Characterization and control of wet-mix sprayed concrete with accelerators

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Als meus pares, Joan i Clara,

i al meu germà Joel,

no seria el que sóc si no haguès estat per vosaltres.

Us estimo.

"Si estàs trist somriu, plorar és molt fàcil"

Marc Gonzalez Galobardes

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ABSTRACT

The development of the wet-mix system and the use of the sprayed concrete as a part of the new Austrian tunnelling method (NATM) marked an increase in the use and in the structural responsibility of the material, with special importance in underground construction. Nowadays, sprayed concrete is used in many applications with clear structural responsibility and an ever-growing pressure for the use of environmentally materials is observed. To cope with these trends, new cements and accelerators are developed.

The use of new materials creates a special type of sprayed concrete. Moreover, the requirement of thinner layers lead to an increase in the level of stress applied and, consequently, in the structural requirements. Also the lack of standardization in the international instructions and the poor quality control of the material are current drawbacks of the use of sprayed concrete. Therefore, it is obvious that more studies are still needed to achieve an optimized design with the new materials.

The general objective of this dissertation is to provide a characterization of wet-mix sprayed concrete with new accelerators and to propose methods for the control of the material. The objective is divided in five different subjects. The first subject considered is the characterization at different levels of mixes with different types of cement and accelerators in laboratory conditions. The results obtained show the differences in behavior of several alkali-free accelerators depending on the type of cement in terms of short and long term properties. The second subject focuses on the adaptation of the UNE-EN 196:2005 for the quality control of mortar mixes with accelerators. An adapted test procedure and new limits for the statistical verification of the results were proposed in order to simplify the comparison between mixes.

The third subject covers the correlation between cement paste/mortar and sprayed concrete properties. A large database is used to identify the parameters measured that present the best correlation with each other. The curves and the confident areas obtained allow the simplified estimation of the properties of sprayed concrete based on the results obtained in a small scale with cement pastes and mortars.

The fourth subject concerns the indirect estimation of the modulus of elasticity of sprayed concrete using as a reference the compressive strength of the material. The suitability of the equations from different codes and instructions were evaluated showing a poor fit with the experimental results. Therefore, an empirical and a semi-analytical equation were proposed to estimate the modulus of elasticity of the sprayed concrete considering its singular characteristics.

Finally, the last subject focuses on the development of an alternative control procedure at sprayed concrete level. For that, finite elements models are used to derive correlations between the compressive strength development and the evolution of temperature of the sprayed concrete layer with different thickness and types of ground. Considering this, the maturity method is adapted to allow a continuous on site indirect estimation of the mechanical properties of the material.

RESUMEN

El desarrollo del sistema de proyección de la vía húmeda y el uso del hormigón proyectado en el nuevo método austríaco de construcción de túneles (NATM) ha marcado un incremento del uso y de la contribución estructural del material, con especial interés en la construcción subterránea. Hoy en día, el hormigón proyectado se utiliza en muchas aplicaciones con clara responsabilidad estructural, observándose una presión creciente que implica el uso de materiales sostenibles. Basándose en estas nuevas tendencias, se están desarrollando nuevos cementos y acelerantes.

El uso de nuevos materiales crea un tipo especial de hormigón proyectado. Además, el requerimiento de capas más finas involucra elevar los niveles de tensión aplicadas y, en consecuencia, en las exigencias estructurales. Además, la falta de estandarización en las instrucciones internacionales y el pobre control de calidad del material son inconvenientes para el uso del hormigón proyectado. De esta manera, es obvio que se necesitan más estudios para conseguir una optimización del diseño y dosificación del hormigón proyectado con estos nuevos materiales.

El objetivo general de esta tesis es caracterizar el hormigón proyectado por vía húmeda con nuevos acelerantes y proponer métodos para el control del material. El objetivo se divide en 5 temas. El primero es la caracterización a distintos niveles de dosificaciones con diferentes tipos de cemento y acelerante en condiciones de laboratorio. Los resultados obtenidos presentan las diferencias en el comportamiento de distintas mezclas con acelerantes libres de álcali dependiendo del tipo de cemento a cortas y largas edades. El segundo tema se centra en la adaptación de la norma UNE-EN 196:2005 para el control de calidad de morteros mezclados con acelerante. En este sentido, se dan los nuevos procesos de fabricación y nuevos límites estadísticos de verificación con el fin de simplificar la comparación entre mezclas estudiadas.

El tercer tema trata la correlación entre las propiedades de los hormigones proyectados y las pastas de cemento y morteros. Una amplia base de datos se utiliza para identificar parámetros estudiados para medir su correlación entre el resto. Así se obtienen curvas y áreas de confianza que permiten simplificar la estimación de las propiedades del hormigón proyectado en base a los resultados obtenidos a niveles de pastas de cemento y morteros.

El cuarto tema concierne la estimación indirecta del módulo de deformación del hormigón proyectado utilizando como referencia la resistencia a compresión. La estimación utilizando las ecuaciones que se encuentran en distintos códigos e instrucciones presenta mala correlación con los resultados experimentales. De este modo se presentan ecuaciones adaptadas teniendo en cuenta aspectos singulares del hormigón proyectado para ser usadas.

Finalmente, se trata el desarrollo de un control de calidad alternativo a nivel de hormigón proyectado. Para eso, un modelo de elementos finitos se utiliza para correlacionar las curvas de evolución de temperatura y las resistencias de capas de hormigón proyectado con distintos espesores y tipos de suelo. Considerando esto, el método de maduración es adaptado para estimar de manera continua en el tiempo las propiedades mecánicas del material.

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CHAPTER 1. INTRODUCTION

1.1. PROLOGUE

At the beginning of the 20th century, sprayed concrete technology was born. Originally, it was used to imitate the rock and in no-engineer applications such as taxidermy. In all of them, the concrete had a rather esthetical function with a very low structural responsibility. The development of the wet-mix system and the use of the sprayed concrete as a part of the new Austrian tunnelling method (NATM) marked an increase in the use and in the structural responsibility of the material, with special importance in underground construction.

In these constructions, the quality and the thickness of the sprayed layer was closely related with the stability and the support provided by the ground. In most cases, to achieve a stable layer it was necessary to add accelerators to the material. These admixtures interacted with the mix, accelerating the chemical reactions and reducing the setting time of the concrete.

The definitions of the thickness or the mix composition were based on trial and error and previous experiences. However, problems still existed regarding the technical decisions during the excavations since the scientific and theoretical bases for the structural design and the quality control were not sufficiently established. To overcome such deficiency, several studies regarding the properties of sprayed concrete were conducted. As a result, different recommendations and guidelines were proposed.

Nowadays, sprayed concrete is used in many applications with clear structural responsibility. In order to minimize the cost and the construction time, a tendency towards the reduction of sprayed layer is observed. Furthermore, an ever-growing pressure for the use of environmentally friendly materials that lead to less contamination and a safer workplace is observed. To cope with these trends, cements and accelerators that provide a better performance were developed.

The use of new materials creates a special type of sprayed concrete. Moreover, the requirement of thinner layers lead to an increase in the level of stress applied and, consequently, in the structural requirements. It is obvious that more studies are still needed to achieve an optimized design with the new materials. Table 1.1 shows some of the issues that must be addressed in order to promote the efficient use of sprayed concrete.

Table 1.1- Main issues to be addressed

Subject	Questions
Characterization at different levels (cement paste, mortar and sprayed concrete) of mixes with different types of cement and accelerators	• Could the mixes of sprayed concrete be improved regarding mechanical properties and sustainability? • What type of cements and accelerators are the ones currently used to spray concrete? • What are their advantages? And drawbacks? • How is the most performed way to characterize cement pastes? And mortars? And sprayed concretes? • How could sprayings of concrete be performed in laboratory conditions? • What type of research could be done with the results?
Control procedure at mortar level	• Are there any drawbacks in the current quality control procedures of cement and mortar mixes? • Could the conventional cement paste and mortar standards be used for these materials with accelerators? Could they be adapted?
Correlation between cement paste/mortar and sprayed concrete properties	• Is there any relationship between experimental results of cement paste/mortar and sprayed concrete mixes? • Could the quality control of the sprayed concrete be done using these relationships?
Correlation compressive strength/modulus of elasticity of sprayed concrete	• Is there any exclusively standard that relates these fundamental mechanical properties of sprayed concrete? • Could the conventional concrete standards be used for sprayed concrete? Could they be adapted?
Control procedure at sprayed concrete level	• Are there any drawbacks in the current quality control procedures of sprayed concretes? • Could the conventional concrete methodologies be used for sprayed concrete? Could they be adapted?

In particular, it is necessary to go deeper in the characterization of the properties of mixes with the new cements and accelerators as mentioned before. This characterization should be done at three different levels: cement pastes, mortars and sprayed concretes. It is also important to provide better methods for the quality control of these materials in the laboratory and in the worksite due to the lack of standardization in the international instructions. Focusing on the main mechanical properties of concrete: compressive strength and modulus of elasticity; which are the basis of the structural analysis, the characterization is a fundamental tool for engineers who wish working with this special concrete. Finally, regarding the quality control of the material and the current test used for this aim, new methods should be proposed to improve the formers. This may lead to facilitate the understanding of the sprayed concrete behaviour and therefore its use may grow in the construction world

In this context, the Universitat Politècnica de Catalunya (UPC) and the chemical company Industrias Químicas del Ebro S.A. (IQE) signed a project in order to do research in the field of sprayed concrete and answer the former questions. The project aimed to study different aspects of the interaction between concrete and accelerators, and to study the mechanical properties of sprayed concrete. The research was focused on two main experimental programs, one for cement pastes and mortars and one for sprayed concrete. The results obtained were the basis of the research presented in this dissertation. The subjects studied during this project are represented in Figure 1.1.

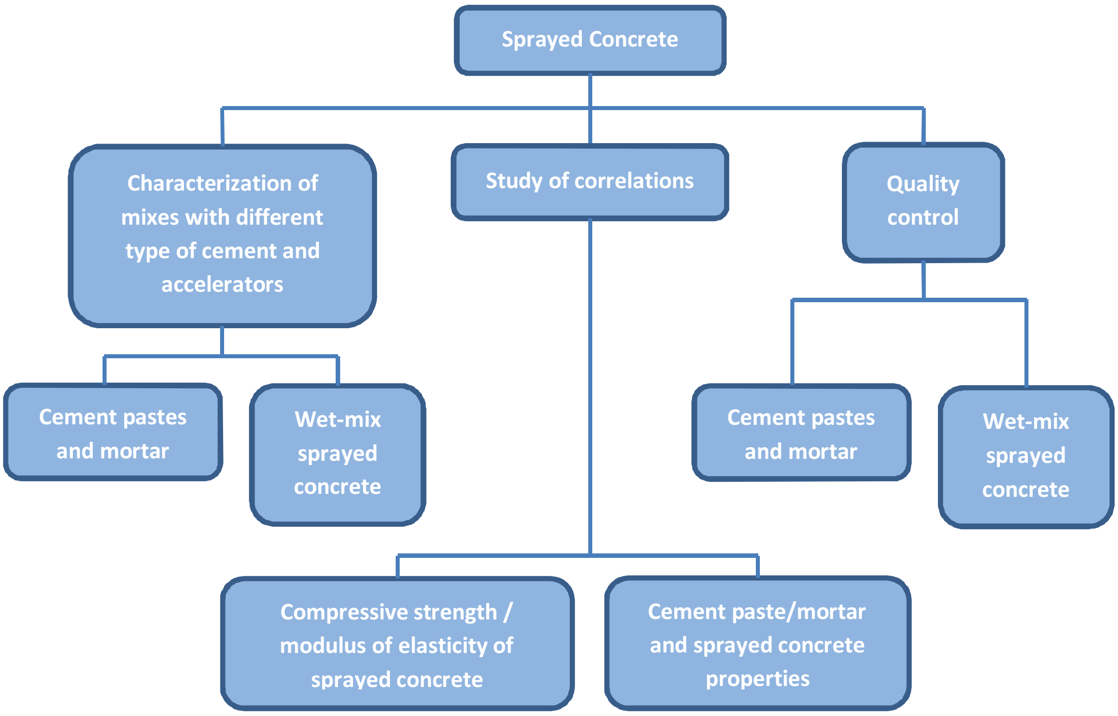


Figure 1.1- Subjects that must be analysed

1.2. GENERAL OBJECTIVE

This PhD thesis aims to provide the answer for some of the problems indicated in the prevision section. Taking that into account, the general objective of this dissertation is to provide a characterization of wet-mix sprayed concrete with new accelerators and to propose methods for the control of the material. The objective was treated considering five different subjects or research lines. The first research line is the characterization at different levels (cement pastes, mortars and sprayed concrete) of mixes with different types of cements and accelerators. The second issue is the control procedure at mortar level. The third subject is the correlation between cement paste/mortar and sprayed concrete properties. The fourth issue is the correlation compressive strength/modulus of elasticity of sprayed concrete. And finally, the fifth subject is the control procedure at sprayed concrete level.

1.3. SPECIFIC OBJECTIVES

In order to accomplish the aforementioned general objective, several specific objectives were proposed. The main ones are presented in Table 1.2.

Table 1.2- Specific objectives

Subject	Specific objectives
Characterization at different levels (cement paste, mortar and sprayed concrete) of mixes with different types of cement and accelerators	• Propose a methodology to produce and conserve cement paste and mortar samples with different types of cements and accelerators; • Propose a methodology to spray concrete under laboratory conditions; • Propose a set of test methods to characterize the mechanical properties of aforesaid materials; • Produce and test cement paste and mortar samples produced with different types of cement and accelerator; • Spray and test different mixes of concrete produced with alkali free accelerators and different types of cement and • Study the behaviour of mixes with different cement types and accelerators.
Control procedure at mortar level	• Compile and study the standards and recommendations to estimate the mechanical properties of conventional mortar mixes and compare them with the experimental data and • Adapt current standards for conventional mortar to be used for mortar with accelerators.
Correlation between cement paste/mortar and sprayed concrete properties	• Study the correlation between experimental results obtained on cement pastes and mortars and the results obtained for sprayed concrete mixes and • Derive expressions to estimate sprayed concrete properties considering the intrinsic scatter of the material.
Correlation compressive strength/modulus of elasticity of sprayed concrete	• Compile and study the standards and recommendations to estimate the mechanical properties of sprayed concrete and compare them with the experimental data and • Adapt current standards for conventional concrete to be used for sprayed concrete.
Control procedure at sprayed concrete level	• Compile and study the information related to the maturity method applied to conventional concrete and • Adapt the maturity method to sprayed concrete to propose a new quality control of the mechanical properties of the material at early ages.

1.4. METHODOLOGY

The study starts with a brief description of the estate of the art in Chapter 2. This chapter was the base of all works conducted. The first subject considered was the characterization at different levels (cement paste, mortar and sprayed concrete) of mixes with different types of cement and accelerators. The characterization of the cement paste and mortar mixes is gathered in Chapter 3, whereas the characterization of the sprayed concrete mixes in Chapter 5 as presented in Figure 1.2. The methodologies of production of the mixes were proposed considering different types of cements and accelerators. Furthermore these methodologies regarded the test to be performed at early and long ages so as to provide a broad view of the behaviour of the material.

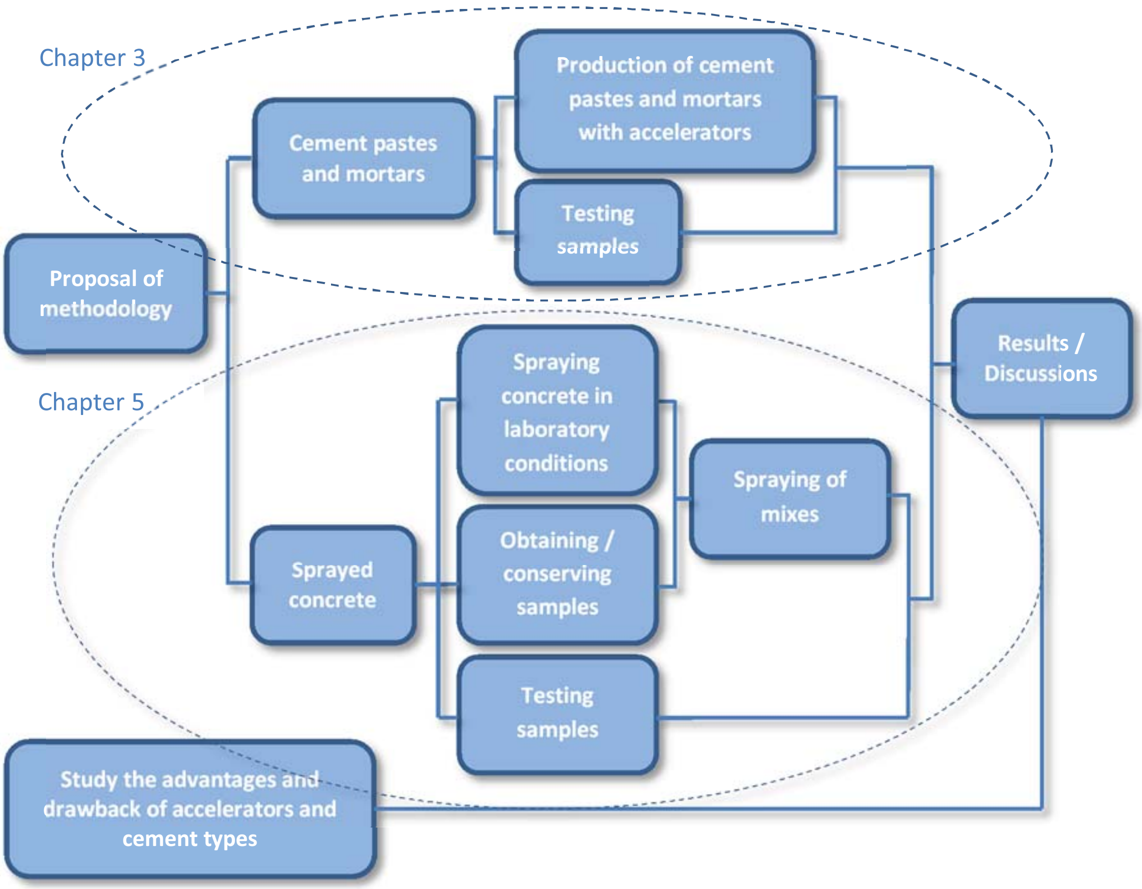


Figure 1.2- Characterization at different levels (cement paste, mortar and sprayed concrete) of mixes with different types of cement and accelerators

As presented in Figure 1.3, the second subject is the Control procedure at mortar level. This subject is presented in Chapter 4. It includes a proposal of quality control procedure for mortar mixes with accelerators. An adaptation of the test used to evaluate the flexural and compressive strength of conventional mortars is presented. This is performed considering the singular aspects of production of the mortar mixes with accelerators. Finally, a statistical analysis of the results presented in Chapter 3 leads to adapt the conventional mortar test in order to properly determine the mechanical strength of mortar mixes with accelerator.

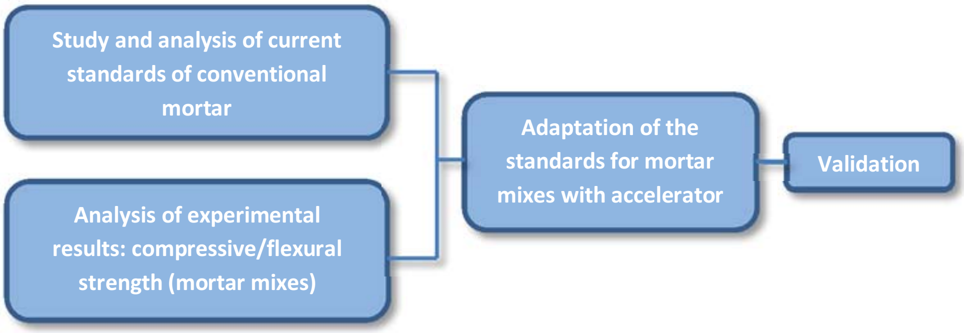


Figure 1.3- Control procedure at cement paste and mortar level

The third subject, correlation between cement paste/mortar and sprayed concrete properties, is presented in Chapter 6. As shown in Figure 1.4, an analysis of the correlation between experimental results obtained testing the cement paste and mortar mixes (Chapter 3) and the sprayed concrete ones (Chapter 5) is performed. This is the basis to obtain expressions to estimate sprayed concrete properties depending on the results assess testing cement paste and mortar mixes. Furthermore, in order to consider the intrinsic scatter of the sprayed concrete, which entails high variability on the experimental results, confident areas are presented.

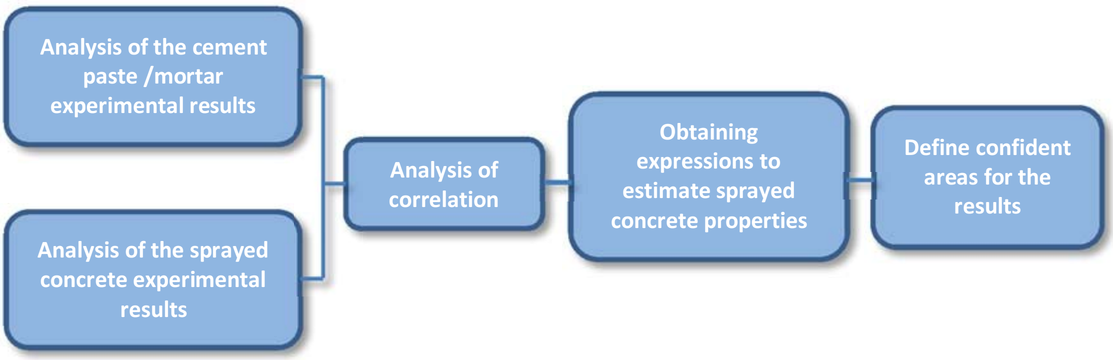


Figure 1.4- Correlation between cement paste/mortar and sprayed concrete properties

The fourth subject is presented in Chapter 7 (Figure 1.5). It concerns an analysis of the experimental results of compressive strength and modulus of elasticity presented in Chapter 5. The current equations used for conventional concrete gathered in international instructions are described and their applicability to sprayed concrete is verified. The adaptation of these equations for sprayed concrete is preformed taking into account the singular aspects of the latter.

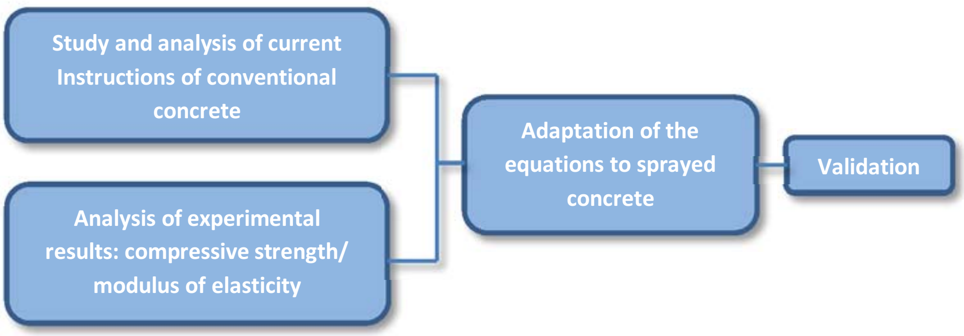


Figure 1.5- Correlation compressive strength/modulus of elasticity of sprayed concrete

Finally, the subject control procedure at sprayed concrete level is presented in Chapter 8. As summarized in Figure 1.6, a quality control procedure for sprayed concrete at early ages is proposed. In this sense, the maturity method, which is the relationship between the evolution of temperature and the development of compressive strength, is analysed and adapted for sprayed concrete. In order to do that a thermal model is presented. This model allows adapting the maturity curves, needed in the maturity method, considering different problem geometries and boundary conditions. All this provides an useful tool so that the compressive strength of the sprayed concrete may be estimated from the evolution of temperature.

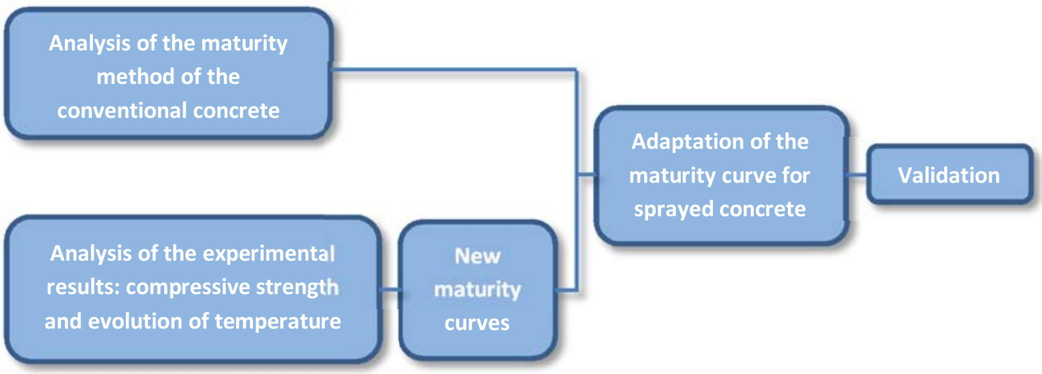


Figure 1.6- Control procedure at sprayed concrete level

CHAPTER 2. ESTATE OF THE ART

2.1. INTRODUCTION

Sprayed concrete, or shotcrete, is a mixture of cement, aggregate and water projected pneumatically from a nozzle into place to produce a dense homogeneous mass. Properly applied, it is a structurally sound and durable construction material which exhibits excellent bonding characteristics to existing concrete, rock, steel and many other materials (1). It can have high strength, low absorption, good resistance to weathering and resistance to some forms of chemical attack (1; 2). Many of the physical properties of sprayed concrete are comparable or superior to those of conventional concrete having the same composition (2; 3).

The force of the impact of this pneumatically propelled material on the surface causes compaction of the shotcrete paste matrix into the fine surface irregularities and results in good adhesion to the surface (1; 4). Within limits, the material is capable of supporting itself in vertical or overhead applications. In this sense, the bonding of sprayed concrete to other materials is often an important design consideration (5).

Sprayed concrete is used instead of conventional concrete, in most instances, for reasons of cost or convenience. Furthermore, it is advantageous in situations when formwork is cost prohibitive or impractical, access to the work area is difficult, thin layers or variable thicknesses are required, or normal casting techniques cannot be employed. Additional savings are possible because sprayed concrete requires only a small, portable plant for manufacture and placement. Spraying operations can often be accomplished in areas of limited access to make repairs to structures.

In this context, sprayed concrete presents a great number of applications. These are characterized by structures with large surfaces and small thickness. The most important and known application is the underground construction: tunnelling and mining. Sprayed concrete was mainly developed for these applications and is considered one of the key tools of the New Austrian Tunnelling Method (NATM) (6). Even though examples of other applications of sprayed concrete are the construction of canalisations, the slope stabilization and the metallic structures protection against fire and corrosion (1; 6). Each use has its particular characteristics regarding aspects such as strength or durability.

This chapter presents a general view of the sprayed concrete, which is the base of all studies presented in this dissertation. In this sense, after explaining a brief history of the use of the sprayed concrete, the estate of the art focuses on the wet-mix sprayed concrete, which is currently the one used in most applications (7).The basic materials that compose the sprayed concrete are presented together with the current tendencies in terms of dosage. Furthermore, the problems and tendencies of the standardization and characterization of this special concrete are presented at the end of the chapter. Finally, some discussions are given.

2.2. BRIEF HISTORY

The sprayed concrete appeared at the beginning of 20th century as a way to imitate rock shapes. In 1907 the naturalist, taxidermist and inventor Carl Akeley (1864-1926) invented the first machine to spray concrete (Figure 2.1.a) (4). He used it for his works of taxidermy at the Public Museum of Milwaukee as shown in .b. Around 1910 the first patent for the process is granted: ‘Apparatus for mixing and applying plastic or adhesive materials’ (8). This apparatus was called ‘Cement Gun’ or Gunite, early synonymous of sprayed concrete. So patented, the sprayed concrete was presented in the ‘Cement Show’ of New York in 1910 and consequently it was introduced in the construction market.

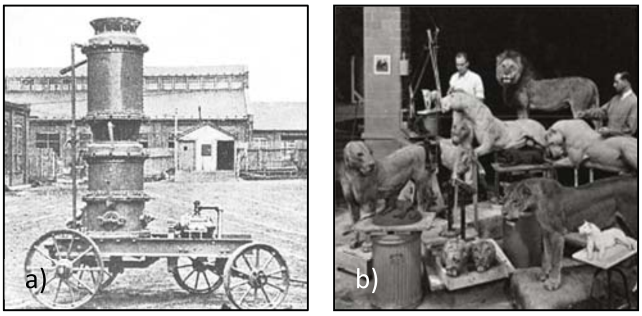


Figure 2.1- Carl Akeley’s spraying machine a) and taxidermy works at Milwaukee b)

Between 1910 and 1945 the technique was widely used entailing the existence of more than 5000 machines for spraying concrete in 120 different countries (8). In this period the material was studied in depth and it was applied in different fields such as the protection of structures (Figure 2.2.a), the stabilisation of slopes or in tunnelling. These applications are corroborated by great examples as the protection of the metallic structures of the Central Station of Houston, the stabilisation of the slopes of the Panama Channel or the construction of the tunnel in Puymorens (Figure 2.2.b). Furthermore, the material was used to build other structural things as barges to cross the Potomac River (Figure 2.2.c) (8).

Figure 2.2- Protection of structures a) tunnel in Puymorens b) and construction of barges c)

After the World War II a crisis period started and lasted until the end of 60's (8). Then, a new spraying process was invented during the 60's: the dry mix process. This method was used by architects such as Jean-Louis Chanéac (1931-1993) or Peter Vetsch (1943), who relaunched the material (Figure 2.3.a). After this period the new technological advances and the development of the chemistry applied on concrete entailed the apparition of a new method at early 80's: the wet mix process (1; 4). Currently, this is the process most used and jointly the new technology applied to sprayed concrete, such as the spraying robots (Figure 2.3.b); this material is raising its importance in the construction sector.

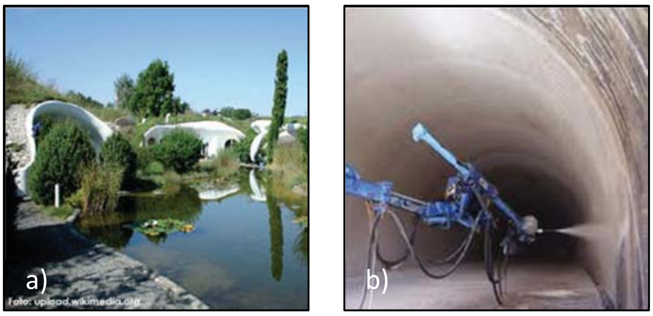


Figure 2.3- Sprayed concrete houses by Vetsch a) and spraying robots b)

2.3. WET MIX PROCESS

Concrete may be sprayed through two processes: dry mix and wet mix. Figure 2.4 presents the operating schemes of each one. In the dry mix process the materials without the addition of water are pumped. The water needed to hydrate the cement is added at the nozzle together with compressed air just before spraying (1; 2; 4). This system presents several drawbacks. Examples are the generation of dust, the high rebound of material during the spraying (around 30%) and the high variability on the properties of the laid material due to the fact that the nozzleman is the one who controls the amount of water added to the mix (1).

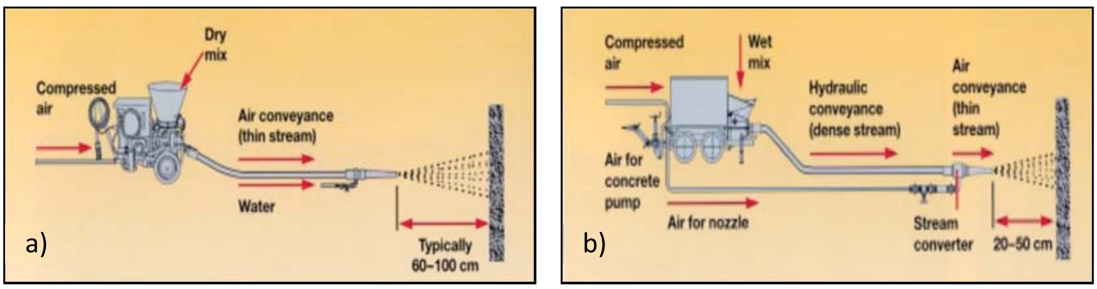


Figure 2.4- Dry mix process a) and wet mix process b)

The development of the technology of the sprayed concrete led to the wet mix process. In this case a conventional concrete is directly discharged into the reception hopper, therefore the material is previously mixed with water before the spraying process. Then it is propelled through the hoses to the nozzle by means of pumps. It is in the nozzle that the compressed air is added to provide the necessary velocity so as to spray the concrete. Depending on the requirements of the application, admixtures such as accelerators are also added in the nozzle.

In the wet mix process, the execution conditions are more controlled as the amount of water is established during the mix of the conventional concrete, entailing more homogenous final product. Moreover, other drawbacks presented by using the dry process are reduced. For example, the generation of dust is considerably smaller and the rebound of material decreases to less than 10% (1; 4).

Despite the advantages of the wet-mix process, in certain applications the dry mix is still used. This is especially true for elements with low structural responsibility that requires a smaller set-up. On the contrary, the wet mix process is usually applied for elements such as tunnels contributing with a certain structural function (9; 10; 11). Therefore, the present state of the art focuses on the wet mix process.

2.4. MIX COMPOSITION

Sprayed concrete is a special concrete that has singular aspects due to the production process used. Two of the main aspects are the porosity and the rebound (1; 4). The first one is higher in the case of sprayed concrete due to the addition of the compressed air during the execution. Part of this air is incorporated in the mix when the concrete is laid. This additional porosity affects the mechanical properties of the final product, being essential to consider it during the characterization of the sprayed concrete. Besides that, when the mix is sprayed at high velocity against a surface, part of it do not become attached and rebound. The rebound is generally related with a loss of material and has important economical repercussion. Furthermore, it affects the final mix composition of the cast layer, decreasing the amount of coarse aggregate and, consequently, the mechanical properties of concrete (12).

To minimize both problems and to assure pumpability, the mix composition of the mix composition is designed according with certain guidelines (12; 13). Even though the same basic constituent materials are used (cement, aggregates and water) to achieve an improved mix design additions and admixtures are included. In this sense, the accelerators and the superplasticizers are essential. Accelerators are basic to reduce the rebound of material and to assure the bonding between the sprayed concrete and the support. They act in the reactions produced by the tricalcium of aluminium (C_3A) from the cement at very early ages. Then, adding these admixtures in the mixes, the consistency of sprayed concrete changes from liquid to plastic while being still on the air and the concrete quickly sets on the surface (1; 14). On the other hand, the superplasticizers are used to improve the workability and therefore the pumpability of the mix and moreover they avoid the hardening of the concrete during its transport (15). Apart of these components, sprayed concrete mixes may incorporate fibres and additions such as fly ash or microsilica, which improve its mechanical properties (15; 16).

In the next sections, the main considerations of the mix composition and the tendencies observed in studies from the literature are presented.

2.4.1. Cement, aggregates and water

Several studies present procedures and recommendations that may be followed to make an adequate mix design for sprayed concrete (17; 18). The European Federation of Producers and Applicators of Specialist Products for Structures (EFNARC) presented in 2001 recommendations related to the materials of sprayed concrete (7). General recommendations are given for cements, aggregates and water. Cements should satisfy the requirements of the European standard UNE-EN 197-1:2011 (19) regarding their composition. The minimum content of cement should not be less than 300 kg/m^3. Finally, the cement should follow the requirements from the standard UNE-EN 206-1:2008 (20) considering aspects of specification, performance, production and conformity.

The considerations for the aggregates are related with the workability of the mix (12). In this sense, the grading of the aggregates must be finer than a conventional mix. Since the concrete travels though the hoses circuit, the finer aggregates help the bigger ones get through the nozzle, reducing the incidence of strokes and blockages. Furthermore, this finer grading contributes to the formation of a support bed for the bigger aggregates therefore decreasing the rebound.

The water used to produce sprayed concrete should comply with the requirements of the standard UNE-EN 1008:2007 (21), as any mixing water used to produce conventional concrete. The maximum water/cement ratio recommended by EFNARC is 0.55. In practice, values around 0.45 are used.

Apart from these general recommendations, current tendencies referred to the use of these components are gaining importance. These tendencies are basically focused on environmental issues and are related to the type of cement used. In the Conference about Climate Change celebrated in Kyoto in 1997, the developed countries agreed on reducing the emissions of greenhouse gases such as methane, nitrous oxide and carbon dioxide (CO_2). As a consequence, the European Union passed the Kyoto Protocol in 2002 forcing the countries members to make a reduction of these detrimental emissions.

Considering the high liability of the construction industry regarding the emissions, many countries are favouring the use of materials that are more environmentally friendly, remarkably better cements. In this sense, two different approaches are considered (22; 23). The first of them focus on the improvement of the processes of the production of clinker, which may be achieved by using new technologies, renewable energies and new raw materials with fewer emissions. On the other hand, the second approach focus on the partial substitution (of about 5-15% by weight) of the clinker utilized in the production of cement by additions (24). This measure started at the end of 90's and is now completely extended. To give an example of that, Figure 2.5 shows the different types of cements produced by Holcim (Switzerland) in 1995, 2000 and 2009 (22). This figure shows that, in 1995, 56% of the production consisted of ordinary Portland Cement (OPC). In 2009, the OCP correspond only to 20% of the total cement production.

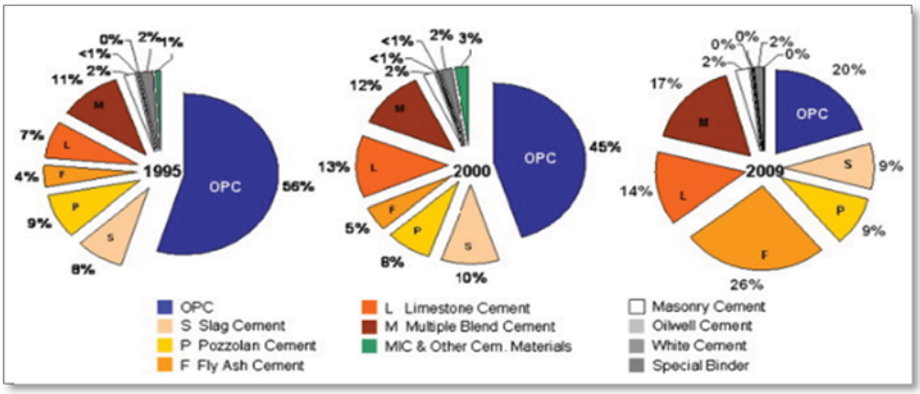


Figure 2.5- Evolution of the use of additions in cement

Focus on the replacement of clinker by additions some research present results of the properties of mortar and concrete mixes. These studied show how the additions act in the hydration process, improving concrete properties. For instance, fly ash or pozzolan add more silica (Si) (15; 25). This extra amount of Si contributes to the formation of more C-H-S chains, which are the responsible of the compressive strength at long ages. Hence, benefits apart from environmental ones are achieved.

In several applications, the cement with high clinker content (CEM I) has been substituted by cements with less clinker and the addition of wastes or by-products (CEM II). Countries from northern Europe have already extended this change to structures constructed with sprayed concrete. In Spain, the general rule still is to apply CEM I for sprayed concrete structures. However, signs of change start to appear. Since the introduction of the new Instruction EHE-08 annexes an index for the structure of the sustainability to obtain results during the project redaction and the construction stage has been introduced (24). One of the aims of this annex is the reduction of the CO_2 during the production of cement. Examples of trials and of applications of CEM II are also present.

In the case of sprayed concrete, the requirements of the compressive strength at early ages entail the necessity of a quick setting (26; 27; 28). Limestone is a good alternative since a concrete produced with cement with limestone harden quicker and demand less water than an equivalent one with OPC (27). Consequently, strength improvements might also be obtained.

2.4.2. Accelerators and superplasticizers

In general, accelerators and superplasticizers should follow the requirements of the standard UNE-EN 934-5:2009 (29). Apart from that, there are also current environmental tendencies referred to the use of the accelerators. In order to understand these considerations some aspects must be treated. Therefore, types of accelerators and interaction cement-accelerator are explained below regarding the current tendencies of their use.

2.4.2.1. Types of accelerator

The first accelerators systematically used for sprayed concrete were based on alkali products, which are aggressive substances for the human beings and for the environment (30).

This family of accelerators was composed by modified silicates and aluminates of sodium or potassium (15). The modified silicates were characterized by a quick effect (lower than 10 s); even though, they provide smaller initial strength and long final setting times (higher than 30 min). The products formed are really amorphous due to the high content of alkalis, entailing a big loss of strength at long age (15).

The aluminates of sodium and potassium made the ones based on modified silicates obsolete. Nowadays, the former are the most common accelerators used for sprayed concrete (1; 30). They interact during the hydration process increasing the transformation of the C_3A of the cement to monsulphate of aluminium and providing an extra gain of initial strength (15). The formation of a non-crystalline chemical net is observed, which lead to a decreases in the mechanical properties at long ages. Furthermore, the high alkali content of these accelerators increases the risk of alkali-aggregate reaction (15; 31). Finally, the main drawback of using accelerators based on aluminates is not a technic aspect but an environmental one due to ecological and safety reasons. The aluminates are chemical components with pH around 13 and therefore strongly alkaline. They may have a negative impact on the environment, contributing for the salinization, hydric stress in the ground and disequilibrium of the pH of sensitive waters (30).

In order to reduce these drawbacks, chemists worked on obtaining alkali-free accelerators that are safer for the technicians, with less negative environmental impact and improved efficacy regarding the compressive strength at long ages (1; 10; 32). Despite these advantages, higher doses of alkali free accelerator are needed to accomplish short term properties equivalent to the ones obtained with alkaline accelerators (30; 33).

The alkali-free accelerators are highly sensitive to the types and the composition of cements (34; 35; 36). For instance studies developed in Stuttgart University show the effect of the alkali free accelerators was at very early age more pronounced on mixes containing CEM I in comparison with CEM II, while the alkaline accelerator had a larger influence on mortar containing CEM II (37). Therefore, new research is focused on developing formulations compatible for all types of cements so as to facilitate its application. In this sense, the study of the interaction cement-accelerator is considered of great relevance.

2.4.2.2. Interaction cement-accelerator

Under normal conditions, the cement reacts spontaneously with water in order to produce harden substances, increasing the strength of the mix (31). This process starts with the hydration of the dry phase of the C_3A that produces the loss of plasticity in few minutes. In order to maintain the workability for longer periods, calcic sulphate is added during the production of the cement as a set regulator (25; 31). This sulphate reacts with the free C_3A and water to generate ettringite. Once the setting regulator is consumed, the ettringite becomes unstable and is converted into monosulphate of aluminium and calcic hydroxide. Later, the calsium silicates (C_2S and C_3S) participate forming the C-S-H chains, which is the responsible of the gain of the mix strength (25; 31).

The chemical phenomena described may be grouped in four sequential phases that generalize the hydration and the hardening of cement in contact with water (38). In Phase I, the dissolution of the ions a superficial hydration of the cement grains takes place and the ettringite is superficially formed around the dry C_3A. The sulphated water migrates from the C_3A due to the waterproof provided by the ettringite layer. Then, during Phase II, an acceleration of the ettringite formation occurs, characterizing the beginning of setting. In phase III, the hydration of the silicates accelerates and the increase of the mechanical properties is observed. In phase IV, the depletion of the sulphates occurs and the hydration of the silicates continues at a slower rate.

Studies demonstrated the relationship between these chemical processes and the heat flow of the mix (38; 39). Figure 2.6 presents a typical calorimetric curve measured during the hydration of OPC paste in which the four phases described previously may be identified. The accelerator addition changes the hydration kinetics of the plain cement system. The stage II and III are the affected by the incorporation of the accelerator since both are reduced from hours to minutes. The accelerators contribute on the hydration of the aluminates fastening the consequent hydration of the silicates (38).

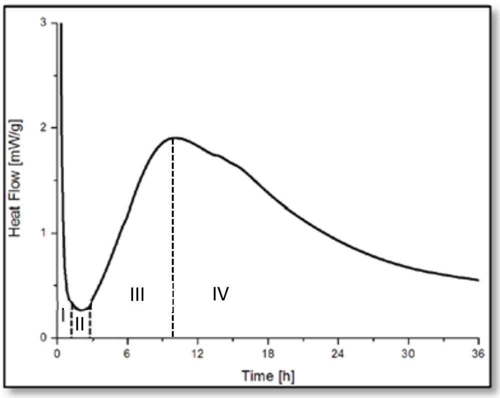


Figure 2.6- Calorimetric curve for a Portland cement paste and phases of hydration

2.5. STANDARDIZATION AND CHARACTERIZATION

The standardisation is defined as the process of developing technical documents to establish criteria, methods, processes and practices involving a formal consensus of technical experts. In this sense, to use a material in a construction with structural behaviour, the material shall be standardized. Its mechanical properties and the procedures to estimate them shall be gathered in technical documents such as recommendations, standards or instructions.

No mention of sprayed concrete properties is found in three of the most important Instructions: Model Code 2010 (40), Eurocode 2 (41) and EHE-08 (24). Several standards and recommendations regarding different aspects related to the spraying process and the mechanical properties at early ages are found in the literature. Most of the existing standards, recommendations and guideless were proposed by the American Concrete Institute (ACI) and the European Federation of Producers and Applicators of Specialist Products for Structures (EFNARC).

The recommendations from the ACI on sprayed concrete are mainly focused on the Specification for Shotcrete (13) and the Guide for the Evaluation of Shotcrete (42). The first technical document concerns the programs for certification of personal performing as nozzlemen. The Specification for Shotcrete gathers the definitions, standards and organization related to shotcrete. Furthermore, there is a part which advises about the properties of the materials used and the execution premises that should be followed to obtain good sprayed concrete layers. Finally, the Guide for the Evaluation of Shotcrete presents the way to estimate the strength and the bond between concrete and steel using non-destructive tests. Also, it includes the test to estimate the density and the permeability of the shotcrete. ACI bases its technical documents on the American standards ASTM of shotcrete. These are presented in Table 2.1.

Table 2.1- ASTM standards for shotcrete

Standard	Title
ASTM C1480/C1480M–07(2012)	Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete
ASTM C1436-08	Standard Specification for Packaged, Pre Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete Application
ASTM C1117-89(1994)	Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance (Withdrawn 2003)
ASTM C1385/C1385M-10	Standard Practice for Sampling Materials for Shotcrete
ASTM C1141/C1141M-08	Standard Specification for Admixtures for Shotcrete
ASTM C1140/C1140M-11	Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels

The main recommendations developed by the EFNARC on the subject, which has the same purpose as in case of ACI, are the European Specifications for Sprayed Concrete (7) and the Execution of Spraying (12). The European Specifications for Sprayed Concrete presents the requirements of the constituent materials of the sprayed concrete and its composition considering the durability. It presents the mix composition and the aspects of the execution of spraying. Finally, it gathers the requirements of the final product presenting the test methods and the quality control procedures. Apart from that, the Execution of spraying presents the Preparatory works that shall be done before the spraying such as clean the rock support, the equipment regarding the spraying process and the dosing of accelerators that shall be used. Furthermore, it gathers the requirements for the Spraying operations such as spraying techniques (nozzleman required), disposal of rebound, finishing, timing or curing. In this sense, EFNARC bases its technical documents on the European standards EN included in Table 2.2.

The mechanical properties of sprayed concrete should be characterized at two different stages regarding its age: early ages and long ages. The mechanical properties at early ages are particularly important in sprayed concrete as the addition of the accelerators in the mix entails a quick change of the behaviour of the material. Currently, the characterization at early ages of the sprayed concrete is performed in most European countries according with the 'Guidelines for Sprayed Concrete' of the Austrian Society for Construction Technology (43). In this sense, the guidelines gather the test which should be performed in order to characterize the sprayed concrete compressive strength at early ages: the penetration needle test and the stud driving method. The guidelines describe how to perform these indirect tests, which must be done at different ages to evaluate the compressive strength development.

Table 2.2- EN standards for Sprayed Concrete

Standard	Title
EN 934-5:2007	Admixtures for concrete, mortar and grout - Part 5: Admixtures for sprayed concrete - Definitions, requirements, conformity, marking and labelling
EN 14487-1:2005	Sprayed concrete - Part 1: Definitions, specifications and conformity
EN 14488-1:2005	Testing sprayed concrete - Sampling fresh and hardened concrete
EN 14487-6:2006	Testing sprayed concrete - Part 6: Thickness of concrete on a substrate
EN 14889-1:2006	Fibres for concrete - Part 1: Steel fibres - Definitions, specifications and conformity
EN 14889-2:2006	Fibres for concrete - Part 2: Polymer fibres - Definitions, specifications and conformity
EN 14488-2:2006	Testing sprayed concrete - Part 2: Compressive strength of young sprayed concrete
EN 14488-3:2006	Testing sprayed concrete - Part 3: Flexural strengths (first peak, ultimate and residual) of fibre reinforced beam specimens
EN 14488-7:2006	Testing sprayed concrete - Part 7: Fibre content of fibre reinforced concrete
EN 14487-2:2006	Sprayed concrete - Part 2: Execution
EN 14488-4:2005+A1:2008	Testing sprayed concrete - Part 4: Bond strength of cores by direct tension

However, the systematic use of both tests highlights a relevant problem (44; 45). Whereas the penetration needle test is performed until the sprayed concrete achieves around 1 MPa, the stud driving method cannot be used until it assesses a minimum of 2 MPa of strength (43; 46). In terms of time, this gap between 1 and 2 MPa correspond to approximately 4 h during which no data is obtained. In order to solve this problem, different studies present other ways to characterize the mechanical properties of the sprayed concrete at early ages. In this sense, studies conducted at the Universidade de Sao Paulo (USP) applied the modified proctor test to assess the compressive strength between 1 and 2 MPa (16). Studies performed in Australia present correlation between the compressive strength and ultrasonic pulse velocity measurements (47). The results obtained suggest that the short term compressive strength in time may be estimated with small devices embedded in the sprayed concrete layer.

A viable alternative are the maturity methods which allow the estimations of the compressive strength based on the evolution of temperature measured during the hydration process. Even though these methods have been successfully applied for conventional concrete (48), they have not been extensively studied in the case of sprayed concrete.

2.6. DISCUSSION

A big number of applications with sprayed concrete were found showing the importance of this special concrete in the construction field. Even though in most of them the material is used with low structural responsibility, a growing trend towards its application as the main resisting material exists. However, to make the optimized and efficient design of structures with sprayed concrete possible, several advances are still needed.

The current structural requirements, recent technological developments and the current environmental tendencies lead to produce sprayed concrete with new types of cements and accelerators. In order to optimize the sprayed concrete design with these new materials a characterization of their mechanical properties at early and long ages is needed.

On the other hand, there is a lack of studies and laboratory result of mechanical properties of sprayed concrete complicating the standardization of the material. The use of conventional concrete equations to assess properties of sprayed concrete over or underestimate the results Therefore there is a necessity of correlating mechanical properties that may be included in standards to account of the consideration of the structural responsibility of the material. Apart from that, new methods for the quality control that may be easily applied in practice allowing a continuous estimation of the mechanical properties are also needed.

CHAPTER 3. EXPERIMENTAL ANALYSIS OF CEMENT PASTES AND MORTARS

3.1. INTRODUCTION

Due to the increasing of the importance of sprayed concrete in civil construction, the analysis of the mechanical properties derivated of the addition of accelerator is essential. Currently, the knowledge of the mechanical properties of sprayed concrete is low. Its singular aspects, commented in Chapter 2, entail high variation of the results obtained in laboratory and in construction. Then the characterization of this special concrete, considering all its singular aspect, must be done so that the standardization of its mechanical properties could be done. This characterization may be done in three different scales: cement pastes, mortars and sprayed concretes.

Regarding the lower scales, cement pastes and mortars, an analysis of the affection of adding accelerators in mixes and how the addition changes their mechanical properties may be assured. However different behaviour is presented between the aforesaid mixtures and the sprayed concrete considering the execution conditions, the results in this reduced scale could be interesting to identify tendencies, which would be helpful in order to explain the sprayed concrete results.

This chapter aims to analyse the results obtained in an experimental program in which cement pastes and mortars produced with different cements and accelerators were tested in order to understand their mechanical behaviour at early and long ages. In this sense, the methodology followed in the experimental program and the results obtained are presented. Furthermore, the analysis of the results considering three parameters of study: type of accelerator (alkali and alkali free accelerators), dose of accelerator and type of cement, is presented.

3.2. METHODOLOGY

In the first stage, the characterization of the accelerators is performed in a reduced scale using pastes and mortars. Materials, mix design processes and test methods are explained in this section. Tests were performed in the Laboratory of Technology of Structures Luis Agulló from the Univeristat Politècnica de Catalunya (UPC).

3.2.1. Materials

The materials used in this experimental program were defined so that the mixes produced were representatives and equivalent to sprayed concretes. A description of them is presented below. This considers cements, water, aggregates, superplasticizer and accelerators. These materials were maintained under controlled temperature (20 ± 2 °C) and humidity (55 ± 5%) in a climatic room to avoid introducing variability to the tests.

3.2.1.1. Cement

Two types of cement were used: CEM I 52.5 R (I) and CEM II/A-L 42.5 R (II) (Characteristics in Appendix A). The former is widely applied around the world for spraying concrete. Its high amount of clinker allows a quick setting of concrete and, therefore, high compressive strength at early ages. Even though this cement is still used in Spain, the European tendency is to favour the use of other types of cements due to environmental reasons. In order to reduce the CO_2 emissions during the production of cement, several European countries apply cements type II, which includes additions that reduce the amount of clinker. Following this trend, this study considered the cement II, which presents a substitution of approximately 20% of clinker by limestone filler. This filler is common in Spain and contributes to reduce the setting time of concrete (49). The Spanish manufacturer Cementos Molins S.A delivered both cements used.

