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Master of Science in Civil Engineering

Master Degree Thesis

Constitutive relationship of Ultra High Performance Concrete in tension

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PREFACE

This thesis is written as part of the Master "Structural Engineering "at the faculty of Structural, Geotechnical and Building Engineering of Politecnico di Torino. It presents my six months of graduation research.

In truth, I could not have achieved my current level of success without a strong support group. First of all, I want to thank Alessandro Pasquale Fantilli for the opportunity to perform my research in accordance with Cemex Company and his role as thesis supervisor. Secondly, I would like to thank Nicholas Sergio Burello for patient advice and guidance as well as his motivating assistance throughout the research process. Furthermore, I want to thank all of my professors who were involved in my graduation journey.

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I am grateful to my family for their endless support, in particular to my parents Tamar Artun and Nurhan Artun who make this happen, without whose confidence in my capabilities, I could never have finished this thesis. I would like to offer my special thanks to my uncle, Maksut Gulleyan for supporting me spiritually throughout my life.

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ABSTRACT

This research mainly focused on developing tests and model for UHPC that directly relates the tensile behavior of the concrete based on strain localization within an individual crack. The core purpose of the present study is to measure the tensile strength by considering the stress in concrete due to the presence of fibers in the specimens. The stress strain relationship is mentioned in terms of the different quality and consistency of the specimens. These several specimens are prepared and sent by Cemex Company. In order to move forward some tests were developed by using the test equipment, three point bending fixture and universal tensile test machine and the use of bone shape specimens and with the completion of each individual test in around an hour. In the first part of this paper, a literature review and brief introduction of area of use, differences and types of concrete technologies are highlighted. Then, a general information of the test methods are carried out to demonstrate the applicability and the further details. Afterwards, the test procedures, application process and experimental steps, which are performed in the laboratory, are specified. Then, based on the results obtained from laboratory, the model is implemented for aiming to compute the tensile properties from the tension tests. In the final part, a review of the applied tests and comparisons among the test results are conducted.

Keywords: *Ultra-High Performance Concrete, direct tension test, flexure test, concrete cylinder compression test, stress-strain response*

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LIST of Abbreviations and Symbols

Abbreviations

JSCE	Japan Society of Civil Engineers
AFGC	Association Française de Génie Civil
DAfStB	DeuDeutscher Ausschuss für Stahlbeton guideline
ASTM	American Society for Testing Materials
EN	European Standards
FRC	Fiber Reinforced Concrete
SCC	Self Compacting Concrete
HPC	High Performance Concrete
HPFRC	High performance fiber reinforced concrete
UHPC	Ultra High Performance Concrete
HPFRCC	High Performance Fiber Reinforced Cement Composites
CC	Conventional Concrete
PFR	Polypropylene Fiber Reinforced Concrete
DFRCC	Ductile Fiber Reinforced Cement Composites
ECC	Engineered Cementitious Composites
RPC	Reactive Powder Concretes
SHCC	Strain Hardening Cement-based Composites
SSM	Solid Suspension Model
CPM	Compressible Packing Model
SF	Silica Fume
SP	Superplasticizers
FA	Fly Ash

RHA	Rice Husk Ash
GGBS	Ground Granulated Blast Furnace Slag
MDF	Micro Defect Free Cement
SIFCON	Slurry Infiltrated Fiber Concrete
DSP	Dense silica particle cement
CRC	Compact Reinforced Composites
MSCC	Multi-Scale Composite Cement
DTT	Direct Tension Test Method
FT	Flexure Test
LVDT	Linear Variable Displacement Transducer
TBR	Tensile Bending Relation

Symbols

E_t	Young's Mosulus in tension
E_{pp}	Young's Mosulus at post peak
P_m	Load applied in the middle of section
P_{cr}	Critical load
$\mathcal{E}_{ty}$	Yielding strain
$\mathcal{E}_{tu}$	Ultimate strain
f_{ty}	Yielding stress
f_{tu}	Ultimate tensile strength
f_{ck}	Compressive strength
M_{ut}	Ultimate bending moment
M_r	Resistant moment of section
N_r	Resistant normal force of section
η	Mid span deflection

CHAPTER 1- INTRODUCTION

1.1 INTRODUCTION

In today's globalizing world, the construction industry keeps developing day by day. Parallel with the innovations in technology many tools and techniques are implemented, in order to obtain sustainable materials for complicated structures. Hence, several studies and researches have been conducted in order to distinguish the suitable concrete type in order to encounter this aim.

The most well known recent concrete technologies and their mechanical properties and features are briefly explained in the following steps. The research discussed herein mainly focuses on the constitutive relationship in Ultra-high performance concrete in tension. UHPC is one of the commonly used concrete technology, which demonstrates great mechanical and durability properties, containing sustained post cracking tensile strength. Several test methods are implemented in the laboratory in order to assess the tensile mechanical properties of concrete, FRC and UHPC.

In this research paper, the specimens that are tested in the laboratory of the university Politecnico Di Torino, were prepared and sent by Cemex Company. The company is founded in 1906 with the opening of the Cementos Hidalgo plant in northern Mexico. Cemex is known as a global building material company, providing high quality and reliable products and services over 50 countries. As a company, their target is to serve innovative and efficient building solutions and to ensure the sustainability for the future. Their production mainly focuses on cement, aggregates and ready mix concrete. Cemex Company is an international corporation surrounded all over the world the Americas, the Caribbean, Europe, Africa, the Middle East and Asia. The company itself has a trade relationship in 102 nations and one of the world's top traders of cement and clinker.

The company is mainly focused on creating sustainable value by providing industry leading products and solutions to satisfy the construction needs of customers from all around the world. One of their target is focused on the climate action such as reducing the emissions and increasing energy efficiency as well as decreasing clinker factor, applying alternative fuels and promoting the use of renewable energy.

They produce their products cement, aggregates, neogem and ready mix concrete in order to overcome the global problems related with engineering and plant optimization. Their purpose is to reduce the impact of challenges posed by environmental factors. Enhancing the raw materials to obtain high quality products is one of the key component of company mission. They have a wide range of working area such as agriculture, landscape, industry could enable an appropriate stability, drainage and consistency in sports ground surfaces in order to provide safe and comfortable environment to athletes. They also provide innovative ideas and decorative solutions.

1.2 RESEARCH SCOPE

The goal of this project is to compute the tensile strength by considering the presence of fibers and to develop two main test methods, which are called respectively Direct Tension Test and Bending Test and Concrete Cylinder Compression Test.

1.3 RESEARCH OBJECTIVE

The objective of this paper is to implement a direct tension test (DTT) applicable to UHPC that relates the full range of uniaxial tensile behaviors through the strain localization and might be applicable for on cast or extracted specimens.

1.4 RESEARCH METHODOLOGY

The methodology behind the preparation process is briefly indicated in the following scheme. This paper mainly contains experimental and theoretical studies together. First of all, the work methodology has started with planning and scheduling and it is followed by the literature review and consulting the past researches and experiences. The next step consisted on implementing test methods on the specimens, sent by Cemex Company. There were 18 mixes and 3 specimens for each. However, this research concentrated on the samples that have a great fiber consistency and high strength. After concluding the process of laboratory testing, the implementation of modelling has launched. To sum up, in the final steps comparisons among the tests and evaluation of results are discussed.

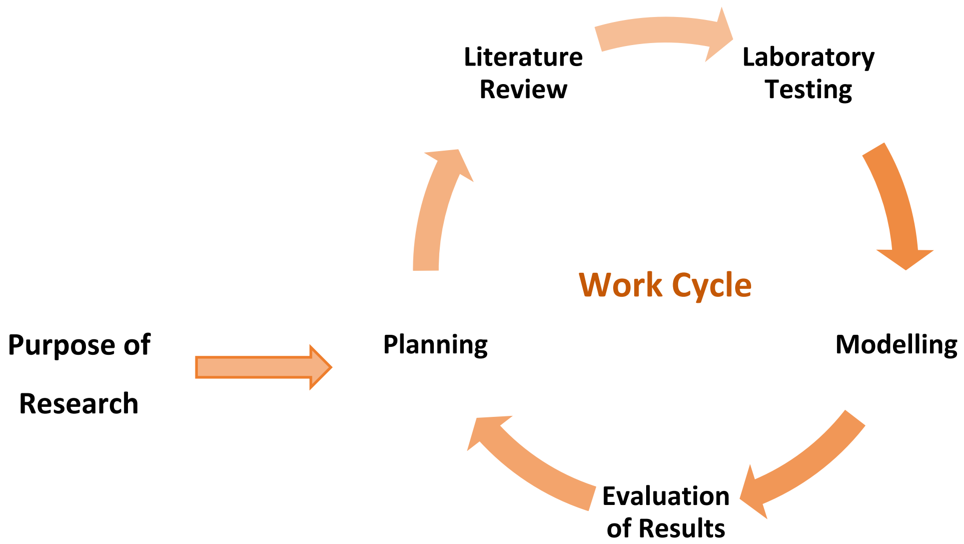


Figure 1. Scheme of Work Methodology

CHAPTER 2 - BACKGROUND

2.1 FIBER REINFORCED CONCRETE (FRC)

The notion of the reinforced concrete with fibers is quite old. During the period of Egyptian and Babylonian eras, fibers have been used to reinforce brittle materials. Fiber Reinforced Concrete also shortened in a form of FRC, is getting popular among the concrete community due to the impact on the reduction of construction time and labor costs. Moreover, to the cost benefit, FRC provides a good quality for a maintenance of construction and has a great impact resistance of reinforced concrete elements both situ-cast and precast. Due to this reason, many structural elements are now reinforced with steel fibers in order to increase the cracking resistance, flexural and shear strength.

In recent decades, major advances have been made in the study of fiber reinforced cementitious materials. The randomly dispersed fibers in bulk concrete allowed the post-cracking method to improve material behavior, leading to the reduction and control of the creation and propagation of cracks. Due to the fiber, bridging effect and the gradual bond loss and slippage of the fibers (pull out effect), which is responsible for preserving the cohesion of the cracked concrete parts, an increase in ductility is also observed.

Fiber Reinforced Concrete is a construction substance that enhances its structural integrity, composed of fibrous material. It involves cement, mortar or concrete mixtures and discontinuous, distinct, uniformly distributed sufficient fibers. Due to plastic shrinkage and drying shrinkage, fibers are commonly used in concrete to control cracking. Moreover, they also decrease concrete permeability and therefore decrease the bleeding of water.

There are plenty of advantages of utilizing FRC, the most significant ones are related with enhancing the impact strength of concrete. It also has a great impact in limiting the crack growth and causes a huge impact in strain capacity of the composite material. FRC can be used in which high tensile strength and reduced cracking are desirable or in the difficult case of positioning traditional reinforcement. It enhances the cohesion of blends, by increasing pumpability over long distances. Moreover, it reduces the steel reinforcement requirements and segregation and enhances the resistance towards plastic shrinkage during curing. Macro-synthetic fibers are used for industrial projects to increase the toughness of concrete. Fatigue strength and the shear capacity of reinforced concrete beams are increased by adding fibers. The addition of fibers to concrete enhances its freeze-thaw resistance and keeps concrete strong.

2.1.1 Types of fiber reinforced concrete

In various sizes and shapes, fibers for concrete are available. A water-cement ratio, percentage of fibers, diameter and length of fibers are the key factors influencing the function of fiber-reinforced concrete. The types of fiber reinforced concrete used in the construction can be classified as follows:

2.1.1.1 Macro synthetic fibers

Macro synthetic fibers are made of a polymer mix and were originally produced in some applications to provide an alternative to steel fibers. They were originally identified as a possible alternative to sprayed concrete steel fibers, but increasing research and development found that they had a role to play in the design and construction of ground-supported slabs and a wide variety of other applications. In aggressive environments, such as marine and coastal structures, they are especially ideal for providing nominal reinforcement since they do not suffer from the problems of staining and spalling that can result from steel corrosion. In addition, since they are non-conducting, they have been used in the construction of trams and light railways.

Figure 2 Macro-synthetic fibers

2.1.1.2 Micro synthetic fibers

Micro-synthetic fibers offer superior resistance versus welded wire reinforcement to the forming of plastic shrinkage cracks, they could not able to provide any resistance to further crack width openings caused by shrinkage drying, structural load or other types of stress. However, in order to improve cracking resistance, spall safety, freeze-thaw toughness and improve the homogeneity of concrete during placement, these items should be defined on a regular basis in any form of concrete.

Figure 3 Micro synthetic fibers

The type of fibers are illustrated in the figure below:

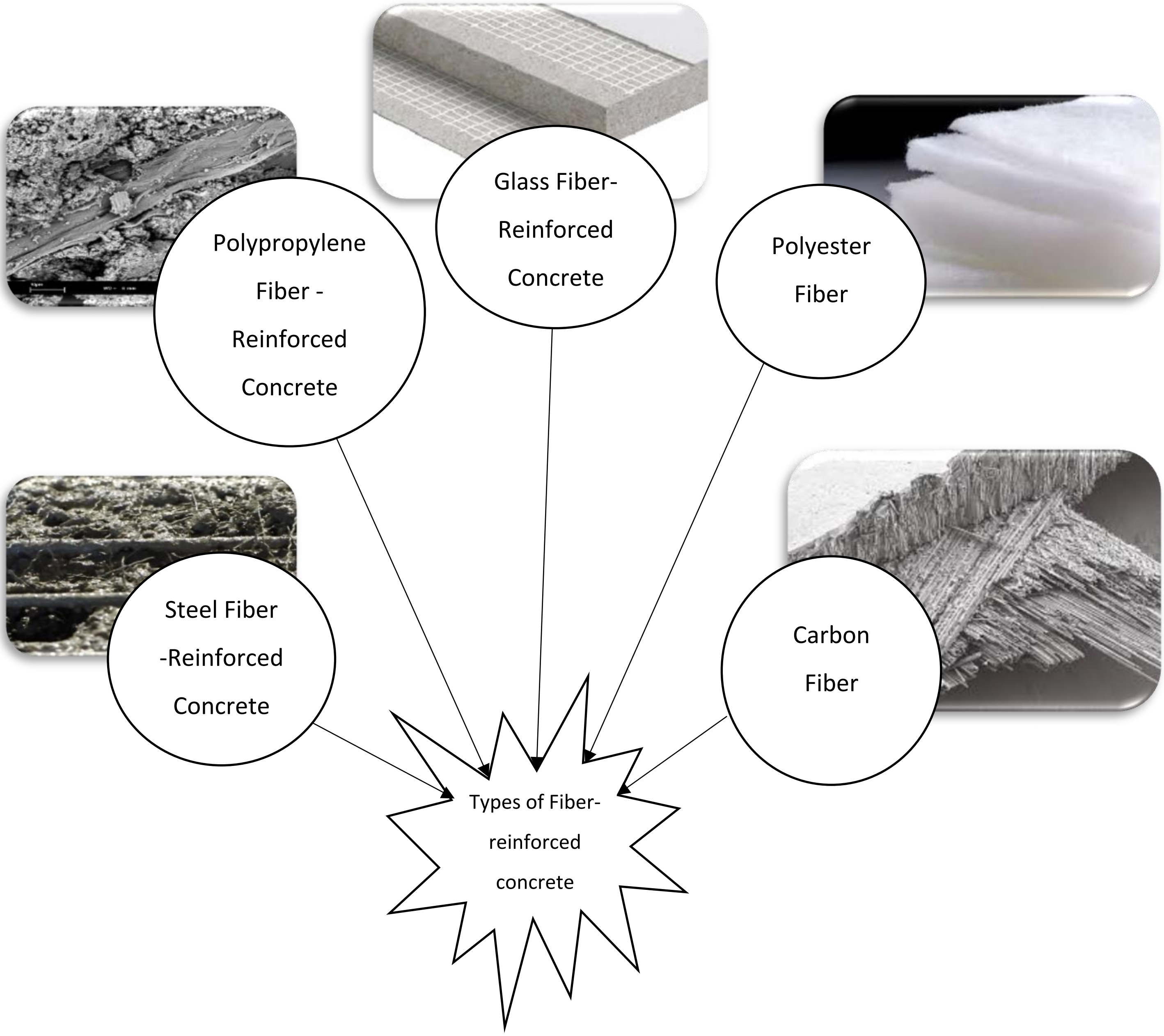


Figure 4 Type of fibers

2.1.1.3 Steel Fiber Reinforced Concrete

Steel fiber is a reinforcement constructed from metal. In concrete, a certain amount of steel fiber may cause qualitative changes in the physical property of concrete. Resistance to fracturing, impact, weakening, and bending, tenacity, resilience, and others can be greatly improved. SFRC is used in structures such as flooring, homes, precast, bridges, tunneling, heavy-duty paving and mining to enhance long-term behavior, increase resilience, durability, and stress resistance. The general types of steel fibers are defined by ASTM A820 are, Type I: cold-drawn wire, Type II; cut sheet, Type III: melt-extracted, Type IV: mill cut and Type V: modified cold-drawn wire.

Figure 5 Steel fiber reinforced concrete

2.1.1.4 Polypropylene Fiber Reinforced (PFR) Concrete

Reinforced concrete with polypropylene fiber is often referred to as polypropene or PP. It is a synthetic fiber used in a variety of applications, transformed from propylene. Due to the plastic shrinkage and drying shrinkage, these fibers are commonly used in concrete to control cracking. They also decrease concrete permeability and therefore decrease the bleeding of water. The fiber of polypropylene belongs to the polyolefin group and is partly crystalline and non-polar. It has similar characteristics to polyethylene, but is stronger and more resistant to heat. Polypropylene fibers is highly resistant to acids, alkalis, and organic solvents and has excellent heat-insulating properties.

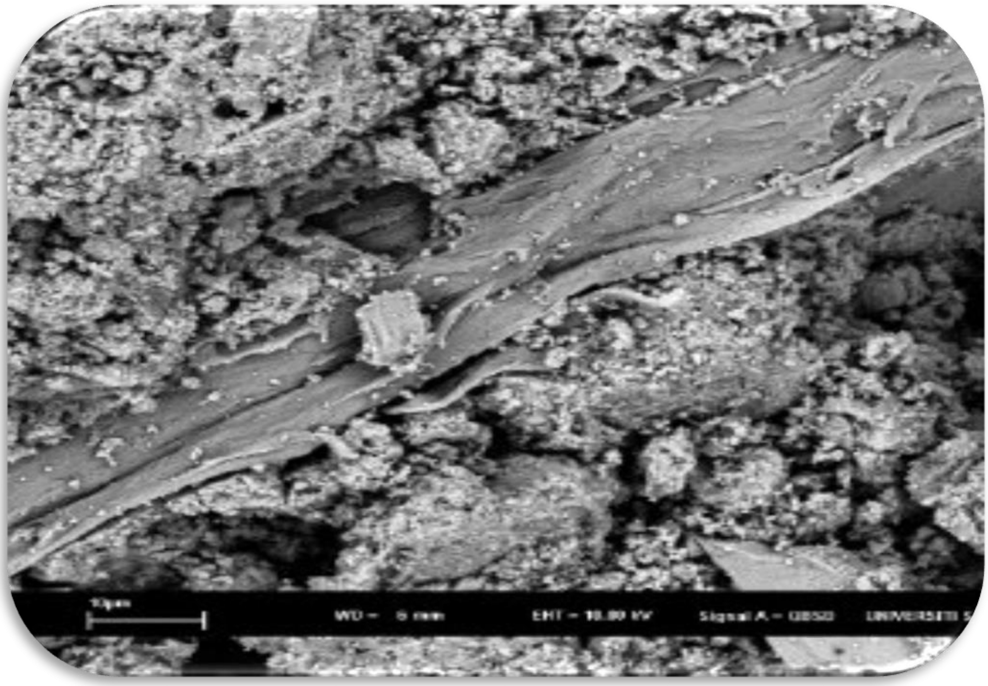


Figure 6 Polypropylene fiber reinforced concrete

2.1.1.5 Glass Fiber Reinforced Concrete

A material composed of various extremely fine glass fibers is glass fiber reinforced concrete. Glass fibers have mechanical properties approximately equal to other fibers, such as polymers and carbon fibers. While not as rigid as carbon fiber, when used in composites, it is much cheaper and significantly less brittle. For several polymer products, glass fibers are therefore used as a reinforcing agent to produce a very solid and relatively lightweight fiber-reinforced polymer (FRP) composite material called glass-reinforced plastic (GRP), often commonly referred to as fiberglass. Glass Fiber Reinforced Concrete contains less air or gas and it is denser. This material contains little amount of air or gas. It is denser and is a weaker thermal insulator than is glass wool.

Figure 7 Glass fiber reinforced concrete

2.1.1.6 Polyester fibers

For factory and warehouse floors, pavements and overlays, and precast items, polyester fibers are used in fiber-reinforced concrete. In concrete, polyester micro- and macro-fibers are used to provide superior resistance to the creation of plastic shrinkage cracks versus welded wire fabric and, when properly constructed, to improve strength and the ability to provide structural capacity.

Figure 8 Polyester fibers

2.1.1.7 Carbon fibers

Carbon fibers are fibers with a diameter of around 5-10 micrometers and consist mainly of carbon atoms. There are many benefits to carbon fibers, including high rigidity, high tensile strength, low weight, high chemical resistance, resilience to high temperatures and low thermal expansion. They are generally combined with other materials aiming to form composites. It forms a carbon-fiber-reinforced polymer (often referred to as carbon fiber) when impregnated with a plastic resin and baked, which has a very high strength-to-weight ratio, and is highly durable but somewhat brittle. To form reinforced carbon composites, which have a very high heat resistance, carbon fibers are often composited with other materials, such as graphite.

Figure 9 Carbon fibers

The type of fibers such as micro or microfiber, metallic, synthetic and straight or hooked-end are playing a significant role. Moreover, the key factors influencing the material response, characterized by softening (progressive residual strength loss with crack localization and progressive collapse) or hardening behavior, are volume and distribution (multi cracking stage with strength increase followed by crack localization and failure.

The crack opening regulation ensures structural durability and concrete strength. Additionally, concrete permeability is decreased and aggressive agents such as chloride ions and sulphates are added. Those are mainly responsible for corrosion of steel bars and concrete degradation. Fiber reinforced concrete (FRC) has a higher ability of energy absorption (toughness) compared to traditional concrete due to the increase in ductility, enhancing structural strength due to static (tensile, torsion, shear) and dynamic (seismic, vibration, cyclic) loads.

The inclusion of fibers leads to the material's heterogeneity. Tensile and bending tests demonstrated greater values of the variance coefficient of FRC products, primarily due to the random distribution and alignment of fibers and the bulk matrix. There is also a decrease in the workability of the concrete blend, which is directly related to the amount of fibers. Part of the problem of FRC workability involving high fiber dosages (> 2 percent) was solved by the development of self-compacting concrete. In addition, modern casting techniques have allowed greater fiber orientation control, reduced variability and increased predictability of experimental tests.

There are many benefits in terms of use of FRC; however, one the most significant reason is that FRC is a cement matrix within which, with respect to the dimensions of the element, random fibers are distributed randomly. Unlike conventional steel bar reinforcement, the short fibers added typically do not increase the concrete's compressive strength, but, thanks to their homogeneous diffusion, they are more efficient in improving the concrete element's post-cracking behavior. Hence, their core aim is to enhance the ductility and capacity to absorb energy, through the control of crack propagation.

The components of the FRC does not vary like as the traditional cementitious materials such as water, aggregates, and additives. They depend on the strength grade, porosity, durability and workability.

FRC has been used mainly for crack control in rigid pavements and tunnels (primary and secondary layers) due to shrinkage, thermal and permanent deformations, helping to increase structural resilience. FRC has some disadvantages for structural use, partially or completely replacing (in particular cases) longitudinal steel bars (flexural capacity) and stirrups (shear and torsion), primarily related to the cost of the materials and the absence of design guidelines in developing countries.

On the one hand, the emergence of new fibers such as carbon, steel, glass and polymer and the rise in the use of materials have led to reducing production costs and enhancing the competitiveness of these fibers. Codes and guidelines for design were published in contributing to the safety design of the last few years. The design models have grown into an analytical approach based on probabilistic models, to a more logical and physical system.

The increasing use of FRC for structural purposes is linked to achieving better structural efficiency, greater durability and simplification of the construction process.

The mechanical behavior of fiber reinforced concrete (FRC) highly depends on the relations among the fibers. The mechanical behavior is mainly affected by friction, chemical and physical adhesion. The steel fibers formed by shearing thin sheets of steel were not very successful because they were too smooth for the matrix to bind well. Consequently, to improve the mechanical anchorage, which is the most significant of the bonding mechanisms, several different fiber geometries were developed and pointed out in the figure below figure 10. Similarly, surface treatment of synthetic (mostly polypropylene) fibers has been used to strengthen the fiber-matrix bond.

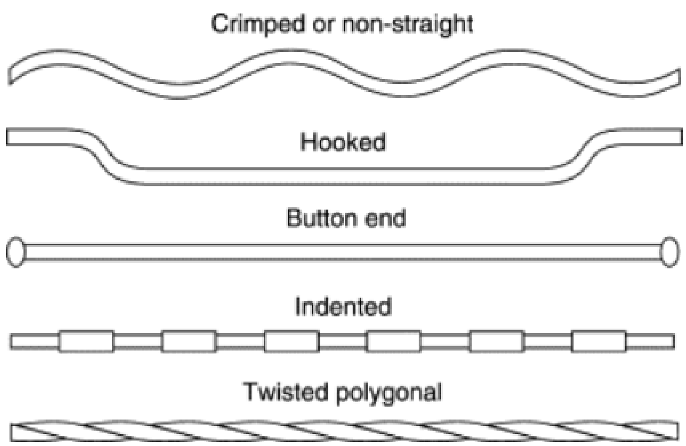


Figure 10 Types of fiber geometries

Depending on the fiber type, there is initially elastic stress transfer between the fibers and the matrix as FRC is stressed either by external loads or by shrinkage or thermal stresses. Since the fibers and the matrix have very different elastic moduli, at the fiber/matrix interface, shear stresses grow. As the shear stress at the interface is surpassed, deboning starts to occur gradually, and frictional shear stresses become the mechanism of dominant stress transfer. Any cracking of the matrix happens at some stage during this gradual transition from elastic to frictional stress conversion, and some frictional slip occurs in the deboned areas.

The core point arises to acknowledge reaction of fibers in FRC towards crack extension and the behavior in the post-cracking zone. This situation is controlled by the pulling out of the fibers from the matrix. On the other hand, smooth fibers cannot develop sufficient adhesive or frictional bond, thus all the fibers currently used in practice are in some way deformed or surface-treated to increase bonding with the matrix.

Mechanical properties of FRC are traditionally determined by utilizing the beam tests, which are generally related with three- or four-point bending tests. Based on the research conducted in the past, the low volume fractions of fibers point out that the characteristic values determined from beam tests are quite low due to the high scatter present in the beam test results. It can be said that the high scatter occurs when low contents of macro fibers are used.

In addition, it is accepted that FRCs with a low volume of fraction of fibers are particularly suitable for the structures, which has a high degree of redundancy in which stress distribution may occur. Due to this redistribution, large fracture areas are involved. Hence, the structural behavior is mainly governed by the mean value of the material properties. Moreover, it can be highlighted that due to the large fracture areas, the scatter of experimental results from structural tests is remarkably lower than that obtained from the beam tests.

The following two graph represents a set of curves obtained from a standard beam (bending) test on notched specimens (figure 11a) and from structural tests on full scale slabs on grade made of the same material (figure 11b).

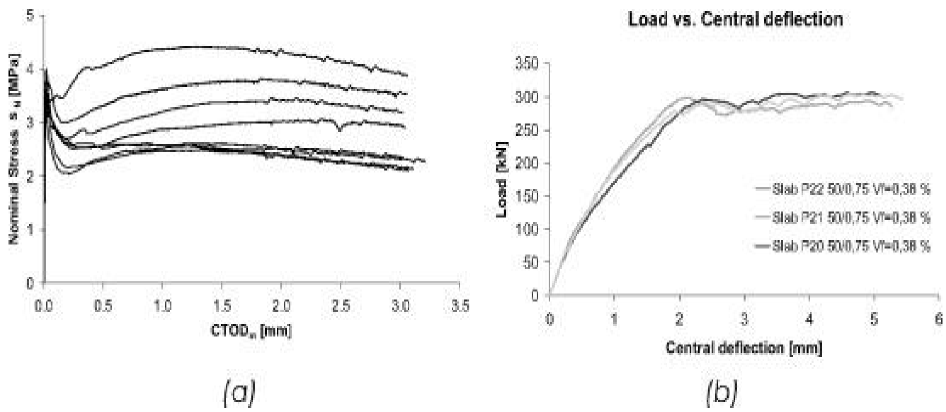


Figure 11 Test results of standard beam bending test on notched specimens

To sum up, in order to obtain a more realistic value of scatter from FRC material tests, specimens having a large fracture area are needed. Thus, it is better to use larger beams or different specimens like slabs.

2.1.2 Application of Fiber-reinforced concrete

The applications of fiber reinforced concrete rely on the applicator and the manufacturer to take advantage of the material's static and dynamic properties. Therefore, it used in a wide range.

Figure 12 Application areas of FRC

The most commonly applied areas are mentioned below:

- Runway
- Aircraft Parking
- Pavements
- Tunnel Lining
- Slope Stabilization
- Thin Shell
- Walls
- Pipes
- Manholes
- Dams
- Hydraulic Structure
- Roads
- Bridges
- Warehouse floors

To sum up, Fiber reinforced concrete has a great impact starting from durability and aesthetics. In today's globalizing world, the use of FRC has been increasing throughout the building industry. Fiber Reinforced Concrete is gaining a growing interest in terms of a decrease in construction time and labor costs among the concrete community. Quality concerns are of vital importance for building, in addition to cost problems, and fiber-reinforced concrete often meets these criteria.

2.2 HIGH-PERFORMANCE FIBER REINFORCED CONCRETE (HPFRC)

High Performance Fiber Reinforced Cementitious Composites, which is commonly pronounced as HPFRCC has a diverse range of efficiency in terms of strength comparing to the regular type of concrete. It is basically composed by a group of fiber reinforced cement based composites that lead to flex and ability for self-strengthening before cracking. The most significant difference from the regular type of concrete is that the resistance is improved by technological measures and the microstructure of concrete is enhanced. Therefore, some of protective measures can be neglected.

A dense concrete microstructure is often paired with an increased strength, or HPFRC always has a dense microstructure, in other words. Thus, in their technologies, HPFRCC and concrete with a thick microstructure do not vary too much. The core aim of HPFRCC is to reduce the reinforcement and the dimensions of structural members. This type of concrete is mainly used for columns and walls of high-rise structures.

In the construction industry, an emerging technology called' High-Performance Fiber-Reinforced Concrete (HPFRC)' has become popular in recent years. High-performance fiber reinforced concrete is increasingly evolving into a high potential, new construction material. This type of concrete was conducted for the aim of solving structural problems inherent in today's traditional concrete, such as its propensity to fail in a brittle way under excessive loading and its lack of long-term durability.

