Trabajo de Investigación CST/MIH

A STUDY OF THE INFLUENCE OF MODERATED TEMPERATURE ON THE BEHAVIOUR OF MACROSYNTHETIC FIBRE REINFORCED CONCRETES.

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Septiembre 2018

Autor / Author: Marta Caballero Jorna		Fecha / Date: 14/09/2018
Título / Title A STUDY OF THE INFLUENCE OF MODERATED TEMPERATURE ON THE BEHAVIOUR OF MACROSYNTHETIC FIBRE REINFORCED CONCRETES.		
Directores del trabajo / Supervisors: Prof. Dr. Pedro Serna Ros	Código / Code: CST/MIH	Nº páginas / Pages: 87
Departamento / Department: INGENIERÍA DE LA CONSTRUCCIÓN Y PROYECTOS DE INGENIERÍA CIVIL		
Universidad / University: UNIVERSITAT POLITÈCNICA DE VALÈNCIA		
Palabras clave / Keywords: Envejecimiento; hormigón reforzado con fibras; macrofibras sintéticas; temperatura moderada; resistencia residual Aging; Fibre Reinforced Concrete; Macrosynthetic fibres; Moderate Temperature, Residual flexural strength		
Código Unesco: 3305/05 Ciencias tecnológicas/Tecnología de la construcción/Tecnología del Hormigón 3312/08 Ciencias tecnológicas/Tecnología de los materiales/Propiedades de los materiales 3312/12 Ciencias tecnológicas/Tecnología de los materiales/Ensayo de Materiales		

Acknowledgements

En este pequeño espacio personal, quiero aprovechar para dar las gracias a todas aquellas personas que me han apoyado, de una u otra manera, durante estos dos años de mi vida académica cursando el Máster Universitario en Ingeniería del Hormigón.

En primer lugar, quiero dar las gracias a Dios por haberme dado la fuerza para llegar a este punto de mi Trabajo Final.

Me gustaría expresar también mi más sincero agradecimiento a mi tutor, Pedro Serna, por haberme guiado en esta andadura y por haber compartido conmigo su pasión por lo que hace. Asimismo, a Francisco Martorell y a Aitor Llano por su ayuda, su paciencia infinita y nuestros momentos de risas.

No quiero dejar pasar por alto a mis amigas, por darme ánimos en los momentos que más se necesitaban y a mis amigos del máster, mil gracias por todo,… juntos hemos logrado vencer muchos obstáculos y estoy segura, que la distancia no será un problema para que nuestra amistad perdure en el tiempo. Quiero dedicar una mención especial a Gaétan Poelman por su tiempo, su ayuda, por escucharme y por motivarme a dar siempre lo mejor de mí, bedankt.

Y por último, a mi familia, la incondicional, gracias por estar siempre ahí. En especial, a Dani y a Alberto, agradecerles su incesante humor y su apoyo, y a mis padres, por haber confiado en mí, apostado por mí, brindándome la oportunidad y la magnífica experiencia que ha supuesto, no solo académicamente sino también personalmente, haber alcanzado esta meta.

Abstract

The addition of fibres to the cement matrix is used since the sixties to take advantage of the benefits they offer in fibres reinforced concrete (FRC) compared to traditional concretes.

The technological advances in the construction sector have not stopped since then, managing to introduce different types of fibres into the market. Macrosynthetic fibres appeared more recently than steel fibres and although their behaviour has been studied, the effect of temperature on macrosynthetic fibres reinforced concrete (MSFRC) has not been evaluated yet in depth. Macrosynthetic fibres may be affected by temperature changes since their mechanical properties are thermally dependent which thus has influences on the properties of MSFRCs.

This Master's Thesis analyses the short-term behaviour of MSFRCs at different temperatures. To do this, a common concrete of the prefabricated industry of 35 MPa, with a maximum aggregate size of 10mm and a relatively high fibre content (10 kg/m³) was selected. Three-point bending test were carried out according to a testing methodology based on the standard UNE-EN 14651:2007+A1:2008 (2/3 scale). This procedure allows to evaluate the mechanical properties of the concrete after reaching its nominal strength and after a conservation period of two months, when the entire mass is at the target temperature as well as the effect of its variation when the concrete is in service condition. The target temperatures were: 5 °C, 20 °C, 35 °C and 50 °C.

Other options have also been considered like pre-fissuring of the specimens and the use of different types of fibres in order to compare and extrapolate results. Compressive strength and workability of the concrete were used as complementary characterization tests.

The results show that moderated temperatures do (to a great extent) not affect performance of macrosynthetic fibre reinforced concrete for this period of conservation, since the short-term mechanical behaviour (residual flexural strengths) of these materials is quite similar (also compared to other results of FRCs), but it can not be affirm that temperature has not a significant influence. This contribution opens the possibility of continuing to further investigate this.

Keywords: Aging; Fibre Reinforced Concrete; Macrosynthetic fibres; Moderate temperature; Residual flexural strength.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACI	American Concrete Institute
ASTM	American Society of Testing Materials
BCN	Barcelona test
CMOD	Crack Mouth Opening Displacement
COV	Coefficient Of Variation
CTOD	Crack Tip Opening Displacement
DAE	Data Acquisition equipment
EC	Eurocode
EHE	EHE-08, Code on Structural Concrete (Instrucción Española del Hormigón Estructural)
EPC	Elasto Plastic Concrete
ESEM	Exploratory Structural Equation Modeling
FLWAC	Fibre Lightweight Aggregate Concrete
FRC	Fibre Reinforced Concrete
FRCA	Fiber Reinforced Concrete Association
GFRC	Glass Fibre Reinforced Concrete
ISO	International Organization for Standardization
LOP	Limit Of Proportionality
MAS	Maximum Aggregate Size
MSFRC	Macrosynthetic Fibre Reinforced Concrete
MTSU	Middle Tennessee State University
OPC	Ordinary Portland Cement
PAN	Polyacrylonitrile
PET	Polyethylene Terephthalate
PP	Polypropilene
PVA	Polyvinyl Alcohol

RC	Reinforced Concrete
RH	Relative Humidity
(R+S)C	(Reinforced + Steel Fibre) Concrete
SCC	Self-Compacting Concrete
SEM	Scanning electron microscopy
SFRC	Steel Fibre Reinforced Concrete
SLS	Service Limit State
TG	Thermogravimetry
UHPC	Ultra High Performance Concrete
UNE	A Spanish Standard (Una Norma Española)
UPV	Polytechnic University of Valencia
XRD	X-ray Powder Diffraction

List of Symbols

A_c	Transversal area of the specimen where load is applied
b	Width of specimen
CO_2	Carbon dioxide
$CMOD_{FL}$	CMOD at LOP
$CMOD_j$	Value of CMOD, j = 1, 2, 3, 4
$CMOD_y$	CMOD at y
df	Fibre diameter
F	Load
F_j	Load, j = 1, 2, 3 or 4
F_L	Load at LOP
f_L, f ___	LOP
f_{Rj}	Residual flexural strength, j = 1, 2, 3 or 4
GPa	Giga Pascal
h	Depth of specimens
h_{sp}	Distance between the tip of the notch and the top of the test specimen in the mid-span section
H_2SO_4	Sulphuric acid
kg/m^3	Kilogram / cubic metre
kg	Kilogram
kN	Kilo Newton
lf	Fibre length
M	Bending moment
M_L	Bending moment corresponding to the load at LOP

M_j	Bending moment value, j = 1, 2, 3 or 4
$MgSO_4$	Magnesium sulphate
MPa	Mega Pascal
mm	Millimetre
N/mm^2	Newton / millimetre square
NaOH	Sodium hydroxide
Vf	Volume of fibres
w/b	Water to binder
y	Distance between the tip of the notch and axis of displacement transducer
%	Percent
$^{\circ}C$	Celsius degrees
#	Number

Chapter 1

Introduction

Chapter 1 provides a general overview of the theme of this Master's Thesis. In the following sections, an introduction is given in order to justify the development of the work. Furthermore, the objectives are defined and the manuscript's structure is explained.

1.1 Introduction and Justification

The constant changes of conception and mentality in our society require materials that meet certain expectations regarding sustainability and other performances. These actions, together with the technological advances in the construction sector, have led to the ascending trend of application of fibres in concrete.

The inclusion of fibres in the cement matrix was introduced in the sixties in order to take advantage of the benefits they offer in fibres reinforced concrete (FRC). These enhancements include a notable residual flexural strength, the capacity to absorb strain energy, a diminution of crack-width and a reduction of the permeability. This means that the addition of fibres gives rise to significant durability improvements compared to traditional concrete.

In the last few decades, distinct types of fibres have appeared on the market. As is know, the utilization of steel fibre reinforced concrete (SFRC) is already spread out worldwide and is being included in standards and codes. This is the fruitful result of many collaborations with the goal of obtaining a better understanding of SFRCs.

Nevertheless, macrosynthetic fibre reinforced concretes (MSFRCs) have emerged not long ago. Their main application is the control of cracks due to shrinkage. This fact restricted their use to non-structural works for years but MSFRCs are becoming gradually accepted in the structural field. Actually, macrosynthetic fibres are put in service as reinforcement in tunnels nowadays. To reach this situation, a characterization of this complex material was needed and although several authors have contributed in the study of their behaviour, many aspects require further investigation in this area.

An analysis of the existing literature (Chapter 2) revealed an important lack of information around some issues; one of them is the influence of moderated temperature on MSFRCs. It is well proven that macrosynthetic fibres are suitable at elevated temperature, however, the effect of usual temperatures (5 °C - 40 °C) is a point of ongoing discussion. Macrosynthetic fibres may be affected by these temperatures since they are thermally dependent which thus affecting the characteristics of MSFRCs. Moreover, climate conditions involve irregular variations of temperature and relative humidity, which may also induce a non-constant state in the concrete day-to-day and could pose a risk for safety conditions. Therefore, it is essential to gain a fairly accurate knowledge of the behaviour (short-term and long-term properties) of MSFRCs in function of the temperature in order to make the most of their mechanical advantages and to avoid problems and accidents in service and limit states.

This context has motivated this Master's thesis, aiming to evaluate the mechanical behaviour of macrosynthetic fibres reinforced concrete subjected to ordinary temperatures. Besides, an experimental program was also developed to analyse whether macrosynthetic fibres may be a viable alternative in applications where they have a limited use. Towards this end, residual flexural strengths at different moderate temperatures are investigated in order to gain conclusions about their influence on MFSRC, mitigating the existing lack of confidence with respect to these fibres or determining that they are not appropriate in some cases.

1.2 General Objective

The principal objective of this project is the study of the influence of moderated temperatures (service temperatures) on the mechanical behaviour of macrosynthetic fibre reinforced concretes, in particular their residual flexural strengths. The effect of the curing temperature, as well as fire exposition, falls outside of the scope of this investigation.

1.3 Specific Objectives

Other specific goals are based on the next chapter, where scarcity of information and studies related to this theme is evident. They are also integrated and conducted in order to accomplish the general aim. These objectives are:

- Expanding the information on this topic to be able to obtain a better understanding, given that the fact that its state of the art is not extensive. It is expected to provide an extra comprehensible knowledge in order to be investigated in subsequent works.
- Carrying out an experimental campaign comprising compressive tests, slumps, three-point bending tests.
- Recognizing the worth of the employed procedure to perform the experimental part (three-point bending test) at target temperatures (a standardized methodology does not exist).
- Studying the complementary effect of other considered factors (type of fibre, condition of conservation and service condition) on the residual flexural strength at different temperatures.

1.4 Structure of the Document

Chapter 1 presents a brief introduction into the field of inquiry, explaining the reasons why it is of interest to conduct this investigation. The general and specific aims are also explained, considering the previous justification. Finally, a short description about the contents in each section is given.

Chapter 2 consists of a complete bibliography outline. It starts by explicating basic and general concepts related to fibre reinforced concretes in order to evaluate the current state of knowledge. Besides, the background of the effect of temperature on the aging of fibres for concrete and the preceding literature around its influence on FRC's properties are summarized.

In Chapter 3, the experimental program that was performed in this study is explained, including variables, materials, equipment, specimens and methodology.

Chapter 4 collects the obtained results during the complementary characterization testing for every sample, as well as the values of the residual flexural strengths as function of the temperature.

In Chapter 5, these previous results are analysed after data processing. These are also compared to other values for different kind of concretes and compared to studies of other authors.

Chapter 6 presents the conclusions of this study and Chapter 7 proposes improvements and possible future research directions.

Finally, references and appendices are attached in order to clarify some aspects of this Master's Thesis.

Chapter 2

State of the Art

The purpose of this chapter is to collect information and give an idea about the existing knowledge on the influence of moderated temperatures on MSFRCs. To do this, an introduction with notions of fibre reinforced concrete is exposed. Concepts regarding macrosynthetic fibre reinforced concretes (including advantages, disadvantages, properties, market position, …), the existing technical data, their applications in the construction sector and their gradual inclusion on the standards and codes are provided.

Afterwards, a review of studies that were carried out at moderate temperatures on macro plastic fibres reinforced concrete, is presented. Thus, Chapter 2 presents the current state of the art, i.e. the currently published results of several researches relating to this issue. It is important to notice that the literature on this topic is quite limited, clearly suggesting that further experimental investigations are needed in order to achieve a consistent agreement. Finally, a critical summary is conducted, besides which, unresolved question are identified and treated.

To do this, studies into the temperature and degradation of synthetic fibres in concrete, as well as designs of materials and products that include synthetic fibres, were carried out. The gathered information originates from doctoral theses and scientific-technical publications of universities, research centres and organizations. In order to facilitate the search of information, the behaviour of other special concretes, temperatures,…, were also consulted.

2.1 Concept of Fibre Reinforced Concrete

Fibre reinforced concrete (FRC) was one of the most significant innovations in the special concretes field. The cement-based materials were generally considered to be fragile with a low tensile strength and deformability. However, fibres have permitted to overcome this limitation. The mechanical properties of a cementitious matrix are modified when fibres are added, producing mixtures with improved mechanical capacity, greater ductility, toughness and durability.

The concept of reinforcing brittle materials with fibres is quite old, but the interest in reinforcing this composite started during the 1960's. Since then, substantial investigations have been developed throughout the world on the topic of fibre reinforced concretes (FRCs).

Because of this increasing relevance, several regulations have included definitions, parameters and recommendations relating to FRCs. For instance, Annex 14 of the EHE-08, Code on Structural Concrete *(Ministerio de fomento, 2008)* describes fibre reinforced concretes as those that have short, discrete and randomly distributed fibres in their mass. According to the definition of the ACI Committee 544 *(ACI Committee 544, 2002)*, FRCs are made from hydraulic cements, containing fine and/or coarse aggregates, water and discontinuous discrete fibres whose mission is to contribute to the improvement of certain characteristics of a concrete. Furthermore, the Model Code *(FIB, 2012)* defines FRCs as composite materials characterized by a cement matrix and discrete fibres (discontinuous). No information is available for FRC in the Eurocode but a section, that includes fibres as structural reinforcement, is in preparation. It becomes clear that similar statements are adopted by the different existing regulations.

The characteristics of the FRCs depend on their components and their mix proportions. Pujadas (Pujadas, 2009) pointed out that the effectiveness of the action of the fibres relies on several factors such as their nature, type and geometry.

Other variables like the fibre content and the mechanical properties of the fibres, the bond between fibre and concrete matrix and the mechanical properties of the matrix also affect the FRC properties.

Thus, it is of interest to consider these statements in order to make an appropriate choice for the fibre type, taking also into account their future applications and economic factors. From this point of view, fibres might be made of steel, polymers, carbon, glass or natural materials. The fibres indicated in Table 1 have generally performed well in Ordinary Portland Cement (OPC) matrices and additionally. Their most important characteristics are also presented in this table.

Table 1. Properties of the most common fibres according to the ACI Committee 544, 2002

Fibre type	Equivalent diameter (mm)	Specific gravity (kg/m³)	Tensile strength (MPa)	Elastic modulus (GPa)	Ultimate elongation (%)
Steel	0.1500-1	7840	345-3000	200	4-10
Carbon	----	1400	4000	230-240	1.4-1.8
Polymer	0.020-1	900-1400	200-860	1.5-8.3	3-13
Glass	0.005-0.15	2500	1000-2600	70-80	1.5-3.5
Natural	0.025-0.40	1020-1500	65-700	0.9-40	1.2-25

Steel fibre reinforced concretes (SFRCs) are the most studied and used ones. Reasons that have justified their use include (amongst others) their manufacturing and effectiveness as reinforcement. The addition of metallic fibres strongly improves the ductility and the mechanical behaviour after post-cracking (or post-peak) of this composite. As a consequence, they are used in structural applications to obtain labour reduction, increased durability and diminution of traditional reinforcement. They are also used for self-compacting concrete, shotcrete applications, high-strength performance concrete and industrial constructions, particularly related to high-responsibility structures such as tunnels, nuclear power plants, bridges, ground support, etc.

This type is followed by plastic and glass fibres. On the one hand, the single largest application of glass fibre reinforced concretes (GFRCs) is the manufacturing of exterior building facade panels. The usefulness of GFRC in other applications, such as electrical utility products, floating dock, surface bonding and building restoration, is increasing *(FIB, 2012)*. On the other hand, macro- and microsynthetic fibre reinforced concretes have opened up new possibilities into the market. The microsynthetic fibres are plastic fibres whose diameter ranges from 5 to 100 μm and length is 5-30 mm *(Nili and Afroughsabet, 2010)*. These effectively control or reduce the plastic shrinkage, minimize thermal cracking, provide good thermal energy storage to concrete and also significantly improve the tensile flexural strength and toughness of concrete. The macrosynthetic fibres normally have a length of 30–60 mm and cross section of 0.6–1 mm² *(Yin et al., 2015)*. The most widespread commercial application of these type is found in slabs on grounds, footpaths, floor slabs and stay-in-place forms in multi-story buildings. MSFRCs are also used for tunnel linings, bridge decks, airport pavements, industrial floors, dams, pipes, swimming pools, screeds, precast elements, shotcretes, power plants and marine structures *(Alani and Beckett, 2013).* They are also extensively researched to estimate the possibility of using these fibres in concrete on grade and other structural applications *(Buratti, Mazzotti and Savoia, 2011).*

In some instances, their roles are still limited with respect to their potentials, mainly due to the scarcity of international guidelines, as Garcia-Taengua et al. *(Garcia-Taengua, Martí-Vargas and Serna, 2016)* pointed out. Regarding this matter, building codes and recommendations are gradually including fibres as a result of the market experience and an increasing confidence. Some of them were mentioned before, for instance: Chapters 5 and 7 of the Model Code contemplate the addition of fibre and their positive effects in concrete. The Eurocode (EC) will incorporate a section that is currently being drafted around this reinforcing material. On its behalf, ACI has presented various report on FRCs. In Spain, the regulatory framework regarding FRCs is constituted by Annex 14 of the EHE Instruction, and it is based on UNE standards. At present, these assist engineers and designers when adding fibres to concrete elements. In spite of this existing regulation, fibre manufacturers and suppliers should confirm the applicability of their fibres for every intended application without dismissing required third-party tests. For instance, Table 2 provides a list of tailored test methods that Sika utilised to evaluate the main characteristics of its FRCs.

Table 2. Example of FRC standards and tests, provided by SikaFiber®TECHNOLOGY

Test method	Standard	Description of the test
Energy absorption	ASTM C1150	Round panel test
	EN 1488-5	Square panel test
Residual strength	EN 14651	Beam test
Fire resistance	RWS	Max 1350 °C, 2 hours
	ISO 834	Starts at low temperature, continuously increasing
	HC modified	Max 1200 °C, 4 hours
Shrinkage cracking	ASTM C 1581-04	Test method to determine restrained shrinkage
Impact resistance	Various local standards	Impact energy tests

Relating to the fibre market, the Fiber Reinforced Concrete Association (FRCA) is an organization, which was formed in 1991, focusing on advancing the development, knowledge and market of FRCs. FRCA members include major manufacturers, suppliers and marketers of the world's most popular fibre reinforcement products in the concrete industry. Table 3 compiles the members of this group, which work in the construction and industrial trade. As is shown here, there are more distributors than manufacturers.

Table 3. Members of FRCA

Company	Role	Location
ABC Polymer Industries, LLC	Manufacturer of synthetic fibres	USA
BASF Corporation	Producer and marketer of chemicals and construction products	Worldwide
Durafiber, Inc.	Plastic fibres distributor	North America
Euclid Chemical	Provider of chemicals and building materials	Worldwide
Elasto Plastic Concrete	Supplier of structural synthetic fibre reinforcement	Worldwide
Fabpro Polymers	Premier developer and manufacturer of plastic fibres	Worldwide
FORTA Corporation	Manufacturer of synthetic fibres	Worldwide
Grace Construction Products	Provider of chemicals and materials for construction	Global
Monahan FiberWorx	Manufacturer and leading innovator on synthetic fibres	USA
Propex Global	Leading developer of innovative solutions	USA
Sika Corporation	Supplier of chemical products and industrial materials	Worldwide
Solomon Colors, Inc.	Decorative concrete pigments, cellulose micro fibres	USA

The FRCA was a joint initiative between Middle Tennessee State University (MTSU) and leaders from the concrete industry. In addition, there is a wide assortment of companies which also distribute or manufacture fibres, such as Bautech®, EKV, Bekaert, Fibratec, Lyodonellbasell, etc. which are also committed to research and developing the awareness of using of FRCs.

2.2 Concept of Macrosynthetic Fibre Reinforced Concrete (MSFRC)

MSFRC is a composite material, combining a cement-based matrix and a discontinuous reinforcement consisting of randomly distributed macrosynthetic fibres. The inclusion of this type of fibres induces some additional demands on concrete, which will have to be taken into account in the dosage.

Table 4 shows several recommendations for dosing macro fibres reinforced concretes, dependent on the maximum aggregate size (MAS).

Table 4. Common ranges of mix proportions of macro fibres reinforced concretes according to ACI Committee 544, 2002

Parameters	Maximum aggregate size		
	10 mm	20 mm	40 mm
Cement (kg/m³)	350-600	300-530	280-415
W/b ratio	0.35-0.45	0.35-0.50	0.35-0.55
Percentage of fine-coarse aggregate	45-60	45-55	40-55
Fibre content (% volume)	0.3-2.0	0.2-0.8	0.2-0.7

These fibres evidently also modify the mechanical properties of this concrete. Regarding their fresh state characteristics, slump tests indicate that the addition of macrosynthetic fibres can decrease slump and workability *(Yin et al., 2015)*, but help to control the segregation. For their part, Mazaheripour et al. *(Mazaheripour et al., 2011)* made the suggestion limit the volumetric content of macrosynthetic fibres (0.1-1%) in order to improve the workability. Moreover, macro plastic fibres can effectively control the plastic shrinkage cracking and thermal contractions (during the initial 24 hours) by improving the integrity of the fresh concrete. It has been analysed that these are effective even with low volume fractions of these fibres (less than 1 kg/m³).

Related to the hardened state properties, diverse researches *(Hsie, Tu and Song, 2008) (Fraternali et al., 2011)* reported that macrosynthetic fibres have no relevant effects on the compressive strength. On the contrary, other authors *(Hsiu-Lung Huang et al., 2012)* showed that the addition of polypropylene (PP) fibres to high strength concretes cause a reduction of the compressive strength by 3-5% as well as a decrease of 5% of the dynamic modulus of elasticity, however this is not a substantial change.

On the other hand, some investigations have found that the macro polymeric fibres do not have an obvious effect on the flexural strength, which is dominated by the matrix properties *(Soroushian, Plasencia and Ravanbakhsh, 2003)*. The principal advantage of using macrosynthetic fibres is an enhanced ductility in the post-crack performance, crack control and flexural toughness of the concrete *(Zollo, 1997)*. Hsiu-Lung Huang et al. *(Hsiu-Lung Huang et al., 2012)* also investigated that residual flexural strength of PP fibre reinforced concrete at 7 days decreased 10% as compared with the reference and at 28 days, but the addition of these fibres tends to improve the toughness index (about 5-10 times) and the impact loading resistance. The use of plastic fibres also achieved a better distribution of the stresses in the concrete, producing a better redistribution of the fissures throughout the element. In these cases, larger volume contents of macrosynthetic fibres (4-8 kg/m³) are used.

The use of all these types of the previously mentioned fibres has increased in recent years as a substitute material for mineral and steel fibres and as an alternative way to improve the behaviour of the concrete. Initial attempts at using synthetic fibres were not as successful as when using glass or steel fibres. However, better understanding of the concepts behind fibre reinforcement, new methods of fabrication, construction techniques and new materials have led researchers to conclude that plastic fibres can be a successful reinforcement for the concrete *(ACI Committee 544, 2002)*.

This ascending trend on the use of polymeric fibres is also due to multiple appealing reasons. Firstly, the cost savings when using synthetic fibres because of the constant price increase of steel and its derivatives. Furthermore, handling is simpler and labour time is shorter due to the minor preparation required when using polymeric fibres *(Cengiz and Turanli, 2004)*. Thirdly, new constructive tendencies and requirements have appeared as well as sustainability benefits that synthetic fibres offer compared to steel fibres (the manufacturing of these fibres may decrease the carbon footprint compared to that of producing steel). Last but not least, the durability of SFRC is still a topic of discussion. Steel is highly corrosive in nature; corrosion of steel reinforcement in concrete structures can lead to their deterioration and failure *(Söylev and Özturan, 2014)*. Macrosynthetic fibres with low densities and excellent corrosion resistance overcome this problem. Therefore, macrosynthetic fibres can be a good option although their long-term yield and other factors that affect their durability (such as temperature) have not been analysed in depth. This aspect represents one of the principal unresolved topics regarding the performance of this material that concern the construction sector, and will be further discussed in the following sections (see sections 2.2.2.2.1 and 2.4).

2.2.1 Macrosynthetic Fibres for Concrete

Macrosynthetic fibres are a result from researches and developments in the petrochemical industries. They are derived from organic polymers which are available in a diversity of formulations.

Their physical and chemical characteristics vary widely depending on the manufacturing techniques. Depending on their chemical composition, polymeric fibres are divided into two groups:

- Polyolefin, which are obtained by the polymerization of olefin.
- Polyamides, which are produced by amide bonds.

The most employed plastic fibre types in concrete and their characteristics are summarized in Table 5. These fibres include: acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene. However, it is possible to find fibres made of others plastic, as polyvinyl alcohol. Among the listed fibres, polypropylene fibres are the most-marketable and most employed polymeric fibre.

On the other hand, macrosynthetic fibres are (in function of their physical forms) > 0.30 mm in diameter, according to the standard UNE-EN 14889-2:2008. This classification, the use of macro fibres (Class II) is recommended for structural applications, resulting in an increase of the tenacity.

Table 5. The most employed synthetic fibres and their properties* according to ACI Committee 544, 2002

Fibre type	Equivalent diameter (mm)	Specific gravity (kg/m³)	Tensile strength (MPa)	Elastic modulus (GPa)	Ultimate elongation (%)	Melt, oxidation or decomposition temperature (°C)	Ignition temperature (°C)	Water absorption per ASTM D 570 (% by weight)
Acrylic	0.015-0.10	1160-1180	270-1000	14-20	7.5-50.0	220-235	----	1-2.5
Aramid	0.01	1440	2930	60	4.4	482	High	4.3
Aramid II	0.01	1440	2345	120	2.5	482	High	1.2
Carbon, PAN HM	0.007	1600-1700	2480-3035	380	0.5-0.7	400	High	Nil
Carbon, PAN HT	0.009	1600-1700	3450-4000	230	1.0-1.5	400	High	Nil
Carbon, pith GP	0.01-0.013	1600-1700	485-795	25-35	2.0-2.4	400	High	3-7
Carbon, pitch HP	0.008-0.018	1800-2150	1515-3105	150-480	0.5-1.1	500	High	Nil
Nylon(**)	0.02	1140	965	6	20	200-220	High	2.8-5
Polyester	0.02	1340-1390	230-1100	15	12-150	260	593	0.4
Polyethylene(**)	0.025-1.016	920-960	75-585	5	3-80	135	-----	Nil
Polypropylene(**)	----	900-910	140-690	3.5-5	15	165	593	Nil

(*) Not all fibre types are currently used for the production of MSFRCs
(**) The listed data are only for fibres that are commercially available.

Besides, the fibres typically present various shapes and indents in order to improve the mechanical bonding strength between the synthetic fibres and the concrete (see Figure 1).

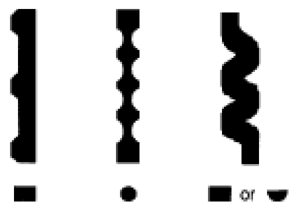


Figure 1. Fibre geometries (from ACI Committee 544, 2002)

As was previously mentioned, polypropylene fibres have become the most common commercial fibre. For this reason, together with their availability, they were used in the present study. From this point on, the following subsection will focus on PP fibres.

2.2.1.1 Polypropylene Fibres

Polypropylene is a synthetic polymer that comes from hydrocarbon polymers, and is an inert material that does not react with concrete. This polymer has a hydrophobic surface so that it does not absorb water. The use of polypropylene fibres has attracted a lot of interest over the last 15 years, in order to have a profitable alternative to other reinforcements. Its use enables reliable and effective use of the intrinsic tensile and flexural strength of this composite.

It is generally accepted that PP fibres have an inferior performance with respect to metallic ones, however this is not certain at all. Despite the fact that steel fibres have a much higher modulus of deformation than polypropylene, they can be used in the same way as steel fibres, reaching and surpassing the capacity of dissipation of energy in high deformations.

The advantages of this type of fibres over steel fibres are their lightness due to their lower density, their versatility for manufacturing, their low conductivity and cost, the absence of electromagnetic interference and their great durability facing problems such as corrosion.

Concerning the durability of SFRC, the conception of this issue is challenging and it is under debate at a technical and scientific level. A review of the published research regarding carbonation and chloride-induced corrosion of SFRCs was recently presented by Marcos-Meson, V. and collaborators *(Marcos-Meson et al., 2018)***.** The study confirms an overall agreement among academics and regulators and a general consensus regarding the durability of un-cracked SFRCs.

Contrariwise, this issue on cracked SFRC is under discussion, as there is a huge dispersion on the experimental data and some of the mechanisms governing the corrosion of carbon-steel fibres in cracks and its effects on the fracture behaviour of SFRCs are not fully understood. Other disagreements exist on the durability of SFRC when exposed to dry-wet cyclic conditions, where some of the guidelines do not recommend the use of carbon-steel fibres in cracked SFRC because their role may be affected by environmental conditions, having a negative effect on the toughness.

On the other hand, synthetic fibres do not destroy equipment through use compared to steel fibres and they have a good behaviour against extremely high temperatures. Even then, it is generally accepted that the addition of PP fibres may reduce the spalling in concrete under the action of fire, but a change in residual stress of concrete should be considered. This is due to the variation of the pore structure which takes place at around 170 °C (when the melting point is reached (see Table 5)), which allows the relaxation of the pore pressure. According to some sources *(Won, Park and Lee, 2009)*, after the fire-resistance test, some pores appeared because macrosynthetic fibres were melted. It was found that at certain depths, some of the macrofibres were partly melted while some were not affected. This result indicated that moisture and heat can be discharged or captured up to a certain depth, prevented spalling, while the fibres remain undamaged beyond this depth.

Depending on the intended application considering the previous advantages, a different amount, geometry and size of the fibre should be used. Manufacturers have to assist clients to obtain an optimum effect in the characteristics of the concrete. Table 6 gives a general vision for orienting the performance towards a correct property improvement of MSFRCs.

Table 6. Best use recommended of the different type of PP-Fibres

State of concrete	Objective	Recommended fibre type	Quantity (kg)
Fresh	Homogeneity improvement	Micro-PP fibres	----
Until 12 hours from manufacturing	Early-age cracking reduction (plastic shrinkage)	Micro-PP fibres	0.5-1
1-2 days	Reduction of cracks induced by restraint or temperature	Micro- & Macro-PP fibres	0.5-1
28 days	Transmission of external forces	Macro-PP fibres	4-8
	Fire resistance	Micro-PP fibres	2-3

2.2.1.1.1 Degradation of PP Fibres in Concrete

The growing use of PP fibres in concrete is leading to applications with higher fibre contents (> 1% of the volume). In these cases, it is essential that the properties of these fibres are ensured to reach the expected lifetime of the structures (over 50 years) and to use them with structural responsibility. Thus, their durability and their properties should be ascertained with the objective of being established fully into the market.

It was reported by Kurtz and Balaguru *(Kurtz and Balaguru, 2000)* that the primary concerns associated with this topic were the durability of fibres in the concrete, the durability of fibres that are exposed to weathering conditions (either due to cracking or partial deterioration of the concrete), the ability of the components to retain its original properties, the resistance to freeze-thaw cycles and the resistance to temperature (fire, frost, etc.).

Relating to the durability of PP fibres, mechanisms of degradation of polypropylene have been extended completely. Polypropylene is fairly resistant to chemical and aggressive agents (salts, chlorides, sulphates, etc.) due to its non-polar nature and it is not susceptible to corrosion. Nevertheless, polypropylene also presents a low resistance to thermo-oxidative and photo-oxidative degradation *(Segre, Tonella and Joekes, 1998)*.

On the one hand, photo-oxidative degradation of PP fibres in cement matrices is not usually expected, except in a cracked cement matrix subjected to natural weathering. In this case, cracks may allow access of oxygen to the fibre. Nowadays, this disadvantage may be treated with commercial chemical stabilizers.

On the other hand, thermo-oxidative degradation should be considered, even at room temperature. This is because polymers are subjected to ageing upon exposure to the environment, as a result of irreversible changes in the composition and structure of polymer molecules (see Figure 2).

