide, and it covers:

- Disposability and Biodegradability for the plastic waste management worldwide. To reduce and manage the amount of plastic material wasted every year, for economic and environmental reasons.
- The use of renewable resources, to offer an answer to maintaining sustainable development of economic and ecological technologies.
- The possibility of use for pollution issues, since their utility in selective sorption of oil-based aliphatic and aromatic compound has been recently shown, in the field of oil spill recovery.
- A biological and sustainable alternative in food grade materials for food packaging and usage.
- A better biological interaction, for the development and manufacturing of high technological and clinical value biomedical devices [1, 2].

Besides, over their characteristic biodegradability and sustainability, this class of polymers can show a wide range of physical and chemical properties.

As a guideline to the biodegradable polyesters properties, some specific characteristics are given in table 3.1

Table 3.1 Main Biodegradable Polyesters properties table

Biodegradable polyesters	**Young's Modulus [MPa]**	**Yield strength [MPa]**	**Elongation at break [%]**	**Melting Point [°C]**	**Average Hydrolytic Degradation rate**
Poly(lactide) PLA	*Up to 5000*	*40-50*	*5-10*	*150-160*	*<1 year*
Poly(ε-caprolactone) PCL	*150-200*	*20*	*Up to 1500*	*60*	*>2 years*
Poly(glycolide) PGA	*6500*	*55*	*1-5*	*230*	*2-4 weeks*
Poly(3-hydroxybutyrate) PHB	*1500*	*30*	*5*	*115*	*1month*
Poly(3-hydroxyvalerate) PHV	*1000*	*25*	*10*	*120*	*2 months*
Poly(butylene succinate) PBS	*900*	*34*	*>500*	*114*	*3 months*
Poly(butylene succinate-co-butylene adipate) PBSA	*500*	*19*	*800*	*96*	*<1 month*
Poly(dioxanone) PDS	*2000*	*>400 (fibers)*	*35*	*106*	*2 weeks*

As object of this work, the complementarity in properties and the potential of two biodegradable polyesters in particular, the Poly(lactide) and the Poly(ε-caprolactone), will be discussed in detail in the following part.

3.2 PLA and PCL as complementary materials

3.2.1 Poly(lactide) structure and properties.

Thermoplastic Poly(lactide) or Poly(lactic acid) (PLA) is so far, the most extensively researched and utilized biodegradable aliphatic polyester in human history. It is obtained by Azeotropic Dehydrative Polycondensation of enantiomers (D or L) of Lactic acid or by ring-opening polymerization of the dimeric structure Lactide (Fig. 3.2) [3].

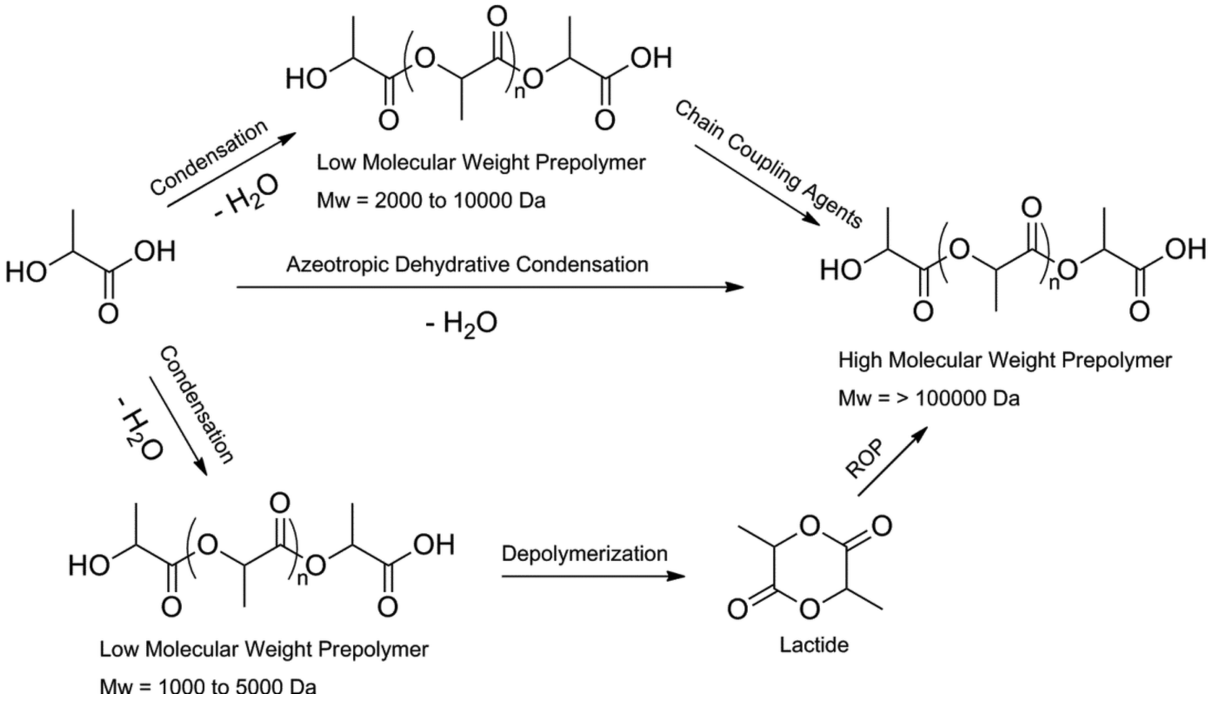


Fig. 3.2 Poly(lactide) polymerization scheme [4]

Lactic acid (LA) can be produced by fermentation of sugars, by sugarcane or corn starch as renewable sources, or even coal, petroleum or natural gas.

It is classified as generally recognized as safe (GRAS) by the United State Food and Drug Administration (FDA) and is safe for all food packaging applications, The research on lactic acid based polymers to be used in medicine, has accelerated since FDA approval, and during the last two decades an increasing utilization of large scale industrial lactic acid based polymers for other uses has been noticed. In particular because, it has been found that even all PLA degradation products are non-toxic, making it a natural choice for biomedical applications. For these reasons it has been succesfully used since its first synthesis, by Carothers in 1932, in many fields. It is worth mentioning in particular the increasing interest in its usage for Drug delivery systems, since the abilities of its nano and micro-particles, as carriers for several kinds of active molecules [3]

PLA has also better thermal processability compared to other biopolymers such as Poly(hydroxyl alkanoate) (PHA). It can indeed be processed by injection moulding, extrusion, blow moulding, thermoforming, fibre spinning, and film forming, considering also its Tm of about 160 °C.

It exhibits very good mechanical properties, like high Yield strength (Up to 60 MPa for some grades of pure Poly(L-lactide)) and Stiffness (Young's modulus up to 4 GPa), but it pays in ductility, being quite brittle at room Temperature (Tg = 60 °C, average Elongation at break < 10%, Work at breakage for standard specimens in the order of 10^{-2} J). Furthermore, PLA, like all the biodegradable polyesters of its class, is sensitive to enzymatic and chemical hydrolysis, having average dissolution time of several months. This being also related to its ability to arrange in various crystalline structures and mainly for its low hydrophilicity because of the methyl group linked to the anomeric carbon atom in the Lactid acid monomer.

PLA has been then bulk modified mainly to improve toughness and degradation rate while surface modification has been attempted to change its hydrophilicity, roughness, and to introduce reactive groups. Improving all of these characteristics is important for both consumer and biomedical applications.

Besides, highest number attempts of blending it with several polymers, of its class or different kinds of thermoplastics, have been followed in recent times. Most of them have been oriented to the manufacturing of mixtures with highly ductile and rubbery biodegradable polyesters [3,4,5].

3.2.2 Poly(ε-caprolactone) structure and properties

Poly-ε-caprolactone (PLC) is a synthetic, biodegradable (both linear and cross-linked) polyester with MW usually > $20*10^3$ g/mol. It is obtained by ring opening polycondensation of ε-caprolactone (2-Oxepanone), according to cationic, anionic, monomer activated, and coordination–insertion mechanisms of polymerization. Stannous, Tin or, more recently, Aluminium alkali based catalysts find use for the reaction in research and industry (Fig. 3.3).

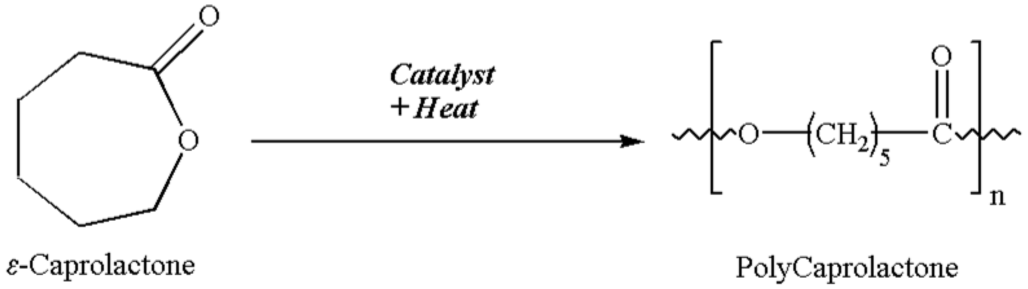


Fig. 3.3 Ring Opening Polymerization scheme for Poly(ε-caprolactone)

It is a proper thermoplastic, rubber-like polymer (Tg = -60°C) with several desirable features, including good stability under ambient conditions and under thermo-mechanical stress, ease of processability (thermal and solution), and has already been approved for use by the U.S. Food and Drug Administration. It is one of the most used polyesters of its class, because of its highest ductility and optimal biological interaction. It is indeed used successfully in the medical research field, in particular for drug delivery systems, scaffolds manufacturing including sutures and wound dressing, cardiovascular tissue engineering, nerve regeneration.

Poly(ε-caprolactone) exhibits probably the highest ductility among polyesters of its class (Elongation at break up to 1500%, Strain at Yield of , Work at breakage in the order of 10 J for standard specimens), a great thermo-mechanical degradation resistance and suitable biodegradation rates for many biological applications.

The mechanical and degradation properties of pure PCL, anyway, could result not adequate with the requirements for some kind of biomedical applications, such as bone tissue engineering. So, PCL can be used as one of the component of blend materials or copolymers. Incorporation of nanostructured filler material into the PCL material could be an important strategy to improve and modulate the mechanical and degradation properties of PCL-based materials [6].

Then, it is understandable how blending these two complementary polyesters, acting on the molar or weight ratio of the mixtures, can lead to a class of biodegradable materials with well-balanced properties. For this reason, as discussed in detail later, many efforts have been recently put in studying and improving properties of blends of these two polyesters.

Because of their different chemical structure anyway, these two polyesters blended together, result in immiscible mixtures, with poor macroscopic properties, because of the macro-phase separation of the components, and the poor interaction between the phases for the thermodynamic reasons discussed above [7].

Concentrating the efforts in obtaining a proper dispersion, and interfacial interaction is then the actual target of the current studies on these promising biodegradable polyester blends.

3.3 Advances in PLA-PCL blending (state of art)

As already mentioned earlier, an almost uncountable number of studies have been aimed at the manufacturing and characterization of Poly(lactide)/Poly(ε-caprolactone) blends.

On an early phase of the research, the target was represented by improving PLA toughness, attempting to that with mixing it with small weight percentages of PCL, to transfer part of its ductility to the resulting blends, in terms for instance of impact resistance or elongation at break [7,8,9]

Dell'erba et co-workers [7] have then for first identified and highlighted the importance of the effects of miscibility on the morphology and then on physical properties of these mixtures. They have also successfully managed to obtain partially miscible blends, by adding a triblock copolymer (PLLA-PCL-PLLA) which anyway had not a very noticeable effect on the physical properties. This can be recognised as the first true attempt to change the morphology of these polyester blends.

Later on and up to nowadays, studies on the processing parameters effects on the physical blends have been conducted, to better understand the mechanisms beyond the miscibility behaviour.

In particular, the following important results have been obtained:

- The morphology and phase structure of the blends after solvent evaporation or thermal treatments, can depend on the mixing ratio and molecular characteristics of the constituent polymers, blending method, and crystallization temperature;
- PLLA and PCL are crystallisable in the presence of PCL and PLLA or PDLLA, respectively, and the mechanical properties of the blends can be controlled by altering the polymer mixing ratio.
- The crystallization dynamics are the key factor in determining mechanical characteristics of physical blends, despite the thermo-mechanical processing method used to manufacture the mixtures, if the proper shear rate is applied during mixing (i.e. Injection moulding resulted better than Compression moulding as last processing phase in terms of dispersion). [10,11]

In general, it has been shown that the resulting interfacial interaction between components, about the shape, size and distribution of the dispersed phase can be determined by a variety of parameters like the composition, viscosity ratio, shear rate, elasticity ratio and interfacial tension among the polyesters, and also processing conditions like time and temperature of mixing, rotors speed and type of mixing.

These findings, clarified and confirmed how some techniques are more suitable than others in blending immiscible polymers, and how the role of thermodynamics interaction has a dominant effect on the macroscopic properties of the mixtures. It is anyway clear how any successful attempt on changing the structural parameters of these multiphasic system, cannot be by any mean similar to what can be obtained by the use of specific additives during processing.

Emulsifying agents like copolymers (triblocks, diblocks, random) of different chemical structures, have been extensively used in this research thread, with very interesting findings. The most important results concern the change in ductility behaviour and general mechanical response of the blends, and in noticeable morphology differences.

Dell’Erba et al., in the previously cited work, used a triblock (PLLA-PCl-PLLA) copolymer to obtain miscibility. They found out that by adding amounts from 0,5 to 5 phr of additive, the crystallization kinetics of polyesters remains unchanged, as reported generally for bulk properties of materials like also the Glass Transition. The copolymer had instead a noticeable effect on the interfacial tension, shown by the reduction in droplet size as observed by optical microscopy (Fig. 3.4). No mechanical characterization was conducted.

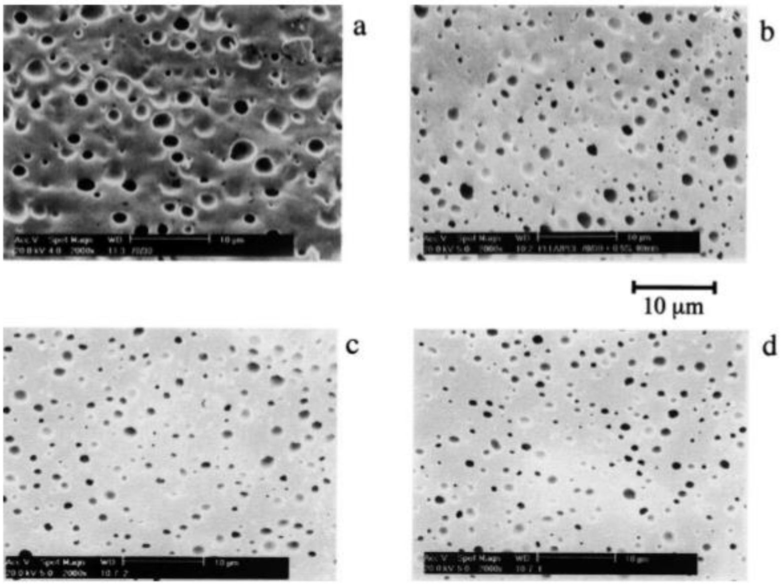


Fig. 3.4, Optical microscopy images of PLA/PCL blends (Wt ratio 70/30) with 0 a), 0.5 b), 2 c), 5 d) phr of PLLA-PCL-PLLA triblock [7]

Later, Tsuji et al. [12] studied instead the effect of 10 wt % of a diblock (PLLA-PCL) copolymer with 1,7*10^5 g/mol of molar mass on solution cast blends of PLA/PCL at various compositions. As a structural change, a noticeable increase in spherulites sizes was noticed as an index of improved miscibility. Increases in the elastic modulus and tensile strength were also found for copolymer added blends for weight ratios from 0,5 to 0,8 (PLLA wt. fraction) as shown in Fig. 3.5.

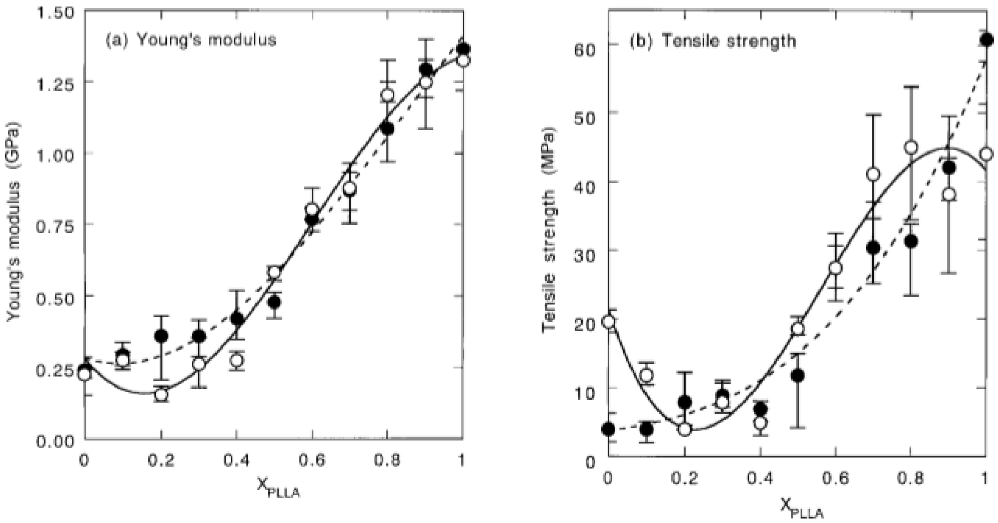


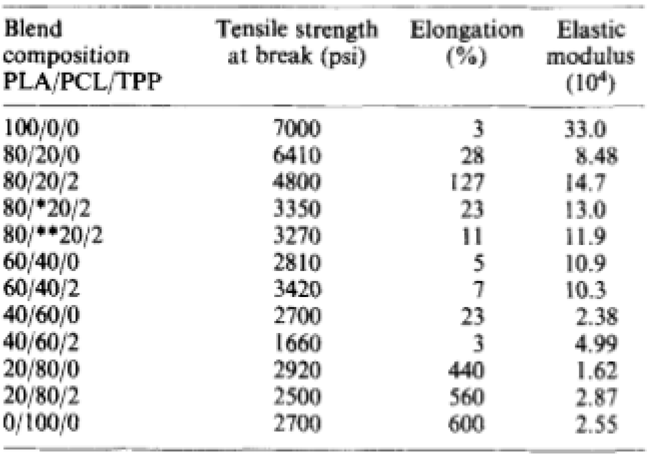
Fig. 3.5, Young's Modulus and Tensile Strength of PLLA/ PCL blends without (black dots) and with (white dots) 10% of PLLA-CL [12]

It is also worth mentioning the mechanical characteristics improvement reached by Chavalitpanya and Phattanarudee [13], using a PEG-PPG block copolymer. Most important changes have been reached by using 7.5 phr of additive, with an Elongation at break improvement, from 8,2 to 74,4 % but a detrimental effect on Tensile strength (from 40,4 to 25 MPa).

These results show that promising structural changes can be obtained by well tailored copolymers used as emulsifiers. The mechanical properties improvements are anyway still far from what can be obtained by chemical methods, like the use of reactive agents, as shown later.

Reactive blending with PLA and PCL has been first achieved by Wang et al. [14] using Triphenyl Phosphite as reactive agent, to promote transesterification reactions leading to branched copolymeric structures, able to improve miscibility. However, despite the noticeable improvements in mechanical properties (Table 3.2), a molecular weight loss has been noticed, as a probable result of a 'back-biting' intramolecular side transesterification which can be catalysed by TPP.

Table 3.2, PLA/PCL/TPP blends mechanical properties



Blend composition PLA/PCL/TPP	Tensile strength at break (psi)	Elongation (%)	Elastic modulus (10^4)
100/0/0	7000	3	33.0
80/20/0	6410	28	8.48
80/20/2	4800	127	14.7
80/*20/2	3350	23	13.0
80/**20/2	3270	11	11.9
60/40/0	2810	5	10.9
60/40/2	3420	7	10.3
40/60/0	2700	23	2.38
40/60/2	1660	3	4.99
20/80/0	2920	440	1.62
20/80/2	2500	560	2.87
0/100/0	2700	600	2.55

Later, among many potential reactive agents, amino-acids structured ones have then moved much interest. In particular, the use of L-Lysine molecules linked to Isocyanate functional groups, able to react with hydroxyls at the chain ends of polymers, started to have a dominant role in reactive blending of aliphatic polyesters.