HPFRCCs have the remarkable ability to plastically yield and harden under extreme loading due to their nature and structure, so that they flex or deform before fracturing, a behavior close to that displayed under tensile or bending stresses by most metals. Strain hardening happens when a material is loaded past its elastic limit and starts to bend plastically, the most desired capability of HPFRCCs. The material is actually reinforced by this stretching or 'straining' action. In contrast to the single crack/strain softening behavior displayed by traditional fiber-reinforced concretes, this phenomenon is made possible by the creation of several microscopic cracks. In HPFRCCs, it happens when many fibers slip past each other. HPFRCCs are more resistant to cracking because of this capability and last much longer than regular concrete. Thus, during the design process of HPFRCC, the prevention of crack propagation or the tendency of a crack to increase in length should be taken into consideration. The existence of fiber bridging, a property that most HPFRCCs are explicitly designed to possess, prevents this phenomenon. In an effort to prevent the crack from growing further, fiber bridging is the act of multiple fibers exerting a force across the width of a crack. This capability is what gives its ductile properties to bendable concrete. Their low density is another highly desirable property of HPFRCCs. A less dense, and thus lighter, material means that HPFRCCs will potentially generate and handle much less energy, finding them to be a more economical building material. Moreover, due to the lightweight structure and strain hardening capacity of HPFRCCs, it has been suggested that they could potentially become a more durable and reliable alternative to traditional concrete. In other words, it can be said that HPFRCCs are simply a subcategory of ductile fiber-reinforced cementitious composites (DFRCCs). Thus, it has the ability to strain harden under both bending and tensile loads.

After the several researches conducted by the several countries such as the article entitled by Japan Society of Civil Engineers (JSCE) (March 2018) and the recent symposium on HPFRCC in Kassel, Germany (April 2008), the popularity of HPFRC is dramatically increased. Afterwards, the studies are maintained with aiming to figure out an international recommendation in terms of designing the structures with HPFRCC. In order to provide the missing information in the related areas, research initiatives are being carried out. A variety of values should be respected in preparing an internationally accepted design recommendation for the HPFRCC.

The concept of 'high performance' is usually intended to differentiate structural materials from traditional ones, as well as to maximize the combination of properties in terms of final applications relating to civil engineering. The materials used in HPFRCC are based on the desired features and the availability of sufficient alternative local economic materials. Concrete is a typical construction material, usually poor in tension, often driven by cracks due to plastic shrinkage and drying. It is possible to use the introduction of short discrete fibers into the concrete to overcome and avoid crack propagation. Due to the increase in interest in the use of HPFRCC in concrete structures, the impact of fibers on concrete properties should be taken under control. Hence, a detailed research about the mechanical, physical, and durability of concrete, by consulting the literature review, crack formation and propagation, compressive strength, modulus of elasticity, stress-strain behavior, tensile strength, flexure strength, drying shrinkage, creep, electrical resistance, and chloride migration resistance of HPFRCC should be done. In general, it has been proven that the addition of fibers to high-performance concrete improves the mechanical properties of concrete, especially tensile strength, flexural strength and ductility performance. Additionally, the integration of fibers into concrete results in decreases in concrete shrinkage and creep deformation. It has been shown, however, that fibers can also have detrimental effects on some concrete characteristics, such as workability, which are minimized by adding steel fibers. Due to their conductivity, the addition of fibers, especially steel fibers, leads to a significant decrease in the electrical resistivity of the concrete, and results in a certain decrease in the resistance of the concrete to chloride penetration.

The most significant feature of HPFRCC is that it can be designed for having high workability and high mechanical properties and enhancing durability comparing with the traditional concrete types. Thus, the use of various types of additives play a key role in terms the protecting the quality of concrete. There are wide range of binders used in the production of HPFRCC, however the most important well knowns are silica fume, ground granulated blast-furnace slag and fly ash. In order to boost the mechanical, physical, and toughness characteristics of concrete, these additives may be applied individually or in different combinations to the concrete mix. There are also benefits to the addition of mineral admixtures. One benefit is that their small size helps the cement paste to be more lightweight. Another benefit is that the use of concrete mineral admixtures contributes to an improvement in the ultimate compressive power. Moreover, the addition of these additives result in better workability and durability. On the other hand, as well as the advantages, there are also some disadvantages of introducing the mineral admixtures in concrete and results in the brittleness of concrete.

To manufacture materials with improved tensile strength, ductility, hardness and enhanced resilience properties, fibers can be integrated into cemented concrete. A special type of HPC, distinguished by a low-water-binder ratio, inclusion of high quality, high tensile strength and high-durability pozzolanic materials is introduced as HPFRCC. The fibers' most effective contribution is the ability to slow the development of cracks in the hardened concrete. The internal stresses cause the development of micro cracks in the hardened concrete. The introduction of randomly spaced steel fibers will move the stress inside the concrete microstructure and prevent the cracks from spreading. The flexural strength, fracture resilience, thermal shock strength, and resistance under impact and fatigue loading properties can be enhanced due to this fiber characteristic. The inclusion of steel fibers in HPC has been demonstrated to minimize concrete brittleness and improve the mode of failure of the concrete framework. There are many types of fibers such as metallic, polymeric or natural and comprehensive description is defined above. Therefore, depending on the conditions, the type of fibers results in significant change in the consistency of HPFRC.

Since the HPFRCC class contains many particular formulas, their physical compositions differ considerably. In general, most of HPFRCCs composed by a superplasticizer, fine aggregates, polymeric or metallic fibers, cement and water. Therefore, the key distinction between HPFRCC and standard concrete composition lies in the absence of coarse aggregates by HPFRCCs. In HPFRCCs, a fine aggregate such as silica sand is usually used. The majority of HPFRCC research studies concentrate on the use of steel fibers as either a single inclusion or a mixture of other non-metallic fibers.

High Performance Fiber Reinforced Cement Composites also called HPFRCC demonstrate a class of cement composites whose stress-strain response in tension undergoes strain-hardening behavior accompanied by multiple cracking, which leads to a high strain capacity at failure.

HPFRCC is defined as a material that points out pseudo strain-hardening characteristics under uniaxial tensile stress among short fiber reinforced cementitious composites-FRCCs, as it is demonstrated in the figure below. As it can be clearly seen from the figure 13, tensile stress is increasing in the pseudo strain-hardening behavior of HPFRCC under direct uniaxial tensile stress after first cracking. Moreover, according to the graph strain softening (1) and (2) occurs in which conventional fiber reinforced concrete FRC indicates a decrease in tensile stress after first cracking. It is generally seen in the case of cement-based materials such as cement, mortar and concrete.

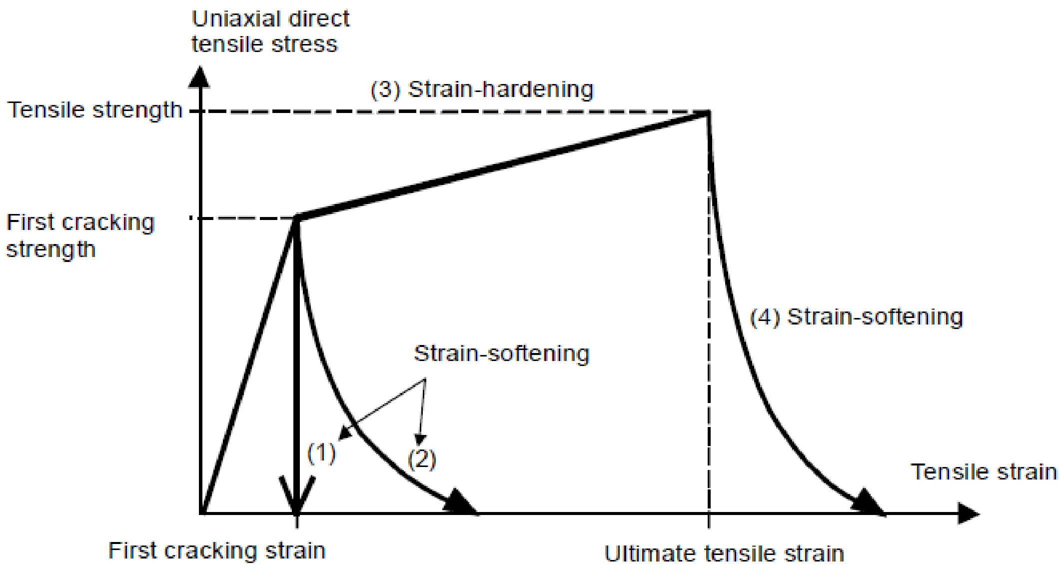


Figure 13 Concept of strain hardening and strain softening under tensile stress

Some materials among Ductile Fiber Reinforced Cementitious Composites shortened as DFRCC, includes HPFRCC, do not demonstrate pseudo strain-hardening characteristics however they point out an increase in flexural stress with an increase in flexural deformation. This is called deflection-hardening characteristics and UHPRC is a relevant example for the deflection hardening materials. This type of materials demonstrate collection of damage at the beginning stage of deformation depending upon size and loading conditions.

Some performance parameters such as the ultimate tensile strain and the averaged crack width needed to be checked in order to enable the pseudo strain-hardening and high durability while using HPFRCC.

Despite their identical compositions, the basis for the engineered design of various HPFRCCs differs considerably. For instance, ECC that is one of the type of HPFRCC, designed by applying the principles of micromechanics. This field of study is best defined as relating mechanical macroscopic properties to the microstructure of a composite and is just one particular method used to design HPFRCCs. Another design technique used in other HPFRCCs formulas is based on the capacity of the material to withstand seismic loading.

HPFRCCs are used in many areas; however, the most well knowns are bridge decks, concrete pipes, roads, structures particularly subjected to seismic and non-seismic loads. There are many structures conducted by the use of HPFRCCs, particularly ECC. For instance, ECC has been used by the Michigan Department of Transportation in order to patch a portion of Grove Street Bridge deck. The goal of ECC patch to replace previously existent expansion joint that linked two deck slabs. In addition, ECC is also used in Curtis Road Bridge in Ann Arbor and MI and Mihara Bridge in Hokkaido, Japan.

2.3 ULTRA HIGH-PERFORMANCE CONCRETE (UHPC)

Over the last two decades, significant developments have taken place in the analysis and application of Ultra-High-Performance Concrete (UHPC) that demonstrates recognizable proof in terms of rheological behaviors including workability, self-placing and self-densifying properties enhanced in mechanical and durability performance with very high compressive strength. It is the 'future' material with the potential to be a feasible alternative for buildings and other infrastructure components to boost their sustainability. A broad variety of commercial UHPC formulations have been produced worldwide after several decades of growth to cover a rising variety of uses and the increasing demand for quality building materials.

UHPC has many advantages over traditional concrete, but due to the high cost and restricted design codes, its use is limited. Ultra-High-Performance Concrete generally demonstrated as UHPC is a class of cementitious composite materials, designed to exhibit exceptional mechanical and durability properties, including sustained post cracking tensile strength. There are many technological studies are held in the field of cement and concrete science which have been brought together in the development of this class of concretes figure 14. These concretes are generally classified as high-performance concrete (HPC); fiber reinforced concrete (FRC) with discontinuous pore structures and enhanced durability properties and self-compacting concrete (SCC). These concrete types tend to have low water to cementitious materials ratio and optimized gradation of granular materials.

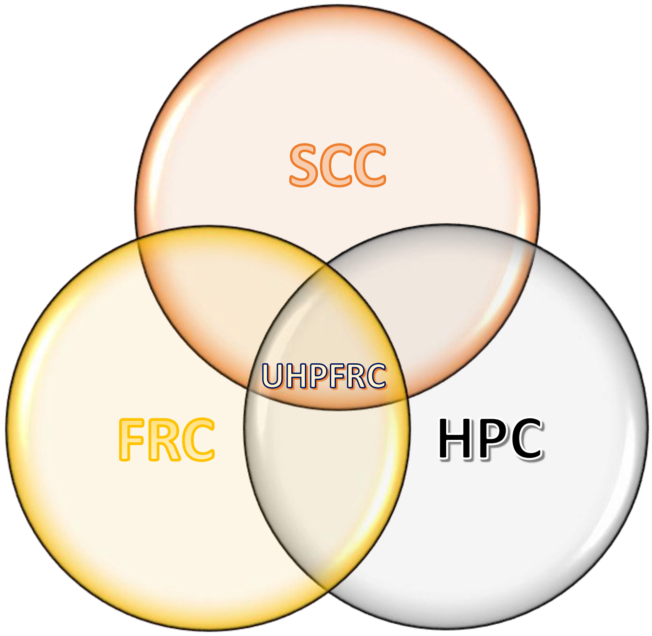


Figure 14 Types of concrete technologies

Throughout the past years, plenty of innovations has been done in concrete technology. Ultra High Performance Concrete with a steel like compressive strength of up to 250 N/mm^2 is one of the biggest technological breakthrough. It leads to an increase in durability compared even with high performance concrete. In combination of steel fibers, it is possible to design lightweight concrete constructions with or even without additional reinforcement.

The use of UHPC is getting popular among many countries due to the diverse range of facilities. Ultra High Performance is generally used many areas such as large span girders, bridges, shells and high-rise buildings. There are many examples about the application areas of UHPC such as construction products, architectural features, repair and reconstruction, vertical components such as windmill towers and utility towers to applications in the oil and gas industry, offshore structures, hydraulic structures and overlay materials. Road and bridge buildings are the most common of all these applications for UHPC applications. In different countries, including Australia, Austria, Canada, China, the Czech Republic, France, Germany, Italy, Japan, Malaysia, the Netherlands, New Zealand, Slovenia, South Korea, Switzerland and the United States, the use of UHPC for bridges and bridge components can be seen. For instance, some pedestrian bridges heavily trafficked road bridges built in France and in the Netherlands, can be an appropriate example. On the other hand, in the case of Germany raw materials for fine or coarse grained, UHPC is used to reduce the cement content. Moreover, fiber mixtures and non-corrosive high strength plastic fibers are utilized in order take the strength under control.

The growing store of material knowledge and adequate design of buildings with UHPC has allowed the technical working groups in France to draw up initial technical recommendations focusing primarily on design (Resplendino 2004, SETRA-AFGC 2002). UHPC was described by the French interim recommendations (AFGC 2002) as concrete with a characteristic compressive strength of at least 150 MPa using steel fiber reinforcement to ensure ductile stress behavior. UHPCs with 130 MPa-150 MPa compressive strength reinforced with either steel or other fibers are known to be UHPCs of lower strength. In general, The term UHPC is usually used to describe a fiber-reinforced, super plasticized, silica fume-cement mixture with a very low ratio of water to cement (W/C), distinguished by the presence of a very fine quartz sand varying in diameter from 0.15 to 0.60 mm instead of the ordinary aggregate. A state-of-the-art study covering all the content and design dimensions was also released in Germany (DAfStB UHPC 2003). This implies that the concrete itself is continuously optimized and a wide variety of new formulations are generated to satisfy the specific needs of a growing number of different applications. The primary aim of this program was to broaden UHPC's knowledge to make it a reliable, widely accessible, economically viable, and frequently used material.

Nowadays, it is possible to observe many projects related with UHPC in all over the world. However, there are still some challenges limiting its implementations. In order to launch an advanced, affordable, sustainable, feasible and economical UHPC in the future, ongoing research and investigation efforts are filling up knowledge gaps, as it will have a significant impact on growing its acceptance.

Based on the literature review, many forms of UHPC have been produced in various countries and by various manufacturers, such as Ceracem1, BSI1, Compact Reinforced Composites (CRC), Multi-Scale Composite Cement (MSCC) and Reactive Powder Concrete (RPC) and also concretes with a compressive strength of up to 800 N/mm^2 have been developed and produced under particular laboratory conditions. They have been compacted and thermally treated under high pressure. In the early beginning period of 1980s, the notion came up to develop fine grained concretes with a very dense and homogeneous cement matrix that prevents the development of micro cracks within the structure after being loaded. They were called "Reactive Powder Concretes (RPC)" (Bache 1981; Richard and Cheyrezy 1995) because of the small grain size of less than 1 mm and the high packing density due to the use of various inert or reactive mineral additions. A wider variety of formulations existed in the meantime, and the term UHPC was developed worldwide for concretes with a minimum compressive strength of 150 N/mm2.

As the world's most common manmade material, concrete is the fundamental construction material that will continue to be in demand well into the future. World concrete production is estimated at about 6 billion cubic meters per year, with China currently consuming around 40 percent of the world's production of concrete. Superior concrete characteristics such as strength and toughness, the ability to put concrete in many ways and its low price have made concrete known to be the most popular and important material in the construction industry. Concrete is generally preferred due to its compressive strength. Throughout the last years, many researches are held in the field of concrete industry. The first commercial implementations began around 1930s in order to enhance concrete compressive strength. According the research (A.Spasojevic, 2008) conducted in Lausanne, Switzerland, the distribution of progress among the years can be clearly seen in the following graph, figure 15.

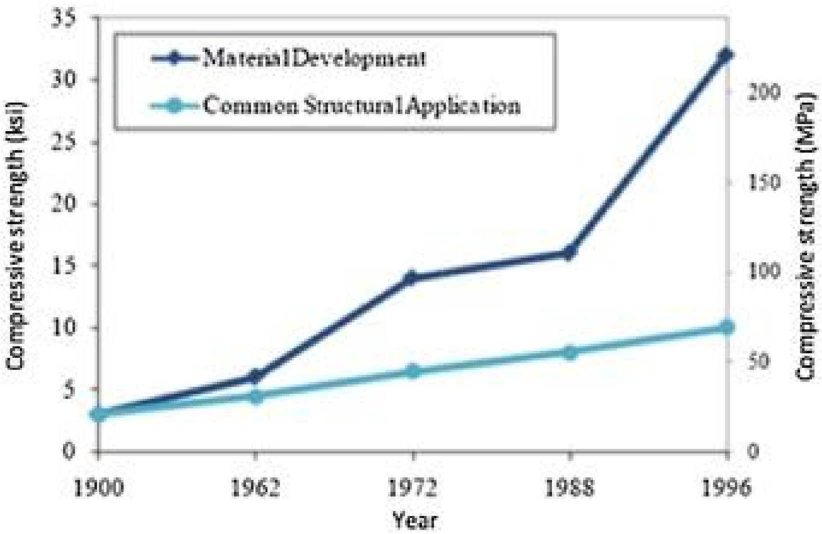


Figure 15 Development of concrete compressive strength for over 100 years

Based on the graph, it can be clearly seen that in 1960s there is a slight increase in the progress of concrete technology with the maximum compressive strength of 15 MPa to 20 MPa. After a decade, the concrete compressive strength is increased up to45 MPa to 60 MPa. Moreover, due to the existing of water reducer compressive strength of concrete reaches to steady increase at about 60 MPa in the beginning of 1970s. During the period of 1980s, the use of superplasticizers, which are known as high range of water reducers, were used to reduce water to binder ratio (w/b) down to 0.30. According to the research (H.H. Bache, 1981), it was reported that, with high content of superplasticizers (SP) and silica fume (SF) , it was achievable to reduce the water to binder ratio (w/b) to 0.16. By optimizing the grain size distribution of the granular skeleton, concrete compressive strength of up to 280 MPa has been achieved by compacted granular materials. This led to the development of a material with a minimal number of defects to achieve ultimate strength and durability improvement, such as micro cracks and interconnected pore spaces. Together with some fundamental knowledge about low-porous materials, these technical breakthroughs have led to the development of ultra-high-performance Portland cement-based materials with remarkable mechanical properties. In general, UHPC's innovations are best represented in four phases prior to the 1980s, 1980s, 1990s, and 2000.

Due to the limited technology, up to 1980s the development of UHPC is restricted only in the laboratory and special methods such as vacuum mixing and heat curing are needed. During this period, researchers have tried various types of methods to achieve denser and more compact concrete in order to maximize its efficiency. It was estimated that the compressive strength of concrete could reach up to 510 MPa with vacuum mixing along with temperature curing. While it is possible to achieve a high compressive strength of concrete, the preparation was very difficult and energy consuming.

The Micro Defect Free Cement (MDF) was invented in the beginning of 1980s. The MDF solution utilizes polymers to fill the pores and eliminate all the cement paste defects. Specific production conditions, including the laminating of the material by passing it through rollers, are necessary for this process. The compressive strength of MDF concrete can be 200 MPa. However, its applications were limited by costly raw material, complicated preparation phase, broad creep, and brittleness. Dense silica particle cement (DSP) was prepared in Denmark by Bache after the invention of MDF. Unlike MDF, DSP preparation does not require harsh conditions for manufacturing. The defects in DSP were removed by improving the particle packing density. The most significant quantities silica fume and superplasticizers are included in DSP concrete, and heat and pressure curing is also used. The overall DSP compressive strength can be as high as 345 MPa. Despite the increase of ultra-high strength, however, these materials are becoming more 'brittle'. In the 1980s, steel fibers were introduced to improve the DSP concrete brittleness problem. Hence, this type of steel fibers can be regarded as a new material. An extremely dense micro structure, very high strength, superior durability and high ductility will characterize it. CRC and slurry infiltrated fiber concrete (SIFCON), which occurred right after DSP, are two good examples. CRC and SIFCON both demonstrate exceptional mechanical properties and durability. However, due to the lack of superplasticizers, both SIFCON and CRC have workability problems that delay in-situ applications.

In the 1990s, components with improved fineness and reactivity were used by Richard et al. to develop RPC by thermal treatment. The RPC is a major milestone in UHPC's development. The notion was based on the placement in a very dense arrangement of various particles. RPC is generally known as the most widely used type of UHPC in laboratory and field experiments. Moreover, RPC is characterized by increased binder content, very high cement content, very low W/C, silica fume (SF) use, fine quartz powder, quartz sand, SP and steel fibers that are generally 12.5 mm in length and 180 mm in diameter. For homogeneity enhancement of the matrix, the coarse aggregates are eliminated. The RPC's compressive intensity varies from 200 MPa to 800 MPa. According to the table (Richard P. & Cheyrezy M., 1995), the mechanical properties and the composition of RPC is highlighted as follows. Comparing to its predecessors, RPC demonstrates a very good workability. This property of workability is an advantage and the most essential requirement for cement-based materials in large-scale applications.

Table 1 Typical composition and mechanical properties of UHPC

Constituent (kg/m^3)	RPC 200	RPC 800
Portland cement	955	1000
Fine sand (150–600 μm)	1051	500
Ground quartz (d_{50} = 10 μm)	–	390
Silica fume	239	230
Superplastisizer (Polyacrylate)	15	19
Steel fibers	168	630
Total water	162	190
Compacting pressure	–	50 MPa
Heat treatment	20 °C/90 °C	250 °C – 400 °C
Compressive strength (MPa)	170 – 230	490 – 680
Flexural strength (MPa)	25 - 60	45 - 102

In 1980, centered on the production of so-called D.SP. mortars in Denmark (Buitelaar 2004). It was mainly used in the protection industry for special applications, such as vaults, strong rooms and defensive security constructions. The primary research studies and developments about the application of UHPC in constructions, launched around 1985. Afterwards, various technological solutions have been developed, one after the other or in parallel. The solutions are mainly focusing on heavily reinforced UHPC prefabricated elements for bridge decks, in situ rehabilitation applications for deteriorated concrete bridges and industrial floors (Buitelaar 2004).

The first UHPC produced using RPC technology was introduced under the name Ductal in the late 1990s. In 1997, the first RPC structure, pedestrian bridge in the world was constructed in Sherbrooke, Canada as it is demonstrated in the figure below.

Figure 16 Sherbrooke pedestrian bridge in Canada

It was the first time that the entire system was designed using RPC. The implementations are still limited because of their costly material and manufacturing costs, despite the success of RPC structures.

Much progress has been made in the growth of the UHPC since 2000. With further advances in concrete technology, engineers realized that, in addition to high strength, the advanced concrete should also have other excellent characteristics leading to the words UHPC and UHPFRC. To cover an increased number of applications, a wide range of new concrete formulations have been produced. Sustainable UHPC formulations are currently being proposed by different researchers to reduce both their content and initial costs. Supplementary cement products, such as fly ash (FA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA) and SF, are utilized to replace cement pieces in an attempt to generate sustainable UHPC and to minimize the existing use of cement. In addition, it is also stated that UHPC can be prepared without losing its properties using normal temperature curing. Due to the advent of environmentally friendly, relatively low cost UHPC, UHPC applications are gaining interest. After the 2000s, several countries have engaged in various applications of UHPC. For instance, a lot of structures such as bridges, facades and slabs have been built with UHPC in France. The tollgate of the Millau Viaduct in France is a great illustration of design taking advantage of the unique benefits of UHPC. Moreover, another example can be in the modification of steel parts of the cooling tower at Cattenom in which UHPC was reinforced about 2.5 to 3 Volume-% of the steel fibers.

The UHPC application areas are increasing day by day and it’s also commonly used in maintenance and development of US highway infrastructures. In Australia, great amount of UHPC construction activities for bridge construction have been carried out. UHPC is also used in-situ reinforcement of structures in Switzerland. There many examples of UHPC bridges have been built in Netherlands and Spain. Malaysia is another country in which UHPC has been used in bridge construction in order to obtain sustainability. Since 2010, 113 UHPC bridges have been constructed in Malaysia, one of the UHPC bridges, located in Perak, pointed out below.

Figure 17 Completed UHPC bridge in Malaysia

2.3.1 UHPC production principles

Over the past two decades, plenty of researches have been developed about enhancing UHPC and extending its application areas. According to the studies, it is demonstrated that the compressive strength of designed UHPC could reach up to 200 MPa. The basic concept of manufacturing concrete had already been put forward in the 1980s with a very high strength and a dense microstructure. The functional breakthrough, however, came after the production of efficient SP, which allowed easy-flowing concrete with a high percentage of optimally packed ultrafine particles to be generated to minimize the composite porosity using extremely low W/B.

Many researchers (Richard P., Cheyrezy M.,Schmidt M., Fehling E., Spasojevic A., Kim D. J., Rossi P. & Schneider H.) have analyzed the basic concept of designing UHPC. The following principles came up:

1. By optimizing the granular mixture through a wide distribution of powder size groups and reducing the W/B, decreasing composite porosity.
2. Enhancement of the microstructure with post-set heat treatment to accelerate the pozzolanic silica fume reaction and increase the mechanical properties of the microstructure.

3. Enhancement of homogeneity by removing coarse aggregates, leading to a reduction in the mechanical effects of heterogeneity.
4. Increase in ductile behavior by adding a proper fraction of small steel fibers to the volume.

The implementation of these principles leads to a very high compressive strength concrete and the addition of steel fibers helps to strengthen the concrete's tensile strength and ductility.

2.3.2 UHPC mixture compositions

Enhancing the micro and macro properties of its mixture ingredients is the main factor in manufacturing UHPC to ensure mechanical homogeneity, maximum particle packing density and minimum flaw size. The choice of UHPC compositions does not depend mainly on the relative proportions of different grain sizes, but rather on the appropriate variety of physical and chemical properties of the materials. Based on available UHPC mixtures existing at the market, demonstrated at the table 2 below, it can be said that high volume of cement content, silica fume and sand are normally used in UHPC. UHPC's initial cost significantly exceeds traditional concrete (CC), and great strides have been made to minimize the cost of material without losing UHPC's beneficial properties.

Table 2 Compositions of commercial UHPC

Materials (kg/m^3)	BCV®	BSI®	Cemtec®	Ductal®	DURA®
Portland cement	2115	1114	1050	712	911
Fine sand	(Premix)	1072	514	1020	911
SF		169	268	231	225
Ground quartz		-	-	211	-
Accelerator	-	-	-	30	-
Steel fibers	156	234	858	156	173
SP	21.5	40	44	30.7	38
Water	159	211	180	109	200

2.3.4 UHPC mixture design

Mixture design is a range of raw materials in optimal proportions to provide concrete for specific applications with the properties needed in a fresh and hardened state. The core purpose of design of UHPC is to obtain a densely compacted cementitious composites with good workability and strength. However, due to its greater number of potential constituent combinations, complex content is expected in the hardened state of UHPC. In recent years, numerous studies have been performed to maximize the proportion of UHPCC mixtures.

There are many models about the mixture design of UHPC have been represented. The linear packing density model proposed by Larrad and Sedran (LPDM) can be a good example. However, this model has limited capacity in solving the relationship between materials proportions and packing density due to its linear nature. Afterwards, this model was improved by taking virtual density theory known as solid suspension model (SSM) into consideration. This latest model allows the manufacture of a 0.14 W/B fluid mortar with a compressive strength of 236 MPa with a curing time of 4 days at 90○C. Once again, on the basis of the compaction index principle and virtual packing density, further improvements have done to the latter model (Larrad D.,2002). This packaging model called as Compressible Packing Model (CPM) was suggested in the design of UHPC. Later on, two UHPC products, named as RPC 200 and RPC 800 have been developed by the two researchers (Richard P. & Cheyrezy M., 1995) with the aim of optimizing the granular mixture using CPM.

During the period of time some other studies (Geisenhansluke C. & Schmidt M., 2004) are done in terms of particle shape, size, and density. The study claims that the cement content can be reduced by using multi-grained fine particles. The other research (Fennis J.C.,2009) stated on an ecological UHPC mixture that based on particle packing technology. It is reported that there is a decrease in cement content by more than 50 percent with the adopted approach. Furthermore, a robust UHPC mixture based on superplasticizer water demand (SWD) approach was proposed by the researchers

(Lohaus L. & Ramge P.,2008) in order to achieve a good workability depending on the water to powder ratio.

UHPC with a compressive strength of 180 MPa is developed by taking the effect of w/b, type, and replacement proportion of filler into account (Park J.,2008).On the other hand, UHPC with an exceeding compressive strength of 200 MPa was introduced by a researcher (Wille K.,2011), obtained through local materials without any special type of mixer and heat treatment. Both of the design method was based on the spread flow properties obtained from slump test. The variation in spread outcomes of UHPC mixtures was found to cause the variation in air quality. A statistical relationship was suggested by considering the combined effect of air voids and W/C in order to estimate the compressive intensity of UHPC.

The study (Gong J.Q.,2007) which was focusing on the dense packing effect of the gradation of mineral powders has done by considering Compressible Packing Model (CPM). The study claimed that the effect became more evident with the decrease of w/c. Using the updated Andreasen & Andersen particle packing model pointed out in the following equation, Yu et al. created an eco-friendly UHPC to achieve a densely compacted cement matrix produced with a relatively low binder dose of about 650 kg/m3.

$$P(D) = \frac{D^q - {D_{min}}^q}{{D_{max}}^q - {D_{min}}^q} \qquad (1)$$

Where,

$P(D)$= the weight percentage of sand passing the sieve with size D

D_{max}= the maximum particle size (µm)

D_{min} = the minimum particle size (µm)

q= the distribution modulus that is related to the sand particle size (for fine particles set as 0.23 q < 0.25)

In addition to empirical approaches, methods of statistical experimental design based on artificial neural networks (ANN) are used to improve all UHPC products and processes. In various studies on concrete actions, these techniques have already been implemented to refine the UHPC mixture to achieve the desired efficiency. Taghados et al. suggested the use of an adaptive neuro-fuzzy inference method (ANFIS) based on the mix architecture and curing conditions to predict the compressive intensity of UHPC. In addition to the dosage of cement, significant issues are the cost and availability of steel fibers adopted in the UHPC mixture. On the other hand, another researcher (Ghafari E., 2014) proposed many ANN models to estimate the performance of UHPC under various curing conditions. The difference in ANN model comparing to SMD model, is that by applying ANN model the compressive strength and the slump flow with higher accuracy can be predicted, because of its nonlinear nature. On the basis of this model study, the optimum quantity of cement and silica fume was found to be 24% and 9% respectively by concrete volume.