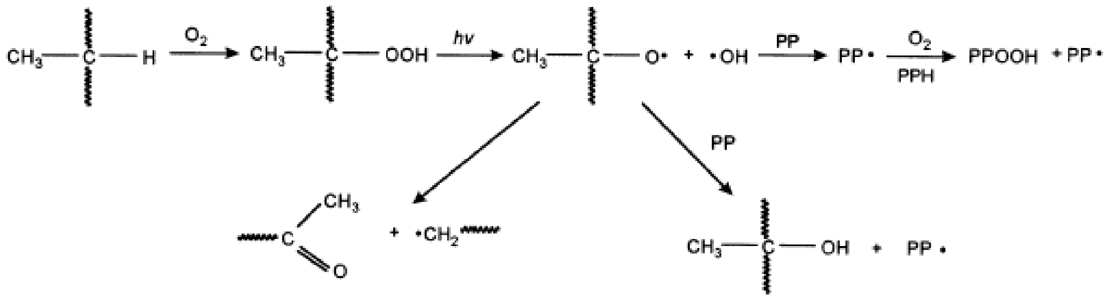


Figure 2. Polypropylene degradation scheme, according to Segre, Tonella, and Joekes (Segre, Tonella and Joekes, 1998)

Regarding to being exposed to weathering conditions, these involve irregular variations of temperature and relative humidity, which can induce different behaviour and a non-constant state in the concrete. Most of the deterioration processes during the service life of structures are predominantly caused by these environmental conditions *(Mirzazadeh, Noël and Green, 2016).*

According to C. Andrade and other researchers, one of the most critical actions that concretes may suffer is the temperature *(Andrade, Sarria and Alonzo, 1999)*. This is a significant factor and must be included in the declaration of the fibre's suppliers who must refer to independent test data. It is necessary to know how the temperature affects the properties of this material in order to determinate its global behaviour and the evolution of its properties over time, considering that properties are thermally dependent. In the following section, the effect of moderated temperatures on MSFRC will be treated.

2.3 Influence of the Temperature on MSFRCs

Firstly, it is important to have some idea relating to temperatures in fibres. Synthetic fibres are said to be melted when the crystalline parts of these polymers are converted upon heating from a solid to a glassy or liquid state. The temperature at which this physical change occurs is called the *'melting point'*. Synthetic fibres have their melting point within the range of 160 °C to 168 °C. Other sources showed that it even includes temperatures between 135 °C till almost 500 °C (Table 5).

Additionally, if a fibre decomposes at a temperature below its melting point during the heating process due to of one of many possible chemical reactions, the temperature at which the decomposition occurs is called the *'decomposition temperature'*. Decomposition is typically noticed because the fibre quickly changes colour, fumes or undergoes an obvious chemical change. For example, one of the typical types of decomposition is oxidation, which is caused by the chemical reaction of the fibre with the oxygen in the air.

2.3.1 Studies Related to the Influence of Moderate temperature (below melting point)

Here, the results of experimental campaigns carried out to analyze the effect of the temperature below melting point on MSFRCs, are presented. Some authors reported that exposures to temperatures below 100 °C, does not appear to affect the behaviour of the fibres and the principal mechanical characteristics of MSFRCs *(Rambo et al., 2018).*

They also indicated that synthetic fibres present a great long-term resistance up to 100 °C. Particularly, PP was found dimensionally stable for short periods of time when exposed to temperatures of 140 °C. These authors also claimed that fibres remain unaltered at temperatures below 60 °C. On the contrary, the use of temperatures from 30–80 °C accelerated the degradation in SFRCs for short exposure times (3-6 months).

Moreover, some investigations were directed towards the mechanical characterization when synthetic fibres are exposed to work temperatures. For example, the company BASF (2011) investigated that residual flexural tensile strengths measured after accelerated ageing tests at 80 °C remain similar to the reference tested at 20 °C.

A company also reported the results of the residual flexural strength of concrete reinforced with three types of fibres of PP in different high proportions at moderated temperature (40 °C). Samples containing PP fibres showed a reduction of the compressive strength and the residual stress at 40 °C for both, cracked and un-cracked specimens (see Figure 3).

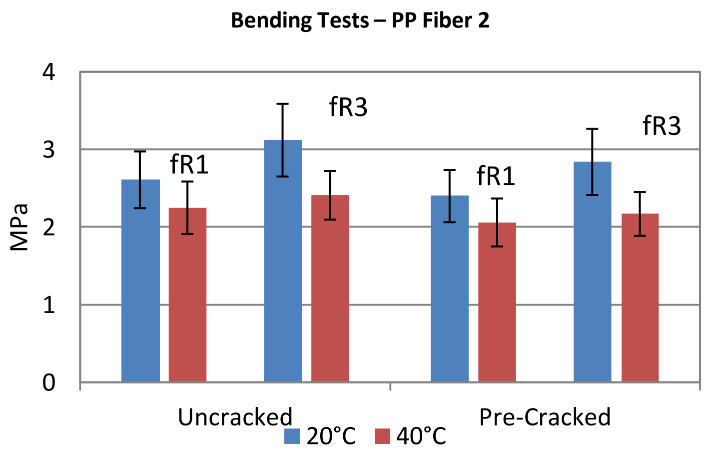


Figure 3. Results derived from a study of the residual strengths at moderated temperatures (from a confidential source)

For their part, Buratti and Mazzotti studied the influence of ordinary temperatures (20 °C to 40 °C) on the long and short term behaviour for SFRC and MSFRC, concluding that SFRCs have a different behaviour with temperature, for which it seems that the effect of temperature is less relevant than for MSFRCs *(Buratti and Mazzotti, 2012)*. Their experimental program consisted in maintaining a constant load for the entire duration of the test while the temperature inside the climate-controlled room was increased according to the following scheme: 15 days at 20 °C, 30 days at 30 °C and 27 days at 40 °C.

These authors, in collaboration with Rossi and Savoia *(Buratti et al., 2011)*, developed two different test procedures to investigate the effects of the loading level and one to analyse the effects of temperature on SFRCs and MFSRCs. For the latter one, the load was constant for the entire process while the temperature was set to three different levels: 20 °C, 30 °C and 40 °C.

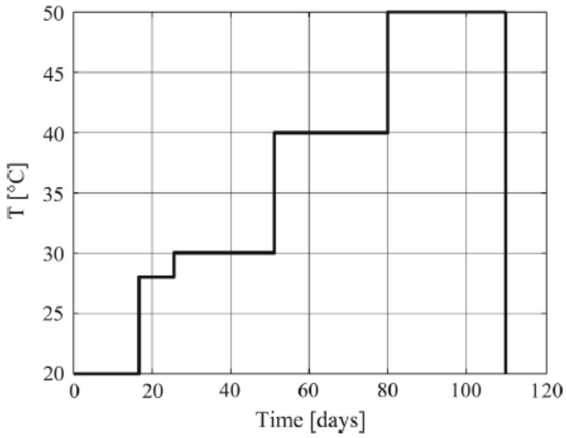


Figure 4. Scheme of temperature proposed in order to evaluate the influence of temperature on MSFRCs (from Buratti et al., 2011)

They also investigated the effect of moderate temperature variations on the short- and long-term behaviour of cracked MSFRCs structural elements. The experimental procedure was performed in two phases: during the first stage, the effect of the temperature on the short-term behaviour of notched prisms was tested by performing three-point bending test at 20 °C and 40 °C. The second stage analysed the long-term behaviour of cracked beams under sustained loads at increasing temperatures according to their proposed method. They concluded that the temperature reduced the short-term residual flexural strength of some of the specimens by 20% and thus that the temperature should be considered as an important factor when designing MSFRCs *(Buratti and Mazzotti, 2015)*. They also determined that the temperature has a large influence on the long-term behaviour of MSFRC but its effect is less extensive than at short term.

Finally, it is important to point out that current regulations do not cover the susceptibility of FRCs exposed to a moderate temperature range, except Model Code 2010 *(FIB, 2012)* which takes into account seasonal variations between about −20 °C and 40 °C, and some sections take into account the influence of substantial deviations from a mean concrete temperature (20 °C).

In short, there are very few data available in the literature about the influence of moderated temperatures on MSFRCs. These outcomes are not coincident about the influence of the temperature. Some of them seem to point out that the temperature caused a reduction on the residual flexural tensile strength but others affirm that the behaviour of MSFRCs remain unaltered at temperatures below melting point.

2.3.2 Studies Related to the Influence of Extreme Environments (considering temperatures)

Here, the results of the mechanical properties of the macrosynthetic fibre reinforced concretes when fibres are exposed to extreme environments are presented. These studies analysed MSFRCs in different aggressive conditions, obtaining dispersed results. It is important to notice that the process attack was different in each case.

Segre et al. *(Segre, Tonella and Joekes, 1998)* evaluated the stability of polypropylene fibres in environments aggressive to cement based materials. PP fibres were left in NaOH, H_2SO_4, artificial seawater and cement-with-water solutions at different temperatures and exposure times. They examined the long term response of PP fibres. Cement-with-water was the most aggressive for fibres, causing oxidation after 100 days. Mortar specimens containing PP fibres and exposed to CO_2, artificial seawater and $MgSO_4$ 0.25M showed a significant decrease in compressive strength after 260 days. The results also exhibited that the compressive strength was roughly 10% lower after 60 days in water.

In comparison with the obtained result for synthetic fibres, others authors *(Fidelis et al., 2016)* studied mechanisms of degradation of concrete reinforced with natural jute textile. Before testing, the specimens were subjected to accelerated ageing conditions. After the period of curing of 28 days in water, samples were exposed to moderated temperature (40 °C) and a relative humidity of 99% during 28, 56, 90, 180 and 365 days. They concluded that the mechanical performance was only slightly affected.

Moreover, the durability in a marine atmosphere, the tidal zone of the Oman Sea and water of SFRC, RC and (R+S)C were also checked in a study carried out by Shaowei Hu *(Shaowei Hu, 2011)* through the flexural behaviour of beams at 28, 90 and 180 days. Based on their results, the effect of adding steel fibres on the increment of load capacity and toughness of pre-cracked RC samples were approximately the same. On the contrary, the addition of steel fibres to un-cracked RC specimens showed that the load capacity and the toughness increased up to 20% in water condition and they were approximately 15% lower in marine and tidal zone.

An exploratory study presented by Hughes et al*.* *(Hughes et al., 2013)* into the mechanical bio-deterioration of synthetic fibre reinforced marine concrete showed that algal fronds grew between the fibre and the cement paste and this is detrimental to the long-term performance of the fibres, having a serious effect on the durability of the concrete.

Shaowei Hu *(Shaowei Hu, 2011)* proposed to study the durability of SFRC under wastewater and dry-wet cycling from the perspective of compressive strength, flexural strength, corrosion coefficient of compressive strength and corrosion coefficient of flexural strength. When the SFRC samples are soaked in the solution, there are differences of corrosive medium which is driven to the interior of SFRC which will then corrode.

2.3.3 Studies Related to the Incidence of Temperature on Special Concretes

The incidence of temperature on the mechanical behaviour up to failure was also evaluated by various works based on self-compacting concrete (SCC), fibre lightweight aggregate concrete (FLWAC), pervious concrete and shotcretes. They are summarized below. It is important to point out that, for all them, the selected ranges of temperatures were superior to the frame of this study.

Xargay et al. *(Xargay et al., 2018)* analysed the effect of temperature on the mechanical behaviour of self-compacting high-strength concrete specimens when subjected to three different tests, corresponding to the uniaxial compression, splitting tensile and three-point bending tests. Concrete samples were kept under laboratory conditions till they were submitted to a thermal treatment. Two different temperatures were considered (300 °C and 600 °C). After 30 days, concrete specimens were subjected to the aforementioned tests up to failure. The experimental evidences demonstrated that the addition of fibres to the cementitious matrix improves concrete fracture energy release capacity not only under control condition, but also under moderate and high temperature. Moreover, the most important changes and degradations took place above 300 °C, causing superficial cracks.

Relating to FLWAC, experiments on the compressive strength and tensile strength after freeze-thaw cycles and high temperature was tested by Cheng et al. *(Cheng et al., 2014)*. Five temperature levels (room temperature, 200 °C, 400 °C, 600 °C and 800 °C) were selected to heat the FLWAC blocks after 25 times of freeze-thaw cycling. The FLWAC test blocks included PVA fibres and polyacrylonitrile (PAN) fibres. It was demonstrated that the compressive strength of FLWAC did not have an obvious change in the temperature range of 20 °C to 200 °C, but an improvement of the tensile strength was observed in the same scope, being higher than that of LWAC without fibre mixing.

For his part, Kevern et al. *(Kevern, Biddle and Cao, 2015)* evaluated the effects of macrosynthetic fibres on pervious concretes on their features and durability. Results indicate that plastic fibres reduce the surface abrasion, the permeability and the infiltration rate, improving the freeze-thaw durability. In agreement with this research, Bolat et al. *(Bolat et al., 2014)* proved that synthetic fibres reduced the capillarity and abrasion of concrete. They also confirmed that MSFRC were most resistance to freeze-thaw factors.

In relation with shotcretes, Bamonte et al. *(Bamonte, Gambarova and Nafarieh, 2016)* investigated the thermo-mechanical properties of three shotcretes at high temperature, compared to plain concrete. The thermal cycle was carried out in an electrical furnace and consisted of a heating phase, a rest at the maximum temperature and a cooling phase. Each specimen was encased in an insulating hollow cylinder after the extraction from the furnace and during the test. Overall, shotcrete exhibited a lower increase in the axial force due to fire, and slightly lower compressive stresses in the heated layers, compared with ordinary concrete.

2.4 Critical Summary and Unanswered Question

This Thesis work aims to analyse the effect of temperature on macrosynthetic fibres, more specifically, polypropylene with a high fibre content. From my point of view, it is important to know how the temperature can affect synthetic fibres in order to exploit the mechanical benefit.

In relation to the previous sections, a review was carried out. This pre-existing background about the influence of moderate temperatures on MSFRCs is still limited. It could be due to their more recent appearance on the market and involved complexity, among other variables. Moreover, it was observed that there is not a completely clear opinion about the effect of temperature in natural environments and under industrial conditions of MSFRCs in literature.

Moreover, there is no methodology or standardized test equipment to evaluate this phenomenon, and there are still uncertainties about the ageing of this material since variables are different (durability after long exposure period in aggressive environments, different range of temperatures, other kind of polymeric fibres, etc.).

Finally, the following table (Table 7 - 8) sums up the most remarkable parameters of the review of the developed experimental investigations about the concerned topic from the most recent works. Here, only the values in bold are concerned in this Master's thesis.

Table 7. Summary of the review of the existing literature about temperature on MSFRCs on this study (I)

First author	Year	Type of fibre	Fibre content (kg/m³)	Temperature (°C)	Details of specimens (mm)	Test description
Rudnik	2018	PP	1.8-3	100, 200, 300, 400, 500 and 600	Standard PN-B-4500 specimens	Standard fire exposure curve according to ISO 834.
Strauss Rambo	2018	Micro and Macrosynthetic BarChip48	0.8 and 8	Up to 600	∅150x150 cylinder	BCN test.
Xargay	2018	PP micro-fibres and steel	0.90 and 60	20, 300 and 600	Cylindrical samples and notched prisms	Compression test, splitting tensile test and three-point bending test.
Alves Fidelis,	2016	Natural jute	Layer of jute fabric	40	Notched thin plates with variable thicknesses	Pull-out test, ESEM.
Buratti	**2015**	**Macrosynthetic**	**3-7**	**20-50**	**Notched prisms of 150x150x550**	**Three-point bending at targeted temperatures according to the defined protocol at controlled room after 3.5 months.**
Colombo	2015	Hooked-end steel	35 and 50	200, 400, 600 and 800	Un-notched slabs	Fast extraction technique or cooling phase within the furnace down to 20°C and then immediately tested though four point bending.
Mehdi Mirzazadeh	2015	-----	----	-25 and 15	(RC) Beams of 200x400x4200	The program consisted of four stages: incrementally loading the beams to 90 kN, sustaining the load for 48 h, cycling the load between 50 - 90 kN for 10 cycles and loading to failure.
Cheng	2014	PVAF and PANF	1-5	Room temperature, 200, 400, 600 and 800	Cubic blocks of 100x100x100	Freeze-Thaw (-17.5~7.5°C) test and then high temperature exposure according to GB/T50082-2009.

Table 8. Summary of the review of the existing literature about temperature on MSFRCs on this study (II)

First author	Year	Type of fibre	Fibre content (kg/m³)	Temperature (°C)	Details of specimens (mm)	Test description
Pizzol	2014	Cellulose pulp and PVA	----	25 and 60	160x30x4 samples	Carbonatation, XDR, TG, SEM.
Teixeira	2013	Sisal and PP	2	70 ± 5	Roofing tiles	50 heat and rain cycles.
Buratti	**2012**	**Macrosynthetic and steel**	**5 and 35**	**20 and 40**	**Notched prisms of 150x150x550**	**Three-point bending at targeted temperatures according to the defined protocol at climate room after 3.5 months.**
Buratti	**2011**	**Macrosynthetic and steel**	**-----**	**20, 30 and 40**	**Pre-cracked beams**	**Three-point bending at climate controlled chamber with constant temperature. This temperature was set to different levels.**
Colombo	2006	Steel	50	200, 400 and 600	Prismatic specimens according to National Recommendation UNI 11039	Stiffness degradation in bending, uniaxial tension and compression at high temperatures (CNR-DT 204/06).
Pigeon	1998	Steel	40 and 60	-30, -10 and 20	Prisms of 100x100x350	ASTM C1018 flexure test.

So far, there are some conclusions related to the subject:

- Researchers have used different methodologies and test set-ups to perform their procedures.
- The dimensions of the tested elements are different across different investigations.
- In most of the cases, the objective is to study the degradation of the fibres or how this fact may affect MSFRCs at low and high temperatures.

The aforementioned differences, the wide contrast between the variables of the experimental programs and the lack of information about this topic open the possibility to continue with this study in order to achieve an in-depth knowledge about the influence of moderated temperature on for MSFRCs.

Chapter 3

Experimental Program

This chapter describes the experimental campaign that was developed in this Master's Thesis to achieve the goals defined in sections 1.2 and 1.3.

To this end, a specific concrete was selected. It corresponds to a mix with a compression strength of 35 MPa, a 10 mm MAS and a high workability. The dosage was designed with OPC Cem II 42.5R, two coarse aggregates (fractions 4/6 and 6/10), river sand (fraction 0/4) and limestone filler. A polycarboxylates superplasticizer (Sika®ViscoCrete®-5980) was employed to adjust the slump of the mixtures. Moreover, the matrix was reinforced with polymeric fibres (Sika M- 48 or Forta Ferro 54mm) and with steel fibres (Dramix 65/40 3D). The fibre contents were relatively high (10 kg/m³ and 30 kg/m³ respectively).

Furthermore, three-point bending tests were performed following a testing methodology based on the standard UNE-EN 14651:2007+A1:2008. The adopted configuration was scaled with a factor 2/3 from the standardized test. In addition, this procedure had a slight modification in order to include and to assess the influence of temperatures on the residual flexural strength (see section 3.4). Notched prisms of MSFRCs and SFRC were tested after 60 days of conservation in diverse conditions, corresponding to the target temperatures of: 5 °C, 20 °C, 35 °C and 50 °C.

These trials were controlled by Crack Mouth Opening Displacement (CMOD) with a linear displacement sensor. Some specimens were subjected to the pre-cracking phase at 28 days where CMOD = 0.5 mm was achieved. The obtained results will be collected and expressed in (Stress-CMOD diagrams) in Chapter 4.

Moreover, accompanying tests were performed to evaluate the quality and uniformity of the composite. After mixing procedure, the slump in the fresh state and the compressive strength tests at 28 days were evaluated, according to UNE-EN 12350-2:2009 and UNE-EN 12390-3:2009 respectively.

As a synopsis, Table 9 summarizes the experimental program implemented in this work. As can be seen, a total of 80 specimens were cast to carry out the planned tests. In order to identify each type of studied combination, each one was assigned the code presented in this table. It compiles in this order: fibre type (P1, P2 or S), pre-cracking condition (N or P) and temperature (05, 20, 35 or 50).

In the following sections, the most important variables that were taken into account, are enlightened. The used materials, design dosage and methodology are presented in order to have a complete understanding of this project. Finally, the duration, organization, specimens production and parameters of the program are discussed.

Table 9. Summary of the experimental program implemented

	Code	Description	Age (Days)	Dimensions (mm)	# of specimens	Tests
Batch 1	P1-N-05	Polymeric fibre (Sika M-48), non-precracked at 5°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P1-N-20	Polymeric fibre (Sika M-48), non-precracked at 20°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P1	Polymeric fibre (Sika M-48)	28	Cylinders of ∅ 150 x 300	3	Compressive strength
Batch 2	P1-N-35	Polymeric fibre (Sika M-48), non-precracked at 35°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P1-N-50	Polymeric fibre (Sika M-48), non-precracked at 50°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P1	Polymeric fibre (Sika M-48)	28	Cylinders of ∅150 x 300	3	Compressive strength
Batch 3	P2-P-05	Polymeric fibre (Sika M-48), precracked at 5°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P2-P-20	Polymeric fibre (Sika M-48), precracked at 20°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P1	Polymeric fibre (Sika M-48)	28	Cylinders of ∅ 150 x 300	3	Compressive strength
Batch 4	P2-P-35	Polymeric fibre (Sika M-48), precracked at 35°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P2-P-50	Polymeric fibre (Sika M-48), precracked at 50°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P1	Polymeric fibre (Sika M-48)	28	Cylinders of ∅ 150 x 300	3	Compressive strength
Batch 5	P2-P-05	Polymeric fibre (Forta Ferro 54mm), precracked at 5°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P2-P-20	Polymeric fibre (Forta Ferro 54mm), precracked at 20°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	P2	Polymeric fibre (Forta Ferro 54mm)	28	Cylinders of ∅ 150 x 300	3	Compressive strength
Batch 6	P2-P-50	Polymeric fibre (Forta Ferro 54mm), precracked at 50°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
			28	Cylinders of ∅ 150 x 300	3	Compressive strength
Batch 6 S	S-P-05	Steel fibre (Dramix 65/40 3D), precracked at 5°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
			28	Cylinders of ∅ 150 x 300	3	Compressive strength
Batch 7	S-P-20	Steel fibre (Dramix 65/40 3D), precracked at 20°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	S-P-50	Steel fibre (Dramix 65/40 3D), precracked at 50°C	60	Prisms of 100 x 100 x 400	4	Three-point bending
	S	Steel fibre (Dramix 65/40 3D	28	Cylinders of ∅ 150 x 300	3	Compressive strength

3.1 Variables

As was identified in Chapter 2, the effect of moderated temperatures has not been thoroughly researched yet. In order to clarify this issue, various variables were defined, and were subdivided into two categories: (i) regarding the materials and (ii) relative to the testing set-up.

The first group is directly related to the dosage. These variables were the mix design, the fibre contents and the type of fibre. On the one hand, only one single representative regular concrete was chosen. Furthermore, two types of synthetic fibres were considered to analyse the influence of temperatures on MSFRCs and one variety of steel fibres was also utilised in order to compare results. The fibre contents were equivalent for both types of fibres. They may be considered relatively high: 10kg/m³ and 30kg/m³.

On the other hand, the variables relative to the testing (the second group of variables) were defined in order to evaluate how temperature affects the behaviour of MSFRCs and, more specifically, the influence on their mechanical properties in a range of common (ambient) temperatures. Thus, the temperature was obviously considered as a factor. Here, four different temperatures were investigated: 5 °C, 20 °C, 35 °C and 50 °C, within different conservation conditions (depending on the logistics and capacity of available means) but the same exposure time (2 months). These data are summarized in the following table (Table 10).

Table 10. Conservation conditions used in the present work

Conservation conditions	Description	Characteristics of conservation	Properties	Image
A	Cool-box Asfri Stock 100	5 °C	203 l	
B	Chamber 1	20 °C RH 100%	---	
C	Thermal bath 1	35 °C Specimens were submerged	1.00 x 1.20 x 0.40 m^3	
D	Thermal bath 2	50 °C Specimens were submerged	0.88 x 1.10 x 0.60 m^3	

The targeted temperatures were selected in order to represent possible situations during the continuous service life. The effect of temperature variations was programmed to be analysed when the concrete was under work conditions and the whole mass was at these temperature. This range was defined to represent Spain’s Mediterranean climate. It is important to notice that temperatures higher than 40°C are difficult to be overcome. Nevertheless, these can be reached in some industrial conditions.

Afterwards, an additional criterion was taken into account. Some of the specimens were precracked in order to investigate how this action can modify the embrittlement of the fibres in the cracked section and simulate a possible situation based on real life. The defined levels were:

- Precracked at 0.5 mm, corresponding to the level 1 of crack mouth opening displacement according to the specification UNE-EN 14651:2007+A1:2008, for which is possible to determinate the residual strength f_{R1}. This value can be compared with a cracked state in service limit state (SLS).
- Non-precracked.

3.2 Materials

MSFRCs and SFRCs are made with the same components than plain concretes with the exception of macrosynthetic and steel fibres.

3.2.1 Cement

Calcium silicate cements, also known as Ordinary Portland Cements, are the most used conglomerate in MSFRCs. MSFRCs may contain 280-600 kg/m³ of cement (see Table 4), being their common frame comprised from 300 to 450 kg/m³. In this case, 325 kg/m³ was selected.

When choosing a cement, it is important to consider the rest of the composing elements, the particle size distribution and all the chemical reactions that take place. For this type of concrete, the matrix tends to contain more fine particles than plain concrete. Thus, the cement plays an important function as fine particle. It is important to notice that a higher quantity of cement is demanded when the MAS is smaller in order to generate more plaster.

It is also noticed that it is possible to use any cement that is suitable for conventional concretes. This material must fulfil the characteristics established in the project and the requirements in the current regulation. Ordinary Portland Cement II 42.5 R was the conglomerate used in all study cases (Figure 5). It was supplied by Lafarge in 3T bags from Sagunto's Factory. In this case, an OPC 42.5 was preferred over an OPC 52.5 because of its slightly bigger particle size and its lower demand for water (lower specific surface). Additionally, the cement complies with the UNE 197-1: 2000 and RC-08 specifications.

Figure 5. OPC Cem II 42.5R

3.2.2 Water

Water is an active agent in the hydration of the binder. Relative to this component, there is a statement in the Spanish Code on Structural Concrete which determines that seawater cannot be used for reinforced concretes. For this reason, tap water from Valencia was used, as it is readily available and fulfils the requirements.

Moreover, it is noteworthy that the addition of fibres decreases the workability of the concrete, depending on their quantity and geometry. Nevertheless, this negative effect should not be compensated with adding water according to EHE-08, Annex *14 (Ministerio de fomento, 2008)*. It is also important to control the relation of water to binder (w/b) due to this influences on strength and durability. The effective w/b ratio was 0.55 in this study.

3.2.3 Aggregates

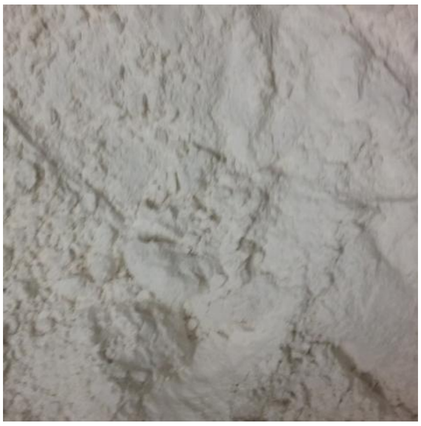
MSFRC presents an increased homogeneity in the face of ordinary concretes because the maximum aggregate size used is smaller than the size of coarse aggregates in traditional concretes. The aggregates are the largest particles of the concrete and they should have a certain compression strength since they directly influence the compression strength of the concrete. Concerning the water demand, sand with a low absorption capacity and higher specific surface is desired.

To fulfil these terms, a suitable mix of aggregate sizes was chosen. The Bolomey curve was employed to adjust the packaging. The aggregates used for this work were river fine sand (fraction 0/4) and two types of crushed limestone coarse aggregates (fraction 4/6 and fraction 6/10). They were provided by Gravera Castellana and Los Montesinos, respectively (Figure 6 a-c). A limestone filler was also used to complete the continuous order of particle sizes, making the transition from cement to fine sand (becoming denser the matrix due to the addition of these mineral addings and reducing workability problems).This material was supplied by Omya from L'Alborç (Tarragona) and it consists of marble powder that is commercially named Betocarb P1-BE. Among its characteristics, whiteness and uniform granulometry (with a MAS of 100 μm) are remarkable (Figure 6 d).

(a)

(b)

(c)



(d)

Figure 6. Materials: (a) Gravel 6/10, (b) Gravel 4/6, (c) Sand 0/4 and (d) Limestone filler

To check the granulometric distribution of the different types of aggregates that were used in this project, sieve tests were used according to UNE-EN 933-1:2012. The results of these tests are displayed graphically in Figure 7.

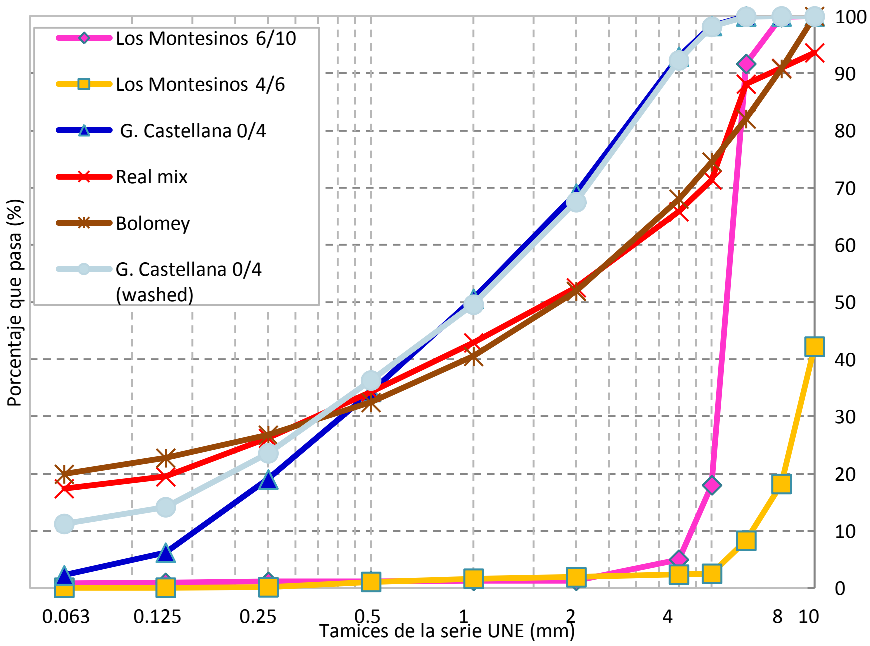


Figure 7. Granulometric distribution

In this case, the biggest aggregate size in the granulometric distribution was 10 mm. It was also defined taking into account several remarks that are generally accepted (it should be 2/3 of the length of the fibre, 1/5 minor side to cast and 3/4 of the free distance between steel traditional reinforcement), in order to maintain the compactness in the granular curve.

3.2.4 Additive

Chemical admixtures are used to adjust specific properties of concretes by chemically influencing the hydration of the cement or its hydration products.

In the case of MSFRCs, it is important to improve their workability. To obtain this, large doses of superplasticizer were added. Superplasticizers are a sort of water-reducers that can achieve a much lower w/b relation while keeping the slump. This characteristic is also required to avoid segregation and honeycombing.

The volume of additive was adapted for each batch in order to obtain a workable mix. The movement of the mixer's blades and the concrete appearance were observed while the concrete mixes were being blended. Based on these observations, additive was added in order to fulfil the previous criterion (i.e. workability).

Since the fibre types are different, their amounts were also adjusted as to maintain acceptable slump values and to prevent segregation. For Batch 1, 0.5% of the weight of the cement was used, while for the other designs, this was higher than the volume initially tested (0.7%). For Batch 6 with Forta Ferro 54 mm polymeric fibre, the volume of superplasticizer was still superior (0.9%).

The selected superplasticizer was Sika®ViscoCrete®-5980, which is a third generation superplasticizer. It is composed of modified polycarboxylates and is generally used for Ultra High Performances Concretes (UHPC). More specifications about this product can be consulted in Appendix A.

3.2.5 Fibres

The addition of fibres randomly spaced in the matrix have positive effects on the concrete. They improve properties of the concrete by providing residual flexural tensile strength to the matrix of the brittle material. There are several types of fibres available in the market, and were mentioned earlier in the introduction of the Chapter 3.

In this study, three types of fibres were selected. They are different in terms of raw material, slenderness length, among other characteristics. Their most stand-out properties are collected in Table 11. They are all so-called macrofibres and are most widely used in the precast industry (Figure 8):

(a) (b) (c)

Figure 8. Fibres: (a) Macrosynthetic Fibre Sika M-48, (b) Macrosynthetic Fibre Forta Ferro 54mm and (c) Steel Fibre Dramix 65/40 3D

Fibre contents from 40 kg/m³ (Volume of fibres (Vf) = 0.51%) to 60-70 kg/m³ (Vf = 0.76 - 0.89%) constitute the referential frame for the typical SFRC structural applications. For MSFRC, fibre contents are equivalent in volume (6 - 10 kg/m³).On the other hand, a minimum required dosage to obtain an average residual flexural strength of 1.5 MPa at CMOD = 0.5 mm and 1.0 MPa at CMOD = 3.5 mm regarding to EN 14651, three-point bending test can be assumed. Moreover, dosage ranges vary depending on the mixture, aggregate types and desired properties. Therefore, it is recommended to determinate the volume of fibre correctly by previous experimental trials, but it was not in this way in this study because of prior experience with these fibres.