As discussed better later, this reactive blending process, results in branched and/or cross-linked co-polyester-urethane networks, causing a deep change in the macromolecular architecture of mixtures and a consequent improvement of physical properties. These reactive agents can exhibit a very high reactivity, apparently without driving to side transesterification reactions. The good biological interaction of co-polyester-urethane networks from biodegradable polyesters and Lysine Isocyanate compounds has also been proved by some recent studies [15, 16].

The works by Takayama and Todo, and by Harada et al. [17, 18] have represented the most important starting points regarding these reactive mixtures. The use of Ethyl Ester L-Lysine Triisocyanate in particular, proved to drive the systems towards great improvements in toughness and ductility.

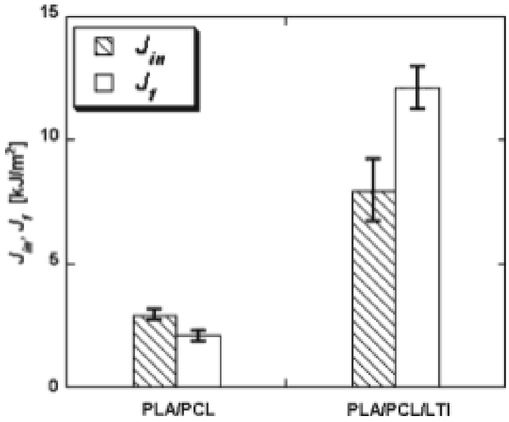
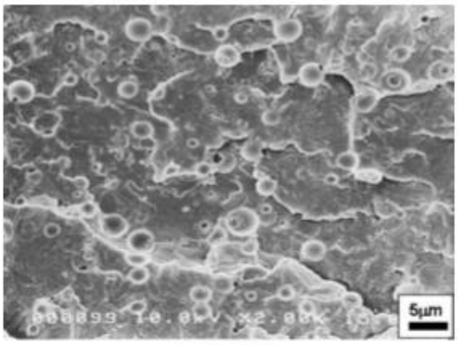
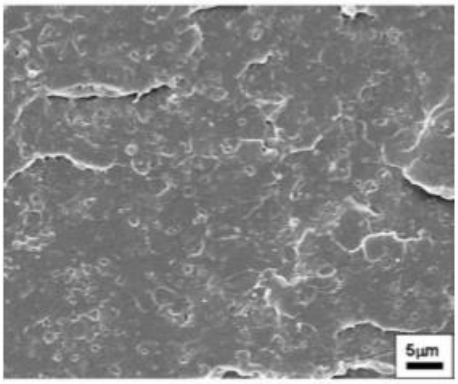


Fig. 3.6, Initial crack (J_{in}) and Average fracture energy (J_f) for PLA/PCL and PLA/PCL/LTI blends [17]

Harada et al., also showed by means of torque measurements during mixing and Melt Flow Rate analysis, how the shear viscosity of the blends increased gradually with the reactive agent amount used (from 0,1 to 0,5 phr), observing as well how probably, since its lower melting temperature, PCL chains would be the first to react in the process, getting then linked to PLA directly at the interface. The latter assumption is suggested by theoretical studies and supported by morphological analyses, clearly showing the size reduction of the dispersed phase particles.



(a) PLA/PCL



(b) PLA/PCL/LTI

Fig. 3.7, SEM images of PLA/PCL and PLA/PCL/LTI (1phr) blends [17]

Studies on modelling the fracture mechanisms of these reactive blends and on post processing attempts have been then conducted [19, 20].

Tuba et al., in particular showed how the LTI addition can result in a great increase in the Work at fracture of these polymeric materials, successfully applying the most reliable models and phenomenological equations, supported by mechanical tests.

Takayama et al., studied instead the effect of an 'annealing' process after mixtures manufacturing, on their physical properties. In this work the differences among quenched or 'annealed' samples are shown, with interesting results on bending and tensile resistance of blends and on their thermal response, in particular in terms of crystalline structures observed.

Besides, they believed that the rougher surfaces of 'annealed' blends were just the result of a PLA re-crystallization process. PLA is indeed known for its ability to crystallize by temperature applying [21].

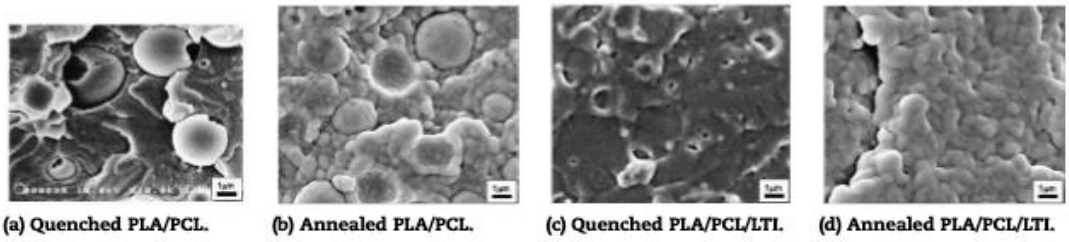


Fig. 3.8 SEM images of quenched and annealed PLA/PCL and PLA/PCL/LTI blends [20]

As shown later in this work, some possible further phenomena can be acting in post-processing of these materials, and they can be explained by a detailed rheological characterization, which, together with a comprehensive mechanical characterization, is the main lack in the actual literature.

The aim of giving a deeper understanding of these promising materials properties, was then the aim of what will follow, in the experimental part of this thesis started as a characterization study and become quickly a research thread of expanding and contemporary interest for the many suitable applications.

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4 Experimental

4.1 Materials

For what discussed in the previous chapter, the literature lack of a deep physical-mechanical investigation on reactive PLA-PCL blends, led to the idea to conduct a comprehensive study on the effects of LTI, and of the co-polyester-urethane structures obtained by its use, on these materials.

For this reason, physical and reactive mixtures of Poly(lactic acid) and Poly(e-caprolactone) have been manufactured and characterized by means of several physical methods described in detail later.

Physical, and reactive blends with 0,5 and 1 phr LTI amounts, were obtained for three weight ratios of PLA and PCL (80-20%, 50-50%, 20-80%). Using instead 2 and 5 phr of LTI, to better underline and study the effect of the reactive agent, equal weight ratio blends (50-50%) were prepared and characterized.

Preliminary experiments have also been conducted on solvent cast blends, obtained with a block copolymer of PLA and PCL (PLA-b-PCL) synthesised *ad hoc* for the purpose. Three different phr amounts of this additive (1; 7,5; 10; 15), have been used on equal PLA/PCL weight ratio blends (50-50%).

All the blends obtained are summarized and codified in the following table.

Table 4.1 Blends codification and components detail

Code	PLA (wt. %)	PCL (wt. %)	Additive (phr)	Colour
A100	100	0	0	White
A80C20	80	20	0	White
A50C50	50	50	0	White
A20C80	20	80	0	White
C100	0	100	0	White
A80C20T05	80	20	0,5 (LTI)	Brown
A50C50T05	50	50	0,5 (LTI)	Brown
A20C80T05	20	80	0,5 (LTI)	Brown
A80C20T1	80	20	1 (LTI)	Brown
A50C50T1	50	50	1 (LTI)	Brown
A20C80T1	20	80	1 (LTI)	Brown
A50C50T2	50	50	2 (LTI)	Brown
A50C50T5	50	50	5 (LTI)	Brown
A50C50SC	50	50	0	White
A50C50B1SC	50	50	1 (PCL-b-PLA)	White
A50C50B7,5SC	50	50	7,5(PCL-b-PLA)	White
A50C50B10SC	50	50	10(PCL-b-PLA)	White
A50C50B15SC	50	50	15(PCL-b-PLA)	White

In the following Tables (4.2, 4.3, 4.4) are reported the main physical properties of the polymers grades and of the reactive agent used, as listed in the data-sheets supplied by the manufacturer.

With the purpose of having a comprehensive understanding of the chemical mechanisms outcomes, regarding the structural changes on the materials brought by the reactive mixing process, Gel Permeation Chromatography analyses have been conducted on the blends component, to obtain a reliable value of their molecular weights.

GPC tests results are shown in Fig. 4.1.

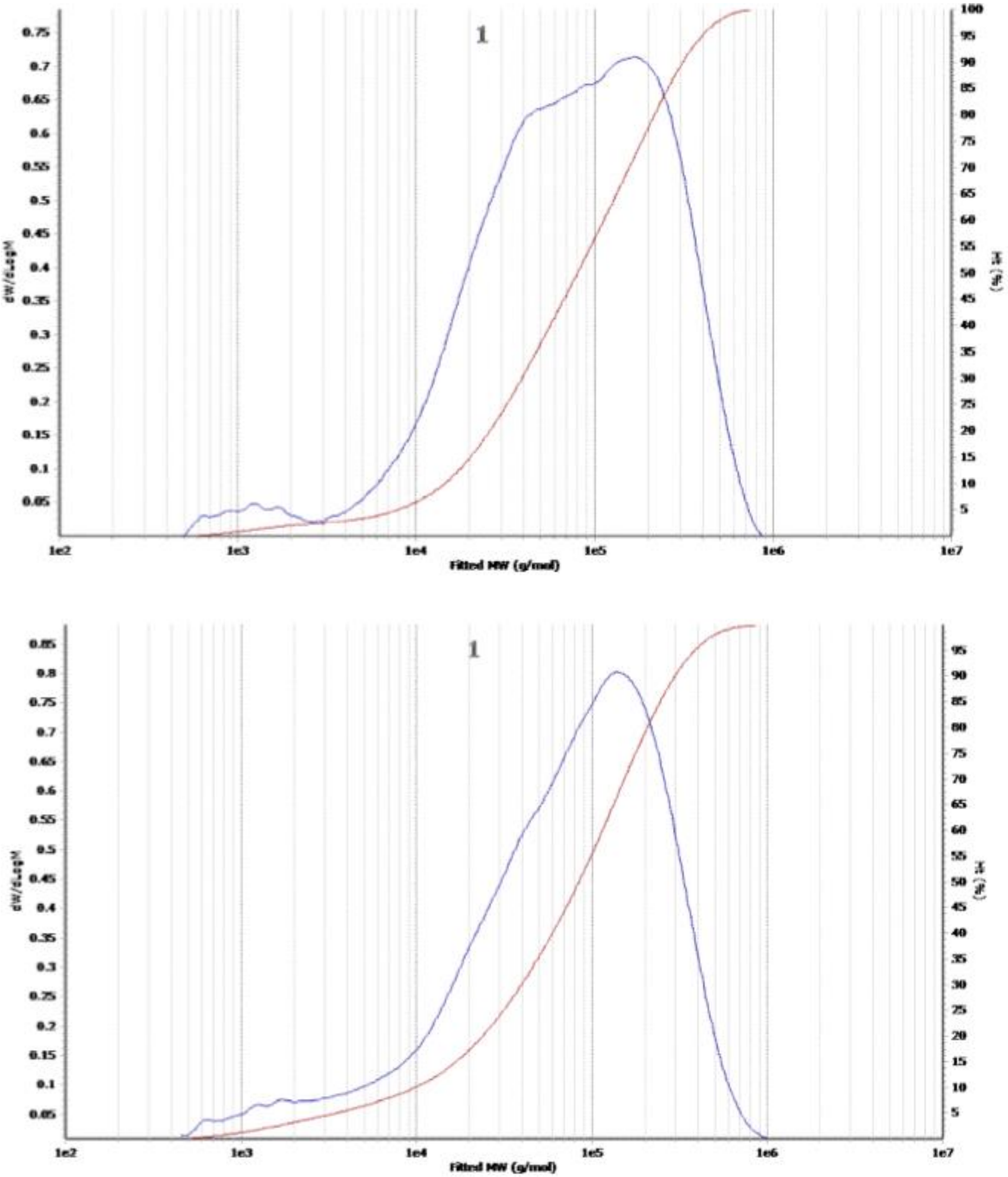

Fig 4.1, Gel Permeation Chromatography data (top PLA, bottom PCL)

Table 4.2 Poly(lactide) properties

PLA 'Bioflex F6510' supplied by FKUR		
Property	**Value**	**Method**
Tensile strength	640 [MPa]	ISO 527
Yield Strain	9 [%]	ISO 527
Stress at Yield	28 [MPa]	ISO 527
Elongation at break	35 [%]	ISO 527
Density	1.24 [g/cm^3]	ISO 1183
Melting temperature	> 155 [°C]	ISO 3146-C
Number Average Molecular Weight (Mn)	40000 [g/mol]	Gel Permeation Chromatography
Weight Average Molecular Weight (Mw)	160000 [g/mol]	Gel Permeation Chromatoraphy

Table 4.3 Poly(ε-caprolactone) properties

PLA 'Bioflex F6510' supplied by FKUR		
Property	**Value**	**Method**
Young's Modulus	155 [MPa]	ASTM D638
Yield Strain	19,5 [%]	ASTM D638
Stress at Yield	11 [MPa]	ASTM D638
Elongation at break	>1500 [%]	ASTM D638
Density	1.14 [g/cm^3]	ISO 1183

Melting temperature	60 [°C]	ISO 3146-C
Number Average Molecular Weight (Mn)	100000 [g/mol]	Gel Permeation Chromatography
Weight Average Molecular Weight (Mw)	160000 [g/mol]	Gel Permeation Chromatoraphy

Table 4.4 LTI properties

Ethyl Ester L-Lysine Triisocyanate supplied by Infine Chemicals L.t.d.		
Property	**Value**	**Method**
CAS Number	69878-18-8	/
Optical purity	80 [%]	/
Density	1.21 [g/cm^3]	ISO 1183
Boiling temperature (1 Atm)	382,9 [°C]	ISO 3146-C
Molecular Weight (Mw)	267,24 [g/mol]	Gel Permeation Chromatography

As suggested first by Harada et al. [1], in this reactive mixing system, the hydroxyls groups, at the polyesters chains ends, can react with the very reactive isocyanate ones of LTI. This reaction gives carbamates and so branched and/or cross-linked co-polyester-urethane structures, following the reaction scheme in Fig. 4.2.

As discussed above according to literature, and confirmed by experimental results reported later, these structures appear to be located directly at the interface between the two polyester phases. They can then directly get anchored to the matrix and the dispersed phase acting as emulsifying agents with noticeable effects on the physical properties of blends.

The reaction stoichiometry suggests that, since from the lowest concentration used of reactive agent, the reactive groups proportion (-N=C=O / -O-H), is always disproportioned in favour of the Isocyanates of the reactive agent, branched structures are always obtained in these blends. In the reactive blend A50C50T05, the addition of 0.5 g of LTI (M_w = 267.24 g/mol), in 100 g of blend corresponds to 0.002 moles and so to 0.006 moles of available -N=C=O reactive groups. Estimating instead the moles of PLA and PCL chain ends (based on the M_n values measured by GPC) a value of available OH in the order of 0.004 moles. When the additive loading is increased, it is easy to conclude that the LTI tends to saturate all possible chain ends, thus forming a 3D, cross-linked network. A more detailed discussion in this regard is given in the following chapter.

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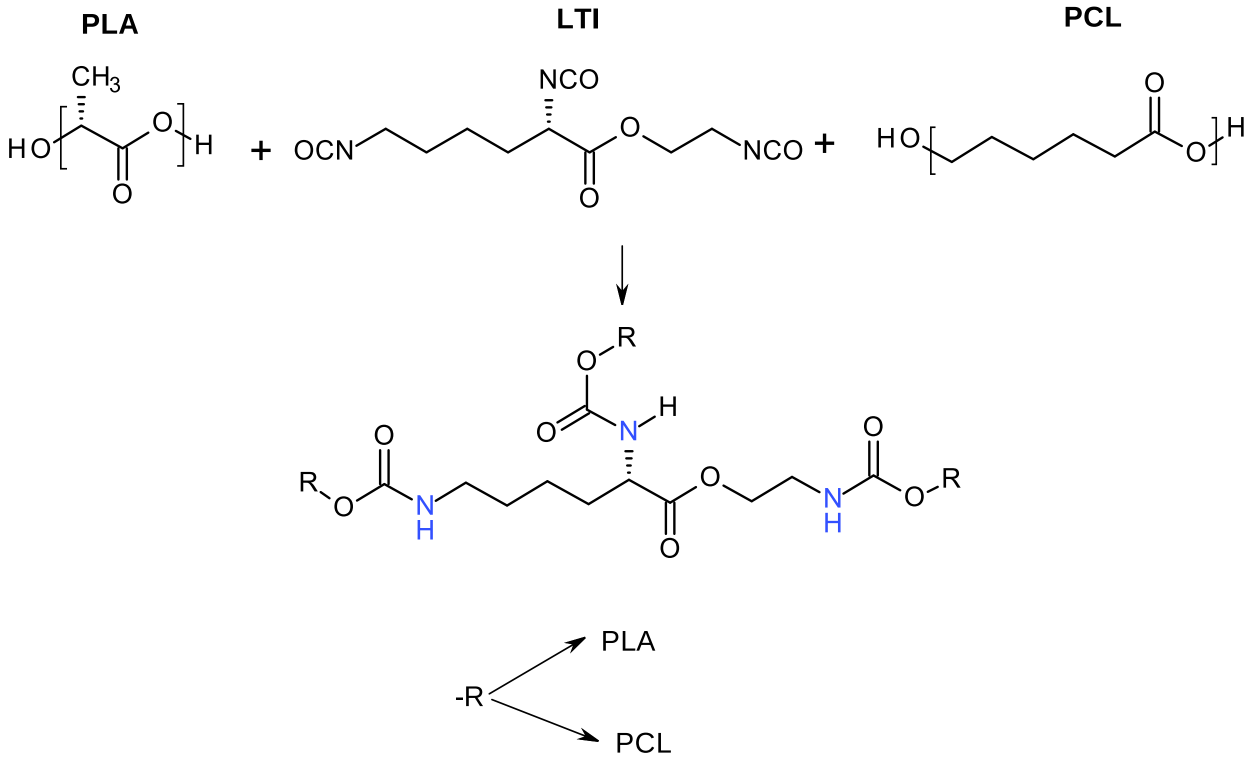

Fig 4.2 PLA-PCL-LTI reaction scheme, first iteration.

Rearding the physical blends obtained by Solution Casting, the block copolymer, PCL-b-PLA, has been synthesised in the ‘Department of Materials’ of ‘Loughborough Uniersity’, following a procedure described by Jacobs et al. [2].

4.2 Techniques and processing parameters

4.2.1 Batch Mixing

Internal mixing was used as recognised as one of the most reliable processing methods to obtain reactive blends. It is considered most valuable on the main synthesis and characterization phase for new polymeric materials, since the very good dispersive mixing that can be obtained, the low raw components request, and the ease in processing parameters setting.

The batch mixer used is a Brabender Plasticorder PL-2000 (shown in Fig. 4.3), linked to an analog/digital interface unit and then to a standard PC. The torque transducer embedded in the gearbox was able to record the torque values during mixing procedures, and their trends vs time have been plotted by means of Microsoft Excel software.

Fig. 4.3, Brabender Plasticorder PL2000

With the aim of filling the mixing chamber completely (about 60 mL), as this is recognised as a parameter to attention, in order to obtain the best dispersive mixing correct amounts of polyesters have been calculated considering their weight ratio for each mixture, and their densities. An example is given below.

$$\rho_{PLA} = 1{,}24\frac{g}{mL};\ \ \rho_{PCL} = 1{,}14\ \frac{g}{mL}\ ;$$

$$\bar{\rho}A50C50 = 0{,}5 * \rho_{PLA} + 0{,}5 * \rho_{PCL} = 1{,}19\frac{g}{mL};$$

$$Wt = \ \bar{\rho}A50C50 * Vch \ = \frac{1{,}19g}{mL} * 60mL = \ 71{,}4g; \qquad Wt(PLA) = Wt(PCL) = 35{,}7\ g$$

All the blends have been manufactured following the conditions reported by Tuba et al. [3] as they have been recognised among all literature studies, to be the less hard thermo-mechanical processing conditions, still brining to the correct degree of mixing. This led materials to maintain their properties, and to develop the desired structural changes, with no degradation :

- Polyesters have been dried overnight at 50 C.
- PLA and PCL have been weighted and mixed manually in a glass beacker.
- The mixture has been put in the mixing chamber at 180 C with a screws speed of 25 rpm for 5 minutes.
- For reactive blends the amount of LTI was then added.
- Blends have been mixed for 10 minutes.