The results in concrete technology over the past 25 years have enabled the development of UHPC with outstanding rheological behavior, including workability, self-placing and self-densifying properties, improved mechanical and durability efficiency with very high compressive strength and non-brittleness behavior. UHPC's production typically begins with the design of the granular structure of the aggregates, which is of crucial importance in selecting and characterizing sufficient fines for optimum packing density. The UHPC design intends to ensure a densely compacted cement composite with reasonable workability and strength. In general, well-chosen raw materials and sophisticated technical procedures are usually needed to achieve the desired properties of a UHPC. Nowadays, in most of the articles about the mixture design of UHPC are based on the reference mixture proposed by the researchers (Richard P. & Cheyrezy M.,1995). A high binder quantity and superplasticizer dosage are generally utilized while working with UHPC as opposed to regular normal type of concrete (CC). UHPC can be manufactured in order to provide high flow ability with enhanced mechanical properties and durability with the required combination of cement materials, sufficient sand gradation, and incorporation of fiber reinforcement and superplasticizers. However, for these excellent mechanical properties expensive technological preparations are needed. Due to the high material cost and tough assembly technique, its application in modern construction industry is limited among the countries.

The high material cost, complex fabrication technique together with the limited available resources severely limits its commercial development and application in modern construction industry, especially in the developing countries. The production of cost-effective UHPC using alternative materials with similar functions to replace costly UHPC composites is further inspired by these constraints in order to increase its acceptance level.

2.3.5 UHPC standards

Two French national UHPC standards known as NF P18-470 and NF P18-710 were released for UHPC in mid-2016 to replace the technical guidelines and professional guidance commonly used in the design of UHPC. Several recommendations and guidelines for the design and development of UHPC were referred to before these standards were established.

Some of the guidelines are demonstrated below:

1. French Interim Recommendations
2. German Recommendations
3. Japanese Recommendations

Although these technical guidelines were well prepared, they have been found inadequate. Due to being classified as an “unofficial” status, it caused problems in terms of referencing and using in the real projects. The availability of new standards allows for transparent and codified requirements, which have led to more international adoption of the UHPC. UHPC's process of standardization in France was initiated in December 2012. These standards were scientifically established on the basis of the earlier guidelines of the French AFGC and technical input from more than 15 years of UHPC projects and achievements. These specifications served as provisions for the adequate procurement of materials, the development and adjustment of the mixture design, and the regulation of production processes. Compliance with these documents will help to achieve UHPC consistency and encourage wider acceptability. Other countries such as Switzerland, China, Canada, and Japan can also see similar standardization efforts.

UHPC refers, as indicated in NF P18-470, to a substance containing metallic fibers with a cement matrix and a characteristic compressive strength of about 150 MPa to achieve ductile behavior under stress. UHPC mixes usually have a low W/B due to the use of admixtures such as superplasticizers. Particular attention should be paid to regulating the quantity of water applied to the concrete by the various mixing components of water, aggregate water and mixtures.

Table 3 UHPC materials requirement for NF P18-470

Properties	Recommended value
Maximum aggregate size	$\leq$10 mm
Concrete density	2200–2800 kg/m^3
Tensile strength at 28 days	$\geq$6 MPa
Water porosity at 90 days	$\leq$9 %
Diffusion coefficient of chloride ions at 90 days	$\leq 0.5 \times 10^{-12}\ m^2/s$
Apparent gas permeability at 90 days	$\leq 9.0 \times 10^{-19}\ m^2$

According to the table 3 exhibited above, each and every UHPC materials should have to satisfy the requirements, highlighted in NF P18-470. The following procedure as set out in NF P18-470 should be followed by the UHPC mix design:

1. Establishing the nominal configuration of the mix.
2. Confirming the configuration of the mix through suitability tests.
3. Following the manufacturing process by applying routine controls.

The nominal configuration of mix design contains:

- Definition and weight of the aggregates (dry ingredients), cement, mixtures and additions of each type used in the UHPC.
- Complete added water, including in the form of ice, pre-existing water on the aggregate surface, water in the mixture, water in the form of additives and additives.

2.3.6 UHPC applications

Due to reasonable performance of UHPC, new application areas such as in infrastructure works and building constructions are being appeared. The UHPC global market size was estimated at USD$ 892 million in 2016, according to market research published by Grand View Research (GVR), and this number is projected to rise by 8.6 percent to USD$ 1867.3 million in 2025 . With its ads available in several countries, such as Australia and New Zealand, Austria, Canada, USA, Germany, France, Italy, Japan, Malaysia, Netherlands, Slovenia and South Korea UHPC has become a worldwide focus. Academics and engineers around the world have undertaken comprehensive research projects over the last two decades to industrialize UHPC technology as the future sustainable building material. In one or more of its elements, a complete search of the literature has found more than 200 completed bridges built using UHPC. In structures, structural reinforcement, retrofitting, precast components and some special applications, some UHPC applications can also be used. At present, both private and governmental bodies are directing their focus and initiative towards the use of UHPC as the potential material for sustainable construction.

2.3.6.1 Infrastructures

The first research and development aimed at applying UHPC to buildings began around 1985. Since then, numerous technological solutions and UHPC formulations have been made available to satisfy the unique requirements of individual projects, buildings, and approaches to architecture. There are many crucial breakthroughs in UHPC application, including the very first pre-stressed hybrid pedestrian bridge over the Magog River in Sherbrooke, Canada, constructed in 1997. The other significant examples could be the installation of corroded steel beams in the rough environment of the French nuclear cooling towers of Cattenom and Civaux and Bourg-les-Valence bridge which is made for cars and trucks, constructed in France, 2001. For several traditional bridge parts, the advanced mechanical properties and durability of UHPC make it possible to revise the conventional methods of design. Many studies have been carried out on optimal UHPC component designs, resulting in the production and construction of UHPC bridges around the world. The Seonyu footbridge in South Korea was built with a main span of 120 m using UHPC in 2002 and was completed in 2004. Seonyu footbridge structure is the world's longest span bridge, designed by using UHPC. The construction of this footbridge needed just about half of the amount of material that would have been used in conventional concrete construction and yet offers comparable strength characteristics. The 50-m-span Sakata-Mirai footbridge was completed in Japan in 2003. The bridge pointed out how a perforated web can both minimize the weight of the structure in a UHPC superstructure and can be aesthetically appealing at the same time. UHPC bridges for pedestrian traffic have been designed in Europe, North America (US and Canada), Asia and Australia following the success of these constructions.

Figure 18 Seonyu footbridge in Seoul, South Korea

The four road bridges such as The Shepherd's Gully bridge, Bourd-les-Valence bridge, Horikoshi C-ramp and Mars Hill Bridge are also known as first bridges constructed by using UHPC technology during the same period of time , located in Australia, France, Japan and US respectively.

A 40 m long UHPC monorail girder was built by Tokyo Monorail and Taisei Corporation in 2007. In 2008, Tokyo International Airport installed the first segmental UHPC composite deck road bridge in the world, making it the world's largest UHPC road bridge.

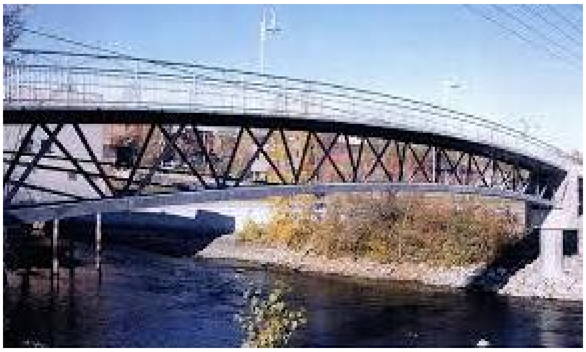


Figure 19 Sherbrooke, pedestrian bridge and Bourd-les-Valence road bridge

Figure 20 Mars Hill Bridge road bridge

A total of 55 bridges using UHPC have been constructed or are under construction in the US and Canada, according to the United States Federal Highway Administration (FHWA) study published in 2013. Across Asia and Australia, there are about 22 UHPC bridges in Europe and 27 UHPC bridges. UHPC may be used as beams, girders, deck panels, protective layers, field-cast joints between various components and so on in these applications. Most bridges designed with UHPC components or joints have a slender look compared to conventional reinforced concrete bridges, with a substantial reduction in volume and self-weight, simpler implementation, and improved longevity.

Most UHPC structures just need half of the conventional reinforced or pre-stressed concrete members' section depth, which decreases their weight by up to 70%. This lighter weight construction used in UHPC structures leads to a sustainable structure due to its low carbon content.

For the Monaco underground train station, UHPC was used to manufacture acoustic panels. To help with their acoustic properties, the thin and light UHPC panels were cast with tiny holes. The non-flammable panels are resistant to impact and create an atmosphere for passengers that is visually appealing and bright. Due to their resistance to vehicle emissions and deicing salts, acoustic panels have also been used along a highway in Châtellerault, France. In the security infrastructure used as barrier defense systems or as intrinsic portions of the critical infrastructure, other potential of UHPC applications are. The mechanical properties of UHPC subject to high strain loading rates, blast resistance and penetration resistance have been extensively researched in safety applications.

2.3.6.2 Buildings

UHPC has also gained interest in the area of construction components particularly in the areas of sunshades, cladding, and roof components during the last years. Due to its ability to produce slim, light, robust, and aesthetic structures, UHPC was selected.

The Foundation called as Louis Vuitton pour la Creation located in Paris is among the newest buildings adopting UHPC technology, as it is demonstrated in Table4. This project, finished in 2014, is distinguished by its high geometric complexity. The cladding is made from prefabricated UHPC panels, each of which is built by molds for vacuum filling. The Museum of European and Mediterranean Civilizations (MUCEM), as shown in Table 4, in the port area of Marseille in France, is another great example. It is the first building to make such extensive use of UHPC in the world. The Shawnessy station is a C Train light rail transit station (LRT) and it locates in Calgary, Canada. The design of this structure was made by using ultra-high performance, fiber reinforced material, which provides a combination of superior technological characteristics, including ductility, strength and toughness, and also a quality surface for highly moldable goods. The other structure which is also constructed by the use of UHPC panels is Jean Boun Stadium located in Paris, France. This panels lead to construct a thin, lightweight envelope and waterproof roof Table 4.

Table 4 Newest structures adopting UHPC technology

Location	Application	Year	Advantages	Image
Louis Vuitton Foundation, France	Cladding UHPC panels	2014	Innovative design	
MUCEM, Marseille France	Column & Façade	2013	Y-shaped column ‘Transparent’ façade Unique design	
Shawnessy LRT Station, Canada	Roof	2004	Light weight Easy construction Little maintenance	
Olympic Museum, Lausanne	Renovation Roof	2013	Trapezoidal concrete ribs Glass façade	
Qatar National Museum, Doha	Cladding UHPC panels	2019	Waterproofing line Thermal insulation layer	
Pulaski Skway Bridge, New Jersey	Bridge	2014-18	Precast bridge decks Field cast	

The Qatar National Museum's shape is also constructed by using precast UHPFRC cladding panels. These panels allows a reduction in the thickness of the cladding without using passive reinforcement.

2.3.6.3 Non-structural products

UHPC has been commonly used as an overlay to rebuild existing concrete structures due to its excellent properties, enhancing its mechanical and reliability characteristics for lower maintenance work. The first UHPC overlay application was recorded on a bridge in Switzerland over the La Morge River. UHPC was used to repair the heavily damaged bridge deck and curbs. After 1 year of its application, no cracks on the prefabricated UHPC curb were found. The performance of these materials has paved the way for similar technologies to be used on damaged bridges in repair and restoration applications. At the Hosokawa River Tunnel in Japan, Caderousse, and Beaucaire Dams in France, the hydraulic systems were restored and rehabilitated using UHPC.

Due to its excellent properties of high flexural strength and dense microstructure, UHPC has the ability to be used for particular conditions. UHPC has been stated to have been used for the cover plates along China's high-speed railway and for the retrofitting of nuclear reactor containment walls in France. Moreover, due to its great resistance to aggressive agents, UHPC usage has also been seen in marine areas. Several windmills in the sea have been successfully designed and rejuvenation of maritime signalization structures with UHPC also has been proved. In Japan, Haneda Airport was expanded by the use of an enormous UHPC slab built over the sea. Up until today, this project is recorded as the largest UHPC project.

UHPC's outstanding performance is responsible for its large potential in various applications, but many have yet to be discovered to use its enhanced strength, durability, and flexural capacity. In areas where conventional or normal type of concrete (CC) fails, UHPC offers an economical and creative solutions. UHPC is known as the future building material, which will remain developing across the globe.

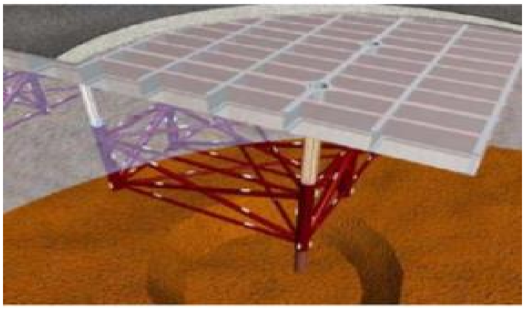



Figure 21 Haneda Airport Runway and pier section

2.3.7 Further potential applications

The main threat to reinforced concrete structures in marine areas has always been chloride-induced corrosion. UHPC's high toughness and chloride resistance makes it an ideal material for use in outdoor conditions or in severely exposed environments. One of the strategies for preventing corrosion of the reinforcement is the use of UHPC in marine structures due to its excellent toughness, which allows great resistance to chloride. The sufficient results are obtained after the application of UHPC in marine structures. According to the results of cross-sea bridges constructed by UHPC demonstrate much lower weight and maintenance and better durability. UHPC also has the potential to build, overlay, repair and reinforce marine structures, such as piers and oil rigs. In addition to chlorides, UHPC also has excellent resistance to most chemical and physical attacks. This offers the possibility of applying UHPC under more severe environmental conditions.

UHPC's ductile behavior enables it to be used in seismic regions for buildings and structures. It was noted that during the earthquakes, the reinforced UHPC columns or beams were able to dissipate greater energy compared to normal reinforced concrete, preventing it from collapsing. Several attempts have been made to reduce the high cost of UHPC by incorporating the use of a hybrid element that combines UHPC with conventional concrete (CC) or other materials in seismic load resistance structures. The two H-shaped precast concrete piles were successfully pushed into clay soils and tested under both vertical and lateral loads. In addition to that the high impact resistance the high impact resistance of UHPC was also studied and the ability of it to be used in piles was investigated.

Due to the outstanding workability, UHPC can be casted in any shapes. Thus, UHPC blocks with different shapes can be assembled easily into a structure. In this way, installation time and labor cost can be reduced. In the basis of this notion, Japan has launched basic studies in terms of modifying the construction industry.

2.3.8 Challenges

UHPC has been used in several countries in the last two decades for both structural and non-structural precast parts. However, owing to its high initial costs and the absence of design standards, this excellent technology has failed to become a popular technology for daily use. In addition, the high cost of UHPC materials and high- energy consumption make it difficult to compete with CC designs, thus limiting its use. Many researches were aiming to reduce the cost and enhance the sustainability of UHPC. In an attempt to minimize the amount of Portland cement, steel fiber and superplasticizer, numerous experiments have been undertaken to change the material mixtures through the use of local raw materials and waste products. Needless to say, UHPC will be accepted and used by the infrastructure market with reduced cost.

The life cycle cost of UHPC structures is another problem concerning the cost. One of UHPC's key benefits is its outstanding durability. Compared to conventional concrete (CC) or (HPC) structures, structures built with UHPC would have a much longer service life with lower maintenance and repair costs in the future. In the past few years, empirical skills and expertise on the design and construction of UHPC systems have been acquired with the UHPC applications. In the past few years, empirical skills and expertise on the design and construction of UHPC systems have been acquired with the UHPC applications. To promote their applications, the distribution of this knowledge is extremely necessary.

It is crucial to establish guidelines for the design and construction of UHPC structures on the basis of past experience and field study, experimental testing, and scientific computation. Due to a significant range of UHPC expertise in various countries, foreign recommendations are difficult to make. Countries such as France, Japan, China, Germany, and Switzerland have made standardization efforts due to the increasing interest and applications for UHPC. France released the first national UHPC standard in the middle of 2016.

For the UHPC systems, the design and construction methods vary from the standard requirements for conventional reinforced concrete. To date, the number of qualified UHPC design and construction architects, engineers, and experts is still low. Since broad application prospects for UHPC can be seen, skilled teams familiar with UHPC technology and specific design problems are required. Recently, there are only five players operating in the global UHPC industry, with which the goods primarily sold in Europe and North America. For instance, since 2006, there is only one locally mixed UHPC that UHPC has been marketed with a name called Dura 1 İn Malaysia. While this product has been successfully used in the construction of local bridges, more studies are needed to refine material in the production of local UHPC blends in order to further enhance its properties and reduce its cost and minimize the effect on the environment. The UHPC research pattern is now connected to nanotechnology. Using nano-particles such as nano-silica and nano-fibers, experimental explorations have been carried out to alter its properties. In addition, some researchers have attempted to study at nano-scale level the structure of hydration products in UHPC. Nanotechnology may be a solution to UHPC's disadvantages, such as the issue of shrinkage, and thus could increase UHPC's overall efficiency.

In general, it can be said that UHPC is a unique and popular material with extraordinary properties with high strengths and great durability obtained by the advancements in homogeneity and packing density. A significant accumulation of information on the material, design, and construction of UHPC structures has been acquired since its introduction in the early 1990s with different countries seeking to apply it to building and bridge applications. In France, Japan, Germany, and Switzerland, technical guidelines have been released. In 2016, two French national UHPC standards were released to replace the technical guidance and professional advice commonly referred to in UHPC design. These new requirements provide consistent specifications, which are expected to lead to more international adoption of the UHPC. Proven advantages of UHPC technology focused on sustainability and service life have been seen in several implementations in Europe, North America and Asia. More than 90 bridges were designed over 10 years of UHPC construction in Malaysia, with another 20 at different tender, design and construction stages.

It is easy to see effective successes in the implementation of UHPC can be seen worldwide. However, UHPC is still facing with some problems in terms of the restriction in its application. Along with the limited resources available, high initial costs, limited codes, design difficulties and complex manufacturing techniques have severely hindered its commercial growth and application in the modern construction industry, especially in developing countries. Local recommendations and design requirements should be set because of the material sensitivity of UHPC. For greater UHPC acceptance, further studies on the production of sustainable and cost-effective UHPC using alternative materials with similar functions to replace UHPC's costly composites and minimize the environmental impact are needed.

In general, UHPC contains discontinuous, dispersed fiber reinforcement. This fiber reinforcement is included with the other constituents during the period of initial mixing and after concrete placement and curing, provides for enhanced tensile mechanical behaviors. Additionally, structural applications of UHPC frequently include short lengths of steel fiber reinforcement, which is included at moderately high percentages, such as 2 percent by volume.

In this thesis project, the post cracking tensile mechanical behaviors commonly associated with UHPC .

The DTT specimen developed can be used effectively to characterize the tensile behavior of ductile fiber-reinforced cementitious materials.

CHAPTER 3 - TESTS IN TENSION AND BENDING

This chapter mainly focuses on the test methods and provides background information about how it is used in conventionally in order to deal with the tensile mechanical properties of concrete such as FRC and UHPC.

As it is discussed before, UHPC is coming from a class which has advanced cementitious composite materials. These concretes with discontinuous pore structures and improved toughness properties can be categorized as high-strength, fiber-reinforced cement composites. These concretes appear to have unusually low water-to-cement ratios and optimized granular material gradation.

UHPC also requires discontinuous, distributed reinforcement, made of fiber. During initial mixing, this fiber reinforcement is included with the other constituents and allows for improved tensile mechanical behaviors, after concrete placement and curing. Structural applications of UHPC also require short steel fiber reinforcement lengths, which are used at relatively high percentages, such as 2% by volume.

The test on concrete's tensile mechanical properties depends on the tensile demand imposed on the concrete. In addition, the available test methods for the precise assessment of these tensile mechanical properties are limited. The implementation of suitable test methods was needed by the development of concretes with greater tensile strength and FRCs that demonstrate sustained post cracking tensile strength. However, basic evaluation of these properties has proved to be difficult, hindering the widespread implementation of this concrete class.

3.1 INDIRECT TEST METHODS

Conventional concrete does not lend itself to the application of DTT methods due to its comparatively limited tensile stress and strain capacities. As such, indirect methods to evaluate elastic tensile response have been established. The most well-known test methods are classified as three and four point bending tests and Brazilian test. The common purpose of these tests are to determine tensile strength and mechanical properties. These testing methods have been updated and expanded over the years to allow FRC and strain-hardening testing of cementitious composites (SHCCs).

Although, the determination of the uniaxial tensile stress-strain response of a concrete by applying these tests, is quite difficult, they are preferred due to their cost saving feature. Moreover, they are easy to perform and require less time comparing to the other tension test methods. The common concern about unnotched flexure-type indirect test methods is related to the strain gradient, which let for restraint of the most heavily loaded tensile face as well as the calculations and observations necessary for back calculating the uniaxial behavior. The other concern about flexure-type indirect test methods is that when they are adjusted in order to contain a notch that predisposes the failure location. In general, this test is applicable for softening materials and they are used in the assessment of the performance of extracted prisms for qualifying the orientation of fibers in the structure.

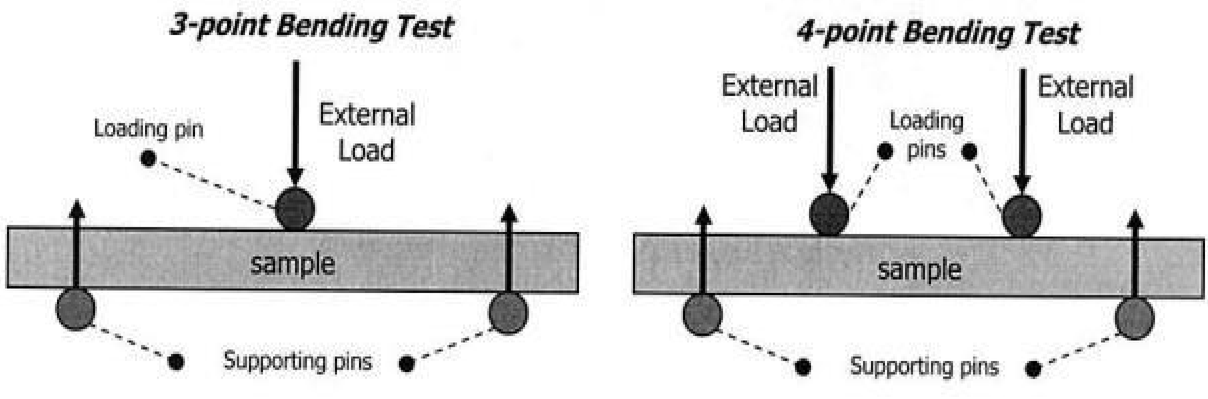


Figure 22 Scheme of three point four point bending tests

There was also some interest in indirect splitting-type tests to evaluate fiber reinforced concrete tensile behavior; however, these tests raise questions about the biaxial state of stress and the effect that this stress state has on the fiber reinforcement bridging a crack's bonding performance.

3.2 DIRECT TENSION TEST METHOD (DTT)

Direct Tension Test Method is a common and frequently applied method since 1928. A 152mm diameter conventional concrete cylinders were tested by the researchers (Gonnerman H.F. & Schuman E.C, 1928) by gripping the specimen ends with cylindrical steel straps friction clamped to the concrete circumference. The two paths have been followed during the development of direct tension test method for concrete. One of these path based on the use of adhesives in order to attach a tensile specimen's end surfaces to the texting fixture of the machine, after which a uniaxial tensile load is applied. The test methods including both standardized and nonstandardized test methods could be a great example.

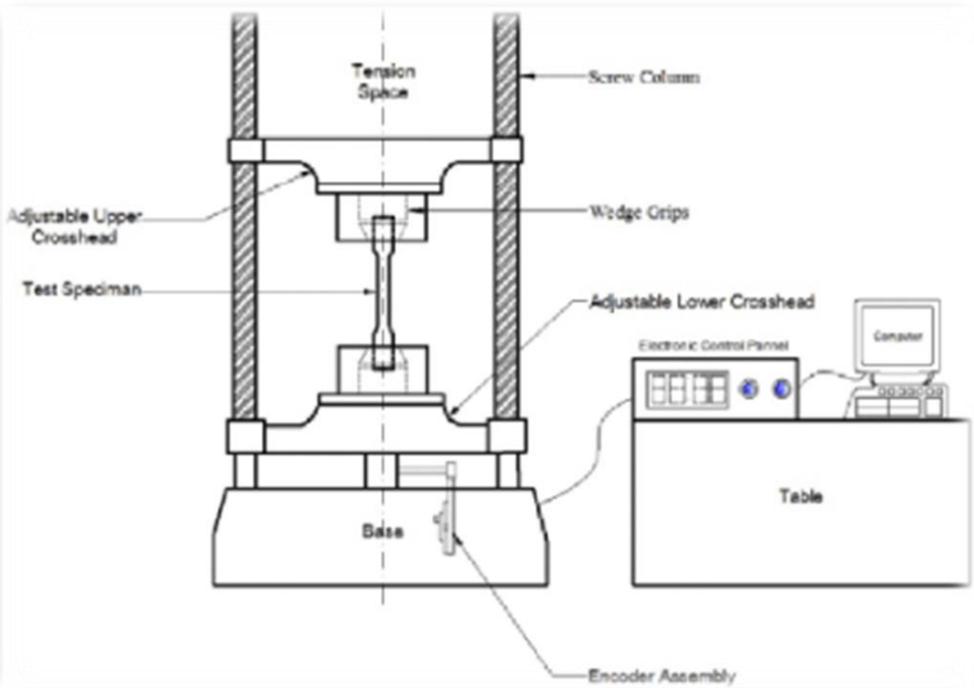


Figure 23 Direct tension test machine

In general, the bone shape concrete specimen is preferred in direct tension testing method. Herein, the shape of the bone shape is illustrated.

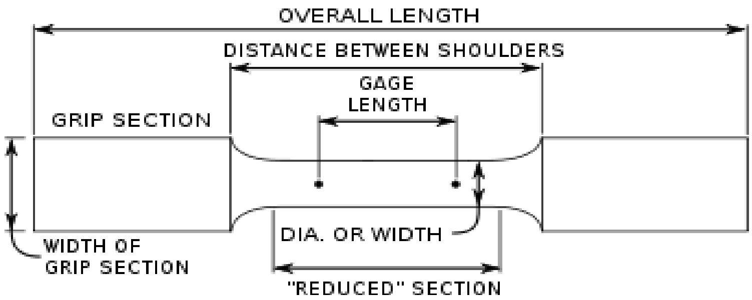


Figure 24 Test specimen nomenclature

A major advantage of this type of test is that the specimen can be loaded at uniaxial strain without significant bending stresses being applied. However, this test allows the specimen to be glued between the crossheads of the test system, thus it affects the duration in a great extent.

The other path related to the test methods regards the grip parallel sides at each end of the concrete specimen. Prior study in this route has aimed toward the use of specimens formed by custom manufactured dog bone. While tests involving custom manufacturing might have useful results, there are inherent limitations to this type of test because it is not commonly applicable to the types of extracted specimens that would accurately reflect the tensile properties. These test methods sometimes allow for relative rotation of the ends of a specimen. Hence, the initial bending is reduced while invalidating the post cracking response. Moreover, the others notch the specimen at the mid span, so the failure location is predetermined while revealing a high stress concentration.

The calculated tensile strength of concrete depends on the process used for testing. The direct tension test method provides results closer to the true tensile strength under pure tension conditions compared to indirect methods. Direct tension test method is a very useful method due to the obtained relevant results of the strength. However, it is tough to perform in terms of managing the specimen due to its dependence towards the specimen length, which can cause a size effect. This test method also has longer computation time.

3.3 CONCRETE CYLINDER COMPRESSION TEST METHOD

One of the most common tests carried out by engineers in structural design is the compressive strength of the concrete cylinder. The purpose of the test is to determine the behavior of the material when it is subjected to load. The maximum stress is evaluated under a load over a period of time. The compression test demonstrates that in perfect conditions, the best possible strength concrete can achieve. Compression test is frequently conducted for the aim of breaking or limiting.

The compression test are generally conducted to distinguish the compressive strength of a material and the ability of material in which to resist the failure in the form cracks and fissure. The push force applied to the both two faces of the concrete sample and the maximum compression that the concrete bears without failure are noted in this test.

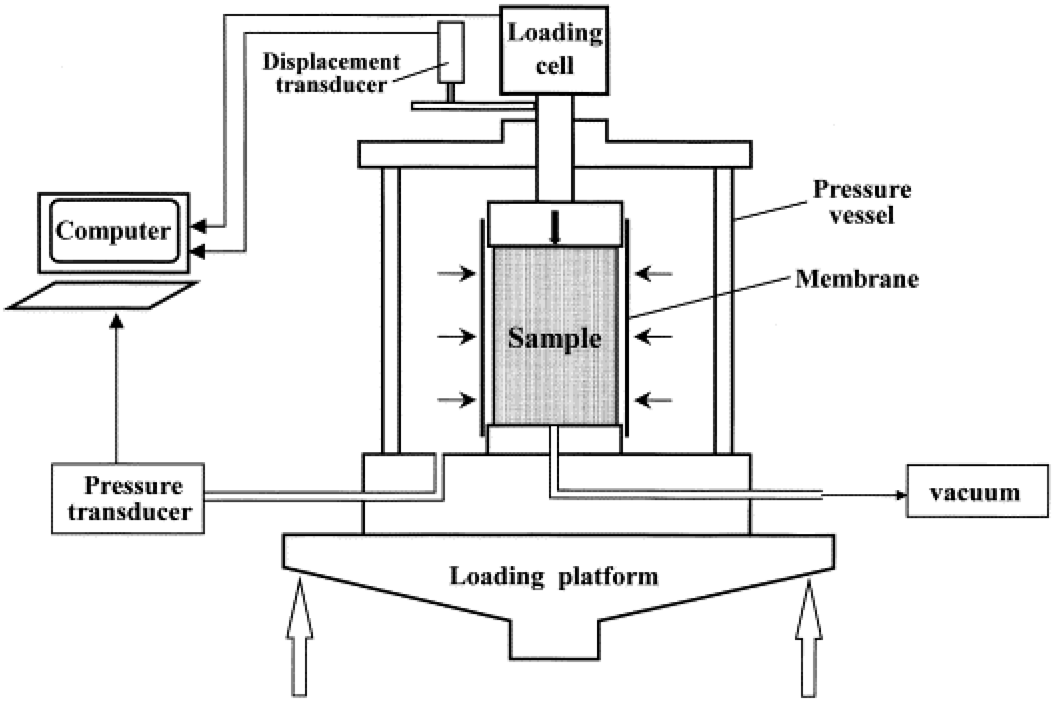


Figure 25 Compression test machine

There are plenty of factors that affects the compressive strength of the concrete such as quality of raw materials, temperature, humidity, curing of the concrete, the ratio of water to cement, the ratio of coarse to fine aggregate ratio and the age of concrete.

CHAPTER 4 - DESCRIPTION OF THE TESTS

4.1 DIRECT TENSION TEST

The test method is designed to establish an effective method of assessment for the tensile mechanical properties of strain hardening FRCs. The steps that are applied during the development of test are mentioned below:

Apparatus for Direct Tension Test:

a) The testing machine for the tensile test should ensure the controlled displacement control
b) The testing machine should allow the alignment among chucks, it is needed to be properly vertical
c) There should be a precise relation of 1/1000mm or higher among the apparatus computing the displacement among the reference points and should avoid any restrictions about deformation among the reference points.
d) The mechanism should be prepared by considering the shape and size of the specimens also the test load. It should let the tensile loading along the specimen's central axis. The specimen should be carefully inserted to the test machine.