Considering the previous criteria and dosage requirements corresponding to the UNE-EN 14889-2, the defined fibre contents were 10 kg/m³ for macrosynthetic fibres and 30 kg/m³ for steel fibres both below 1% (in volume fraction). These volumes of fibre were similar in order to obtain MSFRCs that could be comparable to SFRC, in terms of strength. They were also chosen because they comply with the criteria of practicality, being the values the manufacturers recommended for each type of fibre.

Table 11. Properties of the fibres used in the present study

Code	Type	Trade name	Fibre length (lf) (mm)	Fibre diameter (df) (mm)	Melting point (°C)	Tensile Strength (MPa)	Density (kg/m³)	Shape	Dosage (kg/m³)
P1	Macro Synthetic	Sika M-48	35	---	170	550	920	Corrugated	10
P2	Macro Synthetic	Forta Ferro 54mm	54	---	160	600	910	Intertwined	10
S	Steel	Dramix 65/40 3D	48	0.55	1375	1115	7850	Hooked-end	30

3.3 Dosage

Next, a reference mix was designed, taking into account the aforementioned components. According to the goals defined in this Master's thesis, the research is focused on normal-strength fibres reinforced concretes. Thus, a concrete with a compression strength of 35 MPa was proposed, with a 10 mm MAS, a relatively high fibre content and a high workability.

The designed mixes correspond to the most common concrete that is employed in the precast industry. The dosages are given in Table 12 and Table 13.

The effective w/b ratio was 0.55. The added water includes the water that is absorbed by the sand (1%) and a correction due to the humidity of the fine aggregates (which was measured and controlled before every mix).

Table 12. MSFRC mixture used in the present study

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42.5R	325	24.4	7.6
Gravel (6/10 mm)	430	32.3	11.8
Gravel (4/6 mm)	580	43.5	15.9
G. Catellana Sand (0/4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	10	0.75	---
Additive(*) (**)	0.70%	0.171	---

(*) Determined from the workability; (**) This value was selected for the mixtures except for Batch 1 and Batch 6 P2, which was 0.5% and 0.9% respectively

Table 13. SFRC mixture used in the present study

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42.5R	325	24.4	7.6
Gravel (6/10 mm)	430	32.3	11.8
Gravel (4/6 mm)	580	43.5	15.9
G. Catellana Sand (0/4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	30	2.25	---
Additive(*)	0.70%	0.171	---

(*) Determined from the manufactures recommendations and workability

3.4 Methodology

The experimental procedure that was carried out in this Master's thesis followed the methodology that is summarized in Figure 9.

Today, there is no standard protocol to evaluate the effect of moderate temperatures on FRCs. Thus, a methodology based on the three-point bending test according to standard EN 14651 (2/3 scale) was implemented, considering a modification in order to be able to study influence of the targeted temperatures (5, 20, 35 and 50 °C). This way, only the short-term behaviour of notched MSFRC and SFRC prisms was analysed through the study of their mechanical properties.

The compressive strength and workability of the concrete mixes were used as complementary characterization tests.

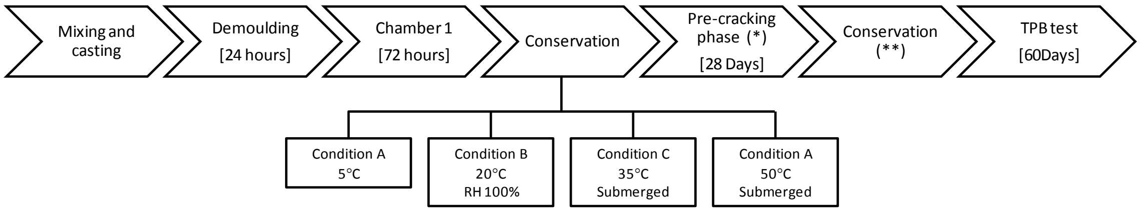


Figure 9. Summary of the used methodology

(*) Depending on the specimens; (**) Same described conditions in this scheme are considered (see Table 10)

Regarding the mixture and casting of the specimens, batches were manufactured during March and April of 2018. 24 hours after their production, they were demoulded and moved to Chamber 1.

On the one hand, the prisms for three-point bending tests were relocated to their respective condition of conservation. After their manufacturing, prismatic specimens were set up to carry out the programmed tests. They were drilled in order to put the corresponding supports for the linear displacement sensors. The central notches of 15 mm were also made with a cutting saw. These were cut on a side face and their depth is smaller than the notches in the standardized specimens (25 mm) due to the size of the samples. The notches were considered because of the easy of locating the crack. At 28 days of conservation, several specimens were taken out of their conditions and were precracked until achieving a crack opening of 0.5 mm. Then, they were returned to their corresponding conservation conditions until their testing at 60 days. Other samples were tested after 2 month of conservation (without subjecting to pre-cracking stage).

On the other hand, the cylindrical samples were kept in Chamber 1 after their production during 28 days before being tested. These permitted to check the uniformity of these mixes.

As a general perspective, Table 14 presents the tests that were initially implemented for every batch. Air content test could not be performed on account of a failure of the equipment.

Table 14. Experimental procedure initially purposed for each batch

Regulation		Time (Days)	Dimension (mm)	Volume (l)
		Fresh state		
Ensayos de hormigón fresco. Parte 2: Ensayo de asentamiento	UNE-EN 12350-2:2009	---	100 x 300 x 200	6
Ensayos de hormigón fresco. Parte 7: Determinación del contenido de aire. Métodos de presión	UNE-EN 12350-7:2010	---	---	8
		Hardened state		
Ensayos de hormigón endurecido. Parte 3: Determinación de la resistencia a compresión de probetas	UNE-EN 12390-3:2009	28	150 x 300	16
Método de ensayo para hormigón con fibras metálicas. Determinación de la resistencia a la tracción por flexión	UNE-EN 14651:2007	60	100 x 100 x 400	32
			Total Volume (l)	65

Specimens were cast in seven different concrete batches. For each batch, two series were produced. The total volume of these were increased for a factor in order to assume possible The batches resulted in three cylindrical samples of ∅150 x 300 for compression tests at 28 days, a slump test and eight prisms of 100 x 100 x 400 mm to perform three-point bending tests, as was showed in Table 9. However, the batch 6 was different because its series were produced from different types of fibres. In this case, each combination was resulted in three cylindrical samples of ∅150 x 300 for compression tests at 28 days, a slump test and four prisms of 100 x 100 x 400 mm to carry out three-point bending tests.

The following sections provide a detailed overview of the production process, the moulds and the specimens. The methods for the characterization and the testing of the residual flexural strength are also explained.

3.4.1 Production of Concrete

The manufacturing of concrete was carried out in the Laboratory of Materials at the Polytechnic University of Valencia (UPV), building 4F. For all the cases, the concrete mixes were produced following the same methodology and sequence (using conventional mixing techniques). The operations are as follows:

- Pouring of coarse aggregate and sand, then premixing for 2 minutes.
- Pouring of cement and filler, then premixing for 2 minutes.
- Pouring of water, then mixing for 1 minute.
- Addition of fibres (gradually during 1 minute).
- Addition of the superplasticizer.
- Mixing for 5 minutes (Figure 10-a).

(a) (b)

Figure 10. (a) Production of concrete (b) Mixer DIEM WERKE model DZ 180V

It is noteworthy that, in contrast to the recommendations of ACI 544 Committee concerning the production of SFRC, the addition of fibres was done before the superplasticizer. This was due to the loss of workability when fibres are added and the limitations of the mixer (energy of mixing). It is also the reason why fibres were not added to the mixer quickly. The used kneading machine is a stationary mixer, with a vertical axis and a fixed drum from DIEM WERKE model DZ 180V (Figure 10-b). It has a maximum capacity of 295 litres.

After mixing, the slump was measured according to standard EN 12350-2:2009. Then, the concrete was taken directly from the mixer and was poured into the moulds according to the UNE EN 12350-1. For compression samples, specimens were cast in three similar layers. After pouring, they were compacted with 25 strokes using the tamping rod. For prisms, the scheme of pouring is depicted in next figure (Figure 11).They were also compacted using the tamping bar. In some cases, due to the workability of the mixtures, table vibrator was employed.

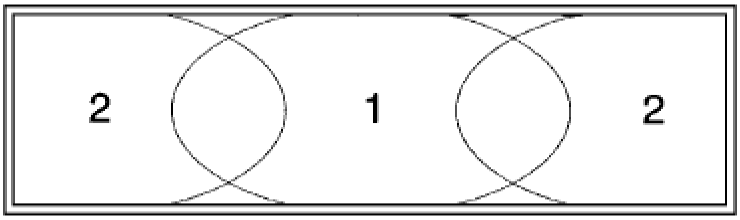


Figure 11. Mould pouring method (from UNE-EN 14651:2007+A1:2008)

3.4.2 Moulds and Casting of Specimens

Two types of specimens were produced, making 80 specimens in total. To control and typify the mixes, cylindrical samples were manufactured. Furthermore, to study the impact of ordinary temperatures on the flexural tensile strength, prisms were cast as well.

On one hand, cylindrical specimens were produced according to standard UNE-EN 12390-3:2009. After 24 hours, they were demoulded and moved to Chamber 1. Here, they were conserved until their testing at 28 days of curing. Their dimensions were ∅ 150 mm and 300 mm long, as was commented previously.

On the other hand, specific moulds were prepared for prismatic specimens. They were produced using pre-existing prismatic moulds with dimensions that were smaller than the normalized ones (2/3 scale): 100 x 100 x 400 mm (width x height x length). This equivalent configuration considered due to the logistics and to facilitate the handling. These were stored in their respective conditions, according to the: 16 prisms were tested at 5 °C, 16 prisms at 20 °C, 8 prisms at 35 °C and 16 prisms at 50 °C.

Figure 12 shows one of the batches that was poured. In this picture, the moulds can be observed.

Figure 12. Specimens produced in a batch of this program

3.4.3 Methodology of Complementary Characterization Testing

In this research, additional characterization tests were performed in parallel to the main experimentation in order to define the workability of the batches. Moreover, one of the most important mechanical properties of concrete in the hardened state (i.e. compressive strength) was determined in order to be capable to compare between different concretes.

3.4.3.1 Slump

A slump test measures the consistency of fresh concrete before it sets. This was performed to check and evaluate the workability for each batch. For this purpose, the procedure to follow in the standard UNE-EN -12350-2:2009 was employed, which describes a simple method to determine this property through settlement tests (Abrams cone). In Figure 13, a result of this test can be observed.

These data were measured just after producing the concrete, for which the results are presented in Chapter 4.

Figure 13. Example of slump test of the Batch 6 S of this study

3.4.3.2 Compressive Strength

The compressive strength of concrete is also taken into account as a companion test. The guideline for determining the compression strength in specimens of concrete in the hardened state was regulation UNE-EN 12390-3:2009.

In this case, specimens were tested in a compression testing machine from IBERTEST conform with EN 12390-4:2001. Through the WINTEST software, all the parameters required by the standard UNE-EN 12390-3:2009 were considered to carry out the testing and to obtain the results.

To obtain the compressive strength, the following equation was applied (Equation 1), which is provided in standard UNE-EN 12390-3:2009.

$$f_c = F/A_c \qquad \text{Equation 1}$$

where f_c is the compression strength (MPa), F is the maximum load and A_c is the transversal area of the specimen where load is applied.

Before testing the samples, it was indispensable that they were capped. The method of capping consisted in covering at least one of their surfaces with sulphur mortar. The employed commercial sulphur (Cepsul Galleta) originated from CEPSA Company. It was heated to the temperature recommended by the manufacturing company to achieve its correct application (140 °C).

3.4.3.3 Methodology of Flexural Test at Determinate Temperatures

UNE-EN 14651:2007+A1:2008 determines the bending behaviour of SFRC in terms of limit of proportionality (LOP) and a set of residual flexural tensile strength values. This process was designed for metallic fibres no longer than 60 mm. It can also be used for combinations of steel fibres and hybrid fibre reinforced concretes. It is limited to concretes with a maximum aggregate size greater than 32 mm. Despite these remarks, the process was adapted in this case for macrosynthetic fibre respecting the MAS limitation.

Given that there is no normative method to perform this test at moderated temperatures, a protocol was developed in this Master's thesis. It is important to distinguish the process of specimens subjected to the pre-cracking phase from the rest of the samples. In the first case, the procedure had two stages: (i) pre-cracking phase at a different temperature at 28 days and (ii) a three-point bending test at diverse temperature. In the last case, this complete test was performed according to the standard UNE-EN 14651:2007+A1:2008.

The pre-cracking process was run under CMOD control. The beams were precracked up to CMOD = 0.5 mm. This value can be fixed at different CMOD, depending on the grade of desired damage In this case, this crack opening was assumed as the limit of the crack width of FRC structural elements under service loads. To do this, a linear displacement sensor from Penny & Giles was installed at the bottom face of each specimen. The SLS320 is a linear position sensors designed to provide stroke lengths from 250 to 1600 mm in a compact, lightweight and easy-to-use design. It is shown in the following figure (Figure 14):

Figure 14. SL320 - Linear Displacement Sensor used in this testing (from Penny & Giles)

Additionally, it is important to notice that three-point bending is the configuration adopted for this stage but it was scaled with a proportion of 2/3. Thus, parameters such as the distance between the support, the specimens dimensions and the depth of the notch were reduced considering the previous factor. The scheme of the standardized protocol is represented in Figure 15.

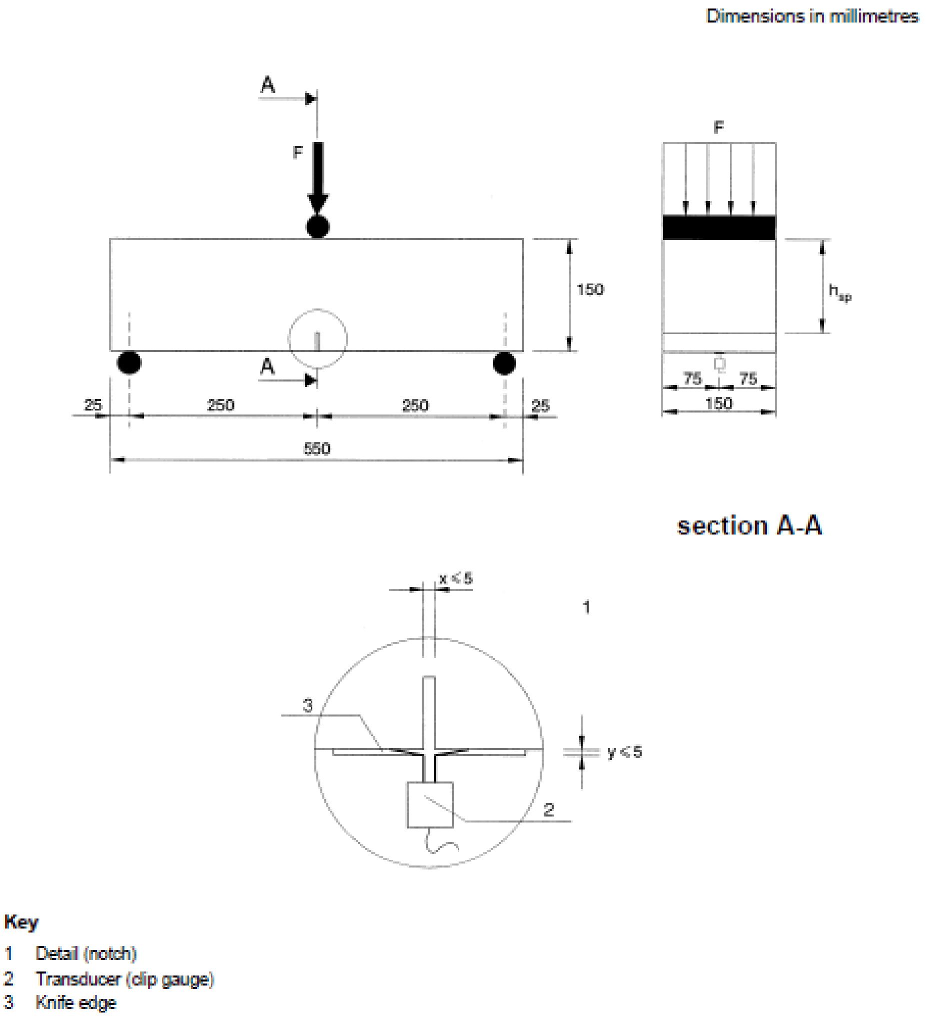


Figure 15. Scheme of three-point bending test (from EN 14651:2005)

According to this procedure, the line of measurement is at a distance y below the bottom of the specimen (see Figure 15). Therefore, $CMOD_y$ is the value obtained directly during the test and CMOD shall be derived from the following expression:

$$CMOD = CMOD_y \cdot \frac{h}{h+y} \qquad \text{Equation 2}$$

where h is the total depth of the specimen (without considering the notch).

Considering the previous mentioned, in order to carry out the test, the load cell and the sensor were connected to the data acquisition equipment (DAE). The first step was to apply a manual preload until reaching a load between 1 to 4 kN in order to optimize the trial time. Afterwards, the load was applied at a velocity of 0.05 mm/minutes until the crack reached a CMOD of 0.5 mm, which usually coincides with the fixed limit. It is also important to know that this force was increased according to UNE-EN 14651:2007+A1:2008. Then, the system and devices were removed from the specimens and they were returned to their corresponding conservation conditions until being tested (the second phase of the test) at 60 days.

After the period of conservation, three-point bending test was performed with the same scheme and configuration as the first phase, except for the velocity that was 0.2 mm/minutes from CMOD = 0.5 mm until reaching a CMOD of at least 4 mm (test completion).

For non-precracked specimens, this methodology was developed in an unique stage according to UNE-EN 14651:2007+A1:2008. The resulted curve of non-precracked specimens is drawn in the Figure 16.

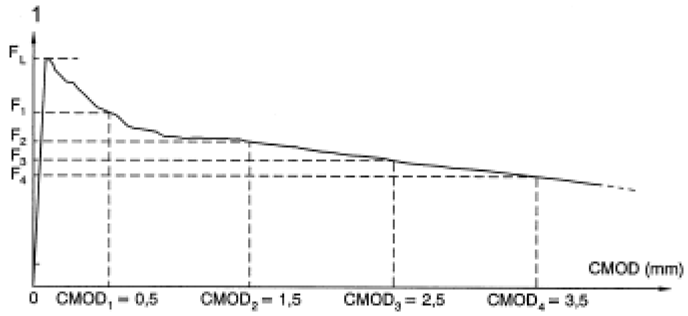


Figure 16. Curve Load-CMOD (from UNE-EN 14651:2007+A1:2008)

To study the effect of temperature on these prisms (both un-cracked and precracked), the concrete mass should be at the targeted temperature while test is being carried out, regardless of the phase of the test. To do this, as novelty in this procedure, a system of insulating thermal covering was implemented. This temperature (superficial and internal) should be kept constant for the entire duration of the trial.

Reusable cold and hot gel compresses were used to provide and preserve the required temperature, while thermal sacks were used for insulation. Before and after testing, the temperature was measured, guaranteeing that the temperature in the concrete specimens was maintained (± 5 °C). It is noteworthy that the temperature inside the concrete was not monitored because several previous authors showed that there was only a small difference (1 °C or 2 °C) between the temperature in the middle of the specimen and close to the surface *(Pigeon and Cantin, 1998)*. Thus, it was not possible to exactly know the temperature during testing.

(a) (b) (c)

Figure 17. (a) Nexcare™ ColdHot™ Maxi gel compress (b) Nexcare™ ColdHot™ Mini gel compress (c) Thermal sack (from Google images)

Nexcare ™COLDHOT™Maxi and Mini were employed. The blue gel of these packs is not toxic and is 99% biodegradable, which makes the product environmental-friendly.

Preparation of cold conditions (Figure 18):

Storing the gel compress in a freezer at least two hours before their use.

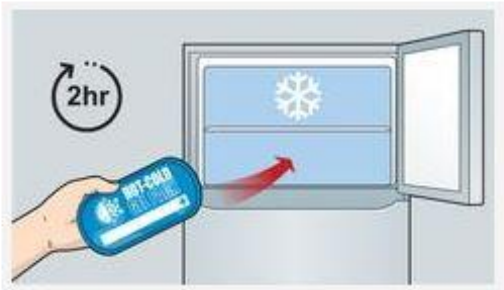
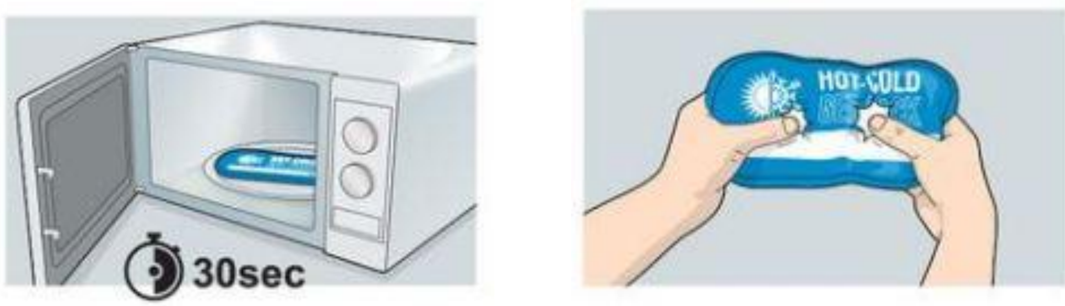


Figure 18. Preparation of the cold conditions (from https://gelpacksdirect.co.uk/pages/how-to-use-a-gel-pack)

*Preparation of hot conditions (*Figure 19*):*

Immersing the pack in water at the targeted temperature (thermal bath) for 8 minutes. When the gel compresses lost their temperature, they were re-heated. The flat packs were laid in a microwave set at 640W and were heated six times for 30 seconds. After each heating, the gel compresses were kneaded to distribute the heat evenly.



(a) (b)

Figure 19. Preparation of the hot conditions: (a) Warm the packs in a microwave set 640W for 30 seconds (b) Knead to distribute the heat evenly (from https://gelpacksdirect.co.uk/pages/how-to-use-a-gel-pack)

They were applied to the specimens as is shown in Figure 20. Fastening tapes of Velcro were used to hold the packs in place.

(a) (b)

Figure 20. Procedure: (a) System of insulating thermal covering in the sample (b) During the test

Once the tests were finished, the fibres of the fractured cross-section were counted in order to obtain the density of the fibres. This process was performed through digitalization of photographs taken over the fractured cross face (a total of 88 pictures were taken) and counting fibres manually. Some methodologies were tried to automate the counting procedure but the results were not acceptable.

Finally, to calculate the residual flexural strength, the bending moment in the centre vain corresponding to the center point load F is shown in Equation 3:

$$M = \frac{F}{2} \cdot \frac{1}{2} \qquad \text{Equation 3}$$

Assuming a linear distribution of the tensions, the tensile residual strength was calculated using the following equations (Equation 4 and Equation 5):

$$f_{\frac{f}{ct,L}} = \frac{6M_L}{bh_{sp}^2} = \frac{3F_L l}{2bh_{sp}^2} \qquad \text{Equation 4}$$

$$f_{R,j} = \frac{6M_j}{bh_{sp}^2} = \frac{3F_j l}{2bh_{sp}^2} \qquad \text{Equation 5}$$

being *F* the axial load recorded during the test, *l* the distance between supports (330-340mm), *b* the width of the sample cross section (100mm) and h_{sp} the distance between top of the notch and top of cross section (85mm).

Operating conditions incidents.

This section summarizes the results of the operation conditions' control. It is used to verify the temperature of Chamber 1, the thermal baths and the cool-box throughout the conservation periods.

Figure 21 presents different measurements of the temperature in each defined condition during 60 days. They were taken with a water-resistant thermometer at the same hour approximately. Here, a constant behaviour for the Conditions A, B and D (5 °C, 20 °C and 50 °C severally) is showed. However, the temperature of the Condition C (35 °C) fluctuated between 20 °C and 50 °C. This variation arose since the sounding line broke down. It can be also observed that there are fluctuations for 50 °C during the first few days because of the overheating of sounding line.

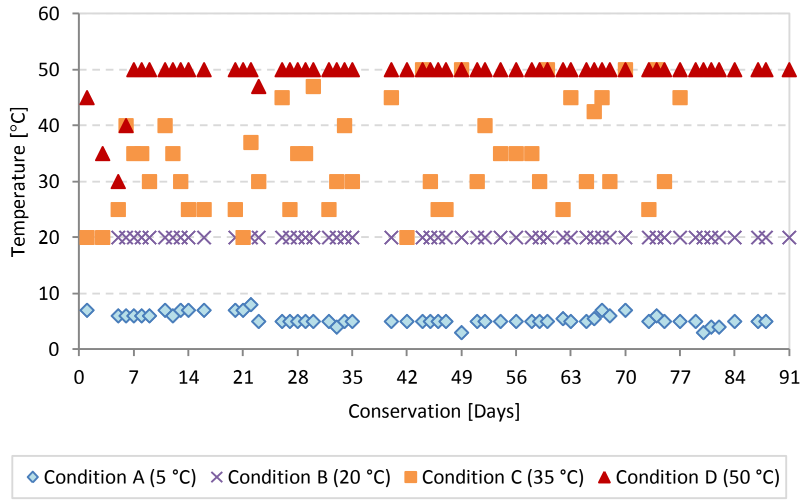


Figure 21. Control of temperature during the conservation period

Moreover, Table 15 collects the mean and the coefficient of variation (COV) of the measured data for all the conditions. It can be concluded that the best results were obtained for the Condition B. It can be explained because of Chamber 1 is always monitored and their temperature and humidity are constantly controlled. For their part, extreme target temperatures (5 °C and 50 °C) corresponding to the Condition A and the Condition D Conditions respectively, were quite stable, presenting acceptable results in contrast to Condition C. It must be considered when the results for 35 °C will be interpreted.

Table 15. Data of the operating conditions' control

	Mean (°C)	COV (%)
Condition A	5.41	18
Condition B	20.00	----
Condition C	34.64	26
Condition D	49.15	7

Chapter 4

Results

Chapter 4 presents the obtained results in this experimental program. Firstly, the values in the characterization tests (i.e. slump and compressive strength) are tabulated and commented briefly. Afterwards, the outcomes of the residual flexural strength in function of target temperatures are collected, in order to show their effect on MSFRCs and SFRC. Finally, the results derived from the visual inspection are also presented.

4.1 Results of the Characterization Tests

Characterization tests were carried out in order to determine the workability and the mechanical behaviour of the different concrete mixes. The following sections collect the principal results obtained in these tests.

4.1.1 Slump

The initial objective of the slump test was to check that the obtained mixes were workable. For this purpose, the dosage of additive into the mixture was modified in order to maintain the settlement constant and to control the expected loss of workability. In no case, the granulometric distribution was redefined, but it is certain that limestone filler was added to minimize the problems of workability, which was earlier already indicated in Chapter 3.

Despite that, it was not possible to achieve similar slump values because the demand of superplasticizer changed significantly when the type of fibre was modified. Table 16 sums up the data related to the slump tests for each batch as well as their mean, range, standard deviation and coefficient of variation.

Table 16. Results of slump tests

Code	Slump				
	h (cm)	Mean (cm)	Range (cm)	Standard deviation (cm)	COV (%)
Batch 1 P1	7.00	7.00	4.00	1.63	23.33
Batch 2 P1	5.00				
Batch 3 P1	7.00				
Batch 4 P1	9.00				
Batch 5 P2	3.00	1.50	3.00	2.12	141.42
Batch 6 P2	0.00				
Batch 6 S	10.50	14.75	8.50	6.01	40.75
Batch 7 S	19.00				

It can be observed the higher settlement values were obtained for SFRC, that is, mixes with metallic fibres (Batches 6 and 7) exhibited the greatest workability without segregation (fibres restrain concrete mixtures from segregation). On the contrary, a huge loss of this property was experimented by mixes reinforced with P2 fibres. On its behalf, the results for P1 concretes were quite regular. These results will be analyse in depth in Chapter 5.

Furthermore, the visual aspect of the concrete mixes was also different. When comparing Figure 22-a with Figure 22-b, it can be seen that the former concrete was drier than the latter, despite having the same w/b ratio. It was in line with the previous values of settlement.

(a) (b)

Figure 22. Examples of the visual aspect of the concrete mixes: (a) Batch 6 P2 MFSRC and (b) Batch 6 SFRC.

Additionally, detailed technical datasheets of this experimental part are presented in the Appendix B.

4.1.2 Compressive Strength

The aim of these compressive strength tests was to control the regularity of the concrete, the quality of their manufacturing and their mechanical properties. It was decided not to study the influence of moderated temperatures on the compressive strength in MSFRCs because it was needed to their characterization and moreover, there are other features that are more interesting in fibre reinforced concretes to define their behaviour.

Table 17 collects the results of the performed tests. During the process, force values were obtained. From these results, the compressive strength was calculated, taking into account the transversal area of the specimens where the load is applied (see Section 3.4.3.2). After that, the mean compression strength was determined for each batch. Another statistical parameters such as range, standard deviation and COV, were also computed.

All the outcomes were around 35MPa, which were initially defined. From a general point of view, a decrease in compressive strength was observed for the SFRC batches. Furthermore, a detailed analysis of these results is given in the following Chapter. Additionally, a summary of this experimental part is presented in the Appendix C.

Table 17. Results of compression strength tests

Code	Age (Days)	Number of specimens	Compression					
			F (kN)	f_c (N/mm²)	f_{cm} (N/mm²)	Range (N/mm²)	Standard deviation (N/mm²)	COV (%)
Batch 1	28	1	620.30	35.10	35.05	1.32	0.66	1.89
		2	607.60	34.38				
		3	631.00	35.71				
Batch 2	28	1	661.90	37.46	37.26	1.83	0.93	2.49
		2	640.60	36.25				
		3	672.90	38.08				
Batch 3	28	1	648.00	36.67	35.68	1.50	0.85	2.39
		2	622.20	35.21				
		3	621.50	35.17				
Batch 4	28	1	616.90	34.91	35.42	0.85	0.45	1.28
		2	629.00	35.59				
		3	632.00	35.76				
Batch 5	28	1	630.70	35.69	35.20	0.81	0.43	1.22
		2	616.30	34.88				
		3	619.30	35.05				
Batch 6	28	1	626.10	35.43	36.47	1.75	0.92	2.53
		2	657.10	37.18				
		3	650.20	36.79				
Batch 6S	28	1	586.10	33.17	31.60	3.58	1.83	5.80
		2	522.80	29.58				
		3	566.50	32.06				
Batch 7	28	1	574.10	32.49	32.73	0.86	0.48	1.46
		2	588.10	33.28				
		3	572.90	32.42				

4.2 Results of the Three-Point Bending Tests

To reach the main purpose of this Master's Thesis, three-point bending tests at different temperatures were performed. According to the procedure already described in Chapter 3, the results of the residual flexural strength corresponding with the limit of proportionality and CMOD = $CMOD_j$ (j = 1, 2, 3, 4) were tabulated taking into account the following variables: type of fibre, pre-cracking conditions and temperatures.

To compare the results of these tests, they are collected in function of the target temperature in Table 18 through Table 21. As can be seen there, the mean value for each of the residual flexural strength at different CMOD together with their COV are showed. Moreover, these data will be examined further in Chapter 5 and are more detailed in Appendix D.

From a general point of view, Table 18 summarized the results of the three-point bending tests at 5 °C. This shows that the P2 specimens present the worst behaviour in cold temperature and the P1 specimens have a better performance than the S samples at 5 °C. The pre-cracking condition seems not to affect the residual flexural strength in this case.

Table 18. Results of the three-point bending tests at 5 °C on studied prisms

Code	P1				P2		S	
	Precracked		Non-precracked					
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
f_L (MPa)	3.67	4.23	4.28	11.37	3.91	8.65	4.43	6.73
f_{R1} (MPa)	2.05	12.52	2.01	9.20	1.26	10.34	2.31	4.74
f_{R2} (MPa)	3.32	12.52	2.77	13.40	1.74	9.10	2.76	11.89
f_{R3} (MPa)	3.52	6.53	3.00	12.35	1.86	10.64	2.35	26.43
f_{R4} (MPa)	3.48	7.39	2.97	16.27	1.88	15.71	2.12	8.53

Furthermore, the results of the three-point bending tests at 20 °C were tabulated in Table 19. In this case, it is interesting to point out that the P1, P2 and S specimens present values much more similar than for other target temperatures. Additionally, P2 specimens present better outcomes in this situation compared to the results at 5°C. The pre-cracking condition seem not to affect the residual flexural strength in this case.

Table 19. Results of the three-point bending tests at 20 °C on the studied prisms

Code	P1				P2		S	
	Precracked		Non-precracked					
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
f_L (MPa)	4.15	9.40	4.58	12.61	4.36	6.85	4.27	3.43
f_{R1} (MPa)	1.45	33.66	1.39	15.36	1.79	38.69	2.95	18.96
f_{R2} (MPa)	2.68	23.59	1.89	15.52	2.93	41.95	3.80	22.83
f_{R3} (MPa)	3.14	18.36	2.18	13.94	3.14	41.36	3.51	26.94
f_{R4} (MPa)	3.31	14.46	2.24	15.55	2.96	50.69	3.21	21.99

Table 20 only collects the outcomes for the P1 samples at 35 °C for both conditions (non-precracked and pre-cracked). Non-precracked specimens show better results than precracked samples but it is also important to note that the non-precracked specimens present a great variability in the results.