During the thermo-mechanical process, the torque values have been recorded every 30 seconds by means of the torque transducer and the Brabender PC Software. They have then been plotted vs time and discussed in detail later.

4.2.2 Post mixing processes

After batch mixing, following the same direction proposed in the work cited above, the blends have been then compression moulded at 100 bars for 10 minutes at 180 °C, to be then cooled down to room Temperature. The equipment used was a Campana s.r.l press (Fig. 4.4), equipped with a water cooling system. A brass mould frame, with upper and lower stainless steel walls, was used to give the molten material the desired shape. PTFE sheets were used as mould releasers.

Fig. 4.4 Compression Moulding Press

Materials samples obtained were then 60x60 mm square shaped sheets of 1mm thickness, to be then processed with a Ray Ran manual die cutter, to obtain dog-bone shaped samples, according to ASTM D638-10, for tensile testing.

Rheology samples were instead obtained with radial symmetry stainless steel closed mould, giving circular shaped sheets of 32 mm of diameter and 1mm in thickness. These samples have been edged with a manual die cutter to 25 mm of diameter, since this was the suggested size for rheometer plates.

4.2.3 Twin screw extrusion

In order to study the differences among a discontinuous process like the batch mixing, and a continuous method of manufacturing for a first applicative definition, reactive blending of PLA/PCL/LTI blends has been conducted as well in a laboratory scale extrusion process. The aim was then to prepare polyester threads to evaluate their applicability as absorbable sutures, also as drug delivery devices.

For this purpose a HAAKE MiniLab II extruder was used (Fig. 4.5 a), equipped with a melt spinning machine (Fig. 4.5 b) designed ‘ad hoc’ for the system, to obtain threads of about 0,5 mm in thickness of various formulations.

Amounts of 6 gr of materials pellets, in equal weight ratio of the two polyesters (A50C50 blends), added with LTI from 0,5 to 5 phr, have been manually mixed and poured into the extruder hopper. After 1 minute of processing, at 160 °C, with the re-circulation system on, LTI was added in drops. After 1 further minute, the actual extrusion was conducted, the resulting thread spun and stretched to the defined thickness by the machine.

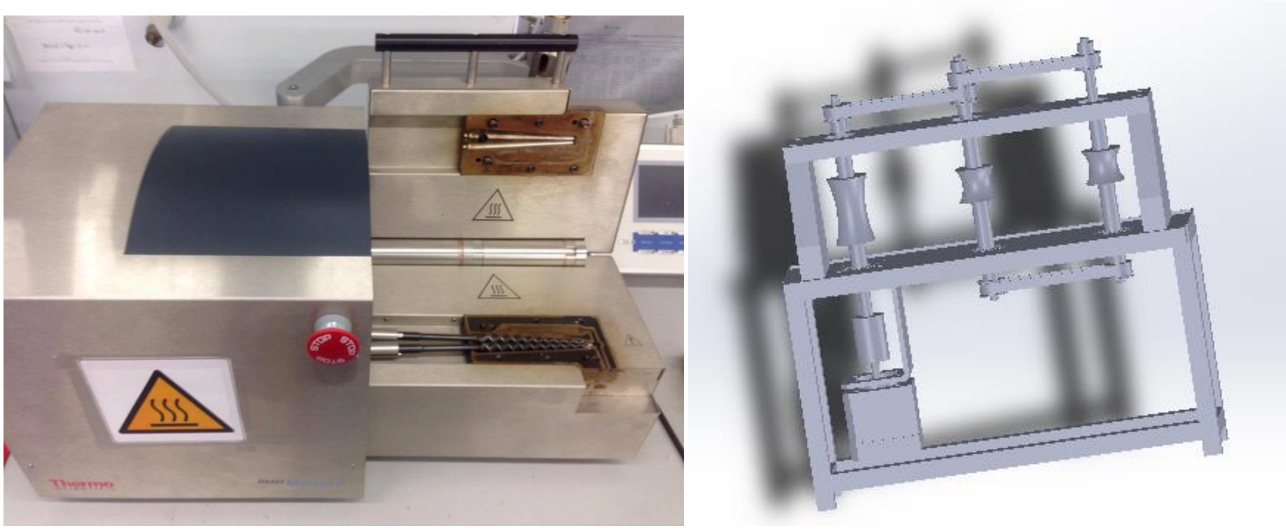

Fig. 4.5 a) Haake MiniLab II twin screw extruder, b) Design of the Melt spinning device

4.2.4 Solvent Casting

For the physical mixtures obtained with PCL-b-PLA, Dichloromethane (DCM) was used as solvent for the solution casting procedure, and processing has been conducted as follows :

- Polyester pellets and the copolymer have been dried overnight in a vacuum oven at 40 °C.
- 3g of PLA pellets, 3g pf PCL pellets and the copolymer amounts (1; 7,5; 10; 15 phr) have been poured into a 500 mL glass ballon with a PTFE coated magnet.
- The glass balloon was kept in an oil bath standing on an electromagnetic stirrer.
- Starting the stirring system, 250 mL of DCM were poured in the glass ballon, reaching 500 rpm of stirred speed.
- The oil bath under the glassware was heated to 45 °C.
- The blends have been mixed for approximately two hours, until an homogeneous mixture was reached.
- The resulting liquid was poured into a 500 mL glass crystallizer, and led to dry under fume hood overnight.
- The solid mixtures have then been dried in a vacuum oven at 40° C overnight again.

An example of blend obtained by this processing method is shown in Fig. 4.5. Materials obtained have then been processed by compression moulding and manual die cutting as described above for every blend manufactured.

4.3 Techniques of characterization used in the work

4.3.1 Tensile testing

Mechanical tests represent since the earliest phases of polymer science and engineering, among the most versatile, reliable and comprehensive sources of information regarding physical properties of materials.

Tensile testing equipment consists briefly in high precision electromechanical machines, impressing precise deformation increments in time on specific geometry samples, and reading the resistant load exhibited by the specimen

The mechanical behaviour of materials can be understood by carefully studying the Stress-Strain (or Load-Displacement) curves obtained during analyses. These curves are usually composed by two parts, a first linear trend, reflecting the elastic behaviour of the material, and a non-linear one, expressing an anelastic response, related to a ‘plastic’ deformation.

The elastic behaviour of solids, is ruled by the Hooke’s equation, defining the proportionality among Stress and Strain, for a constant, expressing the curve slope :

$$\sigma = E\varepsilon \qquad (4.1)$$

The main mechanical characteristics obtained by tensile test curves are:

- The Elastic or Young’s Modulus, “E”. Expressed in MPa, is a measure of stiffness, indicating the stress needed to obtain a unitary strain.
- The strain at yield, “$\varepsilon_{\%}$”. Expressed in %, which is an index of resilience. It indicates the elastic limit of the curve on the strain.
- The stress at Yield, “σ_y”. Expressed in MPa, is instead stress over which the impressed deformation is permanent. Conventionally it refers to its fractions, as upper limits, in mechanical dimensioning of parts under load.

- The maximum stress, "σ_m". Expressed in MPa, is the highest peak on the Stress-Strain curve.
- The strain at break, "ε_b". Expressed in %, is the maximum strain reached by the sample during the tensile test.
- The Work at breakage, "W_b". Expressed in J, is the total amount of mechanical energy necessary to bring the specimen to fracture. With the strain at breakage is a very important index of ductility.

In this study, the mechanical properties of the PLA/PCL physical and reactive blends have been analysed in detail, with the aim of reaching a deep understanding of the materials structural changes effects, on their macroscopic behaviour.

A Lloyd LR 10K Universal testing machine (Fig. 4.6) was used for the purpose, equipped with a 500N Load Cell, with an accuracy of 0,5%.

Fig. 4.6 Lloyd LR 10K Universal Testing Machine

The ASTM D638-10 Standard was followed to determine the testing conditions and the results elaboration. For all the tested samples the following parameters have been used :

- The cross-heads speed was set on 10mm/min, as it was found to be the most suitable intermediate displacement increase rate, since the very noticeable difference among PLA and PCL ductility.
- Regarding samples geometry, Type V specimen was selected, since the new kind of materials tested.
- Each sample dimensions have been carefully measured by means of a digital micrometer with a 0,01 mm precision. Average values over at least three measurements per dimension were recorded and used as samples parameters.

A minimum of 5 samples for each blend have been tested, and Mechanical characteristics were expressed as

$$\bar{P} \pm \sigma \qquad (4.2)$$

Where P is the average value of the generic property and σ is the Standard Deviation.

4.3.2 Differential Scanning Calorimetry

Heat Flux Differential scanning calorimetry is a widely used technique, to determine in a quantitative way the amount of heat absorbed or evolved by a sample, during a first or second-order thermal transition, in comparison to a reference.

Schematically, an oven is equipped with two resistances and two thermocouples, where the sample and the reference (air) are placed within aluminum pans.

When the Heat Exchange starts, since a constant heating rate is set on the pans, temperature increases linearly. The temperature difference among the two pans, recorded whenever the sample exhibits a thermal transition, is proportional to the heat transferred to or from the sample, since the system tends to keep both at the same temperature during the run. The most common method of analysis in polymers thermal characterization, consists in applying a controlled temperature ramp, with repeated heating or cooling scans.

Data obtained by this kind of analysis are usually plotted in a graph, in which the normalized heat flow transferred is reported vs Temperature.

The following data from amorphous or semicrystalline polymers can usually be obtained by Standard DSC tests:

- Glass transition temperature (Tg);
- Crystallization temperature (Tc);
- Melting temperature (Tm);
- Latent heat of fusion or enthalpy of fusion (ΔHf);
- Latent heat of crystallization or crystallization enthalpy (ΔHc);

According to Ehrenfest criteria, Crystallization and melting are referred as proper First order transitions, in which thermodynamic quantities like Enthropy, Volume and Enthalpy, experience a discontinuity or jump.

A peak, within a more or less wide range of temperatures, is then exhibited in the resulting thermograms, and by its elaboration it is possible to obtain thermal characteristics like : Melting Temperature onset, Melting temperature peak, and by integration, the Enthalpy of fusion of the crystals.

A more or less evident change in slope, noticed during the test, is instead associated to a pseudo-thermodynamic (since it has a kinetic nature) second order transition, the Glass-transition, in which, the DSC analysis can register just a variation of the Heat Capacity, C_p, of the sample [5].

Elaborating the data obtained by the Calorimetry tests, by some easy calculations, it is possible to obtain some important structural properties of semi-crystalline polymers, like the Cystallinity degree (χ_c; %) and the Lamellar Thickness (L_m; nm), which are related to many physical characteristics.

Fig. 4.7 TA Instruments DSC Q100

In this study, thermal analyses were conducted by means of a TA Instruments DSC Q100 (Fig. 4.7), with the following conditions:

- Samples stabilization at Room Temperature for 5 minutes
- Heating Scan up to 200°C, with a heating rate of 10 °C/min
- Water cooling of the system.

All the samples tested, were taken from the sheets obtained by compression moulding, as it was the last phase of blends processing.

The crystalline degree of PCL (χ) was calculated using the following equation:

$$\chi = \frac{\Delta H_m}{\varphi \cdot \Delta H_0} \qquad (4.3)$$

where ΔH_m [J/g] is melting enthalpy, φ is the weight fraction, and ΔH_o [J/g] is the theoretical enthalpy of fusion of a 100% crystalline polymer.

Initial crystalline fraction of PLA, χ_i , was calculated using the following equation:

$$\chi_i = \frac{\Delta H_m - \Delta H_{cc}}{\varphi \cdot \Delta H_0} \qquad (4.4)$$

where ΔH_{cc} [J/g] is the “cold-crystallization” enthalpy of PLA, which as well-known, is because of the PLA re-organization in more ordered regions induced by the thermal heating of DSC test [3].

For this reason equation 4.5 has been used to calculate the crystalline degree of the cold crystallized PLA (χ_{cc}) :

$$\chi_{cc} = \frac{\Delta H_{cc}}{\varphi \cdot \Delta H_0} \qquad (4.5)$$

4.3.3 Rheology

The visco-elastic response in the molten state is one of the most wide and important fields of study in polymer blends characterization and development.

So, Rheology, as considered the science of flow and deformation of matter, represents the main tool to identify and evaluate the properties of a polymeric material in terms of visco-elasticity under shear stress application.

Rotational Rheometers, among those machines which purpose is to characterise these properties of macromolecular systems, are probably the most used ones. Strain or Stress feedback systems are embedded in the torsional transducers of these instruments, and they both result most useful in the determination of the main rheological parameters of visco-elastic matter:

- Viscosity, η, expressed as the resistance to flow under an applied shear stress,σ.
- Elastic Shear Modulus, G', expressed as the real part of the complex Shear Modulus, G*
- Viscous Shear Modulus G'', expressed as the part of the complex Shear Modulus, G*
- The tan δ, expressed as the ratio among the latter two quantities
- Transient response properties, like the Relaxation Modulus.γ

All these quantities represent the main parameters of the constitutive equations:

$$\eta(\dot{\gamma}) = \frac{\sigma}{\dot{\gamma}} \qquad (4.6)$$

$$\sigma = \gamma_0(G'cos\omega t + G''sin\omega t) \qquad (4.7)$$

Multiphasic systems Rheological properties are generally difficult to describe theoretically and to determine experimentally, and regarding polymer blends, these difficulties reach another order of complication. It suffices to note that in blends both phases are viscoelastic, the viscosity ratio varies over a wide range, and morphology can be very complex [utracki rheology blends]

The emulsion models elaborated by many authors and work, collected and commented by Utracki and co-authors, constitute a very important starting point in polymer blends and alloys rheology.

With particular regard to miscibility and additives, emulsifying agents improve dispersion, increase the total apparent volume of the dispersed phase, rigidify the interface, and increase interaction, not only between the two phases, but also between the dispersed drops. In the specific case of reactive compounding, furthermore, the chemical bonds given by the process bring to a noticeable increase of the molecular weights at the interface.

All these favourable phenomena, according to the suspensions and emulsions models by Einstein, Taylor and Oldroyd, should bring to an increase in viscosity, elasticity and yield stress of the systems, related also to the viscosity ratio of the components [6].

Besides, many multicomponent polymeric systems, by experimental evidences, seem to behave in an opposite way. In dynamic tests, at low frequencies, immiscible systems result often to an increased Shear Elastic Modulus (G'), and this is related to the shape relaxation of the dispersed phase domains under shear, mainly because of the interfacial energy contribution to G'. This relaxation phenomena, observed on a wide time scale, is attributed to the constant change in the interfacial area among the phased during shear flow. Stretched domains of the dispersed phase, tend to exhibit the minimum surface area, because of the interfacial tension, trying to drive the system towards an isotropic behaviour. This brings to a change in slope in Elastic Modulus trends, with increased elasticity below 1 Hz. [7,8,9]

The addition of an emulsifying agent, reducing the interfacial energy, could also bring to an increase of the free volume of the system, driving to a stable slope in Elastic modulus trends, and reduced overall viscosity of all the blends [6].

In this study, reactive and physical blends of Poly(lactide) and Poly(ε-caprolactone) visco-elastic response in dynamic range, was analysed by means of parallel plate rheology, using a TA Instruments ARES (Advanced Rheometric Expansion System) LS2 (Fig. 4.8), equipped with a climatic chamber, with N_2 purge gas and with 25 mm plate-plate geometries. A temperature ramp experiment was initially conducted from room temperature to 200 °C at 10 Hz and 0.1 rad/s, followed by strain amplitude oscillation, at 10 Hz and 150 °C from 0.1 to 10% of strain. The limit of the linear viscoelastic region was found to be 0.8% of strain for all blends and this limit was used for the other experiments. The thermal response with time was evaluated by applying 0.1 % strain at 10 Hz for 10^5 s at 150 °C. During this experiment, a build-up of the elastic modulus G' was observed. Once the G' reached a plateau value, the frequency response was evaluated at 150 °C, 0.8 % of strain from frequencies of 400 to 10^{-2}rad/s. For the solution cast blends, Temperature variation tests have also been conducted to underline the materials behaviour under shear, regarding the thermal transitions, applying 0,8% of strain with a temperature ramp of 5 °C per minute from 40 to 200 °C.

Fig. 4.8 TA Instruments ARES LS2 Rheometer

4.3.4 Scanning Electron Microscopy

Analysing visually samples surfaces is one of the most accurate and immediate methods to give answers regarding materials morphology.

In Materials Science, and in particular for micro or nano-structured multiphasic systems, the necessity of high resolution images at very small scales, leads to the use of Electronic Microscopes.

A Scanning electron microscope, is schematically represented in Fig. 4.6. An Electron Beam scans line by line over the surface of the specimen in the evacuated microscope column and forms signals based on the interactions between the beam and the sample, which are electronically detected and amplified by suitable equipment. The output signals are represented by:

- The scattered, or Secondary Electrons, low energy electrons, mainly obtained by 'Inelastic scattering', they are the main cause of the SEM images.

- The backscattered electrons, mainly obtained by ‘Elastic scattering’ (or ‘Rutherford Scattering’), they can define the atomic number of the chemical elements in the sample, or can be useful for topographical analyses.
- X rays, caused by the radiation-matter interaction, i.e. the energy levels transitions of shell atomic electrons. They can define the sample composition.

Regarding polymers, and more specifically polymer blends morphological characterization , the ‘Secondary Electrons’ images, are considered the most important, because of the resolution of the sample structure image obtainable with this kind of setting. If the surface layer is removed correctly, or the cross-section is obtained without plastic deformation, a clear morphological quantification regarding the components phase structure can be successfully given by this analysis [10,11,12].

In this work, samples for scanning electron microscopy were obtained by cryogenic fracture in Liquid Nitrogen, in order to investigate the cross-section surfaces of all the A50C50 blends before and after rheological analysis.

The as-compressed materials were characterised with a FEI Quanta FEG 450 microscope (Fig 4.9), operating at an accelerating voltage of 5kV in low vacuum mode, with no metal coating. The samples after rheology were analysed using a JEOL 7800F Field Emission Scanning Electron Microscope at 5kV, after Gold sputter coating.

Fig. 4.9 FEI Quanta FEG 450 Scanning Electron Microscop

4.3.5 Surface and Chemical methods of Analysis

4.3.5.1 Wet-ability

Wet-ability tests, or surface angle measurements, schematically represented in Fig. 4.10, are surface characterization methods to analyse and estimate the interaction among a substrate and a liquid.

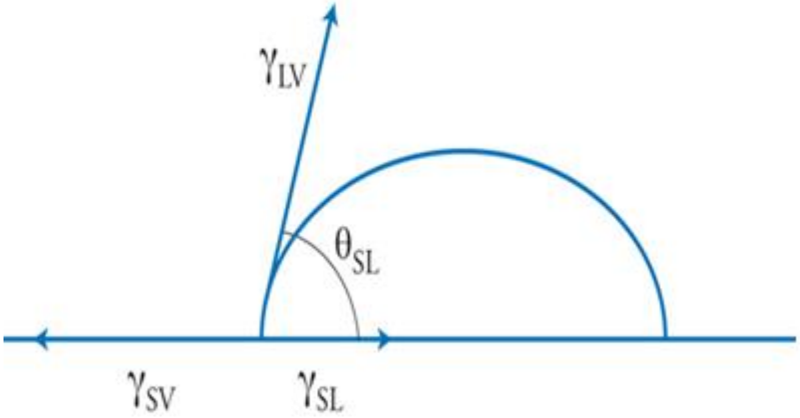

Fig. 4.10 Schematics of the wet-ability measurement test

Drops of fluid are put on the sample and by observing their shape and calculating the angle among the liquid surface and the material is possible to define the interfacial tensions as follows:

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \qquad (4.8)$$

Where:

γ_{sv} = substrate-vapor Interfacial tension;

γ_{sl} = substrate-liquid Interfacial tension;

γ_{lv} = liquid-vapor Interfacial tension.