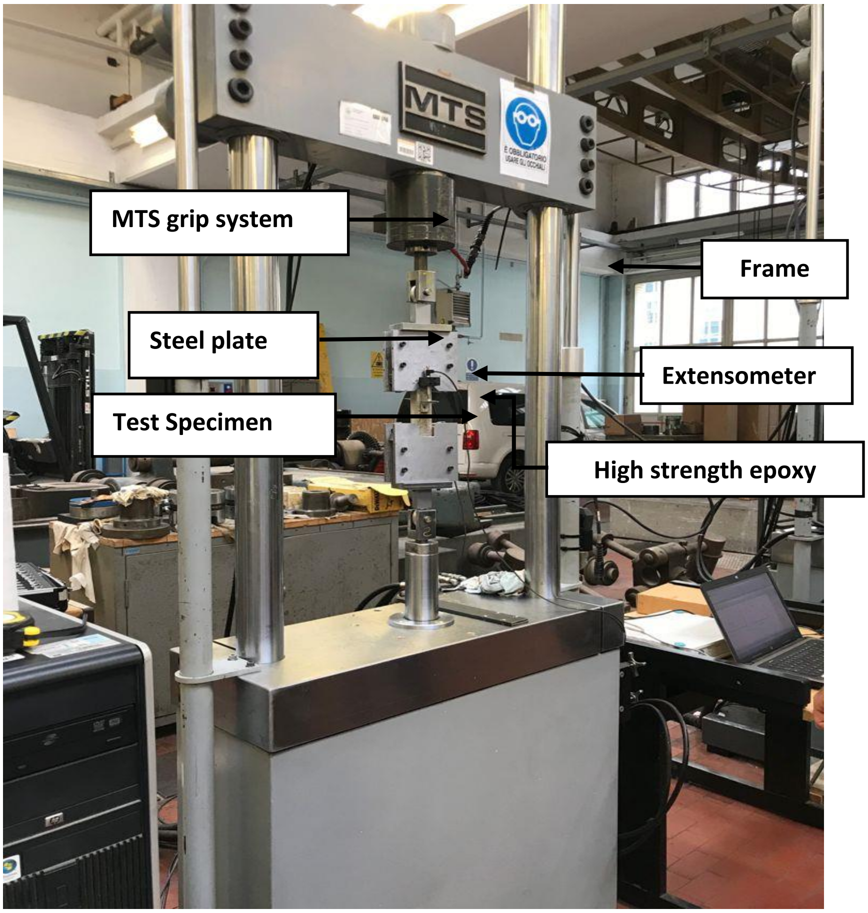


Figure 26 Direct tension test machine

Test method:

a) The load should be applied using a chuck mechanism, which fit to the shape of the specimen.

b) The load should be applied at constant specimen deformation rate of almost 0.5 mm per minute.

c) At least three specimens for each mix should be tested.

Based on the given data, regarding to the class of concrete and fiber content the following computations are held in Excel.

Table 5 Input data covering concrete class and fiber content

C90/105						Mix 8/Mix 15			
C70/85					Resilia HP	Mix 14			
C50/60	Mix 6	Mix 5	Mix 9	Mix 4	Mix 10	Mix 3	Mix 2	Mix 1	Mix 11
C40/50			Resilia			Mix 12			
C30/37						Mix 7/Mix 13			
	0.25%	0.50%	0.75%	1.00%	1.50%	2.00%	3.00%	4.00%	6.00%

The test is concluded under displacement control at rate of almost 0.5mm per minute. Initially, the compressive load at around 5 MPa is applied to the specimen and then tensile load is applied through tensile failure. The strain within the gage length is computed with the help of extensometers, placed parallel to the front and rear.

The correct assembly of extensometer provides a basic and reusable measurement system, and as well as at the same time, it captures the average response and a bending response might have applied to the specimen.

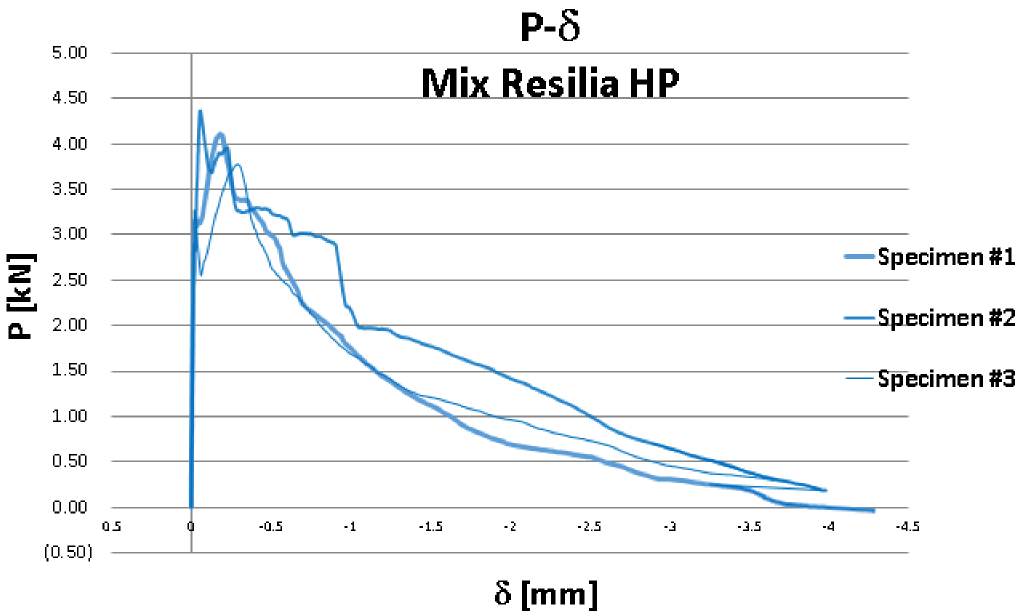


Figure 27 The load deflection curve of Resilia HP specimens obtained from Direct Tension Test

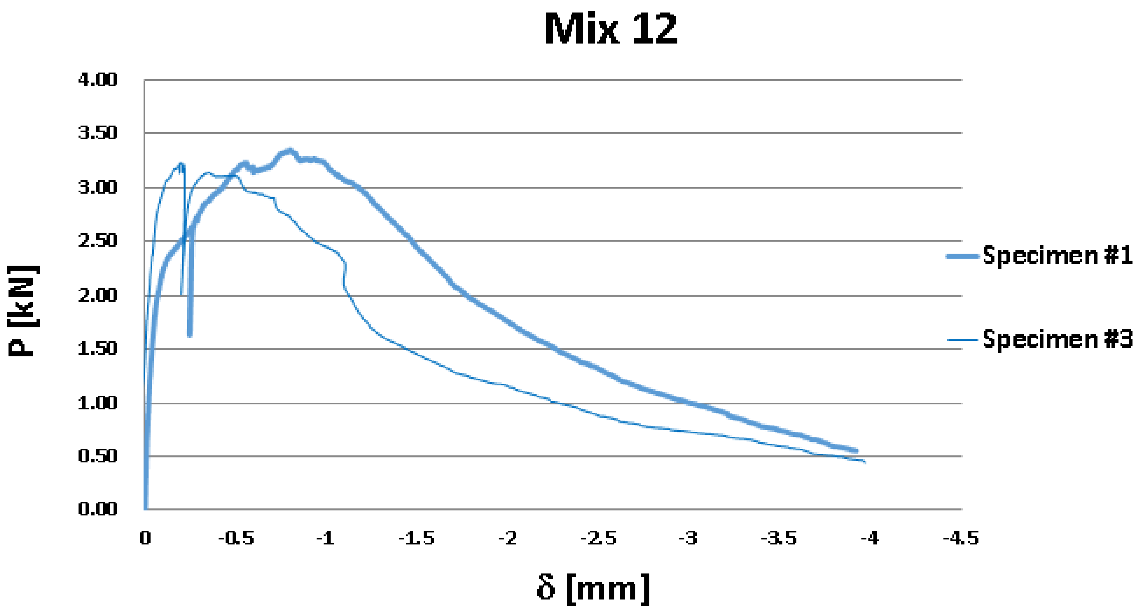


Figure 28 The load deflection curve of Mix 12 specimens obtained from Direct Tension Test

Based on the data, stress is computed by the load per unit area. The maximum stress that a specimen can stand before cracking is called breaking stress and ultimate tensile stress. Since, the specimen is under tension, the load acting on it is trying to stretch the specimen. According to Model Code 2010 and Euro code 2, stress and strain are computed in the following formula:

$$\sigma = \frac{F}{A} \qquad (2)$$

σ= Stress measured in MPa

F= Load in kN

A= cross sectional area in mm^2

The strain is calculated by the ratio between the extension over the original length.

$$\varepsilon = \frac{\delta}{L} \tag{3}$$

ε = Strain it has no units

δ = Length of stretch measured in mm

L = Original length measured in mm

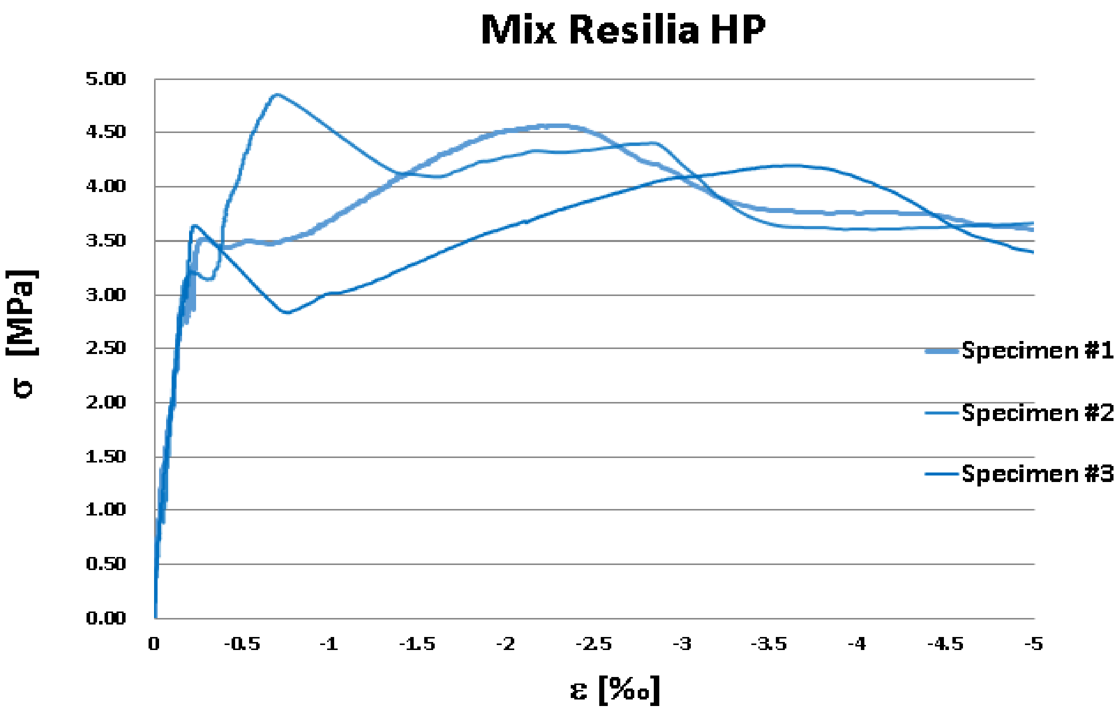


Figure 29 The stress-strain results of mix Resilia HP specimens obtained from Direct Tension Test

The sample results, obtained from the direct tension testing are pointed out in the figure 29 and figure 30. Three specimens of the same mixes tested with success being described as capturing the UHPC's complete tensile stress-strain response including strain localization within the instrumented gage length. The average of stresses obtained from these three responses at each strain increments, are computed in order to obtain the final average response of this set of specimens.

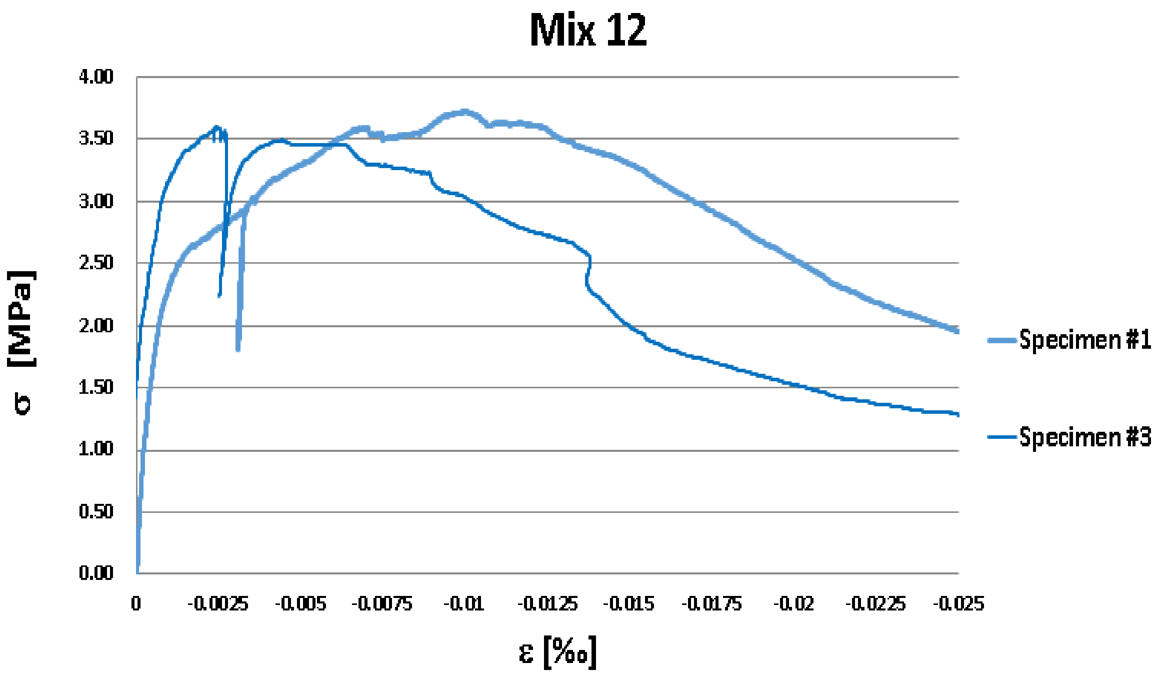


Figure 30 The stress-strain results of mix 12 specimens obtained from Direct Tension Test

The overall results, obtained during the direct tension test program developed herein demonstrate that the theoretical UHPC tensile mechanical response can be defined as pointed out in the figure 31. This general representation is mainly composed of four phases, which are can be classified as follows I: Elastic, II: Multi-Cracking, III: Crack Straining, and IV: Localized, respectively.

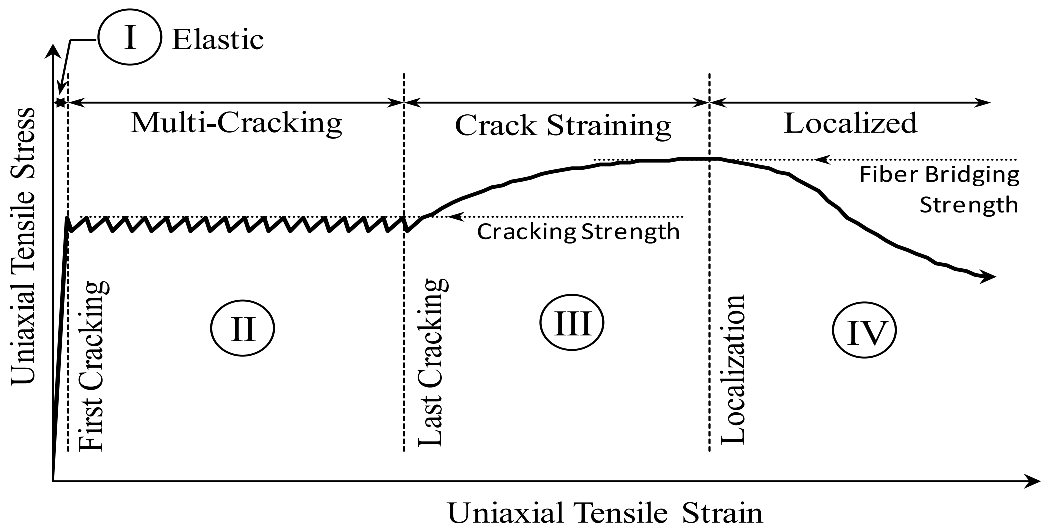


Figure 31 Idealized tensile mechanical response of UHPC

It should be noted that this theoretical response depend on the efficiency of the fiber reinforcement and it may not be observed in reality if relevant fiber reinforcement dosage, orientation and dispersion are not succeeded.

The first phase is called elastic phase, which refers to the global elastic straining of the composite section. This activity persists through the section's first cracking, which happens at the cementitious composite's tensile strength.

The second phase named as the multiple cracking phase and this phase mainly considers the portion where there is the cracks of the cementitious matrix within the gage length. Since the post-cracking strength of each cracked segment, as provided by the reinforcement of steel fiber, is greater than the cracking strength of the cementitious matrix, the specimen accumulates elastic strain both inside cracks and between cracks in the uncracked parts of the cementitious matrix, but does not experience the widening of individual cracks. This phase is also characterized by an almost constant hardening stress level, which is due to the cementitious matrix homogeneity.

On the other hand, the third phase is known as the crack-straining phase. It contains the strain accumulation among the set of cracks. The crack density, which is a function of the dispersion, orientation, geometry, and bond properties of the fiber reinforcement in the beginning of this phase, is such that the generation of additional cracks is unlikely. Hence, the increase in strain occurs due to the increase in crack opening. In this phase, the degradation is observed in stress capacity due to the fiber reinforcement, which undergoes a combination of elastic straining and interface debonding. In the end of this phase, the fiber bridging stress is reached, which leads to crack localization.

The fourth phase is the final phase of idealized tensile mechanical response of UHPC and it is known as localization phase. It is defined by a widening of an individual crack as the bridging fibers that crack the matrix absolutely debond and pull out. In this stage, the remainder of the sample unloads elastically, which means that the behaviors in this stage are related to the crack-opening, not strain. Through this process, the specimen stress continually decreases.

A key objective in the development of this test method is to allow for the creation under a specific set of casting and curing conditions of a characteristic design response appropriate to a specific UHPC. As such, to evaluate an average and a characteristic design response, the results obtained from each group of test specimens were analyzed. An elastic-plastic stress-strain model was assumed. According to the set results of three specimens demonstrated in the figure 29 and figure 30 above, it can be said that the key factor is again the stress during the multi cracking phase. In any of the specimens within the set, this plastic portion of the response extends from the elastic response through the minimum last cracking strain observed.

4.2 CONCRETE CYLINDER COMPRESSION TEST

Concrete Cylinder Compression Test leads to obtain compressive strength of cylindrical concrete specimens such drilled core cylindrical specimen or molded cylinders. This test method is not applicable for concrete that has a unit weight lower than 800 kg/m^3.

The compressive axial load is applied to the concrete cylinder specimens up to reach cracking failure. By dividing the overall load obtained during the test by the cross-sectional area of the specimen, the compressive strength of the specimen is determined. As a basis for quality control of concrete, the findings of this research method are used.

Two steel bearing blocks, one of which is a spherically seated block that will bear the upper surface of the specimen and the other a solid block on which the specimen will be mounted, should be fitted with a measuring machine capable of providing the load rates as prescribed in the standard. (ASTM C39)

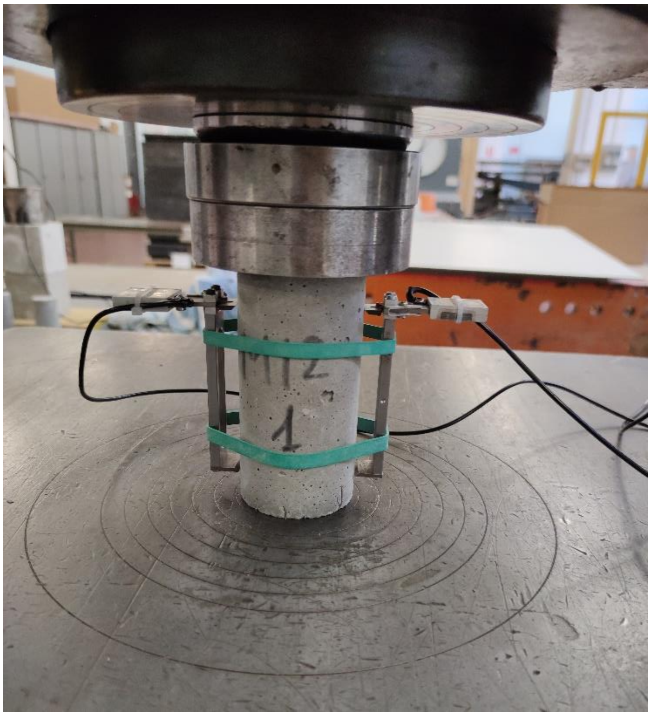


Figure 32 Concrete cylinder compression test machine

The compression concrete cylinder testing machine and the cylindrical concrete specimen have been indicated in the figure above. This type of testing method is easy to apply and it takes less time. Initially, before applying a load, the dimensions of the specimen is measured and noted in the following table.

Table 6 Geometrical properties of concrete cylinder

N.	Specimen	Height after grinding (mm)				Diameter (mm)							Section	Weight	Density	H/D	Maximum load
						upper		center		lower		mean					
		H_1	H_2	H_3	Media	D_1	D_2	D_1	D_2	D_1	D_2	D_{media}	(mm^2)	(g)	(kg/m^3)	(-)	(kN)
1	m12_1	139.21	138.92	138.88	139.00	69.32	69.63	69.50	69.60	69.59	69.65	69.55	3799	1261	2390	2.00	0.0
2	M12_2	137.61	137.73	137.84	137.73	69.56	69.59	69.63	69.56	69.65	69.65	69.61	3805	1248	2380	1.98	1032.0
3	M12_3	140.67	140.97	140.91	140.85	69.58	69.66	69.45	69.63	69.73	69.43	69.58	3802	1275	2380	2.02	0.0
4	RHP1	138.84	138.76	138.73	138.78	69.54	69.73	69.75	69.38	69.48	69.30	69.53	3797	1234	2340	2.00	0.0
5	RHP2	138.24	138.28	138.44	138.32	69.33	69.86	69.73	69.65	69.73	69.67	69.66	3811	1233	2340	1.99	0.0
6	RHP3	136.09	135.99	135.88	135.99	69.74	69.47	69.57	69.60	69.61	69.73	69.62	3807	1197	2310	1.95	0.0

Test method:

1. The specimen is placed on the lower bearing block aiming to align the axis of the specimen with the center of thrust of the spherical bearing block.
2. The load indicator should be set as zero before launching the test.
3. The test take part in under displacement control.
4. The maximum load that the concrete specimen reach, should be recorded during the test and the fracturing pattern should be noted.

The failure of the cylindrical specimens just after the application of compressive load is demonstrated in the following figures. The obtained results are saved and evaluated in Excel.

Figure 33 Failure of the specimens subjected to compressive load

According to the results obtained from data acquisition during the test, load deflection graph was computed in Excel. The data and further details were demonstrated in Appendix.

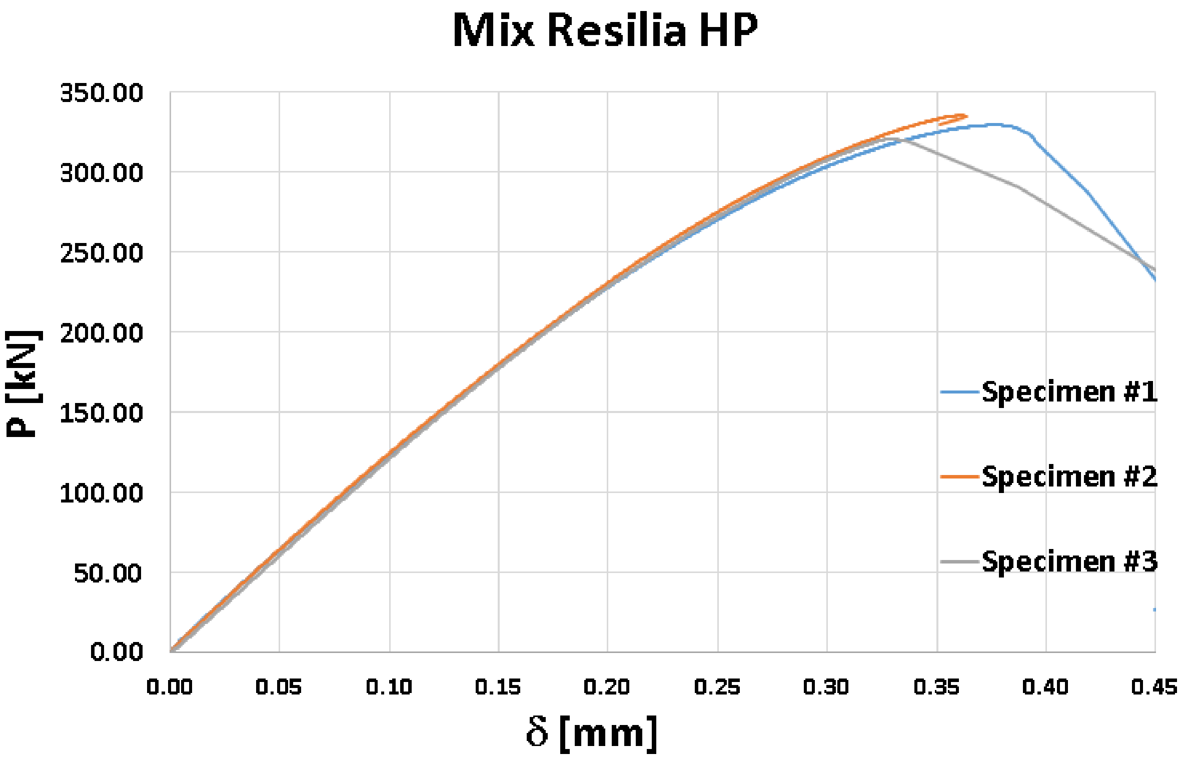


Figure 34 The load deflection curve of Mix Resilia HP specimens obtained from Compression Test

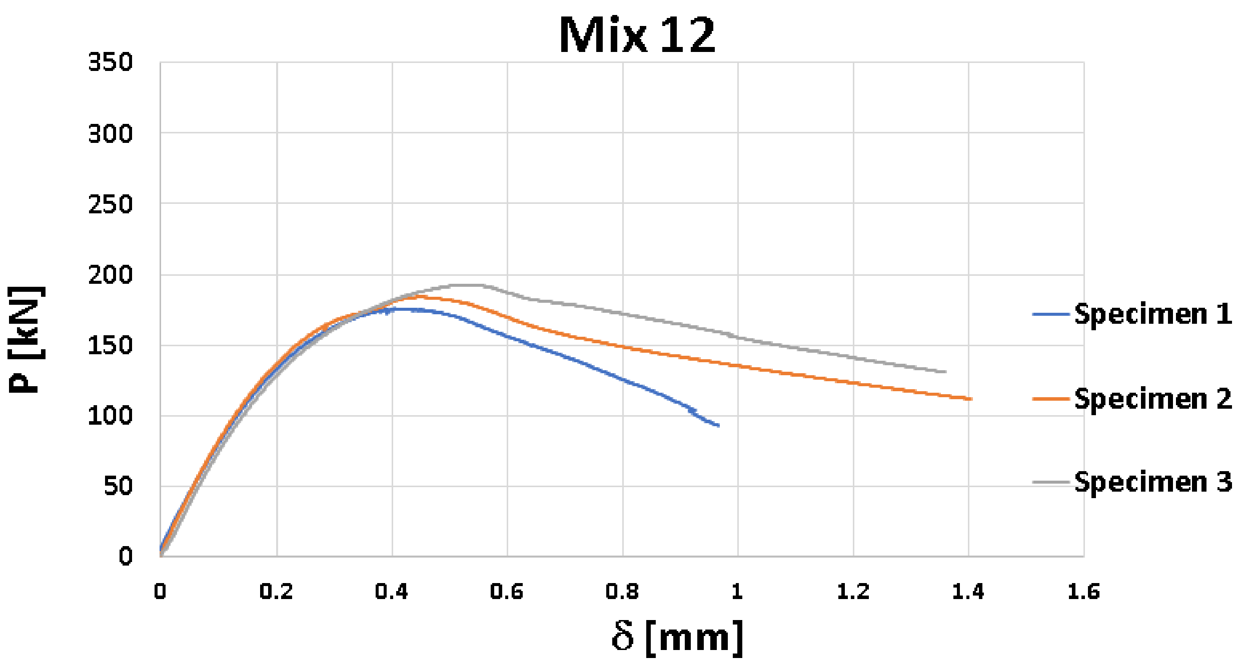


Figure 35 The load deflection curve of Mix 12 specimens obtained from Compression Test

Based on the equation 2 and 3 stress strain relationship is computed and evaluated as follows:

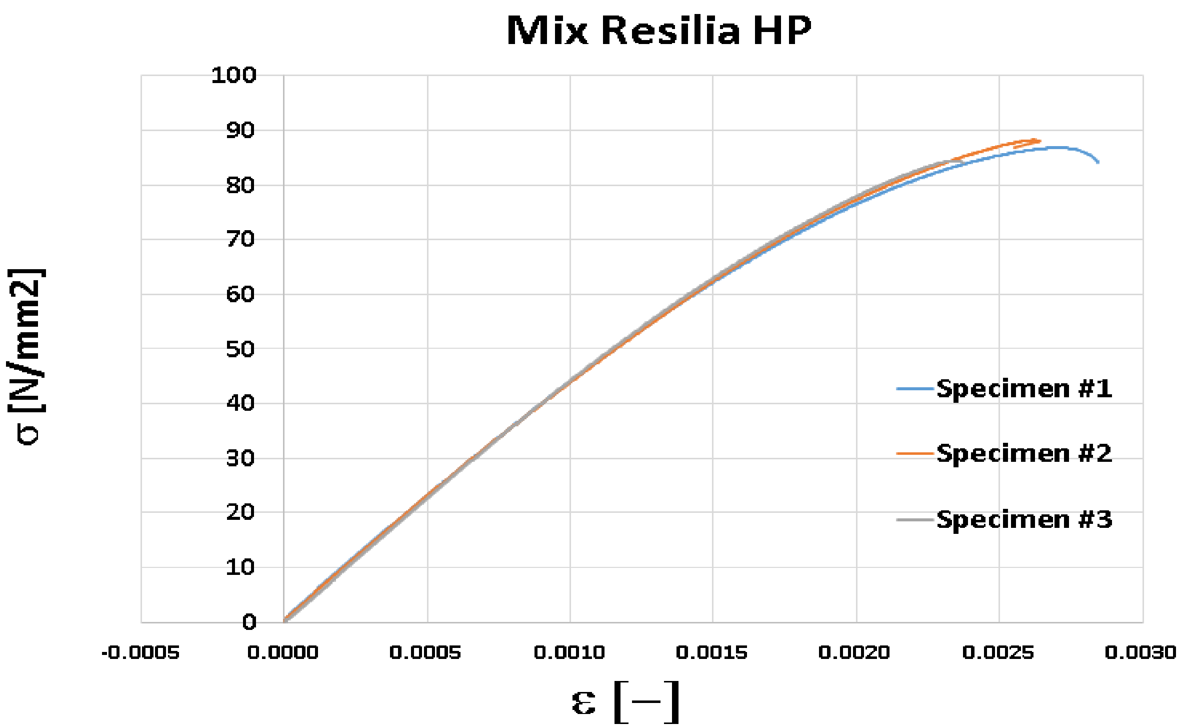


Figure 36 The stress-strain results of Mix Resilia HP specimens obtained from Compression Test

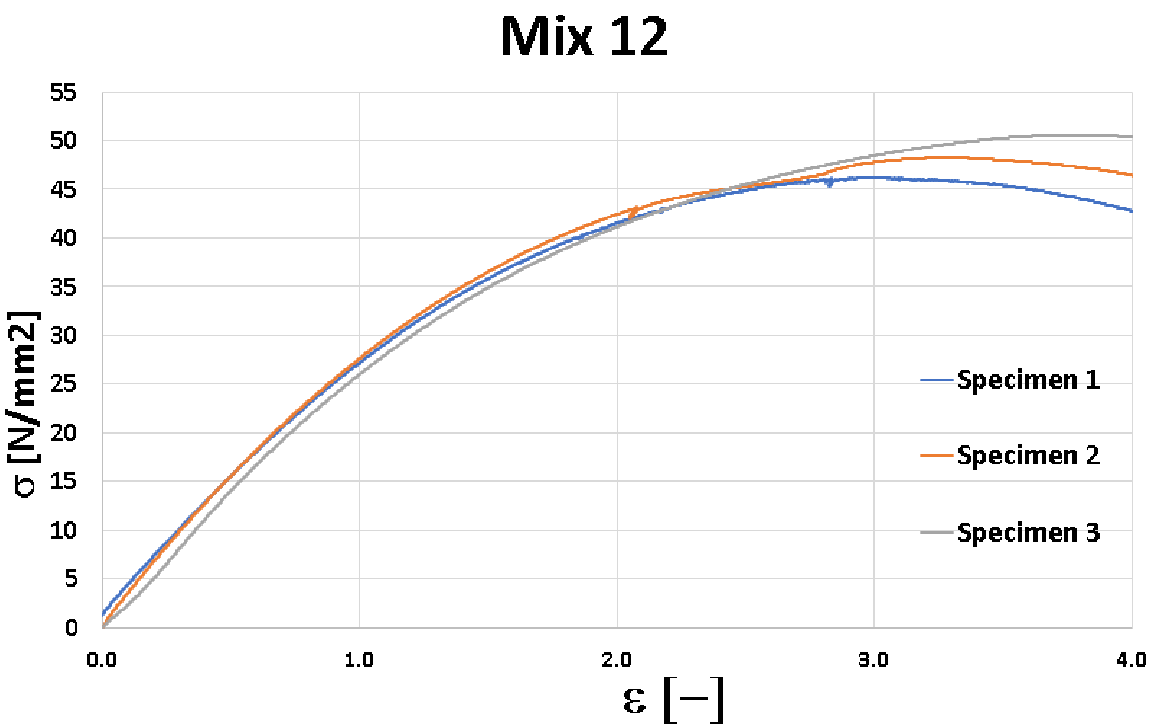


Figure 37 The stress-strain results of mix 12 specimens obtained from Compression Test

Table 7 Compression test results of mix Resilia HP

	Mean diameter Φ [mm]	Mean high [mm]	σ_{max} [N/mm2]	$\varepsilon_{max,peak}$ [‰]	$E_{sec,peak}$ [MPa]
Specimen #1	69.55	139.00	86.80	0.00265	32754719.18
Specimen #2	69.61	137.73	88.22	0.00255	34592931.22
Specimen #3	69.58	140.85	84.41	0.00227	37213903.86
Mean value			86.48	0.00	34853851.42

Table 8 Compression test results of mix 12

	Mean diameter [mm]	Mean height [mm]	σmax [N/mm2]	εmax.peak [‰]	Esec,peak [MPa]
Specimen #1	69.55	139.00	46.24	2.91396	15869.20091
Specimen #2	69.61	137.73	48.27	3.27198	14752.48492
Specimen #3	69.58	140.85	50.60	3.75932	13459.75716
Mean value			48.37	3.32	14693.81

Average results obtained from compression cylinder test are demonstrated for the sets of specimens mix Resilia HP and mix 12, above.