Table 20. Results of the three-point bending tests at 35 °C on the studied prisms

Code	P1			
	Pre-cracked		Non pre-cracked	
	Mean	COV(%)	Mean	COV(%)
f_L (MPa)	3.98	29.76	4.69	9.97
f_{R1} (MPa)	1.60	21.69	2.04	36.14
f_{R2} (MPa)	1.98	14.09	2.83	35.16
f_{R3} (MPa)	2.26	15.76	3.13	38.44
f_{R4} (MPa)	2.38	19.83	3.28	39.15

Table 21 shows the results of the three-point bending tests at 50 °C. For P1 specimens, the residual flexural strengths corresponding with CMOD = $CMOD_j$ (j = 1, 2, 3, 4) present a similar behaviour to the trend at 35 °C. The best results were obtained for the P1 non-precracked specimens and S samples.

Table 21. Results of the three-point bending tests at 50 °C on the studied prisms

Code	P1				P2		S	
	Pre-cracked		Non pre-cracked					
	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
f_L (MPa)	4.24	2.78	4.24	14.36	5.10	6.59	4.36	2.64
f_{R1}(MPa)	1.40	7.22	2.26	19.71	1.84	25.93	2.38	17.20
f_{R2}(MPa)	1.95	16.59	3.46	24.43	2.15	39.96	3.00	21.54
f_{R3}(MPa)	2.23	13.57	4.04	34.84	2.33	29.93	2.69	18.84
f_{R4} (MPa)	2.33	14.98	4.29	37.34	2.30	43.07	2.32	24.51

4.3 Results of the Visual Inspection

After three-point bending tests, a visual examination of the fractured cross surface of the specimens was performed. This was inspected with the aim of analysing the fibre density in the transversal section and the uniformity of the fibre distribution.

Table 22 shows the results of the fibre count for each type of fibre. Additionally, the fibre density on the cracked face (*N/Area*) was calculated. It is important to notice that the count for P2 fibres was not carried out due to the bond between the fibres.

Table 22. Results of fibre counts

Type of fibre	Face		N	N/Area
P1	A	B		
P1-N-20-1	51	39	90	0.91
P1-N-20-2	55	43	98	0.99
P1-N-20-3	39	32	71	0.72
P1-N-20-4	35	33	68	0.69
P1-N-05-1	34	44	78	0.79
P1-N-05-2	39	34	73	0.74
P1-N-05-3	46	41	87	0.88
P1-N-05-4	45	48	93	0.94
P1-N-35-1	51	58	109	1.11
P1-N-35-2	40	48	88	0.89
P1-N-35-3	45	38	83	0.84
P1-N-35-4	71	65	136	1.38
P1-N-50-1	78	67	145	1.47
P1-N-50-2	81	70	151	1.53
P1-N-50-3	49	47	96	0.97
P1-N-50-4	46	58	104	1.06
P1-P-05-1	45	52	97	0.98
P1-P-05-2	59	54	113	1.15
P1-P-05-3	51	50	101	1.03
P1-P-05-4	67	51	118	1.20
P1-P-20-1	53	53	106	1.08
P1-P-20-2	70	45	115	1.17
P1-P-20-3	46	50	96	0.97
P1-P-20-4	31	28	59	0.60
P1-P-35-1	56	57	113	1.15
P1-P-35-2	53	52	105	1.07
P1-P-35-3	34	39	73	0.74
P1-P-35-4	56	58	114	1.16
P1-P-50-1	43	65	108	1.10
P1-P-50-2	49	50	99	1.01
P1-P-50-3	46	59	105	1.07
P1-P-50-4	59	67	126	1.28

Type of fibre	Face		N	N/Area
S	A	B		
S-P-05-1	27	35	62	0.62
S-P-05-2	28	21	49	0.50
S-P-05-3	24	28	52	0.53
S-P-05-4	20	33	53	0.54
S-P-20-1	35	33	68	0.69
S-P-20-2	44	46	90	0.92
S-P-20-3	43	45	88	0.89
S-P-20-4	32	27	59	0.60
S-P-50-1	33	25	58	0.59
S-P-50-2	29	26	55	0.56
S-P-50-3	26	27	53	0.59
S-P-50-4	26	27	53	0.59

(*) N: total number of fibres (**) Area: fracture cross surface area (subtracting the area of the notch)

Chapter 5

Analysis Of Results

An exhaustive analysis of the presented results in the previous chapter, is realized in this Chapter 5. After data processing, the obtained values in the companion test are examined. Afterwards, the outcomes of the influence of the moderate temperatures on fibre reinforced concretes are discussed and the results of the visual inspection are commented. As a result of these analyses, the conclusions of the experiments can be drawn and compared to the conclusions of studies of several authors.

5.1 Analysis Of Results of the Characterization Tests

The results of the characterization tests (i.e. slump and compression strength) are studied in this section, in order to determine the uniformity and quality of the different concrete mixes, discarding production errors.

5.1.1 Slump

Workability of fresh concrete was evaluated by slump test. In general, adding fibres decrease the slump of the fibre reinforced concretes. As was mentioned in Chapter 2, the slump of concrete is affected by the fibre type, its properties (such as water retention capacity) and its geometrical structure *(Bolat et al., 2014)*. This effect of fibres on the slump may be checked in all cases of this study, where different values are observed for each batch (see Table 16).

Moreover, it is of importance to emphasize that this influence is quite important due to the high fibre contents added in the concrete mixes. In spite of using significant amount of fibres, their dispersion was effective in the different matrixes during the mixing, because of the high performance admixture used.

Figure 23 illustrates the slumps for each batch. From a general point of view, polypropylene fibres reduced the workability of fresh concrete more than steel fibres. This could be explained since the air occluded in the mixture is partly increased, and this (in a way) hinders its compactness. This hypothesis could not be confirm because the air content test was not performed on account of a failure of the equipment, as was mentioned in Chapter 3.

In turn, slumps of the concrete mixes with P1 and S fibres allowed that both were workable. Although the values obtained for P1 fibres were lesser than S fibres, it did not mean that there was a loss of workability. This is in agreement with a statement pointed out by Model Code 2010 *(FIB, 2012).*

On the contrary, the slump of concretes with P2 fibres showed the lowest outcomes due to the bond of the fibres. Adding this type of macrosynthetic fibres, due to its high volume fraction and its large surface area, caused that the cement paste was easily absorbed to wrap around them, making these mixes harder to blend and to cast compared to the rest. This indicated that a larger demand of fine particles and/or additive was needed.

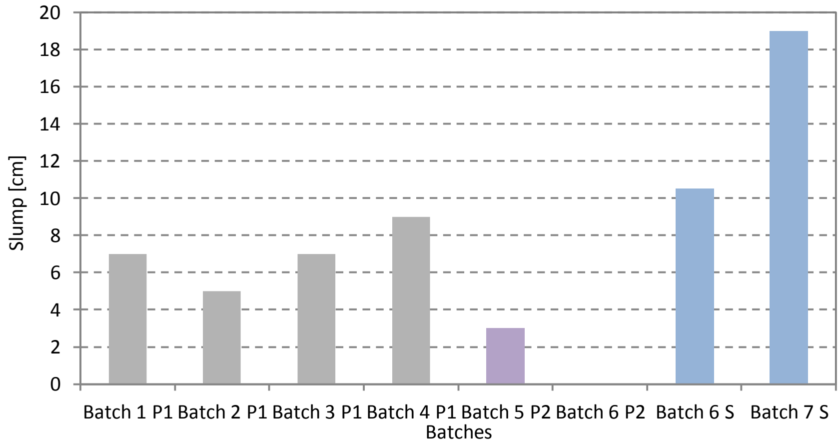


Figure 23. Results of slump

Figure 24 represents the mean slump value for each kind of fibre together with their standard deviation. It is also important to say that the values of the COV (seeTable 17) indicated a great variability, especially for P2 batches.

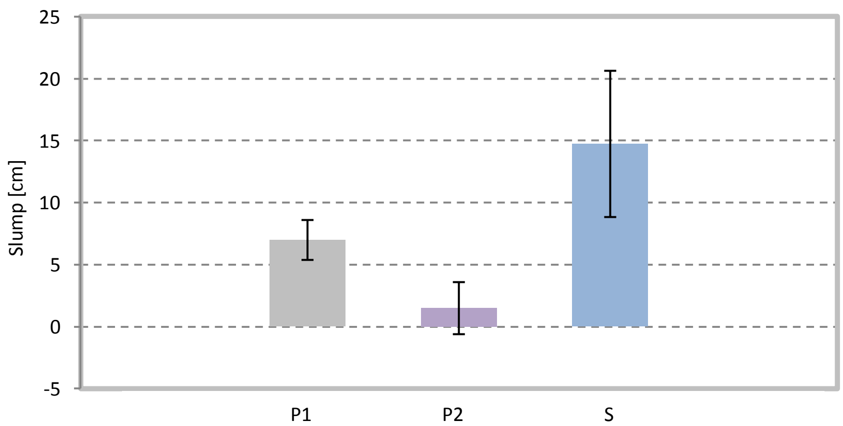


Figure 24. Mean slump and standard variation for each type of fibre

It can be concluded that the effect of adding fibres into the concrete is important on the workability. A decrease in the slump values is observed for macrosynthetic fibres compared to steel fibres. However, this does not imply a reduction in this property for the P1 batches. This fact can indicate that slump test is not the most suitable method for evaluating this property in FRCs. For their part, P2 specimens were not enough workable, but this effect can be overcome using of effective method of compaction and high performance admixtures, resulting on mixes which are capable of being manipulated (the workability restores) and present an appropriate mechanical performance.

5.1.2 Compressive Strength

Compressive strength of hardened concretes was evaluated by simple compression test. The results showed similar values for all cases, around 35MPa (which were initially defined). As expected, adding fibres does not have to lead to an increase of the compressive strength. In fact, CM2010 considers that compressive relations for plain concrete also in general also valid for FRCs *(FIB, 2012).*

From a general point of view, SFRCs present slightly lower values than MSFRCs. An explanation for this was not found, but it is possible to rule out production errors due to the obtained values of the specimens in the three-point bending tests.

Figure 25 shows a comparative graph of the results obtained in simple compression tests for the MSFRC and SFRC batches. It is observed that a great homogeneity was obtained within each series. Moreover, the statistical parameters used to analyse the results indicate that there is no significant deviation between the results. It is important to remark that the COV calculated for Batch 6 S is superior to the rest (see Table 17), but it can be said that all values are quite respected.

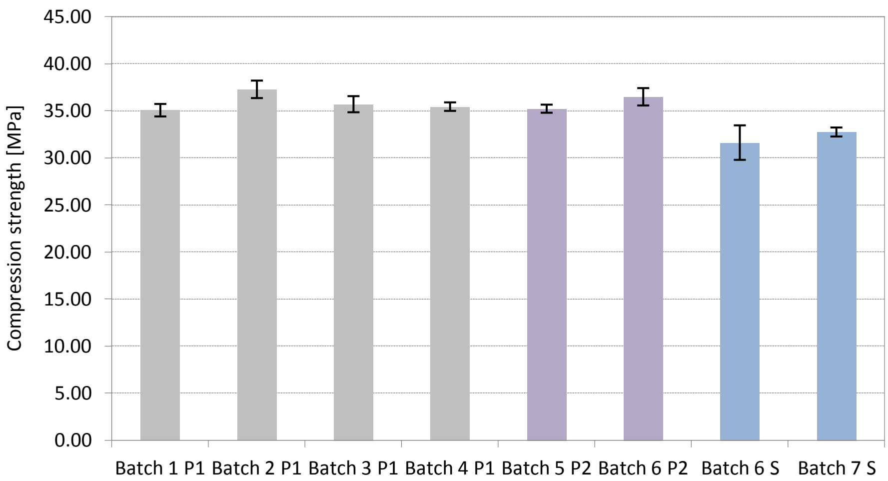


Figure 25. Results of compression tests

It can be concluded that the effect of adding fibres does not lead to an increase of the compressive strength. Actually, a reduction in the compressive strengths is observed for S specimens. In spite of this, the results present a great homogeneity within each series. Thus, it may be affirmed that the concrete mixes are comparable in terms of compressive strength and moreover, it is possible to guarantee the regularity of the procedure.

5.2 Analysis Of Results of the Three-Point Bending Tests

Three-point bending tests at different temperatures were performed to evaluate the influence of moderated temperatures on the mechanical behaviour of FRCs, in particular the post-crack performance of MSFRCs.

This task was carried out by of a comparison between the results. For this purpose, the data of the residual flexural strength corresponding with the limit of proportionality and CMOD = $CMOD_j$ (j = 1, 2, 3, 4) were divided in different sections and analysed separately.

5.2.1 Influence of Moderated Temperature Factor on f_L at $CMOD_{F\_L}$ (at CMOD at limit of proportionality (LOP))

The f_L is defined as the highest force value F_L in the interval of CMOD = 0-0.05 mm in all cases (UNE-EN 14651:2007+A1:2008). To ease the analysis of f_L results, charts derived for the pre-cracking tests (until CMOD = 0.5 mm) at 5 °C are illustrated in Figure 26, Figure 27 and Figure

28. They were selected because, in this way, it is easier to see what is happening at $CMOD_{F\_L}$. In all cases, a non-normalized curve was adopted to express the flexural-tensile behaviour of the FRCs. Here, curves were represented in form of stress and force/load versus CMOD.

These figures show, for each fibre type, similar behaviour in terms of residual flexural strengths at peak-load. It could be due to these values are dependent to the quality of the cement matrix mainly. That is, the LOP is conditioned in the last instance by the compressive strength and this mechanical property presents similar values for all the concretes.

In addition to this, this is also significantly affected by the type of fibre as well as fibre content (when it is up to 1.5% in volume). Furthermore, it is noteworthy that the peak-load values are in a common range for these types of concretes, presenting acceptable values for the calculated coefficients of variation (see Table 18 through Table 21).

Besides, it can be observed in these graphs that the discharge branch is not similar for Figure 26 and the others. This was a result from changing the discharge process. During the first trials, the unloading operation was applied manually. However, an internally programmed procedure was used for the successive tests. It was set up with the objective of determining the final CMOD in this stage with a great accuracy. For this purpose, the velocity of piston displacement was controlled and fixed at 2 mm/minutes.

Additionally, similar figures to the previous ones have been organized in the Appendix D since they present similar forms and trends, despite the temperature. These are thus not shown in order to limit the repeatability of this section. It is important to point out that, in some cases, several incidents occurred during the operating process, which can alter the final results (i.e. the non-proper functioning of the linear displacement sensor), hence the showed behaviours in these figures.

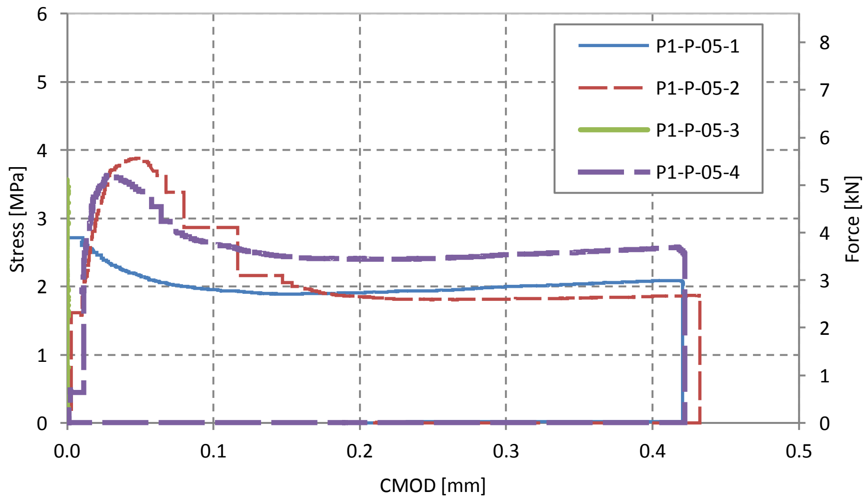


Figure 26. Results of the P1 prismatic specimens during the pre-cracking tests at 5 °C

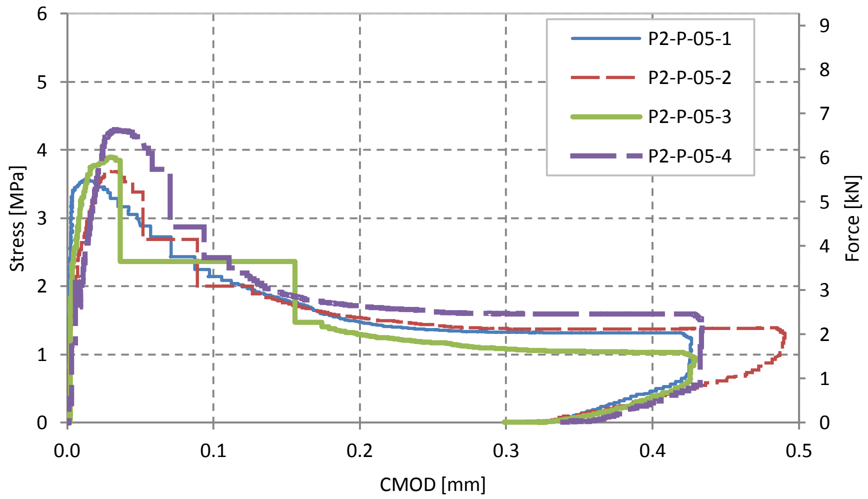


Figure 27. Results of the P2 prismatic specimens during the pre-cracking tests at 5 °C

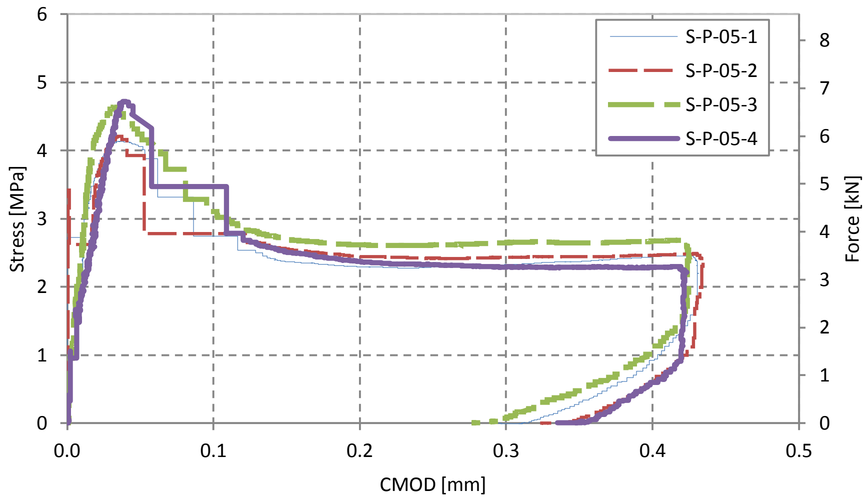


Figure 28. Results of the S prismatic specimens during the pre-cracking tests at 5 °C

On the other hand, another comparative analysis of the obtained results is provided below. Figure 29 displays the average values of f_L for each type of fibre and for each temperature, through a histogram with their corresponding error bar (standard deviation). For a better understanding of these outcomes, a representative colour was defined for each temperature. The blue colour represents the coolest temperature (5 °C) in the bar charts. The temperature of 20 °C is identified by the purple colour. The hot colours depict these temperatures, 35 °C and 50 °C respectively. In addition, the mean value of all the data for every fibre type, without considering the influence of temperature, is also showed, which is the green bar (due to this fact, it is not illustrated in the legend). The explanation here is the same in the following sections and will thus not be repeated here.

In order to ease the identification of relationships between a group of data and draw conclusions that could be extrapolated to the general population bounded to the range of the studied variables, the data was compared using descriptive statistic.

Results comprise exploratory data analysis. They were also treated through analysis of variances (ANOVA). Assuming that the data comes from a normal distribution, ANOVA tests were performed to study the influence of moderated temperatures on the average residual flexural strength at different CMOD. The null-hypothesis, that is the residual flexural strengths at different temperatures are equal to each other, was tested. These analyses were carried out by computing the p-values, which represent the probability for a given statistical model that, when the null hypothesis is true, the statistical summary (such as the sample mean difference between two compared groups) would be the same as or of greater magnitude than the actual observed results *(Wasserstein and Lazar, 2016)*. Thus, the null hypothesis is normally rejected when the p-value is smaller than a predetermined significance level, which is often assumed to be 0.05.

For this purpose, the software *Stat graphics* was employed to process the values and reach this particular analysis. It was possible to study the synergy between some variables as well. Three independent variables were used to perform the analysis: i) the type of fibre, ii) the pre-cracking conditions and iii) the moderate temperature. This part of the investigation is collected in more detail in the Appendix E (in Spanish).

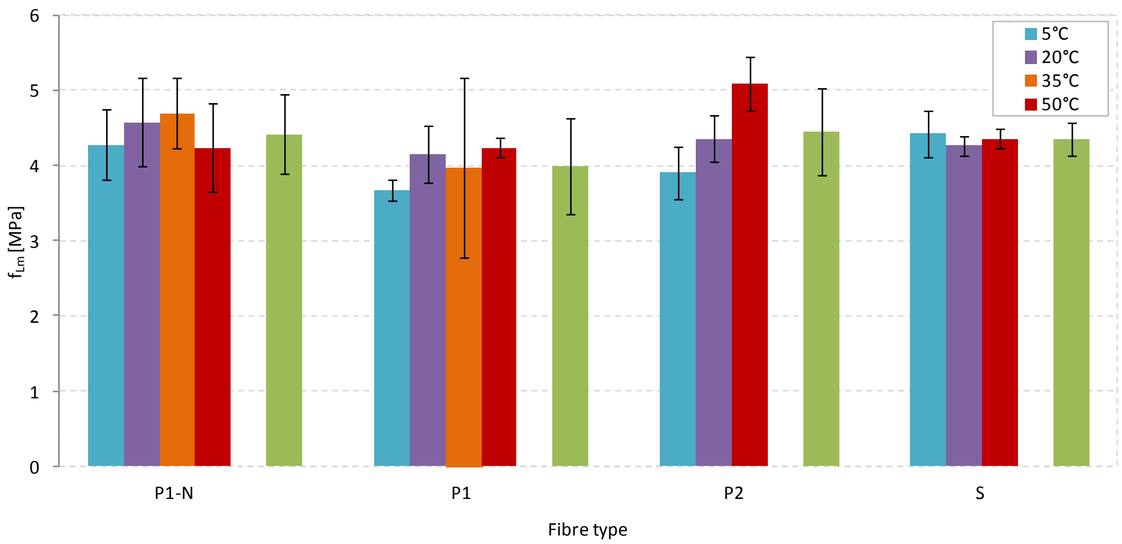


Figure 29. Results of f_{Lm} for each type of fibre at different temperatures

In Figure 29, it is possible to observe that each type of fibre (steel and macrosynthetic) responds in a different way. For S samples, the increase or descent of the temperature has no significant effect on the f_{Lm}. For P1 and P2 specimens, an effect of temperature on f_L was observed but it has limited statistical significance since the p-values are almost at the significance threshold (see Appendix E (in Spanish)). However, if the precracked conditions are considered as a factor at the same time, f_{Lm} does not be affected by the temperature for both cases.

Moreover, the precracked condition is not a significant factor for f_{Lm} because it does not significantly affect the results, as was previously commented. However, it is important to notice that higher residual flexural strength values are obtained for non pre-cracked specimens, regardless of the temperature (except at 50 °C (see interaction graph in Appendix E (in Spanish)). This is logical since the specimens are not weakened due to the pre-cracking test.

For the rest of the temperatures, an increasing trend is observed. For instance, at 5 °C and 20 °C, f_{Lm} increases when the temperature also grows, but it is not remarkable.

5.2.2 Influence of Moderated Temperature Factor on the Residual Flexural Strength f_{R1} at $CMOD_1$ (at CMOD = 0.5 mm)

The f_{R1} is defined as the residual flexural strength at $CMOD_1$ = 0.5 mm (UNE-EN 14651:2007+A1:2008). To exanimate the obtained results for f_{R1}, the following figures (Figure 30-Figure 33) are depicted. These showed the complete process of a three-point bending test at 5 °C for all specimens (both precracked and un-cracked). Here, the X axis represents CMOD and the Y axis expresses the load and the stress, as in the figures of the previous section. In this case, one should pay attention to the values which are around $CMOD_1$.

From a general point of view, the addition of fibres shows a ductile mode of failure and a post-failure structural performance, as was expected in spite of the temperature factor. This is attributed to the ability of the fibres to distribute stresses and to slow down the crack propagation process. However, it is important to consider that, after post-crack, the behaviour is dependent of the type of fibre. That is to say, steel fibres are more useful to enhance the post-peak because of their high elastic modulus and their resistance to pull-out from the matrix. Thus, SFRC presents normally the highest results for f_L but the residual flexural strength is going down with the development of CMOD. On the contrary, synthetic fibres are more effective in the post-cracking behaviour, giving higher results for higher values of CMOD.

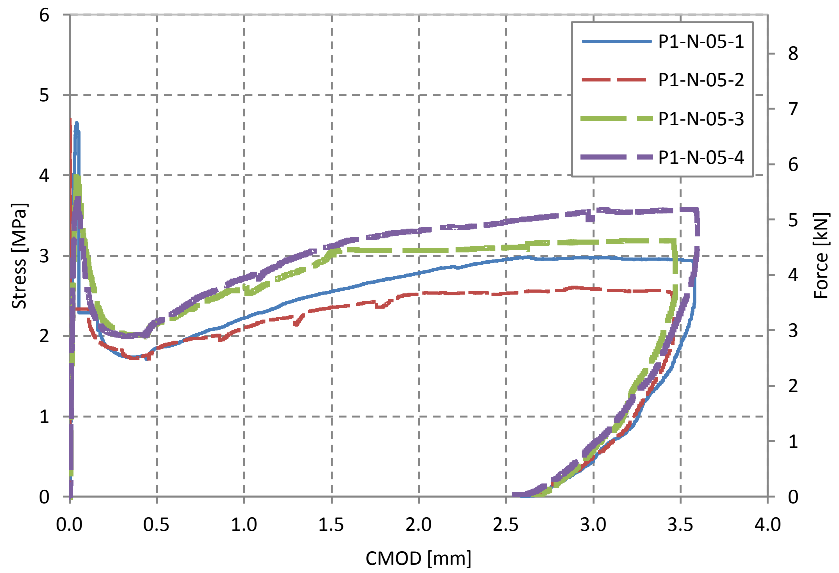


Figure 30. Results of three-point bending test for P1 non-precracked samples at 5 °C

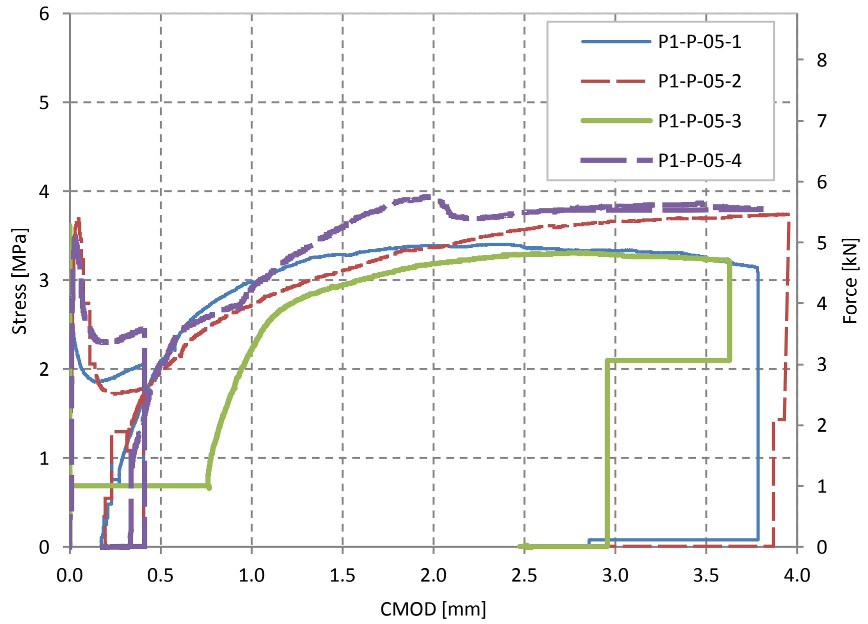


Figure 31. Results of three-point bending test for P1 precracked samples at 5°C

It is important to notice the difference between Figure 30 and Figure 31, which is the pre-cracking condition. On the other hand, the obtained values are practically the same for both conditions. It is certain that they are superior for the pre-cracking condition but this deviation is negligible.

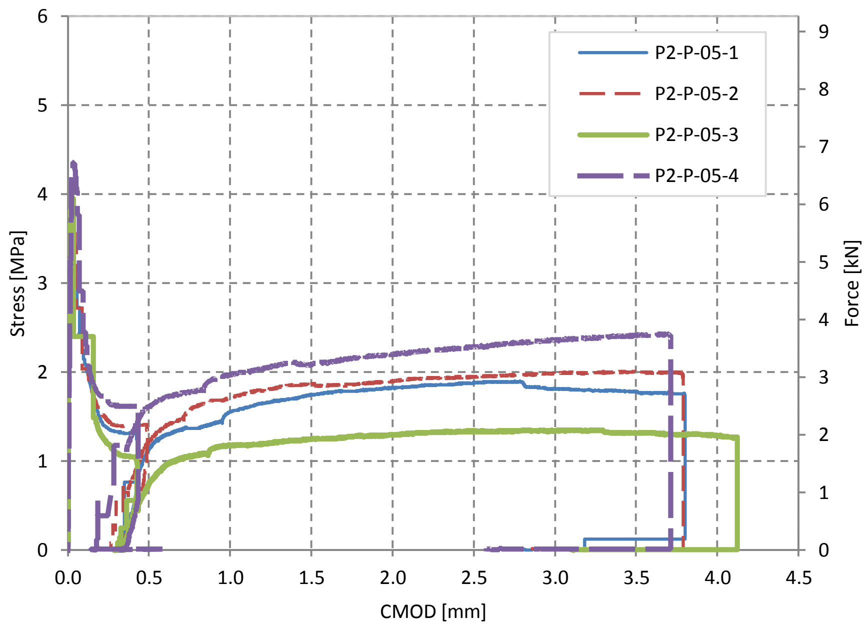


Figure 32. Results of three-point bending test for P2 precracked samples at 5°C

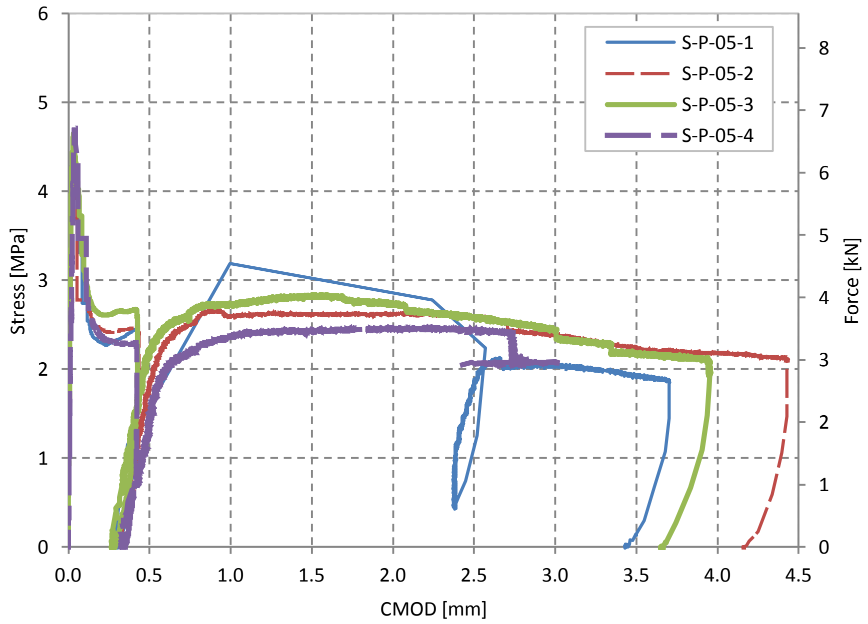


Figure 33. Results of three-point bending test for S precracked samples at 5°C

As was mentioned in the prior section 4.2.1, similar graphs to the previous ones have been organized in the Appendix D since they present quite similar shapes and trends, despite the temperature.

On the other hand, Figure 34 shows the residual flexural behaviour at CMOD = 0.5 mm for every type of fibres at different target temperatures. From a general point of view, it is also possible to observe that the results for P1 samples are inferior to those obtained for S specimens and higher than for P2 specimens. It is noteworthy that the coefficients of variation were larger than in the past case study (see Table 18 through Table 21), indicating a greater variability in each batch. Moreover, these data were ascertained using descriptive statistic.