Considering biodegradable and absorbable polymers and their mixtures this technique of analysis can be used to estimate the degradation rate of these substrates, regarding the interaction with an actual or synthetic biological fluid.

Generally, the surface angle values are related to various factors like the crystalline degree of the polymer substrate, the viscosity of the liquid, the surface characteristics on the interface, and the environment conditions for this kind of testing; their contribution can establish liquid diffusion inside the bulk material, and so its degradation rate.
In this work the Sessile Drop method was used to characterize physical and reactive blends, estimating the effect of the mixtures formulation regarding the PLA/PCL weight ratio and the LTI addition[13]. The liquid used for the tests was a Phosphate Buffered Saline solution (PBS), in order to estimate the interaction of the mixtures with a fluid similar in pH and ions concentration to biological environments. Series of 10 drops of 5µL for all samples have been released on the polymeric surfaces and analysed by means of a Unime prototype wet-ability measurement machine equipped with a camera and a PC with the ImageJ software.

4.3.5.2 FT-IR Spectroscopy

The Fourier Transform Infra-Red Spectroscopy is a characterization method regarding the chemical structure of the sample. When a polymeric material absorbs infrared light, usually in the mid-infrared region, the resulting spectrum (absorbance or transmittance) brings to a distinctive “fingerprint” that can be used to easily test samples for many different applications. Many data about the functional or reacted groups of macromolecules can be obtained by this analytical method, which is then considered one of the main techniques of characterization for many applications.

Among many techniques, infrared (IR) spectroscopy has the advantages of substantially not requiring time and to be non-degradative. On the other hand, the technique also presents disadvantages: to analyse the full thickness the specimens must be in the shape of thin (about 50 μm) films and the molar absorptivity of the product species should be known, otherwise just quantitative results cannot be obtained. [14,15].

FT-IR and ATR spectroscopic analyses were conducted using a Shimadzu FT-IR, on films of about 50 microns in thickness. 64 scans from 600 to 4000 cm-1 were acquired with a resolution of 4 cm-1.

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5 Results and discussion

5.1 Torque trends

As a first result, obtained in the processing phase, the torque acting on the batch mixer rotors during blending, was recorded and plotted vs the mixing time of the blends.

These graphs trends are strictly related to the molten materials viscosity, η, and then to their molar masses, as suggested by Berry and Fox (Eq. 5.1) for any molecular weight M higher than a critical value M_c, defined as double the mass between entanglements, M_e [1]:

$$\eta \propto M^{\alpha} \quad ; \qquad \alpha = 3.4 \qquad (5.1)$$

Regarding the physical blends, as shown in Fig. 5.1, two different trends are noticeable, a 'PLA dominant' one, characterizing the pure PLA mixed at the same conditions and the high PLA content blends, and a 'PCL dominant', related instead to the second component.

At the processing temperature, considering its Tg and its Tm, the Poly(lactide) exhibit naturally a viscosity higher than that of Poly(ε-caprolactone), but it shows immediately its great thermos-mechanical degradation sensitivity, leading the 'PLA dominant' blends (A100, A80C20, A50C50) to show a quick decrease in torque values. 'PCL dominant' behaviour (C100, A20C80) is instead characterized by more stable trends on lower viscosities.

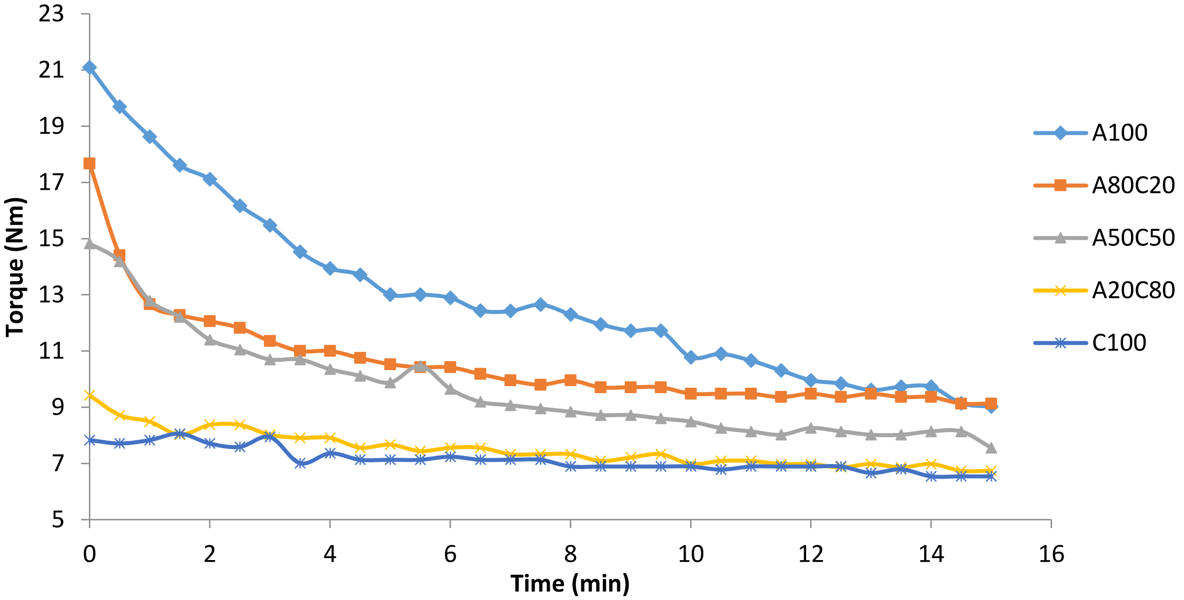

Fig. 5.1 Torque vs Time trends of physical blends

The recorded trends of all reactive blends are instead oppositely different. As shown in Fig. 5.2, for any reactive agent amount added, the viscosity of the systems exhibited a noticeable increase, leading the curves to torque values up to double the initial ones.

This is related to the co-polyester-urethanes grafting and cross-linking reactions, conducted in the mixer. Each LTI molecules bonds to three polyester chains in an iterative process, leading to an exponential increase in the average molecular weight of the mixtures. This increase is naturally proportional to the LTI, as well as the process kinetics which are governed by the reagents concentration.

Besides, it is worth to mention, how the 2 phr LTI amount, seems to be a sort of threshold value, over which the system is probably saturated of reactive agent, remaining localized in some densely cross-linked areas, where the general molecular mobility of the system, and then the reactivity, is lower and its more difficult to find an unreacted polymer chain to react with.

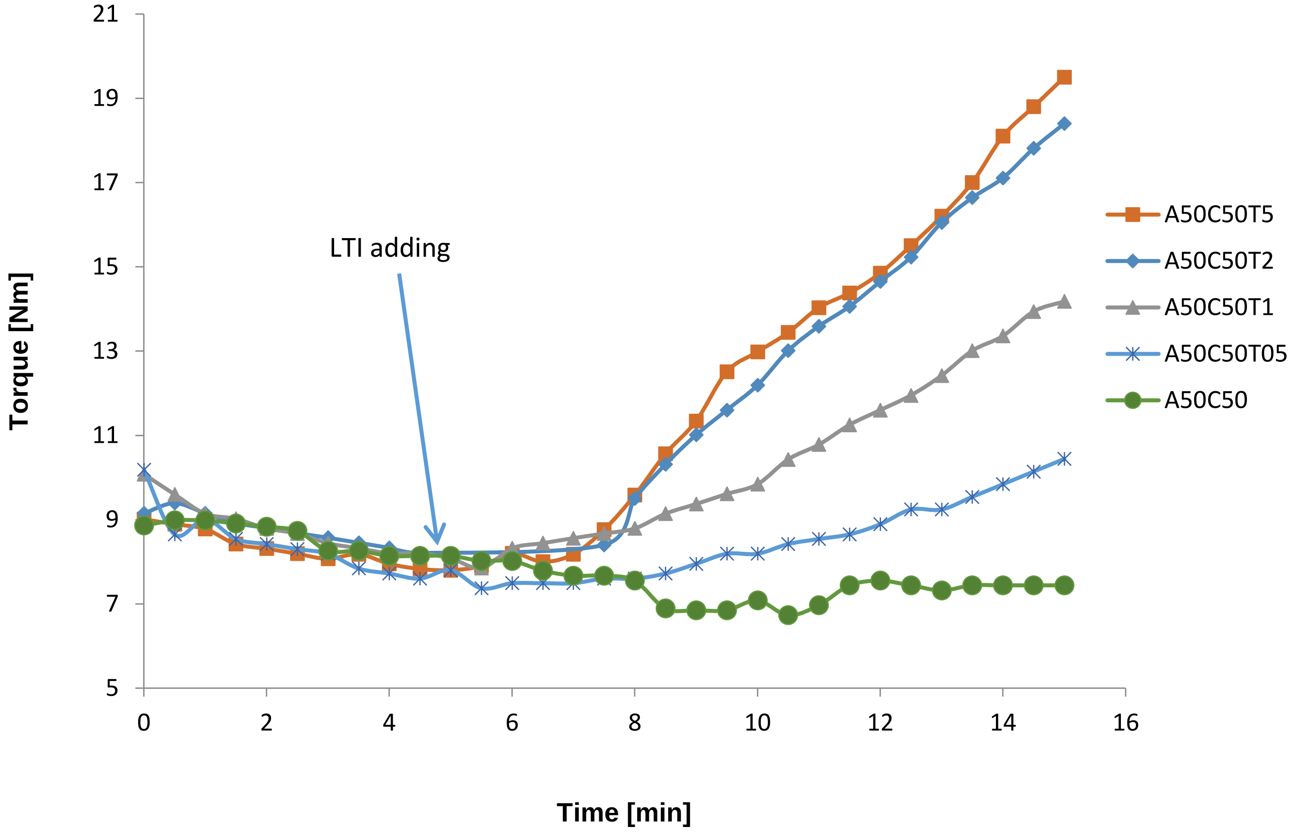

Fig. 5.2 Torque vs Time trends of A50C50 blends with various LTI amounts

A minimum effect on the torque trends of reactive blends, is instead noticed regarding the two polyesters weight ratio. As shown in Fig. 5.3, despite the higher absolute values of torque of the high PLA content blend, the slope of the increasing trends appears to be similar for all the three polyesters weight ratios, indicating that the branching and/or Cross-linking reactions kinetics are ruled mainly by the reactive agent amount. It seems then to not to be a favoured chain among PLA or PCL, to react with Triisocyanate.

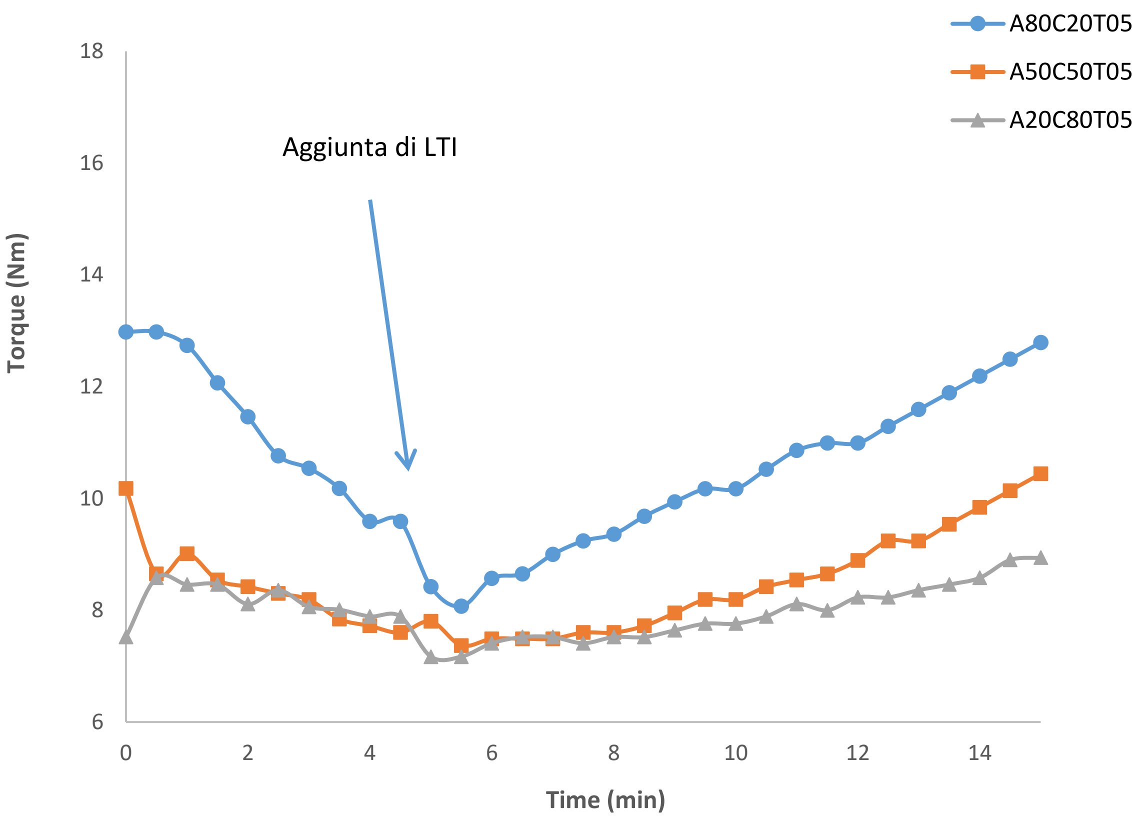

Fig. 5.3 Torque vs Time trends of T05 blends

5.2 Mechanical tensile results

Among the most important results of this study, the change in mechanical properties of the reactive mixtures has to be properly highlighted.

As discussed earlier, the mechanical behaviour, is one of the most reliable and comprehensive indexes of the materials structure. In Fig. 5.4 are shown the dogbone-shaped type V specimens, according to ASTM D638-10 standard, obtained by processing.

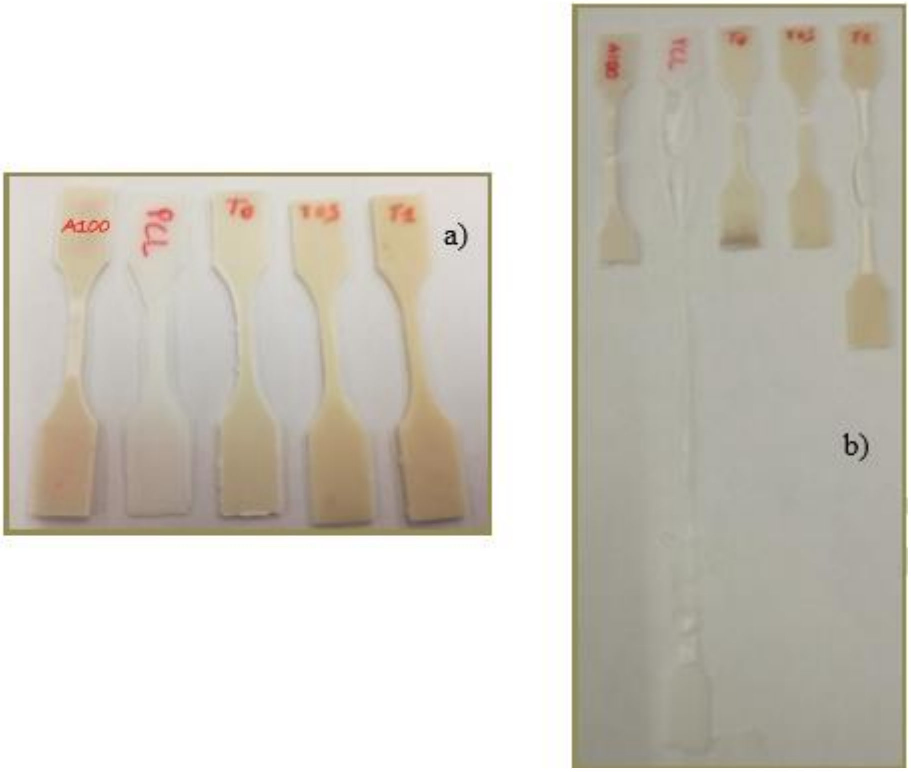

Fig. 5.4 Images of Dog-bone Type V ASTM D638-10 specimens before a) and after b) Tensile tests

Fig. 5.5-a and Table 5.1 show, as a first result, the confirmation of the great difference in ductility of PLA and PCL. The higher yield strength of Poly(lactide) is compensated by its very low elongation at break, whilst the low Poly(ε-caprolactone) stiffness is in contrast to its major Work at breakage. Fig. 5.5-b, shows instead the tensile response of physical blends, which exhibit, as expected, poor mechanical characteristics, confirming the immiscibility of the components and the poor interfacial interaction. The only sample showing a good ductility, is the A20C80, mainly because of the PCL content. At the opposite, the A50C50 blend, exhibit the lowest properties among all the formulations, exhibiting, for example, a Work at breakage value of 0,02 J, orders of magnitude less than PLA showing instead 0,3 J. Blends A100 and C100, representing the pure components processed in the batch mixer, exhibit instead just some differences with the unprocessed polyesters. In particular the A100, shows an increase in the Elastic Modulus, but a noticeable decrease in all the parameters. This is caused by the low thermo-mechanical degradation resistance of Poly(lactide), which opposes to the great stability of the Poly(ε-caprolactone) in this regards.

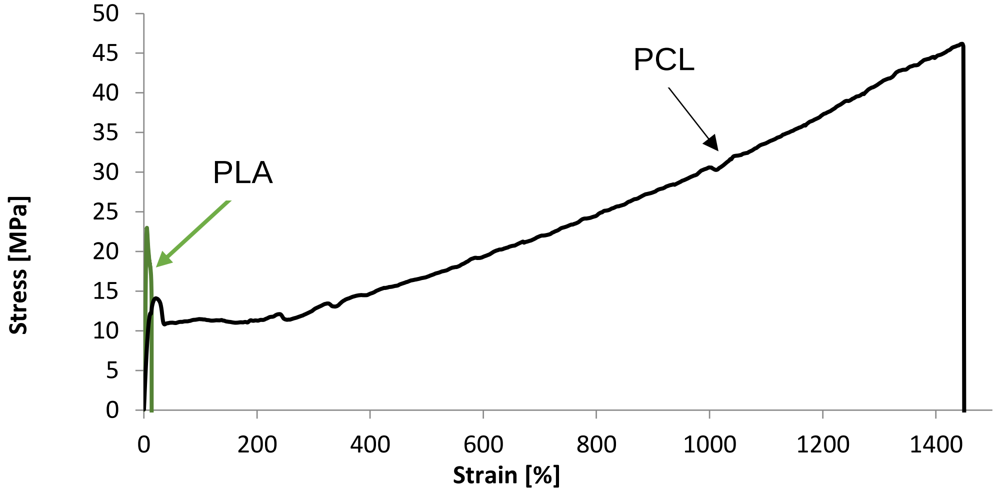

Fig. 5.5-a Stress-Strain Curves of Poly(lactide) and Poly(ε-caprolactone)

Table 5.1 Mechanical Properties of Physical Blends

Sample	E [MPa]	ε_y %	σ_y [MPa]	σ_m [MPa]	ε_r %	σ_r [MPa]	W_b [J]
PLA	640±51	9,0±2,0	28,1±2,1	28,1±2,1	35±10	20,6±1,8	0,307±0,142
A100	816±60	6,1±0,9	22,4±1,7	22,4±1,7	15±4	15,2±0,9	0,084±0,034
A80C20	386±48	5,0±0,9	12,7±1,0	18,1±0,6	12±1	16,9±1,2	0,056±0,008
A50C50	334±35	3,9±0,6	7,2±0,6	10,0±0,9	10,2±2,0	9,6±0,6	0,023±0,008
A20C80	159±23	20,4±2,1	11,4±0,6	21,8±1,0	851±46	21,4±1,2	4,980±0,370
C100	154±26	19,5±3,3	14,0±0,9	43,0±6,0	1405±120	39,8±4,9	10,810±3,014
PCL	155±18	19,5±3,3	11,0±2,5	42,3±2,7	1518±100	/	/

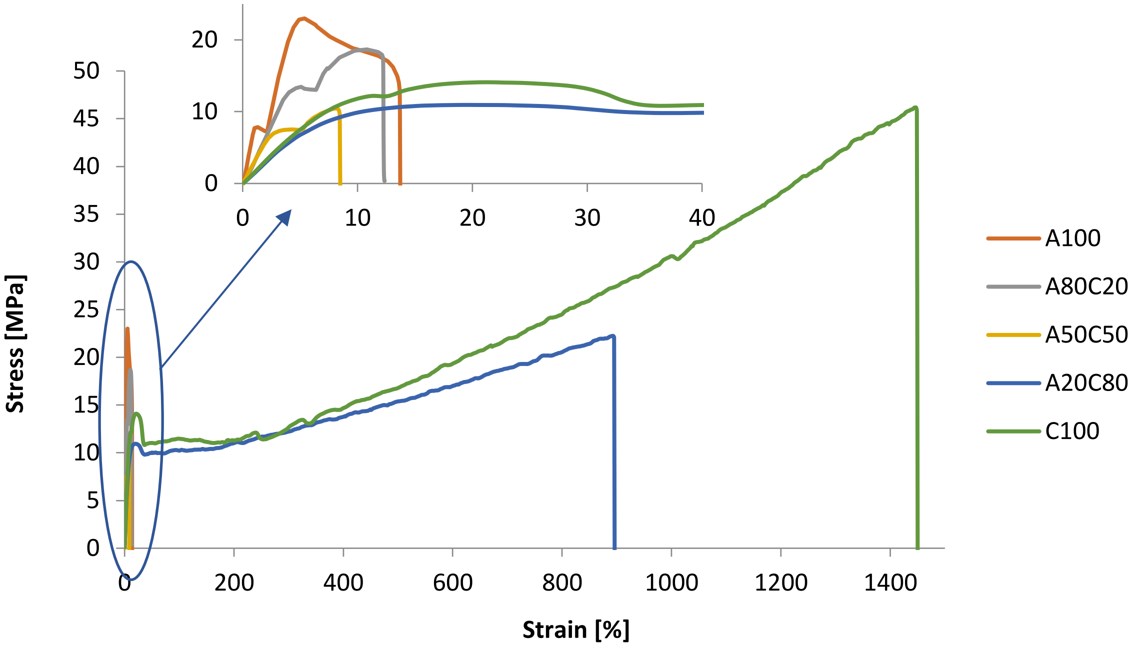

Fig. 5.5-b Physical Blends Stress-Strain Curves

Considering instead the reactive blends, an outstanding and unprecedented improvement on resilience and ductility, for any amount of reactive agent added to the blends, is surely the first great result of this reactive mixing process. From 0,5 to 5 phr LTI content, all the mechanical properties are improved for the mixtures of polyesters analysed.