Figure 38 The sets of mix Resilia HP and 12 specimens subjected to the compression loading

4.3 THREE POINT BENDING TEST

The purpose of this test is to measure the behavior of the materials when they are subjected to simple beam loading. Flexure test method is also named as a transverse beam test. This test mainly focuses on the bending test applied to the set of specimens, aiming to derive the tensile stress-strain response of UHPFRC from three point bending test. The specimen is inserted and supported by the two fixtures in both two edges and it is loaded in the middle. By utilizing the extensometer, the strain measurement on the tensile face is captured at the mid span. The maximum stress and strain are computed for the each increment of the load. The obtained results are demonstrated in the stress-strain diagram. Maximum fiber stress at failure shows the flexural strength.

Figure 39 Three point bending test machine

This test produces tensile stress in the convex side of the specimen and it applies compression stress to the concave side of the specimen. Hence, the area of shear stress is created at the midline. The shear stress must be minimized in order to encounter the initial failure coming from compression or tensile stress, by considering the ratio between span and depth, and also the ratio between the outer span length and the height of the specimen. In general, depending on the material this ratio demonstrates variations, however for most of the materials it is accepted as S/d=16. In order to keep the shear stress low, some type of materials require different ratios such as S/d= 32 to 64.

Flexural testing method is generally applied to the different types of flexible materials such as polymers, composites and woods. This testing method consists of two test types, which are three point bending test and four point bending test. In three point bending test the uniform stress area is less and generally concentrated around under the loading point. On the other hand, in four point bending test the uniform stress area among the inner span loading points.

Three point bending test was performed by using the instrument shown in figure 39. The specimens of each set were tested and the responses of each type of specimens are plotted.

Figure 40 The cracking scheme of mix 12.1

Based on the results obtained from data acquisition during the test, load deflection graph was computed in Excel. The data and further graphs were demonstrated in Appendix.

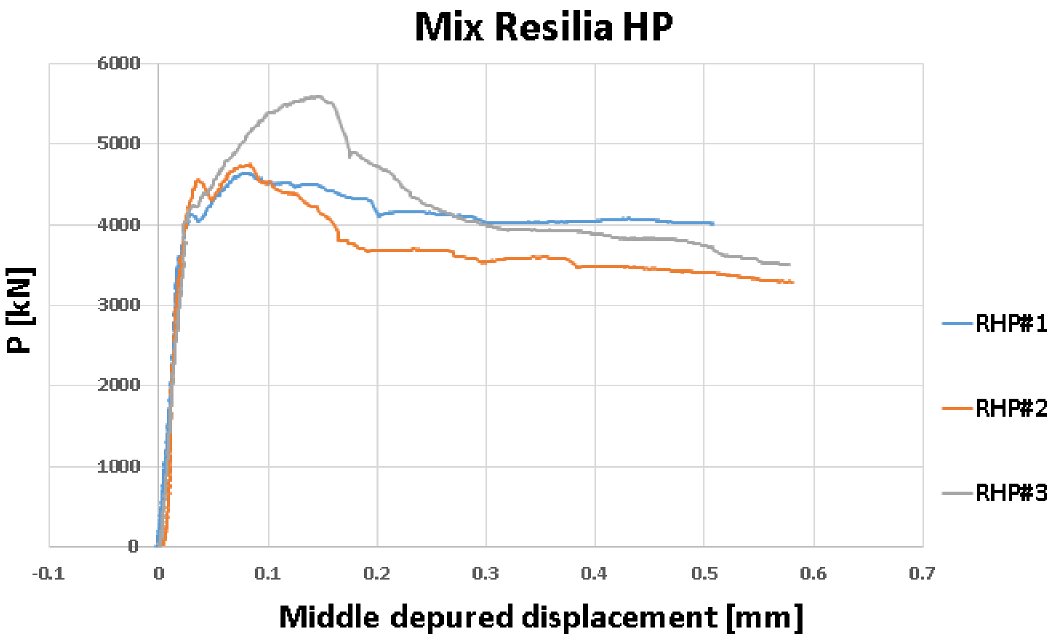


Figure 41 The load displacement curve of Resilia HP specimens obtained from Flexure Test

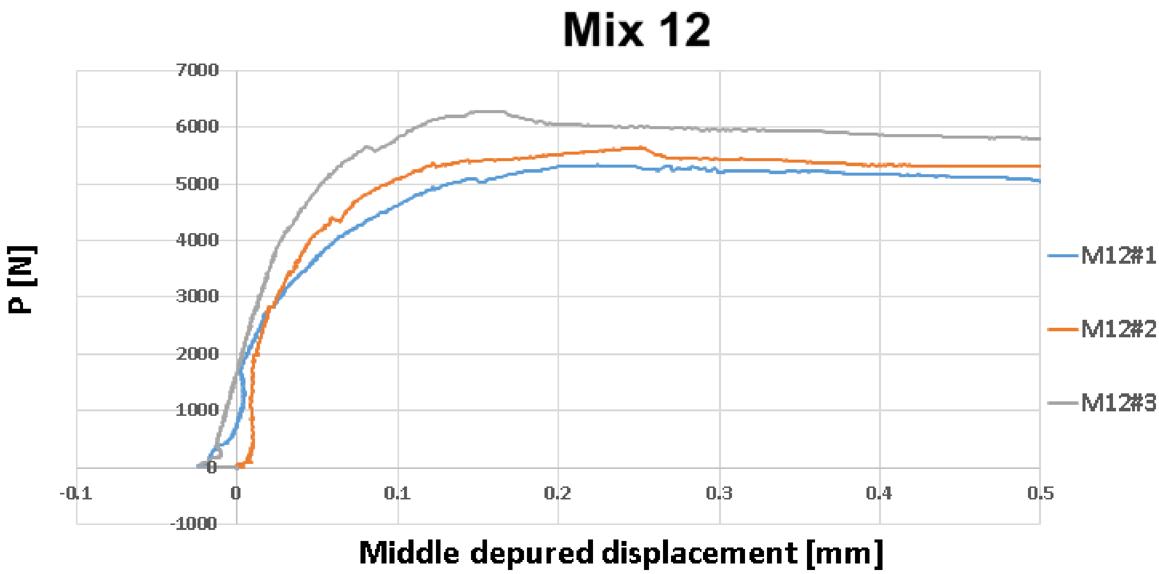


Figure 42 The load displacement curve of Mix 12 specimens obtained from Flexure Test

CHAPTER 5 - MODELLING AND RELATIONS OF TESTS

This chapter of the research is based on the modeling, which is done by using Virtual Basic Application in Excel. The purpose of the model is to define the main parameters of the constitutive law of UHPFRC.

The model is based on the calculation of stress strain method. Hence, the main hypothesis that is assumed concerns that ‘’plane sections remain plane’’. (Eurocode 2,6,1 , p.81).

Thus, the model is based on the range of the load deflection curve in which macroscopic crack are not observed. The goal is to define the four main parameters: Young’s Modulus in tension, yielding strength, Young’s Modulus post peak and ultimate strain.

The first two parameters are deductible by the first part of load deflection curve, which end with a stationary point.

The first sectional analysis leads to define the first two parameters that define the limit of the elastic stage. Basing on the fact that the first part of the test is working in the elastic stage, the relation between displacement and load is effectively working. Hence, the young modulus in tension is given by the reversed formula of the elastic displacement:

$$E_t = \frac{P_m . L^3}{48\eta_m I_x}$$

The second parameter requested is the tensile yielding strength. It can be given by the sectional analysis of middle cross section.

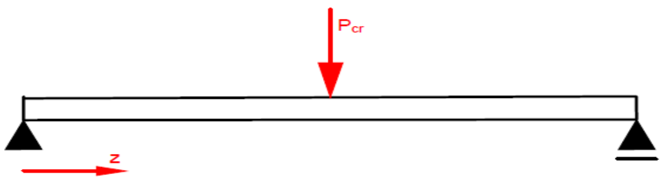


Figure 43 Simply supported beam

For applied P_{cr}, it can be calculated as follows:

$$M(P_1)_{middle} = \frac{P_{cr}L}{4}$$

$$N(P_1) = 0$$

The model starts with an iterative procedure in order to define a stress strain distributions, able to equilibrate the stresses due to the external load application in that point.

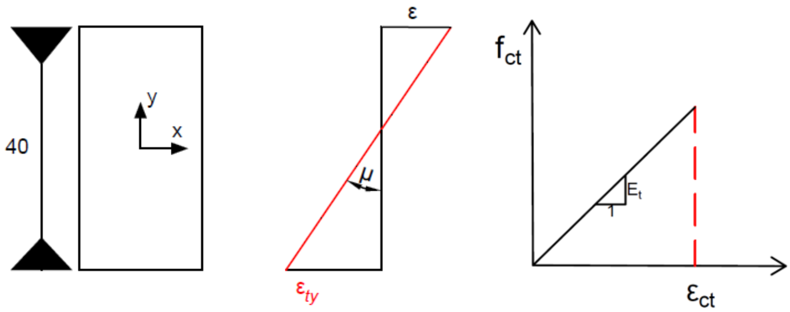


Figure 44 Middle cross section demonstration of a beam

$$\varepsilon_{ct} = \frac{f_{ct}}{E_t}$$

$$\exists!\ \mu_M \ |N = 0 \text{ and } \varepsilon_{ty} = \varepsilon$$

in the bottom edge

On the base of the fact that, the point of flex in load deflection graph gives a sign of change of the behavior of the structure, it can be assumed that the stress reached in the inferior edge of the middle cross section corresponds to the limit of the tensile strength of the material in the elastic stage.

The second part of the model lets to estimate the ''first'' post peak behavior of the constitutive law.

A second iterative procedure is now introduced with the beginning of the plastic stage. It states that the young modulus is no more deductible a priori. The reason why, an arbitrary value is assigned to it.

The procedure is repeated for each section of subdivision of the beam. Each section is subdivided in an elevated number of strips. Hence, the cross sectional analysis is now applied to the each strip of the whole beam. By utilizing the following equations the response of bending moment and normal stress are computed.

$$\int_0^A \sigma y dA = M_r$$

$$\int_0^A \sigma dA = N_r$$

The model looks for the convergence of the equilibrium of each strip of the beam with respect to effects produced by the application of the external load P_2.

After the convergences are reached, the curvature distribution is known for any point of the beam.

By the application of the virtual work, the middle span deflection is estimated by utilizing the following equation.

$$\mathbf{U}\,\boldsymbol{\eta} = \int_0^L \boldsymbol{M^a \mu^b dL} + \int_0^L \boldsymbol{N^a \lambda^b dL}\,,\ \mathbf{U=1}$$

According to this procedure, if the analytical solution is strictly different from the experimental one, the young modulus is changed and the procedure is repeated again.

To sum up, it can be said that the value of the Young's Modulus is changed until to obtain the same displacement and load achieved during the test, always keeping the static equilibrium due to the load.

According to the process herein discussed and demonstrated in the flow chart below, the obtained results are quite conservative for each sets of specimen Resilia HP and Mix 12.

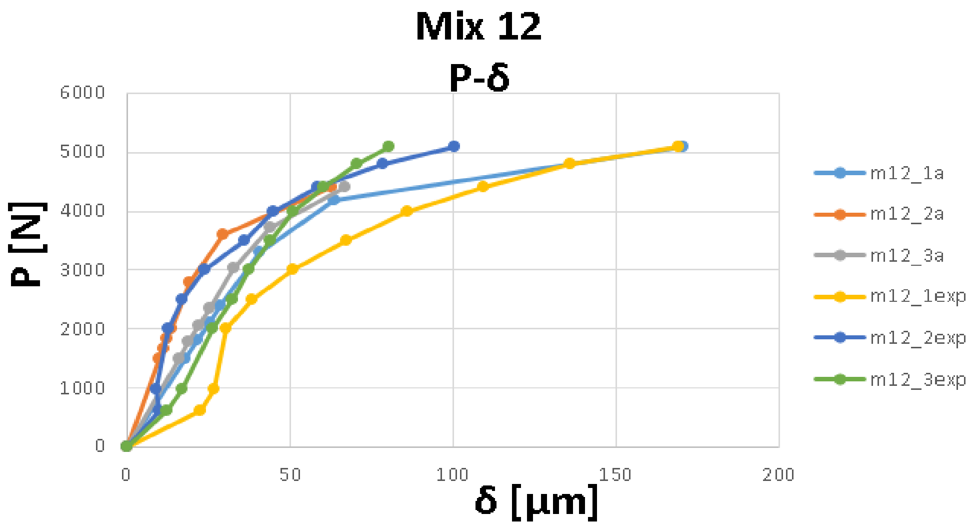


Figure 45 The relation between analytical and experimental method for mix 12

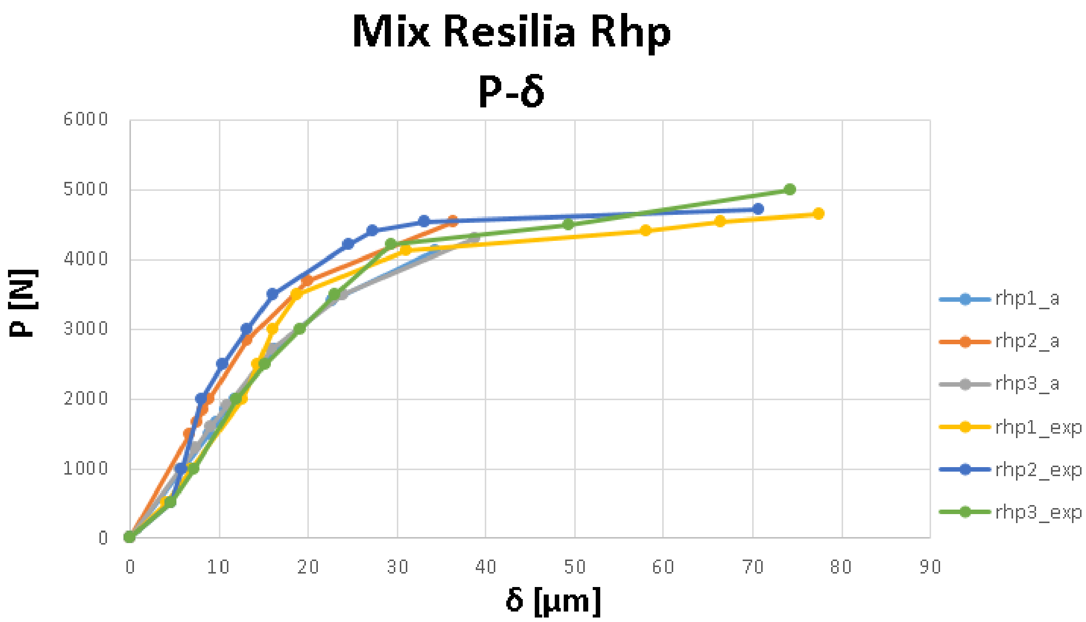


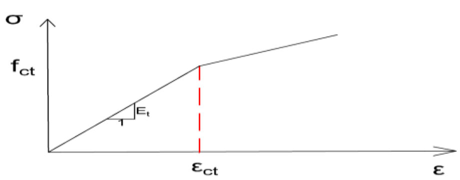
Figure 46 The relation between analytical and experimental method for mix Resilia HP

Based on the figures, it can be said the hypothesis that is assumed satisfies the condition. In addition, the response obtained from the analytical solution is pretty close to the one obtained from experimental solution. Hence, it is said that the analysis is conservative.

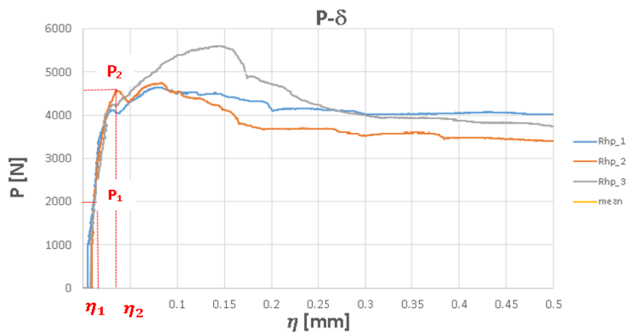
TBR- Relationship

Compressive properties;

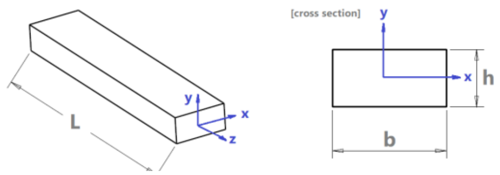
Linear-Elastic Model for stress strain relationship



Initial P-δ graph without discontinuities



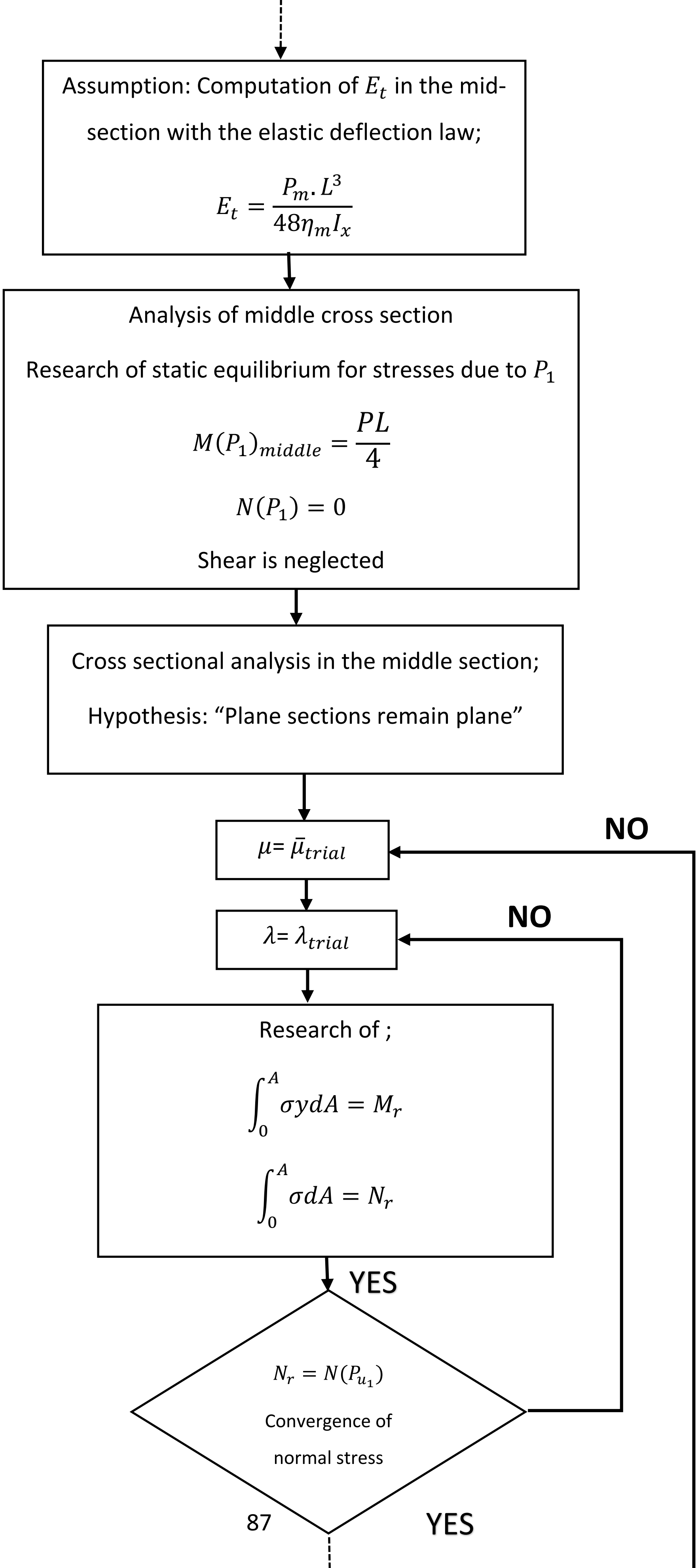
Geometrical parameters

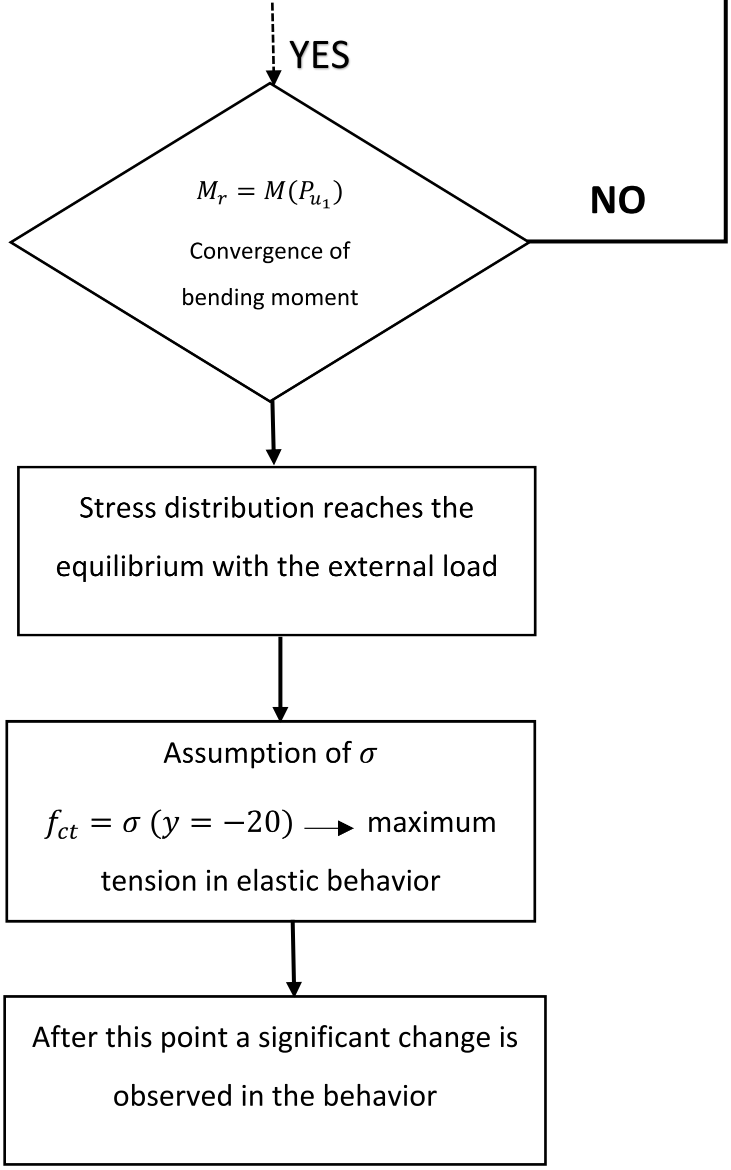


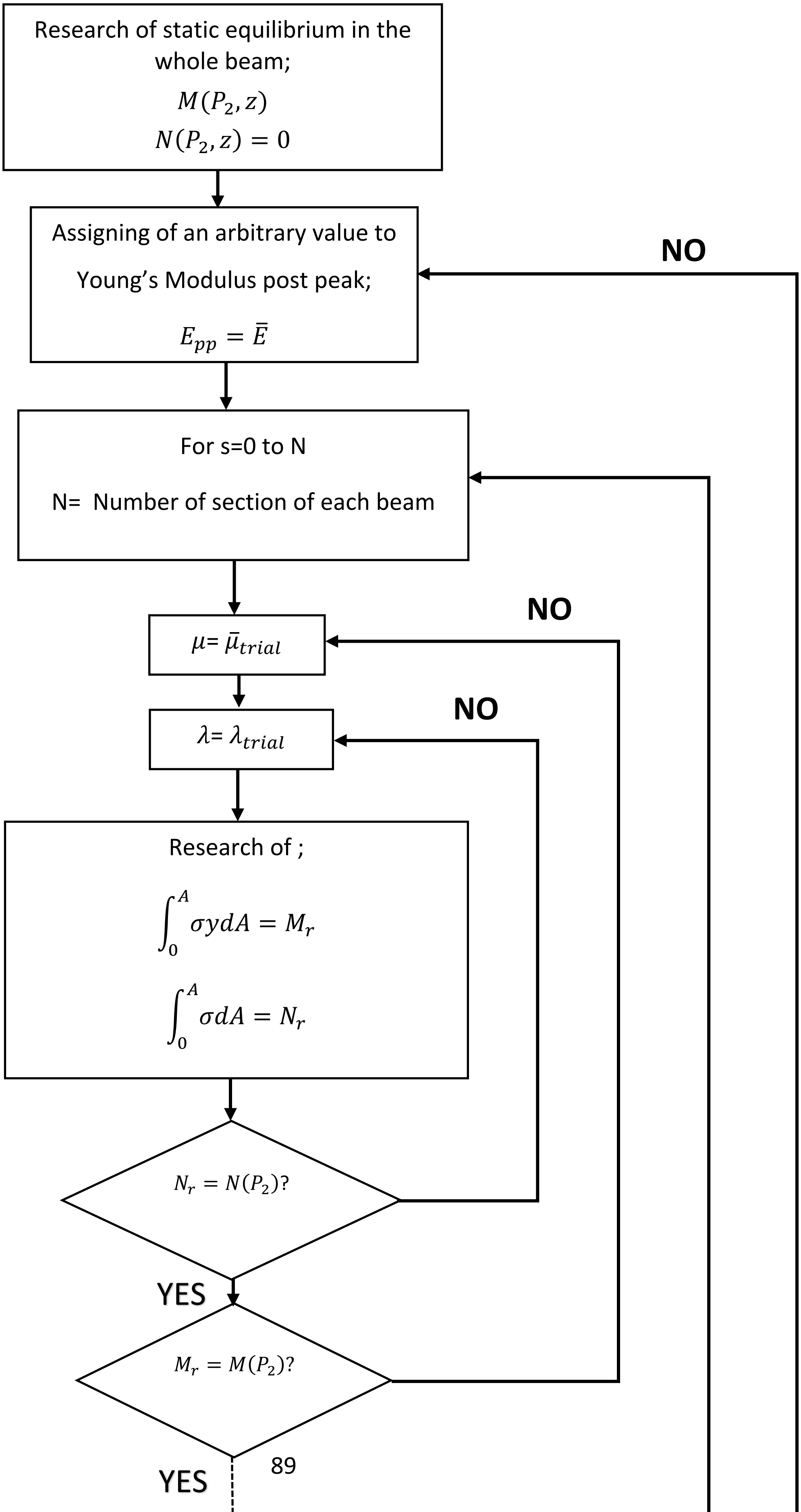
Data acquisition of the specimen

Identifcation of the main properties of P-δ ;