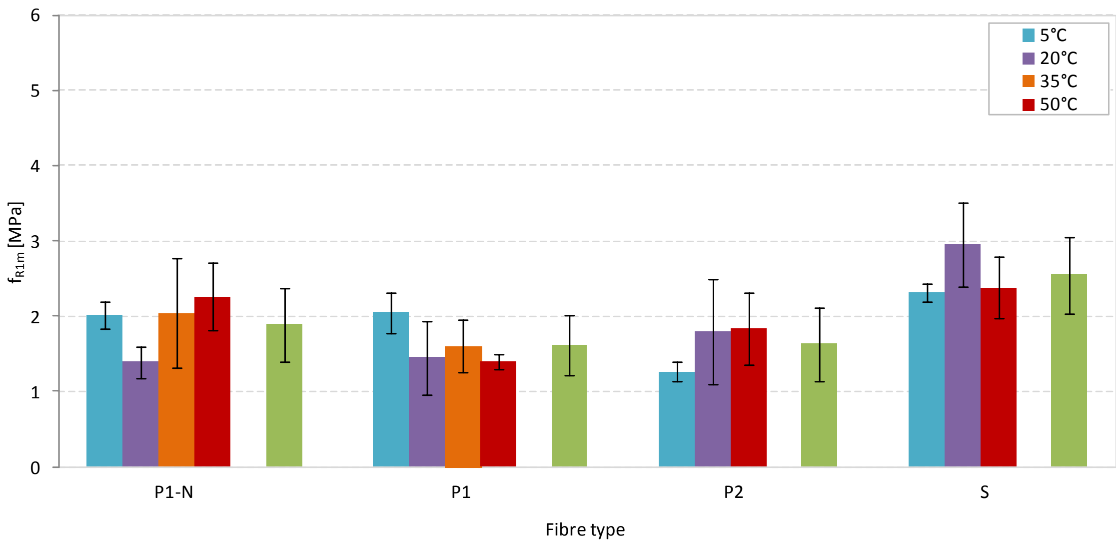


Figure 34. Results of f_{R1m} (at CMOD = 0.5 mm) for each type of fibre at different temperatures

As can be seen in the previous image, S specimens had a negative effect on f_{R1m} which may be due to the temperature difference from the reference (20 °C). The obtained data is almost equal to both extreme temperature (5 °C and 50 °C). However, this effect is not significant since the p-value of the F-test is greater than 0.05.

For P2 elements, it is possible to affirm that a fall in temperature may cause a reduction in f_{R1m}. On the other hand, the obtained residual flexural strengths at CMOD = 0.5 mm at 20 °C and 50 °C were similar. These outcomes are lower than the results for the S specimens. These observations are not important by examining statistical data.

Furthermore, the influence of the temperature on f_{R1m} for P1 samples can be discussed. On the one hand, the values presented for residual flexural strength at CMOD = 0.5 mm are close to each other in both cases. It indicates that the temperature is not a significant factor from a statistical point of view (See Appendix E (in Spanish)) as was aforementioned. On the other hand, if the precracked conditions are considered as a factor at the same time, f_{R1m} appears to be affected by the temperature. This effect shows a significant difference between the mean of f_{R1} between different temperatures, with 95% confidence. Therefore, it is not possible to draw a resolute conclusion.

Related to this, it can be observed that the results are practically equal to the previous case, in both situations. It may be explained because PP homopolymer become susceptible (more brittle) when it freezes and the cold target temperature is superior; therefore, it has no effect on them. For the rest of the temperatures, it could be due to the short period of conservation or the range of temperatures selected.

Moreover, a slight reduction of residual flexural strength f_{R1m} was noticed for the rest of temperatures. It can be due to the concrete (as most solid materials) contracts when the temperature decreases. This is because of the reduction of the kinetic energy of the atoms which causes a decrease of the distance between them. This gives as a result a growth in strength because the attractive inter-atomic forces increase *(Pigeon and Cantin, 1998)*. Additionally, the principal energy absorption mechanism (i.e. pull-out or breaking) may still exist at low temperatures so that the fall of temperature may lead to a growth of strength of the matrix and thus, to the increased energy requirement during the pull-out or breaking of the fibres.

Finally, a rising trend since 20 °C may be observed for P1-N specimens. In this case, fibres were not exposed to the environmental agents and temperature might favour the hardened reaction of the concrete matrix. For P1-P samples, similar behaviour for warm and reference temperatures were shown. P1-P 35 present a non expected behaviour, being difficult to explain the origin of this phenomenon, since the related works make use of diverse temperatures and fibre contents.

5.2.3 Influence of Moderated Temperature Factor on the Residual Flexural Strength f_{R2} at $CMOD_2$ (at CMOD = 1.5 mm)

The f_{R2} is defined as the residual flexural strength at $CMOD_2$ = 1.5 mm (UNE-EN 14651:2007+A1:2008). To analyse the obtained results for f_{R2}, the previous figures (Figure 30-

Figure 33) were also illustrated. Here, one should pay attention to the values which are around $CMOD_2$ and the previous general considerations.

On the other hand, the following figure (Figure 35) displays the residual flexural strengths at CMOD = 1.5mm, for every kind of fibre at different moderated temperatures. From a general point of view, it is not possible to observe any trend. It is also noteworthy that the coefficients of variation were in line with the COVs for f_{R2} (see Table 18 through Table 21), indicating a significant variability in each batch. Moreover, these data were ascertained using descriptive statistic.

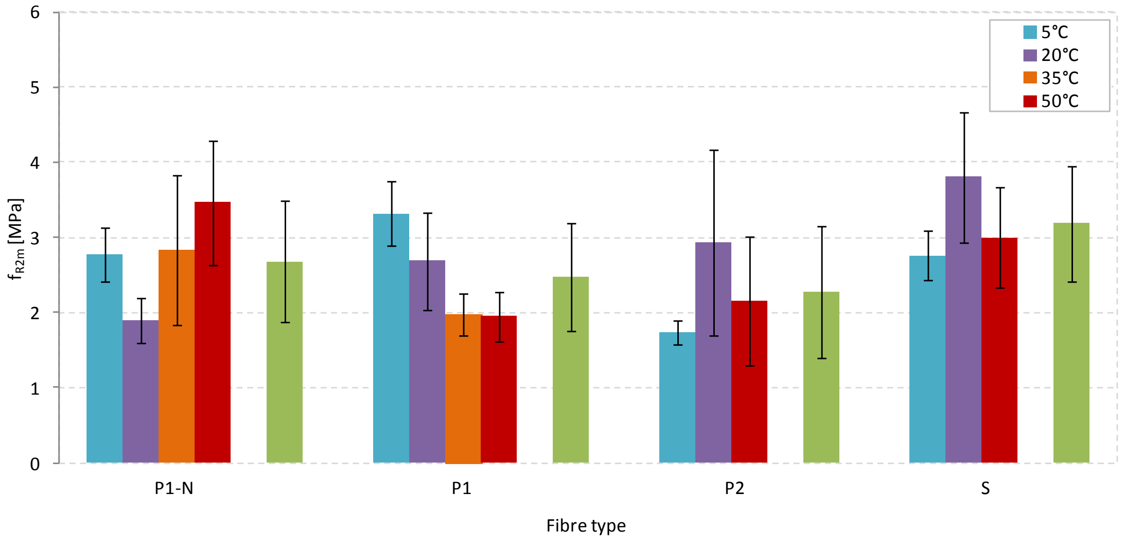


Figure 35. Results of f_{R2m} (at CMOD = 1.5 mm) for each type of fibre at different temperatures

S specimens show the same descending trend for extreme target temperatures. In this case, the cold temperature affects the residual tensile strength at CMOD = 1.5 mm to a greater extent than warm temperatures, but this difference is not meaningful from a statistical point of view.

Moreover, a drop in temperatures or an increase varies the results of f_{R2m} for P2 elements. At 20 °C, the best results were obtained for P2 samples. Thus, a similar behaviour between P2 and S was noticed. It can be concluded that the f_{R2} data presents a reduction when a variation of temperature occurs, having no statistical significance.

Finally, it can been seen in the Figure 35 that the P1 specimens had an increase in the residual tensile strength f_{R2m} at 5 °C. A similar trend was observed for the f_{R1m} values. What is more, P1-N specimens remain ascending results from 20 °C as for residual tensile strength at CMOD = 0.5 mm; for P1-P samples, a descending tendency may be found with an increase of temperature. Given that the p-value of the F-test is smaller than 0.05, there is a statistically significant difference among the mean of f_{R2m} between different target temperatures, with a level of 5% significance. It is also demonstrated that the interaction between temperature and precracked conditions also have an effect on the residual flexural strength at different temperatures (see Appendix E (in Spanish)).

5.2.4 Influence of Moderated Temperature Factor on the Residual Flexural Strength f_{R3} at $CMOD_3$ (at CMOD = 2.5 mm)

The f_{R3} is described as the residual flexural strength at $CMOD_3$ = 2.5 mm (UNE-EN 14651:2007+A1:2008). To study the obtained data for f_{R3}, the previous figures (Figure 30-Figure 33) were also illustrated. Here, one should pay attention to the values which are around $CMOD_3$ and the prior general observations.

Furthermore, Figure 36 illustrates that the behaviour for residual flexural strength at $CMOD_3$ for all types of fibres and all temperatures. From a general point of view, it is not possible to observe any trend. It is also noteworthy that the coefficients of variation were in line with the COVs for f_{R2} and f_{R3} (see Table 18 through Table 21), indicating an important variability within this study. Moreover, these data were ascertained using descriptive statistic.

That is, S specimens exhibited lower values of f_{R3m} for target temperatures of 5 °C and 50 °C than for the standard temperature. Same as in the previous situation, the cold temperature could influence the residual flexural strength of SFRCs more than the warm temperature. Thus, an effect of temperature on f_{R3m} was noted and it has a statistical significance since the p-value is under the significance threshold.

For P2 elements, the temperature can cause changes in the values of f_{R3m} but they are not relevant from a statistical point of view. At 20 °C, the best results were obtained for this type of fibre. At CMOD = 2.5 mm and 3.5 mm, the residual strengths present a reduction when a variation of temperature occurs.

For the specimens reinforced with the macrosynthetic fibre P1, the best behaviour occurred at low temperatures. An equivalent trend can be noted if f_{R3m} is compared to f_{R2m}. P-values obtained from ANOVA are lesser than 0.05, therefore a statistically significant difference exists between the mean of f_{R3} between the levels of temperature, with 95% confidence. However, if the pre-cracking conditions are considered as a factor at the same time, temperature factor does not has influence on f_{R3m}.

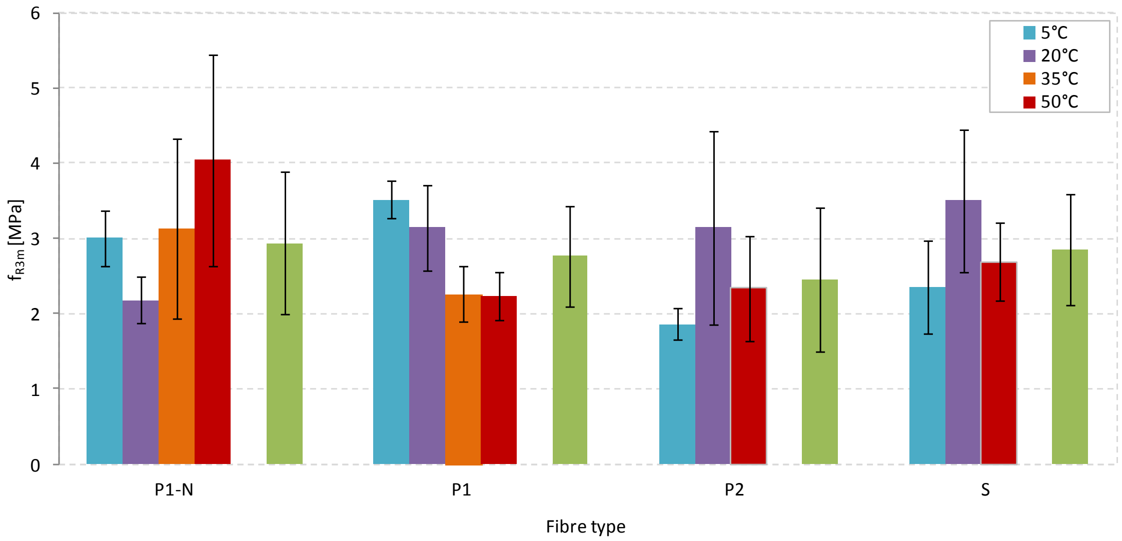


Figure 36. Results of f_{R3m} (at CMOD = 2.5 mm) for each type of fibre at different temperatures

5.2.5 Influence of Moderated Temperature Factor on the Residual Flexural Strength f_{R4} at CMOD₄ (at CMOD = 3.5 mm)

The f_{R4} is described as the residual flexural strength at $CMOD_4$ = 3.5 mm (UNE-EN 14651:2007+A1:2008). To study the obtained data for f_{R4}, the previous figures (Figure 30-Figure 33) were also illustrated. Here, one should pay attention to the values which are around $CMOD_4$ and the aforementioned comments.

Furthermore, Figure 37 illustrates that the behaviour for residual flexural strength at $CMOD_3$ for all types of fibres and all temperatures. From a general point of view, it is important to emphasize that a similar behaviour was observed at $CMOD_4$. It is also noteworthy that the coefficients of variation present the highest values (see Table 18 through Table 21), indicating the most variability in each batch. Moreover, these data were ascertained using descriptive statistic.

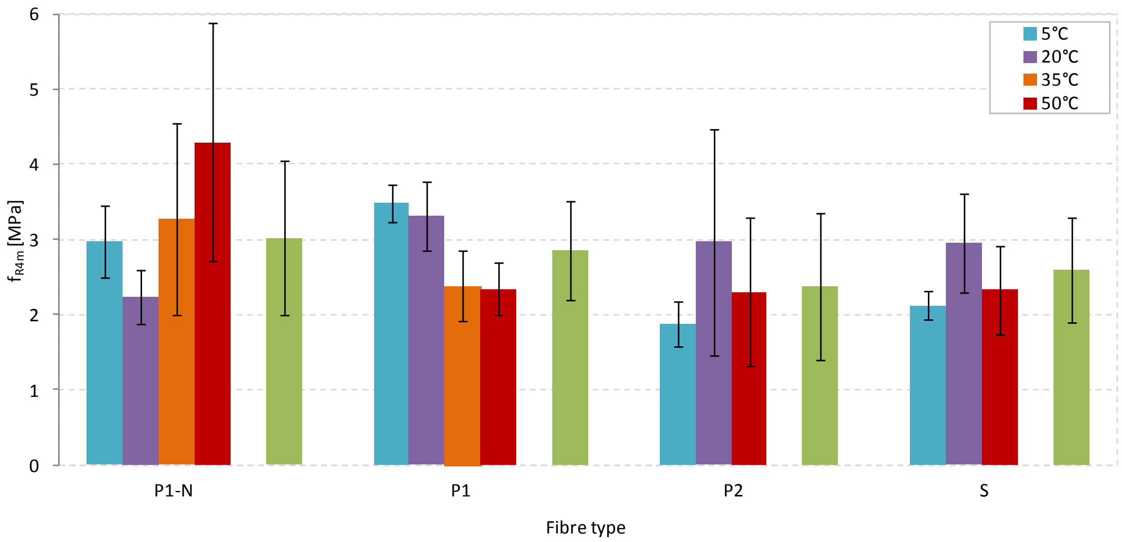


Figure 37. Results of f_{R4m} (at CMOD = 3.5 mm) for each type of fibre at different temperatures

For S specimens, the values of f_{R4} were lower at target temperatures of 5 °C and 50 °C; same as in the previous situation, it can be explained due to the influence of the cold temperature on the residual flexural strength of SFRCs (more than the warm temperature). Moreover, an effect of temperature on f_{R4m} was noted and it has a statistical significance since the p-value is under the significance threshold; for P2 elements, the temperature can cause changes in the values of f_{R4m} (in a similar way that S elements) but they are not relevant from a statistical point of view.

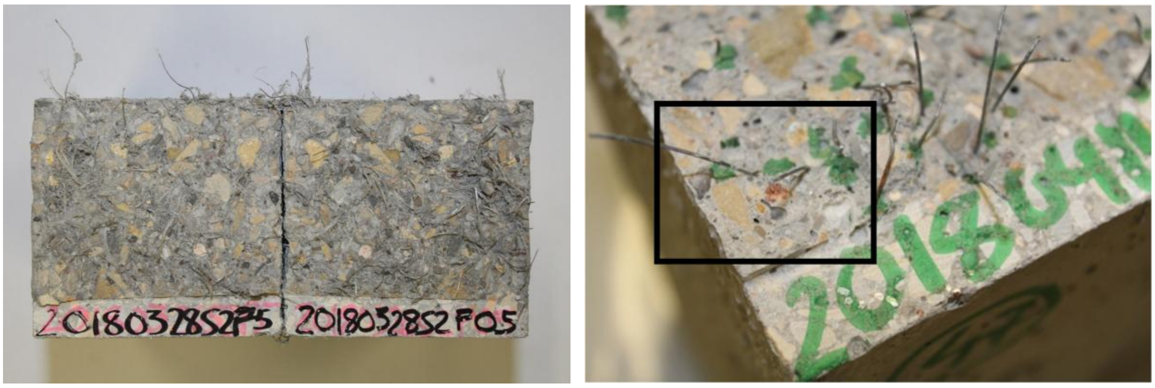
Finally, for the specimens reinforced with the macrosynthetic fibre P1, an equivalent trend can be noted if f_{R4m} is compared to f_{R2m} and f_{R3m}. P-values obtained from ANOVA are lesser than 0.05, therefore there is a statistically significant difference, with 95% confidence, and it can be said that moderated temperatures affect the residual flexural strengths. However, if the pre-cracking conditions are considered as a factor at the same time, f_{R4m} does not be affected by the temperature. This can explained why non-precracked samples show better behaviour at warm moderate temperatures, acting as a catalyst in these cases during the hardening reactions of MSFRCs. On the other hand, it is also important to notice that the interaction between the temperature and the pre-cracking conditions affects the residual flexural strength $f_{R4m.}$.

5.3 Analysis of Results of the Visual Inspection after Three-Point Bending Test

After the three-point bending tests, a visual examination of the fractured cross surface of the specimens was carried out. Here, the uniformity of the fibres' distribution and the fibre density in the transversal section are analysed. It is important to remind that this was not accomplished for P2 fibres, due to the bond between the fibres.

According to Table 22, it is possible to conclude that fibre distribution in the cement matrix was quite uniform. To check this, fractured cross surface was divided in three horizontal bands and the fibres were counted for each brand. In the most of cases, the number of fibres was similar between the bands for each specimens. Regarding the fibre density, the mean value of the specimens with steel fibres are lower than the samples with macrosynthetic fibres. This is coherent with the volume of fibre added.

Furthermore, there is not any surface visible damage and the disintegration of macrosynthetic fibres did not exist (Figure 38-a) for these conditions. However, some steel fibres presented corrosion stains due to their submerged period of conservation (Figure 38-b).



(a) (b)

Figure 38. Results of visual inspection: (a) Fractured cross surface for P2 specimen; (b) Strains of corrosion in S sample

5.4 Summary of Results and General Discussion

As a brief summary of the results of different test, it is possible to say that:

- The aims of the characterization tests were reached. The concrete mixes are comparable in terms of compressive strength, guaranteeing the regularity of the procedure. These also results on mixes which are workable, although slumps tests do not show this fact.
- MSFRC and SFRC specimens have a different behaviour during the three-point bending tests and they are also affected by the temperature factor in a different manner, as was expected since the fibre type was different.

- Different responses are generally presented by the P1 and P2 fibres. Although both are made of polypropylene, they have different behaviours: the former are composed by copolymer of polypropylene according to the manufacturer while the second ones are only derived from PP. This, together with the fibre type, may explain the difference in the obtained data during the development of this experimental program.
- P1 MSFRC elements do not exhibit an understandable behaviour for this range of temperatures.
- There is a negative influence on the residual flexural strength for the P1-P when temperature increases, and on the contrary, this increase of temperature has a positive effect for the P1-N. Nevertheless, they are not significant by examining statistical data. Additionally, the interaction between this factor and the temperature can be influential in some cases.
- P2 MSFRC samples are not affected by the target temperatures.
- SFRC presents an unstable behaviour with variations of temperature in a common range. It means that temperature factor has a slight negative effect on the residual strength for the steel fibres reinforced concrete elements at $CMOD_3$ and $CMOD_4$, but not at peak-load.
- In general, moderated temperatures do not have a clear effect on the f_L strengths, but if the temperature had presented influence on this residual flexural strength, it would have been not important.

Given that the related works make use of diverse temperatures, methodologies, volume and type of fibre, it is complicated to argue about this in a proper way. Therefore, a comparison of these results with the literature is immediately provided from a general point of view.

Firstly, Buratti and Mazzotti *(Buratti and Mazzotti, 2015)* obtained that SFRCs and MSFRCs have a different behaviour with temperature, as can be also seen in the summary of this section. However, they affirmed that the effect of temperature is less relevant for SFRCs than for MSFRCs, but according to the obtained data it cannot be affirmed that the influence on the SFRCs was lower than on the MSFRCs.

Furthermore, they also concluded that the temperature reduced the short-term residual flexural strength of some of the specimens and the temperature should be considered as a factor when designing MSFRCs *(Buratti and Mazzotti, 2015).* In contrast, it is possible to comment that variations of temperature may cause an increase or reduction in the short-term residual flexural strength, but it is not significant for all the cases.

For their part, Rambo et al. *(Rambo et al., 2018)* reported that the temperatures employed for the residual flexural tests in their study (below the melting point) were not capable to alter the mechanical properties of their fibre reinforced concrete. In this study case, conclusions are coinciding. The effect of temperature did (to a great extent) not affect the performance of polypropylene fibres at moderate temperatures.

In relation to the influence of moderate temperatures on SFRCs, the results for S specimens in this campaign were different. Some authors investigated the behaviour of SFRCs under flexural loading *(Pigeon and Cantin, 1998)*, pointing out an increase of the toughness when the temperature decreases. However, SFRC specimens presented a decline in the value of residual strength at low temperatures.

Related to pre-cracking condition, BASF (2018) carried out a study where showed a reduction of the residual flexural strength at 40 °C for non-precracked and precracked specimens. Nevertheless, different behaviours were presented by the studied specimens depending on the CMOD, the fibre type and the pre-cracking condition. This last factor is not influential, but its interaction with the temperature can be considered in some results.

Due to these facts, it is not possible to obtain forceful conclusions about the effect of temperature on the residual flexural strengths of MSFRCs, and but it has been achieved to provide an extra understandable knowledge in order to be investigated in subsequent works.

Chapter 6

Conclusions

In this research, an experimental campaign in order to try to obtain a better understanding of the influence of moderate temperatures (5 °C, 20 °C, 35 °C and 50 °C) on the mechanical behaviour of macrosynthetic fibre reinforced concretes, was carried out. For this purpose, a common concrete with a compression strength of 35 MPa, a 10 mm MAS and a high workability was selected. Moreover, two types of macrosynthetic fibres were employed: Sika M-48 (P1) and Forta Ferro 54mm (P2) in a relatively high content (10 kg/m³). To evaluate the effect of the targeted temperatures on the residual flexural strength of these mixes, three-point bending tests (described in the standard UNE-EN 14651:2007+A1:2008) were performed. Moreover, other criteria have also been considered such as the pre-fissuring of the specimens and the use of steel fibres (Dramix 65/40 3D (S)) in an equivalent volume. The compressive strength and workability of the concrete were used as complementary characterization tests.

Generally, the objective of this work was to develop a detailed analysis of the effect of moderate temperatures on the behaviour of MSFRCs. Furthermore, the following conclusions drawn are:

- An extra understandable knowledge is provided, expanding the current state of the art in this topic.
- Considering that there is no standardized protocol in order to analyse short-term behaviour of MSFRCs at the targeted temperatures and to try to answer to this need, a testing methodology based on the standard UNE-EN 14651:2007+A1:2008 (2/3 scale) is proposed. This modified procedure includes a system of insulating thermal covering which allows to maintain the temperature during the tests. It is concluded that the suggested method, which concerned the temperature as an influential factor, managed to figure out its influence on the short-term behaviour.
- The results of this experimental campaign support the conclusion that the addition of fibres not necessarily leads to an increase of the compressive strength and a loss of workability.
- The outcomes derived from the 80 specimens in the three-point bending test show that P1 MSFRC, P2 MSFRC and SFRC have different behaviours which are affected by the temperature factor. Thus, moderate temperatures can be considered in several cases but then, it would not be significantly important.
- It is also possible to affirm from three-point bending tests that the pre-cracking condition should not be taken into account, however, its interaction with moderate temperatures can be influential in some cases.
- The exploratory data analysis tool facilitates the identification of functional relationships in the particular case, since there is no notable trend within the outcomes. Actually, different responses are generally presented for each studied variable (fibre type, temperature and service condition). It can be accepted that these variations are due to the variability of the results between several specimens from the same production.

In short, the influence of the target temperatures (5 °C - 50 °C) on the residual flexural strength caused variable behaviour for the analysed MSFRCs and SFRCs, after 60 days of conservation. This promotes to continue the investigation in this direction in order to obtain forceful conclusions.

Chapter 7

Improvements and Future Research

Chapter 7 proposes some improvements that should be taken into account in following works, in order to enhance the obtained results. Additionally, future research directions are pointed out with the aim of contributing to the knowledge on the influence of moderate temperatures on macrosynthetic fibre reinforced concretes and to continue to further investigate this in subsequent studies.

Thus, some advances on several aspects of this work, which can be considered in the future, are:

- Increasing the experimental program regarding to the number of specimens, in order to obtain a larger reliability in the final conclusions.
- Introducing modifications in the testing methodology, which aim to determinate the temperature during the test in the concrete with a greater accuracy. Moreover, the temperature after testing can also be considered. These modifications permit to gain additional and complementary information which may help to understand the results in a better manner.

Finally, the following future research directions are suggested:

- Extending the range of target temperatures can be interesting (from -20 °C through 80 °C), in order to study the behaviour of MSFRC in several work-conditions.
- A larger period of conservation can be proposed in order to determine the durability and the degradation of the fibres in these cases.
- Modifying the type and/or content of polymeric fibres in the matrix of the concrete, as well as the concrete matrix. This should be understood as fibres made with others materials and/or brands commercially available.
- Analysing the brittleness of MFSRCs at low temperatures, due to the lack of existing literature on this topic.

References

ACI Committee 544 (2002) ‘ACI 544.1R-96: Report on Reinforced Concrete (Reapproved)’, ACI Structural Journal, 96(Reapproved), pp. 1–66.

Alani, A. M. and Beckett, D. (2013) ‘Mechanical properties of a large scale synthetic fibre reinforced concrete ground slab’, Construction and Building Materials, 41, pp. 335–344.

Andrade, C., Sarria, J. and Alonzo, C. (1999) ‘Relative humidity in the interior of concrete exposed to natural and artificial weathering’, Cement and Concrete Research, 29(8), pp. 1249–1259.

Bamonte, P., Gambarova, P. G. and Nafarieh, A. (2016) ‘High-temperature behavior of structural and non-structural shotcretes’, Cement and Concrete Composites, 73, pp. 42–53.

Bolat, H. et al. (2014) ‘The effects of macro synthetic fiber reinforcement use on physical and mechanical properties of concrete’, Composites Part B: Engineering, 61, pp. 191–198.

Buratti, N. et al. (2011) ‘Temperature and loading level effect on the long-term behaviour of MSFRC and SFRC’, Conference: Fibre Concrete 2011. 8-9th Septiembre. Prague.

Buratti, N. and Mazzotti, C. (2012) ‘Temperature effect on the long term behaviour of macro-synthetic-and-steel–fibre reinforced concrete’, 8th RILEM international symposium on fibre reinforced concrete: challenges and opportunities.

Buratti, N. and Mazzotti, C. (2015) ‘Experimental tests on the effect of temperature on the long-term behaviour of macrosynthetic Fibre Reinforced Concretes’, Construction and Building Materials. Elsevier Ltd, 95, pp. 133–142.

Buratti, N., Mazzotti, C. and Savoia, M. (2011) ‘Post-cracking behaviour of steel and macro-synthetic fibre-reinforced concretes’, Construction and Building Materials, 25(5), pp. 2713–2722.

CEN - Comité europeo de normalización (2008) ‘UNE-EN 14651:2007+A1. Método de ensayo para hormigón con fibras metálicas. Determinación de la resistencia a la tracción por flexión (límite de porporcionalidad (LOP), resistencia residual)’.

CEN - Comité europeo de normalización (2012) ‘UNE-EN 933-1:2012. Ensayos para determinar las propiedades geométricas de los áridos. Pare 1: Determinación de la granulometría de las partículas. Método del tamizado’.

CEN - Comité europeo de normalización (2009) ‘UNE-EN 12350-2:2009. Ensayos de hormigón fresco. Parte 2: Ensayo de asentamiento’.

CEN - Comité europeo de normalización (2009) ‘UNE-EN 12390-3. Ensayos de hormigón endurecido. Parte 3: Determinación de la resistencia a compresión de probetas’.

CEN - Comité europeo de normalización (2008) ‘ UNE-EN 14889-2:2008. Fibras para hormigón. Parte 2. Fibras poliméricas. Definiciones, especificaciones y conformidad’.

Cengiz, O. and Turanli, L. (2004) ‘Comparative evaluation of steel mesh, steel fibre and high-performance polypropylene fibre reinforced shotcrete in panel test’, Cement and Concrete Research. Pergamon, 34(8), pp. 1357–1364.

Cheng, B. et al. (2014) ‘Experiment on the Mechanical Performance of Fiber Lightweight

Aggregate Concrete after Freeze-Thaw and Elevated Temperature', Advanced Materials Research, 919–921, pp. 1790–1793.

FIB - The International Federation for Strucutrual Concrete (2012), Bulletin 66: Model Code 2010 – Final draft, vol. 1. Laussanne, Switzerland, 370pp.

FIB - The International Federation for Strucutrual Concrete (2012), Bulletin 66: Model Code 2010 – Final draft, vol. 2. Laussanne, Switzerland, 370pp.

Fidelis, M. E. A. et al. (2016) 'The effect of accelerated aging on the interface of jute textile reinforced concrete', Cement and Concrete Composites, 74, pp. 7–15.

Fraternali, F. et al. (2011) 'Experimental study of the thermo-mechanical properties of recycled PET fiber-reinforced concrete', Composite Structures. Elsevier, 93(9), pp. 2368–2374.

Garcia-Taengua, E., Martí-Vargas, J. R. and Serna, P. (2016) 'Bond of reinforcing bars to steel fiber reinforced concrete', Construction and Building Materials, 105(JANUARY), pp. 275–284.

Hsie, M., Tu, C. and Song, P. S. (2008) 'Mechanical properties of polypropylene hybrid fiber-reinforced concrete', Materials Science and Engineering: A, 494(1–2), pp. 153–157.

Hsiu-Lung Huang et al. (2012) 'Study on the properties of high strength polypropylene fiber concrete', Conference: The 2012 World Congress on Advances in Civil, Environmental, and Materials Research, at Seous, Korea.

Hughes, P. et al. (2013) 'Microscopic examination of a new mechanism for accelerated degradation of synthetic fibre reinforced marine concrete', Construction and Building Materials, 41, pp. 498–504.

Kevern, J. T., Biddle, D. and Cao, Q. (2015) 'Effects of Macrosynthetic Fibers on Pervious Concrete Properties', Journal of Materials in Civil Engineering, 27(9), p. 06014031.

Kurtz, S. and Balaguru, P. (2000) 'Postcrack creep of polymeric fiber-reinforced concrete in flexure', Cement and Concrete Research, 30(2), pp. 183–190.

Marcos-Meson, V. et al. (2018) 'Corrosion resistance of steel fibre reinforced concrete - A literature review', Cement and Concrete Research, 103, pp. 1–20.

Mazaheripour, H. et al. (2011) 'The effect of polypropylene fibers on the properties of fresh and hardened lightweight self-compacting concrete', Construction and Building Materials, 25(1), pp. 351–358.

Ministerio de fomento (2008) 'Anejo 14. Recomendaciones para la utilización de hormigón con fibras', EHE-08, pp. 505–525.

Mirzazadeh, M. M., Noël, M. and Green, M. F. (2016) 'Effects of low temperature on the static behaviour of reinforced concrete beams with temperature differentials', Construction and Building Materials, 112, pp. 191–201.

Nili, M. and Afroughsabet, V. (2010) 'Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete', International Journal of Impact Engineering. Elsevier Ltd, 37(8), pp. 879–886.

Pigeon, M. and Cantin, R. (1998) 'Flexural properties of steel fiber-reinforced concretes at low temperatures', Cement and Concrete Composites, 20(5), pp. 365–375.

Pujadas, P. (2009) 'Durabilidad del hormigón con fibras de polipropileno'. Universitat Politècnica de Catalunya.

Rambo, D. A. S. et al. (2018) 'Study of temperature effect on macro-synthetic fiber reinforced concretes by means of Barcelona tests: An approach focused on tunnels assessment', Construction and Building Materials, 158, pp. 443–453.

Segre, N., Tonella, E. and Joekes, I. (1998) 'Evaluation of the stability of polypropylene fibers in environments aggressive to cement-based materials', Cement and Concrete Research, 28(1), pp. 75–81.

Shaowei Hu (2011) 'Experimental Research on SFRC Subjected to Wastewater and dry-wet cycling', INFORMATION, 14 (12), pp.4035-4040

Soroushian, P., Plasencia, J. and Ravanbakhsh, S. (2003) 'Assessment of reinforcing effects of recycled plastic and paper in concrete', ACI Materials Journal, 100(3), pp. 203–207.

Söylev, T. A. and Özturan, T. (2014) 'Durability, physical and mechanical properties of fiber-reinforced concretes at low-volume fraction', Construction and Building Materials. Elsevier, 73, pp. 67–75.

Wasserstein, R. L. and Lazar, N. A. (2016). 'The ASA's Statement on p-Values: Context, Process, and Purpose'. The American Statistician, 70 (2), 129–133. Retrieved 30 October 2016.

Won, J-P. et al (2009) 'Performance of synthetic macrofibres in reinforced concrete for tunnel linings', Magazine of Concrete Research, 61, pp. 165–172.

Xargay, H. et al. (2018) 'Temperature effects on failure behavior of self-compacting high strength plain and fiber reinforced concrete', Construction and Building Materials, 165, pp. 723–734.