Analysing the effect of the reactive agent amount on the A50C50 blends, it can be easily noticed first a major change in Young's Modulus and in Resilience. For the lowest LTI content, 0,5 phr, an initial decrease in stiffness (from 334 to 267 MPa; - 20%) is associated with a great increment in the Strain at Yield (from 3 to 27%; + 800%). This result is in line with the visco-elastic properties of emulsified blends discussed earlier, in fact, it has been shown how copolymeric structures, miscible with the blend components, can decrease the interfacial tension, and improve interfacial interaction, with a lowering in elastic response probably because of the increase in macromolecular free volume.

This explanation is also confirmed by a numerical evaluation of mechanical properties, using the Equivalent Box Model theory, elaborated by Kolaric [2] (Eq. 5.2). It represents an expansion on the rule of mixtures and the Halpin and Tsai theory on composites, applied to polymer blends. It was found a very fitting approximation of the Elastic Modulus for the A50C50 physical blend.

The model can estimate the Young's modulus of a blend, using the relative elastic moduli of the components (E1, E2), their volume fractions (v_1, v_2) and the parallel and serial parts of those fractions (v_{1p}, v_{2p}, v_{1s}, v_{2s}). The first ones, are related to the parallel interaction of components, implying that the strain of all phases is equal (the iso-strain model) and that the contribution of each component to the final value of a mechanical property is given by the rule of mixing. The latter ones, are instead describing the series interaction of components, which stands for the lower obtained mechanical properties. Since all components are discontinuous in the direction of the acting force (the iso-stress model), their continuity can be regarded as zero. Contributions of constituents to a system property can then be expressed by the inverted rule of mixing. All of these parameters have been evaluated with a procedure described in literature [3].

$$E_b = E_1 v_{1p} + E_2 v_{2p} + v_s^2/[(v_{1s}/E_1) + (v_{2s}/E_2)] \qquad (5.2)$$

$$E_1 = E_{PLA} = 815{,}91\ MPa;$$
$$E_2 = E_{PCL} = 153{,}70\ MPa;$$
$$v_{1s} = 0{,}31;\ v_{2s} = 0{,}31;\ v_{1p} = 0{,}19;\ v_{2p} = 0{,}19;$$
$$v_p = v_{1p} + v_{2p};\ v_s = v_{1s} + v_{2s}; \qquad (5.3)$$
$$E_b^{A50C50} = 344\ MPa$$

The estimated value, of 344 MPa is very similar to the Elastic Modulus value obtained by experimental characterization (334 MPa), confirming the reliability of the model.

Applying the model to the A50C50T05 reactive blend instead (E = 267 MPa), it doesn't fit with experimental data, because it doesn't consider the co-polyester-urethane structures obtained during the reactive blending process, which as described bring deep changes in the interfacial behaviour of blends.

By increasing the reactive agent amount, a very noticeable improvement of all the mechanical properties of these materials is exhibited. As shown in Table 5.2, and in Fig. 5.6, the tensile strength increases exponentially, both for Yield and Maximum Stress from 7,2 and 10 MPa for the physical blend, to double and 4 times their values, 20,2 MPa and 45,7 MPa for the A50C50T5 blend. The most important improvement anyway is noticed on ductility, with Elongation at break from 10 % for the A50C50 blend, to 646 % for the A50C50T1 blend (+ 6360%), and the Work at breakage with 0,02 J for the Physical blend, to 6,22 J for the A50C50T5, which represents an increase of 31000%.

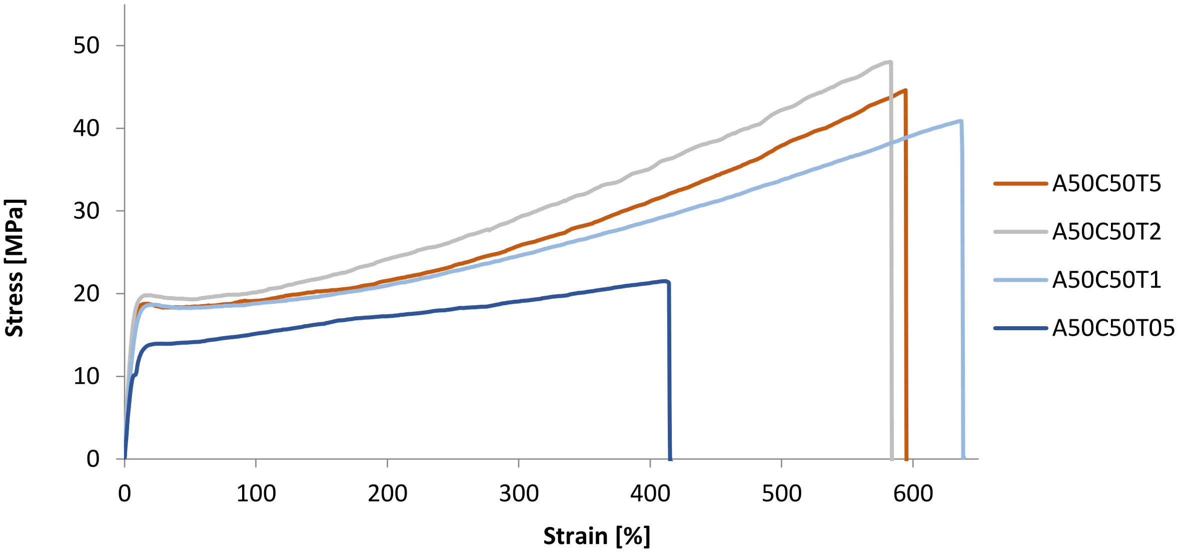

Fig. 5.6 Stress-Strain curves of A50C50 reactive blends

The mechanical strength improvements can be explained with the exponential increase of the molecular weight, because of the branched and/or densely cross-linked structures obtained by the reactive blending. This process, oppositely to what could be expected, lead the materials to exhibit the best ductility too, because despite their density, among each cross-link the molar mass is always that of an entire chain of PLA or PCL.

Table 5.2 Mechanical properties of A50C50 Physical and Reactive Blends

Sample	E [MPa]	ε_y [%]	σ_y [MPa]	σ_m [MPa]	ε_b [%]	σ_b [MPa]	W_b [J]
A50C50	334±48	3±0.7	7,2±0,6	10,0±0,9	10±2	9,5±0,6	0,02±0,01
A50C50T05	267±47	27±8	13,2±1,0	21,8±2,8	446±81	21,5±2,8	3,05±0,92
A50C50T1	370±51	21±5	17,6±1,2	39,0±2,1	646±38	38,8±2,1	5,72±0,41
A50C50T2	473±45	14±2	20,0±0,7	43,4±6,0	534±71	43,0±6,4	6,20±1,36
A50C50T5	485±57	16±1	20,2±1,4	45,7±1,9	586±68	45,6±2,0	6,22±0,50

In table 5.3, with the aim to underline the differences among blends of various composition, the mechanical characteristics of the A80C20, A50C50 and A20C80 physical and reactive blends (LTI amounts of 0,5 and 1 phr) are shown. It is clearly noticeable how the reactive blending process leads the mixtures to maintain their characteristic properties and to improve them where they lack. The A80C20 blends are stiffer, but brittle, so by the reactive agent addition, they exhibit the maximum values of Elastic Modulus (increasing from 386 to 507 MPa; + 31%) and of Yield strength (from 12,7 to 25,2 MPa; + 99%). Their Elongation at break instead, increases from 13 to 360 %, and their Work at breakage increases from 0,05 to 3,33 J (+ 6560%). Regarding the A20C80 blends instead, which exhibit the most ductile characteristics, ε_b increases from 851 to 1090 % (+ 28%), and their Tensile Strength goes from 21,35 to 51,75 MPa (+ 142%).

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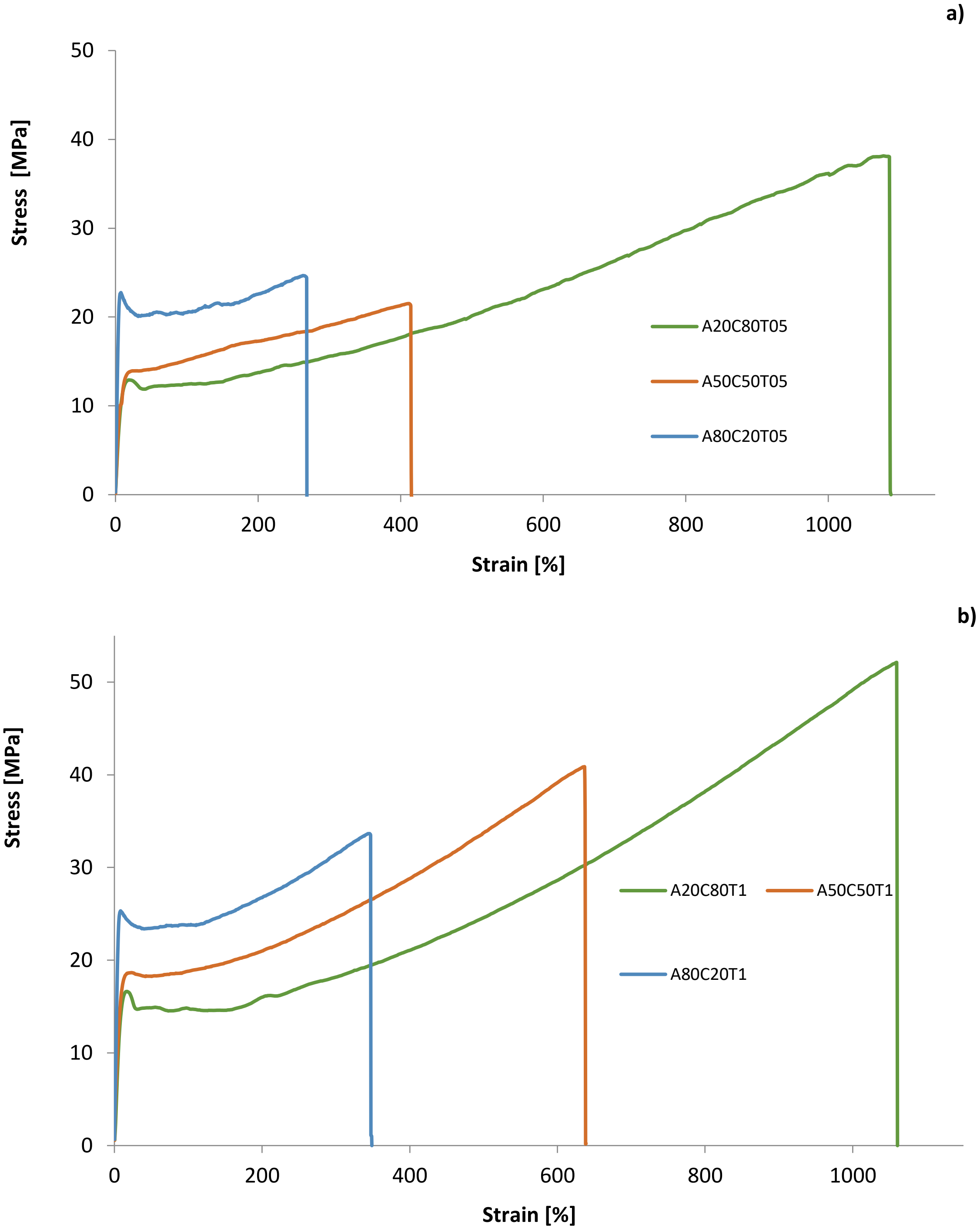


Fig. 5.7 Stress-Strain Curves of physical and reactive blends by composition; a) 0,5 phr LTI b)1 phr LTI.

Table 5.3 Mechanical properties of physical and reactive blends by composition

Sample	**E [MPa]**	**ε_y [%]**	**σ_y [MPa]**	**σ_{max} [MPa]**	**ε_b [%]**	**σ_r [MPa]**	**W_b [J]**
A80C20	386±48	5,0±0,9	12,7±1,0	18,1±0,6	12±1	16,9±1,2	0,056±0,008
A80C20T05	467±99	8,3±1,4	24,1±0,8	26,3±1,4	285±56	25,1±3,2	2,650±0,613
A80C20T1	507±39	8,7±0,7	25,2±0,6	34,1±1,2	360±22	33,9±1,2	3,330±0,240
A50C50	334±35	3,9±0,6	7,2±0,6	10,0±0,9	10,2±2,0	9,6±0,6	0,023±0,008
A50C50T05	267±47	27±8	13,2±1,0	21,8±2,8	446±81	21,5±2,8	3,05±0,92
A50C50T1	370±51	21±5	17,6±1,2	39,0±2,1	646±38	38,8±2,1	5,72±0,41
A20C80	159±23	20,4±2,1	11,4±0,6	21,8±1,0	851±46	21,4±1,2	4,980±0,370
A20C80T05	179±41	20,4±2,6	12,7±0,7	35,9±3,5	1051±90	35,5±3,5	9,120±1,510
A20C80T1	211±56	16,7±1,9	16,4±0,4	51,9±2,0	1090±47	51,7±2,1	10,010±0,900

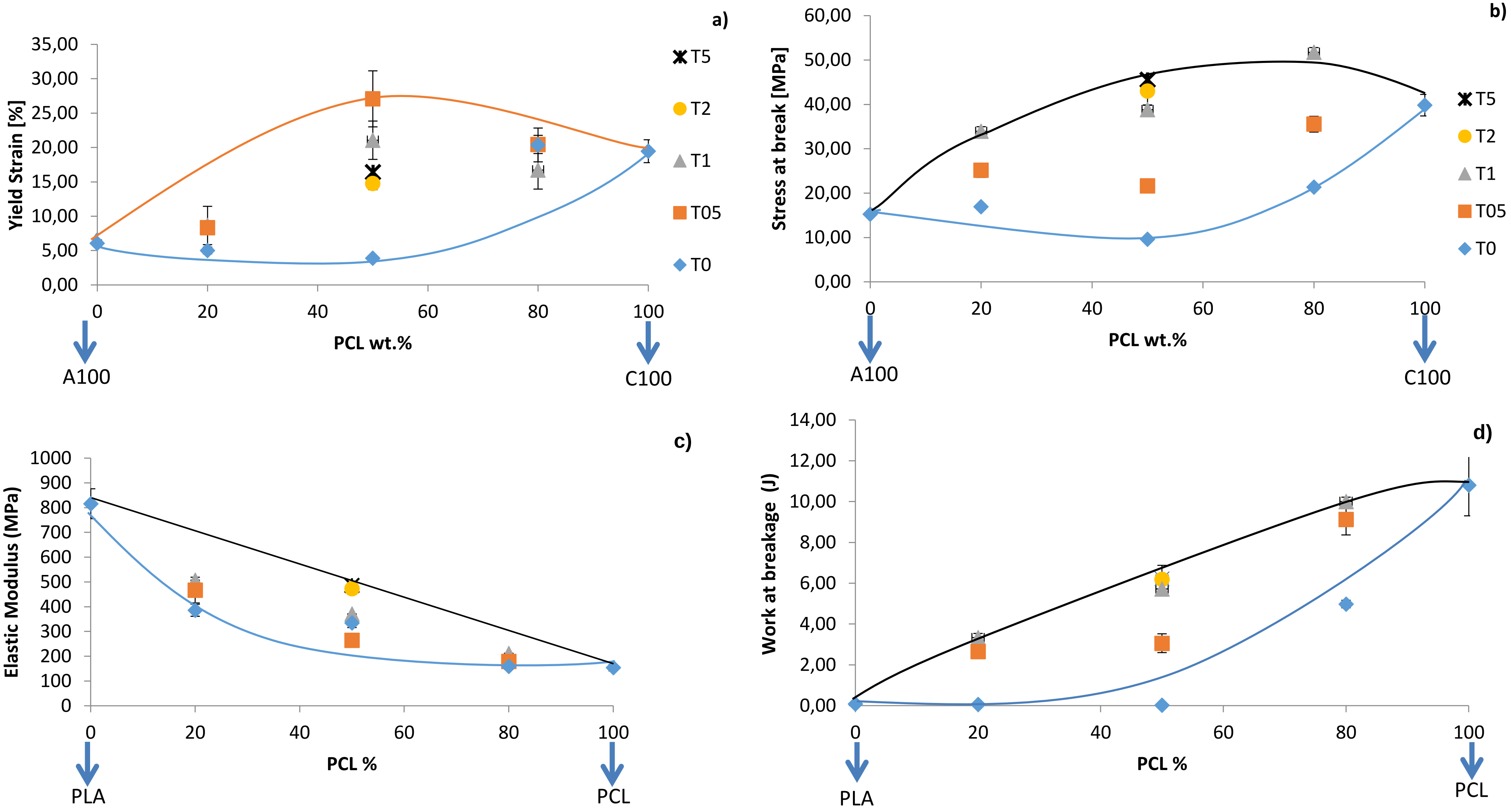


Fig. 5.8 a) Yield Strain, b) Stress at Break, c) Elastic Modulus, d) Work at Breakage of Physical and Reactive Blends by PCL wt%

In Fig. 5.7 are instead shown the Stress-Strain curves for all the 0,5 phr (a) and 1 phr (b) LTI content blends, and in Fig. 5.8 are shown the most important mechanical characteristics trends by PCL wt% amount.

These plots are used to show miscibility ranges in polymer blending and they confirm and underline how, because of the reactive agent addition, by carefully formulating the mixtures it is possible to obtain well tailored properties of the blends, to use them for different applications. Blends A80C20 can result valuable where the stiffness or the tensile strength are considered the most important characteristics, like in the orthopaedics field, instead for applications like sutures, where the resilience and general ductility are the key mechanical properties, blends A20C80 with lower amount of LTI can be used with expected results.