3.2.1.2. Water, Aggregates and Superplasticizer

Distilled water delivered by the Laboratory of Chemistry and Construction Materials (UPC) was used. Such procedure intends to avoid either seasonal composition variations or the existence of polluters diluted in case of using tap water.

The aggregate used for the mortar was 0-2 mm standardised sand supplied by the Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC). This aggregate follows all the requirements defined by the European standard UNE-EN 196-1:2005 (50).

A superplasticizer was applied in all mixes due to its importance in wet-mix sprayed concrete. The superplasticizer Viscocrete CS 305 supplied by SIKA S.A., with an approximate density at 20 °C of 1.1 g/cm^3, pH equal to 4.3 and a 37.5% of dry residue, was used. Superplasticizers are needed to provide fluidity and workability to concrete and to reduce the incidence of stroke problems in the hoses during the wet-mix spraying process (51).

Furthermore, its secondary function as setting retardant contributes to avoid the setting of concrete during its transportation from the plant to the construction site.

3.2.1.3. Accelerators

Four families of accelerators were used. Family 0 was composed by an accelerator based on aluminates (A-0), which is a common admixture used in underground construction in Spain. This accelerator was adopted as a pattern so as to characterize the other accelerators. A-0 is a water solution of sodium aluminate ($Na_2Al_2O_4$) with Molar Ratio $[Al_2O_3]/[Na_2O]$ = 0.76, which is stabilized with a polyol. On the other hand, Families 1, 2 and 3 were composed by new formulations of alkali free accelerators chemically based on hydroxysulphate of aluminium: $Al(SO_4)_x(OH)_{3-2x}$. These accelerators were produced to be environmentally better than the one based on aluminates according to the new European tendency. Family 1 grouped the accelerators AF-1.1 and AF-1.2, which present the lowest molar ratios ($[SO^{2-}_4]/[OH^-]$ and $[Al^{3+}]/[OH^-]$). Family 2, formed by AF-2.1 and AF-2.2, was stabilized with inorganic silicates and had high molar ratios. Finally, Family 3 consisted of the accelerators AF-3.1 and AF-3.2, which had high molar ratios as Family 2 accelerators although stabilized with polycarboxylic acids. Table 3.1 presents the main features of the alkali free accelerators.

Table 3.1- Main features of the alkali free accelerators

Family	Accelerator	Dry matter (%)	Molar ratio $[SO_4^{2-}]/[OH^-]$	Molar ratio $[Al^{3+}]/[OH^-]$	Stabilizer	pH 20°C
1	AF-1.1	38	0.6	0.8	Inorganic acid	3.3
	AF-1.2	48	0.8	1.0	Polycarboxylic acid	3.1
2	AF-2.1	39	3.4	2.6	Inorganic silicate	2.5
	AF-2.2	42	2.8	2.2	Inorganic silicate	2.6
3	AF-3.1	30	3.0	2.5	Polycarboxylic acid	2.7
	AF-3.2	30	4.5	4.0	Polycarboxylic acid	2.7

Three different doses by cement weight (%bcw) were studied for Family 0, Family 1 and Family 2, whereas two doses were evaluated for Family 3. This difference in Family 3 was due to their lower concentration in dry material respect the other accelerators. The doses were established by the results of the initial/final setting time test performed with the mixes with cement II and the optimal time intervals defined by former studies (33; 52). In this sense, the optimal dose of accelerator, defined as medium dose, was the one that entailed an initial setting time lower than 2 min and a final setting time lower than 5 min. The low and high doses were established so that the existent variations on the doses, which occur in construction sites, could be taken into account in this study. This variation considered the amount of optimal dose and was assumed as ± 2%bcw in case of alkali free accelerators, whereas it was ± 1%bcw in case of the pattern. Table 3.2 shows the doses studied for each family.

Table 3.2- Doses established in the study (%bcw)

Admixtures	Low Dose	Medium Dose	High Dose
Family 0	2	3	4
Family 1	5	7	9
Family 2	5	7	9
Family 3	9	11	-

3.2.2. Mixes

All mixes included in the study are presented in Table 3.4. The nomenclature defined for the mixes is formed by the name and the dose of the accelerator, followed by the simplified indication of the cement type (I for CEM I 52.5 R and II for CEM II/A-L 42.5 R). All terms are separated by the symbol '_'.

3.2.2.1. Cement pastes mixes

The cement paste mixes considered in this study are presented in Table 3.3. The materials used were the ones described in the section 3.2.1. The amount of superplasticizer (SP) considered was 1%bcw, which is the usual amount for wet-mix sprayed concrete (9; 51). Regarding the water/cement ratio (w/c), it was considered as 0.27 according to other laboratories experiences (BASF) that related the usual 0.45 ratio of sprayed concrete with this one of cement pastes (33; 52). The water included in the superplasticizer was taken into account in the estimation of the remaining water added to the mixes. The water provided by the accelerators was not considered in the estimation, following the current procedure in tunnels constructed with sprayed concrete.

Table 3.3- Cement Paste and mortar mixes

Material	Content cement pastes (g)	Content mortars (g)
Cement	100	450
Water	27	202.50
Aggregates	-	1350
SP	1.00	4.50
SP water	0.62	2.81
Water added	26.38	199.70

3.2.2.2. Mortars mixes

The mortars mixes considered in this study are also detailed in Table 3.3. The materials used were the ones used for cement pastes and the standardized sand. As in cement pastes the percentages of set accelerating admixture and superplasticizer are given by cement weight. Regarding the water/cement ratio (w/c), it was adopted as 0.45 as normally used in underground construction for wet-mix sprayed concrete. The added water was calculated considering the water present in the superplasticizer. Again, the water incorporated by the accelerator was not taken into account.

Table 3.4- Cement paste and mortar mixes nomenclature

Family	Type of accelerator	Dose (%bcw)	Type of cement	Mix reference
0	A-0	2	CEM I 52.5 R	A-0_2_I
		3		A-0_3_I
		4		A-0_4_I
		2	CEM II/A-L 42.5 R	A-0_2_II
		3		A-0_3_II
		4		A-0_4_II
1	AF-1.1	5	CEM I 52.5 R	AF-1.1_5_I
		7		AF-1.1_7_I
		9		AF-1.1_9_I
		5	CEM II/A-L 42.5 R	AF-1.1_5_II
		7		AF-1.1_7_II
		9		AF-1.1_9_II
	AF-1.2	5	CEM I 52.5 R	AF-1.2_5_I
		7		AF-1.2_7_I
		9		AF-1.2_9_I
		5	CEM II/A-L 42.5 R	AF-1.2_5_II
		7		AF-1.2_7_II
		9		AF-1.2_9_II
2	AF-2.1	5	CEM I 52.5 R	AF-2.1_5_I
		7		AF-2.1_7_I
		9		AF-2.1_9_I
		5	CEM II/A-L 42.5 R	AF-2.1_5_II
		7		AF-2.1_7_II
		9		AF-2.1_9_II
	AF-2.2	5	CEM I 52.5 R	AF-2.2_5_I
		7		AF-2.2_7_I
		9		AF-2.2_9_I
		5	CEM II/A-L 42.5 R	AF-2.2_5_II
		7		AF-2.2_7_II
		9		AF-2.2_9_II
3	AF-3.1	9	CEM I 52.5 R	AF-3.1_9_I
		11		AF-3.1_11_I
		9	CEM II/A-L 42.5 R	AF-3.1_9_II
		11		AF-3.1_11_II
	AF-3.2	9	CEM I 52.5 R	AF-3.2_9_I
		11		AF-3.2_11_I
		9	CEM II/A-L 42.5 R	AF-3.2_9_II
		11		AF-3.2_11_II

3.2.3. Production and conservation processes

3.2.3.1. Cement pastes

The production was performed inside a climatic room with a temperature of 20 ± 2 °C and a humidity of 50 ± 5%. Volumes of 10 cm^3 of cement paste were produced for mix. The materials were mixed manually according with the following procedure:

- First the water and the superplasticizer were mixed in a separate recipient;
- Then the content of the whole recipient was added to a bowl with the cement and the materials were actively mixed with a spatula during 1 min (Figure 3.1.a);
- The accelerator was quickly added;
- All content was mixed energetically for 10 seconds, and
- Finally, the material was quickly used to cast the samples handy compacting the material in a period inferior to 10 s.

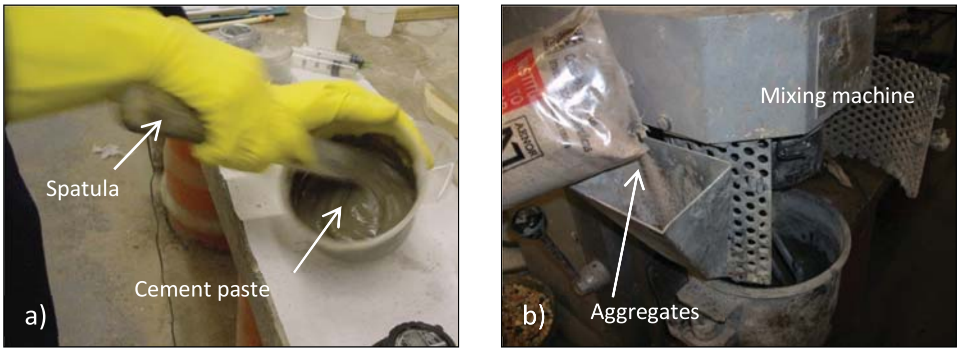


Figure 3.1- Mixing process for the cement pastes a) and mortars b)

The total production process took approximately 80 s. After 10 s of casting the specimens, the tests were performed. Cement paste samples were tested after their production; therefore there was not need of conserving them. In order to characterize the accelerators in a cement paste level a total of 104 mixes were produced. Whereas 64 samples were casted in cylindrical moulds with 25 mm diameter and 40 mm length, the rest were produced to test a spherical volume of 10 cm^3.

3.2.3.2. Mortars

Mortars were produced with a 5 litre-mixing machine that follows the specifications of UNE-EN 196-3:2005 (53) with shovel and planetarium rotation velocities of 225 and 100 rpm, respectively. Volumes of 4 dm^3 were produced for mix. The production process was performed as much as possible in accordance with the abovementioned standard. However, due to the inclusion of accelerators and the rapid setting of the material, some adjustments were necessary. The resulting production process is described below.

- First, the water and the superplasticizer were mixed with the cement in the mixer during 30 s;

- Then the aggregates were added during 30 s (Figure 3.1.b);
- All content was mixed during 30 s more;
- After that, the mixer was stopped during 90 s and next the content was mixed again 30 s more;
- Then the accelerator was quickly added;
- All content was mixed during 20 s, and
- Finally, the material was quickly used to cast the samples, which were compacted with a vibrating table for a period of 10 s.

The total production process took approximately 4 min. After casting the specimens they were kept in a curing chamber at a temperature of 23 ± 2 ^{o}C and humidity of 95 ± 1 % waiting the age to be tested. In order to characterize the accelerators in a mortar level 304 samples were produced. 228 of them were casted in 40x40x160 mm moulds, 38 in 100x100x400 mm moulds and the rest were produced to test a spherical volume of 10 cm^3.

Notice that this production process was established considering aspects of workability of the mixes and recommendations of the standard UNE-EN 196-3:2005. These aspects are commented in Chapter 4.

3.2.4. Test methods

In this section, the test methods and the standards followed included in the experimental program are described. The tests systematically performed for cement paste and mortar samples are presented in Table 3.5. Notice that the test of evolution of temperature does not follow any standard.

Table 3.5- Tests performed for cement pastes and mortars

Material	Test	Standard
Cement pastes	Initial/final setting time	UNE-EN 196-3:2005
	Evolution of temperature (up to 24 h)	-
Mortars	Evolution of temperature (up to 24 h)	-
	Penetration needle test (from 0.25 to 2 h)	ASTM C403/C403M-08
	Density and porosity (28 d)	UNE-EN 1015-11:2000
	Flexural strength (0.5, 1, 7, 28 and 60 d)	UNE-EN 196-1:2005
	Compressive strength (0.5, 1, 7, 28 and 60 d)	UNE-EN 196-1:2005

3.2.4.1. Initial/Final setting time

The initial/final setting time of cement pastes was determined using a manual Vicat device and a chronometer (Figure 3.2.a and Figure 3.2.b). The test was performed using a 25 mm diameter and 40 mm high cylinder mould according to the European Standard UNE-EN 196-3:2005 (53). The initial setting time was obtained when the penetration of the needle was 36 ± 1 mm and the final setting time when the needle stopped penetrating the sample. The tests were performed with a temperature of 22 ± 2 ^{o}C and humidity of 55 ± 5 % in a climatic room. One sample was tested per mix, entailing a total of 38 initial/final setting time tests.

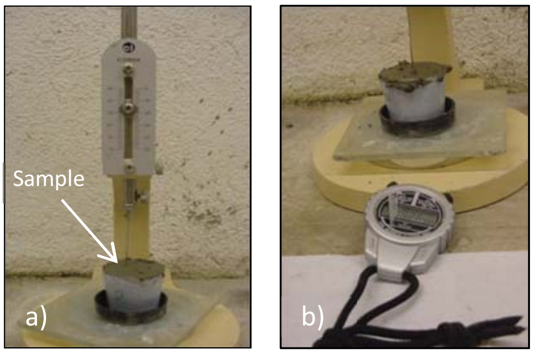


Figure 3.2- Manual Vicat device a) and chronometer b) used to determine the setting time

3.2.4.2. Evolution of temperature

The hydration of cement is an exothermic process that produces temperature variations in the material. To assess such evolution of temperature during the first 24 hours after mixing, k-type thermocouples were introduced in cement pastes and mortars. The thermocouples were connected with a Data logger (Figure 3.3.a) that registered the temperature at intervals of 1 min during the first 24 h. The initial time (or time 0) was the time when the accelerator was incorporated in the mix. One 10 cm^3-sample was tested per mix, entailing 76 tests of evolution of temperature.

In order to reduce heat losses to the environment, the samples were introduced in polyethylene moulds that created a quasi-adiabatic condition (Figure 3.3.b). Furthermore, the tests were performed in a climatic room with a temperature of 20 ± 2 ^{o}C and humidity of 55 ± 5%. This test permitted obtaining the curves that relate the evolution of temperature with time. The integral of this curve yields the estimation of the energy released during the hydration process, which might be correlated with the development of the mechanical properties.

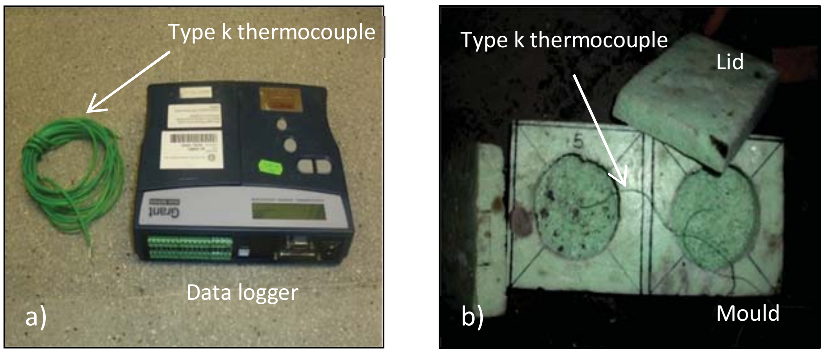


Figure 3.3- Data logger and thermocouples a) and a polyethylene mould b)

3.2.4.3. Penetration needle test

The penetration needle test was performed in accordance with the standard ASTM C403/C403M-08 (54). The test consisted on employing manual force to introduce a 16 mm-diameter needle (Figure 3.4.a) in a sample previously casted in a 100x100x400 mm mould with a total of 40 mm-thickness (Figure 3.4.b). The force was gradually applied on the needle until it penetrated in the mortar a depth of 25 mm. The average force of three measurements is used to indirectly estimate the compressive strength of the mortar with an abacus provided by the

Spanish standard UNE-EN 14488-2:2007 (46). The minimum separation between penetrations was 20 mm. One sample was tested per mix, entailing 38 penetration needle tests.

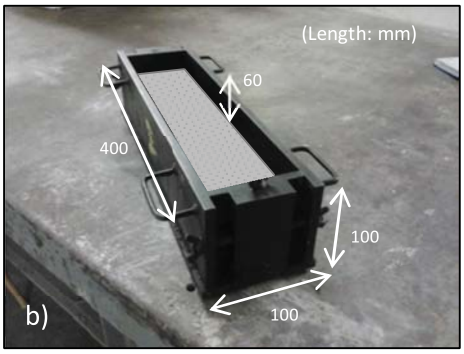


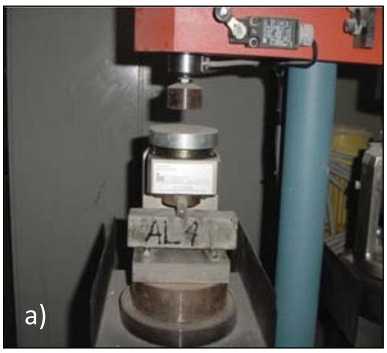
Figure 3.4- Penetration needle device a) and mould used for casting the samples b)

3.2.4.4. Density and porosity

The porosity, which holds a direct relation with the mechanical properties of mortars (25), was determined according to the European standard UNE-EN 1015-11:2000 (55). Initially, 28-days mortars samples (40x40x160 mm) were submerged in water for 48 h, until they were completely saturated. Then, their hydrostatic weight was measured using a hydrostatic balance. Immediately after that, the specimens were dried superficially and their weight in saturated condition was measured. Subsequently, the specimens were introduced in an oven at a temperature of 85 ± 5 °C during 48 h in order to achieve dry condition. Finally, the dry weight of the specimens was measured. The three weight values were used to estimate the density and the porosity of the samples. Three specimens were tested per each mix, entailing a total of 114 tests of porosities done.

3.2.4.5. Flexural and compressive strength

The flexural and the compressive strength of mortars were determined according to the European standard UNE-EN 196-1:2005 (50). Basically, the test consisted on obtaining the flexural strength of three 40x40x160 mm specimens obtaining two parts from each one of them (Figure 3.5.a). Finally, the 6 resting parts were tested to estimate the compressive strength (Figure 3.5.b). Therefore, 114 tests and 228 tests were performed to determine the flexural and the compressive strength, respectively.



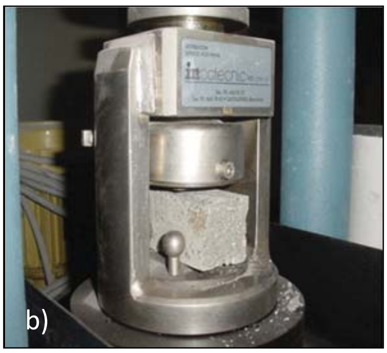


Figure 3.5- Test devices used to measure flexural strength a) and compressive strength b)

3.3. RESULTS AND DISCUSSIONS

The results from the experimental program described in section 3.2 are presented separately for Cement pastes and mortars. Therefore, first the results of the initial/final setting time and the evolution of temperature of cement pastes are shown and analysed. Finally, the results of the evolution of temperature of mortars, the penetration needle test, the density, the porosity and the test of flexural/compressive strength are analysed. These results are focused on the low and medium doses of one accelerator for each family: A-0, AF-1.1, AF-2.1 and AF-3.1. The rest of results, which followed the same tendencies, are included in Appendix B.

3.3.1. Cement pastes

3.3.1.1. Initial / final setting time

The results of the initial (IST) and the final setting time (FST) in minutes obtained for the cement pastes considered in this section are gathered in Table 3.6. These present a high influence between the type of cement and the type of accelerator. In this sense, lower setting times for mixes produced with cement I are achieved with alkali free accelerators, whereas the opposite was observed in the tests with cement II. This is possibly due to the different content of C_3A of the cements and the different fineness, which considerably affect the behaviour of the alkali free accelerators regarding the setting time (37).

Table 3.6- Results of initial / final setting time (min)

Low Dose				
Accelerator	I		II	
	IST	FST	IST	FST
A-0	2.58	8.35	0.97	4.00
AF-1.1	1.05	2.32	2.97	8.18
AF-2.1	0.83	2.47	2.23	7.42
AF-3.1	0.95	2.30	2.22	3.70
Medium Dose				
Accelerator	I		II	
	IST	FST	IST	FST
A-0	1.92	4.97	0.95	3.88
AF-1.1	0.83	1.82	1.85	2.75
AF-2.1	0.68	1.83	1.80	3.95
AF-3.1	0.85	2.23	1.99	3.08

The results are related with the dose of accelerator used since an increase in the dose leads to lower setting time. Such result is reasonable since more amount of accelerator is available to react with the cement in this case. Anyway, the times obtained for mixes with accelerator A-0 and cement II are not sensitive to the increasing of dose of the accelerator since the results are practically alike. Finally, the addition of more quantity of accelerator in all the mixes reduces the average initial times 0.37 min and the average final setting time 1.78 min.

Figure 3.6 compares the values of the initial and final setting time obtained with the interval time, which defines the optimal dose of accelerator. These intervals were defined in section 3.2.1.

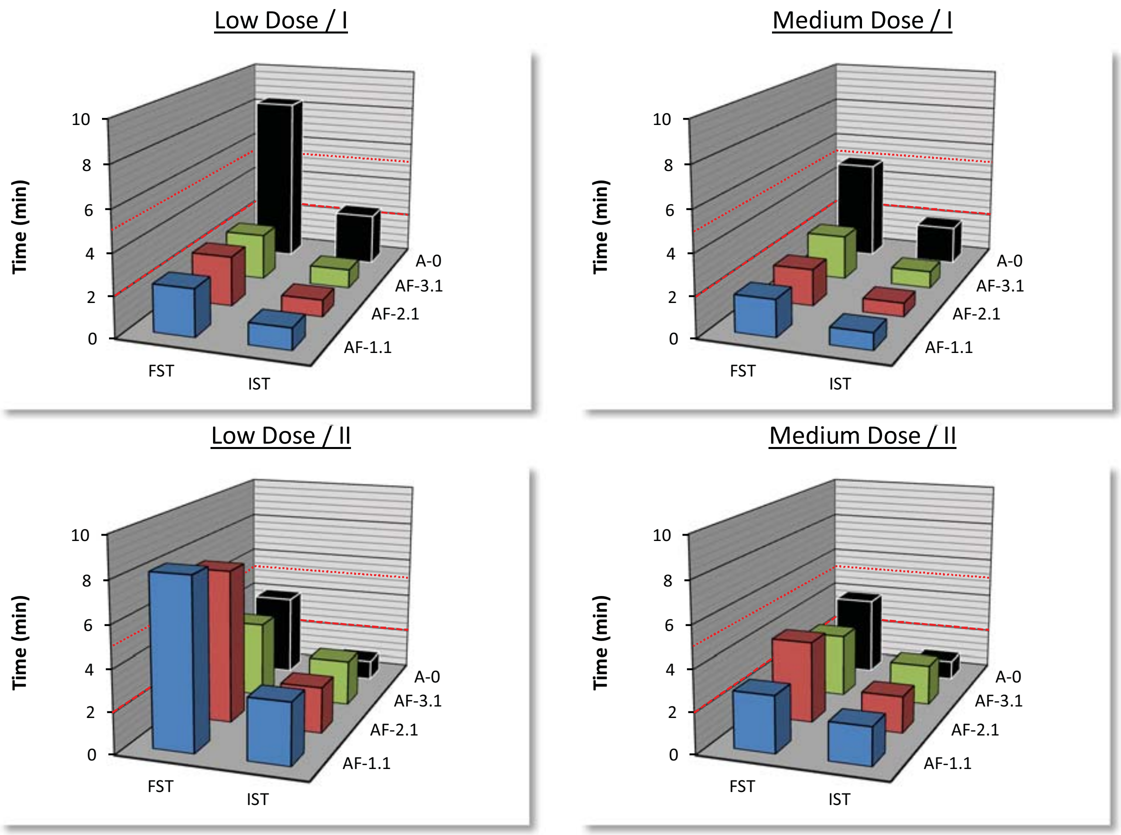


Figure 3.6- Comparison between the optimal dose interval times and experimental results

The mixes with low dose of accelerator produced with cement I and accelerator A-0 present initial and final setting time higher than the established as optimal (2 and 5 min, respectively). Therefore, it is expected that low quality sprayed concrete thin layers would be obtained with this mix. Notice that the same results, with low dose, were obtained with mixes from Family 1, 2 and 3 accelerators produced with cement II. This is possible due to the fineness of the cement since the cement I, which is finer and therefore it has higher specific surface and higher reactivity, presents the same results using less dose of accelerator.

3.3.1.2. Evolution of temperature

The evolution of temperatures (Temperature measured minus ambient temperature) obtained for the cement pastes considered in this section are presented in Figure 3.7. The curves present similar trends showing initially a first peak of temperature due to the hydration of the cement aluminates (C_3A). After that, a decrease on the temperature is observed, which is characteristic of the dormant period. Next, a second peak of temperature due to the hydration of silicates (C_2S and C_3S) is verified in the curves. Finally, the temperature registered tends to stabilize with the ambient temperature.

The only exception is the mix produced with a medium dose of accelerator AF-3.1 and cement II as it does not present a second peak. This is possibly due to an overdose of accelerator, which leads to an increase of hydration of aluminates and a significant reduction of hydration of silicates.

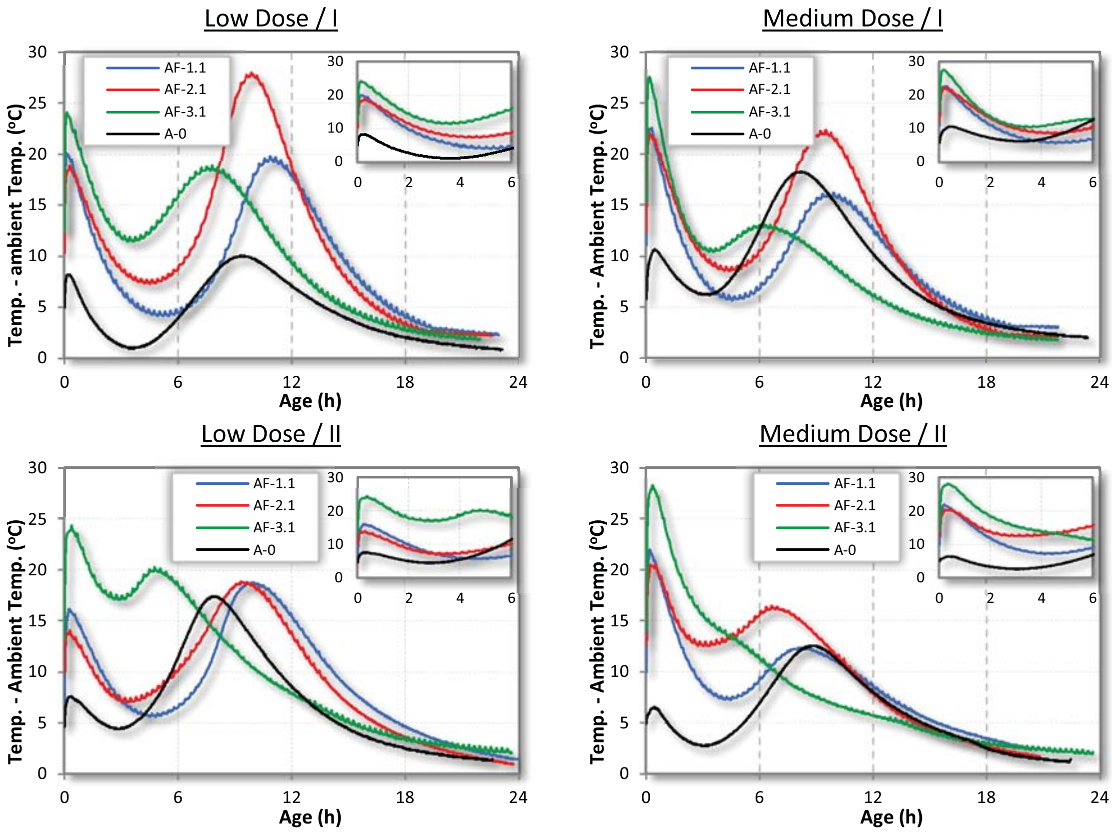


Figure 3.7- Evolution of temperature considering type of cement and dose of accelerator

Regarding the first increase of temperature, mixes with accelerator AF-3.1 present the highest temperature regardless the type of cement and the dose of accelerator. On the contrary, mixes with accelerator A-0 present the lowest temperature, independently of the type of cement and the dose of accelerator. These results may entail that to obtain the same results the accelerators based on aluminates emit lower energy than the alkali free ones. Apart from that, the first increase of temperature is generally higher when increasing the dose of accelerator since more material is available to react with the aluminates of cement. Furthermore, the mixes with cement I present higher temperature than the ones with cement II. This is due to the higher amount of clinker, and therefore aluminates (C_3A), of the cement I has respect the cement II.

Regarding the 2nd peak of temperature in mixes with cement I, the highest values are measured for the accelerator AF-2.1. On the contrary, mixes with cement II present the highest temperature with the accelerator AF-2.1 and AF-3.1 for low and medium dose, respectively. Generally, the results show that the increase of the dose of accelerator leads to peaks of temperature are around 30% lower, regardless of the cement type. Furthermore, the 2nd peak of temperature is higher for mixes with cement I than those with cement II probably due to the bigger clinker content of the former. Notice that the only exception is observed in mixes with A-0, which shows a higher affinity with cement II as observed with the initial/final setting time. It is interesting to remark that mixes with AF-3.1 present the 2nd peak before the ones with other accelerators for all cement types and doses analysed. This indicates that the chemical formulation of AF-3.1 possibly accelerates the hydration of silicates (C_2S and C_3S) in comparison with other accelerators. In this sense, mixes with accelerator AF-1.1 present the 2nd peak later than the other mixes. This is possibly due to the stabilization used (inorganic acid), which retards the hydration of the silicates. An example of this could be the use of phosphoric acid or phosphates as stabilization. They limit the dissolution of some minerals as calcite and alite which could give an explanation for this delay (14; 38).

Table 3.7 resumes characteristic points extracted from the curves. These points are represented in terms of the value and the time of the maximum temperature (T_{max}, t_{Tmax}), of first increase of temperature (T_{1P}), of the second temperature peak (T_{2P}) and of the minimum temperature between peaks ($T_{Min1P-2P}$). Notice that, this last result is related with the dormant period. The table also present the energy released during the hydration (Et_X) related to each characteristic point. This energy was calculated as the integral of the evolution of temperature.

Regarding the first increase of temperature, mixes with accelerator AF-3.1 present the highest temperature regardless the type of cement and the dose of accelerator. On the contrary, mixes with accelerator A-0 present the lowest temperature, independently of the type of cement and the dose of accelerator. These results may entail that to obtain the same results the accelerators based on aluminates emit lower energy than the alkali free ones. Apart from that, the first increase of temperature is generally higher when increasing the dose of accelerator since more material is available to react with the aluminates of cement. Furthermore, the mixes with cement I present higher temperature than the ones with cement II. This is due to the higher amount of clinker, and therefore aluminates (C_3A), of the cement I has respect the cement II.

Regarding the 2nd peak of temperature in mixes with cement I, the highest values are measured for the accelerator AF-2.1. On the contrary, mixes with cement II present the highest temperature with the accelerator AF-2.1 and AF-3.1 for low and medium dose, respectively. Generally, the results show that the increase of the dose of accelerator leads to peaks of temperature are around 30% lower, regardless of the cement type. Furthermore, the 2nd peak of temperature is higher for mixes with cement I than those with cement II probably due to the bigger clinker content of the former. Notice that the only exception is observed in mixes with A-0, which shows a higher affinity with cement II as observed with the initial/final setting time. It is interesting to remark that mixes with AF-3.1 present the 2nd peak before the ones with other accelerators for all cement types and doses analysed. This indicates that the chemical formulation of AF-3.1 possibly accelerates the hydration of silicates (C_2S and C_3S) in comparison with other accelerators. In this sense, mixes with accelerator AF-1.1 present the 2nd peak later than the other mixes. This is possibly due to the stabilization used (inorganic acid), which retards the hydration of the silicates (14; 38).

Table 3.7- Characteristic points of the evolution of temperature

Low Dose								
Reference	**A-0_2_I**	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**A-0_2_II**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
T_{max} (°C)	10.1	20.1	28.0	24.1	17.4	18.8	22.4	27.6
t_T_{max} (h:min)	9:13	0:08	9:50	0:07	7:42	9:52	9:26	0:08
Et_T_{max} (h·°C)	5132.6	331.4	16080.2	349.2	7728.8	12306.9	16083.2	453.6
T_{1P} (°C)	8.2	20.1	18.9	24.1	7.7	16.3	22.1	27.6
t_T_{1P} (h:min)	0:07	0:08	0:16	0:07	0:22	0:14	0:09	0:08
Et_T_{1P} (h·°C)	116.1	331.4	578.9	349.2	322.1	415.7	403.4	453.6
T_{2P} (°C)	10.1	19.8	28.00	18.90	17.40	18.80	22.40	13.20
t_T_{2P} (h:min)	9:14	10:50	9:51	7:47	7:43	9:52	9:26	6:17
Et_T_{2P} (h·°C)	5142.6	12827.5	16108.2	14670.5	7746.1	12325.7	16105.6	10964.0
$T_{min1P-2P}$ (°C)	1.0	4.1	7.30	11.50	4.50	5.70	8.60	10.50
t_$T_{min1P-2P}$ (h:min)	3:23	5:09	4:30	3:18	2:36	4:27	4:07	3:15
Et_$T_{min1P-2P}$ (h·°C)	1588.9	5904.7	6340.6	6613.2	1910.7	5325.1	6940.7	6677.4
Medium Dose								
Reference	**A-0_3_I**	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**A-0_3_II**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
T_{max} (°C)	18.3	22.0	20.5	28.4	12.6	22.6	18.9	24.4
t_T_{max} (h:min)	8:05	0:10	0:12	0:19	8:35	0:18	9:18	0:22
Et_T_{max} (h·°C)	0.0	395.6	463.2	1053.1	6366.4	788.5	12548.0	1051.6
T_{1P} (°C)	10.7	22.0	20.5	28.4	6.6	22.6	14.1	24.4
t_T_{1P} (h:min)	0:25	0:10	0:12	0:19	0:22	0:18	0:17	0:22
Et_T_{1P} (h·°C)	497.0	395.6	463.2	1053.1	282.7	788.5	470.7	1051.6
T_{2P} (°C)	18.3	12.4	16.5	13.0	12.6	16.2	18.9	-
t_T_{2P} (h:min:s)	8:06	8:00	6:36	5:00	8:36	9:35	9:18	-
Et_T_{2P} (h·°C)	10098.4	10873.	11883.8	11127.9	6378.9	12563.6	12566.9	-
$T_{min1P-2P}$ (°C)	6.2	7.3	12.6	12.8	2.8	5.7	7.1	-
t_$T_{min1P-2P}$ (h:min)	3:15	4:09	2:43	4:54	2:43	4:32	3:19	-
Et_$T_{min1P-2P}$ (h·°C)	3170.2	6414.5	5352.6	10960.6	1522.2	6362.2	4033.2	-

Finally, the dormant period is longer in case of low doses of accelerators for both cement types. In this sense, mixes with AF-1.1 present the longest dormant periods as shown in the results (t_$T_{Min1P-2P}$).

3.3.2. Mortars

3.3.2.1. Evolution of temperature

The evolution of temperatures (Temperature measured minus ambient temperature) obtained for the mortars considered in this section are presented in Figure 3.8. The curves present similar trends showing initially a first increase of temperature due to the hydration of the aluminate (C_3A) and the sulphate reaction that entails formation of ettringite. The presence of the accelerator increased the initial aluminium concentration which together with sulfates from gypsum yields ettringite. Notice that this first increase is lower than the one presented in the evolution of temperature of cement pastes. This is possible due to aggregates added, which soften the increase since part of the heat generated by the cement paste is absorbed by them (56). After that, a decrease or a reduction on the temperature increase rate is observed, which is characteristic of the dormant period. Next, a second peak of temperature due to the hydration of silicates (C_2S and C_3S) is verified in some of the curves. Finally, the temperature registered tends to stabilize with the ambient temperature.

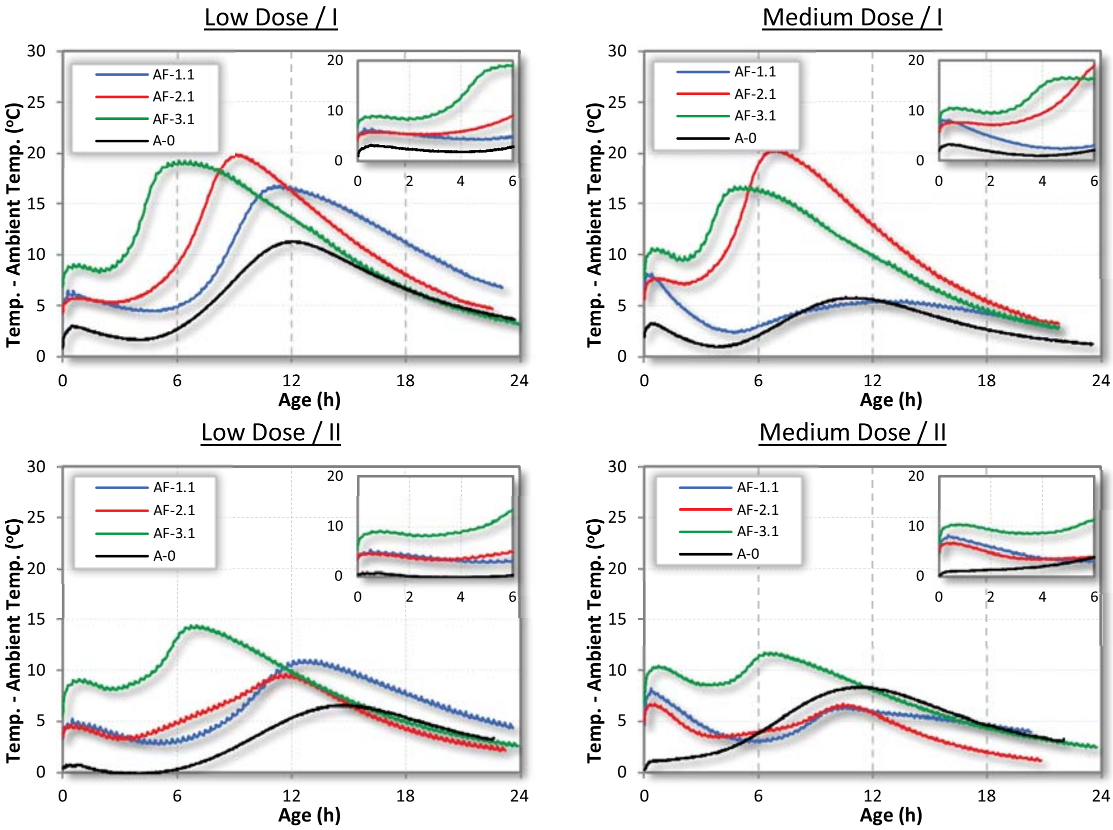


Figure 3.8- Evolution of temperature considering type of cement and dose of accelerator

Table 3.8 summarize the characteristic points extracted from the curves. These points are represented in terms of the value and the time of the maximum temperature (T_{max}, t_{Tmax}), of the first increase of temperature (T_{1P}), of the second temperature peak (T_{2P}) and of the minimum temperature between peaks ($T_{Min1P-2P}$). The table also present the energy released during the hydration (Et_X) related to each characteristic point.

Table 3.8- Evolution of temperature characteristic points

Low Dose								
Reference	**A-0_2_I**	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**A-0_2_II**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
T_{max} (°C)	11.3	16.8	19.9	19.3	6.6	11.1	9.6	14.4
t_T_{max} (h:min)	11:40	11:03	9:05	6:04	14:32	12:40	11:22	6:43
Et_T_{max} (h·°C)	6503.7	10014.4	9963.0	8726.4	3752.4	8037.6	7419.5	7813.5
T_{1P} (°C)	3.1	6.6	5.8	9.1	0.9	5.3	4.7	9.1
t_T_{1P} (h:min)	0:29	0:17	0:36	0:33	1:01	0:30	0:23	0:50
Et_T_{1P} (h·°C)	148.9	196.4	399.6	577.4	70.8	272.6	203.2	845.2
T_{2P} (°C)	11.3	16.8	19.9	19.3	6.6	11.1	9.6	14.4
t_T_{2P} (h:min:s)	11:41	11:03	9:05	6:04	14:32	12:40	11:23	6:43
Et_T_{2P} (h·°C)	6514.9	10031.2	9982.9	8745.7	3758.9	8048.5	7429.1	7827.9
$T_{min1P-2P}$ (°C)	1.7	4.5	5.3	8.3	0.0	2.8	3.2	8.0
t_$T_{min1P-2P}$ (h:min)	3:23	3:59	2:17	1:53	2:34	4:45	2:54	2:32
Et_$T_{min1P-2P}$ (h·°C)	964.6	2572.6	1529.2	1976.1	143.9	2239.2	1414.1	2594.0
Medium Dose								
Reference	**A-0_3_I**	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**A-0_3_II**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
T_{max} (°C)	5.9	8.2	6.7	11.7	8.4	8.2	20.5	16.8
t_T_{max} (h:min)	10:34	0:21	0:18	6:17	11:16	0:06	6:51	5:02
Et_T_{max} (h·°C)	3685.7	313.6	228.4	7184.8	5597.2	93.9	9072.4	7155.4
T_{1P} (°C)	3.3	8.2	6.7	10.4	1.3	8.2	7.7	10.6
t_T_{1P} (h:min)	0:18	0:21	0:18	0:44	1:04	0:06	0:25	0:23
Et_T_{1P} (h·°C)	109.9	313.6	228.4	864.8	136.5	93.9	364.0	458.3
T_{2P} (°C)	5.9	6.4	6.7	11.7	8.4	5.6	20.5	16.8
t_T_{2P} (h:min)	10:34	10:12	10:25	6:18	11:17	11:44	6:52	5:02
Et_T_{2P} (h·°C)	3691.5	5848.0	5958.9	7196.4	5605.5	6238.4	9092.9	7172.1
$T_{min1P-2P}$ (°C)	1.0	3.0	3.4	8.5	1.2	2.4	7.1	9.5
t_$T_{min1P-2P}$ (h:min)	3:30	5:29	3:54	2:57	1:05	4:26	2:07	1:43
Et_$T_{min1P-2P}$ (h·°C)	906.6	3411.7	2316.5	3383.0	137.7	2613.1	1899.5	2099.8

Regarding the first increase of temperature mixes with accelerator AF-3.1 present the highest temperature regardless of the type of cement and the dose of accelerator. On the contrary, mixes with accelerator A-0 present the lowest temperature, independently of the type of cement and the dose of accelerator. Notice that the evolutions of temperature of the cement pastes followed the same tendency. This increase of temperature is generally higher when increasing the dose since more amount of aluminum dissolved from the accelerator is available to react with the sulfate of the gypsum and the C_3A of the cement.. Furthermore, the mixes with cement I present higher temperature than the ones with cement II due to the higher content of C_3A present in the former.

Regarding the 2nd peak of temperature, in case of mixes with cement I the highest values are measured for the accelerator AF-2.1. This result was observed for cement pastes mixes. On the contrary, mixes with cement II present the highest temperature with the accelerator AF-3.1. Generally, the results show that increasing the dose of accelerator these peaks of temperature are around 20% lower, regardless the cement used. Furthermore, the 2nd peak of temperature is higher for mixes with cement I than those with cement II probably due to the bigger clinker content of the former. Notice that the only exception is observed in mixes with

A-0, which shows a higher affinity with cement II. It is interesting to remark that mixes with AF-3.1 present the 2nd peak before the ones with other accelerators for all cement types and doses analysed. This indicates that the chemical formulation of AF-3.1 possibly accelerates the hydration of silicates (C_2S and C_3S) in comparison with other accelerators. All these tendencies were observed in cement pastes.

Finally, the dormant period is longer in case of low doses of accelerators for both cement types. In this sense, mixes with AF-1.1 present the longest dormant periods as shown in the results ($T_{Min1P-2P}$).

3.3.2.2. Penetration needle test

The results of compressive strength and their variance obtained in the penetration needle test are presented in Table 3.9. Regarding the type of cement, the results obtained are similar for the mixes with cement I and the II. This demonstrates the lower importance of the type of cement up to 120 min. Therefore, the type of accelerator is the parameter that most influences the strength measured in the first hours.

This strength is closely related with the dose of accelerator used. In general, an increase in the dose leads to higher strength values. Such result is reasonable since a higher amount of accelerator is available to react with the cement in this case. The higher results are achieved with AF-3.1 regardless the type of cement. These results confirm the tendencies observed in the evolution of temperature regarding the first peak of temperature. Finally, at 150 min it was impossible to obtain values of compressive strength.

Table 3.9- Compressive strength (MPa) obtained in the penetration needle test

Low Dose (MPa)								
Age (min)	**A-0_2_I**	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**A-0_2_II**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
15	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*
30	0.00 *(0.00%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.26 *(1.25%)*	0.20 *(0.02%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.21 *(0.05%)*
40	0.00 *(0.00%)*	0.14 *(0.01%)*	0.00 *(0.01%)*	0.31 *(1.61%)*	0.21 *(1.46%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.26 *(0.10%)*
50	0.00 *(0.00%)*	0.22 *(0.02%)*	0.07 *(0.02%)*	0.35 *(1.97%)*	0.21 *(6.14%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.32 *(0.16%)*
60	0.21 *(4.15%)*	0.22 *(0.03%)*	0.21 *(0.03%)*	0.39 *(2.32%)*	0.22 *(0.02%)*	0.00 *(0.00%)*	0.00 *(0.00%)*	0.39 *(0.21%)*
75	0.25 *(17.41%)*	0.20 *(0.01%)*	0.19 *(0.02%)*	0.63 *(1.01%)*	0.22 *(0.01%)*	0.38 *(0.19%)*	0.21 *(0.01%)*	0.52 *(1.12%)*
90	0.22 *(0.00%)*	0.20 *(0.06%)*	0.21 *(0.02%)*	0.69 *(0.62%)*	0.24 *(9.60%)*	0.33 *(0.04%)*	0.23 *(0.00%)*	0.62 *(1.47%)*
105	0.21 *(5.14%)*	0.23 *(0.10%)*	0.33 *(0.01%)*	0.97 *(0.09%)*	0.22 *(0.00%)*	0.40 *(0.24%)*	0.29 *(1.14%)*	0.77 *(1.16%)*
120	0.22 *(7.02%)*	0.24 *(0.07%)*	0.32 *(0.05%)*	- -	0.30 *(12.85%)*	- -	- -	- -
Medium Dose (MPa)								
Age (min)	**A-0_3_I**	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**A-0_3_II**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
15	0.21 *(5.14%)*	0.21 *(0.01%)*	0.00 *(0.00%)*	0.28 *(1.27%)*	0.00 -	0.26 *(0.05%)*	0.26 *(0.02%)*	0.25 *(0.05%)*
30	0.32 *(10.31%)*	0.38 *(1.19%)*	0.00 *(0.05%)*	0.36 *(2.38%)*	0.26 *(20.76%)*	0.24 *(0.56%)*	0.24 *(0.01%)*	0.33 *(0.77%)*
40	0.37 *(9.26%)*	0.43 *(1.12%)*	0.19 *(0.12%)*	0.43 *(2.08%)*	0.28 *(24.65%)*	0.34 *(0.74%)*	0.35 *(0.79%)*	0.43 *(0.86%)*
50	0.43 *(20.08%)*	0.51 *(1.04%)*	0.33 *(0.20%)*	0.54 *(1.78%)*	0.33 *(27.95%)*	0.46 *(0.93%)*	0.44 *(1.57%)*	0.54 *(0.95%)*
60	0.46 *(23.69%)*	0.64 *(0.96%)*	0.39 *(0.27%)*	0.70 *(1.49%)*	0.34 *(29.05%)*	0.59 *(1.12%)*	0.51 *(2.35%)*	0.68 *(1.03%)*
75	0.40 *(6.44%)*	0.49 *(2.53%)*	0.41 *(0.74%)*	0.93 *(1.97%)*	0.42 *(14.66%)*	0.54 *(0.64%)*	0.65 *(5.40%)*	0.95 *(0.55%)*
90	0.47 *(11.39%)*	0.39 *(0.36%)*	0.50 *(3.33%)*	0.99 *(0.05%)*	0.45 *(21.70%)*	0.74 *(1.91%)*	0.67 *(1.97%)*	- -
105	0.54 *(11.53%)*	0.46 *(0.74%)*	0.69 *(3.31%)*	- -	0.35 *(21.52%)*	0.85 *(0.98%)*	- -	- -
120	0.55 *(11.04%)*	0.52 *(0.00%)*	0.72 *(1.66%)*	- -	0.48 *(29.25%)*	- -	- -	- -

Figure 3.9 illustrates the results obtained comparing the results of the different families of accelerators. The figure presents the development of compressive strength of the mixes during the first 2 h after production.

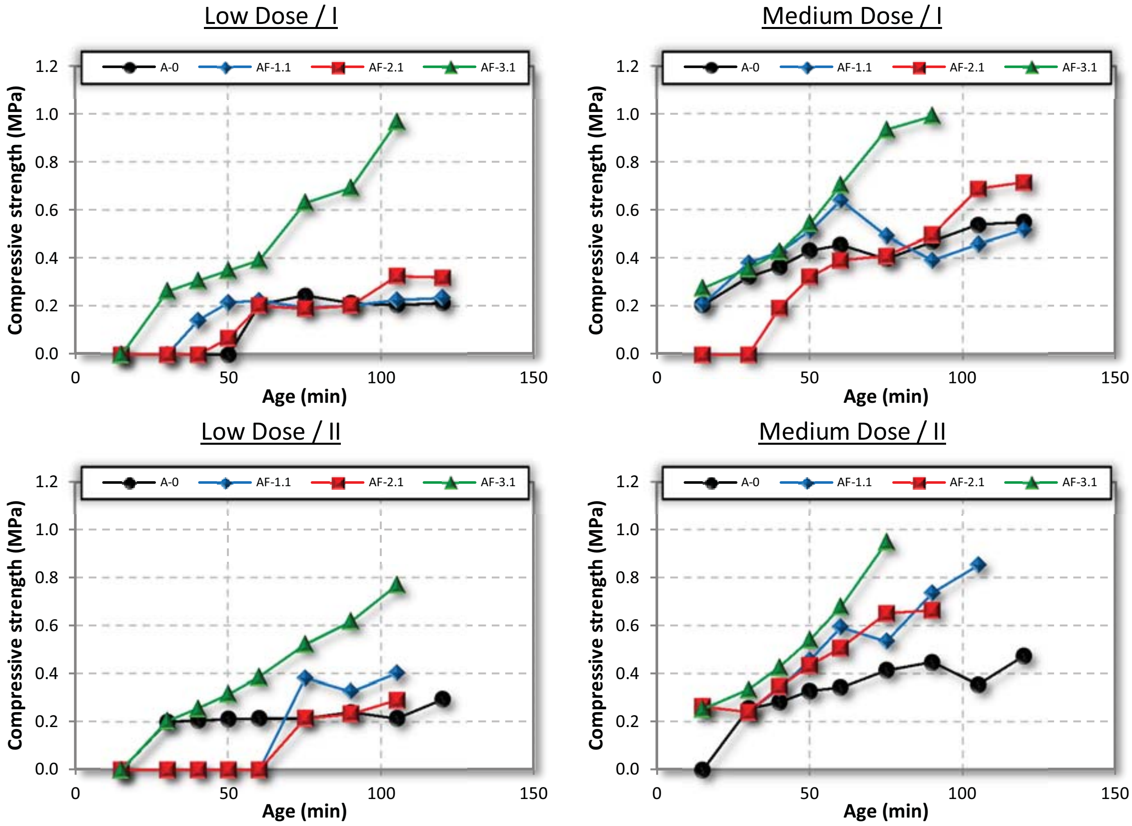


Figure 3.9- Compressive strength results considering type of cement and dose of accelerator

Their slopes of the curves indicate how quick the hardening of the mixes occurs. Mixes produced with accelerator AF-3.1 present higher slopes regardless the type of cement and the dose of accelerator used. Furthermore, regarding the dose of accelerator, the slopes presented are higher when increasing the amount of accelerator. This is possibly due to the higher content of admixture, which entails a higher dissolved aluminum concentration that with the sulfates and C_3A of the cement increases the rate of formation of ettringite. This phase is forming at a very high rate up to 100 minutes of hydration.

3.3.2.3. Density and porosity

Density and porosity tests were performed in the Laboratory of Chemistry and Construction Materials (UPC). The results and their variance are presented in Table 3.10. These show a high influence of the type of cement used since their fineness and density are not the same and these features influence on the package of the samples and therefore, the parameters studied. Furthermore, the results show a high influence of the type of accelerator and its concentration of dried material as it affects the formation of the porous system.