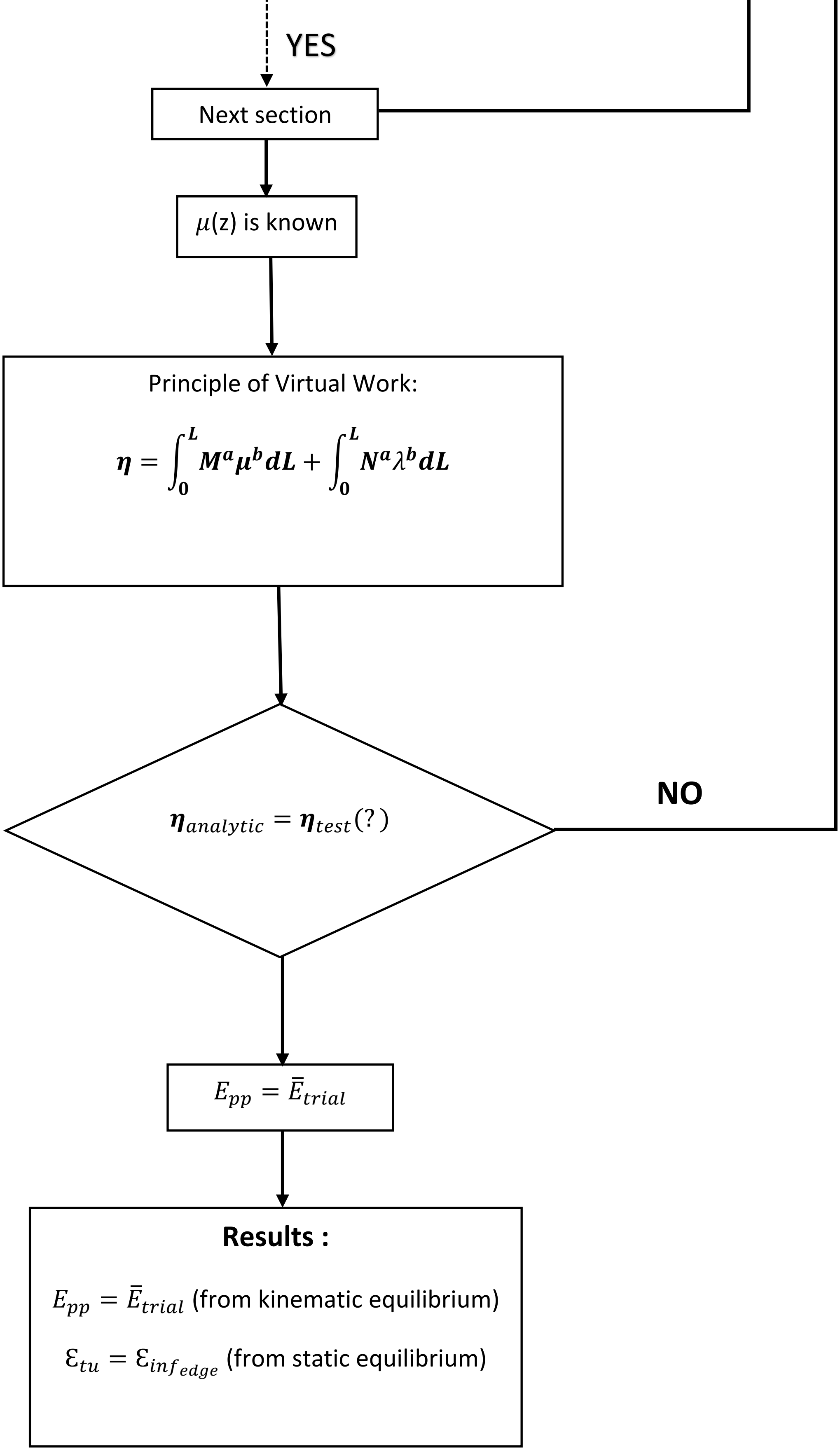
- Point of flex (P_1, η_1)
- Point of 1st macrocrack (P_2, η_2)


Assumption: Computation of E_t in the mid-section with the elastic deflection law;
$E_t = \frac{P_m . L^3}{48\eta_m I_x}$
Analysis of middle cross section
Research of static equilibrium for stresses due to P_1
$M(P_1)_{middle} = \frac{PL}{4}$
$N(P_1) = 0$
Shear is neglected
Cross sectional analysis in the middle section;
Hypothesis: "Plane sections remain plane"
$\mu = \bar{\mu}_{trial}$
NO
$\lambda = \lambda_{trial}$
NO
Research of ;
$\int_0^A \sigma y dA = M_r$
$\int_0^A \sigma dA = N_r$
YES
$N_r = N(P_{u_1})$
Convergence of normal stress
YES


YES
$M_r = M(P_{u_1})$
Convergence of
bending moment
NO
Stress distribution reaches the
equilibrium with the external load
Assumption of σ
$f_{ct} = \sigma\ (y = -20) \longrightarrow$ maximum
tension in elastic behavior
After this point a significant change is
observed in the behavior



Research of static equilibrium in the whole beam;
$M(P_2, z)$
$N(P_2, z) = 0$
Assigning of an arbitrary value to Young's Modulus post peak;
$E_{pp} = \bar{E}$
NO
For s=0 to N
N= Number of section of each beam
NO
$\mu = \bar{\mu}_{trial}$
NO
$\lambda = \lambda_{trial}$
Research of ;
$\int_0^A \sigma y dA = M_r$
$\int_0^A \sigma dA = N_r$
$N_r = N(P_2)?$
YES
$M_r = M(P_2)?$
YES


YES
Next section
μ(z) is known
Principle of Virtual Work:
$\boldsymbol{\eta} = \int_0^L \boldsymbol{M^a \mu^b dL} + \int_0^L \boldsymbol{N^a} \lambda^{\boldsymbol{b}} \boldsymbol{dL}$
$\boldsymbol{\eta}_{analytic} = \boldsymbol{\eta}_{test}(?)$
NO
$E_{pp} = \bar{E}_{trial}$
Results :
$E_{pp} = \bar{E}_{trial}$ (from kinematic equilibrium)
$\mathcal{E}_{tu} = \mathcal{E}_{inf_{edge}}$ (from static equilibrium)

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

This thesis is mainly focused on the development of several test methods for UHPC class materials. Since, UHPC has a high performance and high mechanical properties a procedure has introduced by using tension test methods. In particular, this study based on applying Direct Tension Test (DTT) method for UHPC and moreover to develop Flexure Test methods (FT) in order to obtain characteristic tensile stress-strain response for multiple UHPC formulations.

The objective is to implement a procedure to obtain tensile properties of UHPC by using three point bending test. According to the results, demonstrated above, it can be said that the procedure introduced in advance, satisfies the goal and it is conservative.

In this study, the direct tensile behavior of nineteen UHPC series were experimentally investigated using JSCE guideline. An idealized constitutive model with three linear phases capable of being extracted from DTT experiment, which was proposed to characterize the linear elastic, strain hardening, and strain softening, behavior of UHPC in tension, respectively. The dog bone shaped specimens, which were prepared by Cemex Company, were used in order to conduct the experiment.

The results obtained during the research are listed as follows:

- The DTT method developed and pointed out herein presents a reliable, practical method through which the tensile stress–strain response of UHPC can be captured.
- The test methods meet the key requirements during the procedure including the ability to be completed on time and the ability to be accomplished in commercially available test machines.

- The use of longer test specimens is preferred in order to allow for a reduction in the magnitude of bending stresses imparted during the initial gripping of the test specimen in DTT.
- The tensile response of UHPC was observed to contain distinct phases. However, this research mainly focused on the initial phase called elastic phase, leads to encompass the straining of the intact cementitious composite and searches for the first cracking of the matrix. The developed DTT test method allows for the determination of the tensile stress-strain response of UHPC.
- The three point bending test method developed and demonstrated herein presents a capable means of assessing tensile stress-strain response of UHPC while minimizing the assumptions that can introduce uncertainty in the results.

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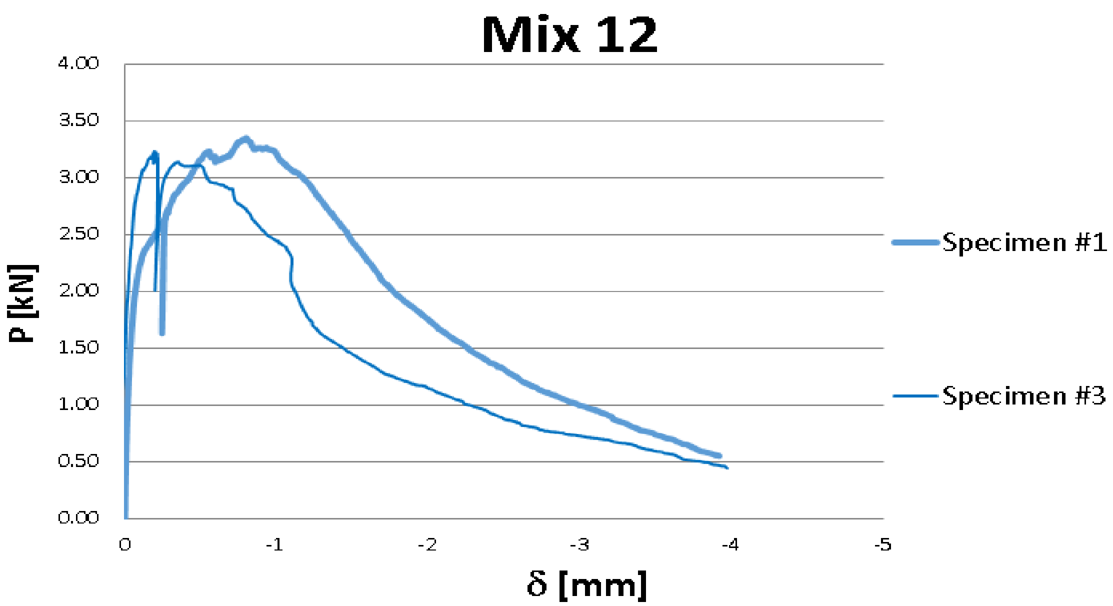
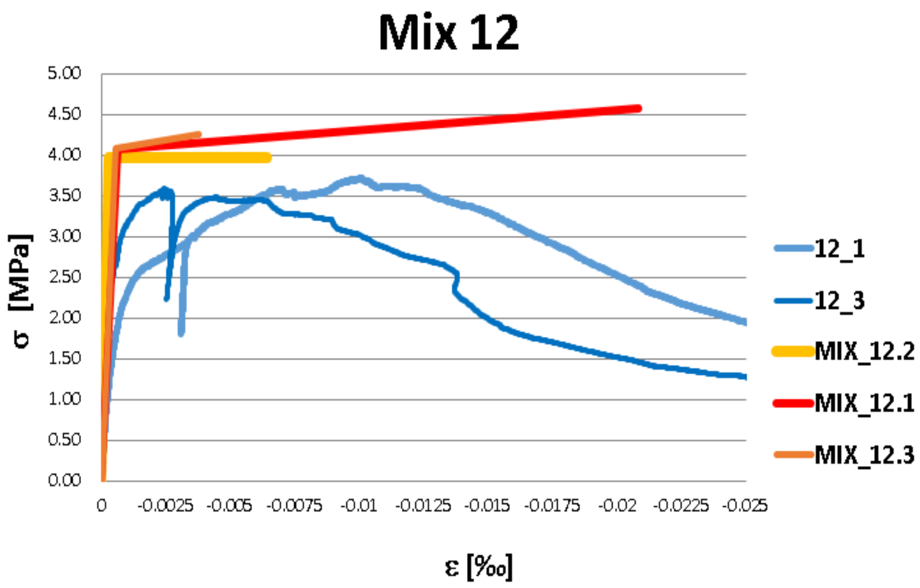
APPENDIX

Direct Tension Test

Mix 12

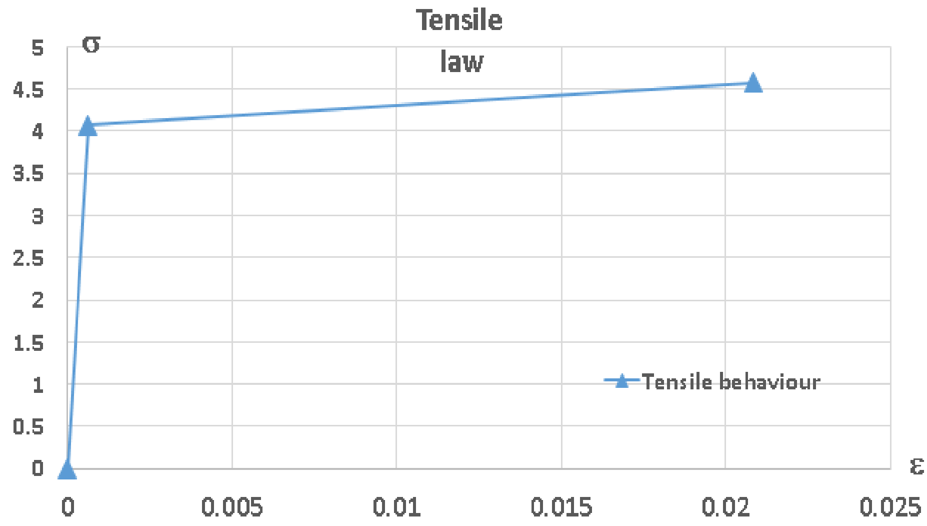


WITHOUT POST PEAK	
MIX_12.1	
0	0
-0.00064147	4.074627541
-0.02082109	4.579117918
MIX_12.2	
0	0
-0.0003	3.971439093
-0.0064	3.971439093
MIX_12.3	
0	0
-0.0005455	4.095087036
-0.00376644	4.25613416



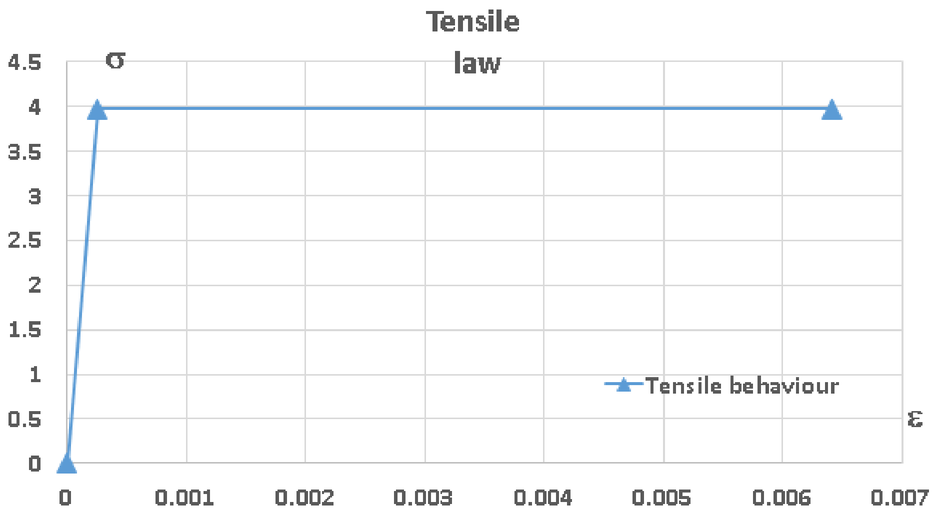
Mix 12-Specimen 1

Tensile behaviour	
ε [‰]	σ [MPa]
0	0
0.000641	4.07
0.020821	4.58



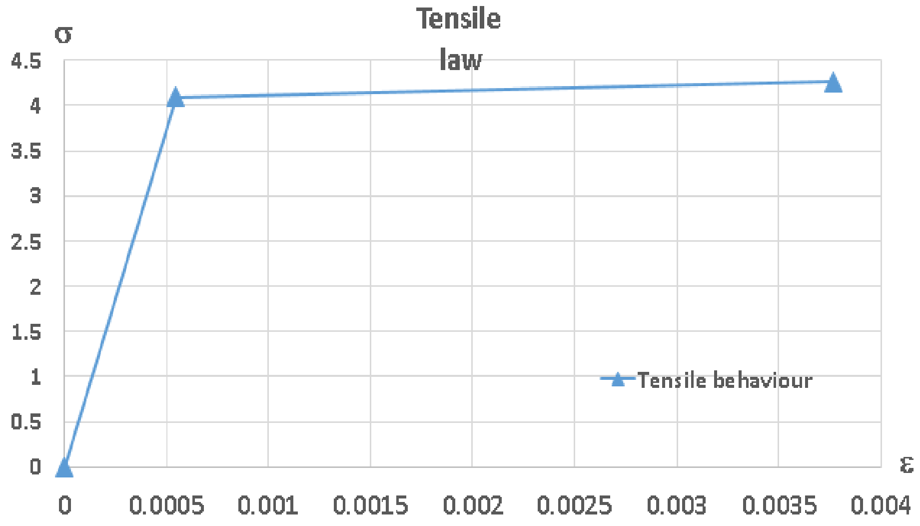
Mix 12-Specimen 2

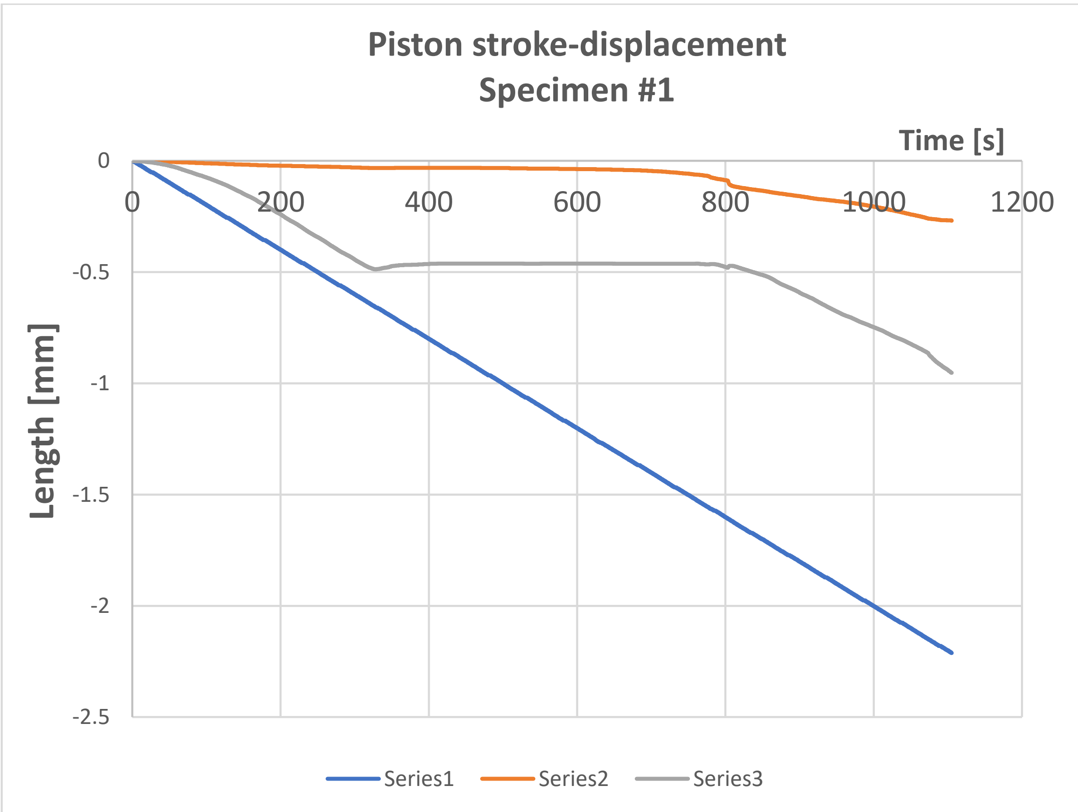
Tensile behaviour	
ε [‰]	σ [MPa]
0	0
0.000257	3.97
0.006407	3.97

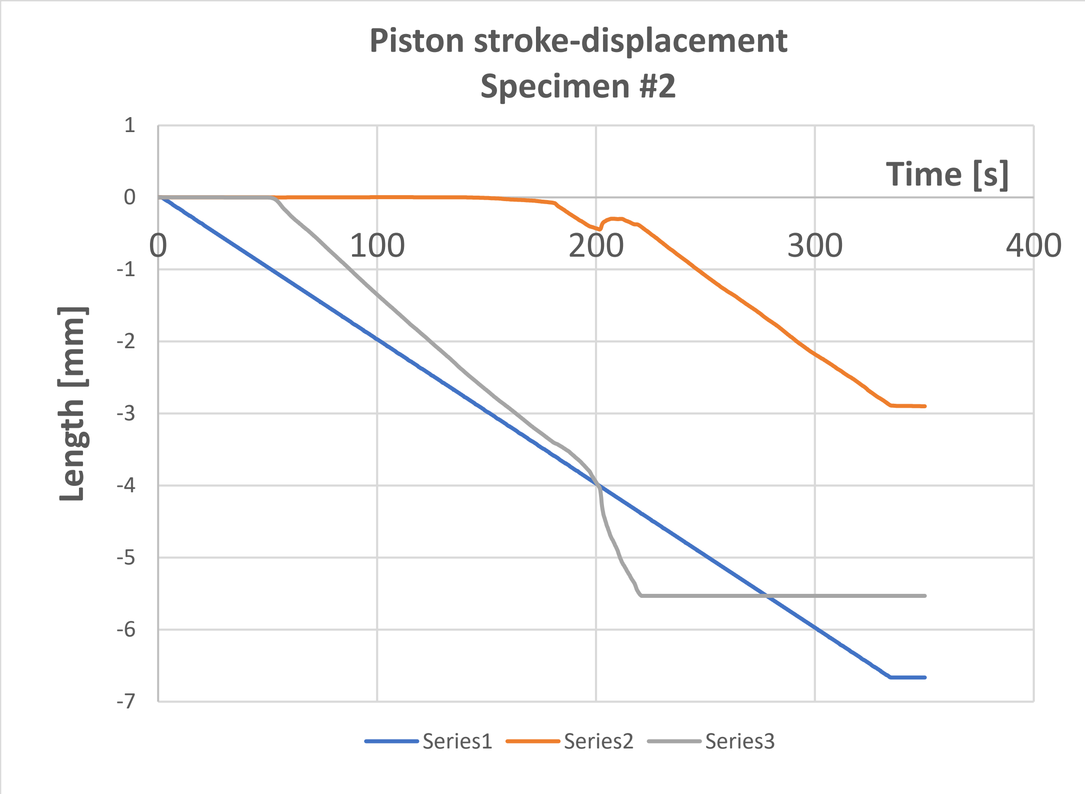


Mix 12-Specimen 3

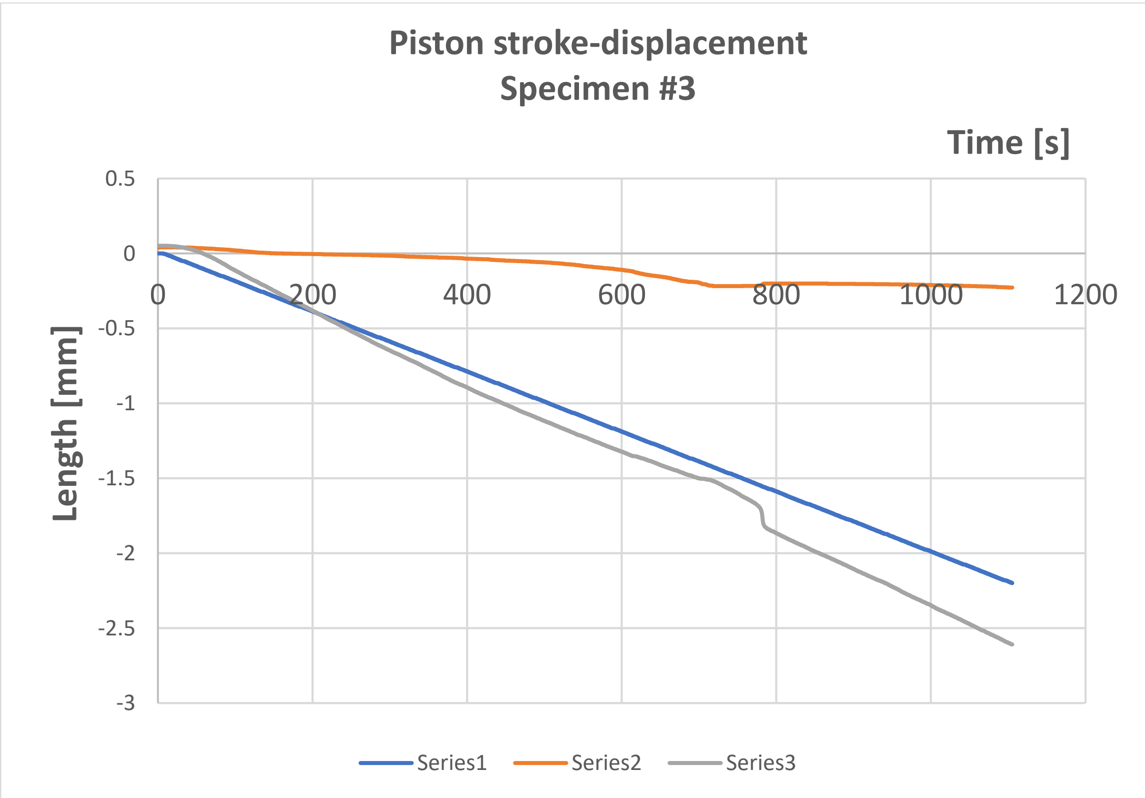
Tensile behaviour	
ε [‰]	σ [MPa]
0	0
0.000546	4.10
0.003766	4.26





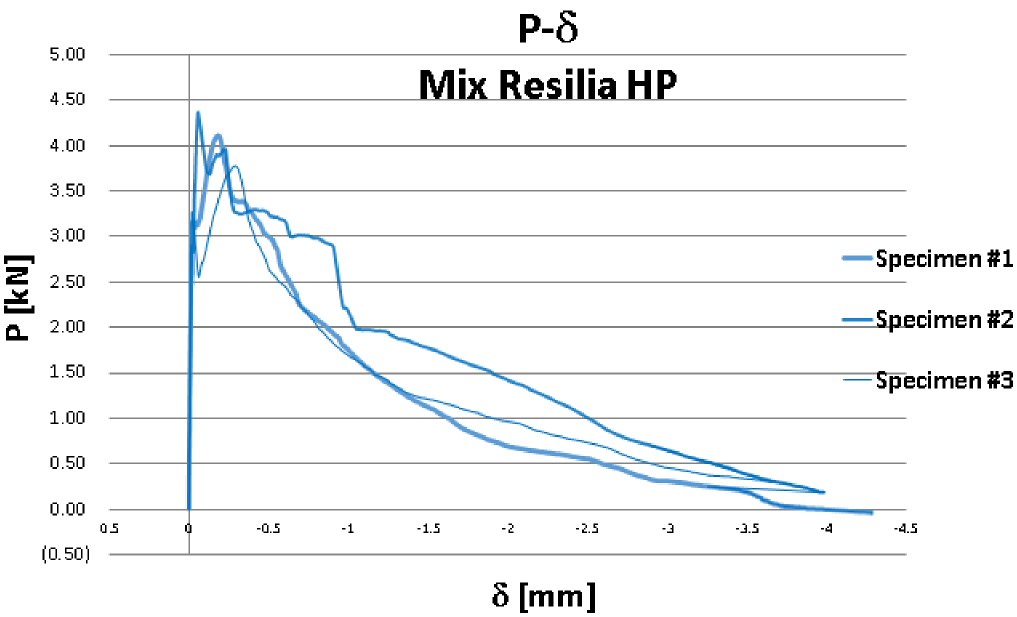


Piston stroke-displacement
Specimen #2
Time [s]
Length [mm]
1
0
-1
-2
-3
-4
-5
-6
-7
0
100
200
300
400
Series1
Series2
Series3

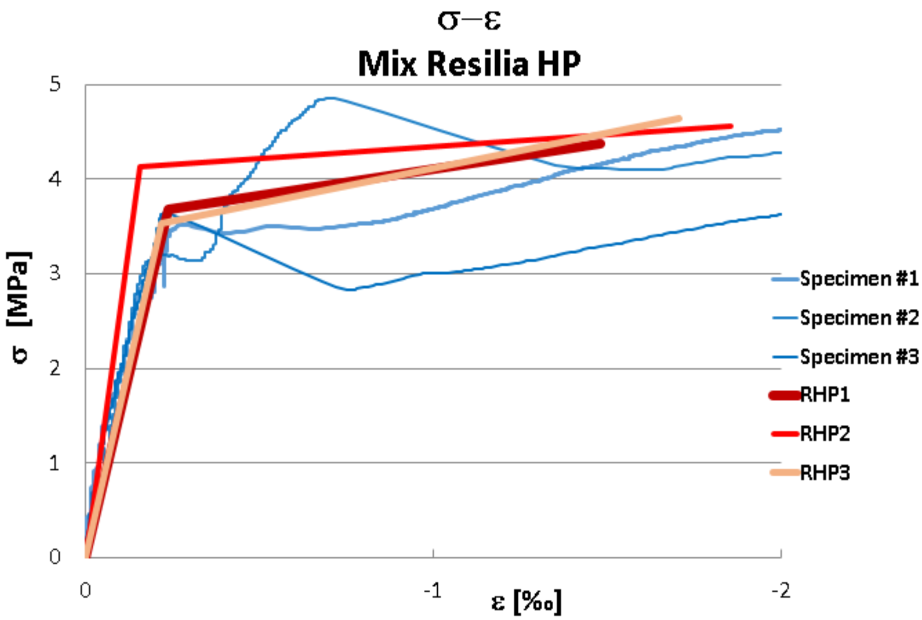


Piston stroke-displacement
Specimen #3
Time [s]
Length [mm]
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
200
400
600
800
1000
1200
Series1
Series2
Series3

Mix Resilia HP

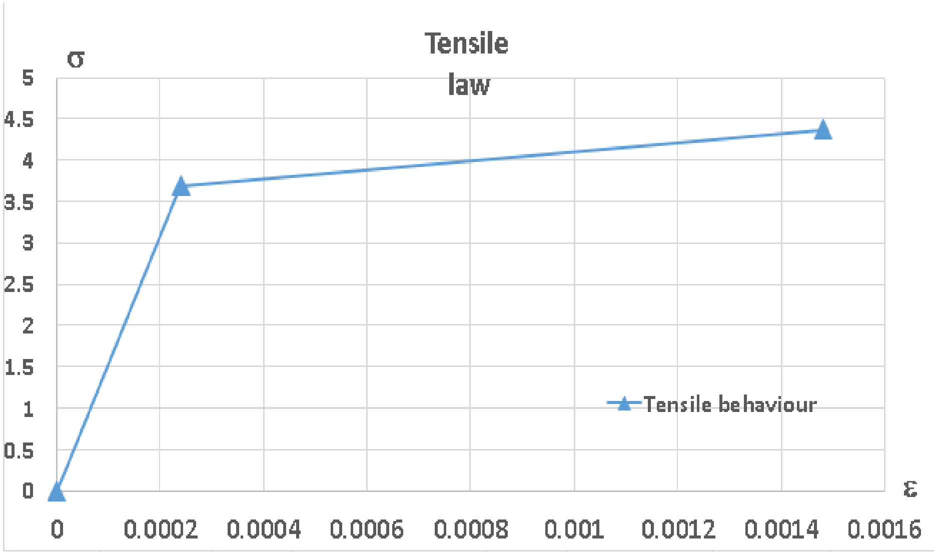


WITHOUT POST PEAK	
RHP1	
0.0000	0
-0.2392	3.6866
-1.4824	4.37031955
RHP2	
0	0
-0.1580	4.1305
-1.8541	4.55454136
RHP3	
0	0
-0.2192099	3.5305948
-1.7083945	4.6474832