5.3 Differential Scanning Calorimetry

Thermal analysis conducted in this work has primarily confirmed the melting and crystallization behavior of PLA and PCL, both as homopolymers and when components of physical and reactive blends in various weight ratios. In tables 5.4 and 5.5, where are all the numerical values of most important thermal characteristics of these polymers, and in Fig. 5.9, is underlined the blends composition effects on the thermal behavior. It can be first noticed how PLA shows two different phase transitions peaks, which are associated to cold crystallization (at about 104-113°C) and melting. The latter peak has usually two components: one related to the initial crystalline fraction (at ~153°C-157°C) and the second to the crystallized component with lamellar reorganization induced during calorimetric test heating (at about 145°C-149°C)[4]. The PCL, at the testing temperature range, exhibits just a normal melting peak, around 60 °C.
When instead LTI is added in reactive blends, it changes the melting behavior of both PCL and PLA. It is worth to mention, that Tm value of PCL in all the blends decreases with increasing the LTI content (from about 62°C to 59°C, from about 64°C to 62°C and from about 64°C to

60°C in the A80C20, A50C50 and A20C80 blends). Also the correspondent ΔH_m decrease from ~ 15 to 11.3 J/g, from ~ 39 to ~ 32 J/g and from ~ 56 to ~ 48 J/g.

Table 5.4 Calorimetric DSC parameters – Polyesters weight ratio effect

Sample	Tm PCL [°C]	ΔHm PCL [°C]	Tcc PLA [°C]	ΔHcc PLA [J/g]	Tm PLA [°C]		ΔHm PLA [J/g]
A80C20	62,25	15,51	104,16	12,32	147,73	155,94	13,41
A80C20T05	62,39	17,27	107,72	12,17	148,38	156,28	13,78
A80C20T1	59,45	11,31	113,73	12,92	149,75	153,51	13,65
A50C50	64,02	39,68	103,61	7,24	146,65	155,74	9,45
A50C50T05	62,83	35,57	111,05	6,21	148,31	154,37	8,35
A50C50T1	62,08	32,43	113,05	7,11	148,88	157,14	8,33
A20C80	64,54	56,11	105,85	3,53	145,97	154,12	3,55
A20C80T05	63,63	54,19	107,44	0,89	147,01	153,99	3,37
A20C80T1	60,92	48,67	111,79	0,61	146,60	156,70	2,88

Table 5.5 Crystalline degree of PLA and PCL – Polyesters weight ratio effects

Sample	χ PLA [%]	χcc PLA [%]	χ PCL [%]
A80C20	1,01	11,41	54,42
A80C20T05	1,49	11,27	60,60
A80C20T1	0,68	11,96	39,68
A50C50	3,28	10,72	55,69
A50C50T05	3,17	9,20	49,92
A50C50T1	1,81	10,53	45,52
A20C80	0,08	13,08	49,22
A20C80T05	9,20	3,29	47,54
A20C80T1	8,40	2,26	42,69

In a similar way, the double melting peaks of PLA seem to be shifted towards one peak for all the weight ratios, with increasing the LTI amount. For example in the A80C20 blend, the melting peaks at ~147°C and ~156°C, became ~149°C and ~153°C in the A80C20T1 blend.
Furthermore, it is noticeable how the PLA melting Enthalpy generally decreases (for example from 9.45 to 8.33 J/g, in the A50C50 blend, and from 3.55 to 2.88 in the A20C80 blend) and

the peaks also change in shapes, as visible in the expansions of figure 5.9, suggesting a crystalline re-organization.

These phenomena become even more evident when the reactive agent content is furtherly increased, as shown in Table 5.6 and Fig. 5.10, in which is underlined the effect of the LTI amount on the A50C50 blends.

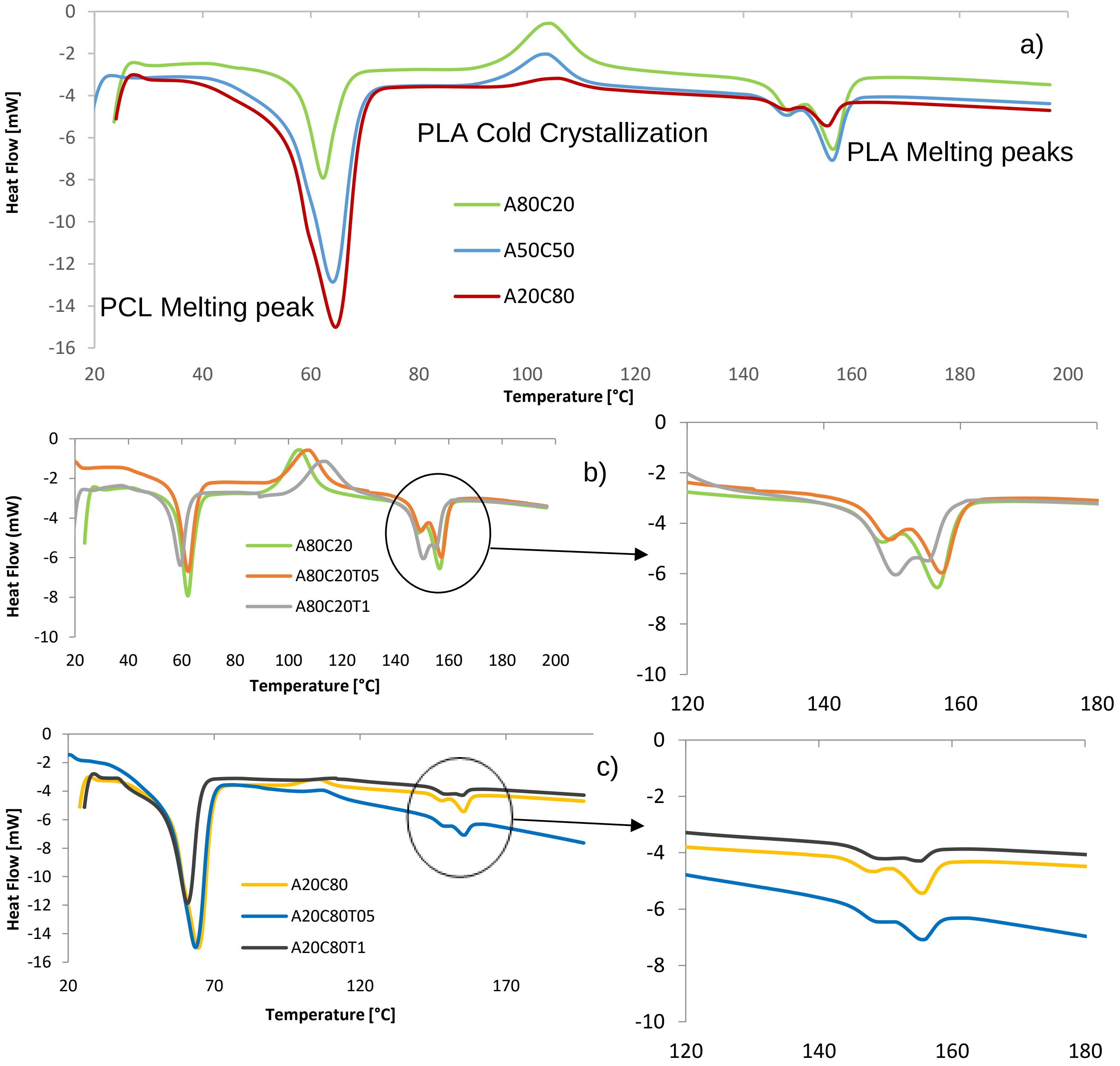


Fig. 5.9 DSC Thermograms of physical (a) and reactive(b,c) blends, Polyester weight ratio effect

These phenomena become even more evident when the reactive agent content is furtherly increased, as shown in Table 5.6 and Fig. 5.10, in which is underlined the effect of the LTI amount on the A50C50 blends.

A progressive decrease of melting and cold crystallization enthalpies, and the shifts of PCL melting (from 64 to 62 °C) and PLA cold crystallization peaks (from 104 to 118 °C) clearly confirm a reduced ability to give crystalline structures by the polyesters. These effects are related to the grafting and/or cross-linking density of the co-polyester-urethane amorphous structures in the blends, obtained by the reactive blending process.

Table 5.6 - Differential scanning calorimetry data for A50C50 blends.

Sample	T_m PCL (°C)	ΔH_m PCL (J)	T_{cc} PLA (°C)	ΔH_{cc} PLA (J)	T_m PLA (°C)		ΔH_m PLA (J)	χ_i PLA (%)	χ_{cc} PLA (%)	χ PCL (%)
A50C50	64.0	39.6	103.6	7.2	146.6	155.7	9.4	3.2	10.7	55.6
A50C50T05	*62.8*	35.5	111.0	6.2	148.3	154.3	8.3	3.1	9.2	49.9
A50C50T1	62.0	32.4	113.0	7.1	148.8	157.1	8.3	1.8	10.5	45.5
A50C50T2	61.8	32.3	113.5	3.8	149.4		6.8	4.3	5.7	45.3
A50C50T5	62.7	31.7	117.8	5.2	149.5		6.4	1.8	7.7	44.6

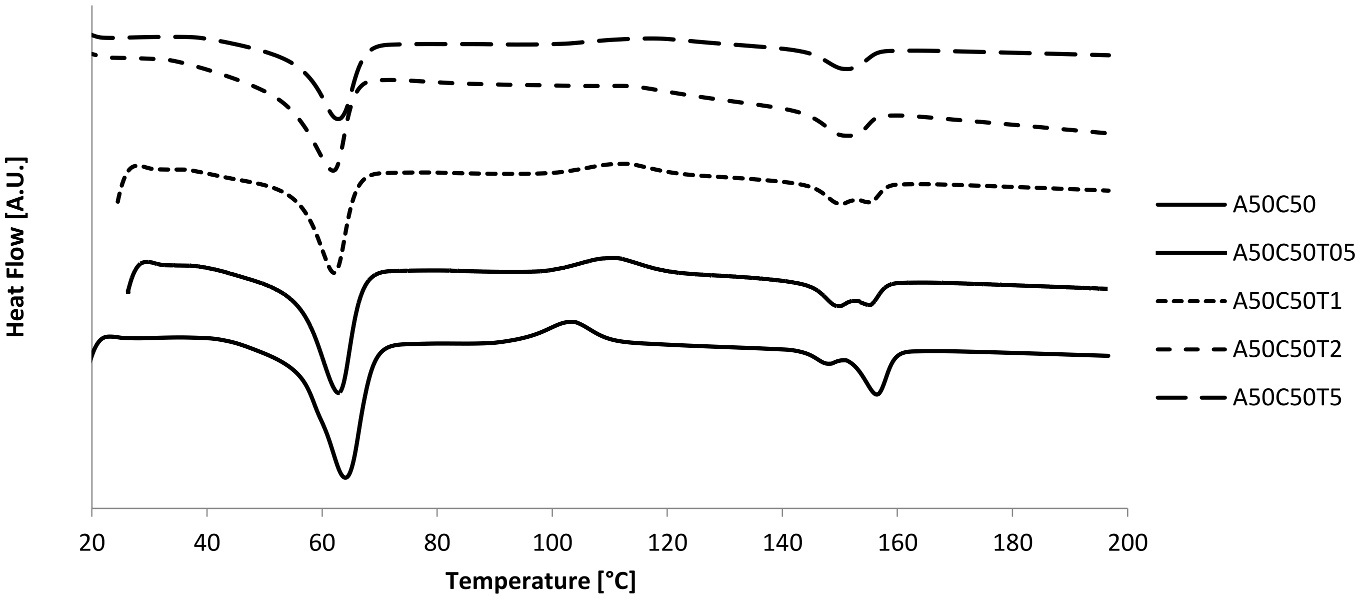


Fig 5.10 A50C50 Physical and Reactive Blends Thermograms, LTI amount effect

5.4 Rheology

Considering all the mechanical and thermal characterizations results, leading to understand how the most important changes in blends properties have been brought by the reactive agent increasing amount, rheological experiments have been conducted on all the A50C50 samples, with LTI content from 0 to 5 phr.

The first noticeable result (Fig. 5.11), is related to the linear visco-elastic region (LVR) of blends, defined as a shear range in which linear trends of the shear moduli are exhibited during the analysis. By the Strain Amplitude variation tests, it is clear how the molecular weight increase, because of LTI addition, brings the Elastic modulus values to increase of several orders of magnitude. Furthermore, observing the trends, as first result of an increased Elasticity of the blends, they show wider ranges of LVR.

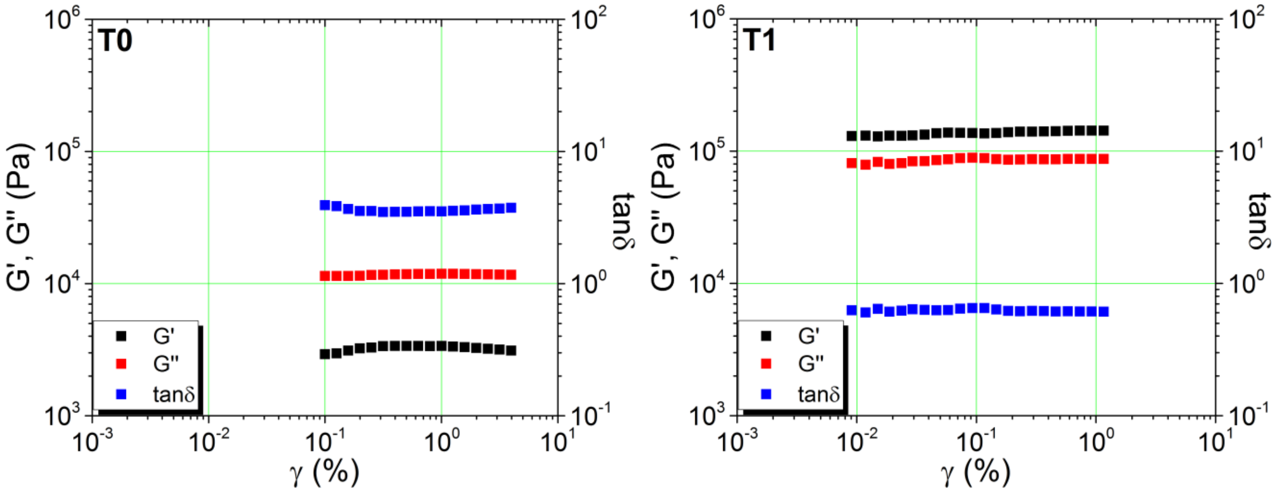


Fig. 5.11, Shear Amplitude variation test of A50C50 and A50C50T1 blends

Since a stable LVR until 0,8% of strain has been observed for the physical blend, this value has been used as a reference for all the further rheological experiments on the blends.

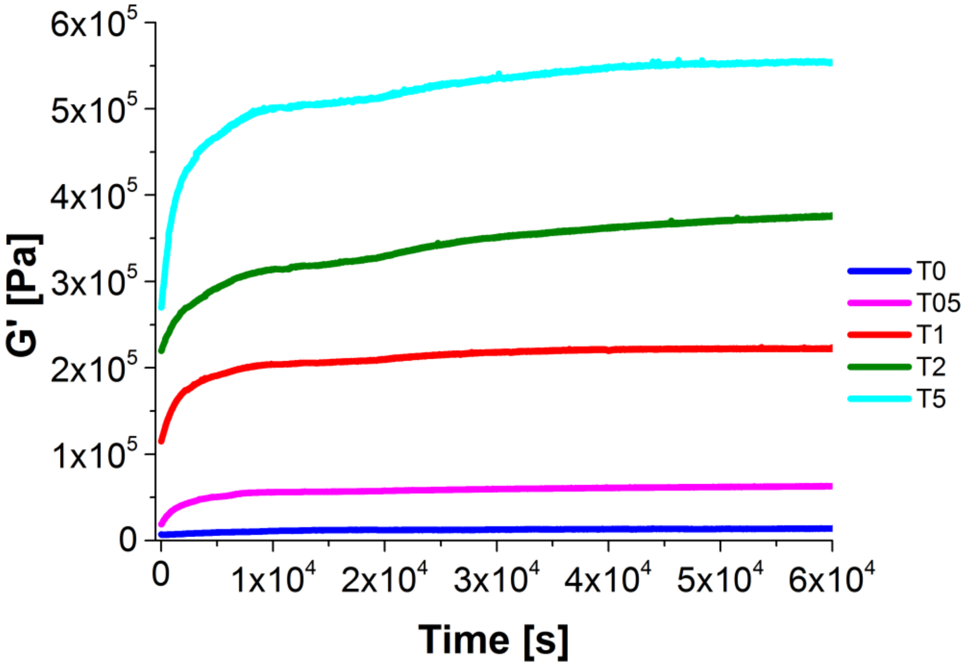


Fig. 5.12 Time evolution of the shear Elasticmodulus G’ for A50C50 blends

From Fig. 5.12, showing G’ vs Time trends of A50C50 blends, a clear build-up of the Elastic Modulus for all the reactive blends is noticeable. These build-ups are represented by logarithmic like trends, progressively increasing with the reactive agent amount. This result can be explained if one hypothesizes that the reaction between LTI and the OH groups at polyesters chains is not completed during the thermo-mechanical processing, and just when constant values of G' in time are exhibited, fully-cured materials with increasing cross-linking density are obtained. As LTI is added to the blends, from 0,5 to 5 phr, both the slope of the build-up curves and the G' values increase proportionally, confirming, as expected by considering easy chemistry rules, that the reaction kinetics and the cross-linking density are ruled by the reactive agent amount. Therefore, from a proper viscous thermoplastic behaviour of the melt from the physical blend, increasing the carbamates links and the molecular weight, a series of materials with an evident elastic and/or rubber-like behaviour have been manufactured. Further experiments have then been conducted on all blends after constant values of G' were obtained. The frequency variation experiments data are plotted in Fig. 5.13, showing the trends for both Elastic (G') and Viscous (G") moduli. The moduli values increase here too, with increasing the LTI content. These results are in line with the previous characterizations, and confirm the densification of a cross-linked network bringing to a proper solid-like behaviour in all blends with 1 phr or more of LTI.

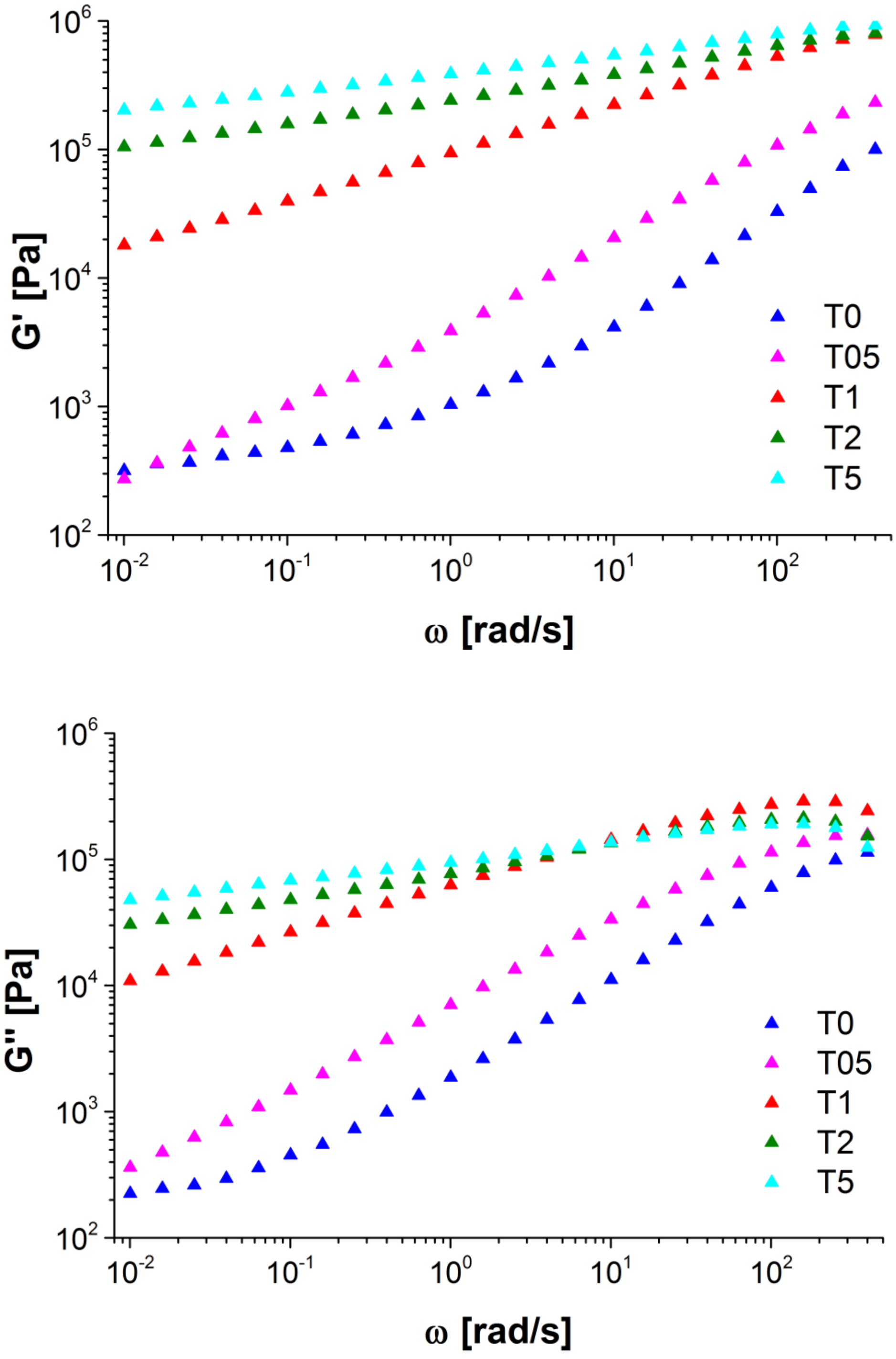


Fig. 5.13 Frequency variation tests trends of Shear Moduli for A50C50 blends (top G', bottom G'').