Table 3.10- Density and porosity results

Low Dose				
Sample	**Density (g/cm^3)**		**Porosity (%)**	
A-0_2_I	2.26	*(0.01%)*	13.33	*(0.84%)*
AF-1.1_5_I	2.26	*(0.00%)*	17.06	*(21.71%)*
AF-2.1_5_I	2.24	*(0.01%)*	17.68	*(1.55%)*
AF-3.1_9_I	2.23	*(0.01%)*	18.09	*(0.51%)*
A-0_2_II	2.17	*(0.09%)*	15.26	*(0.41%)*
AF-1.1_5_II	2.17	*(0.03%)*	12.01	*(22.39%)*
AF-2.1_5_II	2.17	*(0.03%)*	16.44	*(0.12%)*
AF-3.1_9_II	2.27	*(1.73%)*	14.46	*(1.21%)*
Medium Dose				
Sample	**Density (g/cm^3)**		**Porosity (%)**	
A-0_3_I	2.26	*(0.00%)*	14.11	*(11.79%)*
AF-1.1_7_I	2.25	*(0.00%)*	18.43	*(0.11%)*
AF-2.1_7_I	2.24	*(0.03%)*	18.74	*(0.56%)*
AF-3.1_11_I	2.23	*(0.00%)*	19.32	*(21.29%)*
A-0_3_II	2.18	*(0.02%)*	16.05	*(0.33%)*
AF-1.1_7_II	2.20	*(0.00%)*	15.29	*(1.77%)*
AF-2.1_7_II	2.20	*(0.00%)*	17.49	*(0.23%)*
AF-3.1_11_II	2.15	*(0.07%)*	17.71	*(0.94%)*

Regarding the porosity, the results present the opposite tendency aforementioned for the density as the higher the dose of accelerator higher is the porosity in case of mixes produced with cement I. This is possibly due to the difficulty of moulding and compacting because of the incorporation of accelerator, which increases with the amount of accelerator. As previously observed, mixes with cement II follow the same tendency.

Apart from that, Figure 3.10 illustrates the results from the tables showing the average of densities and porosities in both cases.

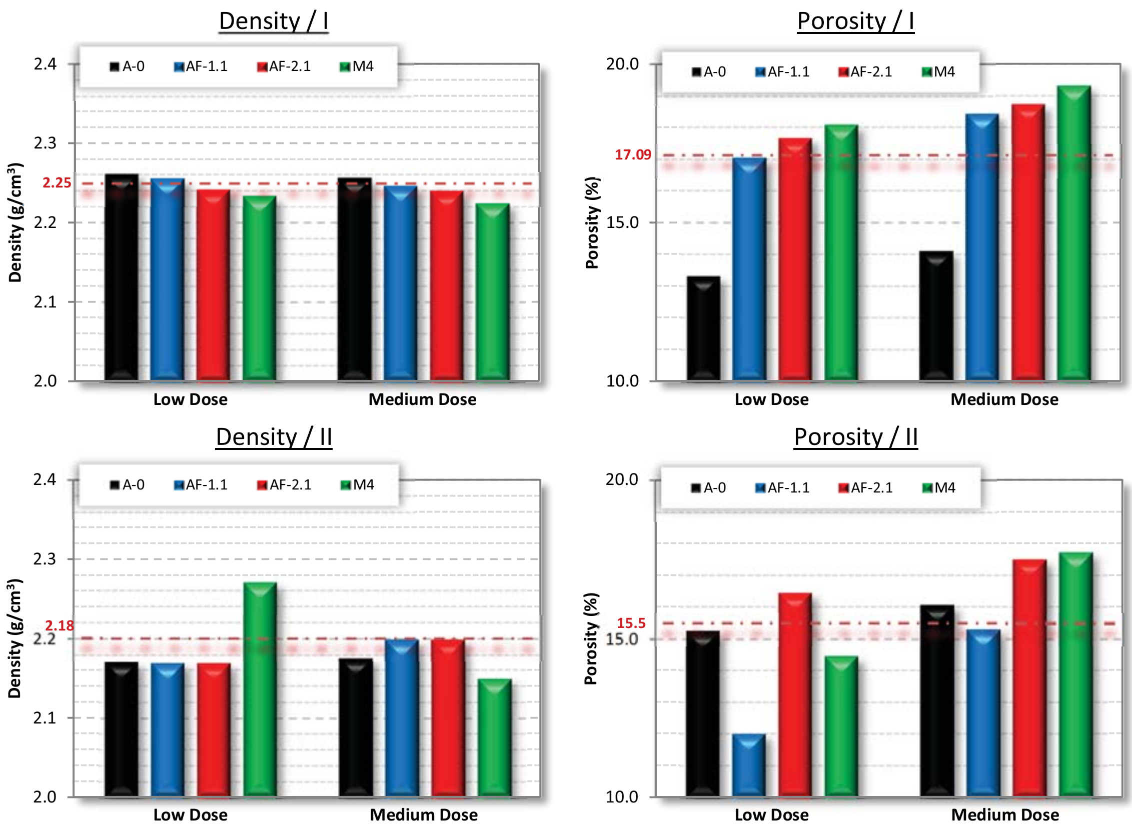


Figure 3.10- Density and porosity results considering type of cement and dose of accelerator

The average of all results of density is 2.25 and 2.19 g/cm^3 for mixes produce with cement I and cement II, respectively. In case of the porosity the average is 17.05 and 15.59%. These values differ from the ones of conventional mortar (density: 2.10 g/cm^3 and porosity: 12.00% (57; 58)). Such differences may be attributed to the new production conditions and the incorporation of accelerators, which reduce the setting time of the mortar and interfere with its compacting. This reduction of the density or increasing of the porosity directly affects the characteristics of the sprayed concrete reducing the mechanical properties.

3.3.2.4. Flexural and compressive strength

The results of flexural strength and their variances obtained are presented in Table 3.11. Regarding the type of cement, the results are similar for mixes produces with cement I and II. In this sense, the type of accelerator is the important parameter that affects the flexural strength.

Table 3.11- Flexural strength results

Low Dose								
Age (d)	**A-0_2_I**	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**A-0_2_II**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
0.5	1.45 *(34.32%)*	1.48 *(16.67%)*	2.21 *(24.67%)*	4.20 *(2.59%)*	1.17 *(6.57%)*	1.68 *(25.58%)*	1.66 *(5.42%)*	2.59 *(12.85%)*
1	3.08 *(3.02%)*	5.14 *(6.08%)*	5.62 *(12.80%)*	4.83 *(10.96%)*	3.69 *(6.88%)*	3.40 *(7.14%)*	3.69 *(8.57%)*	3.51 *(4.62%)*
7	6.60 *(3.43%)*	6.83 *(2.39%)*	7.04 *(10.56%)*	6.64 *(2.15%)*	5.86 *(6.43%)*	6.31 *(5.87%)*	7.20 *(39.38%)*	5.47 *(5.07%)*
28	8.48 *(10.31%)*	8.00 *(7.38%)*	7.83 *(3.68%)*	6.51 *(27.53%)*	6.79 *(4.74%)*	6.64 *(10.62%)*	6.73 *(12.17%)*	6.10 *(3.96%)*
60	8.57 *(10.00%)*	8.06 *(3.94%)*	8.60 *(6.93%)*	8.13 *(5.44%)*	8.62 *(3.00%)*	8.11 *(4.23%)*	6.86 *(1.70%)*	6.28 *(7.58%)*
Medium Dose								
Age (d)	**A-0_3_I**	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**A-0_3_II**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
0.5	1.29 *(25.64%)*	1.54 *(5.13%)*	3.43 *(2.95%)*	3.43 *(16.18%)*	1.89 *(10.95%)*	1.80 *(5.27%)*	1.92 *(3.01%)*	2.18 *(19.10%)*
1	3.25 *(8.72%)*	4.38 *(2.53%)*	5.71 *(6.40%)*	4.88 *(13.51%)*	1.52 *(13.34%)*	3.81 *(6.94%)*	4.15 *(2.33%)*	2.89 *(2.66%)*
7	6.20 *(3.06%)*	6.63 *(4.14%)*	6.67 *(4.50%)*	6.48 *(4.17%)*	6.49 *(4.59%)*	6.60 *(8.85%)*	5.61 *(11.49%)*	5.23 *(7.97%)*
28	8.07 *(1.97%)*	7.83 *(13.54%)*	6.94 *(9.15%)*	5.89 *(13.28%)*	7.11 *(9.16%)*	7.53 *(13.63%)*	6.74 *(13.31%)*	6.76 *(9.73%)*
60	8.48 *(10.00%)*	6.31 *(6.50%)*	7.32 *(13.22%)*	7.17 *(5.49%)*	8.67 *(4.00%)*	6.80 *(10.00%)*	6.92 *(3.88%)*	6.29 *(10.89%)*

The development of the flexural strength is similar for all mixes. Furthermore, the mixes, that present higher compressive strength at early ages, present lower compressive strength at long ages.

On the other hand, the results of compressive strength and their variances obtained are presented in Table 3.12. Regarding the type of cement, the results are similar for mixes produced with cement I and II, even though the mixes produced with cement I present slightly higher results. This is possible due to the strength class of the cement. As observed in flexural strength, the type of accelerator is the important parameter that affects the compressive strength.

Table 3.12- Compressive strength results

Low Dose								
Age (d)	**A-0_2_I**	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**A-0_2_II**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
0.5	3.36 *(42.45%)*	5.21 *(17.56%)*	11.14 *(9.00%)*	16.75 *(8.14%)*	3.36 *(12.22%)*	6.15 *(12.82%)*	5.99 *(12.93%)*	9.90 *(11.83%)*
1	13.02 *(1.14%)*	24.73 *(10.07%)*	28.26 *(4.76%)*	23.81 *(15.88%)*	15.52 *(6.06%)*	15.73 *(3.95%)*	15.32 *(9.00%)*	14.05 *(7.25%)*
7	35.83 *(6.70%)*	51.03 *(5.86%)*	48.19 *(5.88%)*	45.76 *(7.38%)*	37.58 *(21.21%)*	40.06 *(3.95%)*	33.35 *(6.38%)*	32.07 *(4.30%)*
28	51.47 *(3.37%)*	57.57 *(5.68%)*	62.76 *(5.06%)*	40.43 *(28.89%)*	41.11 *(6.73%)*	40.38 *(2.63%)*	40.38 *(7.33%)*	40.98 *(3.07%)*
60	51.41 *(1.99%)*	59.74 *(4.91%)*	62.31 *(7.96%)*	48.05 *(15.37%)*	45.67 *(4.99%)*	53.13 *(6.71%)*	39.31 *(3.80%)*	42.52 *(4.96%)*
Medium Dose								
Age (d)	**A-0_3_I**	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**A-0_3_II**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
0.5	4.52 *(20.17%)*	7.54 *(7.51%)*	15.21 *(2.71%)*	15.70 *(8.41%)*	7.05 *(5.61%)*	5.80 *(11.29%)*	8.42 *(10.49%)*	9.41 *(14.90%)*
1	13.68 *(3.52%)*	18.44 *(20.61%)*	29.52 *(7.20%)*	26.58 *(8.36%)*	15.28 *(5.72%)*	14.86 *(6.91%)*	17.29 *(7.89%)*	13.73 *(4.56%)*
7	32.97 *(13.31%)*	44.05 *(3.58%)*	42.74 *(19.87%)*	42.31 *(14.61%)*	33.66 *(7.81%)*	40.91 *(5.17%)*	36.53 *(6.13%)*	31.74 *(3.14%)*
28	46.61 *(2.83%)*	50.18 *(11.23%)*	52.54 *(8.17%)*	46.07 *(8.20%)*	40.21 *(2.82%)*	50.76 *(3.51%)*	43.17 *(3.22%)*	41.22 *(6.33%)*
60	50.92 *(2.96%)*	42.26 *(12.35%)*	47.14 *(28.03%)*	49.11 *(15.43%)*	45.90 *(3.99%)*	45.53 *(4.69%)*	42.68 *(5.58%)*	43.28 *(3.05%)*

Figure 3.11 illustrates the results presented by the mixes comparing the development of compressive strength over time. The results of mixes produced with A-0 are compared with the ones produced with alkali free accelerators. Regarding former studies (33; 52) the mixes with accelerators based on aluminates usually present higher compressive strength at early ages than the ones with alkali free accelerators. Furthermore, they present a significant reduction of compressive strength at long ages. In this sense, the results obtained, with the accelerators used, were not expected.

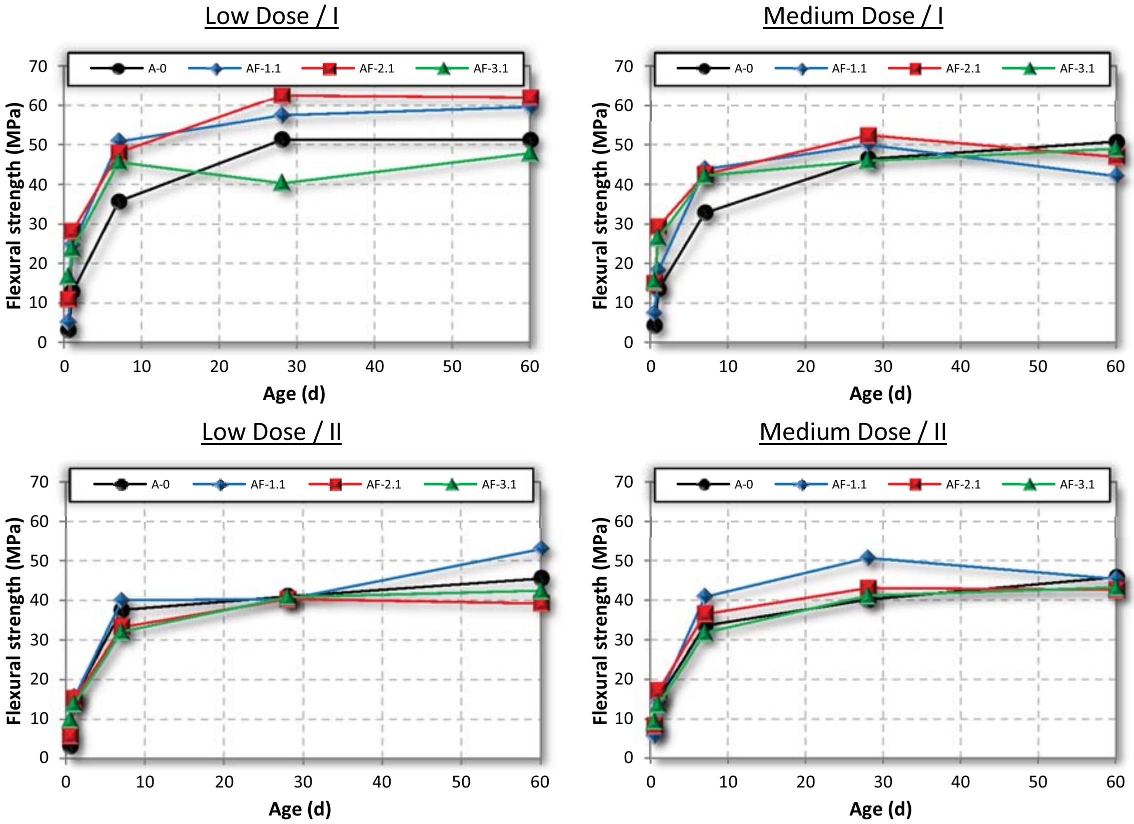


Figure 3.11- Development of compressive strength in time

The development of the compressive strength is similar for all mixes considering the same type of cement. As observed in the flexural strength results, the mixes that present higher compressive strength at early ages present lower strength at long ages. This is possibly due to affection of the incorporation of the accelerator on the micro structure of the mortars. High strength at early ages is obtained with amorphous micro structure, which is more porous and therefore, weaker at long ages entailing less strength.

3.4. CONCLUDING REMARKS

The experimental analysis of cement pastes and mortars described in this chapter presents the steps to follow in order to produce samples in a Laboratory. Also, it allows understanding the mechanical properties of the material at early and long ages. Furthermore, it considers the incorporation of accelerators in the mixes and how they affect in the properties of the materials. Next, the main concluding remarks derived from this chapter are presented.

- The incorporation of accelerator in the mix entails a quick setting. This complicates the production of a homogeneous mortar, affects the plasticity and the compacting of the samples. Basically, there are parts of the samples with more amount of additive that harden quicker than others. This issue probably affects the results (penetration needle test, flexural and compressive strength), entailing higher scatter.

- Considering the optimal intervals presented in section 3.2.1., the optimal dose of accelerator may be established. In this sense, the optimal doses of the accelerator based on aluminates (A-0) are 2 and 3%bcw for cement II and I respectively. On the other hand, the optimal doses for alkali free accelerators are 5 and 7%bcw for cement I and II, respectively.

- The initial and final setting time shows a difference between the alkali free accelerators and the one based on aluminates (A-0) due to the affinity accelerator-cement. Whereas A-0 present optimal results with the cement II, the alkali free accelerators present better results with I.

- The shape of the evolution of temperature depends on the type of cement, the type and the dose of accelerator used in the mixes. The influence of the type of cement is related with the amount of clinker and the specific surface of the Portland cement (particle size). The type of accelerator is important for its more affinity to react either with the aluminates (C_3A; 1st peak) or with the silicates of the cement (2nd peak).

- The evolution of temperature and the energy produced during the hydration of cement (integral of evolution of temperature) are lower in case of mixes produced with A-0. This tendency is observed in results of both cement pastes and mortars. This possibly entails that the alkalis of the accelerator A-0 produces lower heat to obtain same compressive strength regarding the results of the alkali free accelerators.

- The results obtained with the penetration needle test up to 2 h, show a low influence of the type of cement. The strength measured is closely related with the dose of accelerator used. In general, an increase in the dose leads to higher strength values. Such result is reasonable since a higher amount of accelerator is available to react with the cement in this case. Furthermore, the affinity between the type of cement and the accelerator are important.

- In general, the early age strength estimated with the penetration needle test show quicker hardening for mixes with alkali free accelerator regardless of the type of cement. The results of evolution of temperature, which show higher energy for the alkali free accelerators, confirm the compressive strength results. Even though, the doses of A-0 are lower than the doses used for the alkali free accelerators.

- The density and the porosity of mortars tested are 2.22 g/cm^3 and 16.34%, respectively. These values differ to the ones of conventional mortar (density: 2.10 g/cm^3 and porosity: 12.00%). Such differences may be attributed to the variations of the production process due to the incorporation of accelerators, which interfere with its compacting. This difference of density and porosity directly affects the mechanical properties of the sprayed concrete.

- Mixes produced with alkali free and cement I show higher porosity than the one based on aluminates. This is due to the high compatibility between alkali free accelerators and cement I (37) and the fineness of the cement. These increase the setting of the mixes and complicate their compacting. On the contrary, mixes produced with cement II do not present any tendency to compare the families of accelerator because maybe they are equivalent for this type of cement.

- The flexural and compressive strength depend the strength class of the cements. The results of mixes with cement I are around 15% higher than the results obtained with mixes with cement II. Even though, alkali free accelerators and A-0 present similar development of compressive strength considering the doses studied. Finally, regarding the types of cement mixes with medium (optimal) dose of accelerator present similar compressive strength regardless of the type of accelerator.

CHAPTER 4. ADAPTATION OF THE STRENGTH EVALUATION TEST FOR MORTAR WITH ACCELERATOR

4.1. INTRODUCTION

The European standard ‘EN 196-1:2005 Methods of testing cement - Part 1: Determination of strength’ (50) describes the methodology to determine the flexural and the compressive strength of the cements and therefore, conventional mortars are used. This is described under conditions exclusively defined for conventional mortars; ergo it does not regard the incorporation of accelerator. The addition of this type of admixture varies the testing control conditions and therefore entails to readjust the standard in order to consider these new conditions: materials and fabrication process.

This chapter aims to present the adaptation of the standard EN 196-1:2005 to be used to characterize the mechanical properties (flexural and compressive strength) of mortars with accelerator. In this sense, first the standard for conventional mortar is presented. Next the results of flexural and compressive strength of mortar mixes gathered in Chapter 3 are considered in order to perform a statistical analysis. Finally, an adaptation of the standard EN 196-1:2005 is presented to be used for mortar with accelerator.

4.2. STANDARD MORTAR

The European standard EN 196-1:2005 describes the method for the determination of the flexural and the compressive strength of conventional mortar. It is generally used to evaluate the strength class of cement. The method applies to mortars with common cements and no mention is included regarding mortars with a very short setting time such as with accelerators. The next section presents a brief description of the production, the conservation, the testing and the analysis of results specified in the standard.

4.2.1. Composition, fabrication and conservation of mortar

4.2.1.1. Composition and fabrication of mortar

The proportions by mass of the standard mortars are 450 ± 2 g of cement, 1350 ± 5 g of standardized sand and 225 ± 1 g of water. These materials are mechanically mixed in a mixer that follows the requirements established in the standard. The mix sequence should be performed according with the following procedure.

- First the water and the cement are placed in the bowl;
- Then, the materials are mixed at a low speed (140 ± 5 and 62 ± 5 min^{-1} for rotation and planetary movement, respectively) for 30 s. Next, the sand is steadily added during the following 30 s with the mix still on. After that the mixer is switched to the high speed (285 ± 10 and 125 ± 10 min^{-1} for rotation and planetary movement, respectively) and the materials are mixed for 30 s more;
- The mixer is stopped for 90 s. Then the mixing process continues at the high speed for 60 s and
- Finally, the material is used to cast the samples (40x40x160 mm) in 2 sequential layers. For each layer the mould is subjected to 60 jolts of the jolting apparatus described in the standard. In total, three specimens are obtained per mix.

4.2.1.2. Conservation of mortar

Between 20 and 24 h after casting, specimens are demoulded taking care to avoid any damage. If the mortar has not acquired sufficient strength at 24 h to be handled without risk of damage, demoulding may be delayed an extra 24 h.

After this process, the samples are submerged in tap water at 20.0 ± 1.0 °C in containers. Finally, the samples required for testing at any particular age are removed from the water not more than 15 min before the test is performed.

4.2.2. Tests

As mention before, the standard describes the procedures to be followed so as to estimate the flexural and the compressive strength of mortars. Firstly, the flexural strength is obtained using a three-point loading method with one of the types of apparatus described by the standard. The samples are placed in the apparatus with one side facing the supporting rollers and with its longitudinal axis normal to the supports shown in Figure 4.1.a. The load is applied vertically by means of the loading roller to the opposite side of the sample at a rate of 50 ± 10 N/s until failure. The Equation 4.1 is used to estimate the flexural strength, where S_f is the flexural strength (MPa), b is the side of the square section of the sample (mm), F_f is the load applied to the middle of the sample at failure (N) and *l* is the distance between the supports (mm).

$$S_f = \frac{1.5 \cdot F_f \cdot l}{b^3} \quad (4.1)$$

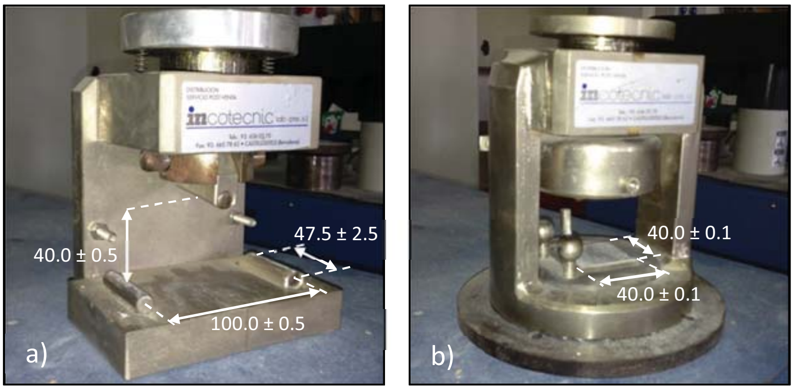


Figure 4.1- Testing machine of flexural strength a) and compressive strength b) (length: mm)

After the flexural test, the halves of the specimens are used to assess the compressive strength. The standard describes the equipment to test each half by loading its side faces (Figure 4.1.b). The specimens are centred to the platens of the machine within ± 0.5 mm accuracy so that the end face of the prism overhangs the platens by about 10 mm. Then, to load is applied at the rate of 2400 ± 200 N/s until failure The compressive strength (S_c) in MPa is obtained after introducing the failure load (F_c) in Equation 4. The value 1600 that appears in the equation indicates the area of the platens in contact with the specimen (40x40 mm) in mm^2.

$$S_c = \frac{F_c}{1600} \quad (4.2)$$

4.2.3. Statistical verification

A statistical analysis is conducted to eliminate outliers from the results and to derive the average compressive strength. This verification is described by the standard and schematized in Figure 4.2. Firstly the compressive strength is calculated as the arithmetic mean of the six individual results obtained from the six determinations made on a set of three specimens. If any of the six individual results varies by more than ± 10% from the mean, such result is discarded and the arithmetic mean of the five remaining ones is calculated. Finally, if one result within the five remaining results varies by more than ± 10% from their mean, the set of results is discarded and the test is considered invalid.

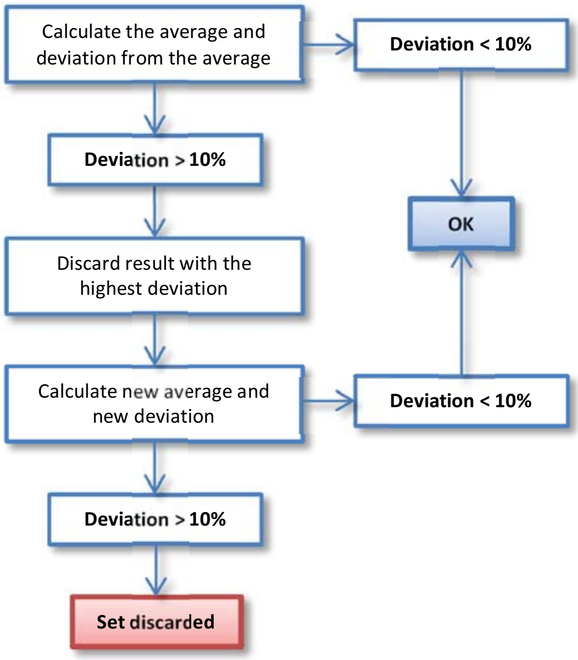


Figure 4.2- Scheme of the statistical verification defined in the standard

4.3. EXPERIMETAL PROGRAM

In order to adapt the European standard EN 196-1:2005 for testing mixes with accelerators, the results of flexural and compressive strength from Chapter 3 are analysed in this section. As the material incorporates accelerator in this case, certain differences must be introduced to the standard procedure described in section 4.2.1.

In the new production process, the mortars are mixed with a 5 litre-mixing machine at a low speed. This process started by mixing the water, the superplasticizer and the cement in the same mixer specified by the standard during 30 s. Then, the aggregates were added gradually during 30 s with the mixer on. The material is mixed for additional 30 s. After that, the mixer was stopped 90 s and all content was mixed during 30 s more. Finally, the whole content of accelerator was rapidly added and then the material was mixed for 20 s.

Notice that the accelerator is added at the end of the production as it happens while spraying concrete. With that, the workability of the mix is not affected during the homogenization of the materials. Furthermore, 20 s were considered to mix the accelerator in the mix. This time was established considering workability and homogenization of the material.

Throughout the mixing process, only low speed is applied (shovel and planetarium rotation velocities of 140 ± 5 and 62 ± 5 min^{-1}, respectively). This was established due to a chemical phenomenon that occurs during the hydration of the cement. The addition of accelerator entails the quick hydration of the aluminates, which causes the formation of ettringite. These ettringite grains play a fundamental role in the early development of mechanical properties of the material. Since these formations are not strong and could be easily broken under big mixing energies, only the low speed was used to produce the samples.

4.3.1. Results and analysis

In total, 588 results of flexural strength and 1176 of compressive strength were obtained during the experimental program. In this section, the results obtained with the mixes with accelerator AF-1.1 are presented as an example. The rest of the results are gathered in Chapter 3 and Appendix B, even though only the averages of the results are presented.

Table 4.1 and Table 4.2 present the results of flexural and compressive strength obtained for the samples fabricated with cement CEM I 52.5 R (I) and CEM II/A-L 42.5 R (II), respectively. The results consider the dose of accelerator and the age of the tests. Both tables include the deviation from the average compressive strength (AvDev) of each set of specimens.

Several mixes show deviation from the average higher than 10%. If the same admissible deviation established in the standard UNE-EN 196-3:2005 was used, most of the results obtained would be eliminated. This would entail the rejection of the majority of the tests performed. This is due to the introduction of the accelerator that complicated the compacting of the samples. And furthermore, to the new production process established, which did not allow a complete homogenous mix between the mortar and the accelerator. Hence, the results presented were expected.

Figure 4.3 shows the deviation from the average obtained for the different variables of the study: type of accelerator, dose of accelerator, type of cement and age of the samples. The values are represented in box plots through their four-number summaries: lower quartile (Q_1), median (Q_2), upper quartile (Q_3), and largest observation (Max). Furthermore, a red line represents the admissible deviation from the average considered by the standard (10%). In all cases the box plots show that the upper whisker is higher than the red line. Therefore, a 25% of the values obtained are higher than the admissible deviation, regardless of the variable considered.

The results show that higher doses of accelerators entail higher deviations. This is possibly caused by difficulties to homogenize the accelerators, to cast and to compact the specimens of mixes with higher doses due to their faster setting. Furthermore, the type of cement affects the results of deviation obtained. Mixes with cement I present higher deviations than the ones with cement II. This is probably due to the higher content of clinker of the cement I. This leads to faster setting making the casting and compaction process more difficult. The influence of the age of testing on de deviation is not clear.

Table 4.1- Flexural and compressive strength obtained for mixes with AF-1.1 and cement I

Dose	Age	Strength (MPa)		AvDev. (%)	Dose	Age	Strength (MPa)		AvDev. (%)	Dose	Age	Strength (MPa)		AvDev. (%)
		Flexural	Compressive				Flexural	Compressive				Flexural	Compressive	
5%	0.5d	1.20	4.28	17.88	7%	0.5d	1.45	6.84	9.28	9%	0.5d	1.84	7.52	2.04
			4.17	20.04				6.83	9.44				8.14	6.03
		1.67	6.33	21.32			1.59	7.69	1.91			1.55	7.65	0.33
			6.20	18.92				7.79	3.23				7.99	4.07
		1.56	5.06	2.90			1.59	8.02	6.30			1.72	7.74	0.90
			5.24	0.58				8.09	7.29				7.01	8.63
	1d	5.44	26.00	5.14		1d	4.51	21.76	18.01		1d	3.98	22.64	24.51
			21.38	13.53				13.00	29.50				17.29	4.92
		4.82	22.37	9.54			4.33	22.03	19.47			4.22	22.08	21.42
			27.24	10.17				15.66	15.07				16.06	11.65
		5.17	27.18	9.92			4.31	21.34	15.74			3.55	18.91	3.99
			24.19	2.16				16.84	8.66				12.12	33.34
	7d	6.73	53.99	5.79		7d	6.64	41.29	6.26		7d	4.10	27.95	0.66
			48.59	4.79				45.67	3.67				23.43	16.74
		6.75	46.68	8.54			6.90	45.03	2.21			4.42	29.46	4.72
			53.98	5.77				45.00	2.15				23.27	17.29
		7.02	52.46	2.80			6.35	43.84	0.49			5.14	35.04	24.54
			50.50	1.04				43.49	1.28				29.66	5.43
	28d	8.49	57.47	0.18		28d	6.61	44.02	12.27		28d	3.98	24.94	8.58
			54.51	5.32				48.76	2.82				27.14	0.52
		7.35	57.53	0.08			8.30	44.97	10.38			3.94	26.46	3.01
			55.08	4.34				58.85	17.29				32.19	18.02
		8.16	63.71	10.66			8.56	50.21	0.06			3.71	22.09	19.01
			57.14	0.74				54.25	8.12				30.85	13.09
	60d	8.29	59.52	0.37		60d	6.77	41.92	0.80		60d	5.34	24.71	25.58
			60.10	0.60				48.25	14.18				39.34	18.46
		8.18	63.75	6.71			5.98	44.41	5.09			5.36	11.94	64.03
			62.06	3.89				35.89	15.07				52.45	57.95
		7.70	56.95	4.67			6.18	36.34	13.99			6.64	18.71	43.67
			56.06	6.16				46.74	10.60				52.09	56.86

Table 4.2- Flexural and compressive strength obtained for mixes with AF-1.1 and cement II

Dose	Age	Strength (MPa)		AvDev. (%)	Dose	Age	Strength (MPa)		AvDev. (%)	Dose	Age	Strength (MPa)		AvDev. (%)
		Flexural	Compressive				Flexural	Compressive				Flexural	Compressive	
5%	0.5d	2.10	6.82	10.86	7%	0.5d	1.71	5.14	11.31	9%	0.5d	1.58	4.97	4.86
			7.33	19.19				5.69	1.83				5.01	5.78
		1.68	5.31	13.63			1.78	5.74	0.97			1.47	4.46	5.83
			5.86	4.69				6.75	16.38				5.43	14.62
		1.24	5.46	11.30			1.90	5.11	11.96			1.42	4.24	10.44
			6.13	0.42				6.36	9.70				4.31	8.99
	1d	3.12	15.59	0.93		1d	3.71	14.73	0.88		1d	2.49	10.89	23.14
			14.83	5.78				13.77	7.35				10.83	22.43
		3.50	16.38	4.11			3.61	13.98	5.96			2.45	7.98	9.73
			15.41	2.05				14.67	1.30				9.86	11.55
		3.58	16.48	4.75			4.11	15.47	4.09			2.20	8.71	1.53
			15.72	0.10				16.56	11.40				4.79	45.85
	7d	6.68	43.05	7.47		7d	5.97	39.93	2.41		7d	4.95	29.78	0.06
			38.89	2.90				39.42	3.65				34.84	17.10
		5.94	38.82	3.09			6.70	43.07	5.27			5.53	28.34	4.75
			39.60	1.14				40.94	0.06				27.72	6.85
		6.31	40.47	1.03			7.13	43.75	6.94			3.86	30.27	1.72
			39.51	1.36				38.37	6.22				27.59	7.29
	28d	5.91	41.79	3.51		28d	6.73	49.28	2.93		28d	6.30	41.33	4.06
			39.88	1.24				48.34	4.78				41.98	5.71
		6.70	39.04	3.32			7.17	52.96	4.32			5.68	41.59	4.72
			39.80	1.43				50.21	1.09				37.83	4.74
		7.32	41.49	2.77			8.69	51.73	1.89			6.82	34.36	13.49
			40.26	0.28				52.08	2.58				41.20	3.74
	60d	8.46	51.92	2.27		60d	6.46	43.59	4.26		60d	6.37	43.88	9.23
			54.32	2.25				43.08	5.38				41.24	2.65
		7.77	59.13	11.29			6.35	46.82	2.84			6.17	39.21	2.41
			50.38	5.18				48.26	6.00				40.79	1.54
		8.10	49.08	7.62			7.58	44.32	2.65			6.01	30.25	24.70
			53.94	1.53				47.09	3.45				45.68	13.69

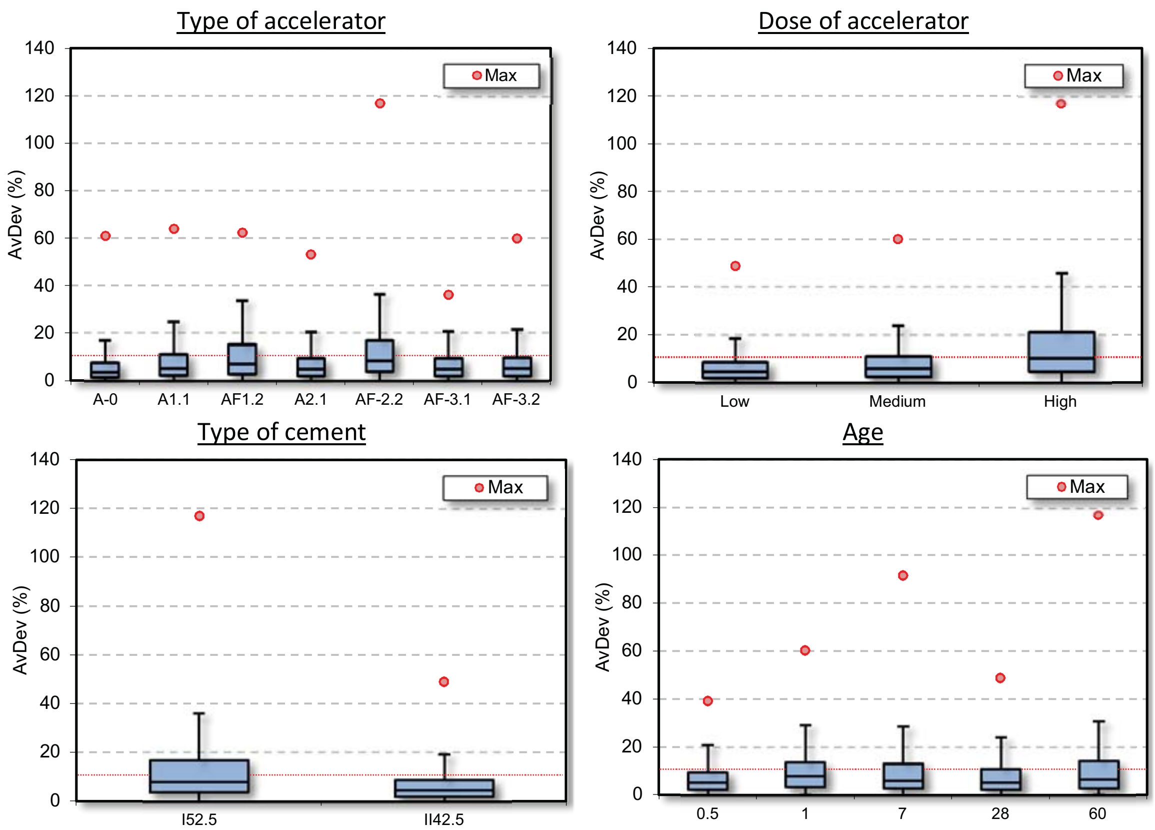


Figure 4.3- Box plot of the deviations over the average

4.4. STATISTICAL VERIFICATION FOR MIXES WITH ACELERATOR

The analysis of the results showed that the incorporation of the accelerators involved working with a material that had different properties than the conventional mortar. Hence, an adaptation of the standard in terms of the statistical verification of the results is needed. This adaptation requires the assessment of new admissible deviation from the average considering the new production process established in section 4.3.1 and the higher scatter typical of the material.

A statistical analysis was performed with the 1176 values of deviation from the average calculated experimentally to obtain a new admissible deviation. This new value was estimated considering that the probability of having the rest of standard deviations were inside the limit established by the standard was 83.33%. In other words, that is the probability of obtaining 5 over 6 results of compressive strength with a lower standard deviation than the admissible one.

In order to achieve that, the software IBM SPSS Statistics, which is a software package used for statistical analysis, was used for that propose. Firstly, all values of deviation were introduced in the software to obtain a histogram. This, presented in Figure 4.4.a, represents the distribution of the data. As a result the probability distribution of the deviations was estimated. The probably distribution chose was the Gamma distribution (Figure 4.4.b) regarding the analysis done plotting the P-P and the Q-Q curves. These are graphical methods for comparing two probability distributions by plotting two cumulative distribution functions and their quartiles, respectively.

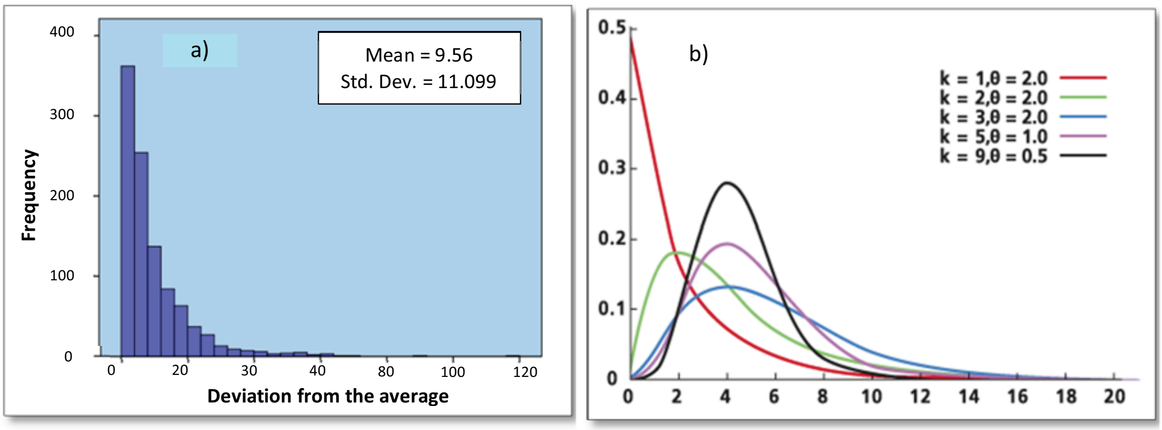


Figure 4.4- Histogram of the values of deviations from the average a) and gamma distribution b)

The results obtained with the P-P and the Q-Q Plot are presented in Figure 4.5. They present a good fit of the values of deviation from the average calculated experimentally and the probability distribution Gamma. This is observed since all values in the graphs of the P-P and the Q-Q curves followed the 45° line x = y. Then the Gamma distribution is a good tool to obtain a new admissible deviation from the average.

Then, the values of deviation from the average (*X*) followed a Gamma distribution. This depends on two parameters: shape (*k*) and range (θ). Equation 4.3 presents the probability density function, which depends on $\Gamma(k)$ (Equation 4.4).

$$f(x;k,\theta) = \frac{1}{\theta^k} \cdot \frac{1}{\Gamma(k)} \cdot x^{k-1} \cdot e^{-\frac{x}{\theta}} \quad \text{for } x > 0 \text{ and } k,\theta > 0 \qquad (4.3)$$

$$\Gamma(k) = (k-1)! \qquad (4.4)$$

$$F(x;k,\theta) = \int_0^x f(u;k,\theta) \cdot du = \frac{\gamma\left(k,\frac{x}{\theta}\right)}{\Gamma(k)} \qquad (4.5)$$

$$\gamma\left(k,\frac{x}{\theta}\right) = \int_0^x t^{k-1} \cdot e^{-t} \cdot d\left(\frac{x}{\theta}\right) \qquad (4.6)$$

Using its cumulative distribution function (Equation 4.5), which depends on the lower incomplete function (Equation 4.6), new admissible deviations were calculated. These considered the values of deviation from the average regarding the variables of the study: type of accelerator, dose of accelerator, type of cement and age of samples. Furthermore, the admissible deviation estimated with the total of the values was calculated. These values are gathered in Table 4.3. The table also presents the values of shapes and ranges that were used to obtain the results.

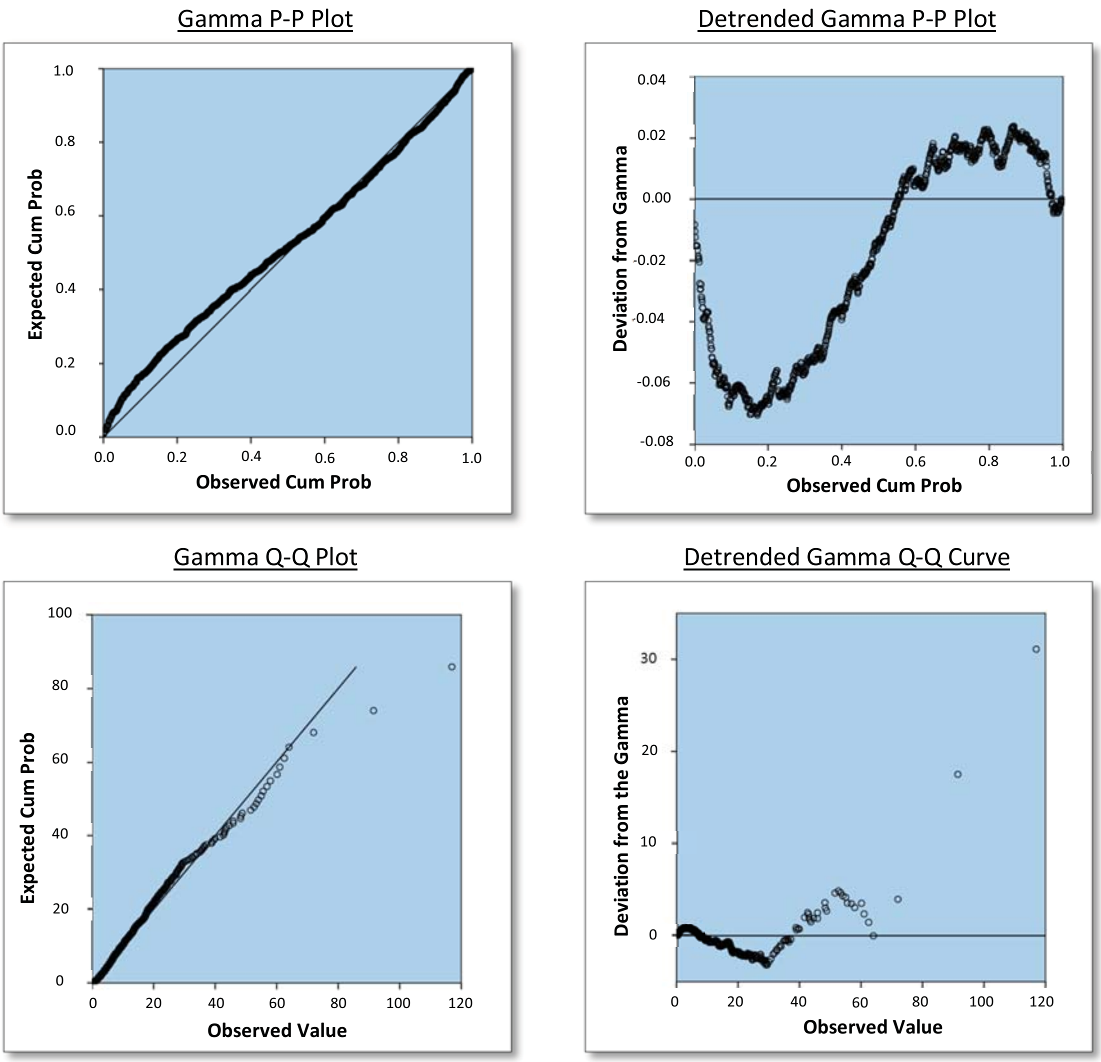


Figure 4.5- Results of the P-P and Q-Q plots and their deviation from Gamma

The new admissible deviations calculated are higher than 10% in all cases. They take a value between 11.89 and 27.65%. Regarding the type of accelerator mixes with accelerator AF-2.2 present the highest deviation equal to 24.06%, whereas mixes with AF-2.1 present the lowest equal to 12.67%. This variation is possibly due to the chemical components in the accelerators, which react differently in the hydration of the cement. These variances entail different behaviour of the samples being compacted, and therefore, unlike deviation of the results. Furthermore, this variation of the deviation from the average is probably due to the non-homogenization of the mixes since the complete mixing of the accelerator in the mortar is difficult to assure. Regarding the dose of accelerator used in the samples, the results show higher deviation when the amount of accelerator increases. The addition of accelerator complicates the compacting of the samples and therefore, the deviations are increased.

Regarding the type of the cement, the mixes with cement I present higher deviation from the average than the mixes with II. This is possibly due to the higher content of C_3A of the cement I, which reacts rapidly entailing a quicker hardening of the mixes. Furthermore, the fineness of the cement also affects as cement I is finer than cement II and therefore it reacts quicker. This complicates the compacting and leads to higher deviations. The results regarding the age of the samples present a clear tendency since the deviation is higher when the samples are older. This is possibly due to the microstructure of the mixes. Even though, the lack of a chemical analysis does not allow analysing these results.

Table 4.3- New admissible deviations considering variables studied

Variable		Shape (*k*)	Range (θ)	Admissible AvDev (%)
Accelerator	A-0	0.476	0.064	14.25
	AF-1.1	0.733	0.084	16.22
	AF-1.2	1.045	0.097	19.18
	AF-2.1	0.973	0.138	12.67
	AF-2.2	0.738	0.057	24.06
	AF-3.1	1.031	0.137	13.43
	AF-3.2	0.722	0.085	15.82
Dose	Low	0.977	0.144	12.19
	Medium	1.040	0.129	14.37
	High	0.933	0.061	27.65
Cement	I	0.949	0.079	21.67
	II	1.003	0.151	11.89
Age (d)	0.5	1.164	0.166	12.30
	1	1.231	0.124	17.28
	7	0.740	0.076	18.08
	28	0.853	0.097	16.07
	60	0.582	0.050	22.08
Total		0.741	0.078	17.65

Finally, considering all the results of deviation from the average obtained in the experimental program, the shape and the range obtained are 0.741 and 0.078, respectively. Therefore, these values entail a new value of admissible deviation from the average equal to 17.65%. In this sense, regarding the results in Table 4.3 a new admissible deviation equal to 20% is considered to adapt the standard to mortar with accelerators. This entails a reduction of the invalid tests equal to 22% (from 31 to 5). Notice that 100% of the invalid tests considering the new admissible deviation are due to the mixes with high dose of accelerator, which are more prone to higher scatter.

4.5. CONLUDING REMARKS

The following concluding remarks are derived from the analysis presented in this chapter.

- The addition of accelerator in the mixes changes the characteristics of the material. Therefore, the standard for the conventional mortar cannot be used in this case. This entails the adaptations of two main points of the standard: the production process and the statistical verification of the results.
- The new production process varies due to the addition of the accelerator and the fast chemical reactions which entails in the mix. In order to emulate the spraying process the accelerator is added at once at the end of the process and mixed during 20 s. This time was established to assure the homogeneity of the

mix of the accelerator. Furthermore, in order to avoid breaking chemical chains derivate of the addition of the additive all process is done with the mixer in low speed.

- An adaptation of the statistical verification of the results is proposed. For that, a new admissible deviation from the average of the results is estimated to account for the higher variability of the mix with accelerator. A value of 20% is suggested after studying all the results from the present study. The new value of admissible deviation may be used for mixes produced with alkali free and non-alkali free accelerators, based on the results obtained.

- It is important to remark that the new admissible deviation from the average is valid for the production process described in this study. New values should be estimated if the production process was modified.

CHAPTER 5. EXPERIMENTAL ANALYSIS OF SPRAYED CONCRETE

5.1. INTRODUCTION

In order to use sprayed concrete as a structural material in construction, the characterization of its mechanical properties must be done. In this sense, different scales were considered: cement pastes, mortars and sprayed concretes. In Chapter 3 the experimental analysis of cement pastes and mortars was presented. These low scales presented tendencies which may be compared with the ones obtained with the sprayed concrete. Furthermore, the analysis between the results assessed with mixes with alkali free accelerators and the ones based on aluminates entailed to decide the only used of the formers in this study since the environmental reasons and the results obtained make this statement evident.

Then, in this chapter the experimental analysis of sprayed concrete with alkali free accelerators is presented. This experimental analysis allows understanding the behaviour of the sprayed concrete changing different parameters: type of accelerator, dose of accelerator and type of cement. In this sense, the methodology followed in the experimental program and the analysis of the results obtained is presented.

5.2. METHODOLOGY

In this second stage, the production and the characterization of the wet-mix sprayed concrete with alkali free accelerators was performed in the Laboratory of Technology of Structures Luis Agulló (UPC). A concrete mix supplied by a ready mix plant was used since the Laboratory did not have the equipment to produce the amount of material needed for the test. After receiving the concrete, the spraying process was conducted with the accelerator provided by IQE. Finally, the tests were performed with the specimens extracted from test panels.

5.2.1. Materials

Even though the concrete was supplied by a ready mix plan, the materials used were selected in order to reproduce a typical compositions found in sprayed concrete tunnels. In this sense, the supplier also produced the concrete for a new underground line in Barcelona. The mixes consisted of cement, water, aggregates, superplasticizer and accelerators.

5.2.1.1. Cement

Two types of cements were used: CEM I 52.5 R (I) and CEM II/A-L 42.5 R (II). Both of them were supplied by the Spanish manufacturer Cementos Molins S.A. Notice that these cements are the same as the ones previously used to characterize the accelerators during the experimental program of cement pastes and mortars described in Chapter 3.

5.2.1.2. Water, Aggregates and Superplasticizer

Potable water following all the requirements defined by the European standard UNE-EN 1008:2007 (21) was used in the mix. Limestone course and fine aggregates complying with the European standard UNE-EN 12620:2003 (59) were used. These aggregates were a 0-2 mm fine sand, a 0-4 mm coarse sand and a 4-12 mm gravel. These fractions were selected to assure a good workability of the mixes as well as to avoid stroke problems during pumping, to reduce the rebound and to generate an optimal packing of the concrete.

The superplasticizer Viscocrete 5940 supplied by SIKA S.A., with an approximate density at 20 ^{o}C of 1.04 g/cm^3, pH equal to 5.0 and a 37.0% of dry residue, was used to improve the workability of the mixes and to facilitate the spraying process (51). Superplasticizers are needed to provide fluidity and workability to concrete and to reduce the incidence of stroke problems in the hoses during the wet-mix spraying process (51). Furthermore, its secondary function as setting retardant contributes to avoid the setting of concrete during its transportation from the plant to the construction site.

5.2.1.3. Accelerators

As shown in Table 5.1, the Families 1, 2 and 3 of accelerators already described in Chapter 3 were used in the study with sprayed concrete. Each family comprise two new formulations of alkali free accelerators chemically based on hydroxysulphate of aluminium ($Al(SO_4)_x(OH)_{3-2x}$).

Table 5.1- Characteristics of the accelerators

Family	Accelerator	Dry matter (%)	Molar ratio $[SO_4^{2-}][OH^-]$	Molar ratio $[Al_3^+][OH^-]$	Stabilizer	pH 20 °C
1	AF-1.1	38	0.6	0.8	Inorganic acid	3.3
	AF-1.2	48	0.8	1.0	Polycarboxylic acid	3.1
2	AF-2.1	39	3.4	2.6	Inorganic silicate	2.5
	AF-2.2	42	2.8	2.2	Inorganic silicate	2.6
3	AF-3.1	30	3.0	2.5	Polycarboxylic acid	2.7
	AF-3.2	30	4.5	4.0	Polycarboxylic acid	2.7

Three different doses by cement weight (%bcw) were studied for Family 1 and Family 2. In the case of Family 3 only two doses were characterized given the recommendations of the supplier. The doses used (Table 3.2) were established in Chapter 3 according with the results of the initial/final setting time and the optimal time intervals defined by former studies (52) and are presented in Table 5.2.