Yin, S. et al. (2015) 'Use of macro plastic fibres in concrete: A review', Construction and Building Materials, 93, pp. 180–188.

Zollo, R. F. (1997) 'Fiber-reinforced concrete: an overview after 30 years of development', Cement and Concrete Composites. Elsevier, 19(2), pp. 107–122.

Appendices

Appendix A

Construcción

Sika® ViscoCrete®-5980

CE

Superplastificante de tercera generación para el bombeo de hormigones

Descripción del Producto	Superplastificante de tercera generación para hormigones bombeables. Está exento de cloruros.
Usos	■ Se utiliza en la confección de hormigones bombeables, tanto en prefabricación, como en obras y centrales de hormigón preparado. ■ Hormigones autocompactantes (HAC). ■ Hormigones con una relación agua/cemento muy baja. ■ Hormigones de altas prestaciones.
Características/Ventajas	■ Ayuda al bombeo del hormigón. ■ Especialmente diseñado para hormigones autocompactantes. ■ Importante reducción del agua de amasado. ■ Altas resistencias iniciales. ■ Ralentiza el proceso de carbonatación. ■ No contiene cloruros ni sustancias que puedan provocar o favorecer la corrosión del acero y por lo tanto puede utilizarse sin restricciones en hormigones armados o pretensados.
Ensayos	
Certificados/Normas	Cumple con las especificaciones de la norma UNE-EN 934-2. Tablas 11.1 y 11.2: retardador / reductor / superplastificante.

Datos del Producto

Forma	
Apariencia/color	Liquido marrón amarillento
Presentación	Contenedores de m³. Bajo pedido puede suministrarse a granel.
Almacenamiento	
Condiciones de almacenamiento/ Conservación	12 meses, desde su fecha de fabricación en sus envases de origen bien cerrados y no deteriorados al resguardo de las heladas y de la luz directa del sol, entre +5°C y +35°C.
Datos Técnicos	
Composición química	Policarboxilatos modificados.
Densidad	Aprox. 1,09 kg/l.
Valor del pH	4,5 ± 0,5.

Construcción

Información del Sistema

Detalles de Aplicación

Consumo/Dosificación	Dosificación recomendada Entre 0,5 y el 1,5% del peso del cemento.

Condiciones de Aplicación/Limitaciones

Compatibilidad	El Sika® ViscoCrete®-5980 puede combinarse con otros aditivos Sika. Se recomienda la realización de ensayos previos en obra.

Instrucciones de Aplicación

Preparación

Herramientas de aplicación	Se deben seguir las normas de buen uso del hormigón, en lo que se refiere a la fabricación y a la puesta en obra. El hormigón fresco debe ser curado correctamente tan pronto como sea posible.
Limpieza de herramientas	Todos los útiles y herramientas deben ser limpiados con agua abundante inmediatamente después de su uso. El material curado/endurecido sólo podrá ser eliminado por medios mecánicos.
Notas de aplicación/ Límites	Si el producto se hiela y no precipita, puede utilizarse sin que se vea disminuida ninguna de sus cualidades después de deshelarse lentamente (sin calentarlo) y agitarlo cuidadosamente.
Nota	Los datos de esta Hoja de Datos de Producto están basados en ensayos de laboratorio. Los valores de las características del producto pueden sufrir ligeras variaciones debidas a circunstancias fuera de nuestro control.

Instrucciones de Seguridad e Higiene

Para cualquier información referida a cuestiones de seguridad en el uso, manejo, almacenamiento y eliminación de residuos de productos químicos, los usuarios deben consultar la versión más reciente de la Hoja de Seguridad del producto, que contiene datos físicos, ecológicos, toxicológicos y demás cuestiones relacionadas con la seguridad.

Notas Legales

Oficinas centrales y Fabrica
Madrid 28108 - Alcobendas
P. I. Alcobendas
Carretera de Fuencarral, 72
Tels.: 916 57 23 75
Fax: 916 62 19 38

Oficinas centrales y Centro Logístico
Madrid 28108 - Alcobendas
P. I. Alcobendas
C/ Aragoneses, 17
Tels.: 916 57 23 75
Fax: 916 62 19 38

Diseño y producción en instalaciones de Alcobendas (Madrid)

Appendix B

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	2.12
Wet weight (g)	0.912
Dry constant weight (g)	0.893
Container weight (g)	0.636
Batch volume (l)	75
Sand absorption (%)	1
Fibre type	Sika M-48
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	24.4	7.6
Gravel (6-10 mm)	430	32.3	11.8
Gravel (4-6 mm)	580	43.5	15.9
Sand G. Catell (0-4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	10	0.75	---
Additive	0.50%	0.122	---

Slump (cm) 7

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	1.6
Wet weight (g)	0.508
Dry constant weight (g)	0.5
Container weight (g)	0.636
Batch volume (l)	75
Sand absorption (%)	1
Fibre type	Sika M-48
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	24.4	7.6
Gravel (6-10 mm)	430	32.3	11.8
Gravel (4-6 mm)	580	43.5	15.9
Sand G. Catell (0-4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	10	0.75	---
Additive	0.70%	0.171	---

Slump (cm) 5

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	1.5
Wet weight (g)	0.337
Dry constant weight (g)	0.332
Container weight (g)	0.636
Batch volume (l)	75
Sand absorption (%)	1
Fibre type	Sika M-48
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	24.4	7.6
Gravel (6-10 mm)	430	32.3	11.8
Gravel (4-6 mm)	580	43.5	15.9
Sand G. Catell (0-4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	10	0.75	---
Additive	0.70%	0.171	---

Slump (cm) 7

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	1.83
Wet weight (g)	0.389
Dry constant weight (g)	0.382
Container weight (g)	0.636
Batch volume (l)	75
Sand absorption (%)	1
Fibre type	Sika M-48
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	24.4	7.6
Gravel (6-10 mm)	430	32.3	11.8
Gravel (4-6 mm)	580	43.5	15.9
Sand G. Catell (0-4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	10	0.75	---
Additive	0.70%	0.171	---

Slump (cm) 9

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	2.7
Wet weight (g)	0.38
Dry constant weight (g)	0.37
Container weight (g)	0.636
Batch volume (l)	75
Sand absorption (%)	1
Fibre type	Forta ferro 54mm
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	24.4	7.6
Gravel (6-10 mm)	430	32.3	11.8
Gravel (4-6 mm)	580	43.5	15.9
Sand G. Catell (0-4 mm)	835	64.29	23
Filler	80	6	2.2
Added water	198	13.19	14,4
Fibre	10	0.75	---
Additive	0.70%	0.171	---

Slump (cm) 3

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	2.13
Wet weight (g)	0.335
Dry constant weight (g)	0.328
Container weight (g)	0.636
Batch volume (l)	50
Sand absorption (%)	1
Fibre type	Forta ferro 54mm
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	16.3	5.1
Gravel (6-10 mm)	430	21.5	7.9
Gravel (4-6 mm)	580	29	10.6
Sand G. Catell (0-4 mm)	835	42.64	15.3
Filler	80	4	1.5
Added water	198	9.06	9.6
Fibre	10	0.5	---
Additive	0.90%	0.1467	---

Slump (cm) 0

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	2.13
Wet weight (g)	0.335
Dry constant weight (g)	0.328
Container weight (g)	0.636
Batch volume (l)	50
Sand absorption (%)	1
Fibre type	Dramix 65/40 3D
Additive	Sika 5980

	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	16.3	5.1
Gravel (6-10 mm)	430	21.5	7.9
Gravel (4-6 mm)	580	29	10.6
Sand G. Catell (0-4 mm)	835	42.64	15.3
Filler	80	4	1.5
Added water	198	9.06	9.6
Fibre	30	1.5	---
Additive	0.70%	0.1137	---

Slump (cm) 10.5

Nominal maximum aggregate size (mm)	10
Aggregate moisture (%)	1.4
Wet weight (g)	0.583
Dry constant weight (g)	0.575
Container weight (g)	0.636
Batch volume (l)	75
Sand absorption (%)	1
Fibre type	Dramix 65/40 3D
Additive	Sika 5980

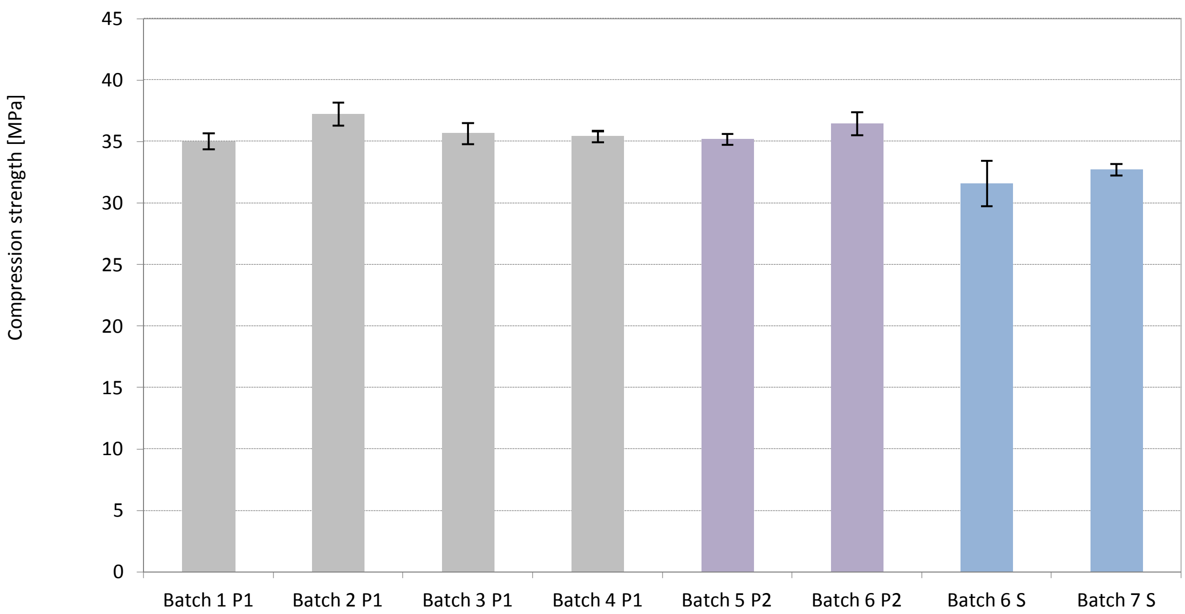
	Dosage (kg/m³)	Weight (kg)	Volume (l)
Cement II 42,5R	325	24.4	7.6
Gravel (6-10 mm)	430	32.3	11.8
Gravel (4-6 mm)	580	43.5	15.9
Sand G. Catell (0-4 mm)	835	63.9	23
Filler	80	6	2.2
Added water	198	13.6	14.4
Fibre	30	2.25	---
Additive	0.70%	0.171	---

Slump (cm) 19

Appendix C

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	----
		Page	01
	OVERVIEW	Author	Marta Caballero Jorna

Code	Age (Days)	fcm (N/mm^2)	Range	Standard deviation	COV (%)
Batch 1 P1	28	35.045	1.320	0.663	1.891
Batch 2 P1	28	37.262	1.830	0.929	2.494
Batch 3 P1	28	35.683	1.500	0.855	2.395
Batch 4 P1	28	35.422	0.850	0.452	1.277
Batch 5 P2	28	35.204	0.810	0.430	1.221
Batch 6 P2	28	36.469	1.750	0.921	2.525
Batch 6 S	28	31.603	3.580	1.834	5.803
Batch 7 S	28	32.729	0.860	0.478	1.461



Observations

Specimens dimensions		
Diameter	150	mm
Length	300	mm
Ac	17671	mm^2

Appendix D

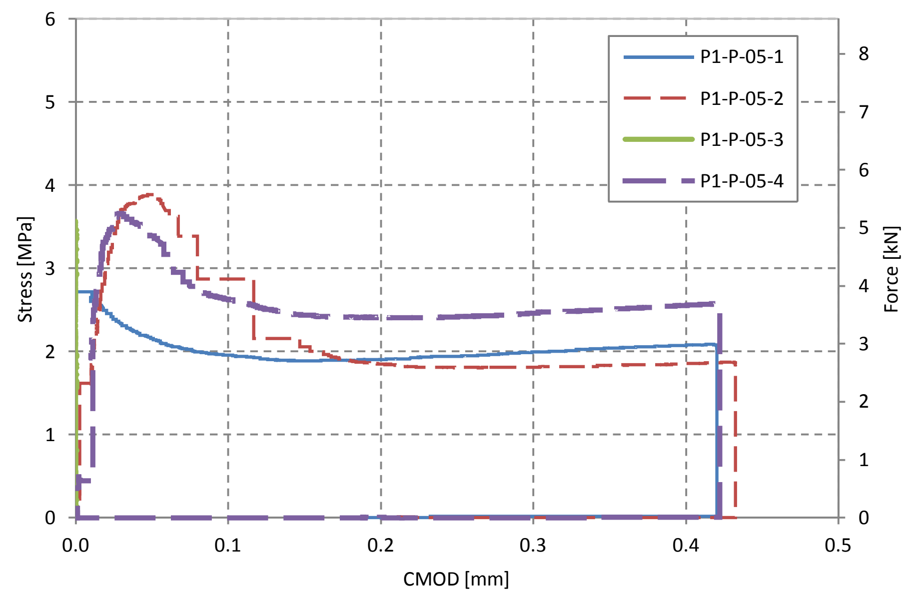
Stress-CMOD at Pre-Cracking test (days)	28
Temperature (°C)	5

Stress (MPa)

P1-P-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	3.87	2.02			
Spec. 2	3.71	1.76			
Spec. 3	3.62	----			
Spec. 4	3.50	2.36			

Max	3.87	2.36			
Min	3.50	1.76			

Mean	3.67	2.05			
COV (%)	4	15			



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 7cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	18/04/2018
		Page	02
	OVERVIEW	Author	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days): 28

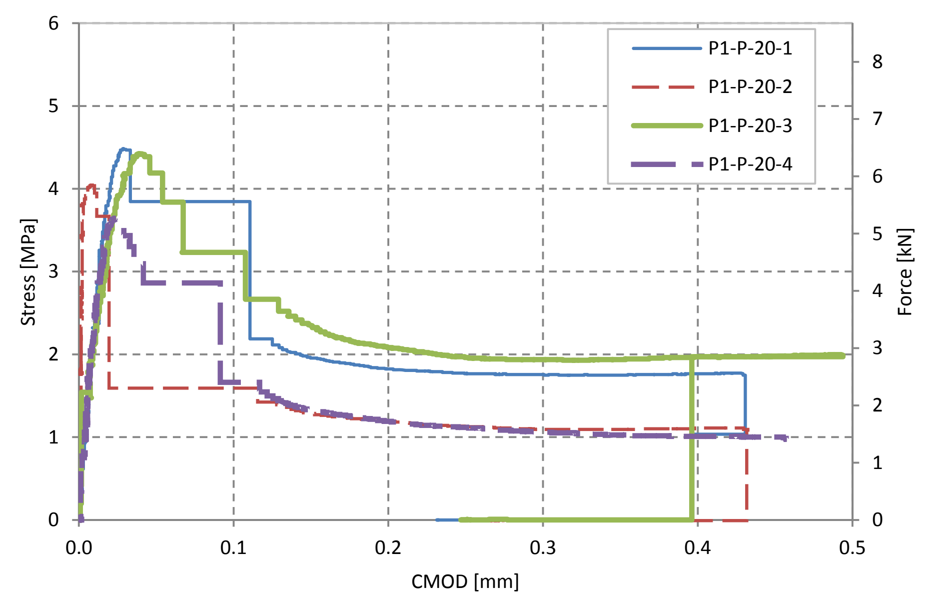
Temperature (°C): 20

Stress (MPa)

P1-P-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.48	1.75			
Spec. 2	4.05	1.09			
Spec. 3	4.42	1.97			
Spec. 4	3.64	0.98			

Max	4.48	1.97			
Min	3.64	0.98			

Mean	4.15	1.45			
COV (%)	9	34			



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 7cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	25/04/2018
		Page	03
	OVERVIEW	Author	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days): 30

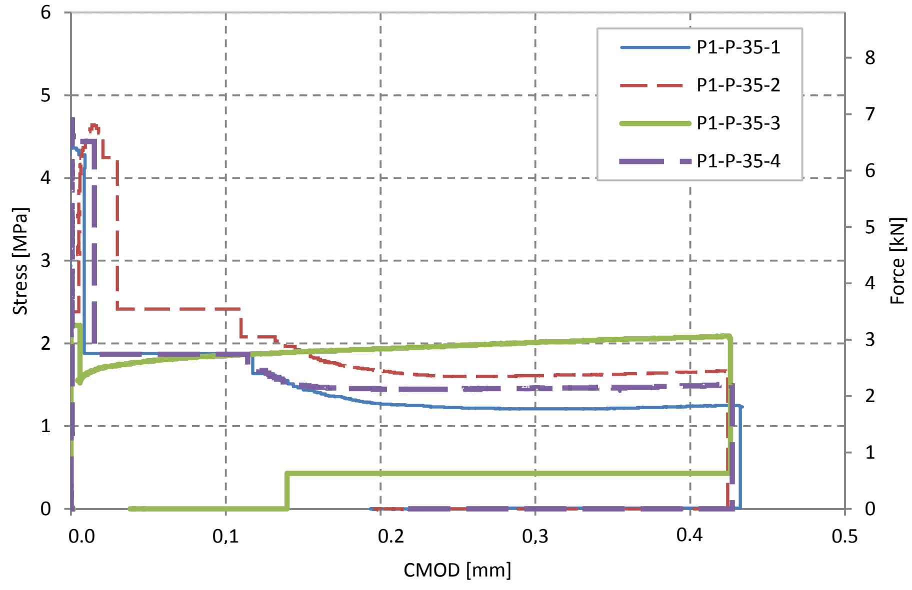
Temperature (°C): 35

Stress (MPa)

P1-P-35	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.36	1.23			
Spec. 2	4.64	1.63			
Spec. 3	2.22	2.06			
Spec. 4	4.70	1.49			

Max	4.70	2.06			
Min	2.22	1.23			

Mean	3.98	1.60			
COV (%)	30	22			



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 9cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	25/04/2018
		Page	04
	OVERVIEW	Author	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days): 30

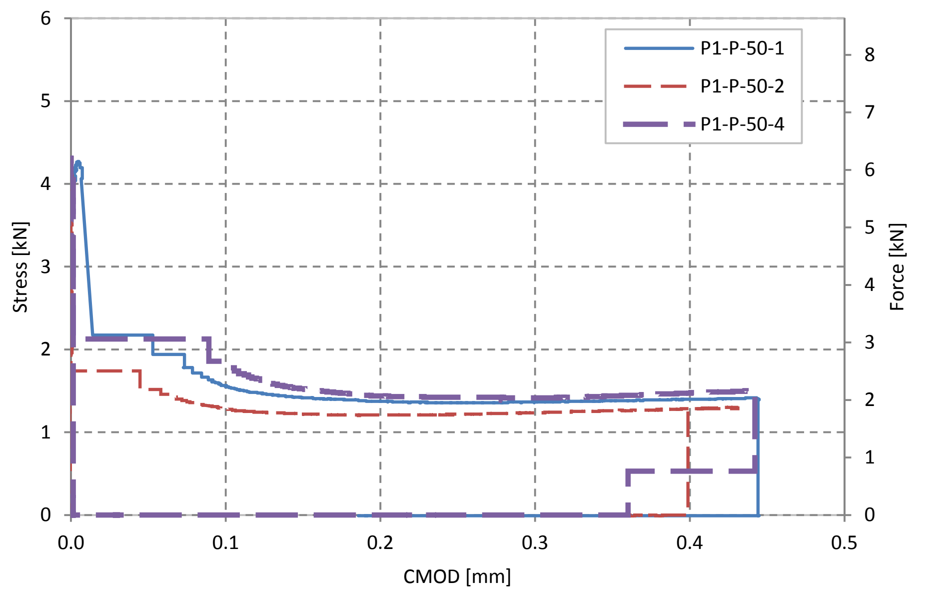
Temperature (°C): 50

Stress (MPa)

P1-P-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.27	1.40			
Spec. 2	4.11	1.29			
Spec. 3	----	----			
Spec. 4	4.34	1.49			

Max	4.34	1.49			
Min	4.11	1.29			

Mean	4.24	1.40			
COV (%)	3	7			



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 9cm

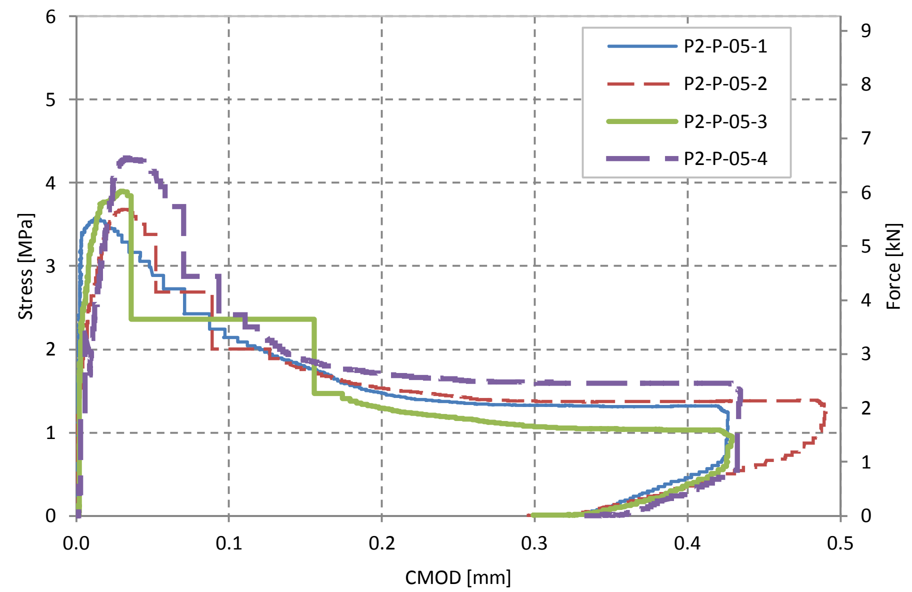
UNIVERSITAT POLITÈCNICA DE VALÈNCIA	**MASTER'S THESIS**	**Date**	26/04/2018
		Page	05
	OVERVIEW	**Author**	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days) 29

Temperature (°C) 5

Stress (MPa)

P2-P-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	3.58	1.24			
Spec. 2	3.74	1.33			
Spec. 3	3.95	0.97			
Spec. 4	4.36	1.52			
Max	4.36	1.52			
Min	3.58	0.97			
Mean	3.91	1.26			
COV (%)	9	10			



Observations

Fibre type: Macrosynthetic P2 (Forta ferro 54mm)
Slump: 3cm

Stress-CMOD at Pre-Cracking test (days) 29

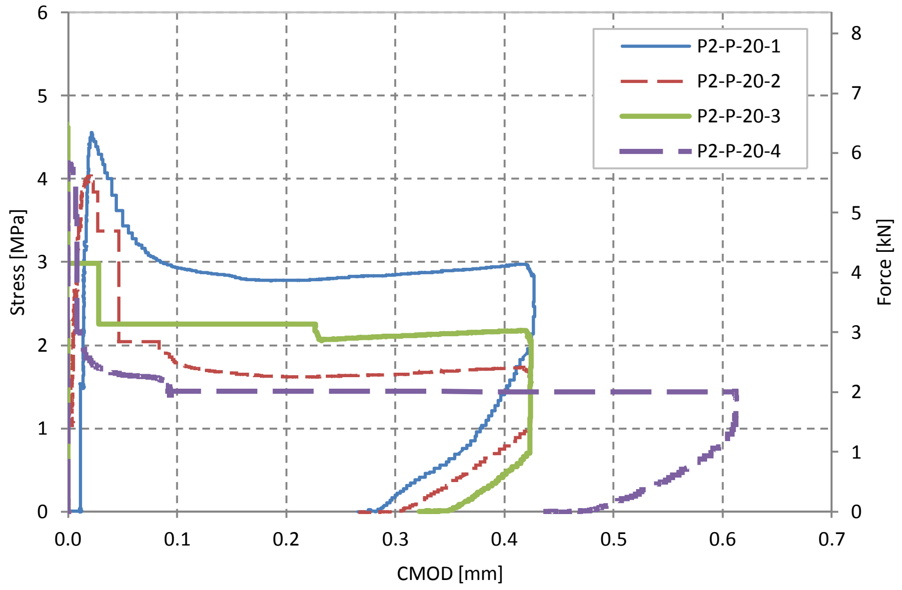
Temperature (°C) 20

Stress (MPa)

P2-P-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.55	2.46			
Spec. 2	4.03	1.28			
Spec. 3	4.67	2.06			
Spec. 4	4.19	1.37			

Max	4.67	2.46			
Min	4.03	1.28			

Mean	4.36	1.79			
COV (%)	7	39			



Observations

Fibre type: Macrosynthetic P2 (Forta ferro 54mm)
Slump: 3cm
The value f_L for P2-P-20-3 was obtained from manual preload

	MASTER'S THESIS	Date	02/05/2018
UNIVERSITAT POLITÈCNICA DE VALÈNCIA		Page	07
	OVERVIEW	Author	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days) | 28

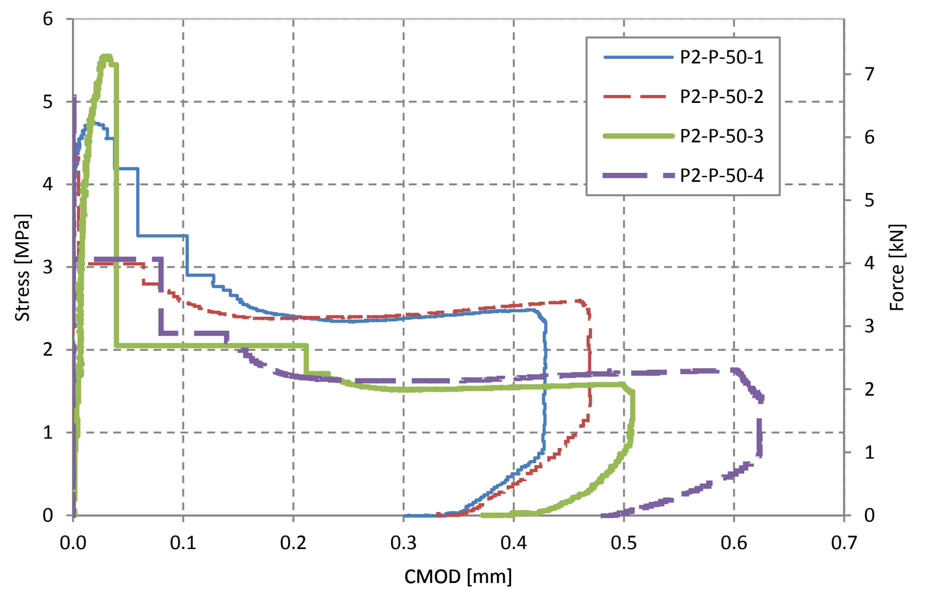
Temperature (°C) | 50

Stress (MPa)

P2-P-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.75	2.00			
Spec. 2	5.00	2.44			
Spec. 3	5.55	1.50			
Spec. 4	5.09	1.42			

Max	5.55	2.44			
Min	4.75	1.42			

Mean	5.10	1.84			
COV (%)	7	26			



Observations

Fibre type: Macrosynthetic P2 (Forta Ferro 54mm)
Slump: 0cm
Specimen 4 was tested on 03/05/2018

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	02/05/2018
		Page	08
	OVERVIEW	Author	Marta Caballero Jorna

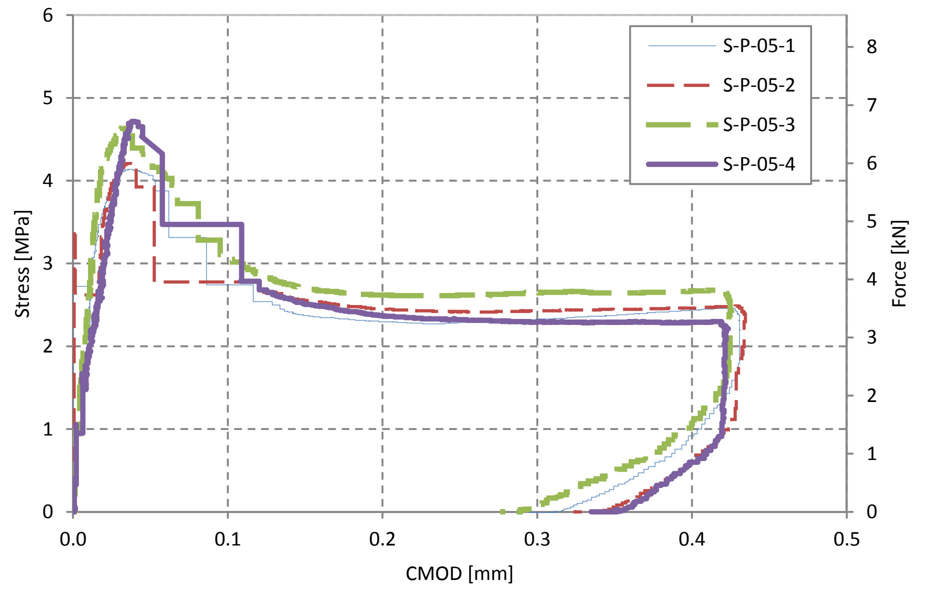
Stress-CMOD at Pre-Cracking test (days)	28
Temperature (°C)	5

Stress (MPa)

S-P-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.14	2.20			
Spec. 2	4.21	2.39			
Spec. 3	4.65	2.44			
Spec. 4	4.72	2.21			

Max	4.72	2.44			
Min	4.14	2.20			

Mean	4.43	2.31			
COV (%)	7	5			



Observations

Fibre type: Steel S (Dramix 65/40 3D)
Slump: 10,5cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	**MASTER'S THESIS**	**Date**	09/05/2018
		Page	09
	OVERVIEW	**Author**	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days) 28

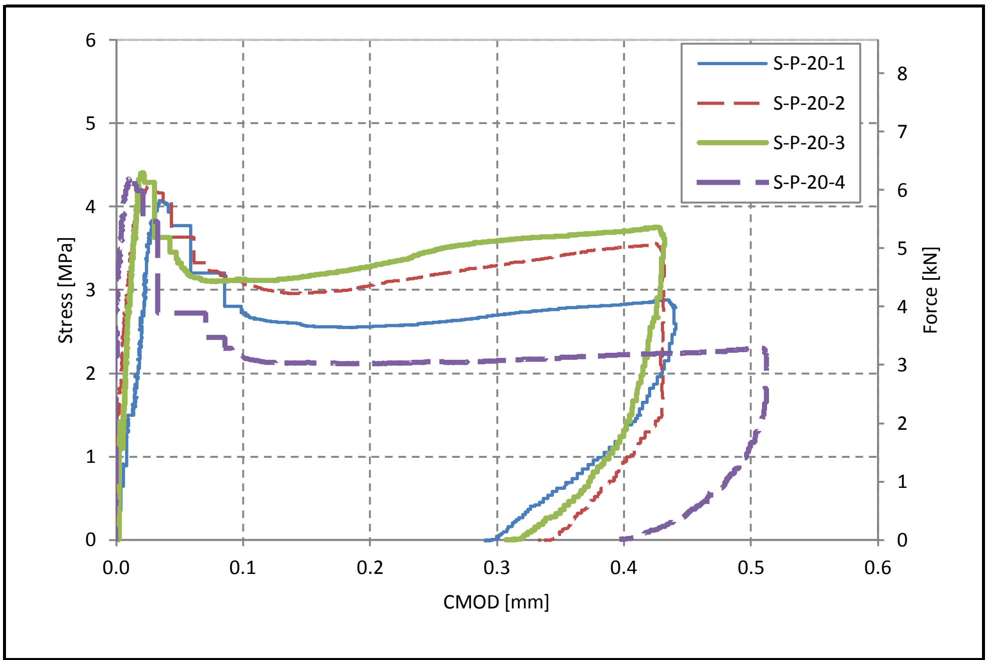
Temperature (°C) 20

Stress (MPa)

S-P-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.07	2.59			
Spec. 2	4.25	3.30			
Spec. 3	4.41	3.62			
Spec. 4	4.34	2.29			

Max	4.41	3.62			
Min	4.07	2.29			

Mean	4.27	2.95			
COV (%)	3	19			



Observations

Fibre type: Steel S (Dramix 65/40 3D)
Slump: 19cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	09/05/2018
		Page	10
	OVERVIEW	Author	Marta Caballero Jorna

Stress-CMOD at Pre-Cracking test (days) | 28

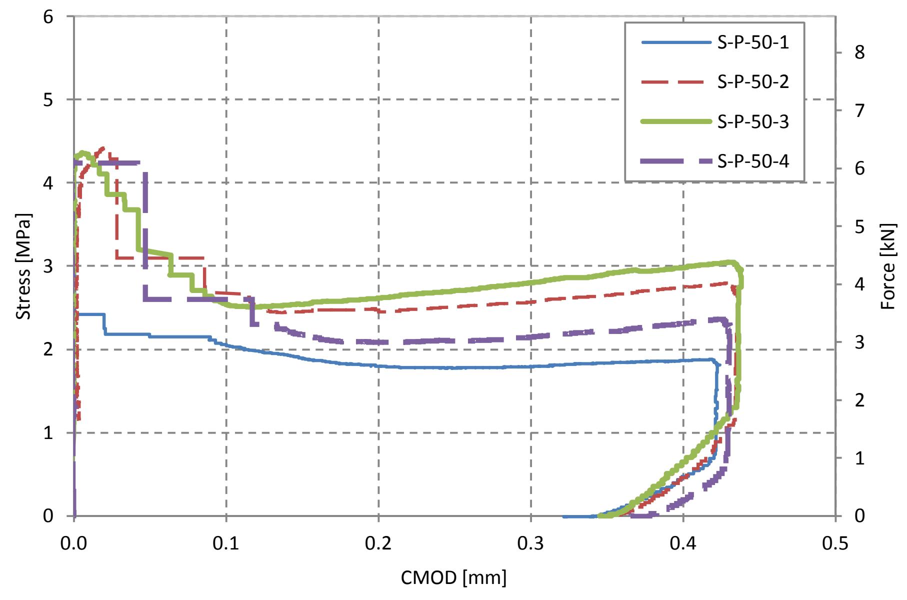
Temperature (°C) | 50

Stress (MPa)