The G' trend of the physical blend shows an evident change in slope below 1 rad/s, exhibiting an increase of the elastic behavior in the low frequencies region, which, according to literature studies, is attributed to the shape relaxation of the dispersed phase, often in the shape of big circular droplets, because of the interfacial energy exhibited by Poly(lactide) and Poly(ε-caprolactone). This result is in line with mechanical characterization and, as discussed earlier, the interfacial tension has an important contribution to G' under shear deformation, which results in this deviation from the standard trends for these polyesters. These phenomena are shown in the low frequencies range, because it represents a time scale in which wider molecular weights and interactions among chains rule the visco-elastic behavior of polymers[5,6].

The disappearance of this slope change and increase in Elasticity in all reactive blends suggests then a much finer dispersion of the two phases, and a lower interfacial energy.

It is worth to mention that the A50C50T05 reactive blend, seems to represent the boundary from a thermoplastic binary system, brought to miscibility by the in-situ reactions of co-polyester-urethane structures to a rubbery cross-linked material in which the effect of a third phase is underlined by the rheological properties.

Indeed, for the reactive blends containing 1phr or more of LTI, the values of G' are major than G'' in the entire range of frequencies examined and the gap between the two moduli becomes wider as the LTI content increases, indicating a denser cross-linking.

5.5 Scanning Electron microscopy

The morphological characterization conducted on blends clearly showed the changes on the phases dispersion and the cross-linked co-polyester-urethane networks effects on it, discussed earlier. SEM images of the A50C50 blends, analysed before the rheological characterization, are shown in Fig. 5.14.

The physical blend (A50C50), according to literature studies, exhibits an low dispersion morphology, with wide PLA spherical droplets, because of the interfacial tension between the polyesters solidifying from molten.

The first noticeable effect of the reactive blending, is that by the addition of 0.5 phr (A50C50T05) and 1.0 phr (A50C50T1) of LTI, the particles progressively reduce their diameter, from ~15 μm for the physical blend, to ~3 μm and ~1 μm. The improved dispersion is clearly noticeable in the reactive blends images, which in the A50C50T05 blend appears like a co-continuous morphology, probably because of the changing viscosity.

Furthermore, in the A50C50T1 blend it is also exhibited a stress preferential direction imposed by the spinning force from the rotors inside the mixing chamber of the batch mixer. This stress preferential direction is not exhibited in the physical blend image (A50C50), leading to understand how this phenomenon is related to the grafting and/or cross-linking reactions during the thermo-mechanical processing of blends with LTI.

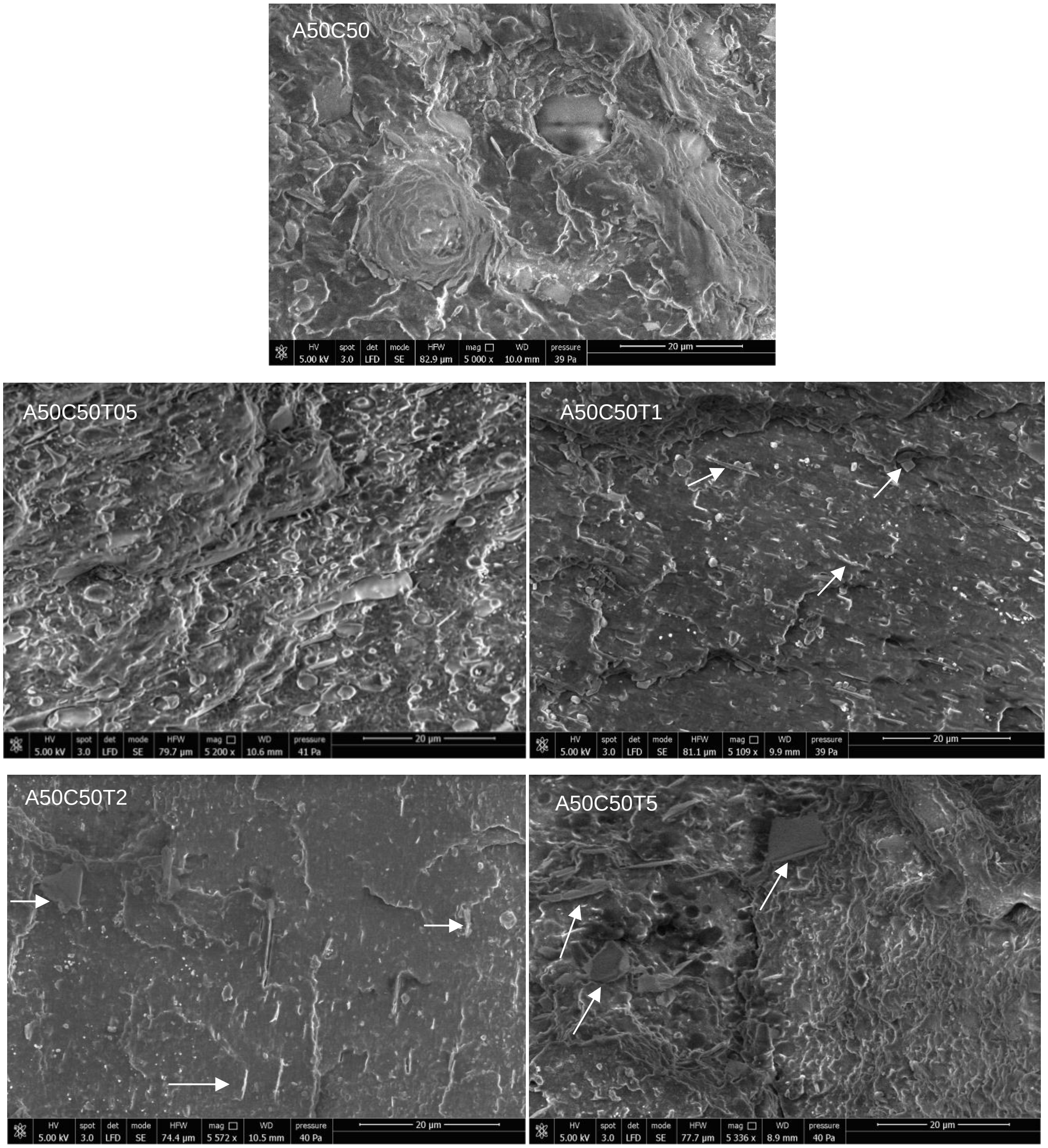


Fig. 5.14 SEM images of physical and reactive blends before rheology tests.

From A50C50T1 to A50C50T5 images, as indicated by the arrows in Fig. 5.14, it is also possible to see a third phase, hypothesized during mechanical and rheological characterizations, which seems to be in acicular shapes. The dispersion of these particles in the blends, could justify a reinforcement effect on the mechanical properties, similarly to what happens when a rod-like particulate is added to blends. Some literature studies have found that mechanical properties, like the Young's modulus or the tensile strength of Poly(lactide) or Poly(ε-caprolactone) composites, were improved by addition of particles like SiO_2 or carbon [7,8].

Therefore, the crinkled surface exhibited by the A50C50T5 blend, could be the result of the wide concentration of these densely cross-linked structures in the mixtures brining to a noticeable morphology change which is proportional to the reactive agent amount in the blends.

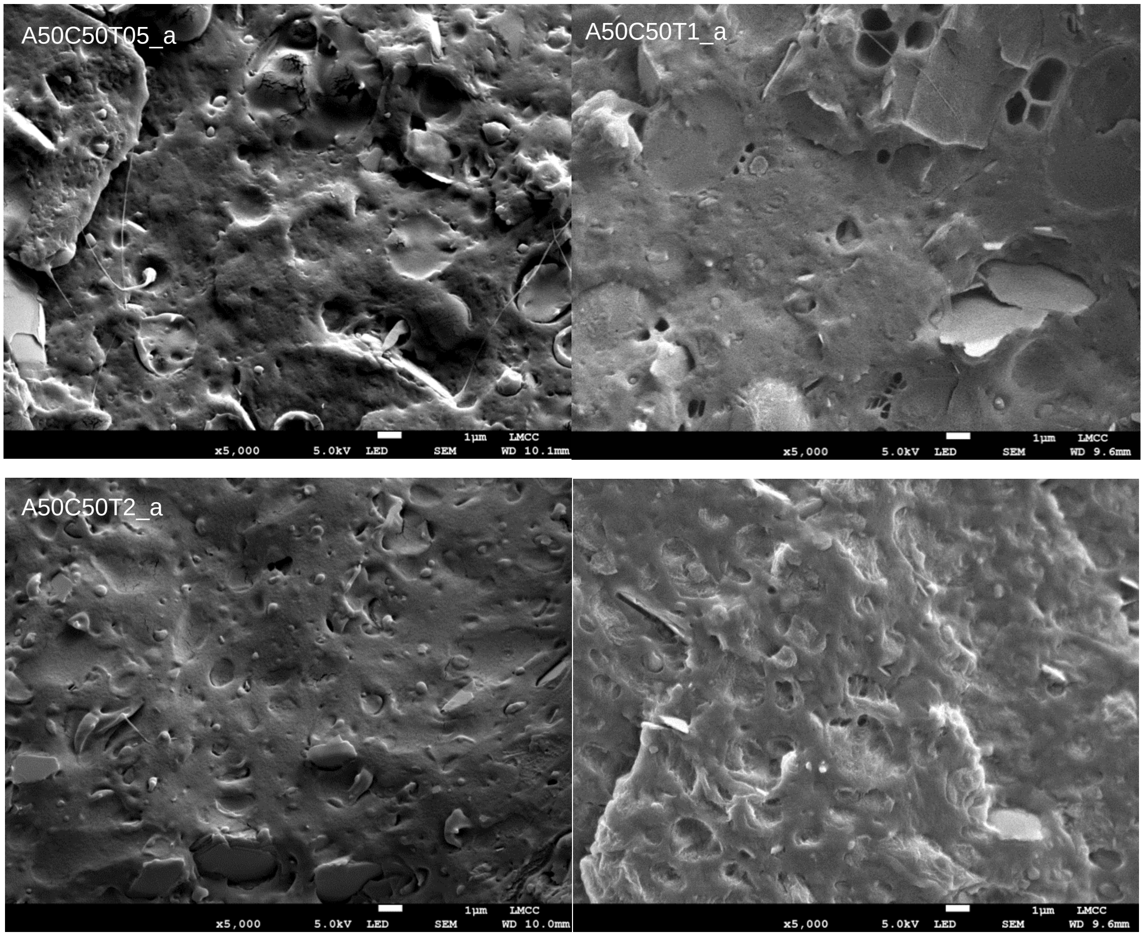


Fig. 5.15 SEM images of reactive blends after rheology tests.

Observing instead the blends morphologies after the 'curing' process conducted in the rheometer, reactive mixtures exhibit a less lined surface, oppositely to what observed previously in particular for the T5 blend (Fig. 5.14). That is probably because of the wider cross-linked network, in which no particles of unreacted polymers are dispersed, following the temperature curing in the rheometer. The third phase is extended exhibiting its effect on morphology as well, confirming what shown in the rheological and mechanical analyses.

5.6 Surface and chemical characterization of Physical and Reactive Blends

5.6.1 Wet-ability

Surface angle measurements conducted on physical and reactive mixtures of Poly(lactide)/Poly(ε-caprolactone) in PBS have confirmed the comprehensive structural changes because of the reactive blending process.

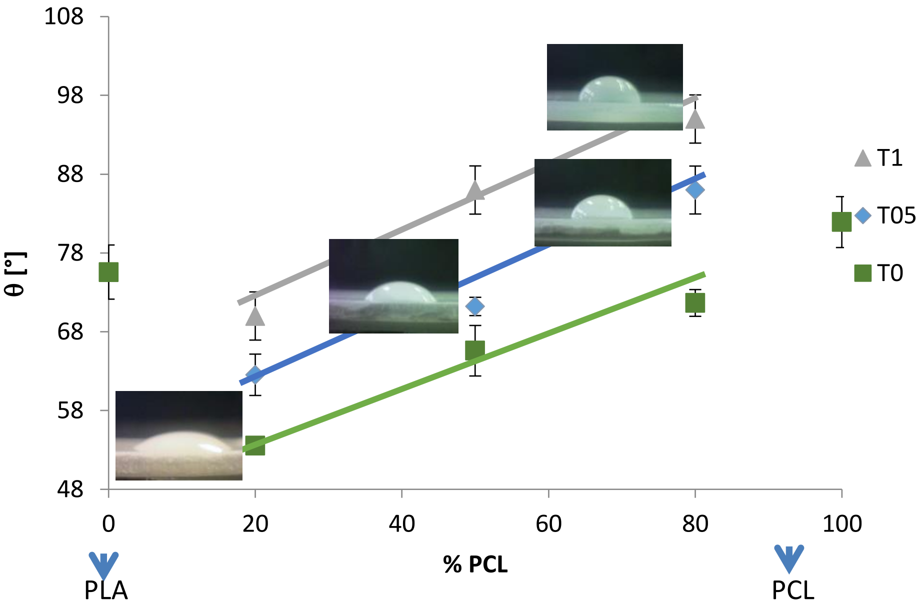


Fig. 5.16, PBS surface angle values of Physical and reactive blends vs PCL weight ratio

For biodegradable materials, a noticeable interaction between fluid and material substrate suggests a faster degradation rate because of the hydrolytic reactions, catalytically lowering the polyesters molecular weight, with a change in physical properties.

The graph in Figure 5.16 shows how the increasing amount of PCL in the PLA/PCL blends brings an increase in surface angle for both physical and reactive blends. This is related to the lower hydrophilic behavior of PCL because of its crystallinity, and of its lower amount of hydrophilic parts (the hydroxyl groups and ester bonds in the macromolecules). Furthermore, in the same graph, it can be noticed how the reactive blends (T05 and T1) surface angle trends are shifted towards increased surface angle values. This could be related to the co-polyester-urethane networks increasing in molecular weight with the reactive agent amount. They could have a lower hydrophilicity because of their specific structural composition lowering the interaction between the liquid and the substrate.

These results suggest a lower degradation rate for all the reactive blends, and then probably that the mechanical properties will be maintained in time with the use of the blend in a biological system.

It is also worth to mention that the polyesters studied in this work are well known for their hydrolytic and/or enzymatic absorption ability and their physical properties trends are in line with the molecular weight changes. It represents then a possibility to manufacture easy drug delivery systems with defined drug absorption kinetics, which can also be studied by software and numerical modeling as found in literature [10,11].

5.6.2 FT-IR Analysis

In order to understand further about the chemical structure and the composition of the blends resulting from reactive mixing process, FTIR-ATR spectroscopy data have been plotted as shown in Fig. 5.17 and discussed in the following.

Many stretching and bending peaks of carbon atoms have been identified and analysed, but just some of them can represent and underline a change in the chemical structure of the blends after the reactive blending process.

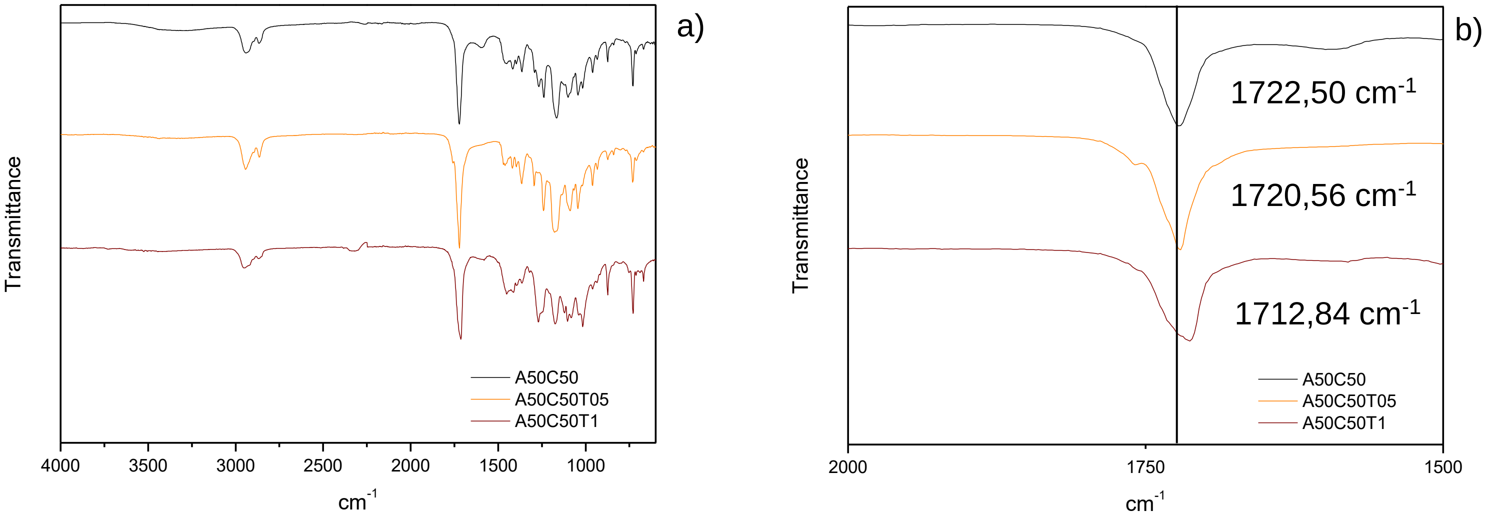


Fig. 5.17 a) FT-IR Spectra of A50C50 physical and reactive blends (0,5 and 1 phr LTI), b) C=O stretching peak zoom

The graph shows the changes in FTIR-ATR spectra because of the LTI addition to the A50C50 blends. The stretching of carbonyl peak, around 1722 cm^{-1} in the A50C50 blend, is shifted to 1720 cm^{-1} after the addition of 0,5 phr of LTI and to 1712 cm^{-1} after the addition of 1.0 phr. This confirms that different structures containing carbonyls (probably the carbamate groups $(-NH(CO)O-)$ are obtained with the reactions conducted in thermo-mechanical processing.

It was expected, in particular for the 5 phr LTI amount, to find the characteristic peak of $N = C = O$ at about 2270 cm-1, but it was not observed, probably because, since the ATR method represents a surface analysis, the unreacted LTI in bulk part of the material does not appear in these Infra-red spectra.