Table 5.2- Doses considered (%bcw)

Family	Low Dose	Medium Dose	High Dose
1	5	7	9
2	5	7	9
3	9	11	-

5.2.2. Concrete mix

The reference mix used in this study is detailed in Table 5.3. Notice that the amount of cement is between 350 and 450 kg/m^3, which is a usual range defined for typical wet-mix sprayed concrete according with (7; 9; 60). The water/cement ratio adopted (0.45) and the amount of superplasticizer (1% bcw) used also fall within typical ranges for sprayed concrete. The water present in the superplasticizer and the aggregates were taken into account to correct the amount of water added to mix. As usual in underground construction, the water from the accelerators was not considered in such correction.

Table 5.3- Reference mix of sprayed concrete

Materials	Content (kg/m^3)
Fine sand 0-2 mm	380
Coarse sand 0-4 mm	900
Gravel 4-12 mm	380
Cement	425
Water	190
Superplasticizer	4.25

The accelerators and the doses studied were applied to the reference mix. The resulting mixes obtained after introducing the accelerators are summarized in Table 5.4. The nomenclature defined for the mixes is formed by the name and the dose of the accelerator followed by the simplified indication of the cement type (I for CEM I R and II for CEM II/A-L 42.5 R). All terms are separated by the symbol '_'.

Table 5.4- Sprayed concrete mixes

Family	Type of accelerator	Dose (%bcw)	Type of cement	Mix reference
1	AF-1.1	5	CEM I 52.5 R	AF-1.1_5_I
		7		AF-1.1_7_I
		9		AF-1.1_9_I
		5	CEM II/A-L 42.5 R	AF-1.1_5_II
		7		AF-1.1_7_II
		9		AF-1.1_9_II
	AF-1.2	5	CEM I 52.5 R	AF-1.2_5_I
		7		AF-1.2_7_I
		9		AF-1.2_9_I
		5	CEM II/A-L 42.5 R	AF-1.2_5_II
		7		AF-1.2_7_II
		9		AF-1.2_9_II
2	AF-2.1	5	CEM I 52.5 R	AF-2.1_5_I
		7		AF-2.1_7_I
		9		AF-2.1_9_I
		5	CEM II/A-L 42.5 R	AF-2.1_5_II
		7		AF-2.1_7_II
		9		AF-2.1_9_II
	AF-2.2	5	CEM I 52.5 R	AF-2.2_5_I
		7		AF-2.2_7_I
		9		AF-2.2_9_I
		5	CEM II/A-L 42.5 R	AF-2.2_5_II
		7		AF-2.2_7_II
		9		AF-2.2_9_II
3	AF-3.1	9	CEM I 52.5 R	AF-3.1_9_I
		11		AF-3.1_11_I
		9	CEM II/A-L 42.5 R	AF-3.1_9_II
		11		AF-3.1_11_II
	AF-3.2	9	CEM I 52.5 R	AF-3.2_9_I
		11		AF-3.2_11_I
		9	CEM II/A-L 42.5 R	AF-3.2_9_II
		11		AF-3.2_11_II

5.2.3. Spraying logistics

A total of 10 days were required to spray all the mixes studied considering the suppliers and the Laboratory facilities. The sprayings are gathered in Table 5.5, which presents them regarding the date of spraying and the type of accelerator and cement used. The accelerators of Family 1 and 2 were separately sprayed with a type of cement in different days, whereas accelerators of Family 3 were sprayed at the same day with the same type of cement.

Table 5.5- Mixes and spraying days

Num. Spraying	Date	Type of Cement	Type of Accelerator
1	27/09/2010	II	AF-1.1
2	30/09/2010	II	AF-2.1
3	22/11/2010	I	AF-1.1
4	24/11/2010	I	AF-2.1
5	21/03/2011	II	AF-2.2
6	23/03/2011	II	AF-1.2
7	09/05/2011	I	AF-2.2
8	11/05/2011	I	AF-1.2
9	09/11/2011	II	AF-3.1 and AF-3.2
10	23/11/2011	I	AF-3.1 and AF-3.2

Each spraying entailed different processes in order to obtain samples to be tested. These processes are chronologically divided on 3 stages: before spraying procedures, spraying procedures and obtaining and conservation of samples.

5.2.3.1. Before spraying procedures

The concrete was sprayed in outdoors conditions next to the Laboratory of Technology of Structures Luis Agulló (UPC). An overview of the place is shown in Figure 5.1.a. The main door of the laboratory is seen on the right of the figure, whereas Gran Capità Street and part of the the 'Cuartel del Bruc' is observed on its left.

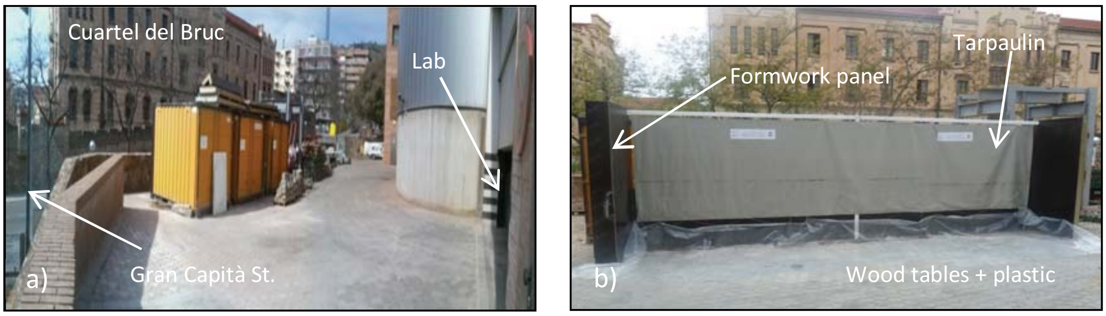


Figure 5.1-Place of spraying processes a) and structure assembled b)

Basically, the arrangement of the place consisted on a group of formwork panels and a tarpaulin to protect the nearby street and the pedestrians. Both, the formwork panels and the tarpaulin were impregnated with non-stick oil to simplify the cleaning process. This structure was installed in front of the yellow containers observed in Figure 5.1.a. Wood tables were put on the floor in order to level the ground. Furthermore, a plastic was placed on the wood tables in order to hold the rebound of the material and therefore facilitate the cleaning of the place. Figure 5.1.b presents the previously mentioned assembly.

The mixes were sprayed on 4 mm-thickness metallic test panels. Two sizes of test panels were used: small and large ones. Their design followed the requirements described by the

European standard UNE-EN 14488-1:2006 (61). The measures of the test panels are shown in Figure 5.2.a and Figure 5.2.b. Furthermore, the position of the test panels on the spraying zone regarded the same standard. Therefore, the small test panels were placed directly on the levelled floor with an angle of 20^{o} from the vertical and the large test panels were placed on supports specially design for the spraying process (Figure 5.2.b).

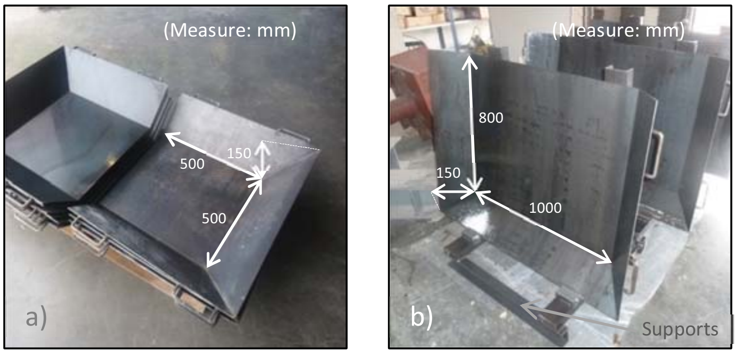


Figure 5.2- View of the small test panels a) and the large ones with its supports b)

In order to optimize the use of space several groups of test panels were used as the sprayings considered different doses of set accelerating admixture. Then, to spray the accelerators of Family 1 and 2, 3 small panels were used in order to gather the evolution of temperature, perform the penetration needle test and extract cores; and 1 large panel to perform the stud driving method. Hence, a total of 9 small test panels and 3 large panels where needed for these sprayings. On the other hand, in case of spraying the accelerators of Family 3 two small panels were used to obtain the evolution of temperature, the penetration needle test and perform the stud driving method, and a large one to extract cores. Therefore, a total of 8 small test panels and 4 large panels where needed for the last 2 sprayings.

5.2.3.2. Spraying procedures

All mixes were sprayed with a wet-mix system, which is currently the main process used in underground constructions (4). In order to do that a compact wet-mix machine MEYCO Altera was used to spray the mixes (Figure 5.3.a). This machine was an oil-hydraulically driven twin-piston pump, which also incorporated a peristaltic dosing unit for the accelerator. Furthermore, the equipment had to be completed with a 10 m^3/min diesel portable air compressor so as to spray the concrete and to mix it with the accelerator at the nozzle. Finally, a simple device was designed to facilitate the handling of the nozzle fixed to the forks of a forklift truck for stability and consistency of spraying position and angle (Figure 5.3.b).

Firstly, pipes and hoses were lubricated with cement paste and the concrete pumping was verified. The parameters of the spraying process were fixed being the pumped concrete flow 4.4 m^3/h (equivalent to 20 strokes per minute) and the air pressure 4 bars. Furthermore, the accelerator-dosing unit allowed a flow between 4.0 and 4.5 l/min depending on both the density of each accelerator and the dose required. Finally, the distances of spraying and the angles were adopted according to the European specification for sprayed concrete established by EFNARC (62).

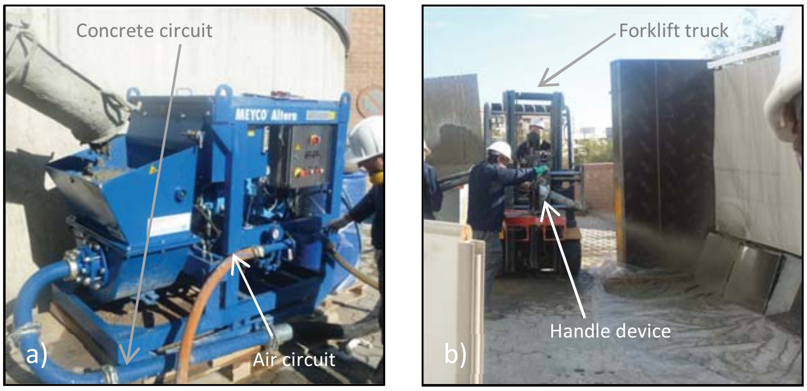


Figure 5.3- View of the spraying machine a) and overview of the spraying process b)

5.2.3.3. Obtaining and conservation of samples

After spraying the test panels, the first step was unmoulding the sprayed concrete pieces at an age of 24 h (Figure 5.4.a). The procedure followed was simple as the spraying concrete pieces were big enough to bear slight blows. Using chains attached to a lift truck the test panels were elevated few centimetres. Finally, the pieces of sprayed concrete were dumped on wood sticks, previously collocated under the test panels in order to cushion the blows. This procedure was only repeated for all sprayed concrete pieces designated to extract cores. No curing was applied to the concrete up to 24 h after being sprayed as it could disturb the tests performed during this time. The unmoulded pieces were simply piled together in outdoor conditions and covered by sackings, which were continuously wetted with water so as to maintain high humidity conditions. Figure 5.4.b shows the curing of the sprayed concrete during this period.

Figure 5.4- Unmould sprayed concrete piece a) and wet sackings b)

The second step was the extraction of cores from the sprayed concrete pieces. These were cylinders obtained using an extracting machine with a 75 mm diameter drill (Figure 5.5.a). Taking into account this diameter and the minimum distances established by the European standard UNE-EN 14488-2:2007 (46), 9 cores and 18 cores were extracted from the small and the large test panels, respectively. Therefore, independently of the spraying, a total of 18 cores were obtained from each mix. Then the roughest face of the cores was cut in order to obtain 150 mm-length. This entailed slenderness equal to 2, value needed according to the Spanish instructions of concrete EHE-08 (24). Figure 5.5.b presents the cutting machine used.

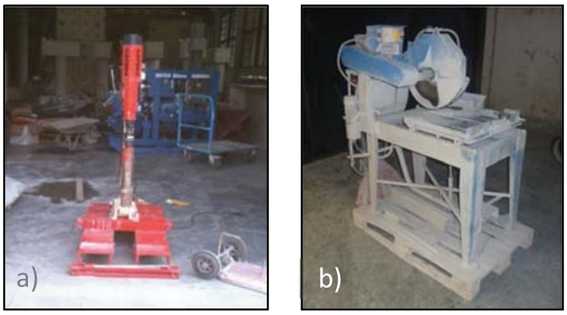


Figure 5.5- Extracting machine a) and radial disc cutting machine b)

Finally, to maximize the contact between the probes and the testing to assure a good load distribution machines, two procedures were done. Facing was performed for the cores from the 2 first sprayings, whereas polishing was done for the rest of the cores. In order to avoid drawbacks of facing, such as toxic gases produced, this change was considered. The first procedure consisted on adding a sulphur layer with high-strength-standardized-sand on the extremes of the probes according to the European standard UNE-EN 12390-3:2009/AC:2011 (63) (Figure 5.6.a). To avoid the aforementioned drawbacks of the polishing machine (Figure 5.6.b) was used after the second spraying.

Figure 5.6- Facing zone a) and polishing machine b)

Samples were maintained in a room with temperature of 20 ± 2 ^{o}C and humidity of 95 ± 2% until the age of testing. Meanwhile, samples were sized and weighted in order to calculate their density and apply corrections to the results, for instance slenderness corrections. This was performed slightly different considering if they were faced or polished. For faced samples 2 diameters (mm), 3 heights before facing (mm), 1 height after facing (mm) and their weight before facing (g) were measured. The density of the samples was calculated with the average diameter and average heights before facing. Furthermore, the slenderness correction factor was estimated with the average of the 2 diameters and the height after facing the samples.

On the other hand, for polished samples, 2 diameters (mm), 1 height (mm) and the weight (g) were measured. The density of the samples was calculated with the average of the diameters, the height and the weight. Finally, the slenderness correction factor was obtained using the same average of diameters and height.

5.2.4. Test methods

The experimental program included both early and long age tests. Table 5.6 summarizes the tests performed and the standards used as reference. Notice that the test of evolution of temperature does not follow any standard.

Table 5.6- Tests performed for sprayed concrete

Age	Test	Standards
Early ages	Evolution of temperature (up to 24 h)	-
	Penetration needle test (up to 30 min)	UNE-EN 14488-2:2007
	Stud driving method (from 4 to 24 h)	UNE-EN 14488-2:2007
Long ages	Density and Porosity (28 d)	UNE 83-134:1990 (modified)
	Compressive strength (1, 7 and 28 d)	UNE-EN 12390-3:2009/AC:2011
	Modulus of elasticity (1, 7 and 28 d)	UNE 83316:1996

5.2.4.1. Early ages

The early age characterization of the sprayed concrete is important due to the quick setting provided by the accelerators. This entails rapid changes on the properties of concrete, which must be studied to characterize the material. Changes such as the increasing of temperature due to the exothermic reactions during the hydration of cement or the immediate strength development are studied. Hence, the evolution of temperature test, the penetration needle test and the stud driving method are explained below.

Evolution of temperature

This test allows obtaining the curves that relate the evolution of temperature with time. The integral of this curve yields the indirect assessment of the energy released during the hydration process, which might be correlated with the development of the mechanical properties of sprayed concrete. The evolution of temperature was obtained using a data logger and thermocouples type K directly attached on selected test panels. Figure 5.7.a shows the device and the thermocouple used and Figure 5.7.b presents a thermocouple attached on a test panels. Temperature was registered every 1 min for the first 24 h from the spraying process. The initial time was defined as the time when the test panel was completely filled. Furthermore, the environmental temperature was obtained with the data logger using a thermocouple type J. One 37.5 dm^3-piece of sprayed concrete (filled test panel) of each mix was tested entailing a total of 32 test of evolution of temperature performed.

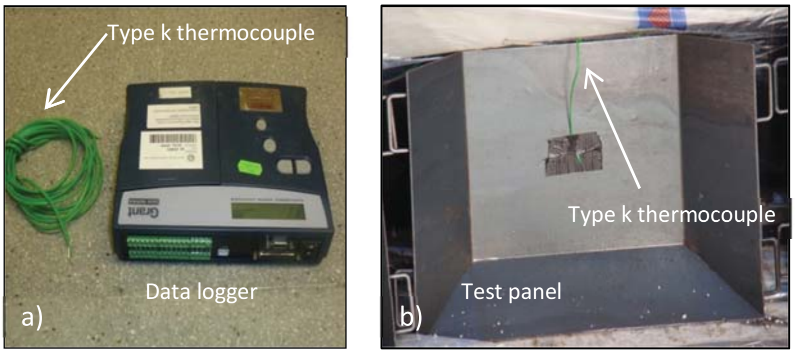


Figure 5.7- Data logger a) and a thermocouple attached on a test panel b)

Penetration needle test

The compressive strength of the sprayed concrete was estimated by the penetration needle test during the first minutes from the spraying. This test was performed according to the European standard UNE-EN 14488-2:2007 (46). Figure 5.8.a presents the device used during the test. This test consisted on introducing a 16 mm-needle in the sprayed concrete employing manual force (Figure 5.8.b). This was gradually and uniformly applied on the device until the needle penetrates in the concrete a depth of 25 mm. Afterwards, the force value obtained in Kp was annotated and used in an abacus given by the same standard to estimate the compressive strength of the concrete. As this is an indirect test to determine the compressive strength, 10 values were taken for points separated a minimum of 50 mm from each other. The compressive strength is given by the average of these 10 values. This test was calibrated using cubic samples, therefore a shape correction factor was considered to obtain the equivalent strength in cylindrical specimens regarding former studies (64). In total, 32 small panels were tested with the penetration needle for a time up to 30 min.

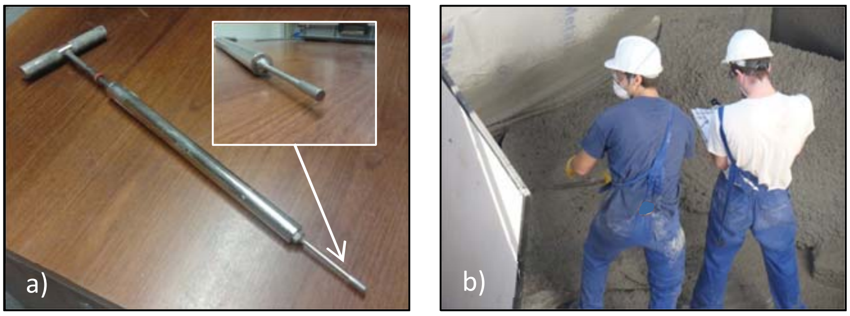


Figure 5.8- Device used for the penetration needle test a) and detail of testing procedure b)

Stud driving method

The compressive strength of the sprayed concrete up to 24 h was estimated with the stud driving method. This test was performed following the requirements of the European standard UNE-EN 14488-2:2007 (46). Figure 5.9.a presents the device used in this test.

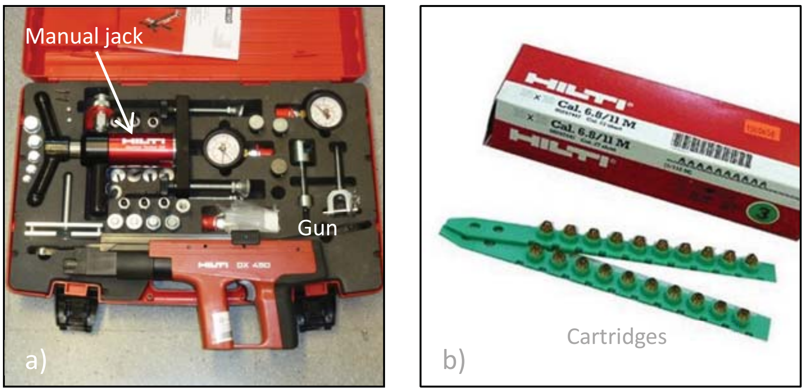


Figure 5.9- Device used for the stud driving method a) and green cartridges b)

This indirect test basically consisted on shooting 10 stubs in the sprayed concrete and extracting them with a manual jack. The minimum separation between stubs was 80 mm. The compressive strength was evaluated for each stud using both the penetration length (mm) and the extraction force (Kp). The average of all results is considered the estimated compressive strength for a certain time. Three different stub lengths were used: 103 mm, 80 mm and 60 mm. These were chosen considering the strength of the sprayed concrete as well as the minimum and maximum penetrations established by the standard. Furthermore, two different cartridges: green and yellow were available, although only the green one was used (Figure 5.9.b). Then the compressive strength (f_c) was estimated with the green cartridge equation (Equation 5.1), the penetration length (L) and the extraction force (F).

$$\mathrm{f_c} = {(\mathrm{F}/\mathrm{L} + 2.70)}/{7.69} \tag{5.1}$$

This test had been calibrated using cubic samples, therefore a shape correction factor was considered to obtain the equivalent strength in cylindrical specimens regarding former studies (64). In total, 32 small panels were tested with the stud driving method, entailing more than 1280 studs shot.

5.2.4.2. Long ages

In this study, the compressive strength and the modulus of elasticity were also measure for long ages. Furthermore, tests to estimate the porosity and density of the samples, which are related with the mechanical properties of the sprayed concrete, were performed.

Density and porosity

The density (ρ) and porosity (p) of the sprayed concrete were determined according to the Spanish standard UNE 83134:1990 (65) and the modification described by former studies performed at the UPC (17). First, 28-days samples were drown in water in a vacuum chamber up to 48 h to produce a saturated condition. Then, their hydrostatic weight (w_h) was measured using a hydrostatic balance. Dried superficially, their saturated weight (w_{sat}) was obtained by a regular balance. Subsequently, the specimens were introduced in an oven with a temperature of 90 °C during 48 h in order to obtain a dry condition. Finally, they were weighted using the regular balance to determine the dry weight (w_d). Using these three values of weight both the density (Equation 5.2) and the porosity (Equation 5.3) of the samples were determined. In this case, three 75 mm diameter cylinder samples of each mix were tested at 28 days entailing 96 tests of density and porosity performed.

$$\rho = \frac{w_d}{w_{sat} - w_h} \tag{5.2}$$

$$p = \frac{w_{sat} - w_d}{w_{sat} - w_h} \tag{5.3}$$

Compressive strength

The compressive strength of the sprayed concrete at long ages was evaluated according the European standard UNE-EN 12390-3:2009/AC:2011 (63). This strength was obtained testing 75 mm-diameter cylinder samples with slenderness equal to 2.0, as established in the European standard UNE-EN 12504-1:2009 (66). Figure 5.10 presents the hydraulic press used to perform the test. A total of 6 samples were tested for each age, and therefore 6 values of compressive strength were obtained. This test was performed at 1, 7 and 28 days, entailing a total of 528 tests performed.

Figure 5.10- Hydraulic press

In case of not having slenderness equal to 2.0 as established by the standard, a correction factor (f_λ) was calculated and multiplied by the compressive strength results. The Equation 5.4 presents the relationship between the compressive strength with slenderness equal to 2.0 (f_c) and the same strength with slenderness λ according to the Spanish instruction for concrete EHE-08 (24).

$$f_\lambda = \frac{2}{1.5 + \frac{1}{\lambda}} \quad (5.4)$$

Modulus of elasticity

The modulus of elasticity of the sprayed concrete was evaluated according to the Spanish standard UNE 83316:1996 (67). The device used to perform the test was a hydraulic press (Figure 5.10). For each mix, 3 samples were tested using LVDTs, which measured the strain of the samples while applying the compressive force (Figure 5.11). In this case, three samples of each mix were tested at 1, 7 and 28 days, entailing 384 tests of modulus of elasticity.

Figure 5.11- View of the LVDTs assembled on the sample

5.3. RESULTS AND DISCUSSIONS

The results from the experimental program described in section 5.2 are presented separately for early and long ages. Therefore, first the results of the evolution of temperature, the penetration needle test and the stud driving method are shown and analysed. And then, the results of porosity and density, the compressive strength and the modulus of elasticity are analysed. These results are focused on the low and medium doses of one accelerator for each family: AF-1.1, AF-2.1 and AF-3.1. The rest of results, which followed the same tendencies, are exposed in Appendix C.

5.3.1. Early ages results and discussions

5.3.1.1. Evolution of temperature

The evolutions of temperature (Temperature measured minus ambient temperature) obtained for the mixes considered in this section are presented in Figure 5.12. The curves present similar trends showing initially a first increase of temperature due to the first phase of the hydration of the cement (formation of ettringite). After that, a slight decrease or a reduction on the temperature increase rate is observed, which is characteristic of the dormant period. Next, a second peak of temperature due to the hydration of silicates (C_2S and C_3S) is verified in some of the curves. Finally, the temperature registered tends to stabilize with the room temperature. Notice than the same trend is followed by the results obtained for cement pastes and mortars in Chapter 3.

The only exception is observed in the case of mixes of cement I with low or medium dose of AF-1.1. This is possibly due to the phosphoric acid present in AF-1.1, which complicates the hydration of the C_3S (alite) of the cement (38). On the contrary, AF-1.1 shows good affinity with II, this may be related with the clinker fineness and the content of limestone filler present (49).

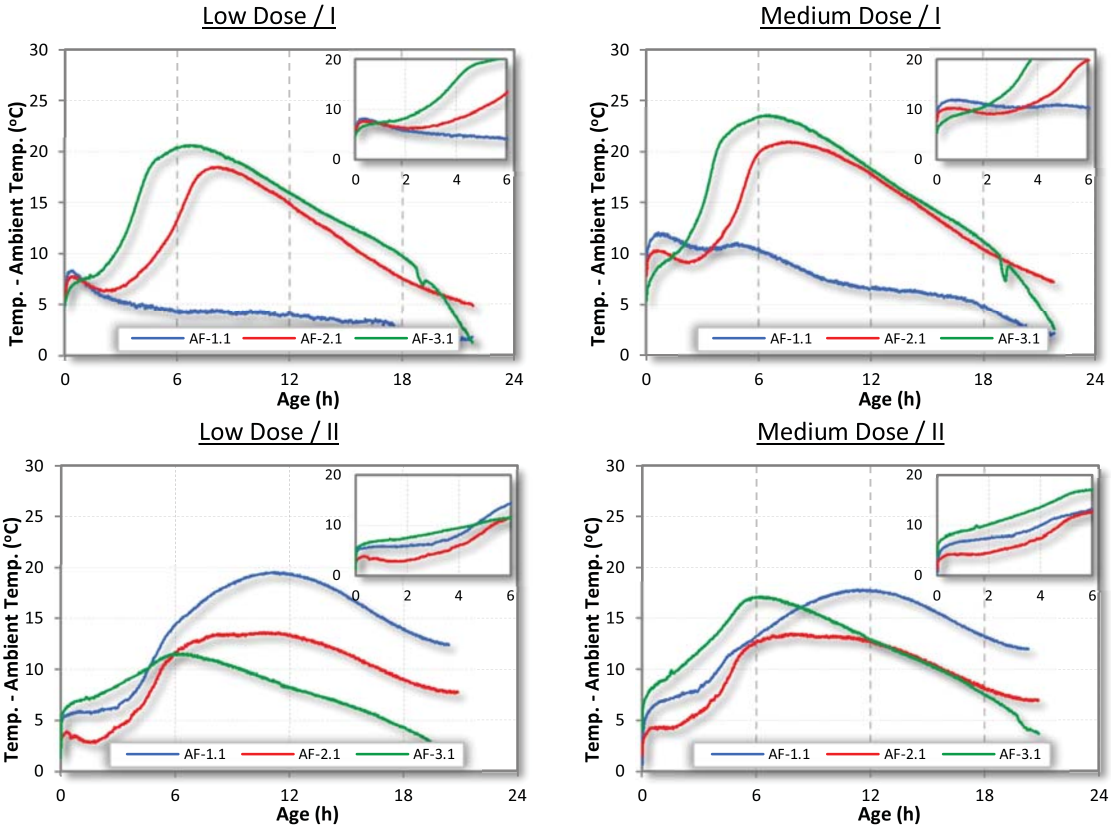


Figure 5.12- Evolution of temperature considering type of cement and dose of accelerator

Table 5.7 resumes characteristic points extracted from the curves. These points are represented in terms of the value and the time of the maximum temperature (T_{max}, t_{Tmax}), first increasing of temperature (T_{1P}), the second temperature peak (T_{2P}) and the minimum temperature between peaks ($T_{Min1P-2P}$). Notice that, this last result is related with the dormant period. The table also present the energy released during the hydration (Et_X) related to each characteristic point.

Table 5.7- Evolution of temperature characteristic points

Low Dose						
Reference	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
T_{max} (°C)	8.37	18.56	20.68	19.59	13.67	11.61
t_T_{max} (h:min:s)	0:26:00	8:09:00	6:39:00	11:11:00	10:27:00	5:55:00
Et_T_{max} (h·°C)	215.06	5156.38	6607.35	8397.89	5499.68	3081.91
T_{1P} (°C)	8.37	7.84	7.97	5.97	3.95	7.37
t_T_{1P} (h:min:s)	0:26:00	0:25:00	1:21:00	0:54:00	0:18:00	1:21:00
Et_T_{1P} (h·°C)	215.06	191.31	583.50	305.56	67.63	544.51
T_{2P} (°C)	-	18.56	20.68	19.59	13.67	11.61
t_T_{2P} (h:min:s)	-	8:09:00	6:39:00	11:11:00	10:27:00	5:55:00
Et_T_{2P} (h·°C)	-	5156.38	5381.44	8397.89	5499.68	3081.91
$T_{min1P-2P}$ (°C)	-	6.37	7.74	5.72	2.83	7.11
t_$T_{min1P-2P}$ (h:min:s)	-	2:29:00	1:30:00	1:35:00	1:48:00	1:29:00
Et_$T_{min1P-2P}$ (h·°C)	-	1048.40	653.78	545.48	358.62	602.23
Medium Dose						
Reference	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
T_{max} (°C)	12.08	21.04	23.66	17.85	13.53	17.16
t_T_{max} (h:min:s)	0:39:00	7:38:00	6:24:00	11:19:00	7:48:00	6:09:00
Et_T_{max} (h·°C)	458.63	6324.95	5072.27	8378.88	3920.94	4535.76
T_{1P} (°C)	12.08	10.42	10.16	7.22	4.44	9.80
t_T_{1P} (h:min:s)	0:39:00	0:35:00	1:28:00	1:30:00	1:07:00	1:29:00
Et_T_{1P} (h·°C)	458.63	360.54	774.99	577.83	276.71	752.49
T_{2P} (°C)	11.02	21.04	23.66	17.85	13.53	17.16
t_T_{2P} (h:min:s)	5:05:00	7:38:00	6:24:00	11:19:00	7:48:00	6:09:00
Et_T_{2P} (h·°C)	3385.17	6324.95	6253.88	8378.88	3920.94	4535.76
$T_{min1P-2P}$ (°C)	10.41	9.17	-	7.22	4.18	9.59
t_$T_{min1P-2P}$ (h:min:s)	3:07:00	2:16:00	-	1:30:00	1:19:00	1:35:00
Et_$T_{min1P-2P}$ (h·°C)	2115.96	1345.94	-	577.83	327.84	811.15

Regarding the first increase of temperature, mixes with accelerator AF-1.1 present the highest temperature in case of mixes with cement I. On the contrary, mixes with cement II present the highest temperature with the accelerator AF-3.1, independently of the dose of accelerator. This increase of temperature is higher when increasing the dose of accelerator since more dissolved aluminum is available to react with the sulfate and aluminates of the cement. Furthermore, the mixes with cement I present higher temperature than the ones with cement II. This is due to the higher amount of clinker, and therefore aluminates (C_3A), the cement I has respect the cement II. Notice that the only exception is observed in mixes with AF-1.1, which show a higher affinity with cement II. This is possibly due to the stabilizer of the accelerator which is an inorganic acid that may increase the affinity accelerator-cement. Even though, the lack of a chemical analysis does not allow discussing this result.

Regarding the 2nd peak of temperature, in case of mixes with cement I the highest values are measured for the accelerator AF-3.1. On the contrary, mixes with cement II present the highest temperature with the accelerator AF-1.1. Furthermore, the results show that increasing the dose of accelerator the peaks of temperature are around 25% higher with mixes with cement I, regardless of the accelerator used. In general, the 2nd peak of temperature is higher for mixes with cement I than those with cement II probably due to the bigger clinker content of the former. Notice that the only exception is observed in mixes with AF-1.1, which show a higher affinity with cement II. Again, the mixes with AF-1.1 present a different behaviour, showing higher affinity with cement II. It is interesting to remark that mixes with AF-3.1 present the 2nd peak before the ones with other accelerators for all cement types and doses analysed. This indicates that the chemical formulation of AF-3.1 possibly accelerates the hydration of silicates (C_2S and C_3S) yielding C-S-H in comparison with other accelerators.

According to the results, mixes that present higher temperatures in the first peak tend to show lower temperatures in the second peak. This may be explained by the phase of cement that reacts with the accelerators. For example, if the accelerator reacts mainly with the aluminates, a higher 1st peak of temperature should be observed. On the contrary, if the accelerators are more active on the silicates of the cement, a higher 2nd peak should be observed. Another explanation could be that less active mixes present smaller 1st peaks, leaving more aluminates to react over time and to contribute in the temperature increase of the 2nd peak. Again, the tendency described is presented by all mixes studied but the one with AF-1.1 and cement I, independently of the dose of accelerator used.

The dormant period is longer in case of low doses of accelerators for both cement types. In this sense, mixes with AF-2.1 present the longest dormant periods as shown in the results ($T_{Min1P-2P}$). This period is not as long in mixes with accelerator AF-3.1 since a decrease of temperature is not observed. Furthermore, the increase on the dose of accelerator produces shorter dormant periods regardless the type of cement used.

5.3.1.2. Penetration needle test

The results of compressive strength (and their variance) obtained by the penetration needle test are presented in Table 5.8. Regarding the type of cement, the results obtained are similar for the mixes with cement I and cement II. This demonstrates the lower importance of the type of cement up to 30 min. Therefore, the type of accelerator and its dose are the parameters that most influence the strength measured in the first minutes (Phase I of the cement hydration).

Table 5.8- Compressive strength (MPa) obtained by the penetration needle test

			Low Dose			
Age (min)	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
3	0.39 *(22.30%)*	0.00 *(12.74%)*	0.19 *(21.48%)*	0.59 *(15.61%)*	0.30 *(17.34%)*	0.50 *(19.20%)*
6	0.45 *(48.14%)*	0.37 *(23.60%)*	0.37 *(10.16%)*	0.78 *(11.90%)*	0.36 *(26.21%)*	0.67 *(16.66%)*
10	0.56 *(23.48%)*	0.42 *(27.38%)*	0.51 *(9.84%)*	1.01 *(5.45%)*	0.43 *(15.27%)*	0.73 *(30.26%)*
15	0.67 *(20.94%)*	0.49 *(19.57%)*	0.56 *(15.49%)*	- -	0.56 *(18.67%)*	1.03 *(21.54%)*
20	0.78 *(18.39%)*	0.57 *(11.75%)*	0.61 *(7.78%)*	- -	0.69 *(22.06%)*	1.24 *(6.01%)*
30	0.98 *(13.56%)*	0.87 *(9.44%)*	0.84 *(6.39%)*	- -	0.86 *(8.40%)*	- -
			Medium Dose			
Age (min)	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
3	0.41 *(19.81%)*	0.44 *(15.09%)*	0.36 *(63.62%)*	0.44 *(19.47%)*	0.43 *(34.32%)*	0.80 *(9.70%)*
6	0.49 *(21.37%)*	0.72 *(10.07%)*	0.40 *(7.31%)*	0.71 *(25.15%)*	0.52 *(25.68%)*	0.98 *(9.21%)*
10	0.55 *(29.72%)*	0.98 *(9.77%)*	0.48 *(12.38%)*	0.98 *(28.66%)*	0.58 *(25.93%)*	1.02 *(5.75%)*
15	0.79 *(20.89%)*	- -	0.80 *(13.48%)*	- -	0.78 *(15.69%)*	- -
20	1.04 *(12.07%)*	- -	0.91 *(10.88%)*	- -	0.99 *(5.44%)*	- -
30	- -	- -	- -	- -	- -	- -

This strength is closely related with the dose of accelerator used. In general, an increase in the dose leads to higher strength values. Such result is reasonable since more amount of accelerator is available to react with the cement in this case. In this sense, the higher results are achieved with AF-2.1 and the one with AF-3.1 for the cement I and cement II, respectively. The main exception is observed in the results of mixes with AF-1.1, which, regardless of the cement type, present the highest compressive strength for the low doses (with lower phosphate content).

It is known that the penetration test has a range of application between 0 MPa and approximately 1.3 MPa. Notice that mixes with low dose of accelerator present values up to 30 minutes in almost all mixes, indicating a slower gain of compressive strength over time. On the contrary, mixes with medium dose could only be tested up to 10 or 20 minutes. It is important to highlight the fast gain of strength in mixes with the low dose of AF-1.1 and cement II, which at 10 min showed the same strength of mixes with other accelerators at 30 minutes. This is probably due to the higher affinity of AF-1.1 with the cement II even for low doses. The phenomenon was also observed in the evolution of temperature over time.

Figure 5.13 illustrates the results presented by the mixes considered in this section compared to the curves for the early strength classes of young sprayed concrete: J1, J2 and J3 (68).

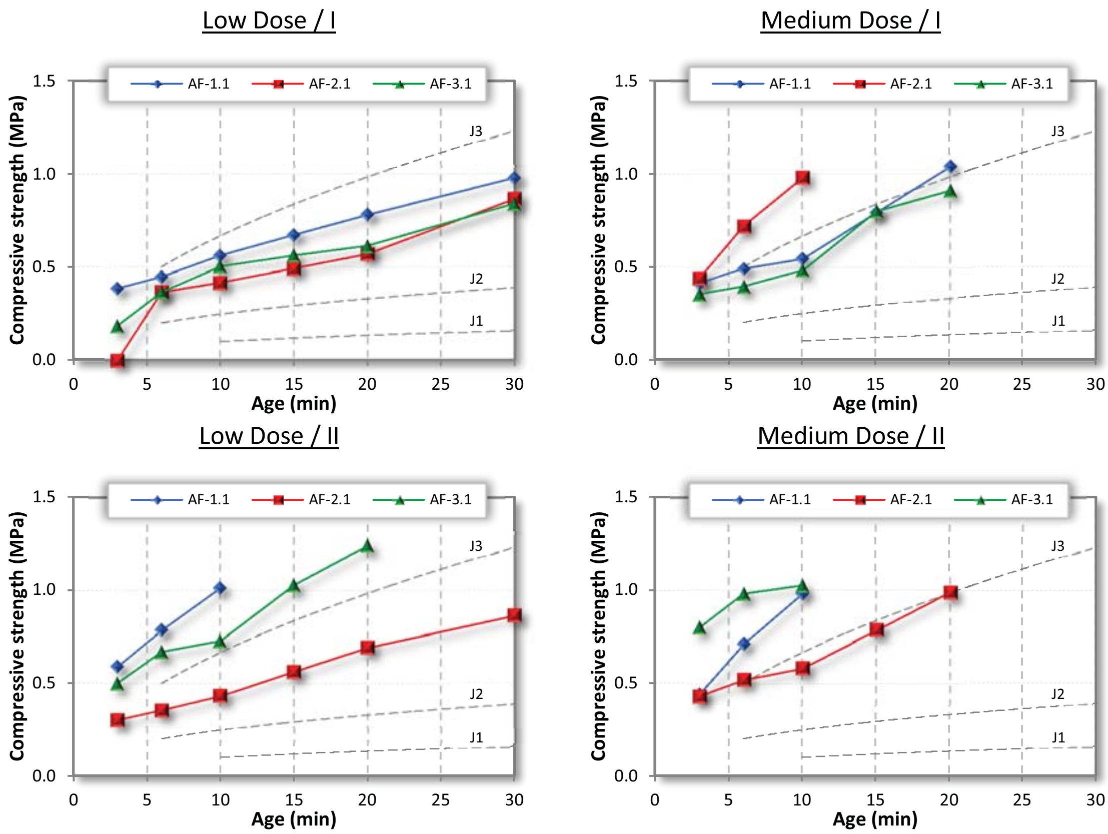


Figure 5.13- Compressive strength results considering type of cement and dose of accelerator

The results show that the curves are classified as J2 or J3. Regarding the type of cement, mixes with II present more curves J3 than the ones with I. This is possible due to the limestone filler in the cement II, which contributes to the nucleation of the hydrated phases increasing the compressive strength at very early ages. In this case the mixes with accelerators AF-1.1 and AF-3.1 present curves J3, whereas AF-2.1 present curves J2, independently of the type of dose used. This shows the lower affinity between the accelerator AF-2.1 and the cement II as observed analysing the evolution of temperature. This tendency was observed in the evolution of temperatures and is probably due to the hydration of C_3A. On the other hand, mixes with cement I and low dose of accelerator present curves J2. An increase in the dose of accelerator produces a small growth in the strength of the mixes with accelerators AF-1.1 and AF-3.1, which are still classified as J2. However, a higher influence is observed in the mix with AF-2.1 that presents a significant increase of strength and is classified as J3 in the graph.

5.3.1.3. Stud driving method

The results of compressive strength (and their variance) obtained by the stud driving method are presented in Table 5.9. Regarding the type of cement, the results obtained are similar for the mixes with cement I and cement II. Even though, results with cement I are slightly higher than the ones with cement II. This is basically due to the higher strength class of the former and the importance of this strength from 4 h on. However, the type of accelerator is still more important during this period.

Table 5.9- Compressive strength (MPa) obtained by the stud driving method

Low Dose						
Age (h)	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
4	-	-	4.15	4.43	3.82	2.90
	-	-	*(16.14%)*	*(14.61%)*	*(20.39%)*	*(22.22%)*
6	-	8.59	12.11	5.89	8.59	7.23
	-	*(17.55%)*	*(10.01%)*	*(26.90%)*	*(19.22%)*	*(16.97%)*
12	5.82	15.63	17.26	17.47	15.63	11.72
	(27.60%)	*(19.22%)*	*(21.43%)*	*(23.03%)*	*(17.76%)*	*(16.63%)*
24	25.39	19.97	17.53	17.13	19.97	15.68
	(11.11%)	*(16.39%)*	*(15.04%)*	*(24.68%)*	*(35.13%)*	*(22.95%)*
Medium Dose						
Age (h)	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
4	-	-	5.44	3.51	5.66	-
	-	-	*(17.07%)*	*(19.61%)*	*(9.38%)*	-
6	3.24	13.16	11.26	6.75	8.66	5.13
	(9.94%)	*(10.42%)*	*(11.95%)*	*(13.33%)*	*(12.43%)*	*(12.95%)*
12	4.88	22.48	14.62	13.18	17.93	7.38
	(16.66%)	*(16.35%)*	*(11.85%)*	*(17.49%)*	*(12.73%)*	*(25.62%)*
24	20.07	20.16	17.34	16.94	17.52	15.44
	(7.62%)	*(22.42%)*	*(30.97%)*	*(28.18%)*	*(19.64%)*	*(13.61%)*

This strength is related with the type of cement used. In general, mixes with cement I present higher compressive strength than the ones with cement II from 6 h on. Regarding the cement type, such results indicate the importance of the strength class from certain time on. Before, the type of accelerator and the additions of the cement have more importance. In this sense, the higher results are achieved with AF-2.1 regardless the type of cement and dose of accelerator. This is possibly related with the quicker hydration of the C_2S and C_3S of mixes with AF-2.1, which produces C-S-H chains able to provide compressive strength. This phenomenon is observed in the evolution of temperature regarding the maximum temperature. On the contrary, mixes with AF-1.1 and AF-3.1 present the lower results in mixes with cement I and II, respectively. This probably indicates a lower affinity between the accelerators and the type of cements. For instance, in case of AF-1.1 the phosphoric acid used as stabilizer could limit the dissolution of the alite reducing the rate of hydration for this C_3S.

It is known that the stud driving method has a range of application from around 3 MPa on. Notice that mixes with cement II present values from 4 h on, indicating a rapider gain of strength. On the contrary, mixes with cement I could only be tested from 6 h on, in most of the cases. This is possibly due to the limestone filler in the cement II, which contributes to the nucleation/precipitation of the hydrated phases increasing the compressive strength at early ages.

Figure 5.14 illustrates the results presented by the mixes considered in this section comparing them with the early classes of young sprayed concrete: J1, J2 and J3 (68).

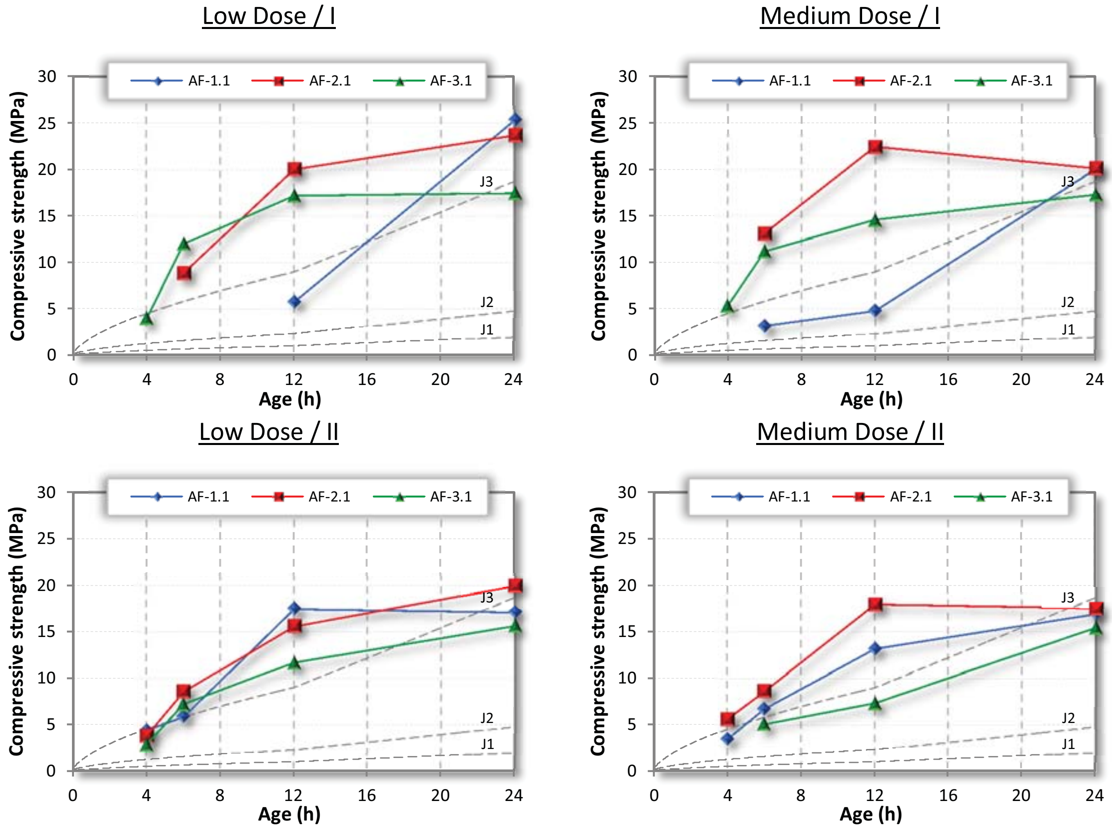


Figure 5.14- Compressive strength results considering type of cement and dose of accelerator

The results show how the curves are classified J2 and J3. Regarding the type of cement, mixes with cement II present more curves J3. As commented before, this is possible due to the limestone filler in the cement II. In this case the mixes are classified as curves J3. The only exception is the mix with medium dose of AF-3.1 that is classified as J2. On the other hand, mixes with cement I present a same behaviour regardless the dose of accelerator. In this sense, mixes produced with AF-2.1 and AF-3.1 present curves J3, whereas the ones with AF-1.1 are classified as J2. This difference is possibly due to the low affinity between the accelerator AF-1.1 and the cement I, observed in the evolution of temperature and previously commented.

5.3.2. Long ages results and discussions

5.3.2.1. Density and porosity

Density and porosity tests were only performed on mixes with accelerators AF-1.2 (Family 1) and AF-2.2 (Family 2) and cement I. These tests were performed in the Laboratory of Chemistry and Construction Materials (UPC) and the low availability of its facilities entailed the non-performance of these tests for other mixes. The results (and their variance) of the tests done are presented in Table 5.10.

Table 5.10- Density and porosity of samples with AF-1.2 and AF-2.2 and cement I

Sample	Density (g/cm^3)		Porosity (%)	
AF-1.2_5_I	2.174	*(0.43%)*	14.672	*(1.56%)*
AF-1.2_7_I	2.153	*(0.19%)*	15.459	*(1.29%)*
AF-1.2_9_I	2.134	*(0.80%)*	16.712	*(3.52%)*
AF-2.2_5_I	2.162	*(0.37%)*	16.296	*(2.54%)*
AF-2.2_7_I	2.171	*(0.03%)*	15.350	*(0.46%)*
AF-2.2_9_I	2.153	*(0.09%)*	16.028	*(2.63%)*

Regarding the results of density, the results show a tendency as the lower the dose of accelerator is, the higher the density is. Therefore the mix with the lowest dose of AF-1.2 presents the highest density (2.174 g/cm^3). Increasing this dose of this accelerator to 7 and 9%bcw mixes present a reduction of density of 0.96 and 1.84%, respectively. In case of mixes with accelerator AF-2.2, they present the same tendency regarding the medium and highest dose as the density is reduced a 0.83%. Even though, the mix with lowest dose of AF-2.2 does not follow the tendency as it present lower density than the medium dose mix. This is possibly due to a bad compacting of the samples used to obtain these results.

Regarding the porosity the results present the same tendency aforementioned for the density as the higher the dose of accelerator is the highest is the porosity. This is possibly due to the difficulty of moulding and compacting because of the incorporation of accelerator, which increases with the amount of accelerator. Therefore, the mix with the lowest dose of AF-1.2 presents the lowest porosity (14.672%). Increasing this dose of this accelerator to 7 and 9%bcw mixes present an increasing of porosity of 0.79% and 2.04% increases, respectively. Finally, apart from the mix with lowest dose this tendency is reflected by the results obtained of mixes with AF-2.2.

Finally, Figure 5.15 illustrates the results from the tables showing the average in both cases.

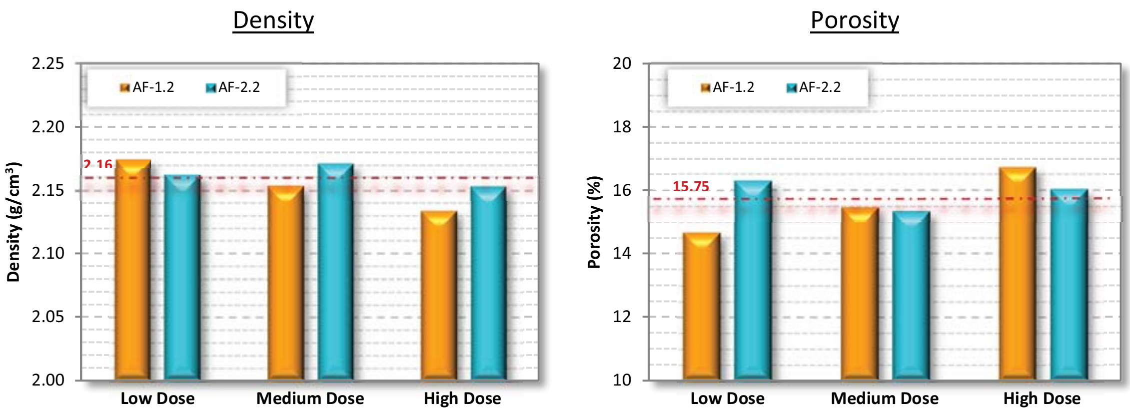


Figure 5.15- Density and porosity of samples with AF-1.2 and AF-2.2 and cement I

The average of all results of density is 2.16 g/cm^3, whereas the average of porosity is 15.75%. These values differ to the ones of conventional concrete (density: 2.30 g/cm^3 and porosity: 7.00%) (69). Such differences may be attributed to the inclusion of compressed air in the concrete during the process and the incorporation of accelerators, which reduce the setting time of the concrete and interfere with its compacting. This reduction of the density or increasing of the porosity directly affects the mechanical properties of the sprayed concrete.

5.3.2.2. Compressive strength

Table 5.11 presents the results of compressive strength (and their variance) at different ages of the mixes considered in this section. Regarding the type of cement, the results with cement I are higher than the ones with cement II (almost doubling them in most of the cases). This is due to the strength class of the cement and shows that at long ages the type of cement has more influence than the type of accelerator.

Table 5.11- Compressive strength (MPa)

Low Dose						
Age (d)	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
1	20.74 *(9.64%)*	38.56 *(10.50%)*	31.21 *(1.74%)*	8.88 *(14.80%)*	19.95 *(5.78%)*	15.76 *(18.26%)*
7	33.48 *(21.91%)*	51.42 *(23.69%)*	41.90 *(9.14%)*	15.73 *(21.63%)*	31.34 *(16.36%)*	27.25 *(9.69%)*
28	45.56 *(11.31%)*	66.69 *(3.28%)*	47.97 *(2.73%)*	25.18 *(17.97%)*	33.43 *(10.22%)*	34.20 *(8.79%)*
Medium Dose						
Age (d)	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
1	11.90 *(16.41%)*	27.94 *(17.11%)*	29.64 *(1.54%)*	12.33 *(14.46%)*	19.80 *(4.29%)*	15.29 *(8.66%)*
7	24.68 *(21.79%)*	49.87 *(12.14%)*	40.27 *(9.82%)*	15.21 *(16.74%)*	33.18 *(10.18%)*	24.37 *(13.69%)*
28	38.38 *(7.20%)*	66.47 *(2.16%)*	45.96 *(3.77%)*	29.22 *(9.68%)*	34.79 *(17.65%)*	29.89 *(12.13%)*

The results are similar independently the type of dose of accelerator. The mixes with accelerator AF-2.1 present the highest compressive strength, independently of the type of cement. On the contrary, all mixes with accelerator AF-1.1 present the lowest compressive strength. This difference is possibly due to the effect of the accelerator at early ages, which effects porosity of the sprayed concrete and therefore its mechanical properties. Notice that the mixes which present higher compressive strength at early ages present lower strength at long ages. This tendency is observed comparing these results with the ones obtained with the penetration needle test. Therefore, mixes with accelerator AF-1.1, which presented higher compressive strength at early ages, present lower strength at long ages. The opposite happens in case of the accelerator AF-2.1.