S-P-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.24	1.81			
Spec. 2	4.48	2.55			
Spec. 3	4.43	3.00			
Spec. 4	4.28	2.15			

Max	4.48	3.00			
Min	4.24	1.81			

Mean	4.36	2.38			
COV (%)	3	17			



Observations

Fibre type: Steel S (Dramix 65/40 3D)
Slump: 19cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	**Date**	14/05/2018
		Page	11
	OVERVIEW	**Author**	Marta Caballero Jorna

Stress-CMOD at TPB test (days) | 60

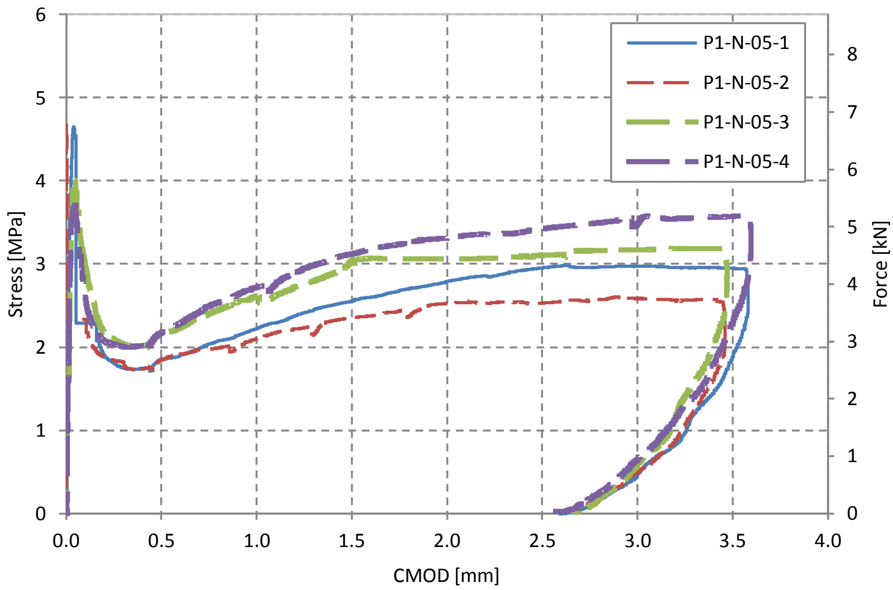
Temperature (°C) | 5

Stress (MPa)

P1-N-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.65	1.85	2.55	2.95	2.95
Spec. 2	4.71	1.84	2.36	2.53	2.39
Spec. 3	4.04	2.15	3.04	3.10	2.97
Spec. 4	3.71	2.18	3.12	3.42	3.58

Max	4.71	2.18	3.12	3.42	3.58
Min	3.71	1.84	2.36	2.53	2.39

Mean	4.28	2.01	2.77	3.00	2.97
COV (%)	11	9	13	12	16



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 7cm
P1-N-05-3 and P1-N-05-4 were tested on 15/05/2018

Stress-CMOD at TPB test (days) 60

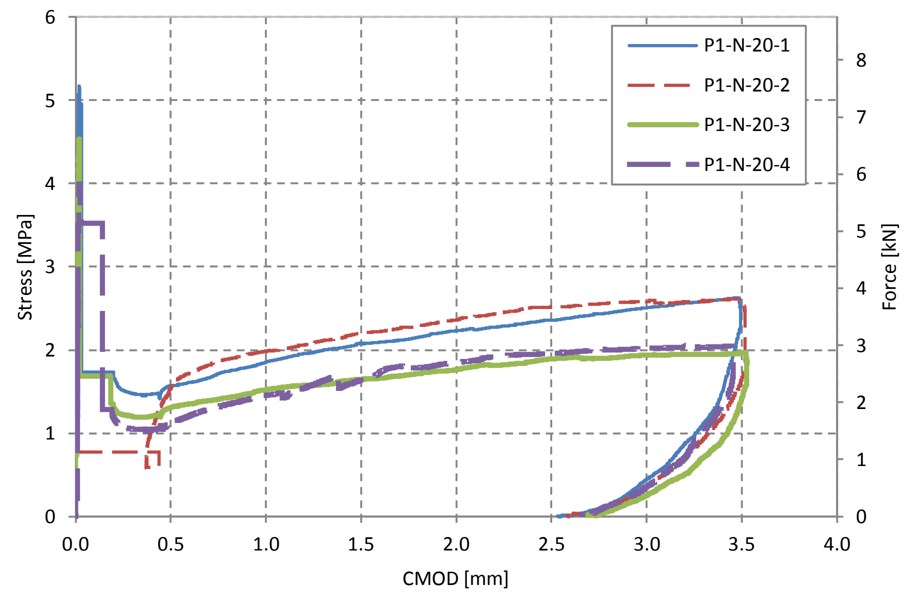
Temperature (°C) 20

Stress (MPa)

P1-N-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	5.18	1.58	2.08	2.36	2.46
Spec. 2	----	1.54	2.20	2.52	2.61
Spec. 3	4.54	1.31	1.65	1.89	1.97
Spec. 4	4.02	1.12	1.64	1.96	1.92

Max	5.18	1.58	2.20	2.52	2.61
Min	4.02	1.12	1.64	1.89	1.92

Mean	4.58	1.39	1.89	2.18	2.24
COV (%)	13	15	16	14	16



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 7cm

Stress-CMOD at TPB test (days) 60

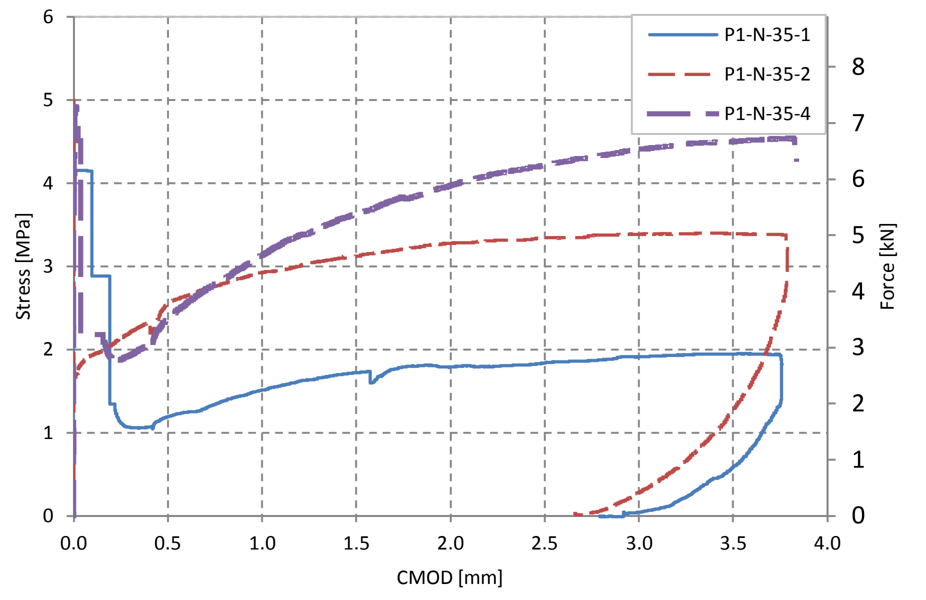
Temperature (°C) 35

Stress (MPa)

P1-N-35	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.16	1.20	1.72	1.84	1.94
Spec. 2	5.00	2.56	3.12	3.35	3.39
Spec. 3	----	----	----	----	----
Spec. 4	4.92	2.38	3.64	4.22	4.50

Max	5.00	2.56	3.64	4.22	4.50
Min	4.16	1.20	1.72	1.84	1.94

Mean	4.69	2.04	2.83	3.13	3.28
COV (%)	10	36	35	38	39



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 5cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	**MASTER'S THESIS**	**Date**	16/05/2018
		Page	14
	OVERVIEW	**Author**	Marta Caballero Jorna

Stress-CMOD at TPB test (days) 60

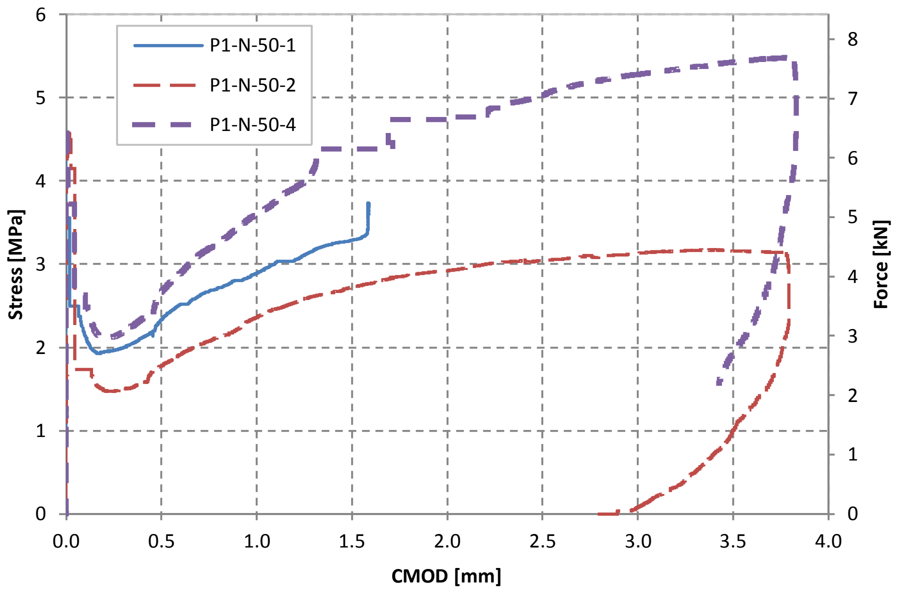
Temperature (°C) 50

Stress (MPa)

P1-N-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.39	2.33	3.29	----	----
Spec. 2	4.58	1.78	2.72	3.04	3.16
Spec. 3	3.34	----	----	----	----
Spec. 4	4.64	2.66	4.38	5.03	5.42

Max	4.64	2.66	4.38	5.03	5.42
Min	3.34	1.78	2.72	3.04	3.16

Mean	4.24	2.26	3.46	4.04	4.29
COV (%)	14	20	24	35	37



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 5cm

Stress-CMOD at TPB test (days) 60

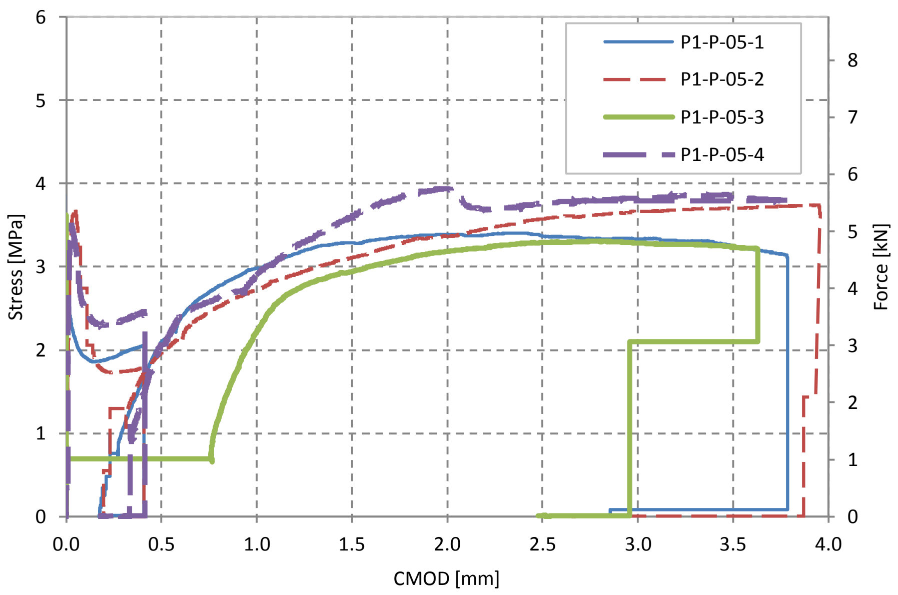
Temperature (°C) 5

Stress (MPa)

P1-P-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	3.87	2.02	3.29	3.37	3.26
Spec. 2	3.71	1.76	3.11	3.57	3.70
Spec. 3	3.62	----	2.94	3.29	3.23
Spec. 4	3.50	2.36	3.93	3.83	3.73

Max	3.87	2.36	3.93	3.83	3.73
Min	3.50	1.76	2.94	3.29	3.23

Mean	3.67	2.05	3.32	3.52	3.48
COV (%)	4	15	13	7	7



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 7cm

Stress-CMOD at TPB test (days) 60

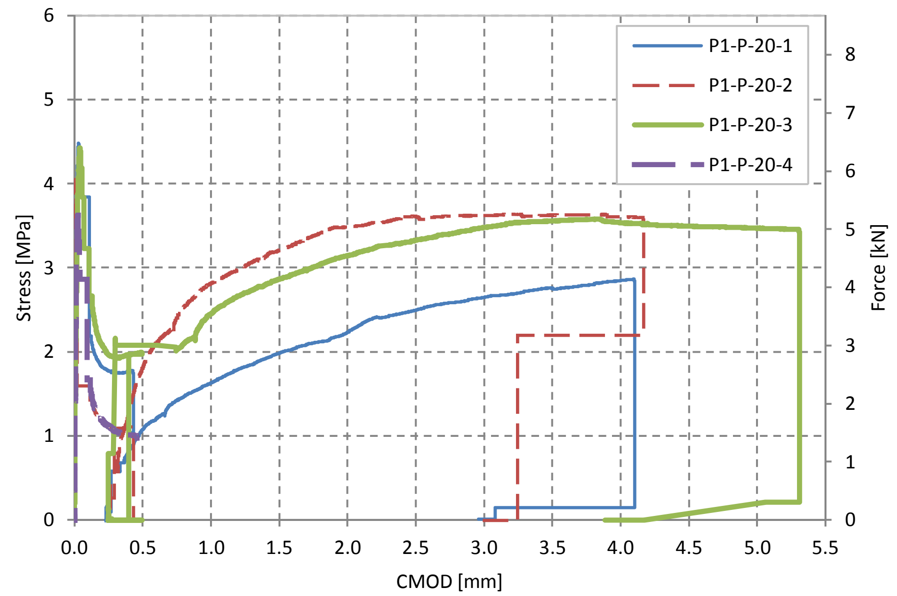
Temperature (°C) 20

Stress (MPa)

P1-P-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.48	1.75	1.98	2.49	2.76
Spec. 2	4.05	1.09	3.21	3.60	3.62
Spec. 3	4.42	1.97	2.86	3.33	3.56
Spec. 4	3.64	0.98	----	----	----

Max	4.48	1.97	3.21	3.60	3.62
Min	3.64	0.98	1.98	2.49	2.76

Mean	4.15	1.45	2.68	3.14	3.31
COV (%)	9	34	24	18	14



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 7cm

Stress-CMOD at TPB test (days): 60

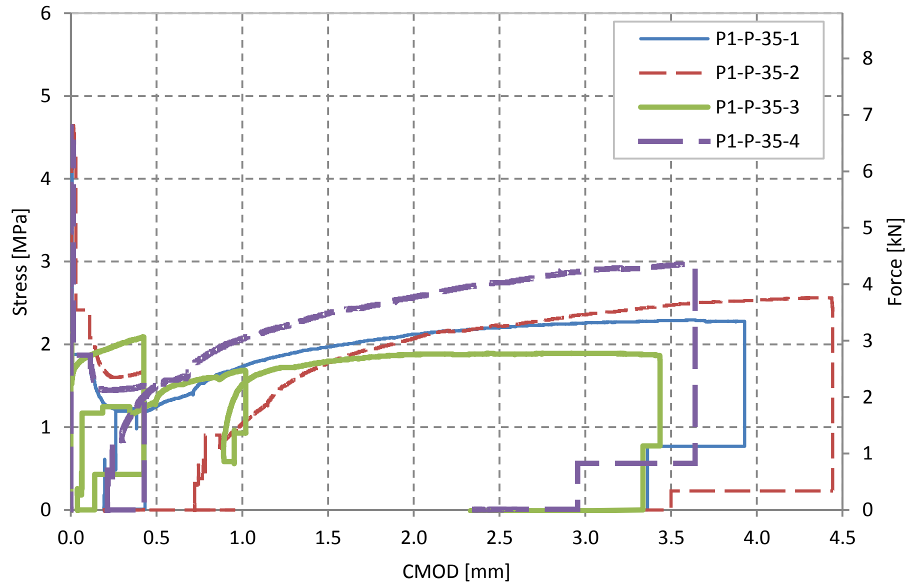
Temperature (°C): 35

Stress (MPa)

P1-P-35	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.36	1.23	1.97	2.21	2.29
Spec. 2	4.64	1.63	1.77	2.22	2.47
Spec. 3	2.22	2.06	1.80	1.88	1.81
Spec. 4	4.70	1.49	2.38	2.74	2.96

Max	4.70	2.06	2.38	2.74	2.96
Min	2.22	1.23	1.77	1.88	1.81

Mean	3,98	1.60	1.98	2,26	2.38
COV (%)	30	22	14	16	20



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 9cm

Stress-CMOD at TPB test (days): 60

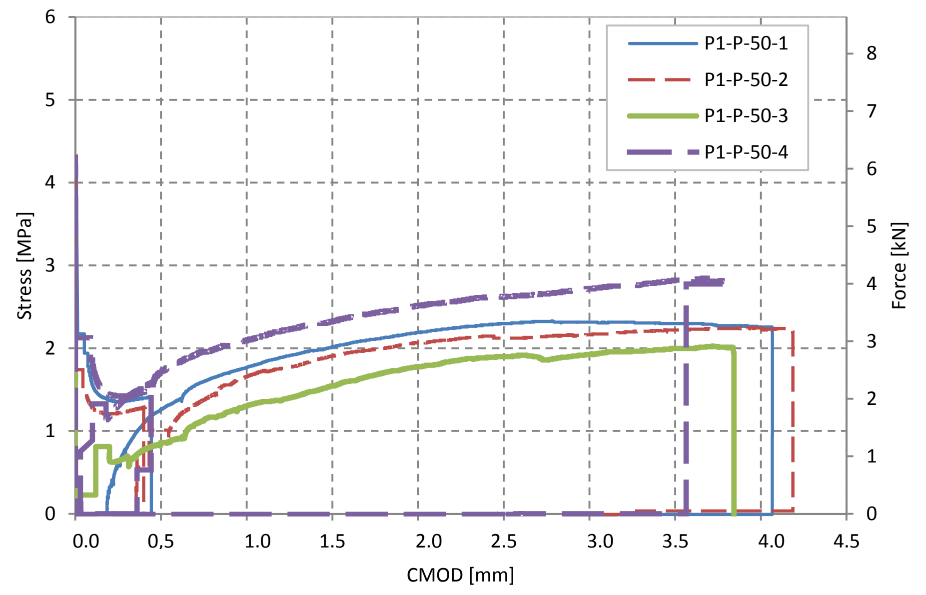
Temperature (°C): 50

Stress (MPa)

P1-P-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.27	1.40	2.01	2.30	2.30
Spec. 2	4.11	1.29	1.91	2.12	2.22
Spec. 3	----	----	1.54	1.90	2.00
Spec. 4	4.34	1.49	2.32	2.62	2.82

Max	4.34	1.49	2.32	2.62	2.82
Min	4.11	1.29	1.54	1.90	2.00

Mean	4.24	1.40	1.95	2.23	2.33
COV (%)	3	7	17	14	15



Observations

Fibre type: Macrosynthetic P1 (Sika M-48)
Slump: 9cm

Stress-CMOD at TPB test (days): 60

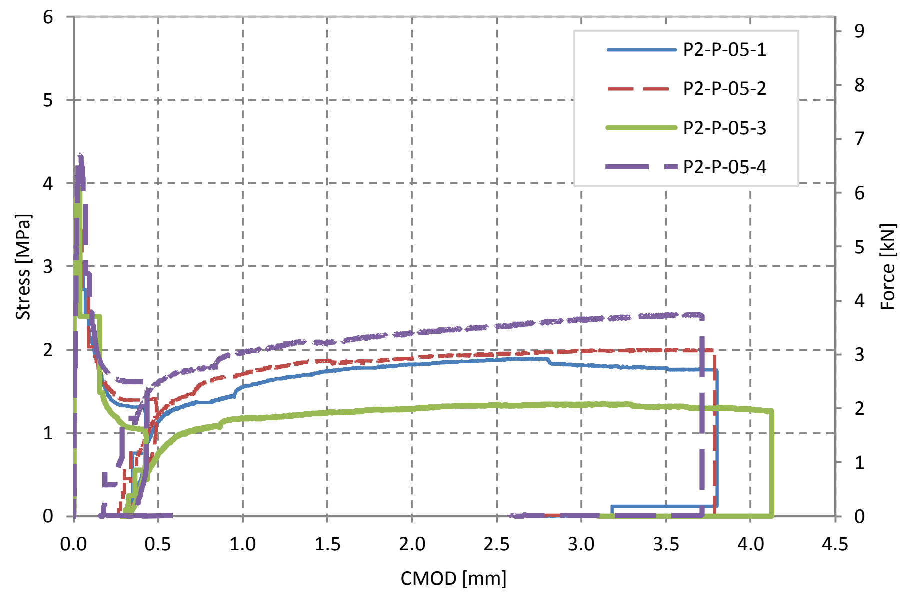
Temperature (°C): 5

Stress (MPa)

P2-P-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	3.58	1.24	1.75	1.88	1.78
Spec. 2	3.74	1.33	1.86	1.95	2.00
Spec. 3	3.95	0.97	1.24	1.34	1.32
Spec. 4	4.36	1.52	2.09	2.29	2.42

Max	4.36	1.52	2.09	2.29	2.42
Min	3.58	0.97	1.24	1.34	1.32

Mean	3.91	1.26	1.74	1.86	1.88
COV (%)	9	10	9	11	16



Observations

Fibre type: Macrosynthetic P2 (Forta ferro 54mm)
Slump: 3cm

Stress-CMOD at TPB test (days) 60

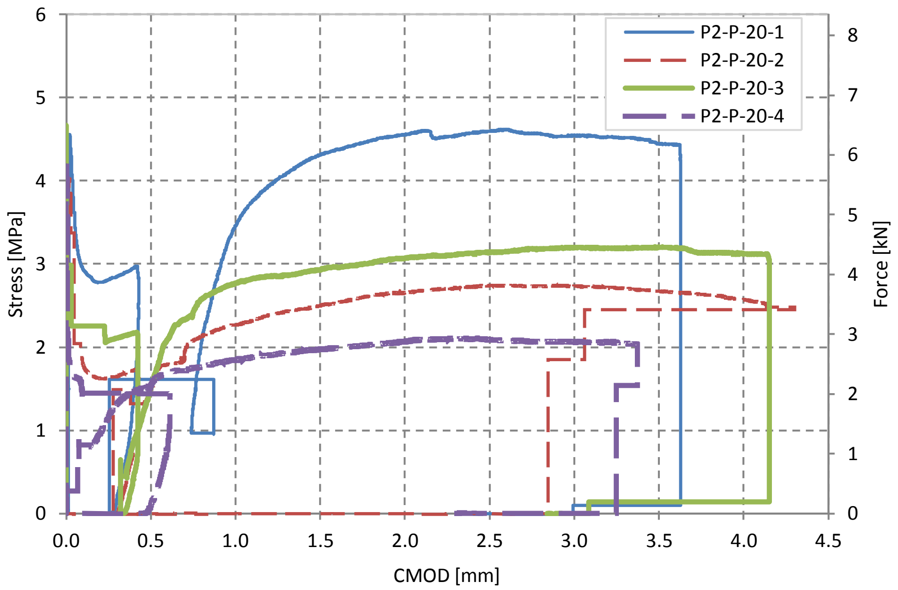
Temperature (°C) 20

Stress (MPa)

P2-P-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.55	2.46	4.31	4.59	4.44
Spec. 2	4.03	1.28	2.50	2.74	2.67
Spec. 3	4.67	2.06	2.93	3.14	3.20
Spec. 4	4.19	1.37	1.97	2.09	1.54

Max	4.67	2.46	4.31	4.59	4.44
Min	4.03	1.28	1.97	2.09	1.54

Mean	4.36	1.79	2.93	3.14	2.96
COV (%)	7	39	42	41	51



Observations

Fibre type: Macrosynthetic P2 (Forta ferro 54mm)
Slump: 3cm
The value f_L for P2-P-20 Specimen 3 was obtained from manual preload

Stress-CMOD at TPB test (days) 60

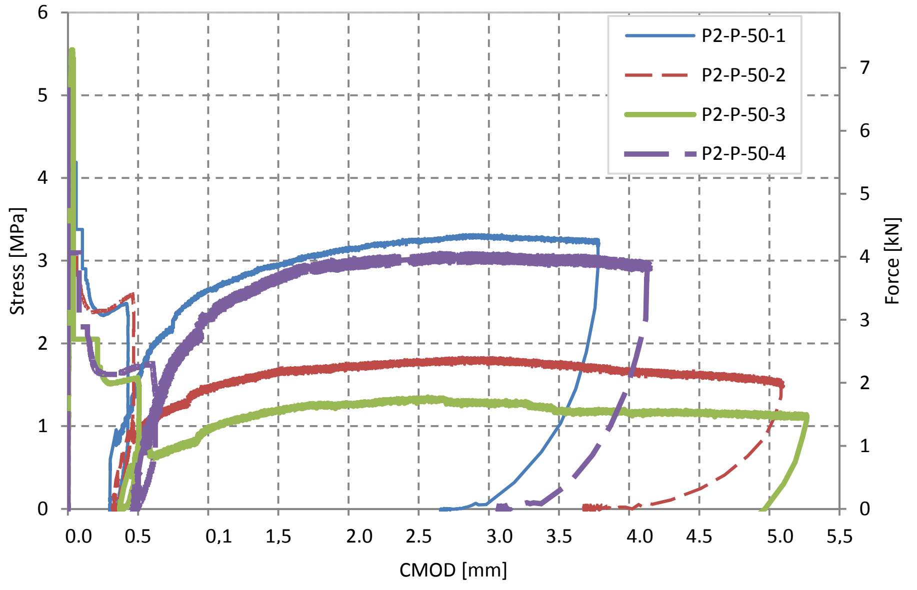
Temperature (°C) 50

Stress (MPa)

P2-P-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.75	2.00	2.96	3.25	3.26
Spec. 2	5.00	2.44	1.67	1.76	1.75
Spec. 3	5.55	1.50	1.19	1.31	1.19
Spec. 4	5.09	1.42	2.80	3.01	3.00

Max	5.55	2.44	2.96	3.25	3.26
Min	4.75	1.42	1.19	1.31	1.19

Mean	5.10	1.84	2.15	2.33	2.30
COV (%)	7	26	40	30	43



Observations

Fibre type: Macrosynthetic P2 (Forta Ferro 54mm)
Slump: 0cm
Pre-cracking test for P2-P-50 Specimen 4 was tested on 03/05/2018

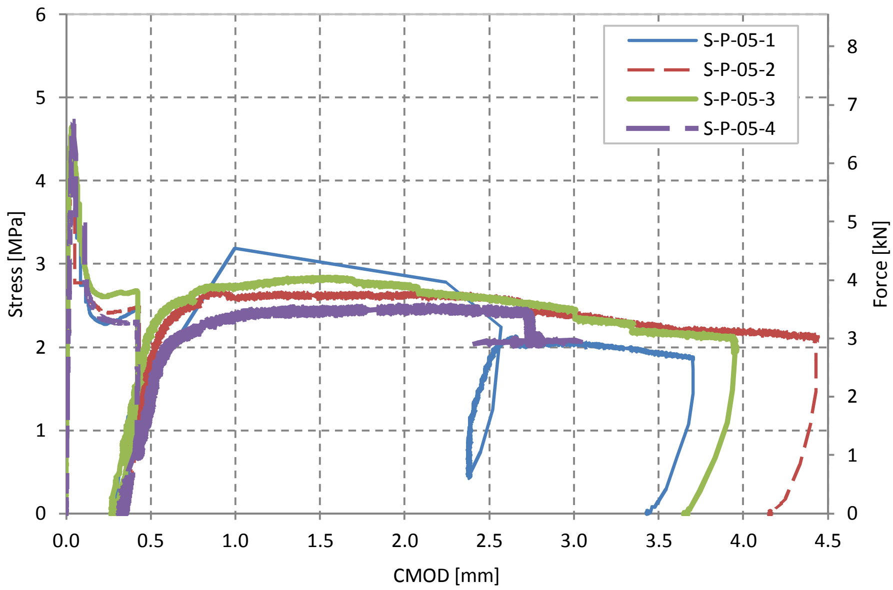
Stress-CMOD at TPB test (days)	60
Temperature (°C)	5

Stress (MPa)

S-P-05	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.14	2.20	3.19	1.77	1.92
Spec. 2	4.21	2.39	2.60	2.59	2.27
Spec. 3	4.65	2.44	2.81	2.59	2.17
Spec. 4	4.72	2.21	2.42	2.45	----

Max	4.72	2.44	319	2.59	2.27
Min	4.14	2.20	2.42	1.77	1.92

Mean	4.43	2.31	2.76	2.35	2.12
COV (%)	7	5	12	26	9



Observations

Fibre type: Steel S (Dramix 65/40 3D)
Slump: 10,5cm

Stress-CMOD at TPB test (days) 60

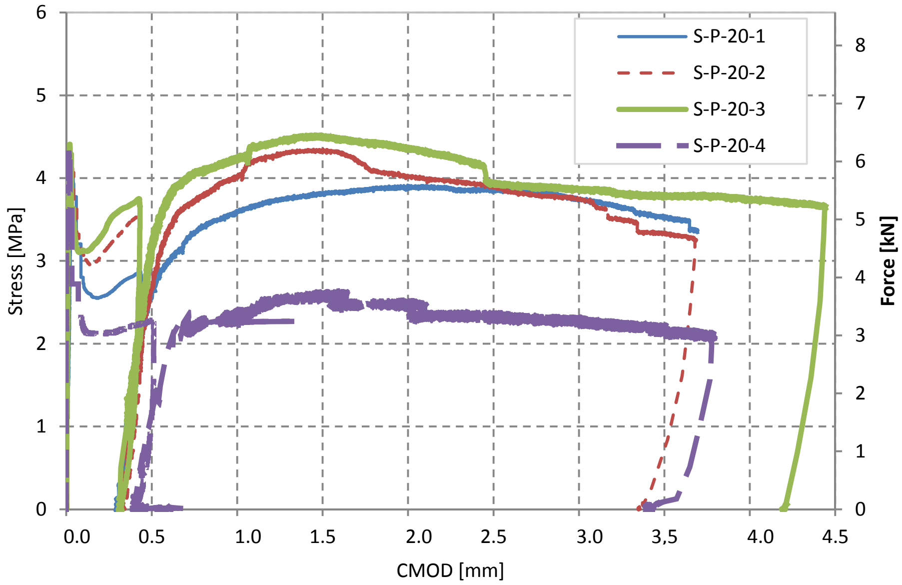
Temperature (°C) 20

Stress (MPa)

S-P-20	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.07	2.59	3.81	3.86	3.52
Spec. 2	4.25	3.30	4.32	3.91	3.34
Spec. 3	4.41	3.62	4.50	3.95	3.79
Spec. 4	4.34	2,95	2.58	2.32	2.19

Max	4.41	3.62	4.50	3.95	3.79
Min	4.07	2.29	2.58	2.32	2.19

Mean	4.27	2.95	3.80	3.51	3.21
COV (%)	3	19	23	27	22



Observations

Fibre type: Steel S (Dramix 65/40 3D)
Slump: 19cm

UNIVERSITAT POLITÈCNICA DE VALÈNCIA	MASTER'S THESIS	Date	13/06/2018
		Page	24
	OVERVIEW	Author	Marta Caballero Jorna

Stress-CMOD at TPB test (days): 60

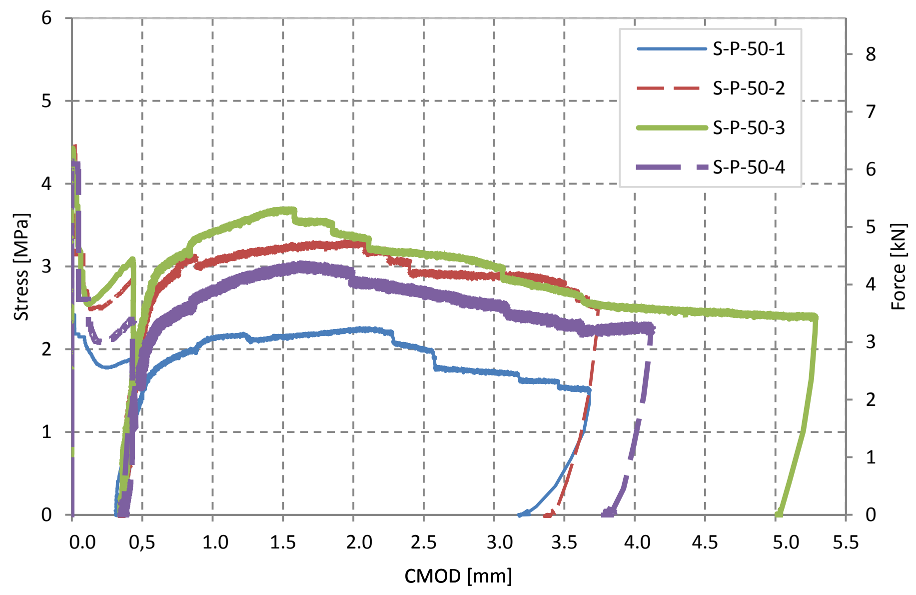
Temperature (°C): 50

Stress (MPa)

S-P-50	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Spec. 1	4.24	1.81	2.14	2.00	1.54
Spec. 2	4.48	2.55	3.21	2.92	2.79
Spec. 3	4.43	3.00	3.68	3.15	2.69
Spec. 4	4.28	2.15	2.97	2.69	2.27

Max	4.48	3.00	3.68	3,15	2.79
Min	4.24	1.81	2.14	2.00	1.54

Mean	4.36	2.38	3.00	2.69	2.32
COV (%)	3	17	22	19	25



Observations

Fibre type: Steel S (Dramix 65/40 3D)
Slump: 19cm

Appendix E

En el primer caso, se están considerando los tres tipos de fibras por separado y cuatro tipos de temperatura en la influencia de las resistencias residuales a flexo-tracción de hormigones reforzados con fibras. En este caso, no se considera las probetas no fisuradas.