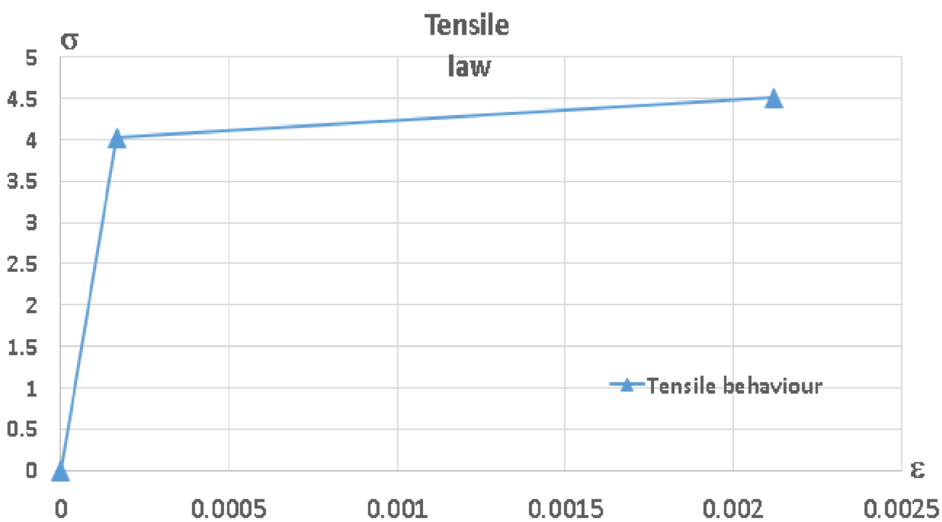
Mix Resilia HP – Specimen 1

Tensile behaviour	
ε [‰]	σ [MPa]
0	0
0.000239	3.69
0.001482	4.37



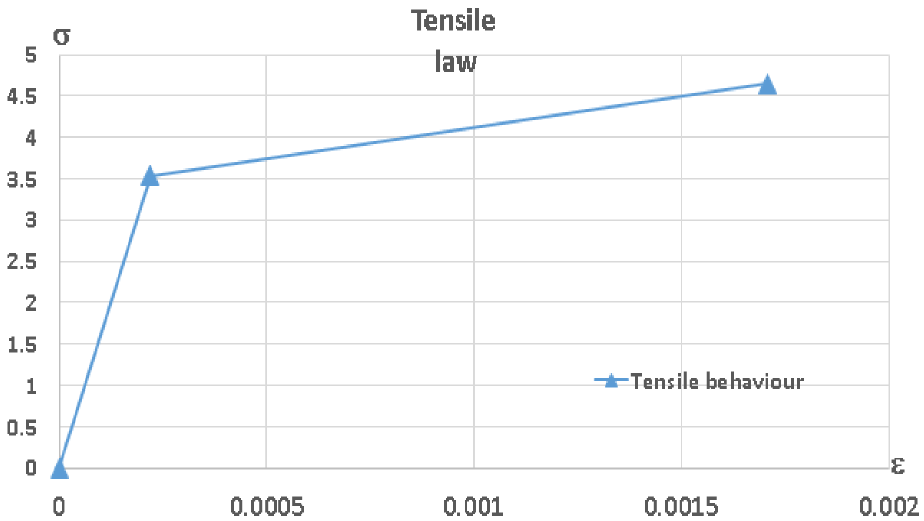
Mix Resilia HP – Specimen 2

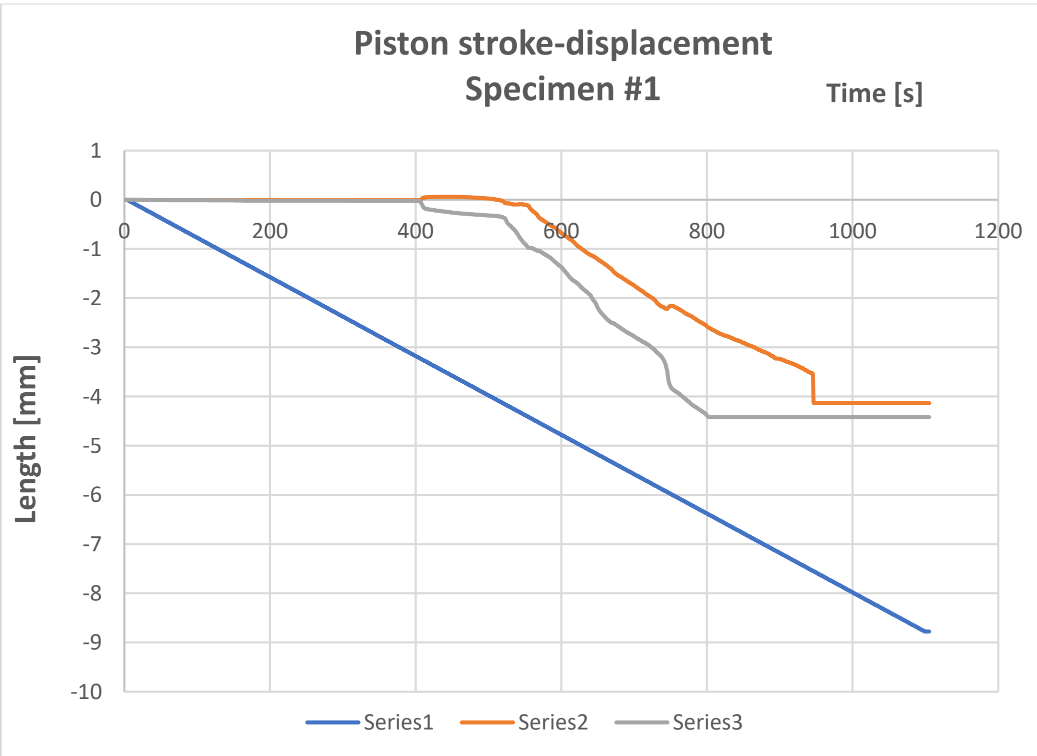
Tensile behaviour	
ε [‰]	σ [MPa]
0	0
0.000167	4.02
0.002121	4.51

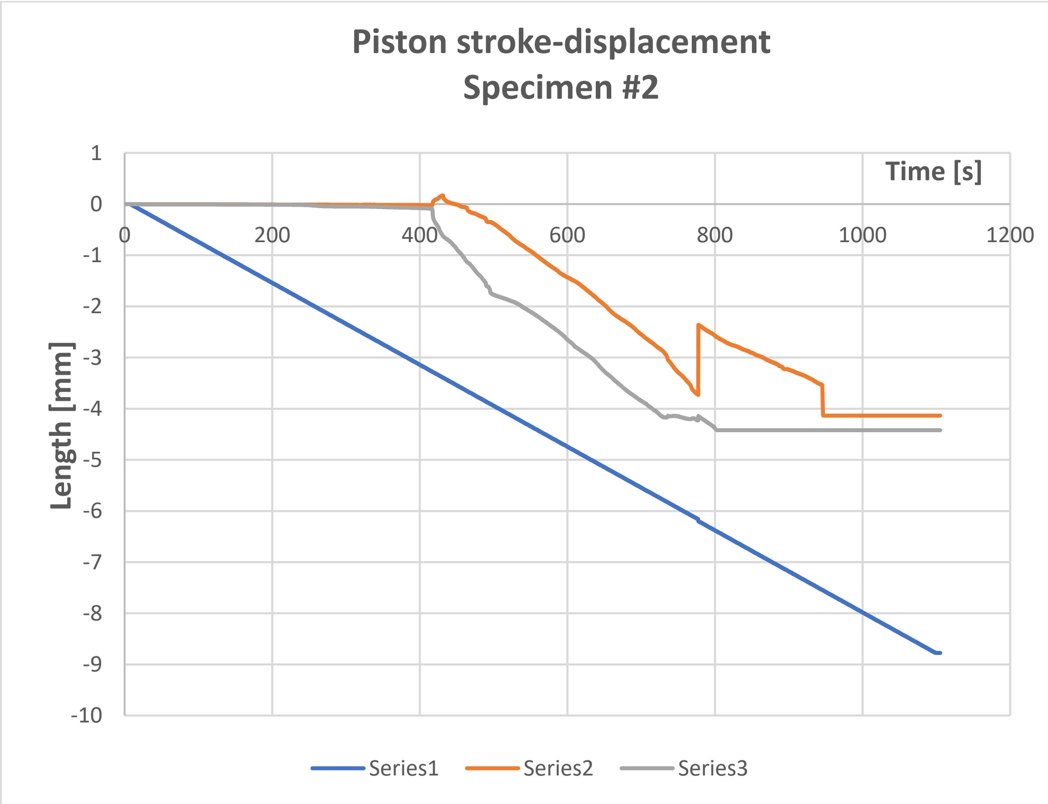


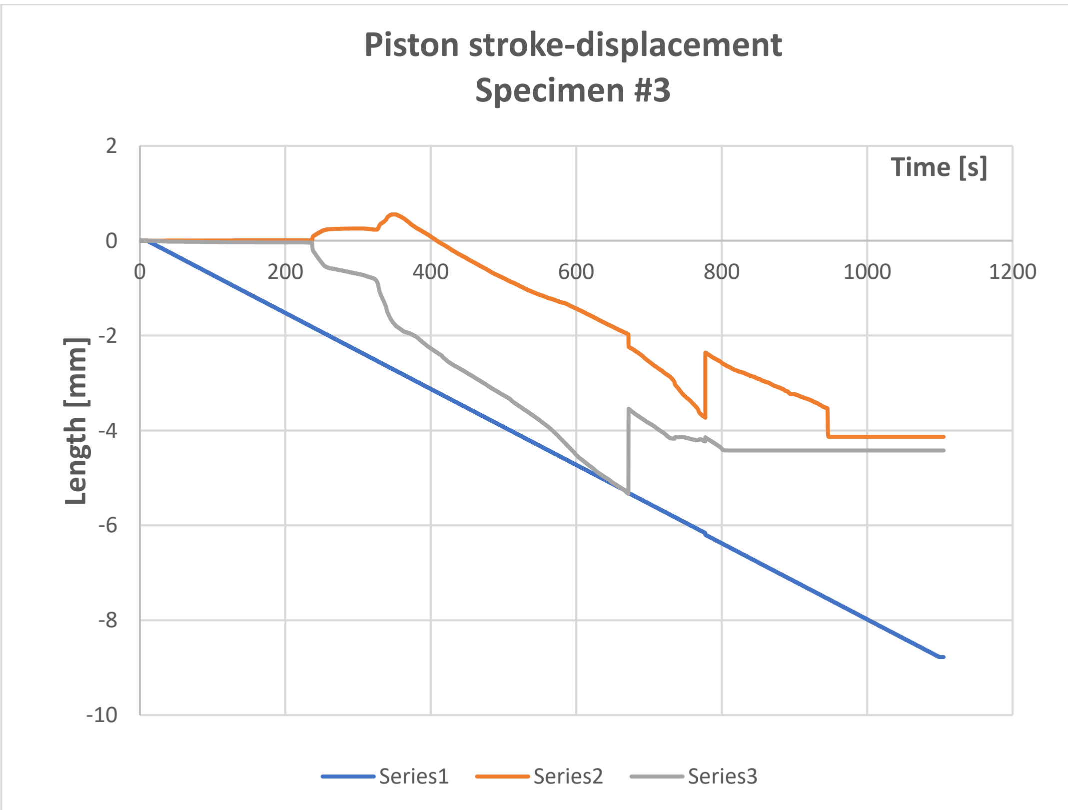
Mix Resilia HP – Specimen 3

Tensile behaviour	
ε [‰]	σ [MPa]
0	0
0.000167	4.02
0.002121	4.51






Piston stroke-displacement
Specimen #2
Time [s]
Length [mm]
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
200
400
600
800
1000
1200
Series1
Series2
Series3


Piston stroke-displacement
Specimen #3
Time [s]
Length [mm]
2
0
-2
-4
-6
-8
-10
0
200
400
600
800
1000
1200
Series1
Series2
Series3

Compression Test

Material properties

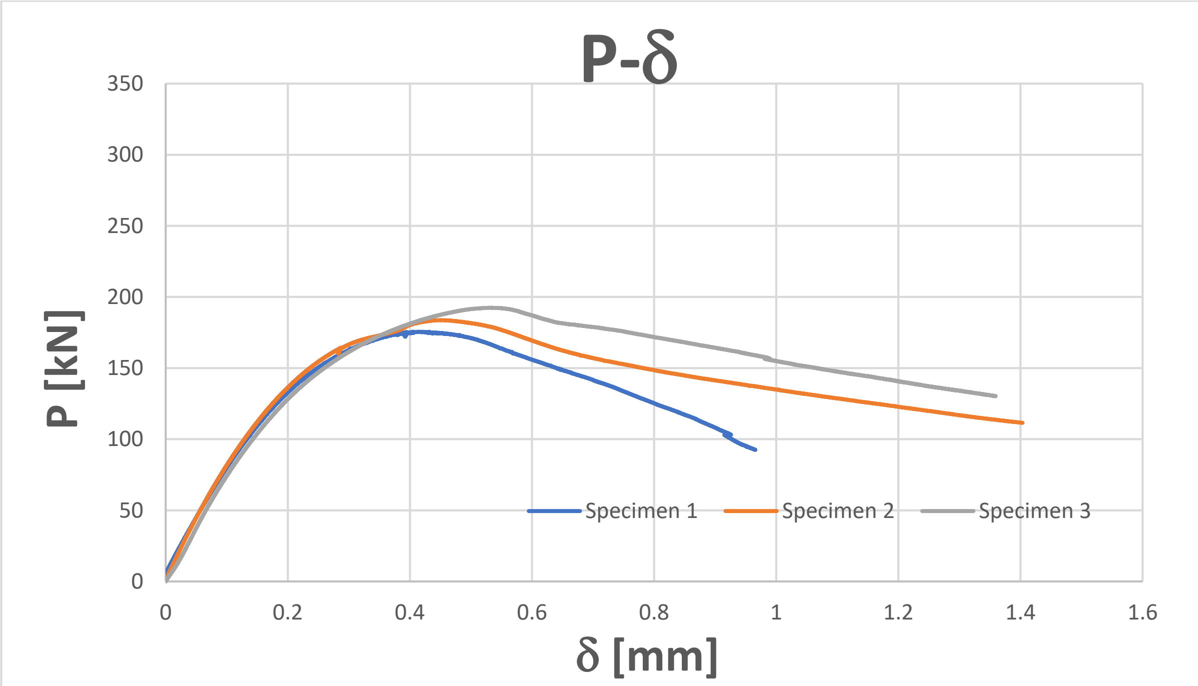
C90/105						Mix 8/Mix 15			
C70/85					Resilia HP	Mix 14			
C50/60	Mix 6	Mix 5	Mix 9	Mix 4	Mix 10	Mix 3	Mix 2	Mix 1	Mix 11
C40/50			Resilia			Mix 12			
C30/37						Mix 7/Mix 13			
	0.25%	**0.50%**	**0.75%**	**1.00%**	**1.50%**	**2.00%**	**3.00%**	**4.00%**	**6.00%**

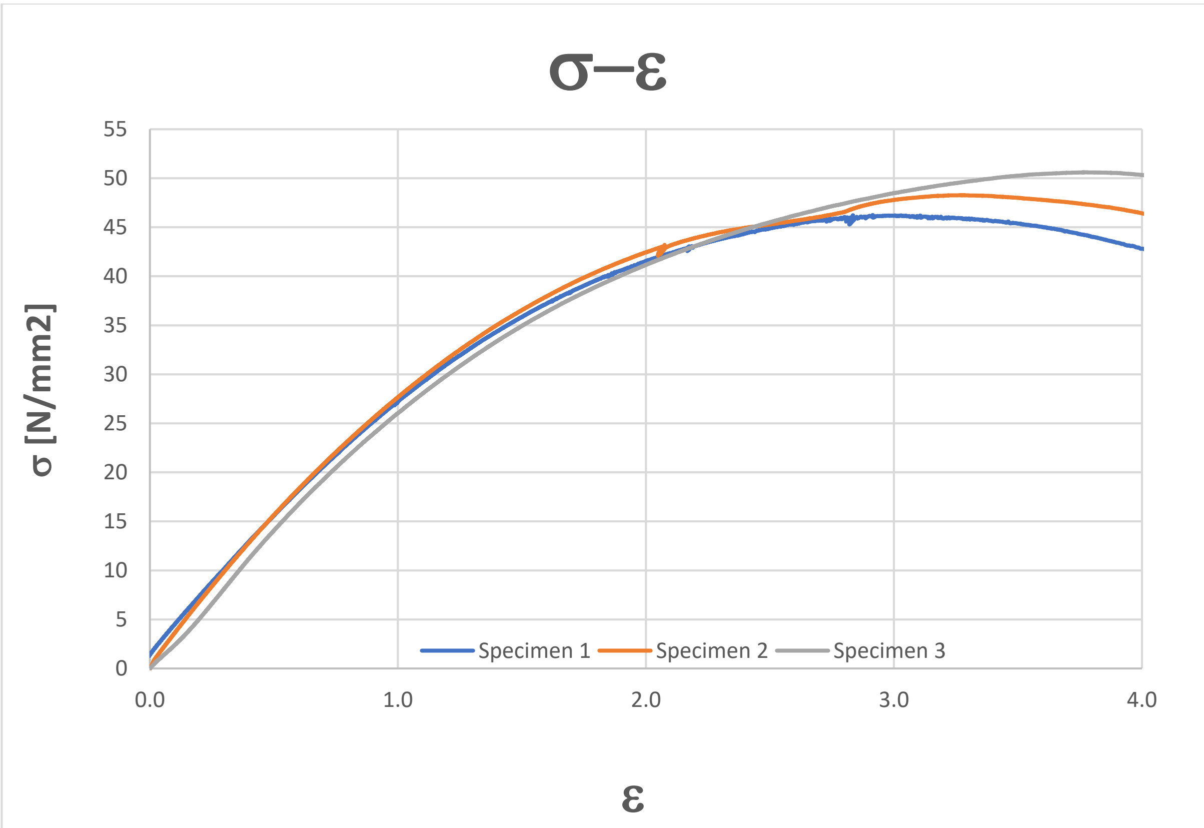
Geometrical properties

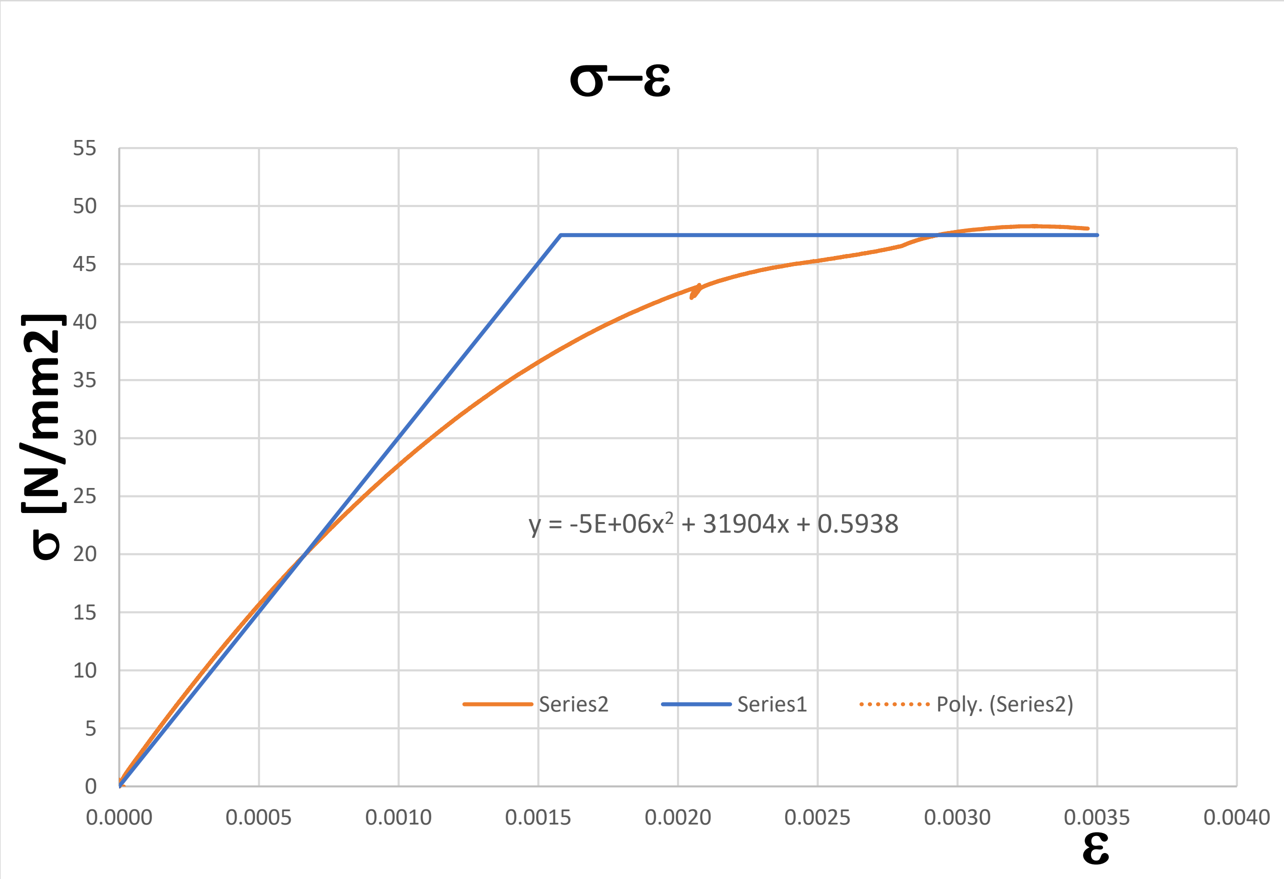
N.	Specimen	Height after grinding (mm)				Diameter (mm)							Section	Weight	Density	H/D	Maximum load	f_c	R_c	Tolerance planarity	Tolerance orthogonality	R_c (N/mm²) Mean
						upper		center		lower		mean										
		H_1	H_2	H_3	Media	D_1	D_2	D_1	D_2	D_1	D_2	D_{media}	(mm²)	(g)	(kg/m³)	(-)	(kN)	(N/mm²)	(N/mm²)	0,6‰·d≦0,06 mm	±0,25 mm	
1	m12_1	139.21	138.92	138.88	139.00	69.32	69.63	69.50	69.60	69.59	69.65	69.55	3799	1261	2390	2.00	0.0	0.0	0.0	Si	Si	81.7
2	M12_2	137.61	137.73	137.84	137.73	69.56	69.59	69.63	69.56	69.65	69.65	69.61	3805	1248	2380	1.98	1032.0	271.2	326.7	Si	Si	
3	M12_3	140.67	140.97	140.91	140.85	69.58	69.66	69.45	69.63	69.73	69.43	69.58	3802	1275	2380	2.02	0.0	0.0	0.0	Si	Si	
4	RHP1	138.84	138.76	138.73	138.78	69.54	69.73	69.75	69.38	69.48	69.30	69.53	3797	1234	2340	2.00	0.0	0.0	0.0	Si	Si	
5	RHP2	138.24	138.28	138.44	138.32	69.33	69.86	69.73	69.65	69.73	69.67	69.66	3811	1233	2340	1.99	0.0	0.0	0.0	Si	Si	0.0
6	RHP3	136.09	135.99	135.88	135.99	69.74	69.47	69.57	69.60	69.61	69.73	69.62	3807	1197	2310	1.95	0.0	0.0	0.0	Si	Si	

Mix 12

	Mean diameter [mm]	Mean height [mm]	σmax [N/mm2]	εmax.peak [‰]	Esec,peak [MPa]
Specimen #1	69.55	139.00	46.24	2.91396	15869.20091
Specimen #2	69.61	137.73	48.27	3.27198	14752.48492
Specimen #3	69.58	140.85	50.60	3.75932	13459.75716
Mean value			48.37	3.32	14693.81

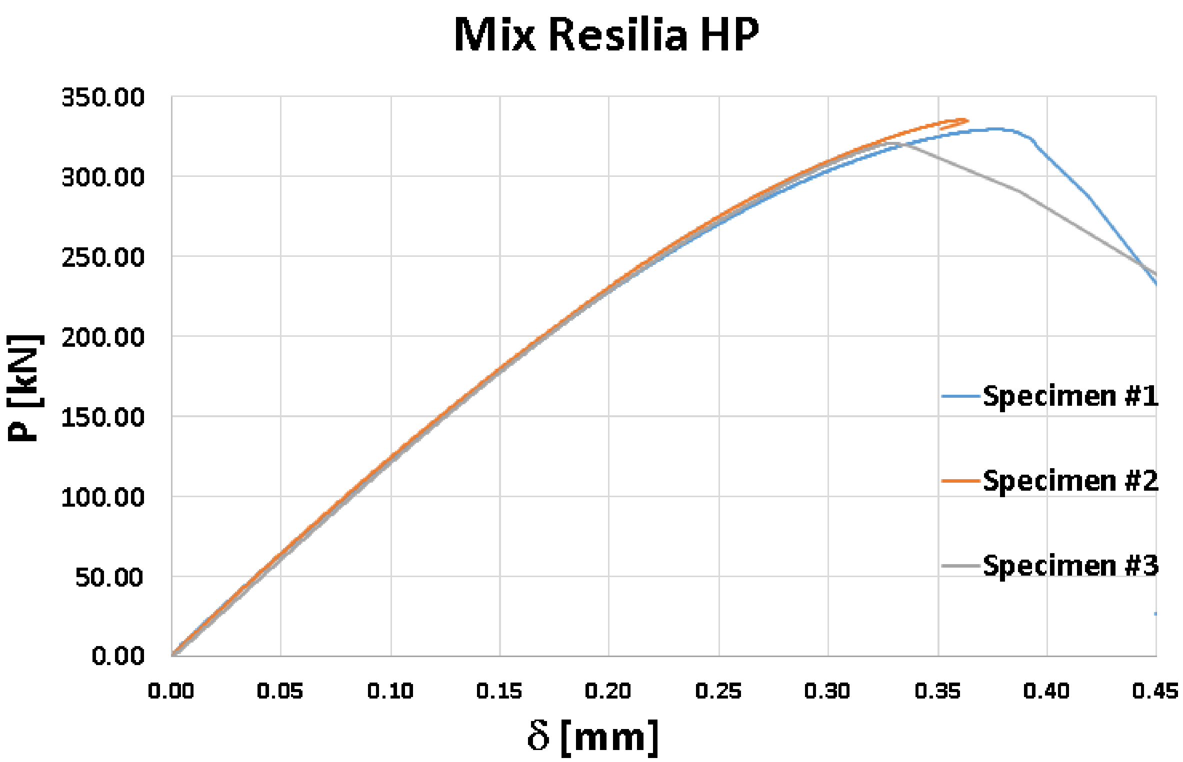

P-δ
P [kN]
δ [mm]
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Specimen 1
Specimen 2
Specimen 3

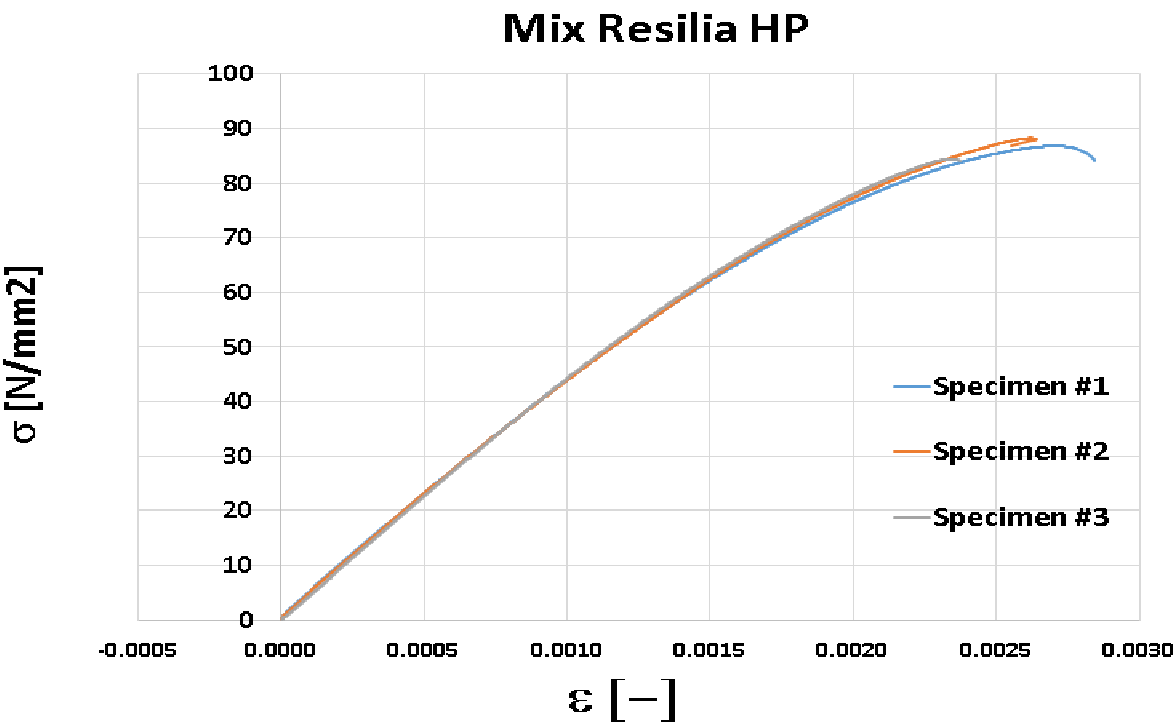

σ−ε
σ [N/mm2]
ε
55
50
45
40
35
30
25
20
15
10
5
0
0.0
1.0
2.0
3.0
4.0
Specimen 1
Specimen 2
Specimen 3



Mix Resilia HP

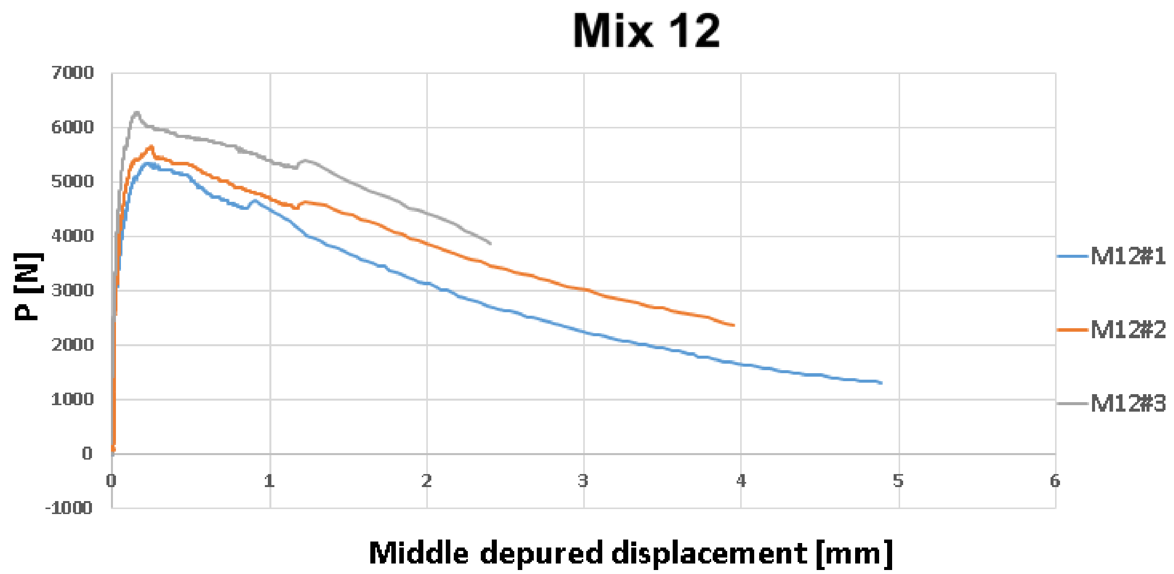
	Mean diameter Φ [mm]	Mean high [mm]	σ_{max} [N/mm2]	$\varepsilon_{max,peak}$ [‰]	$E_{sec,peak}$ [MPa]
Specimen #1	69.55	139.00	86.80	0.00265	32754719.18
Specimen #2	69.61	137.73	88.22	0.00255	34592931.22
Specimen #3	69.58	140.85	84.41	0.00227	37213903.86
Mean value			86.48	0.00	34853851.42