Figure 5.16 shows the development of the compressive strength. It shows how the development of compressive strength is higher between 1 and 7 days than between 7 and 28 days.

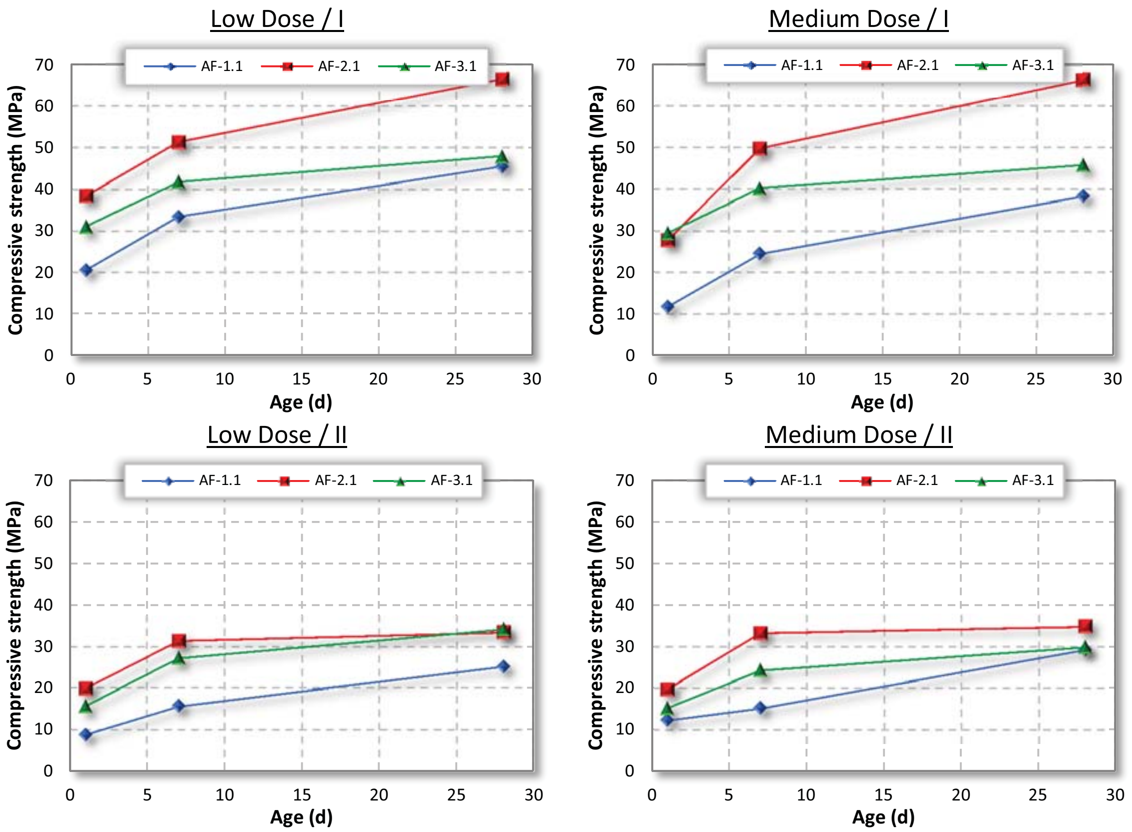


Figure 5.16- Compressive strength results at long ages considering type of cement and dose of accelerator

5.3.2.3. Modulus of elasticity

Table 5.12 presents the results of modulus of elasticity (and their variance) at different ages of the mixes considered in this section. Regarding all the results mixes generally have a same tendency: Stronger increase of the modulus of elasticity between 1 and 7 days, and smaller one between 7 and 28 days. Assuming that, the modulus of elasticity of the sprayed concrete is the addition of the modulus of the aggregates and the one of the matrix. The first one is noticed up to 7 days. After that time is the modulus given by the matrix the one that increases the modulus of elasticity of the sprayed concrete.

The results follow the tendency described by the results of compressive strength. Mixes with accelerator AF-2.1 present the highest results independently of the type of cement and dose of accelerator used. Furthermore, mixes with accelerators AF-1.1 and AF-3.1 present similar results. Even though, the mixes with AF-3.1 present a higher stiffness than the mix with AF-1.1 as its compressive strength is higher and its modulus of elasticity is lower. This is possibly due to the porosity of the material, which is affected by the reactions produced by the type of accelerator at early ages.

Table 5.12- Modulus of elasticity obtained in the Laboratory (GPa)

Low Dose						
Age (d)	**AF-1.1_5_I**	**AF-2.1_5_I**	**AF-3.1_9_I**	**AF-1.1_5_II**	**AF-2.1_5_II**	**AF-3.1_9_II**
1	18.89	26.17	20.44	10.01	19.58	16.92
	(22.44%)	*(1.05%)*	*(12.89%)*	*(21.96%)*	*(10.45%)*	*(7.83%)*
7	25.27	30.46	24.26	18.12	23.83	20.29
	(6.45%)	*(2.60%)*	*(5.60%)*	*(14.93%)*	*(6.84%)*	*(12.08%)*
28	27.06	31.73	24.65	25.08	26.93	21.63
	(2.62%)	*(2.31%)*	*(4.36%)*	*(5.38%)*	*(5.71%)*	*(6.91%)*
Medium Dose						
Age (d)	**AF-1.1_7_I**	**AF-2.1_7_I**	**AF-3.1_11_I**	**AF-1.1_7_II**	**AF-2.1_7_II**	**AF-3.1_11_II**
1	11.97	24.99	20.94	13.88	16.56	13.75
	(3.80%)	*(5.50%)*	*(4.70%)*	*(4.11%)*	*(32.67%)*	*(8.61%)*
7	22.55	25.73	22.85	17.85	24.02	17.58
	(16.11%)	*(11.96%)*	*(4.29%)*	*(15.42%)*	*(3.38%)*	*(10.63%)*
28	25.53	32.22	23.28	25.66	24.08	21.24
	(3.36%)	*(3.50%)*	*(3.78%)*	*(19.98%)*	*(8.30%)*	*(4.53%)*

Figure 5.17 shows the development of these moduli. These are compared with the modulus estimated with the equations from the EHE-08 (24) using the results of compressive strength.

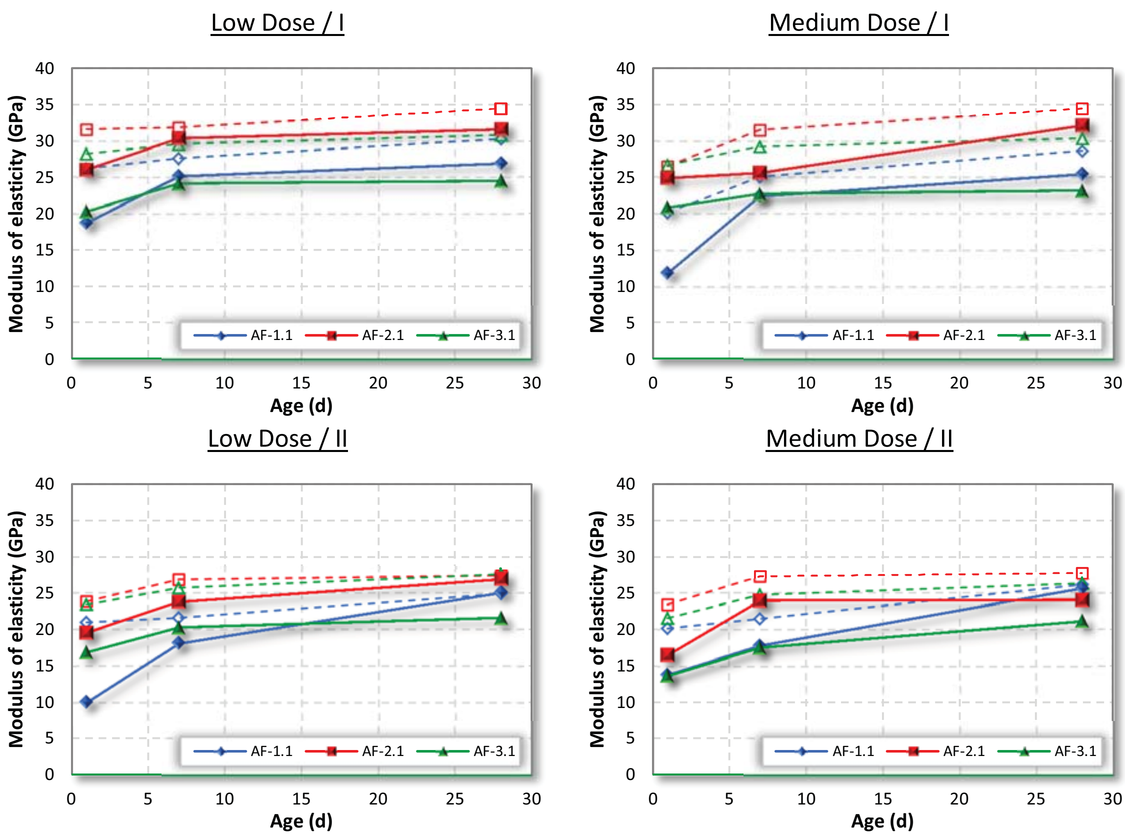


Figure 5.17- Modulus of elasticity measured (continuous lines) and estimated with EHE-08 equations (discontinuous lines) considering type of cement and dose of accelerator

The results evidence that the estimations performed using the equations from the EHE-08 are higher than the values obtained in the laboratory. This is observed in all cases except for the mix with low dose of accelerator AF-1.1 and cement II. Such difference decreases with the age of the sprayed concrete. The average difference is 25, 15 and 10% at 1, 7 and 28 d, respectively. This entails the necessity to find new equations or to adapt the equations of the elastic modulus of conventional concrete to sprayed concrete.

5.4. CONCLUDING REMARKS

The experimental analysis of sprayed concrete described in this chapter presents the steps to follow in order to perform a spraying process in a Laboratory. Also, it allows understanding the mechanical properties of the material at early and long ages. In this sense allows recognizing the mechanical behaviour of the sprayed concrete and how its mechanical properties interact with each other. Furthermore, it considers the incorporation of alkali-free accelerators in the mixes and how they affect in the properties of the sprayed concrete. Next, the main concluding remarks derived from this chapter are presented. These are divided in two groups: Concluding remarks of the spraying process and concluding remarks of the analysis of the results.

5.4.1. Spraying process

- A good lubricate of the hoses is essential before spraying the concrete as to avoid strokes during the spraying process. This must be done with water and cement. Strokes entail the dismantling of the concrete circuit (hoses, reductions and elbows) in order to be eliminated, and therefore a loss of time. And time is vital to assure the workability of the concrete.

- The workability of the concrete must be maintained form the beginning of the spraying to the end in order to assure the same properties of the sprayed concrete. Therefore Consistency Test must be performed during the spraying process. The result of this test should be at least 20 cm (liquid consistency) to avoid problems during the spraying process.

- Spraying concretes with the highest dose of accelerator (9%bcw) entailed problems during several sprayings. Spraying with high doses of accelerator involves strokes in the nozzle, which entail stopping the process. These stops entail spraying with different layers and joints, which negatively affect in the results achieved.

- Using the penetration needle test and the stud driving method, it is not possible to achieve the compressive strength of the sprayed concrete between 30 min and 4 h. Then it is necessary to propose a solution to this problem to understand the whole development of compressive strength in time.

- The low uniformity of the sprayed concrete with accelerator entailed obtaining different results using the stud driving method and the compressive strength test at 1 day. Therefore, it is recommended to perform both tests in order to assure a good quality control of the material.

5.4.2. Analysis of results

- A clear shape of the evolution of temperature in time is presented by the results. This starts with an initial increasing of the temperature due to the ettringite formation by reaction of dissolved aluminium, sulphates (from gypsum and accelerators) and aluminates C_3A of the cement, followed by a dormant period (inactivation of the chemical reactions). Next a second rising of temperature entails a peak due to the hydration of the silicates (C_2S and C_3S); and finally the temperature registered tends to be established with the ambient temperature.

- The shape of the evolution of temperature depends on the type of cement, the accelerator and the dose of accelerator used in the mixes. The amount of clinker depends on the type of cement. This is important during the hydration of the aluminates (C_3A) and the silicates (C_2S and C_3S). The type of accelerator is important for its chemical products which have more affinity to react either with the aluminates (1st peak) or with the silicates of the cement (2nd peak). Therefore if the accelerator has more affinity to react with the aluminate of the cement, low amount of it remains to react with the silicates, and vice versa. Finally, the higher the dose of accelerator used is, the higher the temperature is.

- The evolution of temperature and the energy produced during the hydration of cement (integral of evolution of temperature) are related with the compressive strength at early ages.

- The results obtained with the penetration needle test show the low importance of the type of cement up to 30 min. Regarding the type of cement, the results obtained are similar for the mixes with cement I and cement II. Even though, the type of addition is important due to its affinity with the accelerators.

- The compressive strength measured by the penetration needle test is possibly due to the quicker hydration of the C_3A, which produces ettringite able to provide certain compressive strength during the first minutes. This phenomenon is observed in the evolution of temperature as a first strong rising of temperature.

- The strength class of the cement is important from 4h after the spraying on and it is due to the amount of silicates (C_2S and C_3S) in clinker. This is visible in the results of the stud driving method as they are similar but the mixes with cement I are slightly higher than the ones with cement II.

- All mixes with Family 1, 2 and 3 accelerators analysed entailed sprayed concretes considered curves J2 and J3. Therefore the sprayed concrete analysed could have structural function according to the European Specification for Sprayed Concrete (62).

- The density and the porosity of the sprayed concrete tested are 2.16 g/cm^3 and 15.75%, respectively. These values differ to the ones of conventional concrete (density: 2.30 g/cm^3 and porosity: 7.00%). Such differences may be attributed to the inclusion of compressed air in the concrete during the process and the incorporation of accelerators, which reduce the setting time of the concrete and interfere with its compacting. This reduction of the density or increasing of the porosity directly affects the mechanical properties of the sprayed concrete.

- The mixes that present higher compressive strength at early ages present lower strength at long ages. This tendency is observed comparing the results of compressing strength with the ones obtained with the penetration needle test. This difference is possibly due to the effect of the accelerator at early ages, which effects porosity of the sprayed concrete and therefore its mechanical properties.

- The compressive strength at long ages depends on the strength class of the cement and less on the type of accelerator. The results obtained with mixes with cement I double the results obtained with mixes with cement II.

- The results of modulus of elasticity follow the tendency described by the results of compressive strength. Then, the modulus of elasticity is also affected by the porosity of the sprayed concrete. Finally, the results evidence that the estimations performed using the equations from the EHE-08 are higher than the values obtained in the laboratory. Such difference decreases with the age of the sprayed concrete. This entails the necessity to fins new equations or to adapt the equations of the elastic modulus of conventional concrete to sprayed concrete.

CHAPTER 6. RELATION BETWEEN CEMENT PASTES/MORTAR AND SPRAYED CONCRETE RESULTS

6.1. INTRODUCTION

The characterization of the mechanical properties of the sprayed concrete and the influence of the accelerators in laboratory conditions entails a specific preparation of the procedures in order to obtain realistic results as explained in Chapter 5. This characterization in laboratory requires a considerable investment on equipment and a large number of technicians. Furthermore, the adaptation of the laboratory facilities involves an enormous necessity of space. Apart from that, since the spraying should be in outdoors due to work conditions, the climatology is another variable.

An alternative to minimize these drawbacks would be to characterize the accelerators in a small scale, using cement pastes and mortars. However, this generates a problem of representativeness since the results obtained might not be the same as if sprayed concrete was characterized. Therefore, to make this approach viable, it is necessary to derive correlations that allow the conversion of the results obtained with pastes and mortars to the expected behaviour in sprayed concrete.

The objective of this chapter is to find the relationships between the experimental results obtained for cement pastes and mortars and the ones obtained for equivalent sprayed concrete. For that, initially the methodology used is described and then the best correlations are presented.

6.2. METHODOLOGY

The results of Chapter 3 - for cement pastes and mortars - and of Chapter 5 - for sprayed concrete - were used. Different groups of parameters were defined using these results. The temperature and the energy (which is the integral of the evolution of temperature in time) were obtained for characteristic points of the evolution of temperature in time: first peak of temperature, maximum temperature and the minimum temperature between peaks. The same parameters were also estimated at the fixed times of 3, 6, 10, 15, 20, 30, 40, 50 min and each hour from 1 to 24.

The mechanical and physical properties where divided on early and long ages results. The early age results were the ones obtained with the penetration needle and the stud driving method, whereas the long age ones covered the flexural and/or compressive strength test and the modulus of elasticity test. In addition to that, the results of the density and porosity were also considered. A total of 220 parameters were defined, which gathered a total of 7040 different results due for the 32 mixes studied.

In order to study the relationships between parameters, an analysis was performed in three phases. In the first phase, a preliminary filtering was performed in order to identify the parameters that present the highest correlation with each other. The correlation coefficient (R) was determined for all possible combinations of parameters, analysed by pairs. This led to 48000 estimations of R. Taking into account the intrinsic variability presented by the shotcrete, it was assumed that correlations above 0.50 were acceptable. In the second phase, two cement paste and/or mortar parameters were selected considering the highest values of R for each sprayed concrete parameter. A selection of two parameters was done so as to improve the R^2 of the parametric fitting.

The results of the three parameters were used to obtain an equation that related them through a non-linear regression using the experimental data curve fitting-software (LAB Fit). Furthermore, this software gave the R^2 of each relationship, factor used to consider or not if a relationship between parameters was acceptable. Finally, in order to take into account the intrinsic scatter of the results of sprayed concrete, calibration curves with confidence areas were assessed depending on the deviation of the experimental results. This was done according to the philosophy commonly used in standards to indirectly estimate the properties of sprayed concrete. An example for that is the calibration curve and the confidence area provided by the penetration needle test standard (46).

6.3. RESULTS AND ANALYSIS

This section presents the results and the analysis of the study of the correlation between parameters divided in two main parts. In the first part, the correlations of temperature and energy parameters are presented, whereas in the second part the mechanical and physical properties parameters are included. Notice that the parameters presented are the ones that presented a minimum R^2 equal or superior to 0.50. This value was considered as a minimum for establishing the confidence area for the correlation.

6.3.1. Temperature and energy parameters

The following points show a brief description of the main correlations obtained for the temperature and the energy.

- One of the most important temperature parameters of sprayed concrete is the first peak of temperature (SC_T_{1P}). This is directly related with the hydration of the aluminates presents in the cements (C_3A), a phenomenon that depends of the type of accelerator and its dose as observed in Chapter 3 and Chapter 5. In this sense, a high value of SC_T_{1P} indicates that the accelerator is more active at the beginning of the hydration process. The SC_T_{1P} is estimated using the first peak of temperature (M_T_{1P}) and the temperature attained at a time of 3 h (M_T_{3h}) of a mortar mix.

- Another important temperature parameter of sprayed concrete is the minimum temperature between peaks ($SC\_T_{Min1P\text{-}2P}$). This is directly related with the dormant period of the hydration of the cement. High values of $SC\_T_{Min1P\text{-}2P}$ indicate that the sprayed concrete mix is more active during the dormant period. The $SC\_T_{Min1P\text{-}2P}$ was correlated with the first peak of temperature (M_T_{1P}) and the temperature attained at a time of 1 h 30 min ($M\_T_{1h30min}$) of a mortar mix.

- The maximum temperature of sprayed concrete (SC_T_{max}) is also an important parameter. This is directly related with the hydration of the silicates presents in the cements (C_2S and C_3S). In this sense, the value of SC_T_{max} is related to the quantity of C-S-H chains formed in the mix and, therefore, is and indicator of the strength of the sprayed concrete. The SC_T_{max} was estimated with the flexural strength at 12 h (M_F_{12h}) and the compressive strength at 12 h (M_C_{12h}) of a mortar mix.

- The temperature at 1 h (SC_T_{1h}) was considered since the minimum temperature between peaks usually takes place between 1h and 1h 45 min. This is observed in the results of evolution of temperature of Chapter 5. Then, this parameter is related to $SC\_T_{Min1P\text{-}2P}$. The SC_T_{1h} was correlated with the first peak temperature (M_T_{1P}) and the temperature attained at a time of 1h 45 min ($M\_T_{1h45min}$) of a mortar mix.

- The last temperature parameter is the temperature at 6 h (SC_T_{6h}), which is related with the hydration of both the aluminates and the silicates of the cement (C_2S and C_3S). The SC_T_{6h} is estimated with the flexural strength at 12 h (M_F_{12h}) and the compressive strength at 12 h (M_C_{12h}) of a mortar mix.

- Regarding the energy parameters, a good correlation was obtained for the energy at minimum temperature between peaks ($SC\_E(T_{Min1P\text{-}2P})$). This is directly related with the dormant period of the hydration of the cement and, hence, to the temperature parameter $SC\_T_{Min1P\text{-}2P}$. $SC\_E(T_{Min1P\text{-}2P})$ is estimated using the energy at the minimum temperature between peaks of a cement paste mix ($CP\_E(T_{Min1p\text{-}2P})$) and the same parameter for a mortar mix ($M\_E(T_{Min1P\text{-}2P})$).
- Finally, another parameter considered is the energy at maximum temperature ($SC\_E(T_{max})$). This is directly related with the hydration of the silicates presents in the cements (C_2S and C_3S), phenomenon strictly related with the gain of long age strength of the mix. The $SC\_E(T_{max})$ is estimated with the energy at 3 min ($M\_E(T_{3min})$) and the temperature attained at a time of 24 h (M_T_{24h}) of a mortar mix.

Table 6.1 summarizes the input parameters used to assess the properties of the sprayed concrete. Furthermore, the table gathers the equations that must be used to evaluate the parameters and the coefficients A, B and C obtained fitting the results in the software LABFit. Finally, the R^2 and the relative error (E_r) committed in the estimations are also presented in order to show the goodness of the fits.

Table 6.1- Parameters, equations and error for the temperature and energy parameters

P1	P2	P3	Eq.	A	B	C	R^2	E_r (%)
SC_T_{1P}	M_T_{1P}	M_T_{3h}	6.1	1.95E+01	-5.06E-01	2.30E+01	0.56	5.22
$SC\_T_{Min\ 1P\text{-}2P}$	M_T_{1P}	$M\_T_{1h30min}$	6.2	1.24E+01	8.64E-03	-	0.66	4.83
SC_T_{max}	M_F_{12h}	M_C_{12h}	6.3	-3.30E+01	-1.56E+00	1.33E-02	0.62	5.31
SC_T_{1h}	M_T_{1P}	$M\_T_{1h45min}$	6.4	9.17E+00	-6.01E-03	2.14E+01	0.54	5.71
SC_T_{6h}	M_F_{12h}	M_C_{12h}	6.5	3.71E+01	3.05E-01	-2.24E+01	0.74	5.16
$SC\_E(T_{Min1P\text{-}2P})$	$CP\_E(T_{Min1p\text{-}2P})$	$M\_E(T_{Min1P\text{-}2P})$	6.6	1.55E+03	1.57E+04	1.60E+00	0.61	33.33
$SC\_E(T_{max})$	$M\_E(T_{3min})$	M_T_{24h}	6.7	5.83E-04	-1.05E-05	-3.62E-02	0.52	28.48

$$SC\_T_{1P} = \frac{M\_T_{1P}}{(A + B \cdot M_{T_{3h}}) + C} \tag{6.1}$$

$$SC\_T_{Min1P-2P} = A \cdot M\_T_{1P}^{(B \cdot M\_T_{ah30min})} \tag{6.2}$$

$$SC\_T_{max} = A \cdot [EXP(B \cdot M\_F_{12h}) - EXP(C \cdot M\_C_{12h})] \tag{6.3}$$

$$SC\_T_{1h} = \frac{M\_T_{1h45min}}{(A + B \cdot M\_T_{1P}{}^2) + C} \tag{6.4}$$

$$SC\_T_{6h} = A + B \cdot M\_C_{12h} + \frac{C}{M\_F_{12h}{}^2} \tag{6.5}$$

$$SC\_E(T_{Min1P-2P}) = A \cdot \left\{ \left[\frac{CP\_E(T_{Min1P-2P})^C}{B} \right] \cdot EXP \left[\frac{M\_E(T_{Min1P-2P})}{B} \right] \right\} \tag{6.6}$$

$$SC\_E(T_{max}) = \frac{1}{\left[A + B \cdot M\_T_{24h} + \frac{C}{M\_E(T_{3min})} \right]} \tag{6.7}$$

Considering the R^2 the parameter which presents better fitting is the temperature parameter *SC_T_{6h}* (0.74), whereas the lowest R^2 is presented by the energy parameter *$SC\_E(T_{max})$* (0.52). Regarding the relative error, the average relative error of the estimation of the temperature parameters is around 5%, whereas the energy parameters show errors close to 30%. This indicates that the correlations with the energy parameters should be avoided in favour of correlations with the temperature.

Table 6.2 presents the ranges of applicability of the parameters in each correlation. These ranges were defined according to the experimental results. It is important to remark that using the correlation out of these ranges could not assure a good estimation of the results.

Table 6.2- Ranges of applicability of correlations for the temperature and energy parameters

P1		P2		P3	
Definition	**Range**	**Definition**	**Range**	**Definition**	**Range**
SC_T_{1P}	25-35 °C	M_T_{1P}	24-34 °C	M_T_{3h}	24-33 °C
$SC\_T_{Min1P-2P}$	25-35 °C	M_T_{1P}	24-33 °C	M_T_{1h30mi}n	24-33 °C
SC_T_{max}	25-35 °C	M_F_{12h}	1.50-4.50 MPa	M_C_{12h}	4.50-22 MPa
SC_T_{1h}	25-35 °C	M_T_{1P}	24-33 °C	$M\_T_{1h45min}$	24-33 °C
SC_T_{6h}	25-45 °C	M_F_{12h}	1.50-5 MPa	M_C_{12h}	4-22 MPa
$SC\_E(T_{Min1P-2P})$	1750-11000 h·°C	$CP\_E(T_{Min1p-2P})$	11000-22000 h·°C	$M\_E(T_{Min1P-2P})$	5500-23000 h·°C
$SC\_E(T_{max})$	10000-23000 h·°C	$M\_E(T_{3min})$	120-140 h·°C	M_T_{24h}	20-25 °C

Finally, Figure 6.1 gathers the comparison between the experimental values and the estimations done using the correlations proposed. Each graph presents an area delimited by the range of the parameter (Table 6.2) and a deviation in the result equal to 10%. This deviation was defined considering the typical scatter found in the tests of the sprayed concrete. The percentages of results within the confidence area are also included.

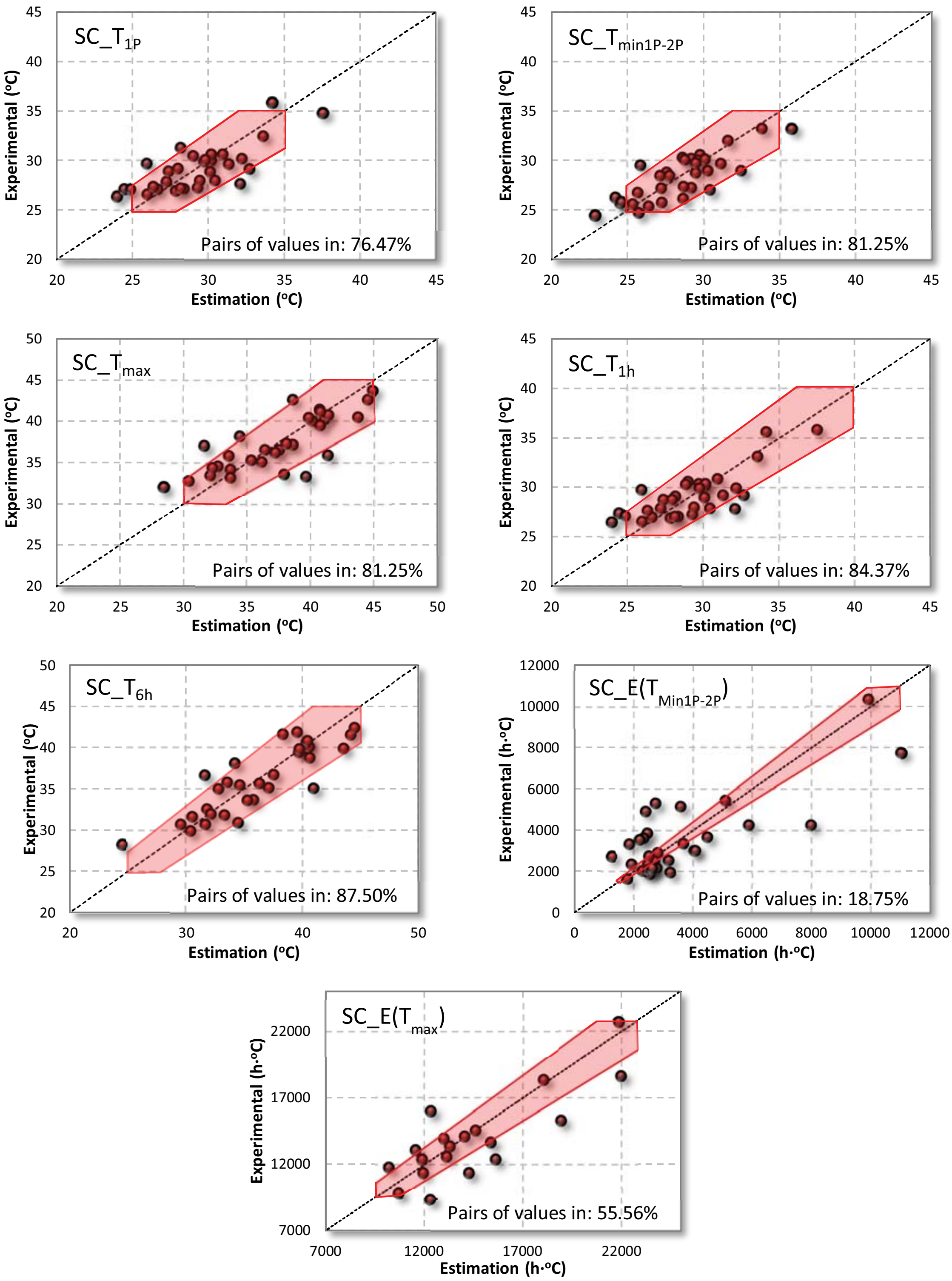


Figure 6.1- Confidence area for the temperature and energy parameters

As observed in Table 6.1 regarding the results of the relative error, the energy parameters present less values inside the confidence area, being the parameter $SC\_E(T_{Min1P-2P})$ the one with the lowest percentage (18.75%). On the other hand, all the temperature parameters present percentages higher than 75%, being the highest 87.50% found for the parameter SC_T_{6h}.

6.3.2. Mechanical and physical properties parameters

Following the same structure as the former section, firstly, the mechanical and physical parameters of sprayed concrete considered are presented describing their importance for the characterization of the material properties.

- The compressive strength at very early ages is important to evaluate the performance of the accelerators in sprayed concrete mixes. Therefore, the compressive strength at 3 min (SC_P_{3min}) is considered. This parameter may be related with the energy produced during the early ages of concrete. The $SC\_E(T_{1P})$. SC_P_{3min} is estimated using the flexural strength at 7 d (M_F_{7d}) and the compressive strength at 7 d (M_C_{7d}) of a mortar mix.

- Another strength parameter related to the performance of the accelerators in the mixes at very early ages is the compressive strength at 30 min (SC_P_{30min}). The SC_P_{30min} is estimated through the assessment of the temperature attained at a time of 5 h of a cement paste mix (CP_T_{5h}) and the temperature attained at a time of 3 min of a mortar mix (M_T_{3min}).

- The compressive strength at 6 h (SC_SDM_{6h}) is linked with the hydration of the silicates of the cement (C_2S and C_3S) between 6 and 12 h. Therefore, this parameter may be related with the energy one $SC\_E(T_{max})$. The SC_SDM_{6h} was correlated with the flexural strength at 12 h (M_F_{12h}) and the compressive strength at 12 h (M_C_{12h}) of a mortar mix.

- Finally, the last strength parameter is the compressive strength at 24 h (SC_SDM_{24h}). This is also considered as indicator of the performance of the accelerator. The SC_SDM_{24h} is estimated using the temperature attained at a time of 11 h (CP_T_{11h}) and the temperature attained at a time of 12 h (CP_T_{12h}) of a mortar mix.

- The physical parameter derived from this study is the porosity at 28 d (SC_p_{28d}) It should be taken into account since the porosity may affect the mechanical properties of the sprayed concrete, such as the compressive strength or the modulus of elasticity. The SC_p_{28d} was correlated with the maximum temperature (CP_T_{max}) and the energy at the minimum temperature between peaks ($CP\_E(T_{Min\ 1P\text{-}2P})$) of a cement paste mix.

The cement paste/ mortar parameters used to obtain each sprayed concrete parameter are shown in Table 6.3. Furthermore, the equations and coefficients to estimate the sprayed concrete parameters are gathered in the table. Finally, the results assessed of the R^2 and the relative errors (E_r) are also presented in order to show the goodness of the fits.

Table 6.3- Parameters, equations and error for the mechanical and physical parameters

P1	P2	P3	Eq.	A	B	C	R^2	E_r (%)
SC_P_{3min}	M_F_{7d}	M_C_{7d}	6.8	1.40E+00	-1.11E-01	-1.33E-04	0.50	26.49
SC_P_{30min}	CP_T_{5h}	M_T_{3min}	6.9	1.89E+00	-4.19E+00	-	0.67	2.91
SC_SDM_{6h}	M_F_{12h}	M_C_{12h}	6.10	-2.63E-01	4.27E-02	3.00E+00	0.64	34.12
SC_SDM_{24h}	CP_T_{11h}	CP_T_{12h}	6.11	8.48E+00	-6.54E+01	-9.72E-01	0.63	9.01
SC_p_{28d}	CP_T_{max}	$CP\_E(T_{Min1P-2P})$	6.12	2.53E-01	2.41E-04	3.57E+06	0.95	0.00

$$SC\_P_{3min} = A + B \cdot M\_F_{7d} + C \cdot {M\_F_{7d}}^2 \tag{6.8}$$

$$SC\_P_{30min} = A \cdot {M\_T_{3min}}^{\left(\frac{B}{M\_T_{3h}}\right)} \tag{6.9}$$

$$SC\_SDM_{6h} = \frac{1}{\left(A + B \cdot M\_C_{12h} + \frac{C}{M\_C_{12h}}\right)} \tag{6.10}$$

$$SC\_SDM_{24h} = EXP\left[A + \frac{B}{CP\_T_{12h}} + C \cdot \ln(CP\_T_{11h})\right] \tag{6.11}$$

$$SC\_p_{28d} = A \cdot CP\_T_{max} + B \cdot CP\_E(T_{Min1P-2P}) + \frac{C}{{CP\_T_{max}}^4} \tag{6.12}$$

The physical parameter *SC_p_{28d}* is the one that presents the best fitting (0.95) regarding the R^2. On the other hand the lowest R^2 is presented by the energy parameter *SC_P_{3min}* (0.50). Regarding the relative error, the average relative error of the estimation of the mechanical properties parameters is around 20% whereas, the one of the physical one is around 0%. Notice that different estimation equations are presented for each parameter.

Apart from that, the ranges of applicability (and their units) of the parameters in the equations are presented in Table 6.4. The experimental results defined these ranges. As mentioned for the temperature and energy parameters, using the equation out of these ranges could not assure a good estimation of the results.

Table 6.4- Ranges of applicability of correlations for the mechanical and physical parameters

P1		P2		P3	
Definition	Range	Definition	Range	Definition	Range
SC_P_{3min}	0.2-1.0 MPa	M_F_{7d}	4.0-7.5 MPa	M_C_{7d}	23-52 MPa
SC_P_{30min}	0.8-1.0 MPa	CP_T_{5h}	24-33 °C	M_T_{3min}	14-20 °C
SC_SDM_{6h}	2.5-15 MPa	M_F_{12h}	1.5-4.5 MPa	M_C_{12h}	4.5-20 MPa
SC_SDM_{24h}	10-15 MPa	CP_T_{11h}	23-46 °C	CP_T_{12h}	23-42 °C
SC_p_{28d}	14-17 Kg/m^3	CP_T_{max}	35-45 °C	$CP\_E(T_{Min1P-2P})$	14000-21000 h·°C

The comparing between the experimental values and the estimations done for each sprayed concrete parameter are presented in Figure 6.2. The figure presents the confident area delimited by the range of the parameter (Table 6.2) and a deviation in the result. In this case, the deviation was calculated considering the experimental results since different values were determined for each experimental test. Finally, in the graph there is presented the percentage of pairs of values which are inside the confident area.

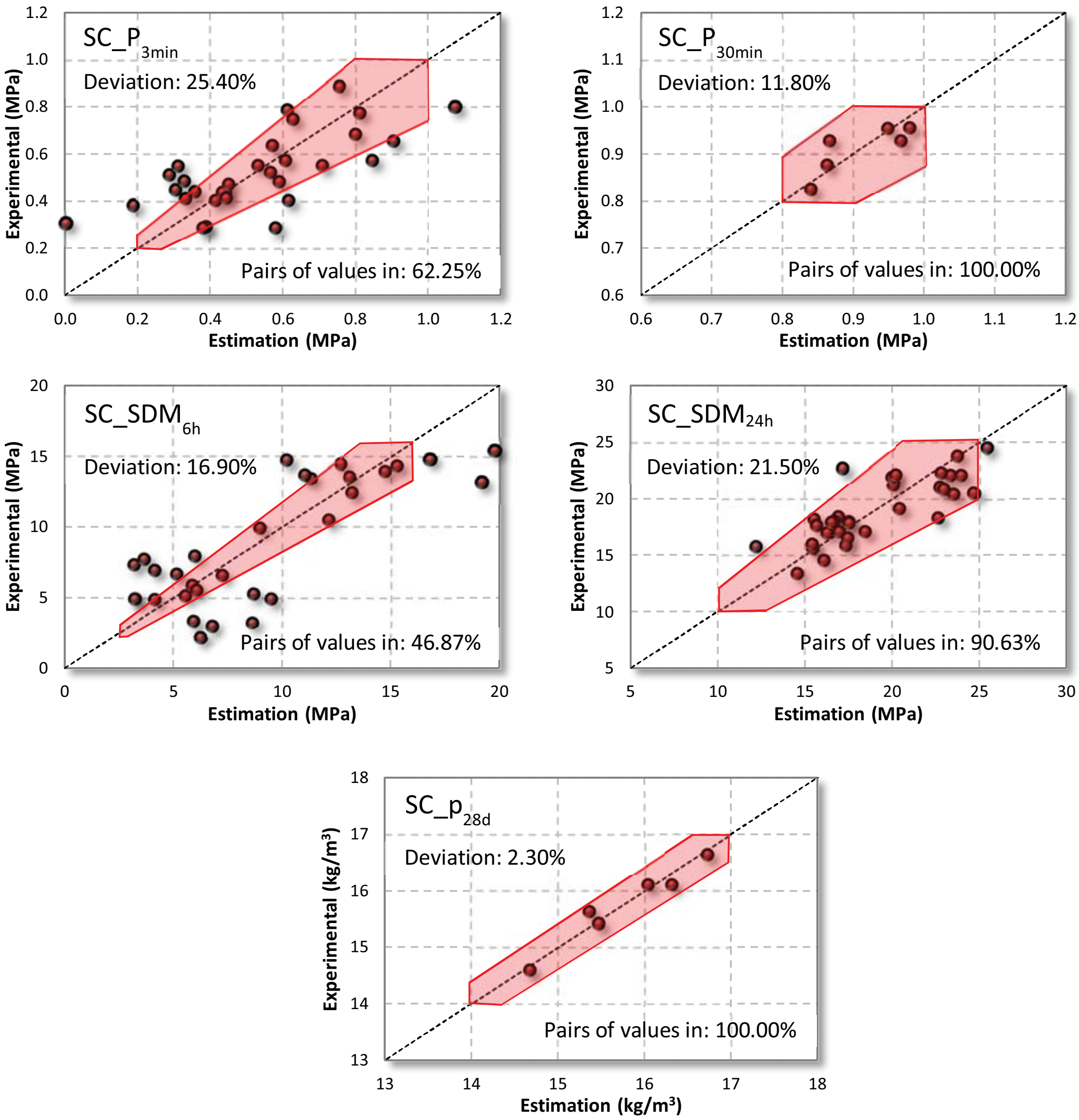


Figure 6.2- Confidence area for the mechanical and physical parameters

All the parameters present percentages higher than 60%, less SC_SDM_{6h}, which presents a 46.87% of pairs of values inside the confident area. Notice, the parameters SC_P_{30min} and SC_p_{28d} present all pairs of values inside the confident area. This may be possibly due to the low number of results available.

6.4. CONCLUDING REMARKS

The following concluding remarks are derived from the analysis presented in this chapter.

- Although many parameters were measured, in most cases the correlation between the results for pastes, mortars and sprayed concrete do not present a good fit.

- The high scatter of the results, the differences in the composition of the mix and the differences in the production processes are responsible for the poor correlation obtained for most parameters.
- The high scatter observed is intrinsic to sprayed concrete. To account for that, the definition of a confidence area for the correlation curves is a necessary approach.
- Using this approach, acceptable correlation curves and the corresponding confidence areas were obtained. This shows that it is possible to use the results from cement pastes and mortars to estimate the properties of sprayed concrete.

It is important to remark that better correlation could be obtained if a similar production process through spraying of cement paste and mortars was used.

CHAPTER 7. ESTIMATION OF THE MODULUS OF ELASTICITY FOR SPRAYED CONCRETE

7.1. INTRODUCTION

As widely explained in Chapter 2 sprayed concrete is a special concrete that combines the placement and the compacting of the material in only one process (52; 70). This is a large advantage from an engineering point of view because the execution period of a construction can be reduced using this technology. Recent improvement focused on attaining high quality, homogeneous, environmental safe sprayed concrete has been achieved by the use of wet-mix process, advances in mix proportions, and the development of alkali-free accelerators (2). These improvements jointly with the aforesaid advantage increased the importance of sprayed concrete in the construction world. Hence, this material is widely used in underground construction such as tunnelling, although with little structural responsibility (3; 11). However, it could be interesting to consider the sprayed concrete contribution as structural element in order to reduce the thickness of other structural elements (71). Therefore a reduction of the execution time and the production costs of the whole construction could be achieved. In this sense, the sprayed concrete needs to be studied deeper as it does not have the same characteristics of a conventional concrete. These differences are due to the spraying process which entails both variation of the mix proportions of the concrete (rebound) and higher porosity. Therefore fundamental parameters of structural design such as compressive strength and modulus of elasticity must be studied considering these differential aspects.

One of the aforementioned fundamental parameters is the modulus of elasticity which is important in structural design in order to determinate strain and displacements. This property is normally measured using tests based on specimens subjected to uniaxial compressive loading according to specific standards (67; 72). Furthermore, simplified empirical expressions obtained after linear regression of experimental data are also available for conventional and high performance concrete based on the compressive strength of the material (73). In this sense, former studies from the literature focused on the modulus of elasticity, although they were based on the results obtained with sprayed mortar instead of sprayed concrete. These studies also gave empirical expressions to estimate its modulus of elasticity (74). However, all these expressions are not adequate to evaluate the modulus of elasticity of the sprayed concrete. Therefore, no expression to estimate the modulus of elasticity of the sprayed concrete currently exists.

This chapter analyses the experimental results obtained in Chapter 5 in order to propose analytical and empirical equations to estimate the modulus of elasticity of sprayed concrete. The proposed equations are based on the expressions to estimate the modulus of conventional concrete (24; 40; 41). Finally, these proposals are validated with results experimentally obtained in-situ.

7.2. DEFINITIONS

Before analysing the data obtained in Chapter 5 some definitions are presented in this section. The Modulus of Elasticity (E) is defined as the mathematical description of material's tendency to be deformed elastically when a force is applied to it. Hence, it is defined as the slope of its stress–strain curve (σ-ε) in the elastic deformation region (Figure 7.1). Furthermore, the modulus of elasticity is defined in two different ways according with the scientific literature. Firstly, the Tangent Modulus of Elasticity (E_{ci}) is the tangent at a certain point of the stress-strain diagram (Figure 7.1). On the other hand, the Secant Modulus of Elasticity (E_{cm}) is given by the slope of a straight line between the coordinate system origin and a certain point of the stress-strain diagram (Figure 7.1).

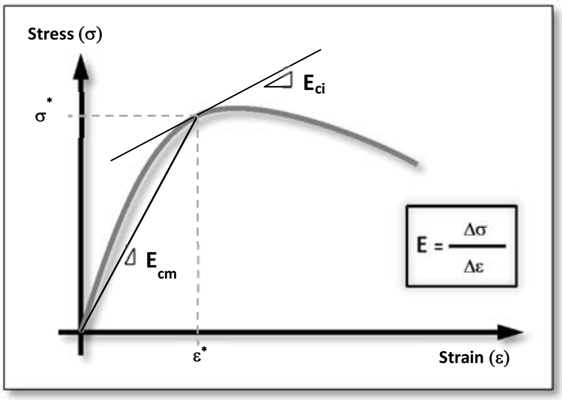


Figure 7.1- Stress–strain curve

The study focuses on the secant modulus of elasticity. This is the one obtained during the experimental program presented in Chapter 5, being the point chosen in the diagram 0.30·σ_f (σ_f: failure stress). Therefore, from here on the statement modulus of elasticity refers to the secant and not the tangent one.

7.3. EXPERIMETAL PROGRAM

The first step to obtain new expressions to estimate the modulus of elasticity for sprayed concrete is analysing the results from Chapter 5. This analysis is focused on the results at long ages: compressive strength and modulus of elasticity. Furthermore, the results of porosity are also analysed as it is a differential parameter between conventional and sprayed concrete.

7.3.1. Method

The experimental program, which was performed in the Laboratory of Technology of Structures Luis Agulló (UPC), was presented in the Chapter 5. This presents the materials and the composition of the mixes, the spraying processes followed and the test methods performed.

7.3.2. Results and analysis

The experimental program detailed in the previous section allowed obtaining results of compressive strength, modulus of elasticity and porosity. In this section these are analysed. The results of compressive strength (f_{cm}) and modulus of elasticity (E_{cm}) are gathered in Table 7.1 by family, type and dose of accelerator and type of cement.

The results show a direct relation between the compressive strength and the modulus of elasticity as the higher the first is, the higher the second is, independently of the age of the mixtures and the doses of accelerators. This direct relationship is similar to the observed in conventional concrete and in other special concretes (25). Apart from that, the mixtures with CEM I 52.5 R (I) present the highest results with the accelerator AF-2.2, whereas the mixtures with CEM II/A-L 42.5 R (II) present the highest results AF-2.1. All mixtures present the lowest results when they are mixed with AF-1.1, independently of the type of cement.

Regarding the dose of accelerator, the results of the mixes produced with cement I and lowest dose of accelerator present the highest compressive strength independently of the type of accelerator. The same tendency is seen by the mixes with accelerators AF-2.2, AF-3.1 and AF-3.2 in mixes with the cement II. In this sense the values followed a desired tendency because former studies in UPC indicate an optimal dose of alkali-free accelerator of around 6%bcw (33; 52). Furthermore, a second tendency is observed as the highest the dose of admixture is, the lower the compressive strength obtained is. This reveals a possible overdose of the set accelerating admixture which entails a formation of amorphous components during the early hydration of the cement that negatively affects the compressive strength of the sprayed concrete at long ages.

Table 7.1- Compressive strength (MPa) and modulus of elasticity (GPa)

Family	Accelerator	Age (d)	Dose (%)	CEM I 52.5 R		CEM II/A-L 42.5 R	
				f_{cm}	E_{cm}	f_{cm}	E_{cm}
1	AF-1.1	1	5	20.74	18.89	8.88	10.01
			7	11.90	11.97	12.33	13.88
			9	12.59	-	7.98	7.78
		7	5	33.48	25.27	15.73	18.12
			7	24.68	22.55	15.21	17.85
			9	15.84	12.08	14.48	15.29
		28	5	45.56	27.06	25.18	25.08
			7	38.38	25.53	29.22	25.66
			9	31.17	23.87	29.52	26.00
	AF-1.2	1	5	30.56	23.44	16.87	13.39
			7	29.25	23.55	15.21	13.84
			9	23.20	21.29	20.35	18.17
		7	5	45.71	26.92	33.23	21.86
			7	41.26	26.26	29.27	22.37
			9	37.09	23.30	32.20	25.45
		28	5	51.96	29.04	45.34	26.98
			7	47.07	26.48	46.75	27.36
			9	46.73	26.72	38.45	25.51
2	AF-2.1	1	5	38.56	26.17	19.95	19.58
			7	27.94	24.99	19.80	16.56
			9	27.84	23.02	19.81	16.89
		7	5	51.42	30.46	31.34	23.83
			7	49.87	25.73	33.18	24.02
			9	47.79	26.89	33.42	22.34
		28	5	66.69	31.73	33.43	26.93
			7	66.47	32.22	34.79	24.08
			9	57.39	29.40	33.09	26.39
	AF-2.2	1	5	32.61	24.22	17.70	19.01
			7	34.00	23.53	14.69	14.77
			9	31.73	24.28	7.32	7.22
		7	5	42.60	26.17	34.09	25.45
			7	43.37	26.71	30.87	23.78
			9	40.34	24.86	15.75	21.22
		28	5	48.73	28.13	41.15	25.61
			7	53.49	29.89	38.98	24.19
			9	45.79	25.43	32.19	23.88
3	AF-3.1	1	9	31.21	20.44	15.76	16.92
			11	29.64	20.94	15.29	13.75
		7	9	41.90	24.26	27.25	20.29
			11	40.27	22.85	24.37	17.58
		28	9	47.97	24.65	34.20	21.63
			11	45.96	23.28	29.89	21.24
	AF-3.2	1	9	27.67	20.81	16.74	16.28
			11	13.12	13.33	14.92	14.71
		7	9	38.43	23.89	28.03	21.93
			11	28.24	17.81	26.66	20.75
		28	9	45.44	26.31	31.55	22.37
			11	34.97	19.35	29.84	23.32

In order to deeply analyse the experimental results Figure 7.2 is presented. It shows the results considering the age of the samples and the type of cement used.

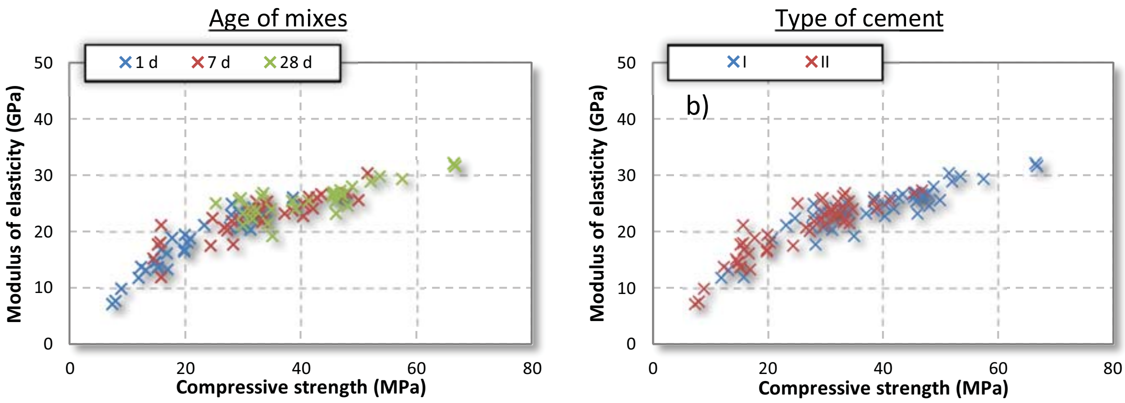


Figure 7.2- Relationship between the compressive strength and the modulus of elasticity regarding age of samples and type of cement

Considering the results plotted in Figure 7.2, the older the mixture is, the higher its compressive strength is and hence, its modulus of elasticity. A decrease of compressive strength at long ages, which can be observed in mixes with accelerators based on aluminates, is not visible in the results as alkali-free accelerators were used (52). Furthermore, considering the type of cement, Figure 7.2 shows higher results when the mixes are produced with cement type I. This was expected since the strength class of cement I is higher than the one of cement II.

The porosity was evaluated on two different mixes at 28 days. The results are shown in Table 7.2 with the results of compressive strength according to the doses of accelerators.

Table 7.2- Porosity

Cement	Accelerator	Dose (%)	Compressive Strength (MPa)	Porosity (%)		
				By Dose	By accelerator	Mean
I	AF-1.2	5	45.34	14.67	15.61	15.75
		7	46.75	15.46		
		9	38.45	16.71		
	AF-2.2	5	41.15	16.30	15.89	
		7	38.98	15.35		
		9	32.19	16.03		

The results show that the porosity obtained is similar in both mixtures. Therefore, a porosity of around 16% could be assumed as a reference value for sprayed concrete. As observed, the porosity of sprayed concrete is higher than the one of conventional concrete (7-9%) (75). This is basically due to the spraying process. It is known that the increase of porosity may lead to a reduction of the compressive strength and the modulus of elasticity of the material (76). Then, as the porosity of the sprayed concrete is higher than the one of conventional concrete, it entails smaller compressive strength and, therefore smaller modulus of elasticity.