En el segundo caso, se están considerando dos factores (temperatura y condición de pre-fisuración) y su interacción.

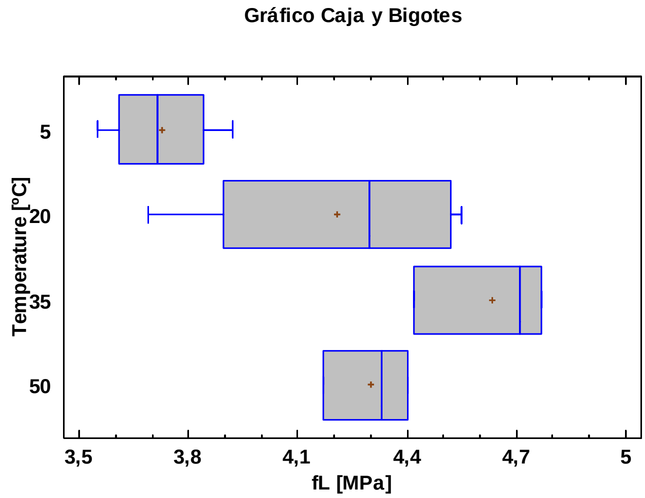
PRIMER CASO: Resultados Tabla ANOVA para resistencias residuales a flexo-tracción por temperaturas

Tipo de fibra P1:

- Influencia de la temperatura en f_{Lm}

Tabla ANOVA y gráfico de caja y bigotes para f_L por temperatura

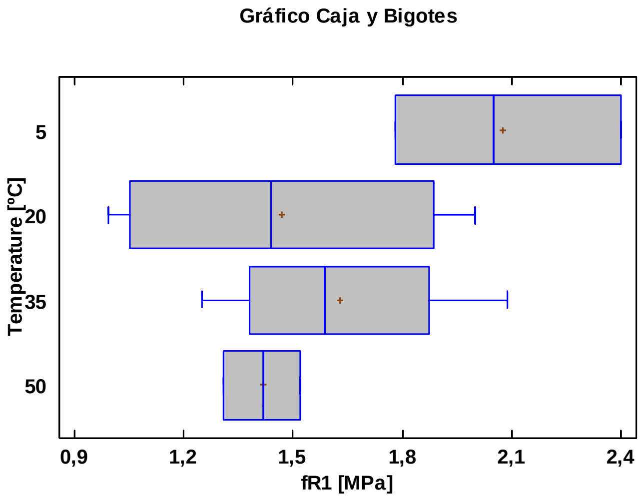
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	1,49085	3	0,49695	7,68	0,0059
Intra grupos	0,647242	10	0,0647242		
Total (Corr.)	2,13809	13			



- Influencia de la temperatura en f_{R1}

Tabla ANOVA y gráfico de caja y bigotes para f_{R1} por temperatura

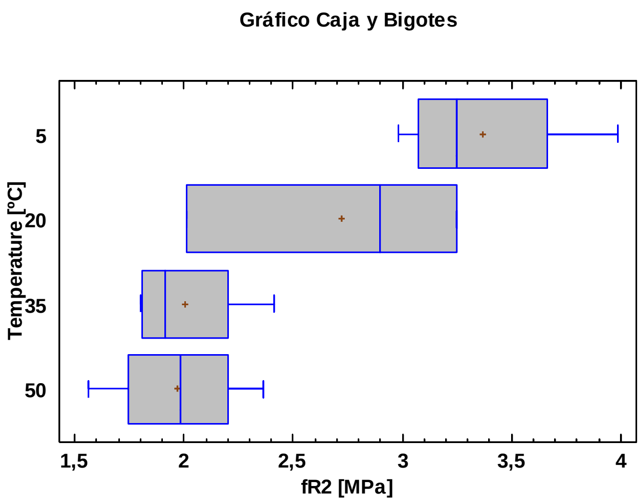
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	0,840602	3	0,280201	2,13	0,1603
Intra grupos	1,31748	10	0,131748		
Total (Corr.)	2,15809	13			



- Influencia de la temperatura en f_{R2}

Tabla ANOVA y gráfico de caja y bigotes para f_{R2} por temperatura

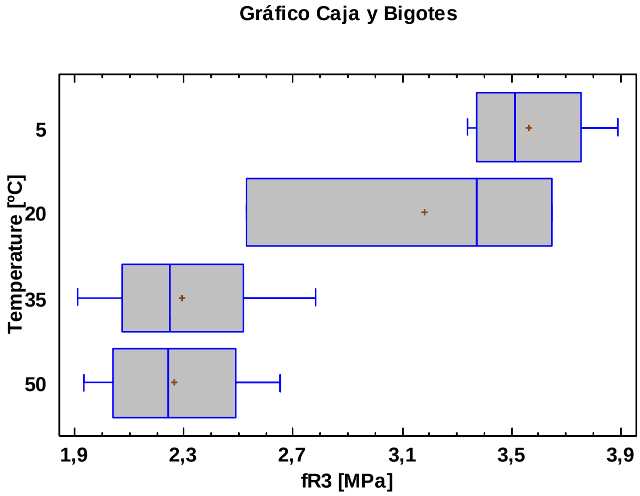
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	5,23851	3	1,74617	9,77	0,0020
Intra grupos	1,96583	11	0,178711		
Total (Corr.)	7,20433	14			



- Influencia de la temperatura en f_{R3}

Tabla ANOVA y gráfico de caja y bigotes para f_{R3} por temperatura

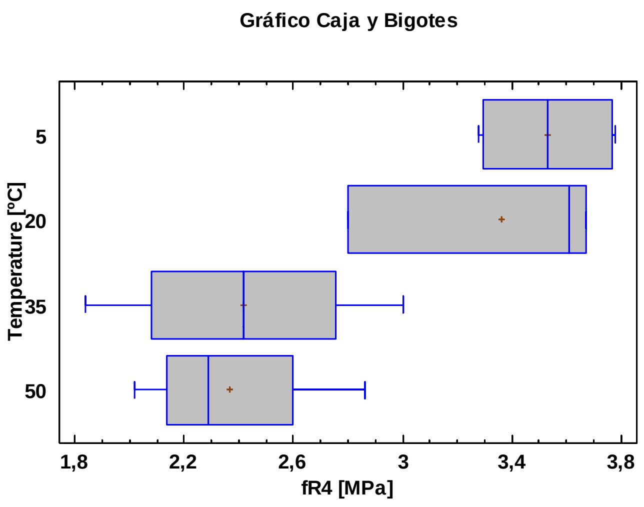
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	4,94657	3	1,64886	11,86	0,0009
Intra grupos	1,52917	11	0,139015		
Total (Corr.)	6,47573	14			



- Influencia de la temperatura en f_{R4}

Tabla ANOVA y gráfico de caja y bigotes para f_{R4} por temperatura

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	4,2966	3	1,4322	8,93	0,0028
Intra grupos	1,76337	11	0,160307		
Total (Corr.)	6,05997	14			

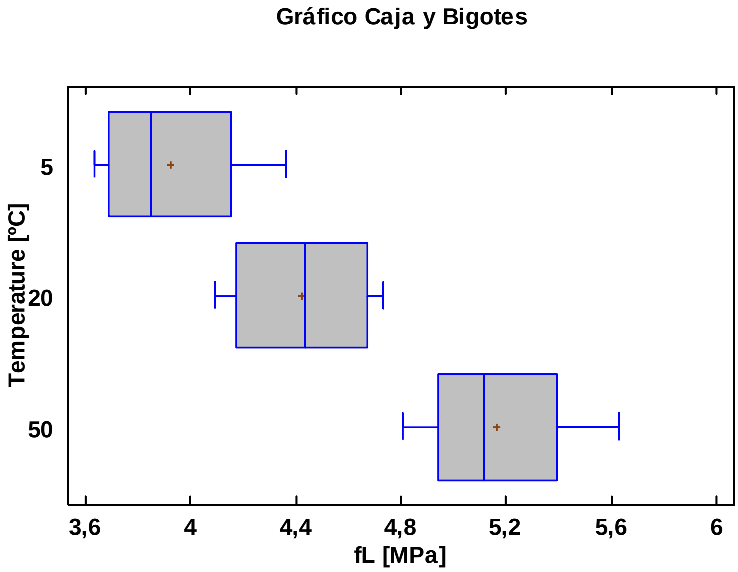


Tipo de fibra P2:

- Influencia de la temperatura en f_{Lm}

Tabla ANOVA y gráfico de caja y bigotes para f_L por temperatura

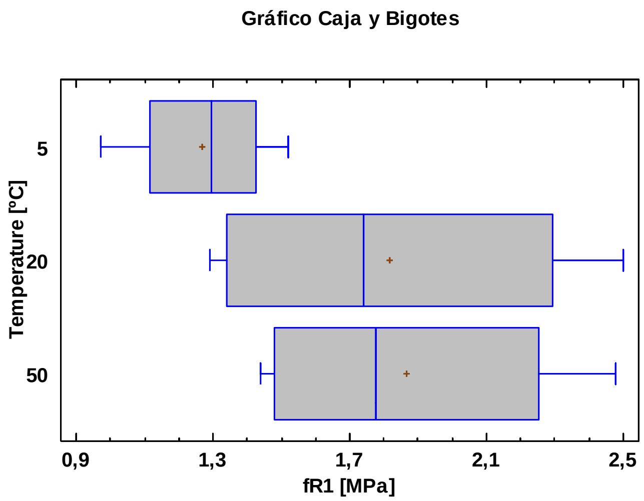
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	3,15172	2	1,57586	15,15	0,0013
Intra grupos	0,93615	9	0,104017		
Total (Corr.)	4,08787	11			



- Influencia de la temperatura en f_{R1}

Tabla ANOVA y gráfico de caja y bigotes para f_{R1} por temperatura

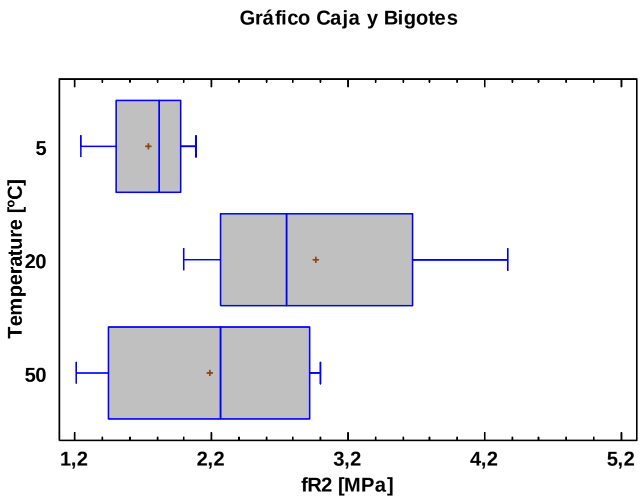
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	0,879017	2	0,439508	2,12	0,1756
Intra grupos	1,86235	9	0,206928		
Total (Corr.)	2,74137	11			



- Influencia de la temperatura en f_{R2}

Tabla ANOVA y gráfico de caja y bigotes para f_{R2} por temperatura

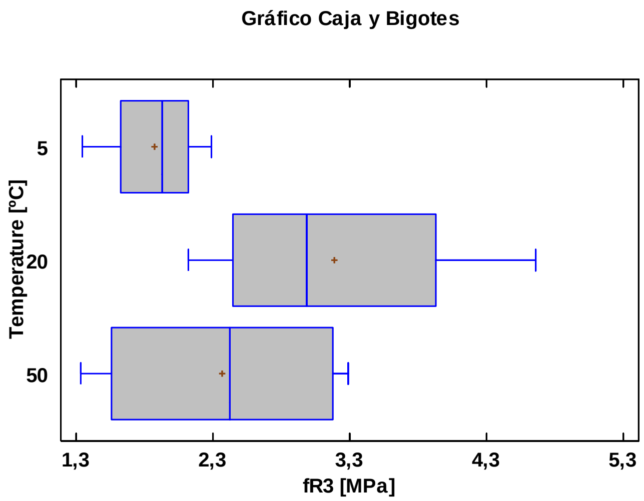
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	3,08945	2	1,54473	2,41	0,1452
Intra grupos	5,77118	9	0,641242		
Total (Corr.)	8,86063	11			



- Influencia de la temperatura en f_{R3}

Tabla ANOVA y gráfico de caja y bigotes para f_{R3} por temperatura

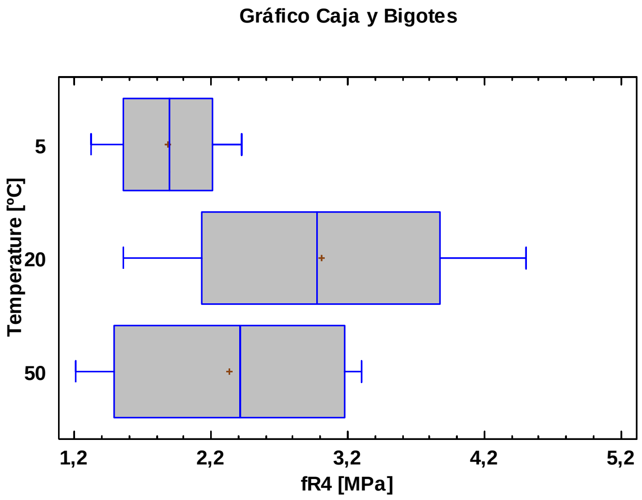
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	3,53105	2	1,76552	2,37	0,1485
Intra grupos	6,69125	9	0,743472		
Total (Corr.)	10,2223	11			



- Influencia de la temperatura en f_{R4}

Tabla ANOVA y gráfico de caja y bigotes para f_{R4} por temperatura

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	2,54255	2	1,27127	1,40	0,2946
Intra grupos	8,14847	9	0,905386		
Total (Corr.)	10,691	11			

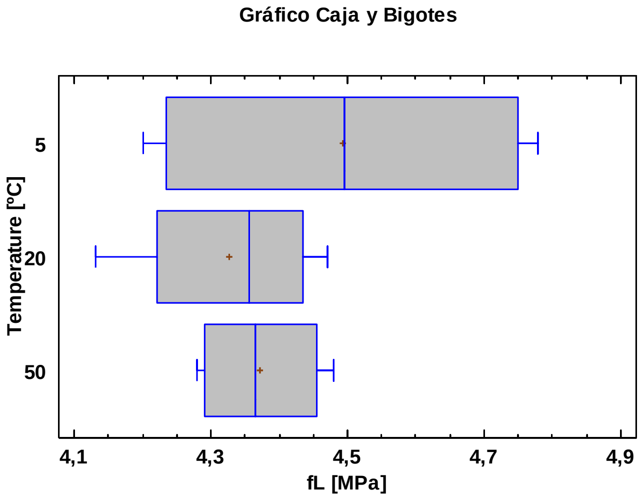


Tipo de fibra S:

- Influencia de la temperatura en f_{Lm}

Tabla ANOVA y gráfico de caja y bigotes para f_L por temperatura

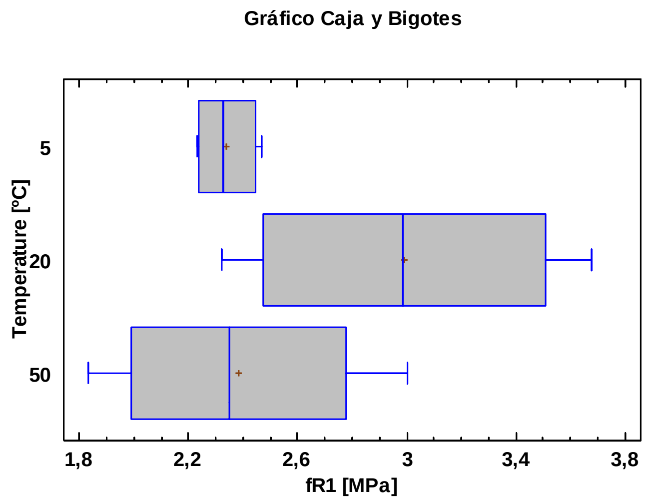
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	0,0582	2	0,0291	0,72	0,5122
Intra grupos	0,363025	9	0,0403361		
Total (Corr.)	0,421225	11			



- Influencia de la temperatura en f_{R1}

Tabla ANOVA y gráfico de caja y bigotes para f_{R1} por temperatura

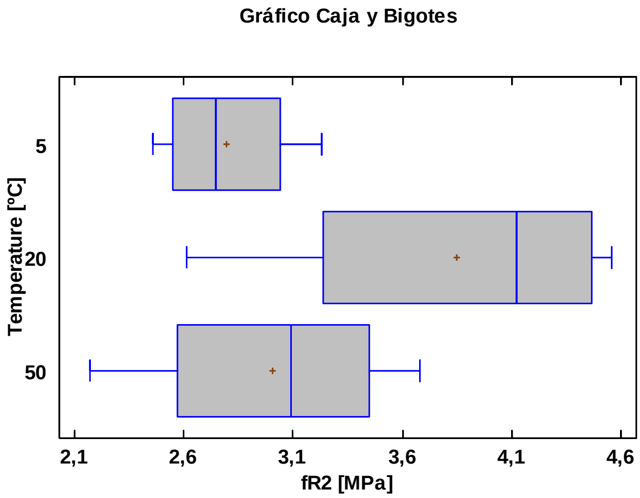
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	1,06622	2	0,533108	2,41	0,1452
Intra grupos	1,99115	9	0,221239		
Total (Corr.)	3,05737	11			



- Influencia de la temperatura en f_{R2}

Tabla ANOVA y gráfico de caja y bigotes para f_{R2} por temperatura

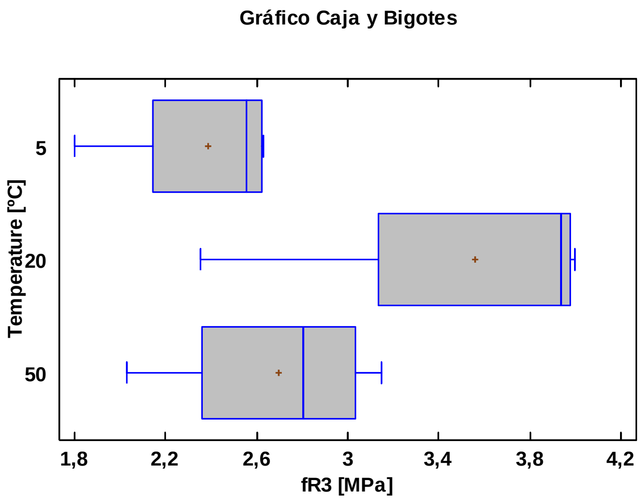
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	2,50332	2	1,25166	2,93	0,1048
Intra grupos	3,84725	9	0,427472		
Total (Corr.)	6,35057	11			



- Influencia de la temperatura en f_{R3}

Tabla ANOVA y gráfico de caja y bigotes para f_{R3} por temperatura

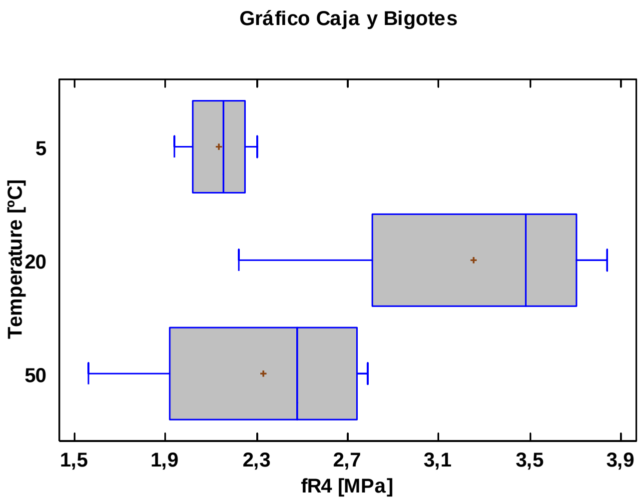
Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	2,94935	2	1,47468	4,26	0,0499
Intra grupos	3,11565	9	0,346183		
Total (Corr.)	6,065	11			



- Influencia de la temperatura en f_{R4}

Tabla ANOVA y gráfico de caja y bigotes para f_{R4} por temperatura

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
Entre grupos	2,86895	2	1,43447	5,08	0,0333
Intra grupos	2,53927	9	0,282142		
Total (Corr.)	5,40822	11			



<u>SEGUNDO CASO: Resultado Tabla ANOVA con dos factores e interacción.</u>

Variable dependiente: f_{Lm}, f_{R1m}, f_{R2m}, f_{R3m}, f_{R4m}

Factor A: Condiciones de pre-fisuración (2)

Factor B: Temperatura (4)

Interacción AB: se comparan las resistencias residuales para cada temperatura y condición de pre-fisuración.

- Influencia en f_{Lm}

Gráfico de Interacciones en f_{Lm}

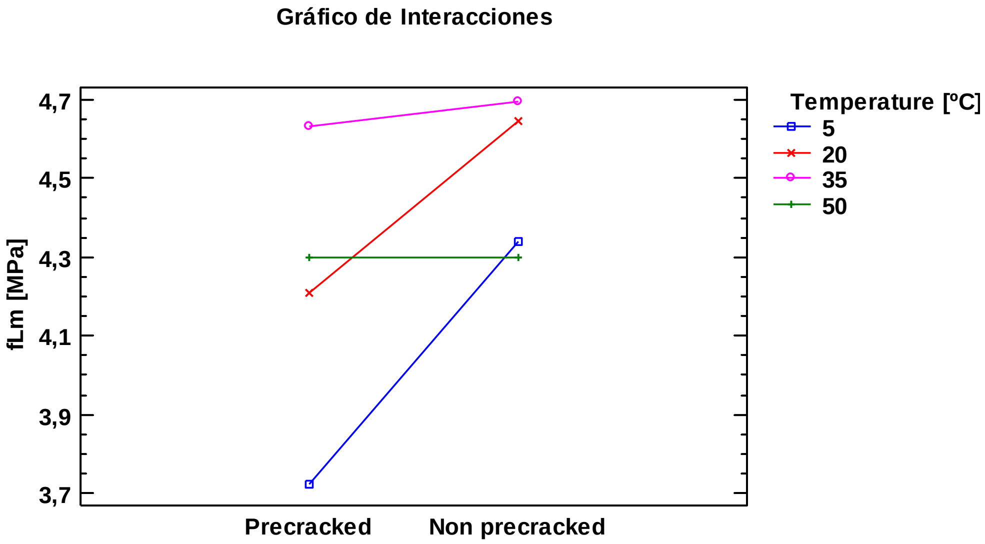


Tabla ANOVA para f_{Lm}

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
EFECTOS PRINCIPALES					
A:Precracked	0,532015	1	0,532015	2,93	0,1026
B:Temperature	1,44529	3	0,481762	2,65	0,0768
INTERACCIONES					
AB	0,472332	3	0,157444	0,87	0,4750
RESIDUOS	3,63678	20	0,181839		
TOTAL (CORREGIDO)	6,1399	27			

- Influencia en f_{R1m}

Gráfico de Interacciones en f_{R1m}

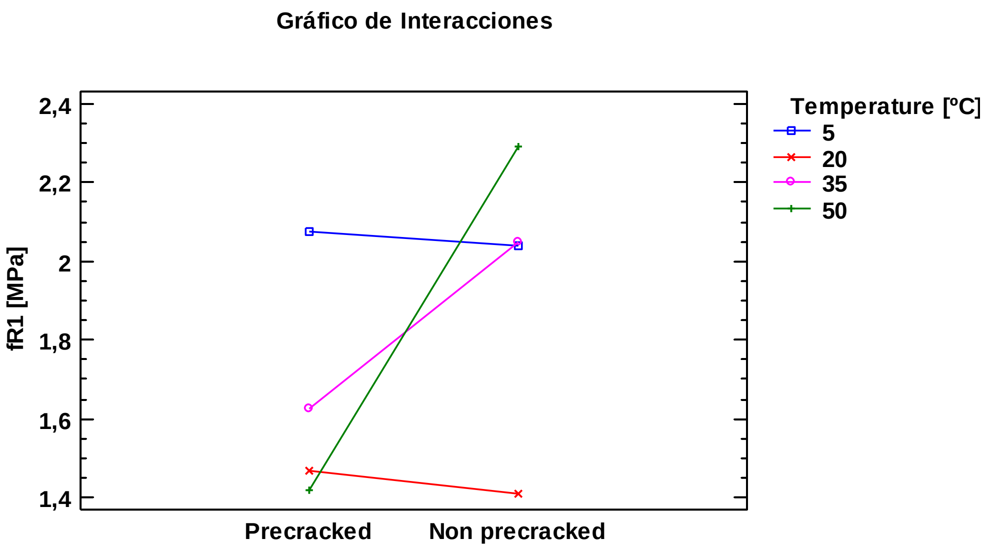


Tabla ANOVA para f_{R1m}

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
EFECTOS PRINCIPALES					
A:Precracked	0,610305	1	0,610305	3,98	0,0599
B:Temperature	1,51952	3	0,506505	3,30	0,0413
INTERACCIONES					
AB	0,965695	3	0,321898	2,10	0,1325
RESIDUOS	3,0673	20	0,153365		
TOTAL (CORREGIDO)	6,02361	27			

- Influencia en f_{R2m}

Gráfico de Interacciones en f_{R2m}

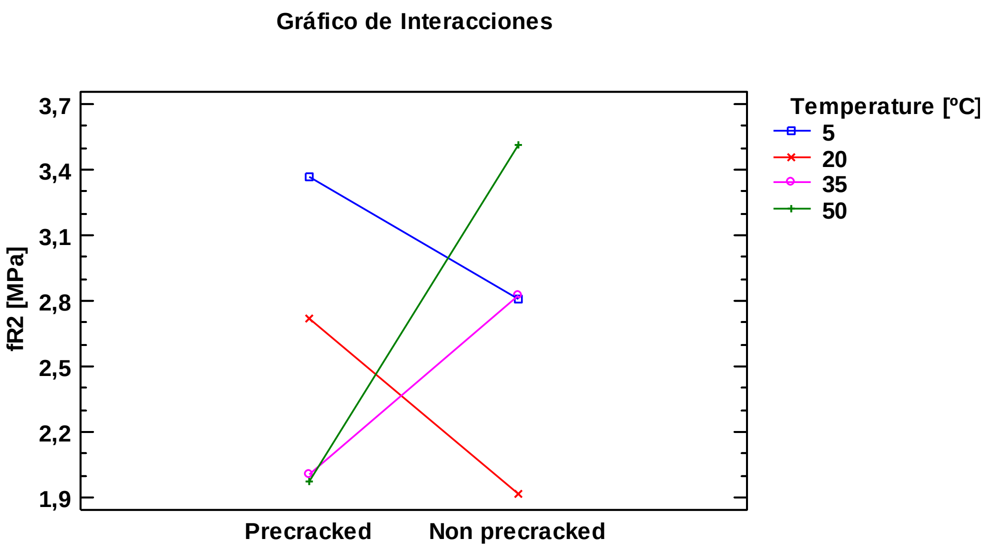


Tabla ANOVA para f_{R2m}

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
EFECTOS PRINCIPALES					
A:Precracked	0,442225	1	0,442225	1,53	0,2303
B:Temperature	2,71234	3	0,904113	3,12	0,0478
INTERACCIONES					
AB	6,61521	3	2,20507	7,61	0,0013
RESIDUOS	6,08391	21	0,28971		
TOTAL (CORREGIDO)	16,1545	28			

- Influencia en f_{R3m}

Gráfico de Interacciones en f_{R3m}

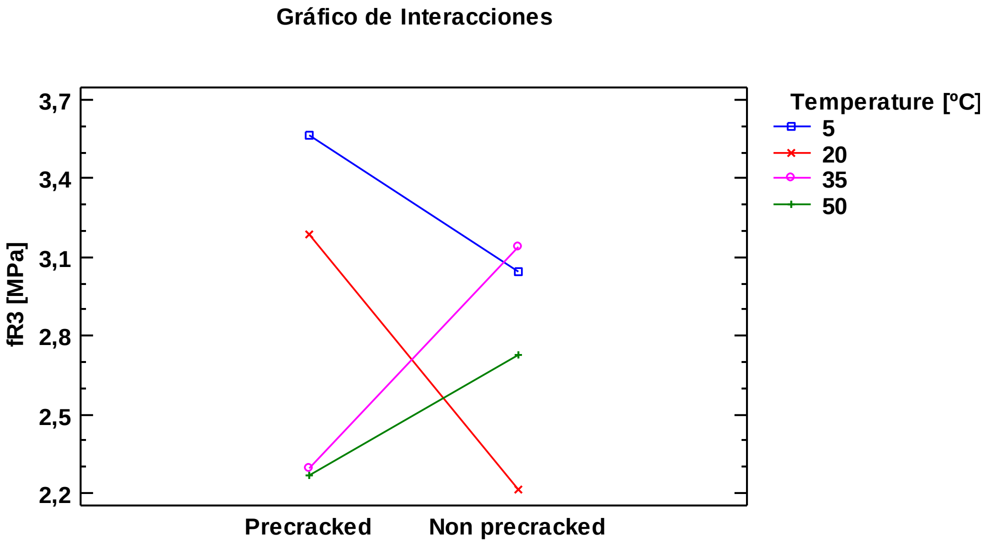


Tabla ANOVA para f_{R3m}

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
EFECTOS PRINCIPALES					
A:Precracked	0,0154864	1	0,0154864	0,02	0,8953
B:Temperature	2,7615	3	0,920501	1,05	0,3895
INTERACCIONES					
AB	3,716	3	1,23867	1,42	0,2654
RESIDUOS	18,3394	21	0,873304		
TOTAL (CORREGIDO)	25,247	28			

- Influencia en f_{R4m}

Gráfico de Interacciones en f_{R4m}

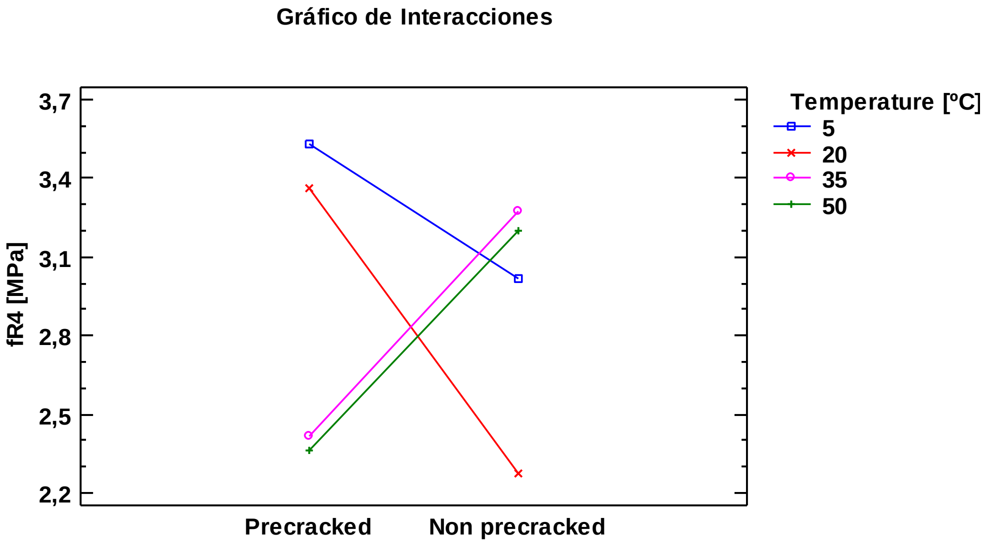


Tabla ANOVA para f_{R4m}

Fuente	Suma de Cuadrados	Gl	Cuadrado Medio	Razón-F	Valor-P
EFECTOS PRINCIPALES					
A:Precracked	0,00288095	1	0,00288095	0,01	0,9259
B:Temperature	1,11001	3	0,370003	1,14	0,3577
INTERACCIONES					
AB	4,28993	3	1,42998	4,41	0,0163
RESIDUOS	6,15862	19	0,324138		
TOTAL (CORREGIDO)	12,5776	26			