5.7 Reactive exrusion

As discussed earlier, A50C50 physical and reactive blends have been extruded to manufacture polyester matrix threads and mechanical tensile tests conducted on the resulting samples to evaluate their properties. Extruded physical (a) and reactive blends (b) threads are shown in Fig. 5.18

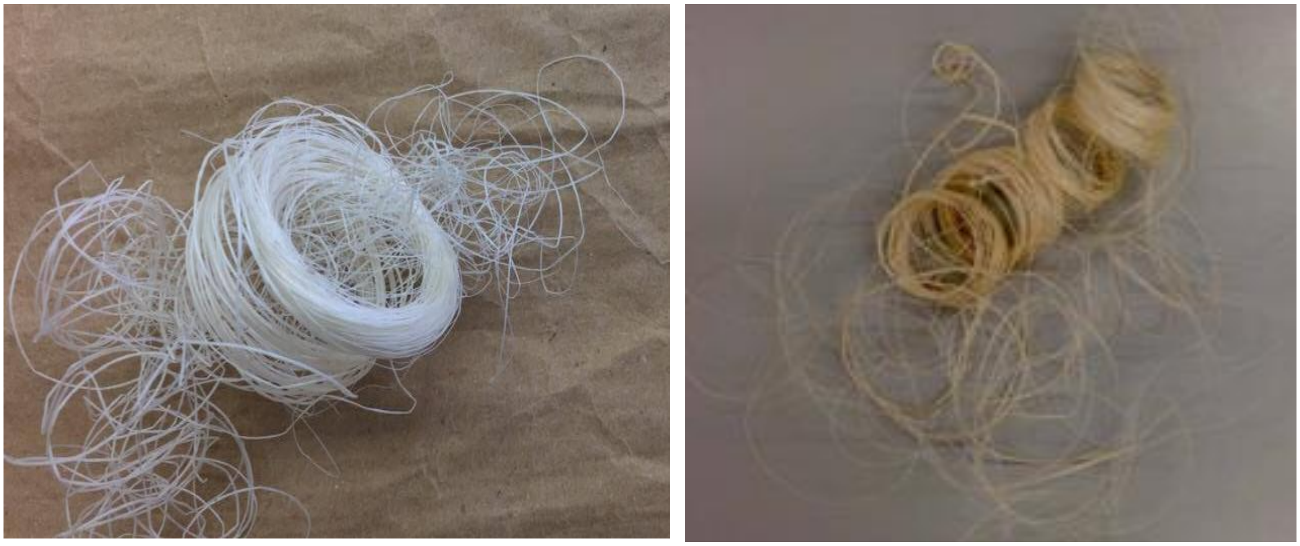


Fig. 5.18 a) A50C50 and b) A50C50T5 extruded blends

Fig. 5.19 and Table 5.7 are instead the Stress-Strain curves and the most important mechanical characteristics of the tested extruded blends.

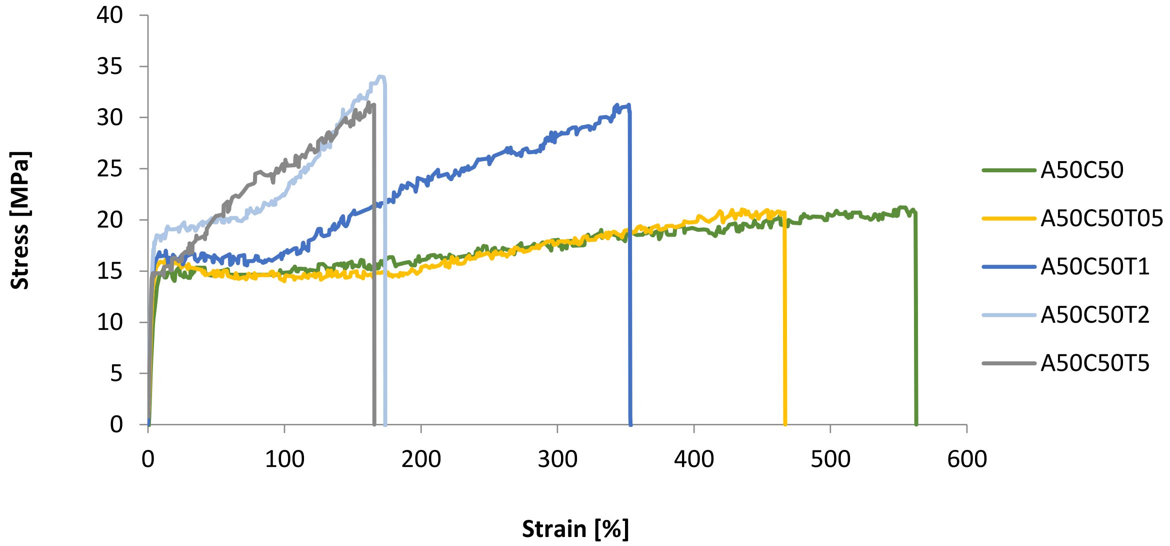


Fig. 5.19, A50C50 extruded physical and reactive blends Stress-Strain trends.

The first important difference with the batch mixtures is the noticeable increase in resilience and ductility of the extruded physical blend, when the batch one showed a decrease in all the mechanical properties because of the immiscibility among the phases ($\varepsilon_{y\ EXT}$ = 11,5%; $\varepsilon_{y\ BATCH}$ = 3,0%. $W_{b\ EXT}$ = 0,32 J; $W_{b\ BATCH}$ = 0,02 J. $\sigma_{y\ EXT}$ = 14,4 MPa; $\sigma_{y\ BATCH}$ = 7,2 MPa). This phenomenon is because of the degree of mixing obtained with a most dispersive technique like extrusion, bringing to a decrease in droplets diameter from blending under those values of shear rate. As a result of the improved dispersion, an increase of all the most important physical properties is observed for the A50C50 blend.

Table 5.7 Mechanical properties of extruded A50C50 physical ad reactive blends

Sample (Extruded)	E [MPa]	ε_y [%]	σ_y [MPa]	σ_m [MPa]	ε_b [%]	σ_b [MPa]	W_b [J]
A50C50	378±69	14,4±1,1	11,5±3,6	20,1±1,4	518±64	20,2±2,0	0,320±0,090
A50C50T05	497±90	15,0±1,4	10,6±2,4	20,8±1,8	475±79	20,8±2,0	0,350±0,090
A50C50T1	657±96	16,4±0,6	7,28±2,7	28,2±3,1	320±65	27,8±3,0	0,260±0,050
A50C50T2	643±80	20,4±2,1	7,1±1,5	37,8±4,8	177±68	37,4±4,8	0,150±0,012
A50C50T5	577±91	16,2±3,0	6,5±2,3	28,7±5,3	172±69	28,6±5,5	0,150±0,060

Besides, as noticeable in the graph and in the table above, oppositely to what happens for batch mixed blends, the LTI addition leads towards a decrease in ductility for all the reactive blends.

Blend A50C50T05 showed an Elongation at break of 475%, and blend A50C50T5 o 172%, when that of the A50C50 was 518%. It is also worth mention how the Elastic modulus increases from 378 MPa for the physical blend to 657 MPa for the A50C50T1 (see Fig. 5.20).

These results lead to understand how the thermo-mechanical degradation is a key factor in this processing, and probably how, the LTI addition, catalyzes this effect with exothermic reactions of grafting and cross-linking.

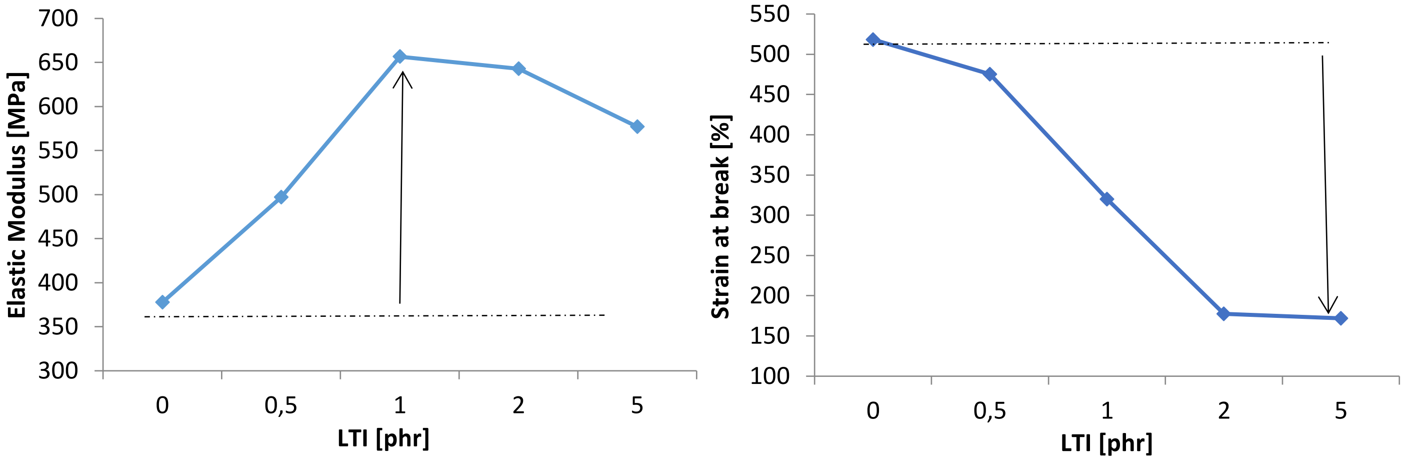


Fig. 5.20 Elastic Modulus and Strain at break vs LTI amount in extruded blends

5.8 Physical Emulsification

As briefly discussed in Chapter 4, to start studying a physical method of emulsification was also the target of this work and some results, regarding the solvent cast blends characterization will be discussed in the following.

The PLA-b-PCL block copolymer synthesized for the purpose, has primarily brought a variation in the crystalline structures of Poly(lactide) during solidification or the cold crystallization process.

Fig. 5.21, shows the temperature ramp tests conducted on PLA/PCL/PLA-b-PCL blends, in the Poly(lactide) cold crystallization temperature range.

The physical agent effects observed were substantially consisting in a shift of the peak towards higher temperature, and for the 7,5 phr amount, a noticeable increase in elasticity (from about 45000 Pa for the A50C50SC to about 72000 Pa for the A50C50B7,5SC blend), probably because of an improvement in the interfacial interaction among the components.

As the block copolymer amount was increased (10 and 15 phr) a trend inversion was observed, probably indicating the physical agent acting as a proper lower molecular weight third phase in blends, with a plasticizing effect instead than that of an emulsifier to improve miscibility and interfacial properties.

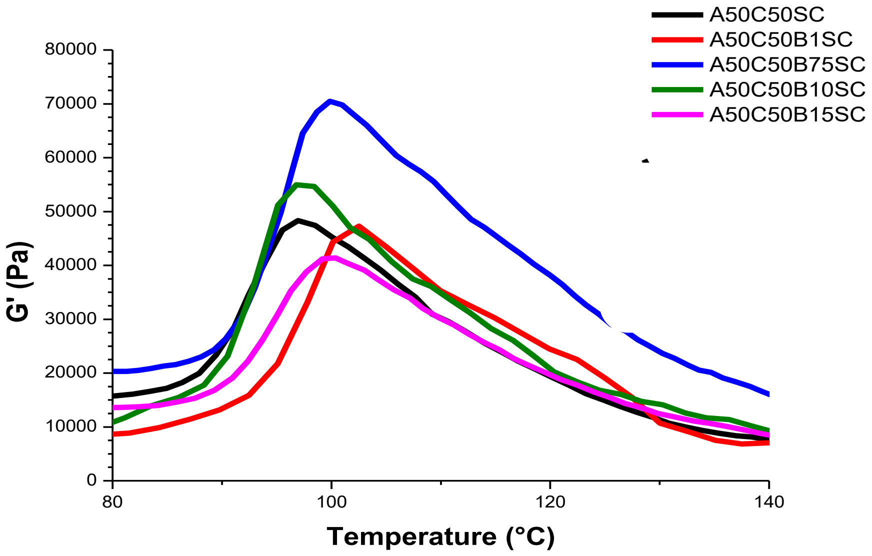
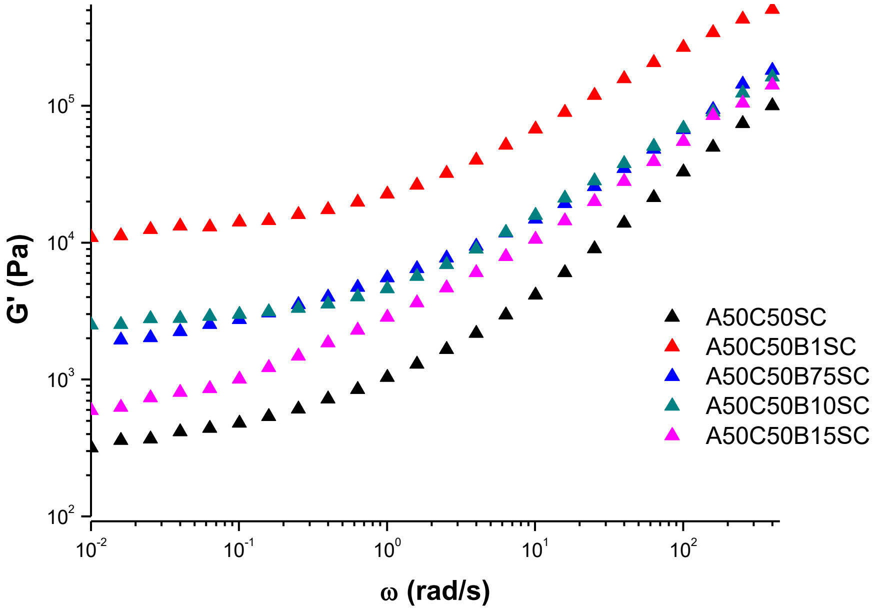


Fig. 5.21 Rheology Temperature ramp test trend of solvent cast blends, PLA Cold Crystallization temperature range



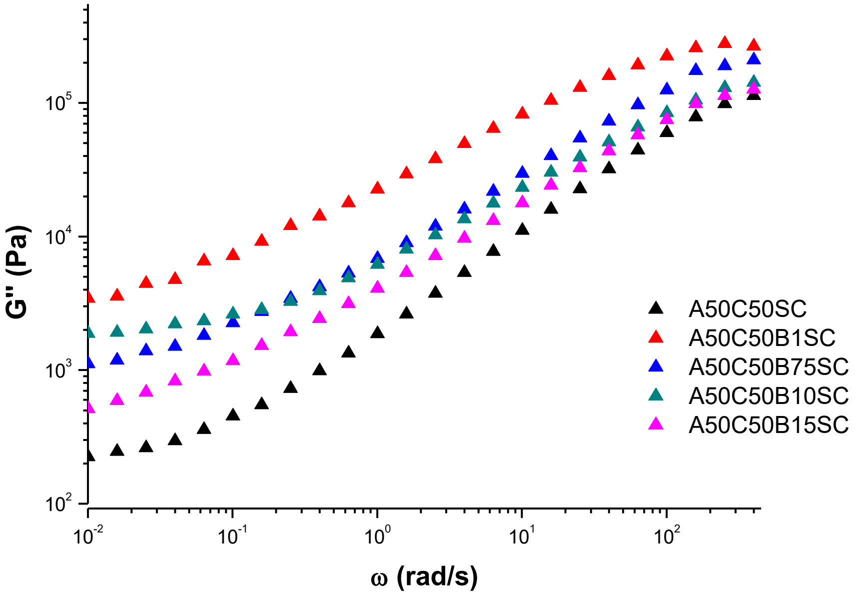


Fig. 5.22 Frequency variation tests trends of Shear Moduli for A50C50 Solution cast blends (top G’, bottom G’’).

The frequency variation tests under constant strain rate, are shown in Fig. 5.22, and as underlined by the low frequencies region trends, they have confirmed the low molecular weight of the physical agent added to the blends.

Except for the A50C50B1SC blend, for which a noticeable increase in viscosity and elasticity is observed considering the shear moduli trends, with a mechanism that is still under study, no important variations in the viscoelastic properties of blends under shear can be defined.

The slope trends in the low frequencies test range indicates that no substantial improvements in dispersion have been obtained. It is worth mention anyway, how observing the G' trend for the A50C50B15SC blend, a shift of the slope change towards lower frequencies can be noticed and could confirm the plasticizing effect of the physical agent used at that amount, increasing the chains mobility at those time scales since the entanglement density of the polyester blends.

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6. Conclusions

6.1 Innovation and findings

As discussed in many parts of this work, the main target of it, was initially to conduct a comprehensive and descriptive analysis of Poly(lactide)/Poly(ε-caprolactone) reactive blending results.

The effects on the physical properties of both, Polyesters weight ratios and reactive agent amount, have been studied by characterizing many blends formulations, finding that the most important factor, determining the visco-elastic behaviour too, is the Ethyl-Ester L-Lysine Triisocyanate content in blends. LTI amounts from 0,5 to 5 phr have been used first to improve phase dispersion among the blend components, known for their immiscibility, and then finding how the variations in the blends formulation can bring to an innovative series of tailorable characteristic materials, with unprecedented improvements of all physical properties.

Primarily, the mechanical tests, conducted on all samples, have shown how from the lowest amount of reactive agent used, a diametral change in ductility is observed for all blends.

The most resilient blend was the A50C50T05 (Yield Strain of 27 %), with a moderate elastic modulus (344 MPa), the most ductile the A20C80T1 with an Elongation at break of over 1000 % and a Work at breakage of 10,1 J and the most resistant the A50C50T5, exhibiting a maximum Stress of 45,7MPa, showing clearly how the cross-linking density can act as a proper reinforcement on the mechanical properties.

Thermal analyses have underlined how the chemical changes in the macromolecular systems studied brought to variations in the crystalline degree and to the polymers ability to get the chains into ordered structures, after the thermo-mechanical processing.

Rheological characterization led instead to understand how a ‘curing’ process is necessary to obtain constant behaviour materials after the reactive mixing process. Considering the polyesters molar masses, their macromolecular mobility and that the reactive agent amounts used rule the kinetics of the chemical reactions towards co-polyester-urethanes networks, it is easy to see how there can be many unreacted molecules after blending.

The morphological characterization has first underlined the improvement in dispersion and interfacial interaction because of the co-polyester-urethane structure obtained by using LTI. Furthermore, it has then confirmed the appearance of a third phase, a densely cross-linked part of the mixtures expanding with the reactive agent amount, with, as discussed widely, an important effect on all the physical properties.

Reactive Extrusion processing conducted, confirmed the degree of dispersive mixing of this technique, but showing also as the thermo-mechanical degradation phenomena become important when scaling the process.

The early phase of blends emulsification by use of physical agents, confirmed the importance of the copolymers molecular weight in improving the interfacial interaction and the viscoelastic behaviour of these polyester blends. The temperature ramp tests under shear in particular, have shown substantial changes in the crystallization ability of PLA, with an increase in the elastic part of the Shear Modulus for the 7,5 phr amount of emulsifier, leading to understand also how the copolymer amount have an important effect on the physical properties of blends.

These findings added value to the polyester blends research field, showing how from immiscible systems of two among the most used biodegradable polymers, unprecedented improvements of commercially and academically interesting characteristics can be obtained by reactive blending.

Furthermore, for what discussed above, these materials showed to fit for many clinical and bio-medical applications, in which the most important property among all is tailorability, since in biological systems the variability of characteristics is considered the main concern for design and manufacturing of devices.

6.2 Further Developments

Many aspects about the structural changes in these materials, obtained by reactive blending, have been studied and underlined by several methods of analysis. But since the width of this research field, there are still properties to be studied and analyses to follow .

The Biological interaction is still to be studied, and bio-degradation tests will be conducted in order to understand the behaviour of these blends when interacting with biological systems looking for an application.

Then, to furtherly improve the mechanical properties like the tensile strength or the Elastic Modulus, the use of proper fillers like Hydroxyapatite or bio-glasses can be considered for bone tissue engineering, since the specific properties necessary for this application.

The degradation phenomena are also still to be analysed, both during the thermo-mechanical processing, and the use time of the blends. It needs to understand if the LTI, as expected could act as radical scavenger, reacting with lower molecular weight chains of the polyesters.

Furthermore, conducting the processing on a wider scale, by using industrial extruders and N2 environment to not to have oxidization, will lead to further improvements in the physical properties.

Regarding instead the physical emulsification process, first results have been shown and led to understand how increasing blocks molar masses is the key factor to obtain a substantial increase of properties in blends.