7.4. EQUATIONS FROM THE LITERATURE

As said before, currently the modulus of elasticity for sprayed concrete cannot be estimated using any equation presented in any code or recommendation. Therefore, to treat this concrete as structural material equations are needed. In order to know if the equations used for conventional concrete may be used or adapted for sprayed concrete a review of the codes and recommendations is done. Then, three different Instructions are presented: the Model Code (40), the Eurocode 2 (41) and the Instruction EHE-08 (24).

7.4.1. Model Code 2010

The Model Code 2010 aims to synthesize research findings, to define new research directions and to produce design recommendations. It had a considerable impact on the national codes in many countries. The Code presents Equation 7.1 which is used to estimate the modulus of elasticity for normal weight concrete with natural sand and gravel at 28 days. Furthermore, when the actual compressive strength of concrete at an age of 28 days (f_{cm}) is known, the modulus of elasticity may be estimated from Equation 7.2 ($f_{cm} = f_{ck} + \Delta f$).

$$E_{cm} = E_{co} \cdot \alpha_E \cdot \left(\frac{f_{ck} + \Delta f}{10}\right)^{1/3} \quad (7.1)$$

$$E_{cm} = E_{co} \cdot \alpha_E \cdot \left(\frac{f_{cm}}{10}\right)^{1/3} \quad (7.2)$$

In accordance with the notations used, E_{cm} is the modulus of elasticity at concrete age of 28 days (GPa); f_{ck} is the characteristic strength (MPa); Δf is equal to 8 MPa; E_{co} is equal to $21.5 \cdot 10^3$ MPa, and the coefficient α_E depends on the type of aggregate (Table 7.3). In this case, α_E is equal to 1.2 since dense limestone aggregates were used in the mixes.

Table 7.3- Effect of type of aggregate on modulus of elasticity

Types of aggregates	α_E	$E_{co} \cdot \alpha_E$ (GPa)
Basalt, dense limestone aggregates	1.2	25.8
Quartzite aggregates	1.0	21.5
Limestone aggregates	0.9	19.4
Sandstone aggregates	0.7	15.1

Apart from the equations to estimate the modulus of elasticity at 28 days, the Model Code also presents an equation (Equation 7.3) to estimate its development in time. Where, E_{cm} and $E_{cm,j}$ are the modulus of elasticity at 28 and *j* days, respectively (GPa); *t* is the age of concrete (d), and the coefficient *s* depends on the type of cement (strength class) and the compressive strength of the concrete (Table 7.6). In this case, *s* is equal to 0.20 as cements with strength class 42.5 R and 52.5 R were used in the mixes.

$$E_{cm,j} = \sqrt{\exp\left\{s \cdot \left[1 - \left(\frac{28}{t}\right)^{0.5}\right]\right\}} \cdot E_{cm} \tag{7.3}$$

Table 7.4- Coefficient *s* to be used in Equation 7.3 for different types of cement

f_{cm} (MPa)	Strength class of cement	s
≤ 60	32.5 N	0.38
	32.5 R, 42.5 N	0.25
	42.5 R, 52.5 N, 52.5 R	0.20
> 60	All classes	0.20

7.4.2. Eurocode 2

The Eurocode 2, focused exclusively on concrete construction, is the code used in Europe. In case of the modulus of elasticity the code presents estimations considering the strength class of the conventional concrete. These values are gathered in Table 7.5. The values are based on the Equation 7.4, where E_{cm} and f_{cm} are the modulus of elasticity (GPa) at concrete age of 28 days and the mean value of concrete cylinder compressive strength (MPa), respectively.

Table 7.5- Values of modulus of elasticity (GPa)

Strength Class	C12/15	C16/20	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60
E_{cm}	26.0	27.5	29.0	30.5	32.0	33.5	35.0	36.0	37.0

$$E_{cm} = 9.5 \cdot \sqrt[3]{f_{cm}} \tag{7.4}$$

The code explains that the values (Table 7.5) are related to concrete cured under normal conditions and made with aggregates predominantly consisting of quartzite gravel. Then when deflections are of great importance, tests should be performed on concrete made with the aggregate to be used in the structure.

Finally, since the strength classes of concrete correspond to strength at an age of 28 days, the values for E_{cm} in Table 7.5 also relate to that same age. When great accuracy is not required, the modulus of elasticity may also be determined from Equation 7.6 for a concrete age *j* other than 28 days. In this case, the strength class is replaced by the actual concrete strength at the time *j* ($f_{cm,j}$).

$$E_{cm,j} = 9.5 \cdot \sqrt[3]{f_{cm,j}} \tag{7.5}$$

7.4.3. EHE-08

The Instruction EHE-08 defines design recommendations for concrete structures in Spain. It presents Equation 7.6 to estimate the modulus of elasticity at an age of 28 days (E_{cm} in GPa) considering the mean value of concrete cylinder compressive strength (f_{cm} in MPa).

$$E_{cm} = \alpha \cdot 8.5 \cdot \sqrt[3]{f_{cm}} \tag{7.6}$$

In this sense, the coefficient α depends on the nature of the aggregates. The values of this coefficient are presented in Table 7.6. In case of the study α is equal to 1.2 as dense limestone aggregates were used in the mixes.

Table 7.6- Coefficient α to be used in Equation 7.8 in function of the type of aggregate

Type of aggregate		α
Quartzite		1.0
Sandstone		0.7
Limestone	Normal	0.9
	Dense	1.2
Ophite, ballast, and other volcanic stones	Porous	0.9
	Normal	1.2
Granite and other plutonic stones		1.1
Diabases		1.3

In order to estimate the modulus of elasticity at ages other than 28 days, the Spanish instruction considers the difference between the development of the compressive strength and modulus of elasticity in time. Therefore, that estimation is done with the Equation 7.7. Where E_{cm} and $E_{cm,j}$ are the modulus of elasticity at 28 and *j* days (GPa); f_{cm} and $f_{cm,j}$ are the mean value of concrete cylinder compressive strength at 28 and j days (MPa), respectively.

$$E_{cm,j} = \left(\frac{f_{cm,j}}{f_{cm}}\right)^{0.3} \cdot E_{cm} \tag{7.7}$$

7.5. EVALUATION OF EXISTING FORMULATION

The compressive strengths measured in the laboratory were used in the equations described in section 4 to estimate the modulus of elasticity of sprayed concrete. Figure 7.3.a, 4.b and 4.c compare the estimated values and the elastic modulus measured in the laboratory respectively at 1, 7 and 28 days. Moreover, Figure 7.3.d presents the relation between the experimental data and the estimations obtained with all data.

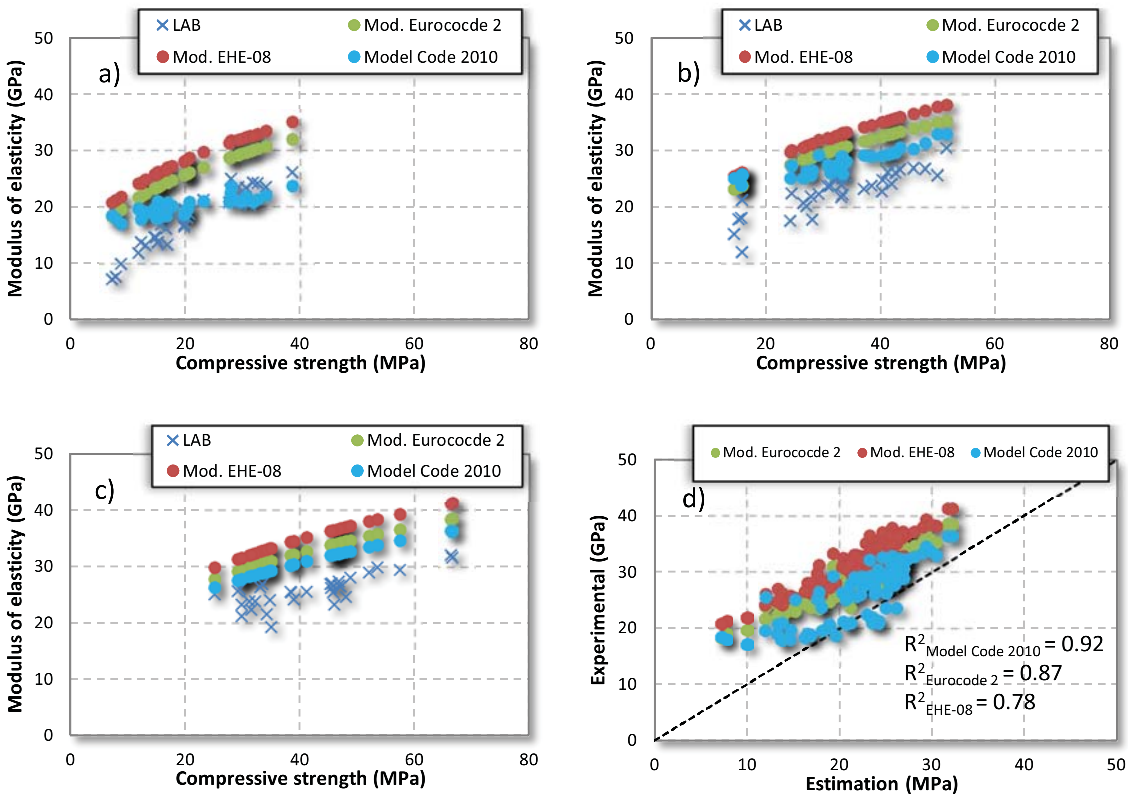


Figure 7.3- Comparison between results from laboratory and estimation from Instructions at 1 day a); 7 days b); 28 days c) and evaluation of the fit considering all data d)

In general, the results obtained in the laboratory are significantly lower than the estimated with the equations from the codes and instructions analysed. The differences observed in the tendencies were expected since the empirical formulations do not take into account specific characteristics of the sprayed concrete such as the higher porosity, the fast setting and the different mix proportions due to the rebound. The influence of these parameters should be more noticeable for mixes with smaller strength or at early ages, when the accelerators are the responsible for the gain in the mechanical properties. As time passes, the hydration of the cement takes place and decreases the overall repercussion of the factors mentioned before. Consequently, the predictions of the modulus of elasticity should be more accurate for long ages. This is clearly observed for the predictions of the Eurocode 2 and EHE-08 in Figure 7.3.a, 4.b and 4.c.

Regardless of the age of the mixes, the results obtained with the equations of the Model Code 2010 present the best fit with the experimental results, showing a R^2 of 0.92. On the other hand, the results obtained with the equations from EHE-08 shows the biggest deviation from the experimental results (R^2 equal to 0.78). Finally, the estimations obtained with the equations from the Eurocode 2 present a R^2 equal to 0.87. It is clear that the use of the equations from the literature would lead to an overestimation of the modulus of elasticity of sprayed concrete.

7.6. PROPOSALS

The results obtained indicate that new equations to estimate the modulus of elasticity of sprayed concrete accounting for the specific characteristics of the material are required.

Therefore, two equations to predict the elastic modulus of sprayed concrete are proposed following either an empirical approach or a semi-analytical approach. In each case, the idea was to adapt the formulation already provided in codes and guidelines. For that, the new proposals are based on the Eurocode 2 and the EHE-08. Notice that the Model Code 2010 is not considered since in this case the evolution of elastic modulus does not depend on the compressive strength of concrete.

7.6.1. Empirical approach

This modification was performed applying correction factors to the equations from the literature in order to fit the results from the sprayed concrete. In the empirical approach, these correction factors were obtained through a non-linear regression using the experimental data and a curve fitting-software (LAB Fit). All data is used and no distinction is made regarding the age, the porosity and the rebound.

In the case of the Eurocode 2, only one equation relates the compressive strength at a certain age and the modulus of elasticity at the same age (Section 4.2). As shown in Equation 7.8, the coefficient γ is multiplied to the original formulation to account for the reduction of the modulus of elasticity of sprayed concrete. The value of γ for sprayed concrete obtained through linear regression is 0.76.

$$E_{cm,j} = \gamma \cdot 9.5 \cdot \sqrt[3]{f_{cm,j}} \tag{7.8}$$

In case of the EHE-08, one equation relates the compressive strength and the modulus of elasticity at 28 days, whereas another shows the evolution over time (Section 4.3). The coefficients γ_1 and γ_2 are multiplied to the original formulation as presented in Equation 7.9 and Equation 7.10, respectively. The coefficient γ_1 is applied with the same purpose already indicated for γ in the correction of the formulation from Eurocode 2. In addition to that, the coefficient γ_2 accounts for the lower elastic modulus presented by the sprayed concrete at early ages.

$$E_{cm,28} = \gamma_1 \cdot 8.5 \cdot \sqrt[3]{f_{cm,28}} \tag{7.9}$$

$$E_{cm,j} = \left(\frac{f_{cm,j}}{f_{cm}}\right)^{0.30/\gamma_2} \cdot E_{cm} \tag{7.10}$$

The values γ_1 and γ_2 for sprayed concrete are respectively 0.88 and 0.60, leading to a R^2 equal to 0.99 with the experimental results. As expected, the smaller modulus of sprayed concrete leads to a reduction in the correction parameters γ_1. Moreover, the γ_2 entails a higher power in Equation 7.10, thus leading to a less steep increase in the elastic modulus at early ages.

Figure 7.4 presents the estimations of the modulus of elasticity obtained with the modified empirical formulations. The results indicate that the latter present a better fit with the experimental results if compared with the observed in Figure 7.3. In fact, the modified formulation from the Eurocode 2 shows a R^2 equal to 0.98 with the experimental results, in contrast with the 0.87 obtained for the original formulation. The improvement is even more evident in the modified formulation from the EHE-08, which show a R^2 of 0.98 in comparison with the 0.78 from the original formulation.

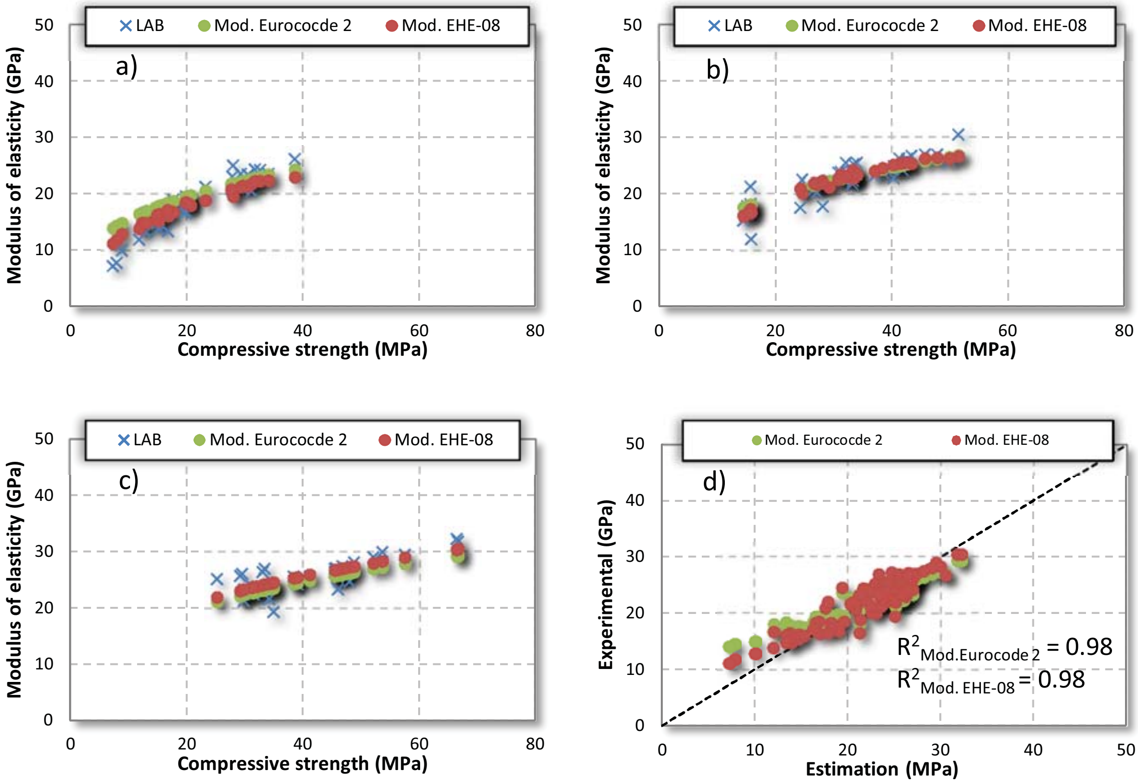


Figure 7.4- Comparison of results for the empirical proposal at an age of 1 day a); 7 days b); 28 days c) and evaluation of the fit considering all data d)

In order to quantify the improvement obtained, Table 7.7 shows the average relative errors between the real elasticity modulus measured in the laboratory and the estimated with the original and the empiric modified formulations. The standard deviation of the relative errors is also included.

Table 7.7- Average relative errors considering empirical formulation

Equations		Age (d)	Average Relative Error (%)	Totals (%)	Std. Deviation of Error (%)
Original formulation	Eurocode 2	1	52.57	37.95	32.93
		7	33.90		15.92
		28	27.37		10.35
	EHE-08	1	68.19	50.01	38.01
		7	45.07		17.66
		28	36.76		11.12
Empirical proposal	Eurocode 2	1	19.03	11.17	22.52
		7	7.59		9.45
		28	6.90		4.91
	EHE-08	1	12.79	8.73	12.62
		7	7.75		7.95
		28	5.65		5.84

As observed before, the average relative error decreases with time in all formulations because of the higher influence of the rebound and of the accelerators at early ages. Such influence reduces with time as the hydration of the cement occurs, which justifies an improved fit. The analysis show that the modified equation from the EHE-08 allows a better fit of the experimental results at early ages. On the contrary, the modified equation from the Eurocode 2 estimates with slightly more accuracy the modulus of elasticity at long ages.

Moreover, it is clear that the average relative errors from the original formulations are bigger than the ones of the modified ones. In this sense, the proposals based on the Eurocode 2 lead to a reduction of 33.54%, 26.31% and 20.47% of the error estimated respectively at age of 1, 7 and 28 days. In the case of the modified EHE-08, reductions of 55.40%, 37.32% and 31.11% are observed. The reductions regarding the totals are 26.78% and 41.28% for the Eurocode 2 and EHE-08 modified equations, respectively. This indicates a significant improvement in the prediction of the modulus of elasticity of sprayed concrete with the empirical formulation proposed.

7.6.2. Semi-analytical approach

In the semi-analytical approach, the correction factors that should be applied to the formulation of the Eurocode 2 and the EHE-08 are obtained through a simplified mathematical deduction. The aim is to derive a proposal capable of giving a physical meaning to the equations. For that, the influences of the higher porosity and of the rebound are taken into account in the case of sprayed concrete.

In order to develop the formulation, the ideal situation of a sheet with area *A* and infinitesimal thickness *dx* of a material without any porosity is considered. Suppose that a uniaxial load (*F*) is applied to the area *A*. In this scenario, the stress (σ) and the strain (ε) experienced by the sheet may be related with the modulus of elasticity (*E*) of the material without voids according with the Hook's law.

Suppose now that certain porosity (*p*) is introduced in the sheet. If the same uniaxial load *F* is applied to the surface with area *A*, the effective stress perceived by the material (σ') will be actually higher than the average stress (σ) since the voids reduce the area of solids available to receive the forces. A simple geometrical conversion may be used to estimate σ' depending on σ, as shown in Equation 7.11. Notice that this equation takes into account the effective area without voids (*A'*) of the porous sheet.

$$\sigma' = \sigma \frac{A}{A'} \tag{7.11}$$

Although *A'* may be estimated according with different approaches, a good approximation is obtained by the division of the volume of solids (V_S) and the thickness of the sheet (*dx*). In turn, V_S may be calculated by the product of the total volume of the sheet considering the voids (*A·dx*) and the remaining volumetric proportion of solids given by (*1-p*). This yields the Equation 7.12.

$$A' = \frac{V_s}{dx} = A \cdot (1 - p) \tag{7.12}$$

It is known that the strain (ε') experienced by the porous sheet will be higher than in the case of the material without voids. Assuming that no plastification occurs and that the Hook's law is valid for the material, the strain (ε') should be proportional to the ratio between the effective stress (σ') and the modulus of elasticity of the solid without voids (E), as shown in Equation 7.13. On the other hand, the modulus of elasticity obtained when the porous sheet is tested may be given by the ratio between the stress σ applied during the test to the area A and the strain ε' (Equation 7.14).

$$\varepsilon' = \frac{\sigma'}{E} \tag{7.13}$$

$$E' = \frac{\sigma}{\varepsilon'} \tag{7.14}$$

Combining Equations 7.11 to 7.14 allow the deduction of equation 7.15 for the estimation of the modulus of elasticity of the material depending on the porosity p introduced. Equation 7.15 makes it possible to estimate the relation between the elastic modulus of a homogeneous material with two different porosity inclusions. Assuming that the first material has the porosity of conventional concrete (p_C) and the second material has the porosity found in shotcrete (p_S), this relation could be approximated by Equation 7.16. In the present study, this relation between the elastic modulus of conventional (E_C) and sprayed concrete (E_s) is called the coefficient of porosity (γ_p).

$$E' = E \cdot (1 - p) \tag{7.15}$$

$$\frac{E_S}{E_C} = \frac{1 - p_S}{1 - p_C} = \gamma_p \tag{7.16}$$

Nevertheless, the deduction of γ_p assumes that the composition of the materials is the same regardless of the porosity inclusion. In the case of sprayed concrete and conventional concrete this not correct since the former tend to present a higher paste content due to the definition of the mix and to the rebound phenomenon. In order to reflect this effect in the expressions for estimating the modulus of elasticity a relationship between the initial and final volume of aggregates was used. The deduction assumes that the modulus of elasticity of a composite (E) may be estimated through the Equation 7.17 given by Voigt (77) depending on the volume of aggregates (V_a) and mortar (V_m) and their correspondent modulus of elasticity (E_a and E_m, respectively).

$$E = V_a \cdot E_a + V_m \cdot E_m \tag{7.17}$$

Since $V_a + V_m = 1$, Equation 7.17 may be rearranged to gives Equation 7.18. Consider now that the aggregates and the mortar of conventional concrete and sprayed concrete are identical. Furthermore, consider that the difference between the volumes of aggregate of conventional concrete ($V_{a,c}$) and sprayed concrete ($V_{a,s}$) is described in Equation 7.19 as a function of the volumetric rebound (r).

$$V_a = \frac{E - E_m}{E_a - E_m} \quad (7.18)$$

$$V_{a,s} = V_{a,c} \cdot (1 - r) \quad (7.19)$$

Combining Equations 7.18 and 7.19 for the conventional and the sprayed concrete gives Equation 7.20. It shows that the modulus of elasticity of sprayed concrete not only depends on the modulus of elasticity of conventional concrete but on the modulus of the cement paste. Notice that the major part of the porosity is concentrated in the mortar since the aggregates usually present small porosity values. Therefore, it is reasonable to assume that E_m is considerably smaller than E_c. In addition to that, considering that the volumetric rebound in underground construction is approximately 10%, the term r should be approximately 9 times smaller than $(1 - r)$.

$$E_s = E_c \cdot (1 - r) + E_m \cdot r \quad (7.20)$$

All these observations point out that the influence of the second part of the Equation 7.20 that depends on the characteristics of the cement past should be several times smaller than that of the first part. Therefore, given its minor relative importance, the term $(E_m \cdot r)$ may be disregarded in order to simplify the deductions. The relationship between the modulus of elasticity of conventional and sprayed concrete considering the rebound is given by Equation 7.21, which is adopted as a coefficient of rebound (γ_r).

$$\frac{E_S}{E_C} = (1 - r) = \gamma_r \quad (7.21)$$

The coefficient of porosity and of the rebound may be used to adapt the equations from the literature used to predict the elastic modulus. Equation 7.22 presents the modified proposal based on the Eurocode 2. It is important to remark that this equation is also adequate for conventional concrete since the coefficients of porosity and rebound are equal to 1 as *r* is 0 and $p_s = p_c$.

$$E_{cm,j} = \gamma_p \cdot \gamma_r \cdot 9.5 \cdot \sqrt[3]{f_{cm,j}} \quad (7.22)$$

In the case of the Instruction EHE-08, the proposal for the age of 28 days is given by equation 7.6. This equation is adapted considering the coefficients of porosity and rebound as shown in Equation 7.23. On the other hand, it is also necessary to adapt the Equation 7.7, which estimates the modulus of elasticity of concrete at ages different than 28 days. Hence, the modification indicated in Equation 7.24 is proposed since it is expected that the early modulus of elasticity should be smaller as either the porosity or the rebound increases.

$$E_{cm,28} = \gamma_p \cdot \gamma_r \cdot 8.5 \cdot \sqrt[3]{f_{cm,28}} \quad (7.23)$$

$$E_{cm,j} = \left(\frac{f_{cm,j}}{f_{cm,28}}\right)^{\frac{0.3}{\gamma_p \cdot \gamma_r}} \cdot E_{c,j} \tag{7.24}$$

Figure 7.5 presents the comparison between the modulus of elasticity estimated with the semi-analytical equations and the measured in the experimental program. The estimations were obtained using a porosity equal to 7% for conventional concrete, an average porosity equal to 16% measured in the experimental program for the sprayed concrete and a volumetric rebound of 10% (2; 4; 9). These values entailed a R^2 equal to 0.98 for the modified formulation from the Eurocode 2 and 0.97 for the modified formulation from the EHE-08. A sensibility analysis showed that the fit of the proposal is also acceptable if the values of rebound, of the porosity of conventional concrete and sprayed concrete are 5-15%, 7-9% and 15-17%, respectively.

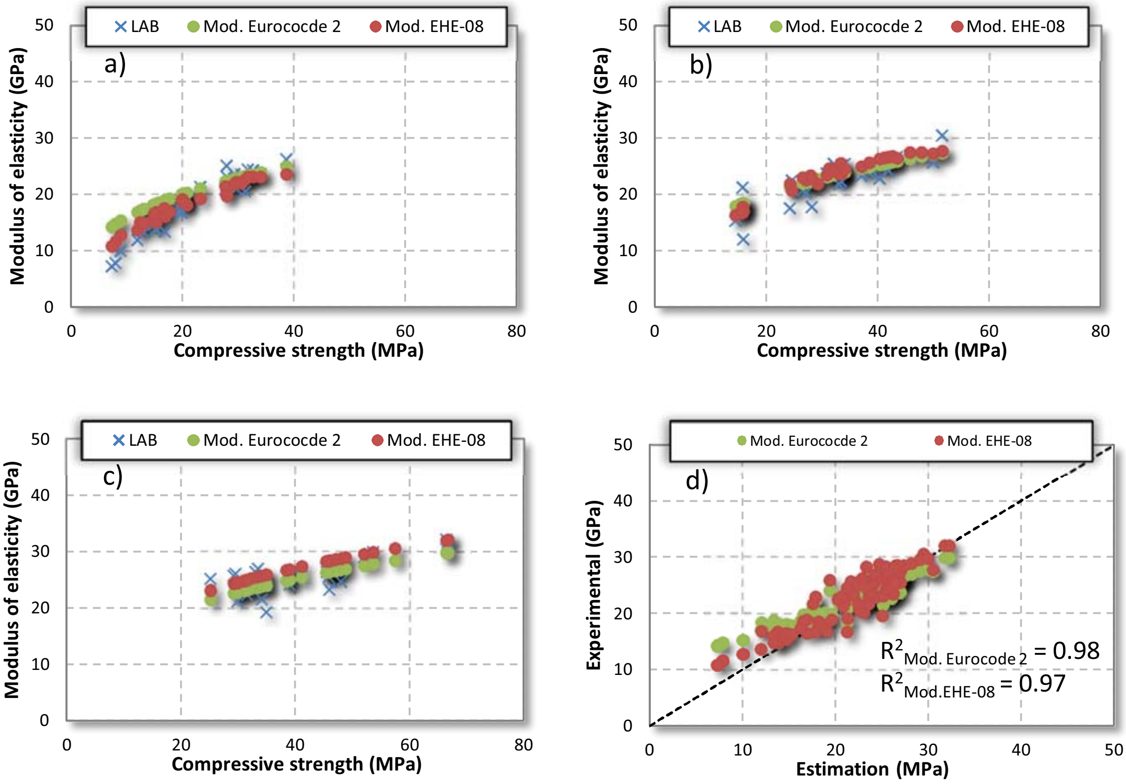


Figure 7.5- Comparison of results for the semi-analytical proposal at an age of 1 day a); 7 days b); 28 days c) and evaluation of the fit considering all data d)

In order to show the improvement on the estimation of the modulus of elasticity, Table 7.8 is presented. This shows the average of the relative errors in the prediction of the elastic modulus with the original and the semi-analytical modified equations.

Table 7.8- Relative errors considering semi-analytical proposal

Equations		Age (d)	Average Relative Error (%)	Totals (%)	Std. Deviation of Error (%)
Original formulation	Eurocode 2	1	52.57	37.95	32.93
		7	33.90		15.92
		28	27.37		10.35
	EHE-08	1	68.19	50.01	38.01
		7	45.07		17.66
		28	36.76		11.12
Semi-Analytical proposal	Eurocode 2	1	20.50	11.46	23.98
		7	7.96		10.22
		28	5.92		5.44
	EHE-08	1	12.46	9.78	11.99
		7	8.91		8.86
		28	7.96		7.03

Again, the modified equations provide a significant improvement in the prediction of the elastic modulus of sprayed concrete. The relative error of the proposals based on the Eurocode 2 equations present a reduction of 32.07, 25.94 and 21.45% at ages of 1, 7 and 28 days, respectively. These reductions are 55.73, 36.16 and 28.80% for the modified EHE-08 proposal. The reductions regarding the totals are 26.49 and 40.23% for the Eurocode 2 and EHE-08 modified equations, respectively. Notice that these values are similar to the ones obtained with the empirical equations.

7.7. PROPOSALS VALIDATION WITH IN SITU RESULTS

In this section, different experimental programs previously conducted in the Tunnel of Bergara, the Tunnel of Bracons and the Tunnel of Torrassa are used to validate the empirical and the semi-analytical proposals.

7.7.1. Short description and presentation of the results

The first real case validation was performed with the results from the experimental program conducted at the Tunnel of Bergara. It is part of the future high velocity train network (AVE) in Euskadi (Spain), located at municipal district of Bergara, in the Province of Guipúzcoa. In this tunnel, the sprayed concrete was used exclusively to build the final lining. Mixes containing a special CEM I 52.5R with a very high initial strength and a special CEM III/B 52.5 N were tested to achieve a high strength sprayed concrete with less consumption of accelerators. The second validation is performed with the data from the tests at the tunnel of Bracons, located in the municipal district of La Vall d'en Bas in the Province of Girona as part of the road C-37 between Vic and Olot (Spain). The sprayed concrete was used to build the lining, to stabilize the opening after the excavation and to contain short and medium-term loads. The concrete was produced different type of fibres. The last real case validation was performed with the results from the tests accompanied at the tunnel of Torrassa, which is part of the new underground line in Barcelona (Line 9). In this tunnel, the sprayed concrete was used to build the final lining. In this sense, Table 7.9 summarizes the mixes of sprayed concrete used in the three tunnels.

Table 7.9- Mixes of sprayed concrete used in the tunnels of Bergara, Bracons and Torrasa

Material	Unity	Bergara		Bracons		Torrassa
		Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
CEM I 52.5 R	kg/m3	475	-	450	450	425
CEM III/B 52.5 N		-	475	-	-	-
Fine sand	kg/m3	468	468	160	160	-
Coarse sand		843	843	1190	1190	1100
Gravel		450	450	370	370	475
Superplasticizer	%bcw	1.40	1.40	1.26	1.26	1.2
Stabilizer		0.35	0.35	-	-	-
Microsilica	%bcw	-	-	1.00	1.00	1.5
Metallic fibres	kg/m3	4	4	Yes	-	-
Polymeric fibers		-	-	-	Yes	-
w/c ratio	-	0.31	0.40	0.42	0.42	0.45
Alklai free accelerator	%bcw	2.50	3.00	-	-	-
Alkali accelerator		-	-	3-8	3-8	2-3

All the spraying processes were performed with a spraying robot. As much as possible, the spraying parameters followed the described by the standards and recommendations (62; 68). The mixes were sprayed on test panels similar to the ones used during the experimental program described in Section 3.2. Cylindrical samples (75x150 mm) were extracted from the test panels and tested at different ages.

Table 7.10 presents the results of compressive strength, elastic modulus and porosity from the in situ experimental programs. It is important to remark that the porosity was only measured in the tests at the Tunnel of Bergara, whereas no result was available for the Tunnel of Bracons and Torrassa.

Table 7.10- Results from the in situ experimental programs

Mix	f_{cm} (MPa)	E_{cm} (GPa)	p (%)
1	46.40	30.41	14.3
	59.70	29.04	
2	87.80	38.05	7.1
	64.70	33.30	
3	27.60	27.50	-
4	24.67	20.00	-
	27.17	20.18	
	31.56	24.89	
5	33.07	22.53	-

7.7.2. Analysis of the results

Table 7.11 presents the relative errors obtained using the original and the modified equations from the Eurocode 2 and the EHE-08. The estimations with the semi-analytical proposal considered porosity equal to 7% for conventional concrete and a volumetric rebound of 10% (2; 4; 9). An average porosity of 16% was assumed for mixes 3 to 5.

Table 7.11- Relative errors obtained for the in situ experimental programs (%)

	Original Eq.		Empirical Eq.		Semi-analytical Eq.	
Mix	**Eurocode 2**	**EHE-08**	**Eurocode 2**	**EHE-08**	**Eurocode 2**	**EHE-08**
1	12.24	20.51	14.83	11.39	12.80	6.38
	27.87	37.29	2.97	0.95	0.66	6.66
2	10.97	19.14	15.80	12.39	13.79	7.44
	14.53	22.96	13.10	9.58	11.03	4.47
3	4.41	12.10	20.77	17.57	18.89	12.91
4	38.26	48.45	4.91	9.16	7.41	15.33
	41.50	51.93	7.37	11.71	9.93	18.03
	20.61	29.50	8.48	4.78	6.30	0.61
5	35.33	45.30	2.69	6.84	5.13	12.88
Average	22.86	30.24	10.10	9.37	9.55	9.41

The results show that the original formulations lead to an error of up to 51.93% in the prediction, with average values of 22.86% for the Eurocode 2 and 30.24% for the EHE-08. A considerable improvement is obtained with the modified proposals. For instance, empirical and semi-analytical equations based on the Eurocode 2 entail an average relative error of 10.10 and 9.55%, respectively. Likewise, the modified proposals from the EHE-08 present average errors of 9.37% and 9.41%, respectively. Notice that, despite the simplifications and assumptions considered, the accuracy of the semi-analytical modified equations is comparable to those of the empirical modified equations.

7.8. CONLUDING REMARKS

The following concluding remarks are derived from the analysis presented in this chapter.

- The different characteristics of sprayed concrete and conventional concrete are not taken into account in the equations available in the literature to predict the elastic modulus of the material. The predictions performed with such equations lead to an overestimation of the elastic modulus of sprayed concrete. The extensive experimental program conducted indicates average overestimations of 24.22%, 37.56% and 49.59% for the Model Code 2010, the Eurocode 2 and the EHE-08.

- The empirical and semi-analytical formulations proposed in this paper lead to a considerable improvement on the prediction of elastic modulus of sprayed concrete. The new proposals yield at 28 days an error of around 10%, in contrast with the 37.95% and 50.01% obtained at the same age for the original formulation from the Eurocode 2 and the EHE-08, respectively;

- Estimations given by empirical and semi-analytical models to predict the modulus of elasticity are similar when a porosity of sprayed concrete of 14-18%, a porosity of conventional concrete of 6-9% and a volumetric rebound of 5-15% are considered. These parameters may be adopted as references for sprayed concrete in case no further information is available;

- The estimations at early ages using the modified Equations from the EHE-08 are more precise than the ones from the Eurocode 2. The opposite occurs with the estimations at long ages, and

- The modified equations proposed were validated with results obtained in real tunnels. The predictions of modulus of elasticity with these equations are between 2 to 5 times more accurate than the obtained with the original formulation, regardless of the type of cement, the type of accelerator, and the additions incorporated.

CHAPTER 8. MATURITY METHOD APPLIED TO SPRAYED CONCRETE

8.1. INTRODUCTION

The maturity method can be used in different applications such as concrete pavements or precast to improve their production since, for instance, the curing time can be minimize (48; 78; 79). Furthermore, it is used in construction elements to help determine the time to remove the formwork which is important for productivity and for the safety of the in-site construction (48). However, according to available literature, there is not any use of the method for sprayed concrete. The maturity method adapted to sprayed concrete would help Engineers decide when the advance of the excavation could be done safely whilst considering the technical specifications of the projects. Furthermore, the advantage of using the maturity method to estimate the compressive strength of sprayed concrete at early ages instead of a typical standardized test (e.g. penetration needle test and/or stud driving method (46) is a reduction in time of the estimation of results and of personal working in a poor environment.

The aim of this study is to obtain an expression for the maturity curve for spraying concrete. This could be used by Engineers to determine when the concrete has sufficient strength to continue excavating a tunnel considering the minimum compressive strength previously defined in the specification. Furthermore, concrete and accelerator manufacturers would be able to sell their products taking into account these maturity curves as they currently consider the curves J (J1, J2 and J3), which classified the strength class of the sprayed concrete at early ages (43).

This chapter presents an experimental program involving the spraying of different mixes and analysing the evolution of temperature and the compressive strength, the relationship between these two parameters and hence the maturity curves obtained. Subsequently a finite element model is presented, which aims to adapt the maturity curves considering design parameters such as the thickness of the sprayed concrete layers and the ground support available. Finally, a description of the application of the maturity method to sprayed concrete construction is outlined.

8.2. EXPERIMENTAL PROGRAM

In order to obtain the maturity curves needed to estimate the compressive strength in function of the evolution of temperature, the results at early ages from Chapter 5 are analysed in this section. To do that, the methodology followed in the experimental program and the results obtained are summarized as a reminder.

8.2.1. Methodology

The experimental program was performed in the Laboratory of Technology of Structures Luis Agulló at the Universitat Politècnica de Catalunya. Concretes were sprayed in outdoor conditions using a wet-mix spraying machine MEYCO Altera, which is an oil-hydraulically driven twin-piston pump that also incorporated a peristaltic dosing unit for accelerators.

Two different types of cement: CEM I 52.5 R (I) and CEM II/A-L 42.5 R (II) and 6 alkali-free accelerators based on hydroxysulphate of aluminium ($Al(SO_4)_x(OH)_{3-2x}$) were used to produce the mixes: AF-1.1, AF-1.2, AF-2.1, AF-2.2, AF-3.1 and AF-3.2. Different doses of accelerator were considered. Finally, all mixes were produced with a polycarboxylic superplasticizer to increase both the fluidity and the workability of the concrete. Hence, the result of studying 2 types of cement and 6 types of set accelerating admixture entails 12 different sprayed concretes to be tested. Considering the doses a total of 32 mixes were studied.

The concrete mix design was: 425 kg/m^3 of cement, 380 kg/m^3 of fine sand (0-2 mm), 900 kg/m^3 of coarse sand (0-5 mm) and 380 kg/m^3 of gravel (5-12 mm) with a w/c ratio of 0.45. Even though the concrete was supplied by a ready mix plan, the materials used were selected in order to reproduce a typical composition found in sprayed concrete tunnels.

Two different methods were used to evaluate the development of compressive strength of the sprayed concrete at early ages according to the European standard UNE-EN 14488-2:2006 (46): Penetration needle test and stud driving method. On the other hand, the evolution of temperature was obtained using a data logger and thermocouples introduced in the concrete.

8.2.2. Results and analysis

Figure 8.1 presents the results of evolution of temperature and development of compressive strength of mixes with medium dose of accelerators AF-1.1, AF-2.1 and AF-3.1, and type of cement I. The rest of the results were presented in Chapter 5 and in Appendix C.

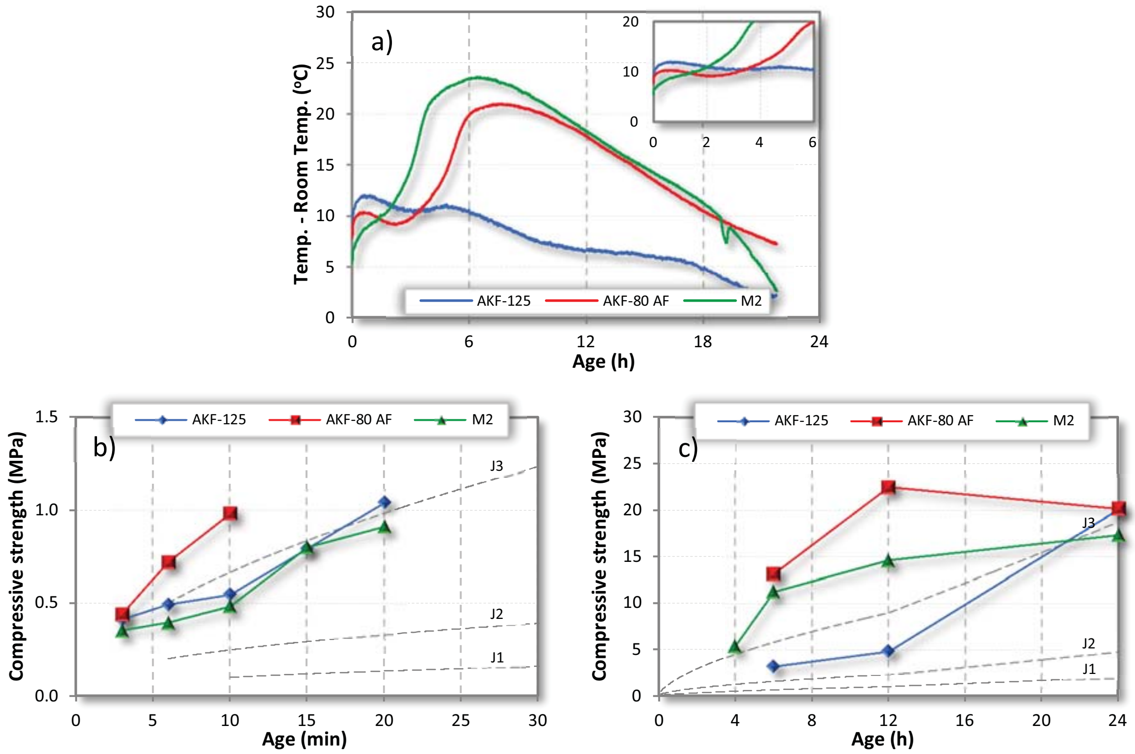


Figure 8.1- Results of evolution of temperature a), penetration needle test b) and stud driving method c)

Regarding the results of evolution of temperature, the curves present similar trends showing initially a first increase of temperature due to the hydration of the cement aluminates (C_3A). After that, a slight decrease or a reduction on the temperature increase rate is observed, which is characteristic of the dormant period. Next, a second peak of temperature due to the hydration of silicates (C_2S and C_3S) is verified in some of the curves. Finally, the temperature registered tends to stabilize with the room temperature.

Regarding the development of compressive strength, the results obtained with the penetration needle test show the low importance of the type of cement up to 30 min. The results obtained are similar for the mixes with cement I and the one II. Even though, the type of addition is important due to its affinity with the accelerators. This strength measured is possibly due to the quicker hydration of the C_3A, which produces ettringite able to provide certain compressive strength during the first minutes. This phenomenon is observed in the evolution of temperature as a first strong rising of temperature. Finally, the strength class of the cement is important from 4h after the spraying on and it is due to the amount of clinker, and therefore silicates (C_2S and C_3S). This is visible in the results of the stud driving method as they are similar but the mixes with cement I are slightly higher than the ones with II. The hydration of silicates is related with the second peak of temperature observed in the evolution of temperature.

Hence, the hydration of aluminates (C_3A) and silicates (C_2S and C_3S), which entails the hardening of the mixes, may be related with the evolution of temperature. The analysis of this relationship may result at obtaining the maturity curves needed to apply the maturity method to sprayed concrete.

8.3. RELATIONSHIP EVOLUTION OF TEMPERATURE/COMPRESSIVE STRENGTH

The maturity concept uses the principle that concrete strength is directly related to both age and evolution of temperature in time (48; 79). In this sense, a function of temperature and age may be used to estimate the strength development of concrete. The Nurse-Saul maturity function (Equation 8.1) is one commonly used today (48), which only considers the evolution of temperature in time. Then, the function relates a Maturity Index (*M*) with the integral of the evolution of temperature (*T*) in time (*t*), considering a datum temperature (T_o). This last parameter, which is equal to -10 °C in different studies (48), takes into account the minimum temperature that permits the chemical reactions of the hydration of the cement.

$$M = \sum_0^t T - T_o \cdot \Delta t \qquad (8.1)$$

The maturity index is based on pre-determined calibrations of the time-temperature-strength relationship development from laboratory tests. Using the experimental results described in section 8.3, the maturity indexes were obtained for each mix studied considering the Equation 8.1 as described in Figure 8.2.

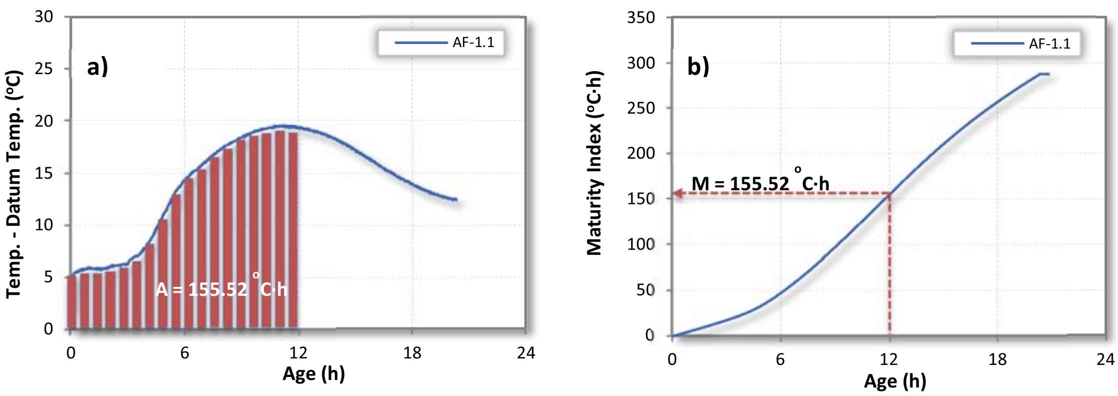


Figure 8.2- Relation between the evolution of temperature a) and the maturity index b)

Next, the maturity index was related to the compressive strength of the sprayed concrete obtaining their pair of values. These pairs of values considered all the compressive strength results obtained using the penetration needle test and the stud driving method (from 0 to 24 h), although the study only regards the pairs of values up to 12 h. Due to the use of accelerators this time is considered enough so that the sprayed concrete achieved the minimum compressive strength gathered in project of underground contractions.

The aforementioned pairs of values were introduced in a curve fitting software for the treatment and analysis of experimental data in order to obtain an expression for the maturity curves of sprayed concrete. LAB Fit v.7.2.48 by Wilton and Silva (DF/CCT/UFPB) was the free software used so as to achieve the expression. The reduced Chi Squared distribution (Chi Squared/Degrees of freedom) is considered by the program so as to order the goodness of fit of the equations. In this sense, all the pair of values empirically fitted in the Equation 8.2, which relates the maturity index (*M*) with the compressive strength (*S*) depending on 3 parameters: *A*, *B* and *C*. However all experimental results were fitted using the same equation, these parameters were different for each sprayed concrete. In this sense, Table 8.1 presents the value of each parameter depending on the mixes of the sprayed concrete (type of accelerator, dose of accelerator and type of cement). Notice that, as presented in section 8.2, the results shown are related to the accelerators AF-1.1, AF-1.2 and AF-1.3 and their low and medium doses. The rest of results are gathered in Appendix D.

$$S = A \cdot EXP[B \cdot EXP(C \cdot M)] \quad (8.2)$$

Table 8.1- Parameters obtained by LAB Fit

Accelerator	Cement	Dose	A	B	C	R^2
AF-1.1	I	Low	5.821	-2.718	-0.023	0.9998
		Medium	4.060	-2.575	-0.048	0.9255
	II	Low	31.966	-3.535	-0.003	0.9958
		Medium	15.920	-3.302	-0.006	0.9978
AF-2.1	I	Low	23.724	-4.115	-0.006	1.000
		Medium	24.160	-3.616	-0.007	1.000
	II	Low	17.292	-3.954	-0.008	0.997
		Medium	21.085	-3.430	-0.006	0.998
AF-3.1	I	Low	17.367	-12.739	-0.014	0.9988
		Medium	15.204	-3.864	-0.009	0.9944
	II	Low	14.536	-3.050	-0.006	0.9825
		Medium	7.982	-2.196	-0.006	0.9995

Figure 8.3 presents the relationship between the maturity index and the compressive strength. Furthermore, the maturity curves obtained with the Equation 8.2 are also shown. These present values squared-R ratios between 0.9734 and 1.000, showing an excellent fit.

Notice that the maturity curves obtained depend on the parameters studied: type of cement, type of accelerator and dose of accelerator. Regarding the type of cement all mixes present similar tendencies except the one produced with cement I and accelerator AF-1.1. This difference is possibly due to the low affinity cement-accelerator. Regarding the type of accelerator mixes with AF-2.1 present higher compressive strength regardless of the type of cement. The lowest compressive strength is presented by mixes with AF-1.1 and AF-3.1 for cements I and II, respectively. Finally, regarding the dose of accelerator, the results of mixes with accelerator AF-1.1 and AF-3.1 show that an increase of the dose entails higher values of maturity index to achieve the same compressive strength. This is not observed for mixes produced with AF-2.1.

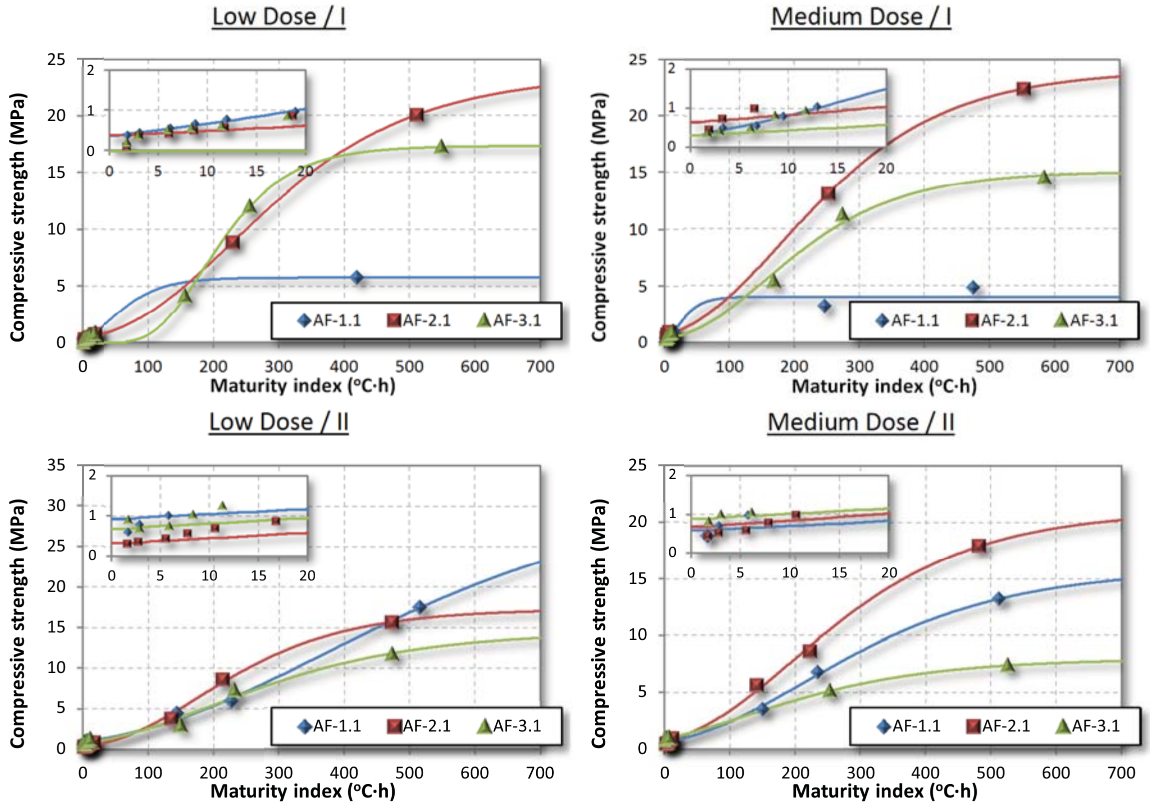


Figure 8.3- Relationship between the maturity index and the compressive strength

8.4. DESIGN CONSIDERATIONS

In underground construction, the thickness of concrete is chosen due to structural reasons; with the weaker is the ground support, the thicker the lining (considering same compressive strength). The maturity curves presented in section 8.3 were obtained experimentally by spraying concrete into moulds with a thickness of 150 mm, but the thickness of the tunnel lining may be different. Furthermore the ground support in a tunnel has different properties than the mould used in the laboratory. These changes will entail variations in the evolution of temperature inside the concrete, and therefore variations in the maturity curves. These changes are due to the effect of the heat transfer between the different materials.