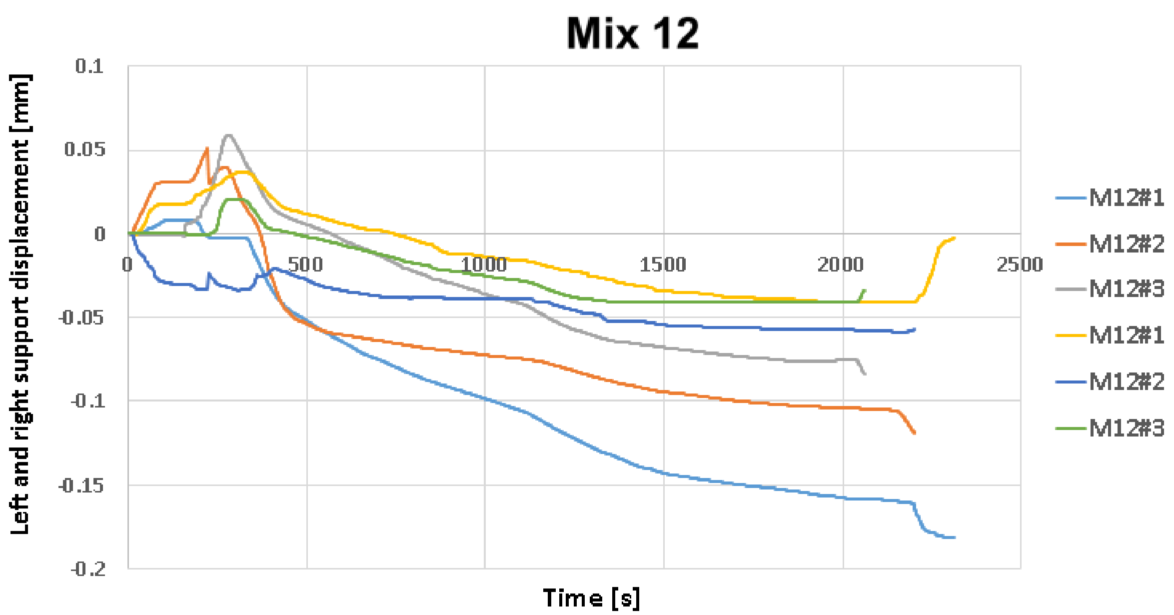

Mix Resilia HP
P [kN]
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
δ [mm]
Specimen #1
Specimen #2
Specimen #3

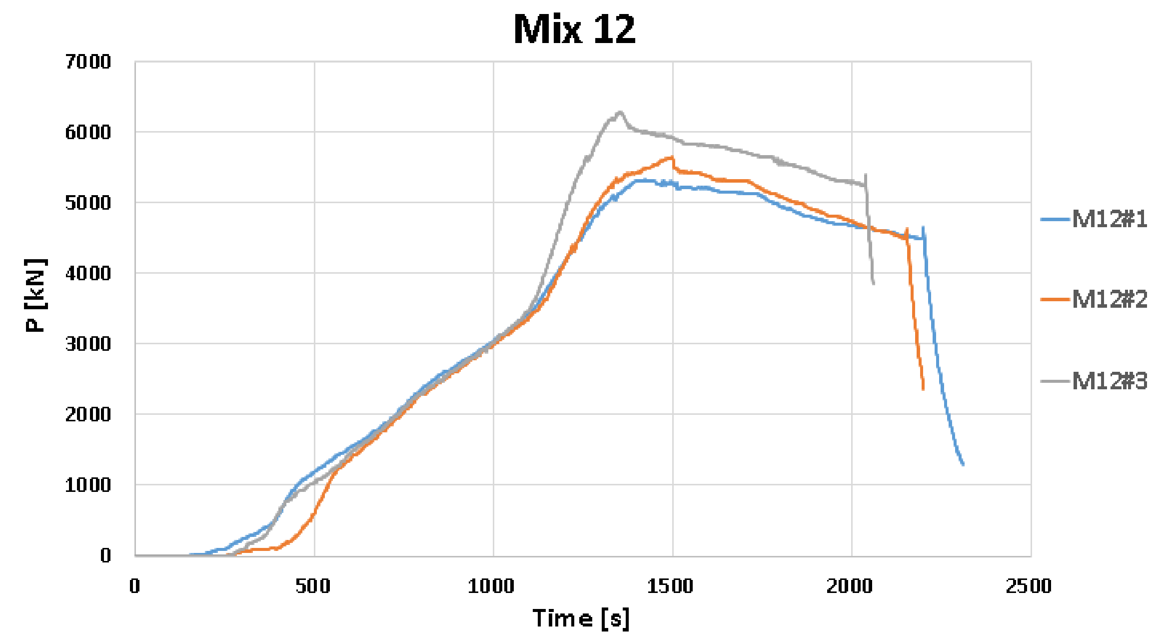

Mix Resilia HP
σ [N/mm2]
100
90
80
70
60
50
40
30
20
10
0
-0.0005
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
ε [−]
Specimen #1
Specimen #2
Specimen #3

Flexure Test

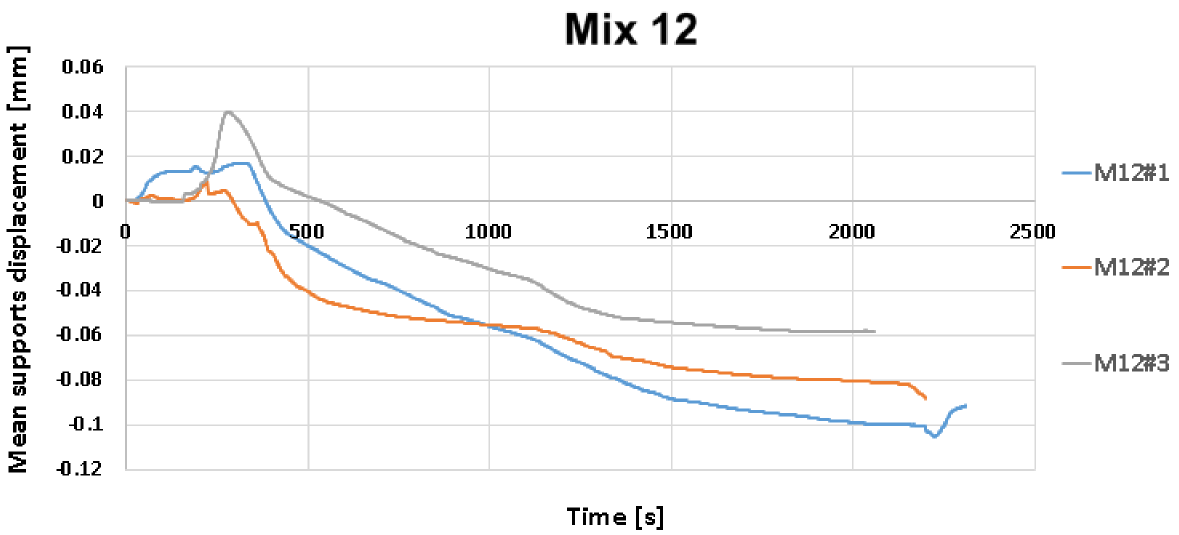
Mix 12



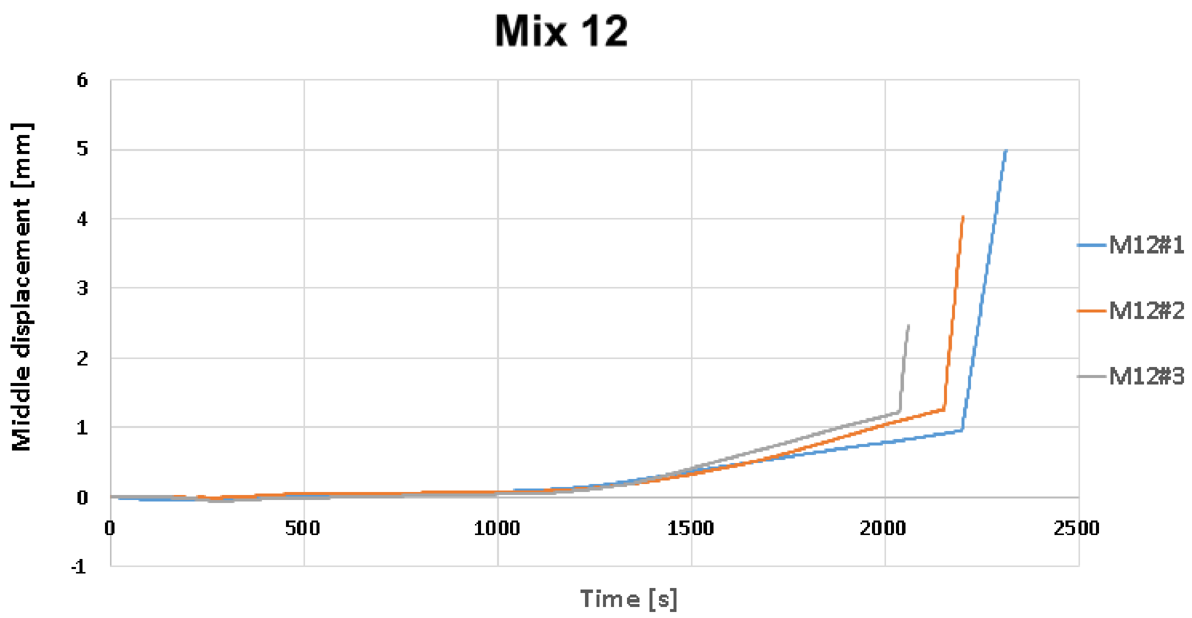




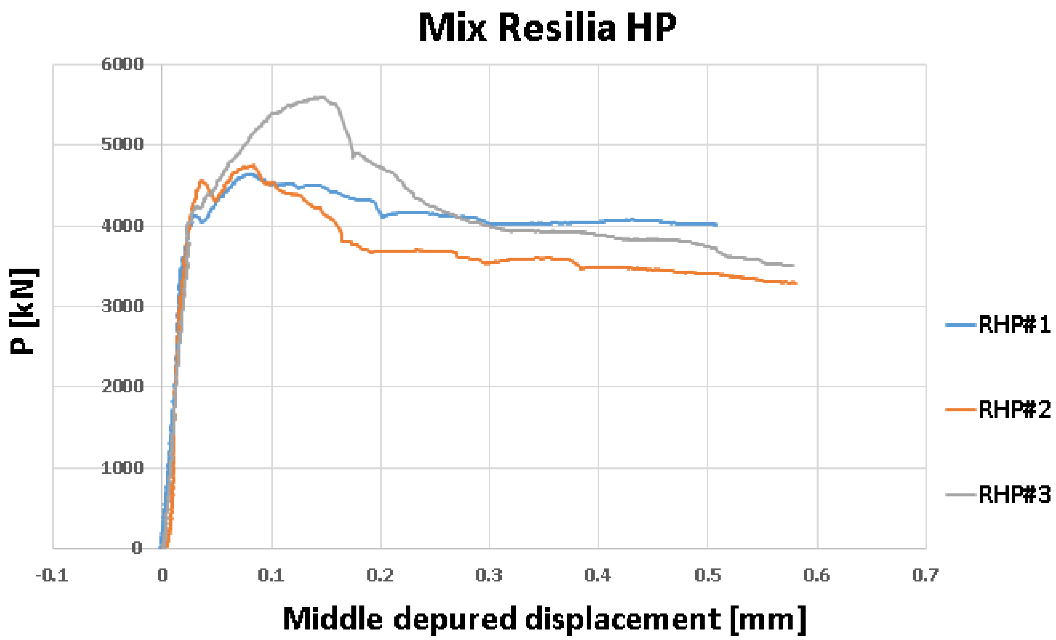
Mix 12
7000
6000
5000
4000
3000
2000
1000
0
P [kN]
0
500
1000
1500
2000
2500
Time [s]
M12#1
M12#2
M12#3

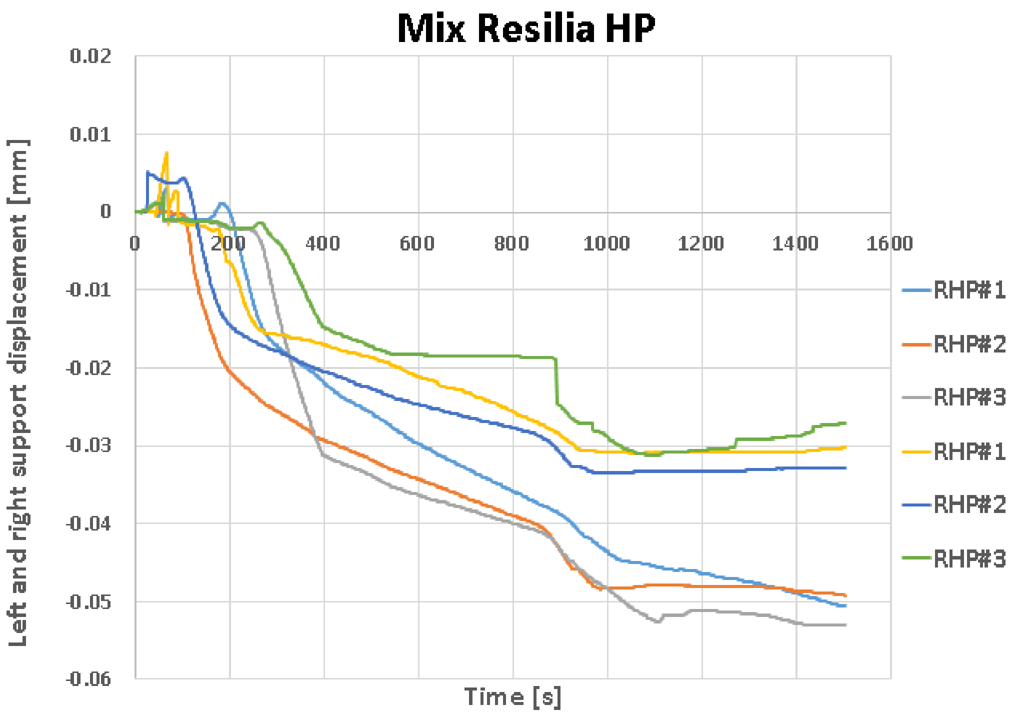


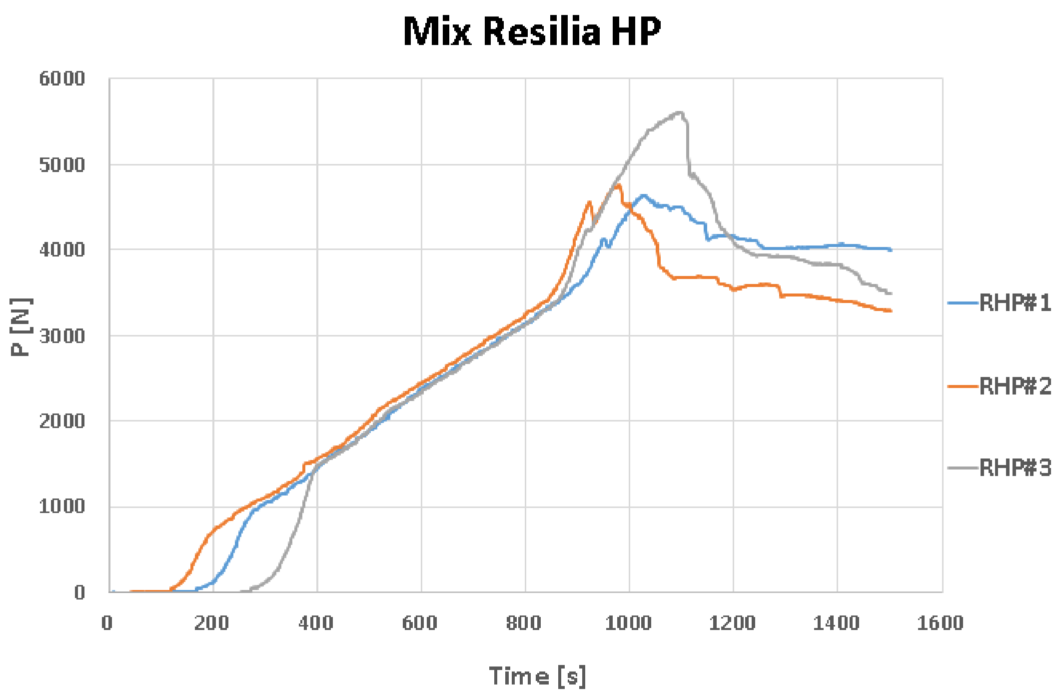
Mix 12
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
Mean supports displacement [mm]
0
500
1000
1500
2000
2500
Time [s]
M12#1
M12#2
M12#3

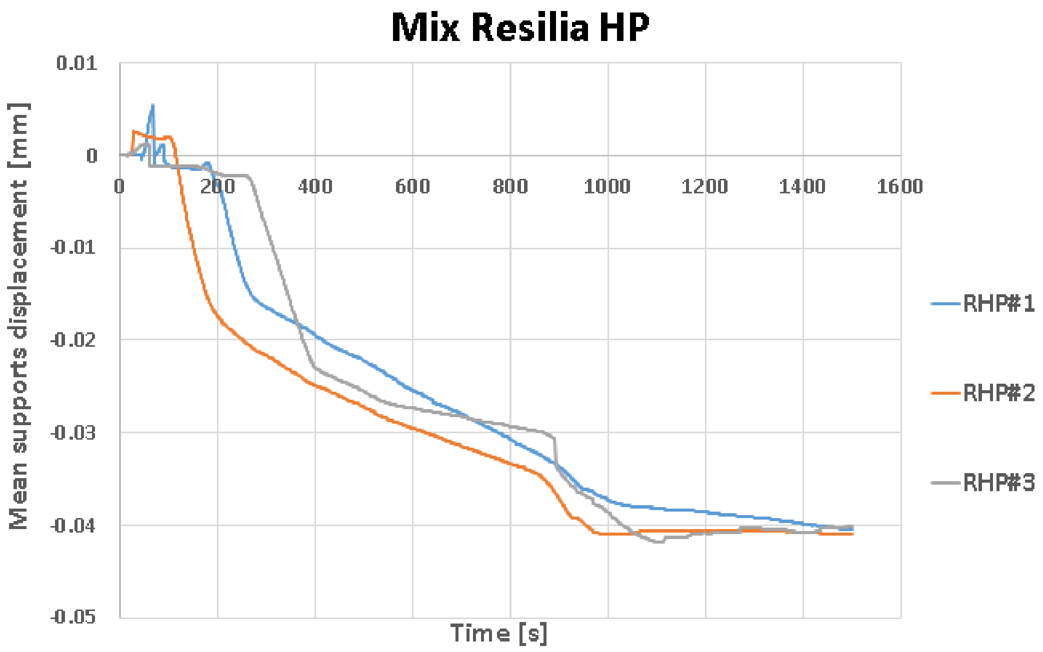


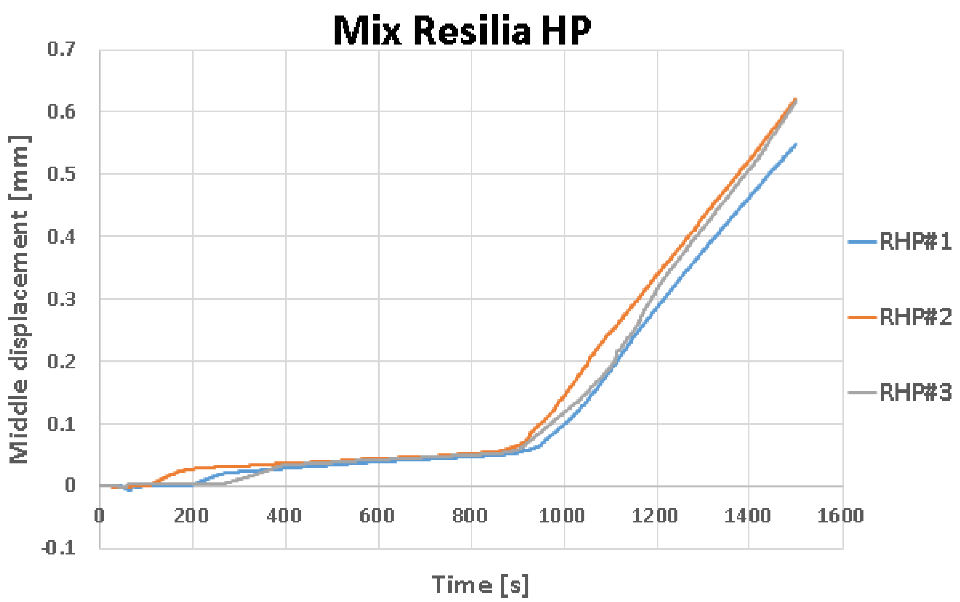
Mix Resilia HP




Mix Resilia HP
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
0
200
400
600
800
1000
1200
1400
1600
Left and right support displacement [mm]
Time [s]
RHP#1
RHP#2
RHP#3
RHP#1
RHP#2
RHP#3


Mix Resilia HP
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
P [N]
Time [s]
RHP#1
RHP#2
RHP#3


Mix Resilia HP
Mean supports displacement [mm]
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
200
400
600
800
1000
1200
1400
1600
Time [s]
RHP#1
RHP#2
RHP#3


Mix Resilia HP
Middle displacement [mm]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
200
400
600
800
1000
1200
1400
1600
Time [s]
RHP#1
RHP#2
RHP#3

TBR Relation

Mix 12

Sample Input Data for Specimen 1

Compressive properties of the specimen			
E	45000	[Mpa]	Young modulus
fck	86.5	[Mpa]	Compressive yielding stress
ε_{cy}	0.00350	[‰]	Compressive yielding strain
ε_{cu}	0.0035	[‰]	Ultimate compressive strain
Geometrical properties of the specimen			
b	40	[mm]	Width of the specimen
h	40	[mm]	Height of the specimen
L	100	[mm]	Length of the specimen
Input Data from Three Point Bending Test			
P_{el1}	1500	[N]	Beginning of linear behaviour in P-δ
P_{el2}	2400	[N]	End of linear stage in P-δ
P_{u1}	5080	[N]	Ultimate load before of first big crack
P_{ut}	5340	[N]	Ultimate load of the test
Ultimate research	0	-	Research of Post peak behaviour

Sample Input Data for Specimen 2

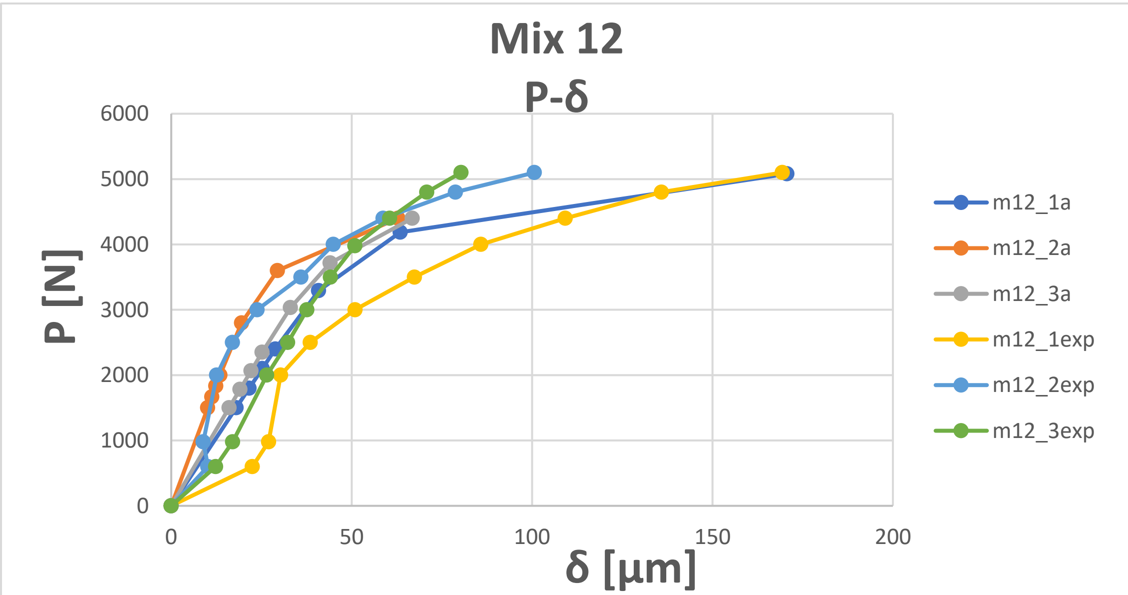
Compressive properties of the specimen			
E	45000	[Mpa]	Young modulus
fck	86.5	[Mpa]	Compressive yielding stress
ε_{cy}	0.00350	[‰]	Compressive yielding strain
ε_{cu}	0.0035	[‰]	Ultimate compressive strain
Geometrical properties of the specimen			
b	40	[mm]	Width of the specimen
h	40	[mm]	Height of the specimen
L	100	[mm]	Length of the specimen
Input Data from Three Point Bending Test			
P_{el1}	1500	[N]	Beginning of linear behaviour in P-δ
P_{el2}	2000	[N]	End of linear stage in P-δ
P_{u1}	4400	[N]	Ultimate load before of first big crack
P_{ut}	5640	[N]	Ultimate load of the test
Ultimate research	0	-	Research of Post peak behaviour

Sample Input Data for Specimen 3

Compressive properties of the specimen			
E	45000	[Mpa]	Young modulus
fck	86.5	[Mpa]	Compressive yielding stress
ε_{cy}	0.00350	[‰]	Compressive yielding strain
ε_{cu}	0.0035	[‰]	Ultimate compressive strain
Geometrical properties of the specimen			
b	40	[mm]	Width of the specimen
h	40	[mm]	Height of the specimen
L	100	[mm]	Length of the specimen
Input Data from Three Point Bending Test			
P_{el1}	1500	[N]	Beginning of linear behaviour in P-δ
P_{el2}	2350	[N]	End of linear stage in P-δ
P_{u1}	4400	[N]	Ultimate load before of first big crack
P_{ut}	6240	[N]	Ultimate load of the test
Ultimate research	0	-	Research of Post peak behaviour

P-δ Analytical					
Mix 12_1		Mix 12_2		Mix 12_3	
η [μm]	P [N]	η [μm]	P [N]	η [μm]	P [N]
0	0	0	0	0	0
17.99378	1500	10.1282	1500	16.04509	1500
21.61463	1800	11.25983	1666.667	19.09422	1783.333
25.24311	2100	12.39279	1833.333	22.14939	2066.667
28.87943	2400	13.52705	2000	25.21067	2350
40.87194	3293.333	19.50221	2800	33.05274	3033.333
63.45957	4186.667	29.46285	3600	44.05861	3716.667
170.6788	5080	62.87574	4400	66.80464	4400

P-δ Experimental					
Mix 12_1		Mix 12_2		Mix 12_3	
η [μm]	P [N]	η [μm]	P [N]	η [μm]	P [N]
0	0	0	0	0	0
22.51	600	10.18	600	12.32	600
27.015	980	8.885	980	17.045	980
30.335	2000	12.62	2000	26.5	2000
38.54	2500	16.97	2500	32.315	2500
50.955	3000	23.83	3000	37.63	3000
67.425	3500	35.96	3500	44.13	3500
85.85	4000	44.94	4000	50.925	3980
109.21	4400	58.735	4400	60.55	4400
135.9	4800	78.775	4800	70.855	4800
169.385	5100	100.675	5100	80.335	5100
248.96	5340	251.225	5640	103.825	5640



Mix Resilia HP

Sample Input Data for Specimen 1

Compressive properties of the specimen			
E	45000	[Mpa]	Young modulus
fck	86.5	[Mpa]	Compressive yielding stress
εcy	0.00350	[‰]	Compressive yielding strain
εcu	0.0035	[‰]	Ultimate compressive strain
Geometrical properties of the specimen			
b	40	[mm]	Width of the specimen
h	40	[mm]	Height of the specimen
L	100	[mm]	Length of the specimen
Input Data from Three Point Bending Test			
P_{el1}	1500	[N]	Beginning of linear behaviour in P-δ
P_{el2}	2000	[N]	End of linear stage in P-δ
P_{u1}	4120	[N]	Ultimate load before of first big crack
P_{ut}	4580	[N]	Ultimate load of the test
Ultimate research	0	-	Research of Post peak behaviour

Sample Input Data for Specimen 2

Compressive properties of the specimen			
E	45000	[Mpa]	Young modulus
fck	86.5	[Mpa]	Compressive yielding stress
εcy	0.00350	[‰]	Compressive yielding strain
εcu	0.0035	[‰]	Ultimate compressive strain
Geometrical properties of the specimen			
b	40	[mm]	Width of the specimen
h	40	[mm]	Height of the specimen
L	100	[mm]	Length of the specimen
Input Data from Three Point Bending Test			
P_{el1}	1500	[N]	Beginning of linear behaviour in P-δ
P_{el2}	2000	[N]	End of linear stage in P-δ
P_{u1}	4540	[N]	Ultimate load before of first big crack
P_{ut}	4760	[N]	Ultimate load of the test
Ultimate research	0	-	Research of Post peak behaviour

Sample Input Data for Specimen 3

Compressive properties of the specimen			
E	45000	[Mpa]	Young modulus
fck	86.5	[Mpa]	Compressive yielding stress
εcy	0.00350	[‰]	Compressive yielding strain
εcu	0.0035	[‰]	Ultimate compressive strain
Geometrical properties of the specimen			
b	40	[mm]	Width of the specimen
h	40	[mm]	Height of the specimen
L	100	[mm]	Length of the specimen
Input Data from Three Point Bending Test			
P_{el1}	1000	[N]	Beginning of linear behaviour in P-δ
P_{el2}	1900	[N]	End of linear stage in P-δ
P_{u1}	4300	[N]	Ultimate load before of first big crack
P_{ut}	5600	[N]	Ultimate load of the test
Ultimate research	0	-	Research of Post peak behaviour

Mix Resilia HP

P-δ Analytical					
Rhp 1		Rhp 2		Rhp 3	
η [μm]	P [N]	η [μm]	P [N]	η [μm]	P [N]
0	0	0	0	0	0
8.810707	1500	6.712074	1500	5.709811	1000
9.7906	1666.667	7.458567	1666.667	7.423984	1300
10.77066	1833.333	8.205197	1833.333	9.138742	1600
11.75096	2000	8.95197	2000	10.85412	1900
16.21691	2706.667	13.12317	2846.667	15.89589	2700
22.70795	3413.333	20.00656	3693.333	23.98395	3500
34.27891	4120	36.30612	4540	38.74057	4300

P-δ Experimental					
Rhp 1		Rhp 2		Rhp 3	
η [μm]	P [N]	η [μm]	P [N]	η [μm]	P [N]
0.0000	0	0	0	0	0
4.1650	500	4.7	500	4.7	500
6.8250	980	5.815	980	7.105	980
12.6750	2000	8.115	2000	12	2000
14.4250	2500	10.485	2500	15.26	2500
15.9850	3000	13.11	3000	19.13	3000
18.8750	3500	15.99	3500	23.065	3500
31.0000	4120	24.51	4220	29.34	4220
57.9800	4400	27.37	4400	49.42	4500
66.4300	4540	33.1	4540	74.25	5000
77.5150	4640	70.67	4700	114.39	5500