Heat transfer, also called diffusion, is the exchange of energy through the boundary between two systems. When an object is at a different temperature from another body or its surroundings, heat flows so that the body and the surroundings reach the same temperature. Heat transfer always occurs from a region of high temperature to another region of lower temperature, as described by the second law of thermodynamics. In the case of underground construction, thermal conduction is the fundamental heat transfer mode that occurs between the concrete and the ground, whereas convection is the one that occurs between the concrete and the atmosphere (Figure 8.4).

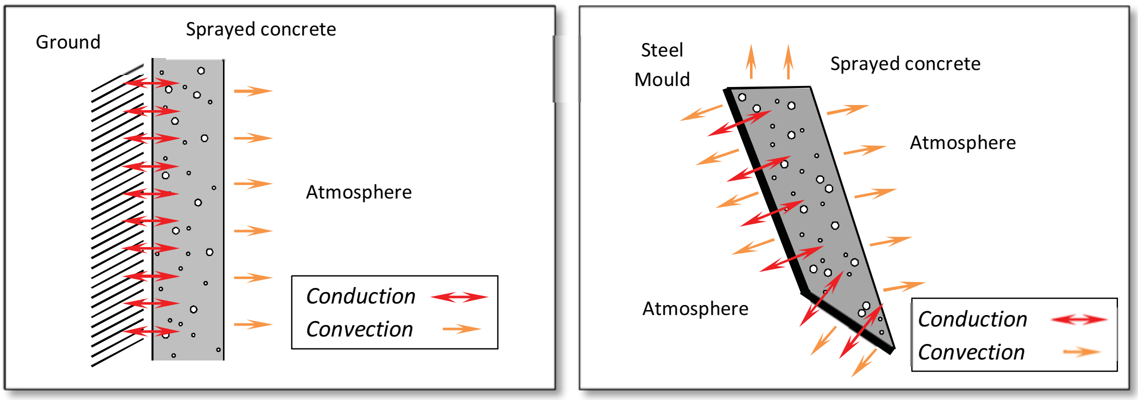


Figure 8.4- Heat transfer modes in a tunnel a) and for a sprayed mould b)

In order to understand this phenomenon, an experimental program was design to study the variation of the evolution of temperature considering the thickness of the sprayed concrete layer and the type of support. The results obtained were used to calibrate a finite element model that was used to obtain the evolution of temperature in the concrete considering the thickness of the sprayed concrete layer and the properties of the ground support. In order to calibrate the model the heat generation was used. The experimental program designed, the model proposed and the results obtained are exposed below.

8.4.1. Methodology

8.4.1.1. Experimental program

The experimental program design was performed during the sprayings of the mix with the low dose (9%bcw) of accelerator AF-3.1 and cement I, described in 8.2.1. The mix was sprayed in a mould with two thermocouples arranged at different positions considering the thickness as shown in Figure 8.5. The first thermocouple was centred on the mould at 150 mm from the top in a low position (TC_L), whereas the second (TC_H) was set at the same position but at a height of 75 mm. This height was achieved using a piece of wood since this material has a very low thermal conductivity.

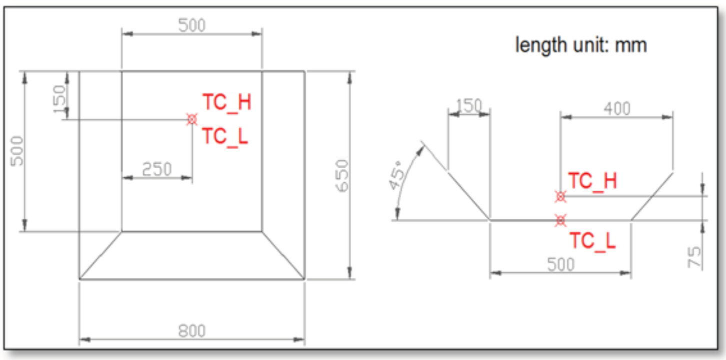


Figure 8.5- Arrangement of the thermocouples in the mould

The temperature was recorded every 1 min for the first 24 h from the spraying process. The initial time was defined as the time when the test panel was completely filled. Figure 8.6 presents the evolutions of temperature recorded and the evolution in time of the maturity index obtained in this experimental program. Notice that the tendency shown for both evolutions of temperature is the same and furthermore it is equal to the ones presented in Chapter 5.

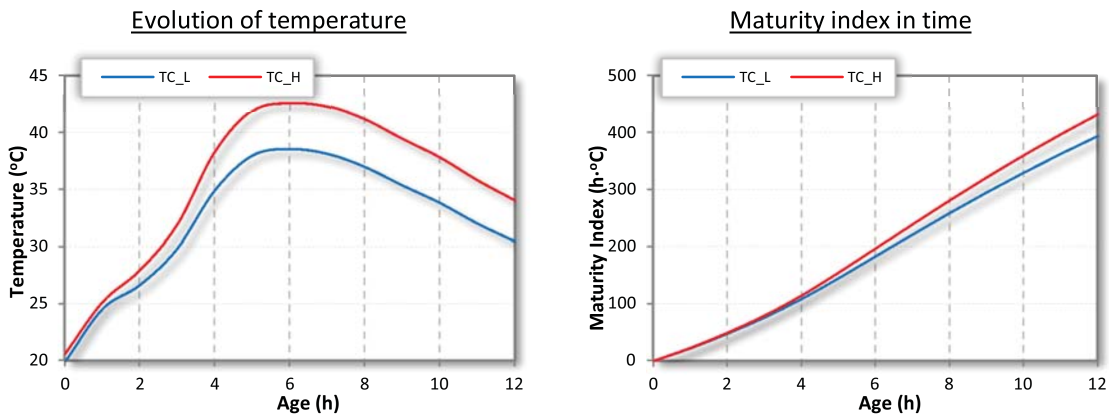


Figure 8.6- Experimental results of temperature and time

The evolutions of temperature obtained are similar in shape since they present an initial increase of temperature, a low dormant period, a second increase of temperature and a decrease of temperature after the maximum. The temperatures gathered for the TC_H are higher than the ones obtained for the TC_L due to their position and the consequent heat transfer. TC_H was in the middle of the sprayed concrete and therefore the heat generated was higher than for TC_L.

8.4.1.2. Modelling

To understand these variations, a thermal analysis was performed using finite element methods (FEM). ANSYS 9.0 was used, as it can model mechanical and thermal behaviours of construction materials under established boundary conditions. In this sense, ANSYS uses the equations of Fick's law of diffusion applied to heat transfer (Equation 8.3). This equation relates the evolution of temperature (*T*) in time (*t*) with the temperature in a determined location (*x*) multiplied for the diffusivity of the material (*D*). This parameter depends on the conductivity (*K*), the specific heat (*c*) and the density (*ρ*) of the material studied.

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \mathrm{D} \cdot \frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2} = \left(\frac{\mathrm{K}}{\mathrm{c} \cdot \rho}\right) \cdot \frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2} \tag{8.3}$$

A 2D model of the central section of the sprayed mould was considered. Firstly, the geometry of the model was introduced in ANSYS as presented in Figure 8.7.a. Next the thermal characteristics of the sprayed concrete and the steel were introduced including the conductivity (*K*), the specific heat (*c*) and the density (*ρ*) (Table 8.2). Then ASNYS meshed the geometry using triangular elements as shown in Figure 8.7.b. Regarding the mesh, the model was run with a more accurate mesh giving the same results, and then as it is non-meshing sensitive it was decided to analyse the problem with the mesh presented. Finally, the generated heat was introduced manually to calibrate the model. And, the boundary conditions were defined: Initial temperature of materials, ambient temperature and generated heat. In this sense, 293.70 K and 292.15 K were defined as the initial temperature for the sprayed concrete and steel since they were measured in-situ. The ambient temperature was a convective boundary condition and it was introduced as a bulk temperature in the model since it was gathered together with the evolutions of temperature in the sprayed concrete. Apart from this bulk temperature the convective boundary condition needed film coefficients taken as 0.10 and 19.00 kJ/(h·m·K) for sprayed concrete and steel respectively. The code of the model is presented in Appendix E.

Table 8.2- Material features

Material	K (kJ/(h·m·K))	c (kJ/(kg·K))	ρ (kg/m³)
Steel	154	0.49	7600
Sprayed concrete	6.12	0.75	2000

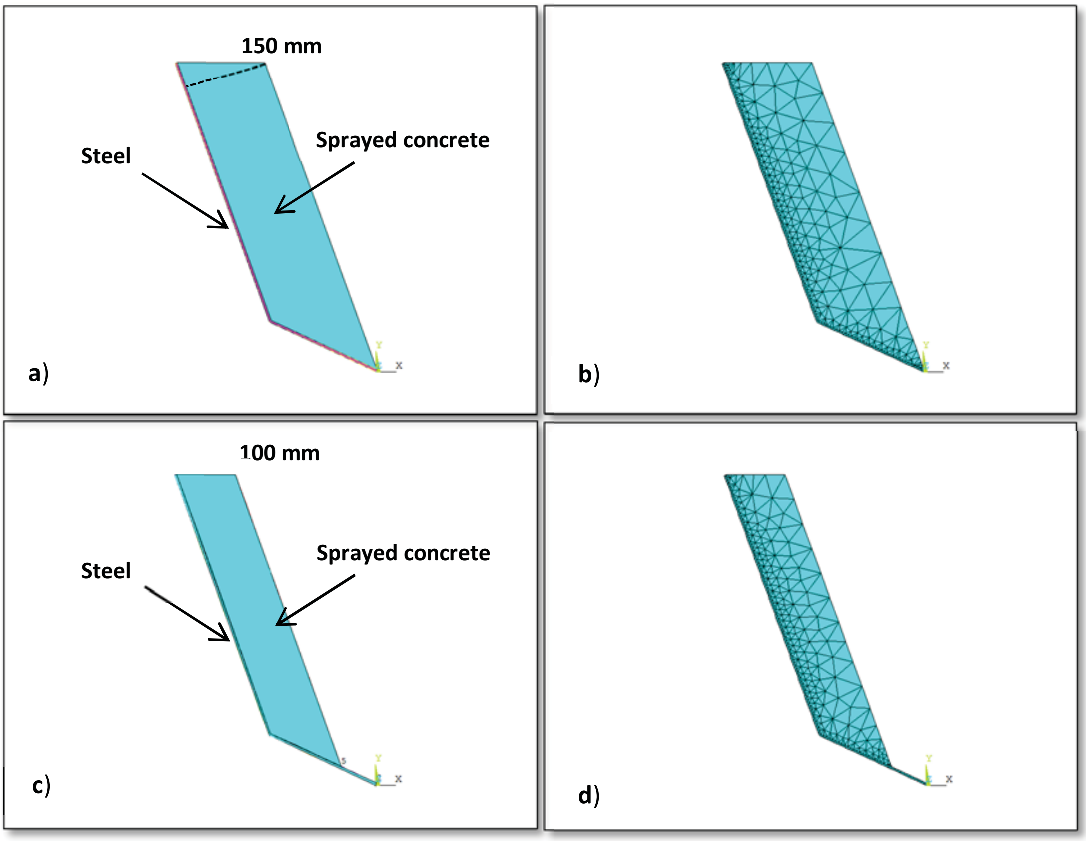


Figure 8.7- Geometry of the model a) and mesh generated by ANSYS b)

Running the model the results obtained were the evolutions of temperature of the nodes were the thermocouples were collocated. Then introducing and changing the generated heat in the model the results were adjusted to the experimental data. This adjustment is presented in Figure 8.8.a showing correlations of 0.996 and 0.993 with the results given by TC_L and TC_H, respectively. Once adjusted, the model was used with a different geometry in order to consider the affect of the thickness. In this sense, the geometry used (Figure 8.7.c) was the section of a sprayed mould with a 100mm-thickness (Appendix E). After meshing it (Figure 8.7.d) and running the model the evolution of temperatures in the lower and medium position were obtained. These are presented in Figure 8.8.b showing a same tendecy, even though with lower temperature than the ones obtained with the 150-mm thickness geometry.

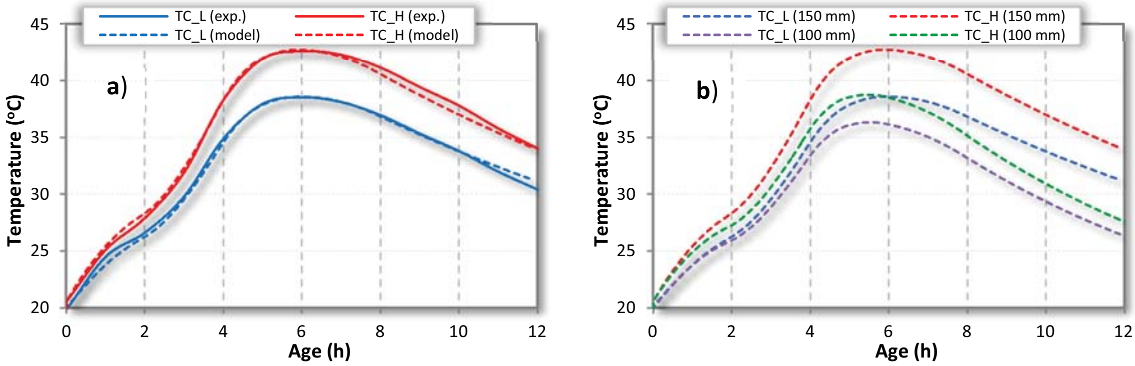


Figure 8.8- Adjustment model-experimental data a) and results from the model b). No continuous lines are results from the model

Using this model the thickness of the layer of sprayed concrete is taken into account. Once this is done the geometry, which depends on the thickness of the layer, may be changed and the results are easily achieved. Even though, as the evolution of temperature depends on the type of accelerator, the dose of accelerator and the type of cement, a model of each mix design shall be done to apply the maturity method to sprayed concrete.

8.4.1.3. Thickness and ground support on the maturity curves

Firstly, the results of the development of compressive strength of mixes with low dose of accelerator AF-3.1 and cement I and the maturity indices obtained by the model are considered (Table 8.3).

Table 8.3- Results of compressive strength and maturity index in time

Age (h)	Compressive strength (MPa)	Maturity index (h·C°)			
		TC_L (150 mm)	TC_H (150 mm)	TC_L (100 mm)	TC_H (100 mm)
0.05	0.19	1.37	1.72	1.35	1.69
0.10	0.37	3.30	12.30	3.25	11.97
0.17	0.51	6.52	15.62	6.47	15.00
0.25	0.56	8.02	18.84	7.97	18.21
0.33	0.61	9.22	20.64	9.05	20.00
0.50	0.84	17.40	29.27	17.00	28.27
4.00	4.15	153.21	162.44	147.43	153.25
6.00	12.11	249.55	266.10	238.91	248.71
12.00	17.26	506.02	546.29	484.84	508.86

Regarding all the maturity index results, TC_H (150 mm) presents the highest values, whereas TH_L (100 mm) presents the lowest. The difference between them, calculated as the overall average of relative difference, represents a 37.79%. As observed with the evolutions of temperature, the 150 mm-thickness presents the higher values.

Using LAB Fit v.7.2.48 the parameters A, B and C from Equation 8.2 may be empirically obtained, and therefore, the new maturity curves may be obtained (Figure 8.9).

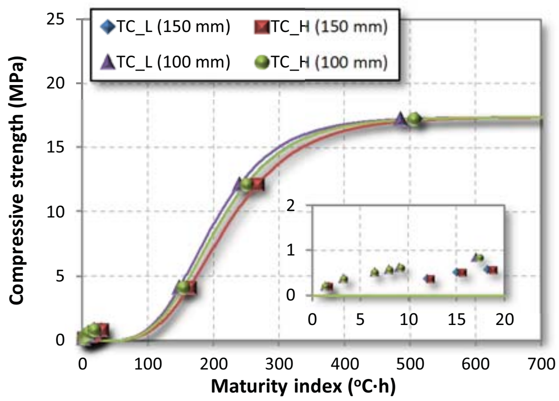


Figure 8.9- Maturity curves considering thickness

The results show how the variations in the thickness of the sprayed concrete layers do not importantly affect the relationship between the compressive strength and the maturity index. Therefore, considering the case studied, the maturity curves depend only on the mix designs.

The model presented in section 8.4.1.2 was used to study the affection of the concrete thickness and the ground support on the maturity curves. The aim of this was to adjust the results obtained from spraying a mould of thickness equal to 150 mm in order to estimate the results gathered in a tunnel with different boundary conditions. Then, a new geometry, presented in Figure 8.10 , was used to run the model. This was changed slightly in order to adapt the new boundary conditions. In this sense, since the temperature in a tunnel is usually constant the ambient temperature was considered as 18 ^{o}C. Furthermore, the geometry reflected a wall of the lining of a tunnel and it was enlarged in order not to affect the temperature in the control point by the conditions in the extremities. This new model is presented in Appendix E.

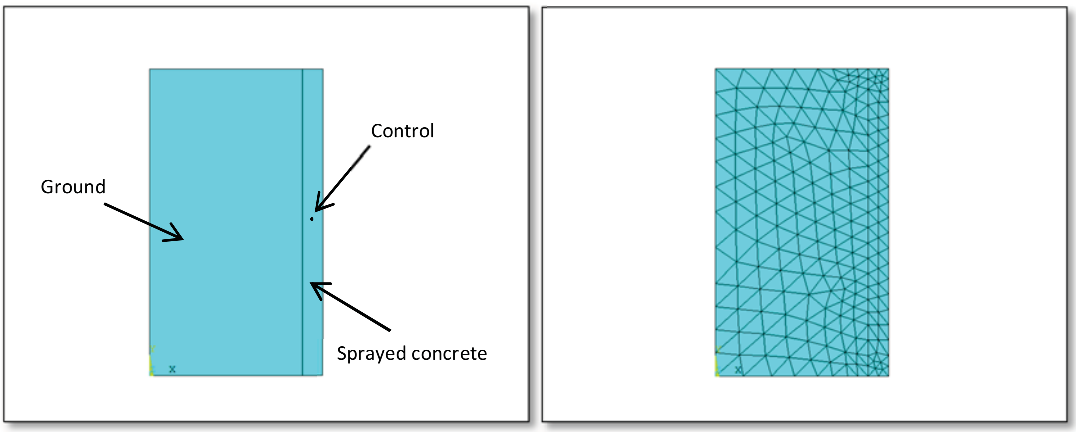


Figure 8.10- Geometry of the model of the lining of a tunnel

Three different thicknesses of sprayed concrete were used: 100, 150 and 200 mm. Furthermore, three types of ground were considered: satured clay (clay), limestone and hard stone (stone). The thermal properties of these three materials are shown in Table 8.4.

Table 8.4- Thermal properties of the grounds

Ground	K (kJ/(h·m·K))	c (kJ/(kg·K))	ρ (kg/m^3)
Clay	5.40	0.92	800
Limestone	4.68	0.91	2300
Stone	18.00	0.84	2600

By running the new model the evolutions of temperature of the lining of the tunnel were obtained, hence the developments of the maturity indices in time were calculated. Table 8.5 presents the results obtained for spraying layers of 100 and 150 mm thick on clay. Furthermore, it gathers the results obtained for the concrete sprayed on the mould. Remaining results followed the same tendencies and therefore they are not presented.

Table 8.5- Development of maturity index in time

Time (h)	Mould (150 mm)	Clay (150 mm)	Clay (100 mm)
0	0.00	0.00	0.00
1	24.12	45.45	24.02
2	49.62	77.03	50.43
3	78.80	115.16	79.30
4	113.70	160.58	112.98
5	153.84	207.73	149.63
6	195.91	253.39	184.27
7	238.09	296.71	215.29
8	279.31	337.21	242.21
9	318.96	375.48	264.84
10	357.07	412.16	283.70
11	393.76	447.61	299.10
12	424.24	454.79	305.54

The results show the affection of the thickness on the results since the results obtained for the layer with thickness 100 mm differ from the ones obtained for the layer with thickness equal to 150 mm. Furthermore, the supporting ground influences the results as the results of spraying concrete on steel are not equal to the results obtained for clay.

The differences observed entail adjusting the results from the mould to the results of the lining in order to estimate the compressive strength. Then, to do that, the pairs of values of maturity indices obtained from the mould and from the lining were graphed together. Figure 8.11 presents the results obtained from spraying different layers with different thicknesses on clay and the results from spraying layers of 150 mm on different ground supports. A linear tendency of the results is observed and therefore, considering the slope of the straight lines the adjustment may be done. This adjustment shall be done by multiplying the results obtained from the mould with a redactor/amplifying parameter, i.e. the value of the slope. This parameter is called η.

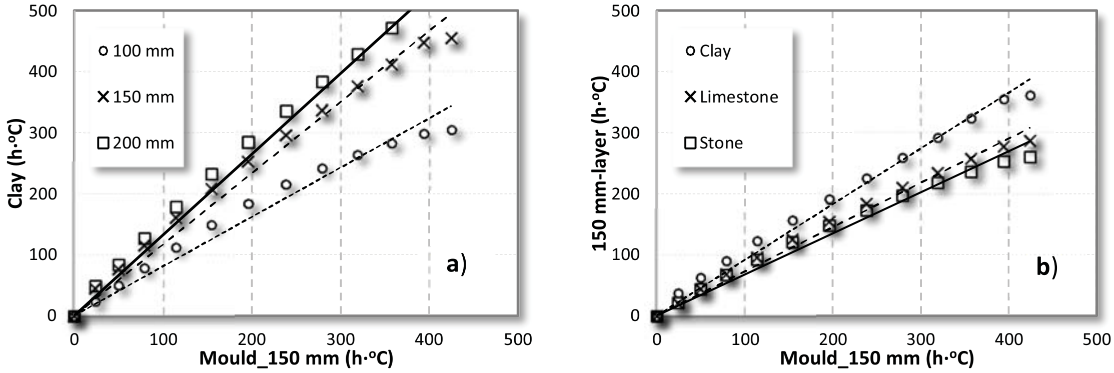


Figure 8.11- Influence of the thickness a) and the ground support b) on the maturity indices

Table 8.6 presents the η-parameters analysing the results obtained running the model considering the different established boundary conditions. Furthermore, it presents the R^2 of the straight lines.

Table 8.6- η-parameters and corresponding R^2

Thickness	Type of ground		
	Clay	**Limestone**	**Stone**
100 mm	0.809 *(0.966)*	0.726 *(0.988)*	0.672 *(0.977)*
150 mm	1.168 *(0.981)*	0.913 *(0.986)*	0.686 *(0.985)*
200 mm	1.323 *(0.981)*	0.964 *(0.987)*	0.911 *(0.985)*

As previously observed the development of the maturity indices over time depends on the thickness and the type of ground support, as well as the mix design. Regarding the thickness of sprayed concrete, a decrease involves a reduction of the η entailing a reduction of the results gathered from the mould, regardless of the ground support type. Furthermore, the thermal characteristics of the ground support affect the value of the parameter η.

8.5. MATURITY METHOD FOR SPRAYED CONCRETE

In order to apply the maturity method to sprayed concrete, two main steps should be followed: the laboratory step and the in-situ step, illustrated in Figure 8.12. Firstly, the laboratory step develops the maturity curves that will be used in the construction following the requirements of the European standard UNE-EN 14488-2:2006 (46). Therefore, 150 mm-thickness moulds should be sprayed and the mechanical properties of the sprayed concrete studied. The early compressive strength of the sprayed concrete should be estimated using the penetration needle test and the stud driving method. Furthermore, the evolution of temperature should be recorded using thermocouples and a data logger. Next, considering the thickness of the layers and the ground support of the construction the evolution of temperature should be adapted using the η-parameter obtained using the thermal model previously adjusted considering the mix design including type of accelerator, dose of accelerator and type of cement. Once adjusted, the evolution of temperature is used to obtain the development of the maturity index in time. Finally, the developments of the maturity index and the compressive strength are used to obtain the maturity indices of each mix.

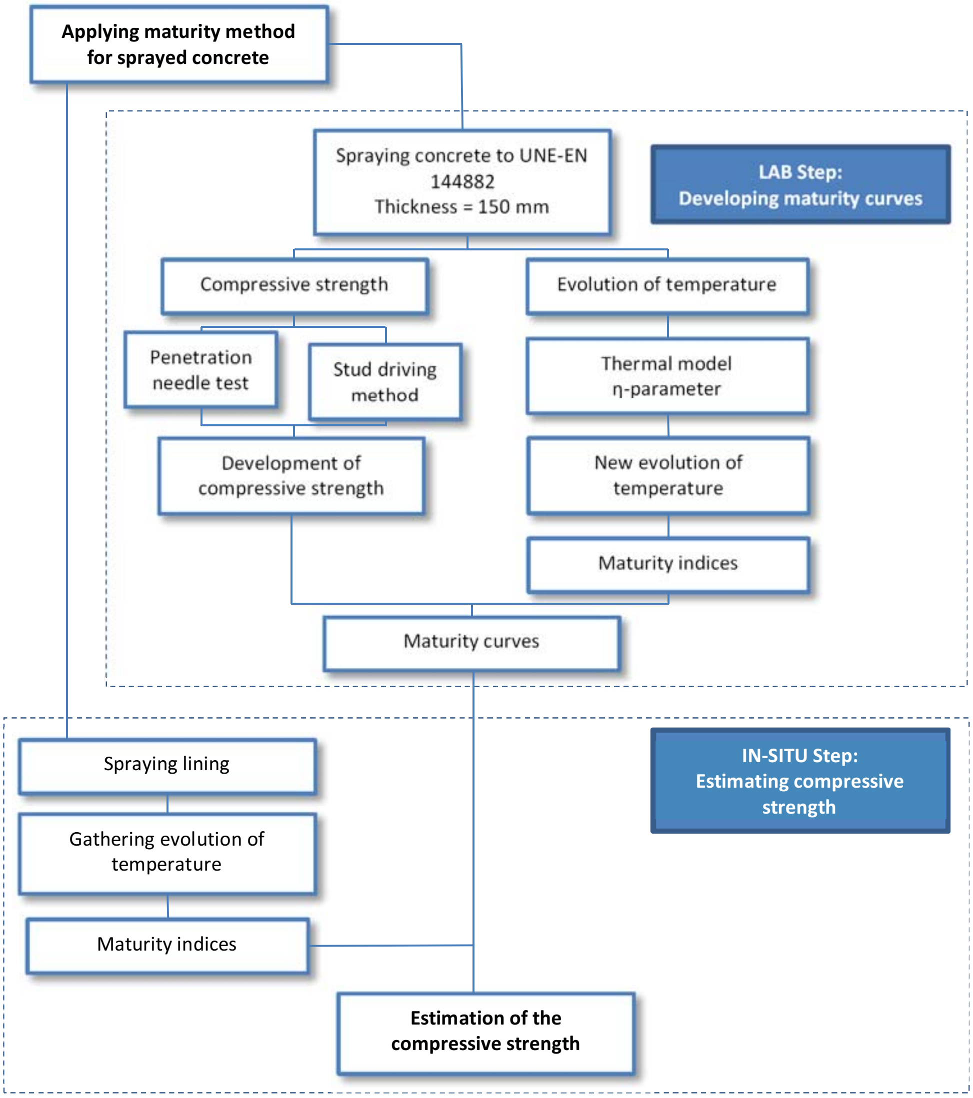


Figure 8.12- Application of the maturity method to sprayed concrete

For the in-situ step the thermocouples are carefully collocated on the ground and the concrete is sprayed on to them. A data logger connected to a laptop records the evolution of temperature every 1 min. The screen of the laptop should show the evolution of temperature in real time. Furthermore, the maturity index should be estimated using the evolution of temperature gathered. Then, using the maturity index and the maturity curves previously found the compressive strength is estimated in real time. Finally, considering the minimum strength requirements of the construction engineers should be able to, for example, continue excavating a tunnel whilst estimating the compressive strength based on the maturity curves.

8.6. CONCLUDING REMARKS

The following concluding remarks are derived from the analysis presented in this chapter.

- The results of the evolution of temperature and compressive strength development may be related using the maturity index, which is calculated by the Nurse-Saul maturity function (Equation 8.1).
- The relationships between the compressive strength development and the maturity index presented by the mixes studied fitted with a single equation. This depends on three different parameters that should be obtained empirically using curve fitting software for the treatment and analysis of experimental data.
- The maturity curves depend on three variables: type of accelerator, dose of accelerator and type of cement. Therefore a maturity curve can be defined for each mix design.
- Design parameters such as thickness of the sprayed concrete layers and the ground support should be considered to adjust the maturity curves obtained experimentally. The maturity curves can be adjusted using η-parameters, which depend on the aforementioned design considerations.
- The maturity method can be applied to sprayed concrete in order to estimate the compressive strength development in real time considering experimental programs in the laboratory, FEM modelling and application in situ as described in Figure 8.12.

CHAPTER 9. CONCLUSIONS AND FUTURE PRESPECTIVES

9.1. GENERAL CONCLUSIONS

As previously mentioned, different aspects of the sprayed concrete such as the use of new materials or the new structural requirement entail more studies. Therefore, a rather generalist work was outlined in order to obtain clear and practical answers to the general objective: provide a characterization of wet-mix sprayed concrete with new accelerators and to propose methods for the control of the material. In this sense, the work was focused on five important research lines: the characterization at different levels (cement paste, mortar and sprayed concrete) of mixes with different types of cement and accelerators, the control procedure at mortar level, the correlation between cement paste/mortar and sprayed concrete properties, the correlation compressive strength/modulus of elasticity of sprayed concrete and the control procedure at sprayed concrete level. This section presents the general conclusions obtained for each one of them in response to the general objectives defined in Chapter 1.

The study of the first subject shows that the characterization of the materials at three different levels may be performed in a laboratory after the facilities are adapted. With that, it was possible to identify and to compare the behavior of several mixes with different accelerators and cement types. The outcomes of the second subject represent an advance regarding the quality control procedures for mortar with accelerator. In this sense, an adaptation of the flexural and compressive strength test of conventional mortar to be used for mortar with accelerator was proposed for the production process and the statistical analysis of the results.

The study of the third subject shows that it is possible to correlate the properties of cement pastes/mortar mixes and the ones of sprayed concrete. This represents a contribution towards the characterization of the effect of accelerators in the mixes based on the results of small scale test. Consequently, a fair prediction is obtained without using a complicated, time-consuming and expensive testing setup.

In the fourth subject, it becomes clear that the correlations used in several standards to predict the modulus of elasticity of conventional concrete overestimates the results obtained for the sprayed concrete. In this sense, an empirical and a semi-analytical equation were proposed taking into account the characteristics of the sprayed concrete, which may be useful for a more reliable design of structure.

The outcome of the last subject also represents an advance considering the current quality control methodology for sprayed concrete. The maturity method was adapted to be used for sprayed concrete using experimental data and a thermal analysis with finite elements. This is an engineering tool to estimate the development of the compressive strength of sprayed concrete at early ages based mainly on the evolution of temperature.

9.2. SPECIFIC CONCLUSIONS

In view of the specific objectives, for each one of the five subjects studies in this thesis, several results and improvements were detailed in previous chapters. The most relevant conclusions are described below.

Characterization at different levels (cement paste, mortar and sprayed concrete) of mixes with different types of cement and accelerators

- The addition of accelerator entails a quick setting which complicates the production of a homogeneous mortar affecting the plasticity and the compacting of the samples. This issue affects the results leading to higher scatter in the tests of pastes and mortars.

- The optimal doses of the accelerator based on aluminates (A-0) are 2 and 3% bcw for cement II and I respectively. On the other hand, the optimal doses for the wide range of alkali free accelerators are 5 and 7% bcw for cement I and II, respectively.

- Regarding the results of the initial and final setting time in pastes, a difference between the alkali free accelerators and the one based on aluminates (A-0) is observed. This is possibly due to the affinity accelerator-cement. Whereas A-0 present optimal results with the cement II, the alkali free accelerators tested present better results with I.

- The type of cement, the type and the dose of accelerator used in the mixes affect the evolution of temperature. The influence of the type of cement is related with the amount of clinker and additions present. As expected, the increase of the dose of the accelerator leads to higher temperatures. By the results it is clear that some accelerators show more affinity to react with the aluminates of cement (thus affecting the first peak of temperature and the setting times), whereas others have more affinity to react with the silicates of cement (thus affecting the second peak of temperature and the early compressive strength).

- The type of cement show little influence on the compressive strength evolution up to 30 min after production or spraying. In this case, the main parameter that affects the compressive strength is the dose of accelerator used. Although, the affinity between the type of cement and the accelerator is also important.

- The mixes that present higher strength results at early ages present lower strength at long ages. This difference is possibly due to the influence of the accelerators in the hydration of cement and in the compaction process. At early ages, a more effective accelerator contributes to a faster setting, thus increasing the strength at a certain time. On the other hand, since the microstructure is formed more rapidly, the compaction process is less effective. This leads to higher porosity and, consequently, smaller strengths at long term. The results obtained with mixes with cement I are twice as big as the results obtained with mixes with cement II.

- Using the penetration needle test and the stud driving method, it was not possible to measure the compressive strength of the sprayed concrete between 30 min and 4 h. Furthermore, the stud driving method and the compressive strength test at 1 day show quite different results. Therefore, it is recommended to perform both tests in order to assure a good quality control of the material.

Control procedure at mortar level

- The addition of accelerator in the mixes changes the characteristics of the mortar. Therefore, the production process and the statistical verification of the results specified in the standard UNE-EN 196-1:2005 must be adapted in order to make it applicable to the characterization of mixes with accelerators.

- The new production process varies due to the fast chemical reactions generated in the mix. In order to emulate the spraying process the accelerator is added at once at the end of the process and mixed during 20 s. This time was established to assure the homogeneity of the mix of the accelerator. Furthermore, in order to avoid breaking chemical chains derivate of the addition of the additive all process is done with the mixer in low speed (shovel and planetarium rotation velocities of 225 and 100 rpm, respectively).

- An adaptation of the statistical verification of the results is proposed. Based on the analysis of an extensive experimental program a new value of admissible deviation equal to 20% is proposed. It is important to remark that this value is valid for the production process described in this study.

Correlation between cement paste/mortar and sprayed concrete properties

- In most cases, the correlation between the results for pastes, mortars and sprayed concrete do not present a good fit. The high scatter of the results, the differences in the composition of the mix and the differences in the production processes are responsible for the poor correlation.

- The temperature, energy, mechanical and physical parameters that showed highest correlations are SC_T_{6h}, $SC\_E(T_{Min1P\text{-}2P})$, SC_P_{30min} and SC_p_{28d} , respectively. Their values of correlations are 0.74, 0.61, 0.67 and 0.95, respectively.

- The high scatter observed is intrinsic to sprayed concrete. To account for that, the definition of a confidence area for the correlation curves is a necessary approach. Then using this approach, acceptable correlation curves and the corresponding confidence areas were obtained. This shows that it is possible to use the results from cement pastes and mortars to estimate the properties of sprayed concrete.

Correlation compressive strength/modulus of elasticity of sprayed concrete

- The higher porosity and the bigger mortar content present in sprayed concrete produce a reduction in the modulus of elasticity. Therefore, for the same compressive strength it is expected that the sprayed concrete show an elastic modulus smaller than that of conventional concrete. This is observed in the experimental results, being more noticeable as the compressive strength considered decrease.

- Estimations given by empirical and semi-analytical models proposed to predict the modulus of elasticity provide similar results if a porosity of sprayed concrete of 14-18%, a porosity of conventional concrete of 6-9% and a volumetric rebound of 5-15% are considered. These parameters may be adopted as references for sprayed concrete in case no further information is available.

Control procedure at sprayed concrete level

- The results of the evolution of temperature and compressive strength development may be related using the maturity index.

- The relationships between the compressive strength development and the maturity index presented by the mixes studied fitted a single equation. This depends on three different parameters that should be obtained empirically. Type of accelerator, dose of accelerator and type of cement affects the maturity curves. Therefore a maturity curve may be defined for each mix design.

- Design parameters such as thickness of the sprayed concrete layers and the type of ground should be considered to adjust the maturity curves obtained experimentally using η-parameters presented.

9.3. FUTURE PRESPECTIVES

In spite of the advances described in the previous section, there still exists a lot of space for further studies in the subjects treated in this thesis and in many other subjects about the properties of sprayed concrete. Based on that, this section presents some suggestions for future researches and experimental campaigns.

- The characterization of mixes should be still performed at different levels widening the study of the cement paste level. In this sense, results obtained from chemical tests may allow understanding the interaction cement/accelerator.

- New composition of mixes could be studied. On one hand, the mechanical behaviour of the material with the addition of metallic or polymeric fibres should be studied. On the other hand, the influence of addition such as the microsilica or nanosilica in the evolution of properties should also be studied and it should be considered.

- It is important to extend the mechanical and rheological characterization of sprayed concrete, for instance, focusing on shrinkage or bond between sprayed concrete and steel bars.

- The characterization of sprayed cement pastes and mortars should be studied in depth. It is possible that the use of a production process closer to the applied for sprayed concrete would improve the correlation of properties measured in small and in large scale.

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APPENDIX A- INFORMATION ABOUT TYPE OF CEMENTS

CEMENTOS MOLINS INDUSTRIAL, S.A.

LABORATORIO CENTRAL

Número: 75121 **Descrip:** AUTOCONT AENOR - C.PORTLAND CEM I 52,5 R ENSACADO

Fecha : 12-06-06 **Desadd:** DÍA 9 SEMANA 23 UPC

Clave: AU21EN

ANÁLISIS QUÍMICO	
SiO2	20.46
Al2O3	5.46
Fe2O3	3.46
FeO	
CaO	62.73
MgO	1.88
SO3	3.40
Na2O	.15
K2O	.85
TiO2	
P.F.	1.61
Suma	100.0
R.I.	
CaCO3	
CaO libre	1.34
Cloruros	
Sulfuros	
Humedad	.35
T.O.C.	
Azul	
Cr(VI)	

MÓDULOS Y CONSTITUYENTES	
L.S.F.	95.1
L.C.F.	93.0
M.S.	2.29
M.A.	1.58
C3S	48.52
C2S	22.06
C3A	8.63
C4AF	10.52
C4AF+C2F	
CA	
C12A7	
C2F	
Al/Ca	
Fe2O3/Fe3T	
Color	
Na2O equiv.	.70

PASTA PURA	
Agua amasado	147
Penet. sonda	35
Inicio fraguado	85
Fin fraguado	140
Exp. agujas	.0
MORTERO	
Asentamiento	160
FINURA CEMENTO	
Blaine	4533
3µm	
32µm	
45µm	
63µm	
D10	
D50	
D90	
Peso esp. Densidad aparente	

COMBUSTIBLES	
Hum.Ambiental	
Humedad Total	
Volatiles	
Cenizas	
Azufre	
SO3	
Potencia Calorífica (cal/g)	
Superior	
Inferior	

AGUAS	
Amonio	
Cl2 libre	
Cl2 total	
pH	
Conduct.	
DQO	
Mat.Susp.	
Sol.Dis.	
Dureza	
Sulfato	
Cloruros	

R E S I S T E N C I A S   M E C Á N I C A S

	MEDIA	ROTURAS						D.S.	C.V.
FLX-001D	5.7	5.8	5.6					.1	2.48
FLX-002D	6.8	6.7	7.1	6.7				.2	3.38
FLX-007D	8.9	8.9						******	*******
COM-001D	29.2	28.6	29.8	29.1	29.4			.5	1.73
COM-002D	39.6	41.3	40.5	39.8	38.1	38.6	39.2	1.2	3.02
COM-007D	52.7	52.5	52.8					.2	.4

V.B. Adj. DIRECTOR PRODUCTO-CALIDAD JEFE DEL LABORATORIO

(resultad) 21-06-06 1 / 1

Dragón AL

CIMENT PÒRTLAND AMB CALCÀRIA

EN 197-1-CEM II / A-L 42,5 R

Descripció

El nostre "DRAGÓN AL" és un ciment d'una resistència mitjana-alta pensat principalment per al sector del formigó preparat i del morter sec. Les característiques principals d'aquest ciment són:

- Resistències finals elevades.
- Necessita poca aigua i és fàcil de treballar.
- Menor risc de fissures.

Expedició i emmagatzematge

- Disponible només a granel.
- L'emmagatzematge de ciment a granel ha de fer-se en sitges estanques.

Recomanat per a:

- Formigó armat o en massa.
- Formigó projectat.
- Prefabricats no pretesats.
- Pavimentació i ferms de carreteres.

No indicat per a:

- Formigó pretesat.
- Elements estructurals prefabricats pretesats o posttesats.

Precaucions de posada a l'obra

És important posar atenció en les operacions de cura, sobretot amb climes calorosos, secs i, eventualment, amb vent.

Taula de característiques del ciment

	Valors habituals	Especificacions segons norma	
Clinker (%)	88	mín. 80 - màx. 94	
Caliça (%)	10	mín. 6 - màx. 20	
Component minoritari (%)	2	mín. 0 - màx. 5	
Sulfat, SO_3 (%)	3,3	màx. 4,0	(1)
Clorurs, Cl^- (%)	0,01	màx. 0,10	(1)
Superfície específica Blaine (cm^2/g)	3900	-	(2)
Expansió Le Chatelier (mm)	0,5	màx. 10	(2)
Inici adormiment (min)	120	mín. 60	(2)
Final adormiment (min)	180	màx. 720	(2)
Compressió a 1 dia (MPa)	13	-	(3)
Compressió a 2 dies (MPa)	25	mín. 20,0	(3)
Compressió a 7 dies (MPa)	39	-	(3)
Compressió a 28 dies (MPa)	52	mín. 42,5 - màx. 62,5	(3)

(1) Químiques (2) Físiques (3) Mecàniques

AENOR certifica que aquest ciment s'adequa a les especificacions de la norma UNE-EN 197-1:2000 (ciments comuns) i l'avalua segons allò establert en el Reglament Particular RP 15.01 (Marca N). Per tant, té també el certificat de conformitat de la CE corresponent. Aquest ciment conté un agent reductor del crom (VI). AENOR certifica també, el compliment del límit reglamentari del contingut en Cr (VI) soluble segons la norma UNE 80601:2005.

SAC 936 80 60 30

CIMENTS MOLINS INDUSTRIAL

Ciments Molins Industrial, S.A. té informació complementaria a la seva disposició d'aquest producte.

Ed. 01/07

APPENDIX B- EXPERIMENTAL ANALYSIS OF CEMENT PASTES AND MORTARS

Appendix B presents the results of the experimental program of cement pastes and mortars referred to the mixes with high dose of accelerator AF-1.1, AF-2.1 and AF-3.1, and all doses of accelerator AF-1.2, AF-2.2 and AF-3.2. Notice than all results are compared with the ones obtained with mixes with accelerator A-0.The results are divided on cement pastes and mortar mixes. Firstly, the results of initial and final setting times and the evolution of temperature of cement pastes are presented. Then, the evolution of temperature of mortars, the penetration needle test, the density and porosity and the flexural and compressive strength are shown.

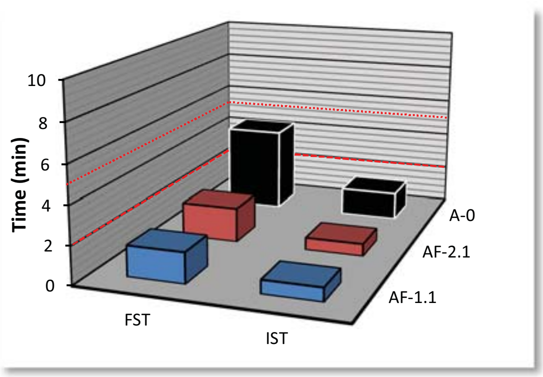
CEMENT PASTES

Initial / final setting time

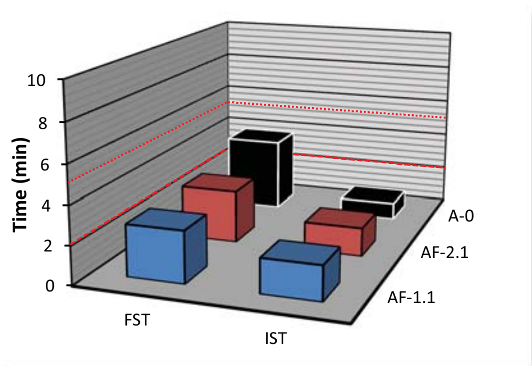
Results of initial / final setting time (min)

HIGH DOSE				
Accelerator	CEM I 52.5 R		CEM II/A-L 42.5 R	
	FST	IST	FST	IST
A-0	4.42	1.45	3.83	0.88
AF-1.1	1.62	0.72	2.70	1.80
AF-2.1	1.82	0.65	2.75	1.50

High Dose / I



High Dose / II

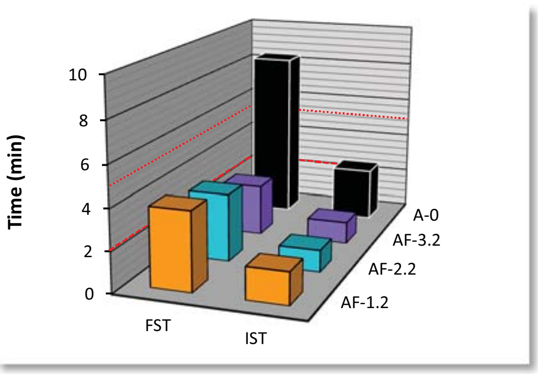


Comparison between the optimal dose interval times and experimental results

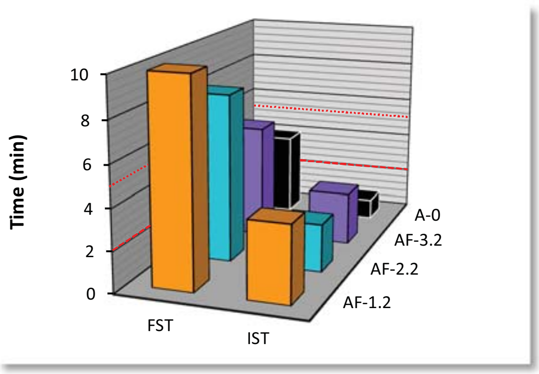
Results of initial / final setting time (min)

Accelerator	CEM I 52.5 R		CEM II/A-L 42.5 R	
LOW DOSE				
	FST	IST	Final ST	Initial ST
A-0	8.35	2.58	4.00	0.97
AF-1.2	3.87	1.58	11.82	3.75
AF-2.2	3.33	1.08	8.18	2.33
AF-3.2	2.52	1.08	5.53	2.55

Low Dose / I



low Dose /I I

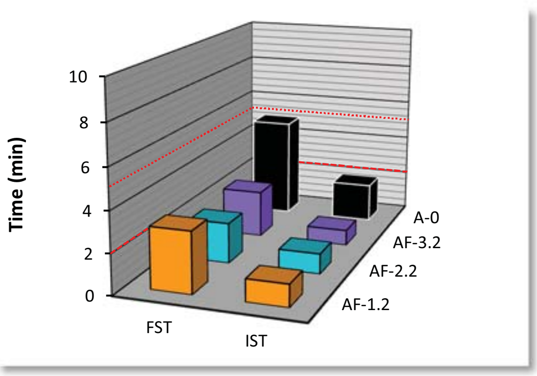


Comparison between the optimal dose interval times and experimental results

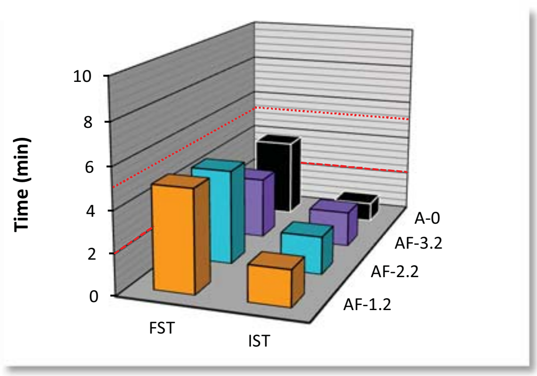
Results of initial / final setting time (min)

Accelerator	CEM I 52.5 R		CEM II/A-L 42.5 R	
MEDIUM DOSE				
	Final ST	Initial ST	Final ST	Initial ST
A-0	4.97	1.92	3.88	0.95
AF-1.2	3.02	1.10	4.98	1.77
AF-2.2	2.00	1.00	4.62	1.85
AF-3.2	2.32	0.77	3.02	1.73

Medium Dose / I



Medium Dose / II

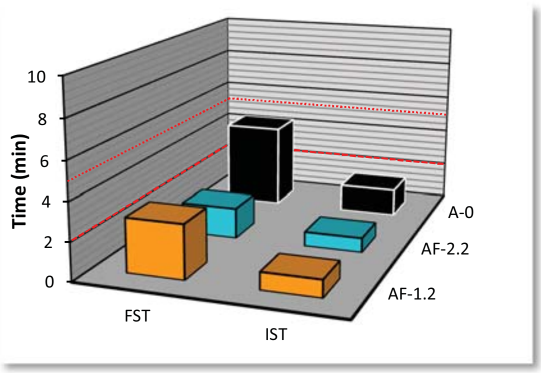


Comparison between the optimal dose interval times and experimental results

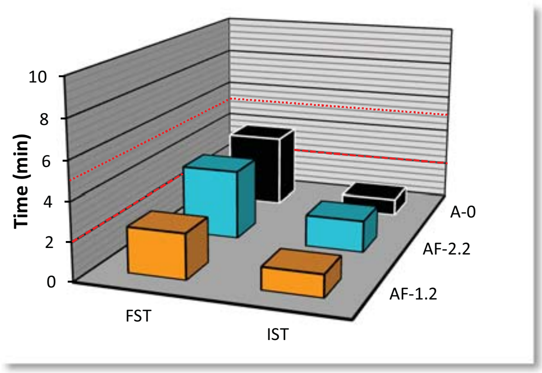
Results of initial / final setting time (min)

Accelerator	HIGH DOSE			
	CEM I 52.5 R		CEM II/A-L 42.5 R	
	Final ST	Initial ST	Final ST	Initial ST
A-0	4.42	1.45	3.83	0.88
AF-1.2	2.83	0.92	2.37	1.17
AF-2.2	1.62	0.77	3.62	1.67

High Dose / I



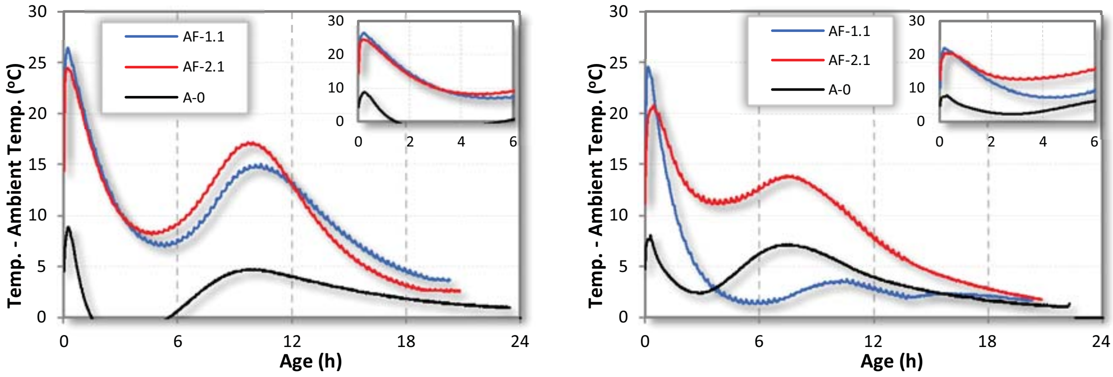
High Dose / II



Comparison between the optimal dose interval times and experimental results

Evolution of temperature

High Dose / I *High Dose / II*

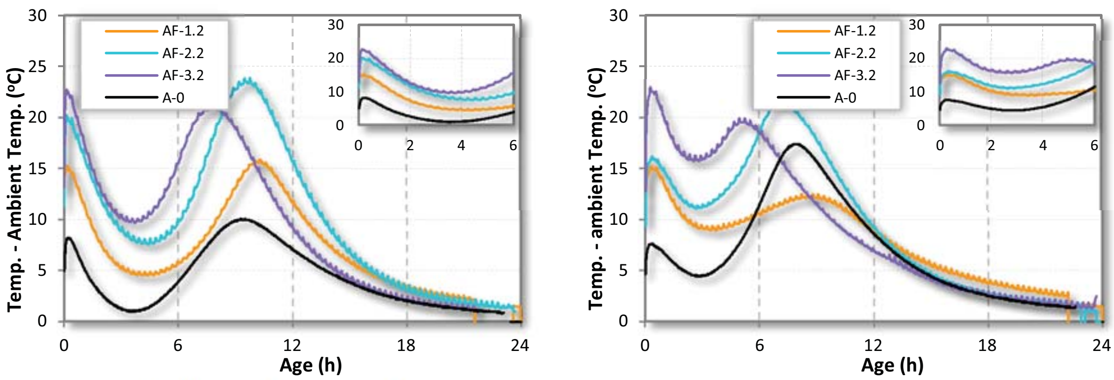


Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

	High Dose					
Reference	**A-0_4_I**	**AF-1.1_9_I**	**AF-2.1_9_I**	**A-0_4_II**	**AF-1.1_9_II**	**AF-2.1_9_II**
T_{max} (°C)	8.90	26.60	24.50	8.10	24.60	20.80
t_T_{max} (h:min)	0:12:00	0:11:30	0:10:30	0:16:30	0:09:00	0:24:30
Et_T_{max} (h·°C)	188.45	588.00	504.05	250.95	412.75	959.70
T_{1P} (°C)	8.90	26.60	24.50	8.10	24.60	20.80
t_T_{1P} (h:min)	0:12:00	0:11:30	0:10:30	0:16:30	0:09:00	0:24:30
Et_T_{1P} (h·°C)	188.45	588.00	504.05	250.95	412.75	959.70
T_{2P} (°C)	4.80	15.10	17.20	7.20	3.80	13.90
t_T_{2P} (h:min)	9:36:30	10:04:00	9:39:00	7:11:30	10:34:30	7:24:30
Et_T_{2P} (h·°C)	2207.05	14813.15	15124.00	3994.25	6721.85	12152.45
$T_{min1P-2P}$ (°C)	0.00	7.00	8.20	2.40	1.40	11.20
t_$T_{min1P-2P}$ (h:min)	1:26:30	5:01:30	4:37:00	2:31:30	5:09:00	3:28:30
Et_$T_{min1P-2P}$ (h·°C)	799.00	8393.40	7830.80	1378.75	5132.60	6352.20

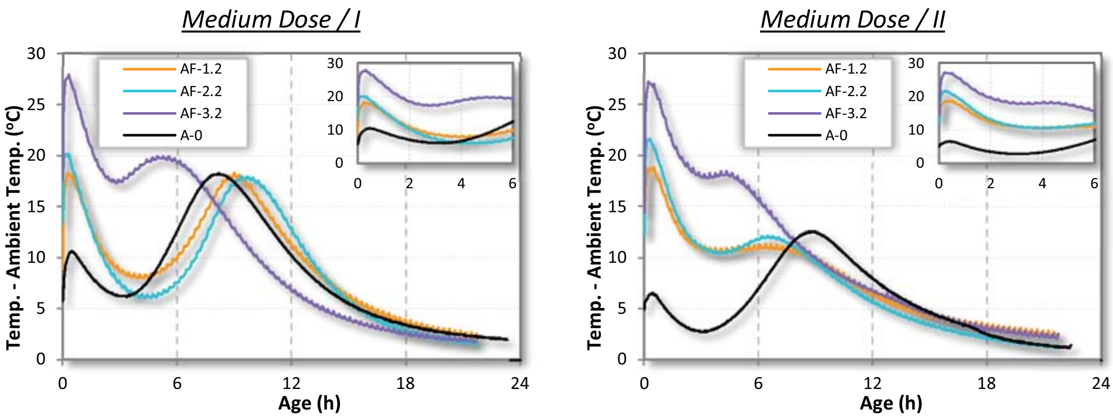
Low Dose / I *Low Dose / II*



Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

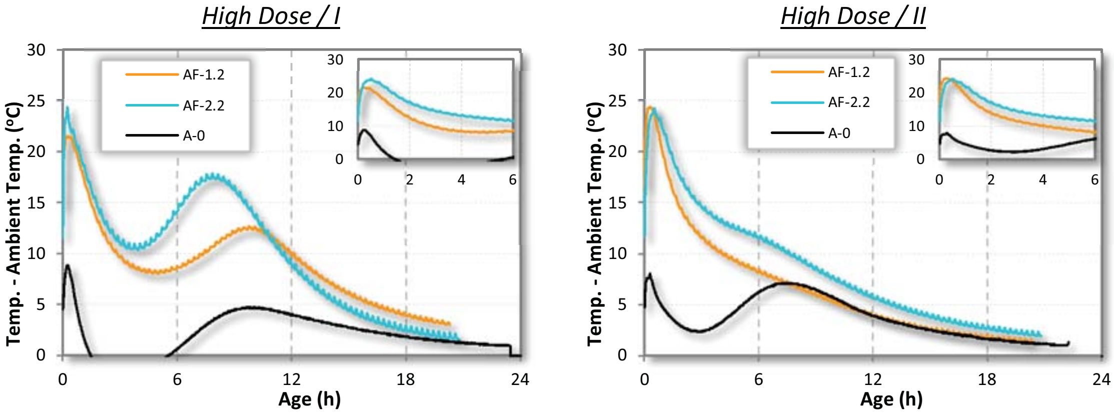
	Low Dose							
Reference	**A-0_2_I**	**AF-1.2_5_I**	**AF-2.2_5_I**	**AF-3.2_9_I**	**A-0_2_II**	**AF-1.2_5_II**	**AF-2.2_5_II**	**AF-3.2_9_II**
T_{max} (°C)	10.10	15.90	23.90	22.80	17.40	15.30	21.60	23.00
t_T_{max} (h:min)	9:13:30	10:17:00	9:27:00	0:08:00	7:42:30	0:17:30	7:05:00	0:15:00
Et_T_{max} (h·°C)	5132.60	10831.40	15310.70	352.80	7728.80	510.55	12511.50	642.50
T_{1P} (°C)	8.20	15.30	20.30	22.80	7.70	15.30	16.20	23.00
t_T_{1P} (h:min)	0:07:30	0:10:00	0:07:30	0:08:00	0:22:00	0:17:30	0:21:00	0:15:00
Et_T_{1P} (h·°C)	116.10	308.30	291.00	352.80	322.15	510.55	648.00	642.50
T_{2P} (°C)	10.10	15.90	23.90	21.20	17.40	12.50	21.60	20.00
t_T_{2P} (h:min)	9:14:00	10:17:30	9:27:30	7:37:00	7:43:00	8:11:30	7:05:30	5:14:00
Et_T_{2P} (h·°C)	5142.60	10847.30	15334.60	13455.60	7746.10	10806.95	12533.10	11468.40
$T_{min1P\text{-}2P}$ (°C)	1.00	4.60	7.60	9.70	4.50	9.00	11.10	15.80
t_$T_{min1P\text{-}2P}$ (h:min)	3:23:00	3:45:30	4:07:30	3:30:30	2:36:30	3:22:00	2:40:00	2:28:30
Et_$T_{min1P\text{-}2P}$ (h·°C)	1588.95	3991.40	6264.90	6256.20	1910.70	4712.60	4357.70	5649.05



Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

	Medium Dose							
Reference	**A-0_3_I**	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**A-0_3_II**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
T_{max} (°C)	18.30	18.40	20.20	28.00	12.60	18.90	21.70	27.30
t_T_{max} (h:min)	0:05:30	0:15:00	0:07:30	0:18:30	8:35:30	0:29:30	0:15:30	0:12:00
Et_T_{max} (h·°C)	0.00	511.25	303.00	1006.55	6366.40	1081.85	648.55	614.25
T_{1P} (°C)	10.70	18.40	20.20	28.00	6.60	18.90	21.70	27.30
t_T_{1P} (h:min)	0:25:30	0:15:00	0:07:30	0:18:30	0:22:30	0:29:30	0:15:30	0:12:00
Et_T_{1P} (h·°C)	497.05	511.25	303.00	1006.55	282.75	1081.85	648.55	614.25
T_{2P} (°C)	18.30	18.40	18.10	20.10	12.60	11.40	12.20	17.60
t_T_{2P} (h:min:s)	8:06:00	8:59:30	9:41:00	5:32:00	8:36:00	6:22:30	6:10:30	5:01:00
Et_T_{2P} (h·°C)	10098.40	13095.15	13119.70	13575.15	6378.95	9638.25	9897.30	12288.95
$T_{min1P\text{-}2P}$ (°C)	6.20	8.00	6.10	17.30	2.80	10.60	10.50	17.50
t_$T_{min1P\text{-}2P}$ (h:min)	3:15:30	3:57:00	4:17:30	2:51:30	2:43:30	3:37:00	3:40:00	5:00:00
Et_$T_{min1P\text{-}2P}$ (h·°C)	3170.25	5751.20	5867.65	7482.85	1522.25	6031.25	6553.40	12253.90



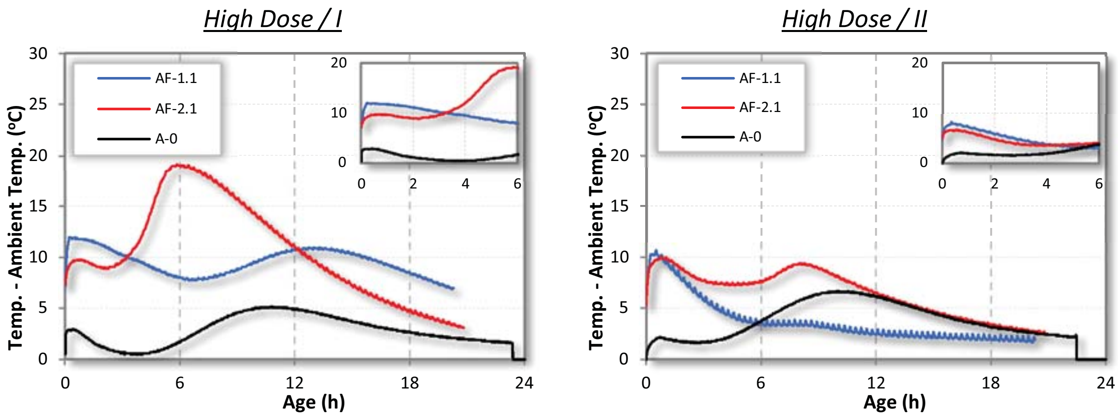
Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

	High Dose					
Reference	**A-0_4_I**	**AF-1.2_9_I**	**AF-2.2_9_I**	**A-0_4_II**	**AF-1.2_9_II**	**AF-2.2_9_II**
T_{max} (°C)	8.90	21.50	24.40	8.10	24.40	24.30
t_T_{max} (h:min)	0:12:00	0:10:30	0:13:30	0:16:30	0:12:30	0:30:30
Et_T_{max} (h·°C)	188.45	443.25	606.60	250.95	593.60	1345.70
T_{1P} (°C)	8.90	21.50	24.40	8.10	24.40	24.30
t_T_{1P} (h:min)	0:12:00	0:10:30	0:13:30	0:16:30	0:12:30	0:30:30
Et_T_{1P} (h·°C)	188.45	443.25	606.60	250.95	593.60	1345.70
T_{2P} (°C)	4.80	12.70	17.90	7.20	9.20	12.40
t_T_{2P} (h:min)	9:36:30	9:45:30	7:50:00	7:11:30	5:07:30	5:11:30
Et_T_{2P} (h·°C)	2207.05	13510.55	13837.35	3994.25	8818.75	10384.85
$T_{min1P-2P}$ (°C)	0.00	8.10	10.40	2.40	9.00	12.20
t_$T_{min1P-2P}$ (h:min)	1:26:30	4:42:00	3:35:30	2:31:30	5:03:00	5:02:30
Et_$T_{min1P-2P}$ (h·°C)	799.00	7355.40	6808.25	1378.75	8737.05	10164.65

MORTARS

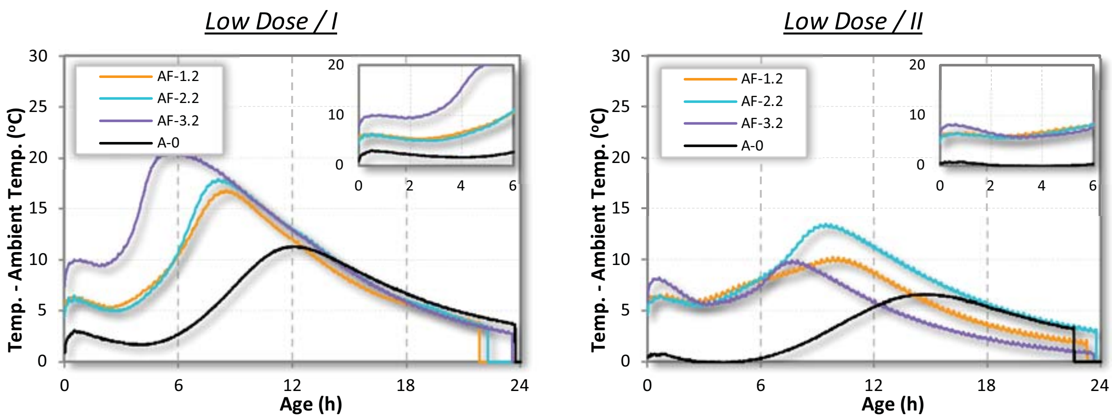
Evolution of temperature



Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

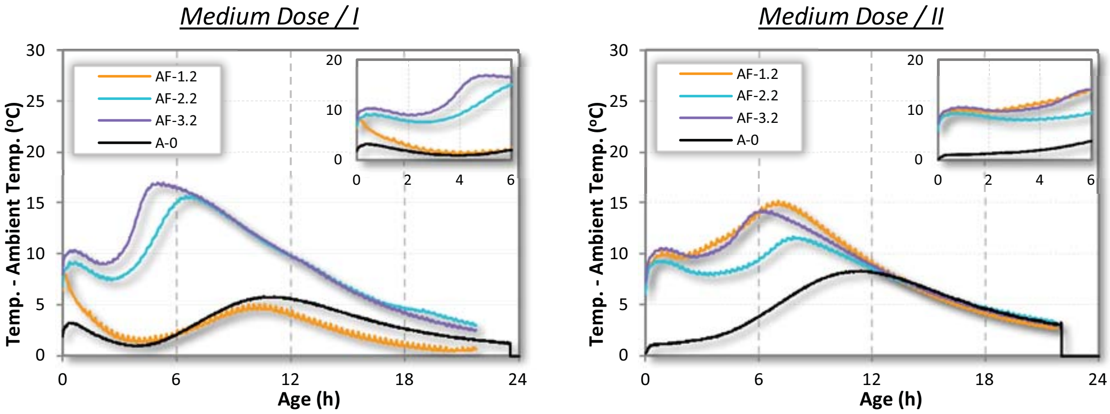
	High Dose					
Reference	**A-0_4_I**	**AF-1.1_9_I**	**AF-2.1_9_I**	**A-0_4_II**	**AF-1.1_9_II**	**AF-2.1_9_II**
T_{max} (°C)	5.20	12.00	19.20	6.70	10.70	10.00
t_T_{max} (h:min)	10:44:00	0:12:00	5:49:30	9:52:30	0:31:00	0:44:00
Et_T_{max} (h·°C)	3142.95	255.45	8237.35	4118.50	589.90	807.00
T_{1P} (°C)	3.00	12.00	9.80	2.20	10.70	10.00
t_T_{1P} (h:min)	0:24:30	0:12:00	0:35:00	0:39:30	0:31:00	0:44:00
Et_T_{1P} (h·°C)	136.30	255.45	653.30	131.40	589.90	807.00
T_{2P} (°C)	5.20	11.00	19.20	6.70	4.20	9.40
t_T_{2P} (h:min)	10:44:30	12:26:30	5:50:00	9:53:00	5:09:00	7:58:00
Et_T_{2P} (h·°C)	3148.10	14387.15	8256.55	4125.10	4225.75	7912.50
$T_{min1P-2P}$ (°C)	0.50	7.80	8.90	1.60	3.70	7.30
t_$T_{min1P-2P}$ (h:min)	3:07:00	6:15:30	2:00:30	2:18:00	5:01:30	3:51:00
Et_$T_{min1P-2P}$ (h·°C)	643.80	7563.90	2261.65	500.85	4167.30	3985.50



Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

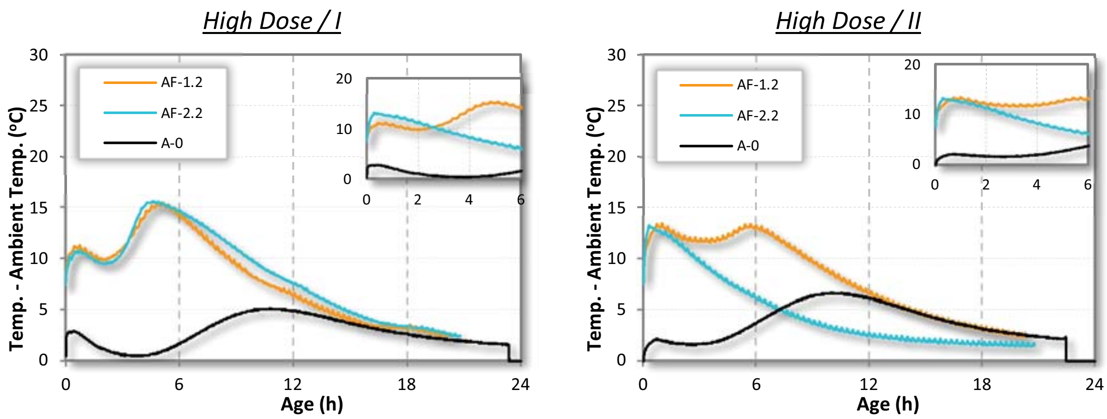
	Low Dose							
Reference	**A-0_2_I**	**AF-1.2_5_I**	**AF-2.2_5_I**	**AF-3.2_9_I**	**A-0_2_II**	**AF-1.2_5_II**	**AF-2.2_5_II**	**AF-3.2_9_II**
T_{max} (°C)	11.30	16.80	17.90	20.50	6.60	10.20	13.50	9.90
t_T_{max} (h:min)	11:40:30	8:12:00	8:03:30	5:24:30	14:32:00	9:47:30	9:25:00	7:38:30
Et_T_{max} (h·°C)	11.30	8501.60	8311.75	8230.10	6.60	8767.40	9005.20	6501.60
T_{1P} (°C)	3.10	6.30	6.50	10.10	0.90	6.60	6.50	8.20
t_T_{1P} (h:min)	0:29:30	0:19:00	0:30:30	0:48:00	1:01:30	1:01:30	0:38:00	0:19:00
Et_T_{1P} (h·°C)	148.90	233.20	360.65	926.25	70.85	772.80	461.80	289.75
T_{2P} (°C)	11.30	16.80	17.90	20.50	6.60	10.20	13.50	9.90
t_T_{2P} (h:min)	11:41:00	8:12:30	8:04:00	5:25:00	14:32:30	9:48:00	9:25:30	7:39:00
Et_T_{2P} (h·°C)	6514.95	8518.30	8329.65	8250.60	3758.90	8777.60	9018.70	6511.45
$T_{min1P-2P}$ (°C)	1.70	5.30	5.00	9.40	0.00	5.60	5.40	5.60
t_$T_{min1P-2P}$ (h:min)	3:23:00	2:19:30	2:22:30	1:46:00	2:34:00	2:03:30	2:55:00	2:53:00
Et_$T_{min1P-2P}$ (h·°C)	964.65	1645.45	1611.70	2055.35	143.90	1521.65	2068.10	2430.85



Evolution of temperature considering type of cement and dose of accelerator

Characteristic points of the evolution of temperature

	Medium Dose							
Reference	**A-0_3_I**	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**A-0_3_II**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
T_{max} (°C)	5.90	8.00	15.70	17.00	8.40	15.20	11.70	14.30
t_T_{max} (h:min)	10:34:00	0:09:00	6:29:00	5:00:00	11:16:30	7:01:00	7:48:30	6:04:30
Et_T_{max} (h·°C)	3685.70	143.40	7794.05	6777.30	5597.20	9611.55	8501.65	7929.35
T_{1P} (°C)	3.30	8.00	9.20	10.40	1.30	10.30	9.40	10.60
t_T_{1P} (h:min)	0:18:30	0:09:00	0:22:00	0:39:30	1:04:30	0:52:30	0:30:00	0:47:30
Et_T_{1P} (h·°C)	109.95	143.40	378.70	795.05	136.55	975.10	514.80	934.00
T_{2P} (°C)	5.90	5.10	15.70	17.00	8.40	15.20	11.70	14.30
t_T_{2P} (h:min:s)	10:34:30	9:47:30	6:29:30	5:00:30	11:17:00	7:01:30	7:49:00	6:05:00
Et_T_{2P} (h·°C)	3691.50	3749.00	7809.75	6794.25	5605.50	9626.75	8513.35	7943.55
$T_{min1P-2P}$ (°C)	1.00	1.40	7.50	8.90	1.20	9.60	7.90	9.70
t_$T_{min1P-2P}$ (h:min)	3:30:30	3:36:00	2:20:30	2:11:00	1:05:00	1:36:30	3:19:30	2:10:00
Et_$T_{min1P-2P}$ (h·°C)	906.65	1639.45	2373.00	2544.30	137.75	1846.95	3453.60	2625.75



Evolution of temperature considering type of cement and dose of accelerator

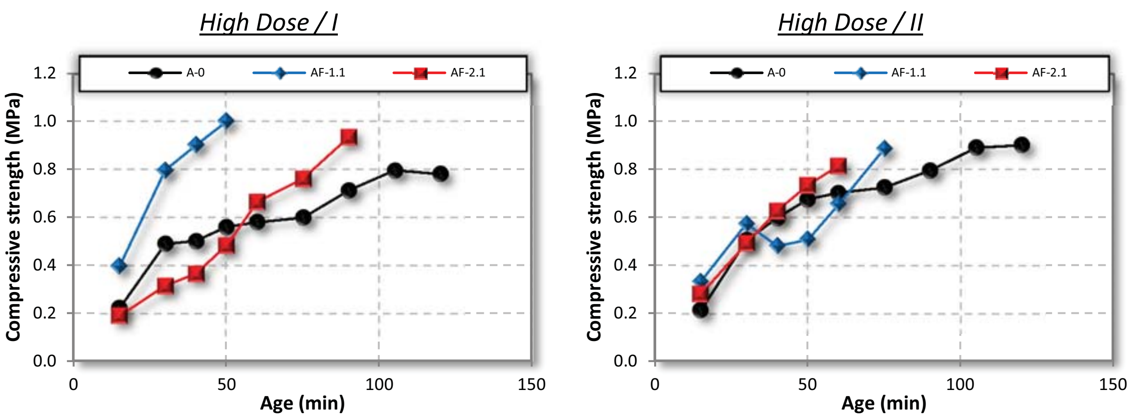
Characteristic points of the evolution of temperature

	High Dose					
Reference	**A-0_4_I**	**AF-1.2_9_I**	**AF-2.2_9_I**	**A-0_4_II**	**AF-1.2_9_II**	**AF-2.2_9_II**
T_{max} (°C)	5.20	15.50	15.60	6.70	13.50	13.30
t_T_{max} (h:min)	10:44:00	4:48:30	4:32:00	9:52:30	1:00:30	0:18:00
Et_T_{max} (h·°C)	3142.95	6667.10	6117.65	4118.50	1492.05	418.80
T_{1P} (°C)	3.00	11.30	10.80	2.20	13.50	13.30
t_T_{1P} (h:min)	0:24:30	0:28:00	0:31:00	0:39:30	1:00:30	0:18:00
Et_T_{1P} (h·°C)	136.30	580.25	618.90	131.40	1492.05	418.80
T_{2P} (°C)	5.20	15.50	15.40	6.70	13.40	7.40
t_T_{2P} (h:min)	10:44:30	5:06:00	5:00:30	9:53:00	5:25:00	5:00:30
Et_T_{2P} (h·°C)	3148.10	7202.90	7002.65	4125.10	7966.90	6233.65
$T_{min1P-2P}$ (°C)	0.50	9.90	9.50	1.60	11.60	7.10
$t\_T_{min1P-2P}$ (h:min)	3:07:00	1:44:30	1:49:00	2:18:00	3:32:30	4:54:00
$Et\_T_{min1P-2P}$ (h·°C)	643.80	2209.50	2215.95	500.85	5194.95	6138.75

Penetration needle test

Compressive strength (MPa) obtained in the penetration needle test

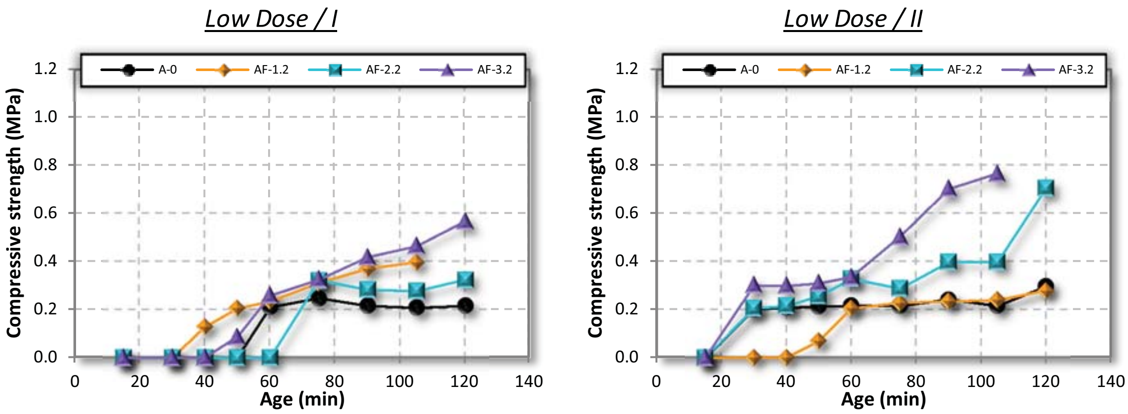
	High Dose (MPa)					
Age (min)	**A-0_4_I**	**AF-1.1_9_I**	**AF-2.1_9_I**	**A-0_4_II**	**AF-1.1_9_II**	**AF-2.1_9_II**
15	0.22 *(3.91%)*	0.40 *(0.14%)*	0.19 *(4.80%)*	0.22 *(9.92%)*	0.33 *(0.30%)*	0.28 *(0.46%)*
30	0.49 *(13.14%)*	0.80 *(4.53%)*	0.32 *(0.37%)*	0.51 *(22.91%)*	0.57 *(1.15%)*	0.49 *(2.21%)*
40	0.50 *(13.19%)*	0.90 *(3.02%)*	0.37 *(1.64%)*	0.60 *(16.05%)*	0.48 *(1.01%)*	0.63 *(1.63%)*
50	0.56 *(7.62%)*	1.00 *(1.51%)*	0.48 *(2.90%)*	0.68 *(8.45%)*	0.51 *(0.87%)*	0.73 *(1.05%)*
60	0.58 *(5.76%)*	- *(0.00%)*	0.67 *(4.17%)*	0.70 *(5.92%)*	0.66 *(0.74%)*	0.81 *(0.46%)*
75	0.60 *(6.33%)*	- -	0.76 *(1.85%)*	0.72 *(5.98%)*	0.89 *(0.60%)*	- -
90	0.71 *(12.10%)*	- -	0.93 *(1.65%)*	0.80 *(9.85%)*	- -	- -
105	0.80 *(6.29%)*	- -	- -	0.89 *(4.24%)*	- -	- -
120	0.78 *(4.02%)*	- -	- -	0.90 *(3.98%)*	- -	- -



Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained in the penetration needle test

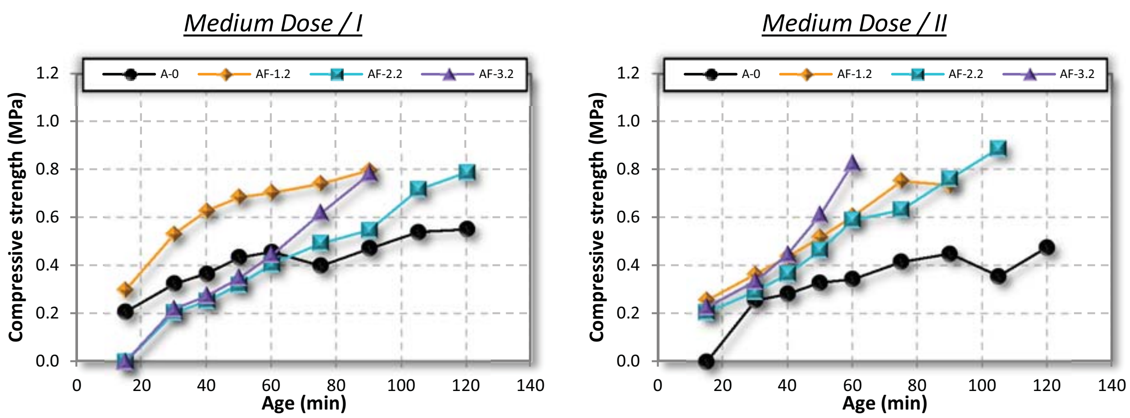
	Low Dose (MPa)							
Age (min)	**A-0_2_I**	**AF-1.2_5_I**	**AF-2.2_5_I**	**AF-3.2_9_I**	**A-0_2_II**	**AF-1.2_5_II**	**AF-2.2_5_II**	**AF-3.2_9_II**
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-	*(0.00%)*	*(0.00%)*	*(0.00%)*	-	*(0.00%)*	*(0.00%)*	*(0.00%)*
30	0.00	0.00	0.00	0.00	0.20	0.00	0.21	0.30
		(0.00%)	*(0.00%)*	*(0.00%)*	-	*(0.00%)*	*(0.05%)*	*(0.05%)*
40	0.00	0.13	0.00	0.00	0.21	0.00	0.21	0.30
	-	*(0.10%)*	*(0.00%)*	*(0.77%)*	-	*(0.00%)*	*(0.13%)*	*(0.10%)*
50	0.00	0.21	0.00	0.09	0.21	0.07	0.26	0.31
	-	*(0.20%)*	*(0.00%)*	*(1.55%)*	-	*(1.47%)*	*(0.21%)*	*(0.16%)*
60	0.21	0.23	0.00	0.26	0.22	0.21	0.33	0.33
	(4.15%)	*(0.30%)*	*(0.00%)*	*(2.32%)*	-	*(1.16%)*	*(0.28%)*	*(0.21%)*
75	0.25	0.31	0.32	0.33	0.22	0.23	0.29	0.50
	(17.41%)	*(0.05%)*	*(0.33%)*	*(1.01%)*	*(0.00%)*	*(0.01%)*	*(0.02%)*	*(1.12%)*
90	0.22	0.37	0.28	0.42	0.24	0.23	0.40	0.70
	-	*(0.33%)*	*(0.51%)*	*(0.62%)*	*(9.60%)*	*(0.16%)*	*(2.33%)*	*(1.47%)*
105	0.21	0.40	0.28	0.46	0.22	0.24	0.40	0.76
	(5.14%)	*(0.40%)*	*(0.30%)*	*(0.09%)*	-	*(0.10%)*	*(2.33%)*	*(1.16%)*
120	0.22	-	0.32	0.57	0.30	0.28	0.70	-
	(7.02%)	-	*(0.68%)*	*(0.82%)*	*(12.85%)*	*(0.21%)*	*(1.65%)*	-



Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained in the penetration needle test

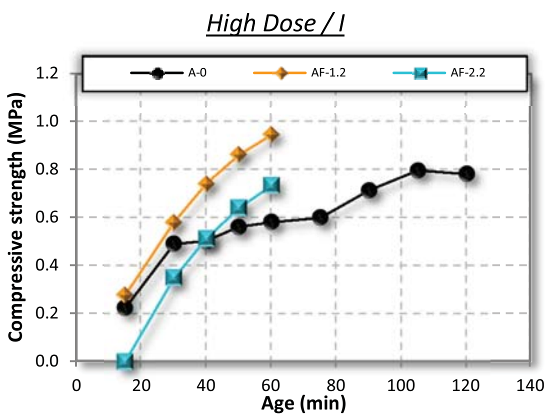
Medium Dose (MPa)								
Age (min)	**A-0_3_I**	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**A-0_3_II**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
15	0.21	0.30	0.00	0.00	0.00	0.26	0.21	0.23
	(5.14%)	*(2.56%)*	*(0.00%)*	*(0.00%)*	-	*(0.01%)*	*(0.10%)*	*(0.05%)*
30	0.32	0.53	0.21	0.22	0.26	0.36	0.29	0.33
	(10.31%)	*(0.69%)*	*(0.21%)*	*(2.38%)*	*(20.76%)*	*(0.48%)*	*(0.07%)*	*(0.77%)*
40	0.37	0.63	0.25	0.27	0.28	0.44	0.36	0.45
	(9.26%)	*(0.95%)*	*(0.10%)*	*(2.08%)*	*(24.65%)*	*(0.57%)*	*(0.20%)*	*(0.70%)*
50	0.43	0.68	0.32	0.35	0.33	0.52	0.46	0.61
	(20.08%)	*(1.21%)*	*(0.20%)*	*(1.78%)*	*(27.95%)*	*(0.66%)*	*(0.33%)*	*(0.63%)*
60	0.46	0.70	0.41	0.44	0.34	0.60	0.59	0.82
	(23.69%)	*(1.47%)*	*(0.30%)*	*(1.49%)*	*(29.05%)*	*(0.75%)*	*(0.46%)*	*(0.55%)*
75	0.40	0.74	0.49	0.62	0.42	0.75	0.63	-
	(6.44%)	*(1.98%)*	*(1.05%)*	*(1.97%)*	*(14.66%)*	*(3.35%)*	*(1.88%)*	-
90	0.47	0.80	0.55	0.78	0.45	0.73	0.76	-
	(11.39%)	*(0.48%)*	*(4.71%)*	*(0.05%)*	*(21.70%)*	*(0.49%)*	*(0.21%)*	-
105	0.54	-	0.72	-	0.35	-	0.89	-
	(11.53%)	-	*(3.04%)*	-	*(21.52%)*	-	*(0.69%)*	-
120	0.55	-	0.79	-	0.48	-	-	-
	(11.04%)	-	*(6.29%)*	-	*(29.25%)*	-	-	-

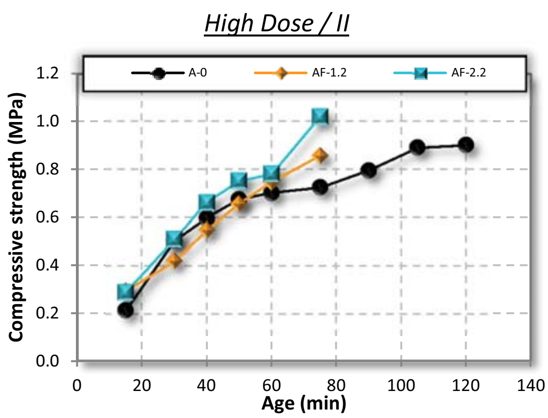


Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained in the penetration needle test

	High Dose (MPa)					
Age (min)	**A-0_4_I**	**AF-1.2_9_I**	**AF-2.2_9_I**	**A-0_4_II**	**AF-1.2_9_II**	**AF-2.2_9_II**
15	0.22 (3.91%)	0.28 (0.09%)	0.00 (0.00%)	0.22 (0.00%)	0.30 (0.30%)	0.29 (0.48%)
30	0.49 *(13.14%)*	0.58 *(0.02%)*	0.35 *(0.21%)*	0.51 *(0.00%)*	0.42 *(1.15%)*	0.51 *(2.29%)*
40	0.50 *(13.19%)*	0.74 *(0.18%)*	0.51 *(0.15%)*	0.60 *(0.00%)*	0.55 *(1.01%)*	0.66 *(1.68%)*
50	0.56 *(7.62%)*	0.86 *(0.35%)*	0.64 *(0.10%)*	0.68 *(0.00%)*	0.66 *(0.87%)*	0.75 *(1.08%)*
60	0.58 *(5.76%)*	0.94 *(0.51%)*	0.73 *(0.05%)*	0.70 *(0.00%)*	0.75 *(0.74%)*	0.78 *(0.48%)*
75	0.60 *(6.33%)*	- -	- -	0.72 *(0.00%)*	0.86 *(0.60%)*	1.02 *(0.69%)*
90	0.71 *(12.10%)*	- -	- -	0.80 *(0.00%)*	- -	- -
105	0.80 *(6.29%)*	- -	- -	0.89 *(0.00%)*	- -	- -
120	0.78 *(4.02%)*	- -	- -	0.90 *(0.00%)*	- -	- -





Compressive strength results considering type of cement and dose of accelerator

Density and porosity

Density and porosity results

High Dose				
Sample	**Density (g/cm^3)**		**Porosity (%)**	
A-0_4_I	2.26	*(0.00%)*	16.38	*(4.32%)*
AF-1.1_9_I	2.21	*(0.04%)*	20.48	*(0.58%)*
AF-2.1_9_I	2.19	*(0.09%)*	22.12	*(37.84%)*
A-0_4_II	2.18	*(0.00%)*	16.45	*(25.86%)*
AF-1.1_9_II	2.21	*(0.01%)*	31.39	*(7.16%)*
AF-2.1_9_II	2.21	*(0.01%)*	17.81	*(0.01%)*

Density and porosity results

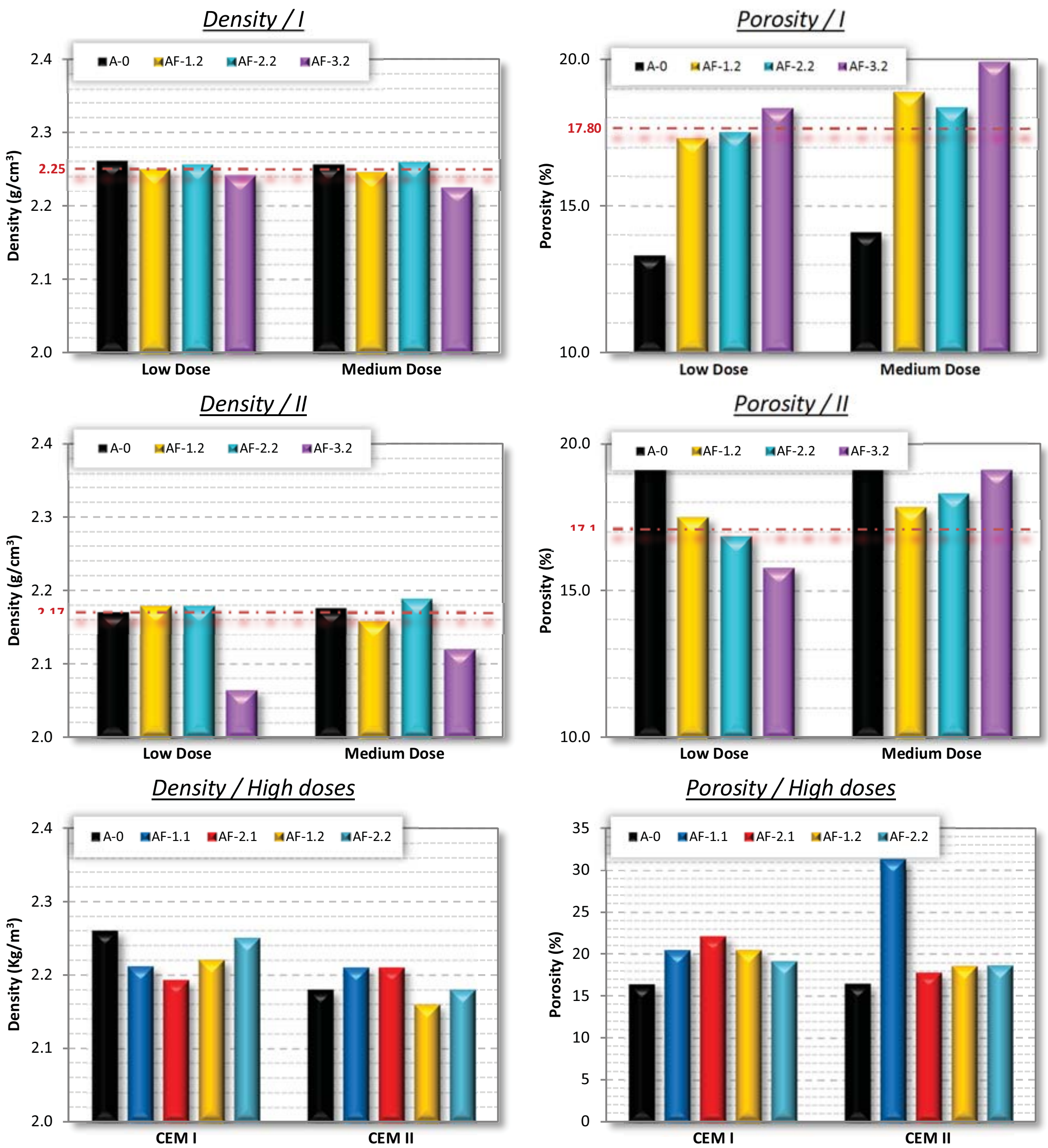
Low Dose				
Sample	**Density (g/cm^3)**		**Porosity (%)**	
A-0_2_I	2.26	*(0.01%)*	13.33	*(0.84%)*
AF-1.2_5_I	2.25	*(0.00%)*	17.33	*(5.37%)*
AF-2.2_5_I	2.26	*(0.00%)*	17.52	*(2.64%)*
AF-3.2_9_I	2.24	*(0.02%)*	18.36	*(0.04%)*
A-0_2_II	2.17	*(0.09%)*	217.04	*(8.82%)*
AF-1.2_5_II	2.18	*(0.01%)*	17.48	*(2.69%)*
AF-2.2_5_II	2.17	*(0.01%)*	16.83	*(0.36%)*
AF-3.2_9_II	2.06	*(0.23%)*	15.80	*(79.39%)*

Density and porosity results

Medium Dose				
Sample	**Density (g/cm^3)**		**Porosity (%)**	
A-0_3_I	2.26	*(0.00%)*	14.11	*(11.79%)*
AF-1.2_7_I	2.25	*(0.01%)*	18.91	*(2.00%)*
AF-2.2_7_I	2.26	*(0.01%)*	18.37	*(0.01%)*
AF-3.2_11_I	2.23	*(0.19%)*	19.94	*(10.47%)*
A-0_3_II	2.18	*(0.02%)*	217.55	*(2.26%)*
AF-1.2_7_II	2.16	*(0.03%)*	17.84	*(0.59%)*
AF-2.2_7_II	2.19	*(0.00%)*	18.30	*(0.07%)*
AF-3.2_11_II	2.12	*(0.07%)*	19.10	*(1.35%)*

Density and porosity results

High Dose				
Sample	**Density (g/cm^3)**		**Porosity (%)**	
A-0_4_I	2.26	*(0.00%)*	16.38	*(4.32%)*
AF-1.2_9_I	2.22	*(0.08%)*	20.51	*(0.86%)*
AF-2.2_9_I	2.25	*(0.01%)*	19.12	*(1.25%)*
A-0_4_II	2.18	*(0.01%)*	217.70	*(10.57%)*
AF-1.2_9_II	2.16	*(0.01%)?*	18.58	*(0.45%)*
AF-2.2_9_II	2.18	*(0.02%)*	18.66	*(0.05%)*



Density and porosity results considering type of cement and dose of accelerator

Flexural strength

Flexural strength results (MPa)

High Dose								
Age (d)	A-0_4_I	AF-1.1_9_I	AF-2.1_9_I		A-0_4_II	AF-1.1_9_II	AF-2.1_9_II	
0.5	0.60	1.70	3.45		1.94	1.49	1.98	
	(3.49%)	*(8.50%)*	*(12.77%)*		*(6.85%)*	*(5.47%)*	*(20.43%)*	
1	0.70	3.92	4.94		1.40	2.38	3.41	
	(7.42%)	*(8.70%)*	*(9.08%)*		*(8.12%)*	*(6.63%)*	*(7.35%)*	
7	6.30	4.55	5.83		5.98	4.78	5.88	
	(5.11%)	*(11.78%)*	*(2.97%)*		*(11.83%)*	*(17.74%)*	*(11.15%)*	
28	7.87	3.88	5.83		6.87	6.27	7.06	
	(1.63%)	*(3.73%)*	*(15.88%)*		*(12.18%)*	*(9.14%)*	*(2.66%)*	
60	7.92	5.78	7.45		7.67	6.18	7.25	
	(6.00%)	*(12.88%)*	*(15.77%)*		*(1.00%)*	*(2.85%)*	*(5.68%)*	

Flexural strength results (MPa)

Low Dose								
Age (d)	A-0_2_I	AF-1.2_5_I	AF-2.2_5_I	AF-3.2_9_I	A-0_2_II	AF-1.2_5_II	AF-2.2_5_II	AF-3.2_9_II
0.5	1.45	3.25	4.18	4.56	1.17	1.73	1.81	3.03
	(34.32%)	*(5.12%)*	*(2.56%)*	*(3.71%)*	*(6.57%)*	*(15.93%)*	*(19.75%)*	*(2.36%)*
1	3.08	5.08	4.61	5.90	3.69	3.37	2.82	3.78
	(3.02%)	*(0.66%)*	*(14.63%)*	*(10.26%)*	*(6.88%)*	*(2.75%)*	*(28.78%)*	*(8.19%)*
7	6.60	6.05	7.09	6.36	5.86	6.72	6.28	5.22
	(3.43%)	*(8.56%)*	*(6.09%)*	*(8.99%)*	*(6.43%)*	*(2.27%)*	*(17.86%)*	*(6.19%)*
28	8.48	7.68	7.47	5.82	6.79	6.93	6.94	6.12
	(10.31%)	*(2.40%)*	*(6.26%)*	*(9.94%)*	*(4.74%)*	*(6.07%)*	*(6.35%)*	*(3.58%)*
60	8.57	7.62	7.28	7.77	8.62	8.05	7.12	7.04
	(10.00%)	*(2.96%)*	*(13.39%)*	*(9.43%)*	*(3.00%)*	*(7.49%)*	*(4.32%)*	*(3.62%)*

Flexural strength results (MPa)

Medium Dose								
Age (d)	A-0_3_I	AF-1.2_7_I	AF-2.2_7_I	AF-3.2_11_I	A-0_3_II	AF-1.2_7_II	AF-2.2_7_II	AF-3.2_11_II
0.5	1.29	3.36	4.05	4.25	1.89	1.93	2.28	2.53
	(25.64%)	*(9.96%)*	*(3.58%)*	*(0.00%)*	*(10.95%)*	*(7.40%)*	*(8.34%)*	*(0.00%)*
1	3.25	4.34	4.41	5.51	1.52	2.89	3.38	3.62
	(8.72%)	*(10.50%)*	*(4.24%)*	*(0.00%)*	*(13.34%)*	*(6.80%)*	*(5.59%)*	*(0.00%)*
7	6.20	6.77	7.41	6.37	6.49	5.99	6.20	6.18
	(3.06%)	*(8.25%)*	*(5.69%)*	*(0.00%)*	*(4.59%)*	*(15.21%)*	*(4.53%)*	*(0.00%)*
28	8.07	7.36	7.04	5.78	7.11	5.37	6.30	6.09
	(1.97%)	*(7.94%)*	*(11.14%)*	*(0.00%)*	*(0.00%)*	*(15.09%)*	*(13.23%)*	*(0.00%)*
60	8.48	6.45	7.10	7.34	8.67	7.32	6.86	6.17
	(10.00%)	*(16.55%)*	*(5.13%)*	*(0.00%)*	*(0.00%)*	*(6.44%)*	*(5.77%)*	*(0.00%)*

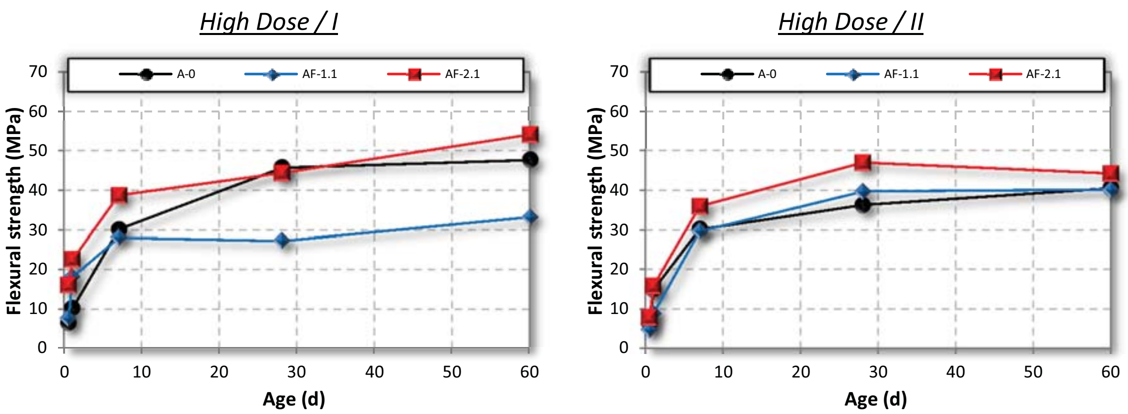
Flexural strength results (MPa)

High Dose								
Age (d)	**A-0_4_I**	**AF-1.2_9_I**	**AF-2.2_9_I**		**A-0_4_II**	**AF-1.2_9_II**	**AF-2.2_9_II**	
0.5	0.60	2.96	3.68		1.94	2.21	2.23	1.94
	(3.49%)	*(19.65%)*	*(6.10%)*		*(6.85%)*	*(3.93%)*	*(16.32%)*	*(6.85%)*
1	0.70	4.15	3.46		1.40	2.34	3.70	1.40
	(7.42%)	*(30.66%)*	*(34.25%)*		*(8.12%)*	*(22.89%)*	*(5.42%)*	*(8.12%)*
7	6.30	6.35	3.93		5.98	4.53	5.63	5.98
	(5.11%)	*(13.58%)*	*(17.93%)*		*(11.83%)*	*(21.39%)*	*(17.41%)*	*(11.83%)*
28	7.87	4.83	5.97		6.87	5.27	6.44	6.87
	(1.63%)	*(20.60%)*	*(14.31%)*		*(12.18%)*	*(16.34%)*	*(10.94%)*	*(12.18%)*
60	7.92	6.53	4.48		7.67	5.54	6.64	7.67
	(6.00%)	*(5.75%)*	*(30.96%)*		*(1.00%)*	*(8.94%)*	*(7.40%)*	*(1.00%)*

Compressive strength

Compressive strength results (MPa)

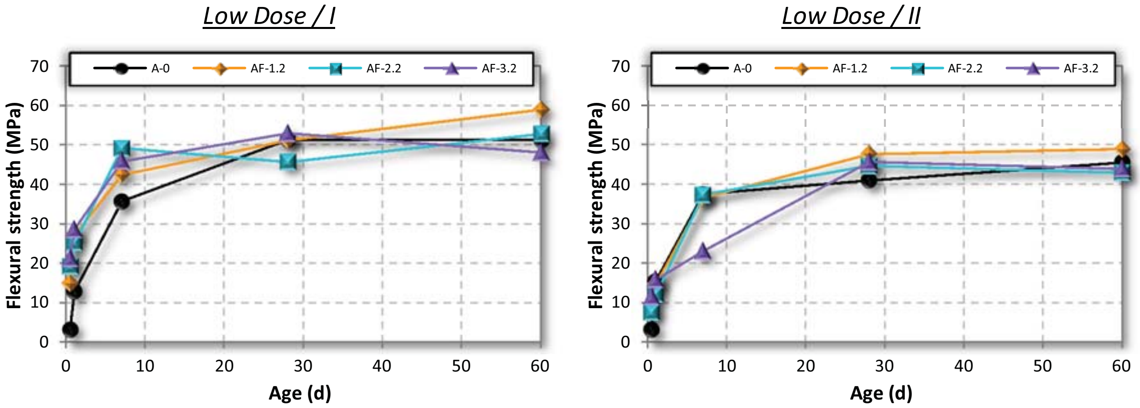
	High Dose					
Age (d)	**A-0_4_I**	**AF-1.1_9_I**	**AF-2.1_9_I**	**A-0_4_II**	**AF-1.1_9_II**	**AF-2.1_9_II**
0.5	6.56	7.68	16.21	6.47	4.74	7.90
	(38.77%)	*(5.15%)*	*(7.51%)*	*(5.64%)*	*(9.95%)*	*(10.15%)*
1	10.23	18.18	22.59	14.93	8.84	15.86
	(31.06%)	*(21.67%)*	*(17.75%)*	*(3.40%)*	*(25.97%)*	*(5.32%)*
7	30.15	28.13	38.75	30.27	29.76	35.97
	(13.47%)	*(15.71%)*	*(23.36%)*	*(5.50%)*	*(9.14%)*	*(7.50%)*
28	45.83	27.28	44.42	36.29	39.71	47.03
	(2.94%)	*(13.71%)*	*(14.92%)*	*(5.22%)*	*(7.61%)*	*(4.13%)*
60	47.77	33.21	54.14	40.63	40.17	44.25
	(1.89%)	(52.14%)	(7.50%)	(3.09%)	(13.40%)	(7.58%)



Development of compressive strength in time

Compressive strength results (MPa)

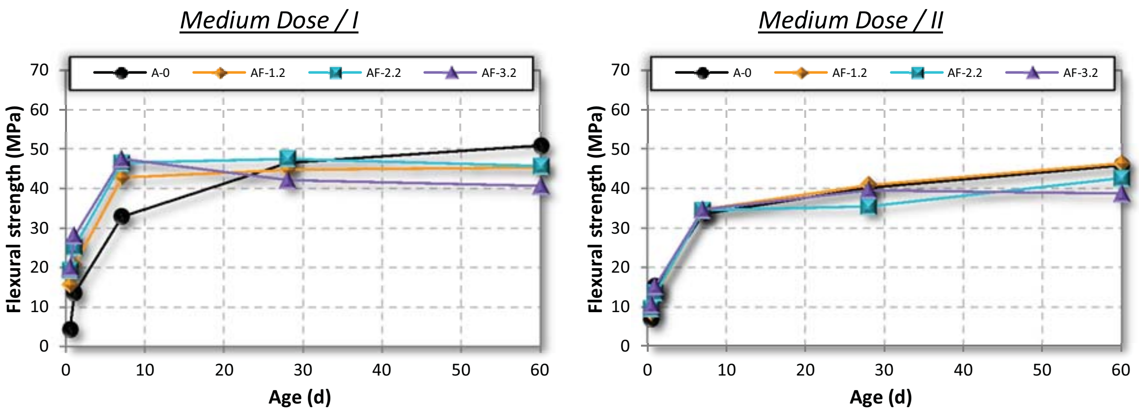
	Low Dose							
Age (d)	**A-0_2_I**	**AF-1.2_5_I**	**AF-2.2_5_I**	**AF-3.2_9_I**	**A-0_2_II**	**AF-1.2_5_II**	**AF-2.2_5_II**	**AF-3.2_9_II**
0.5	3.36	14.98	19.38	21.26	3.36	7.87	7.72	11.58
	(42.45%)	*(8.86%)*	*(6.48%)*	*(3.72%)*	*(12.22%)*	*(11.11%)*	*(7.10%)*	*(2.47%)*
1	13.02	27.27	25.37	28.66	15.52	14.81	12.23	15.94
	(1.14%)	*(6.36%)*	*(11.27%)*	*(7.86%)*	*(6.06%)*	*(3.22%)*	*(16.01%)*	*(6.05%)*
7	35.83	42.58	49.35	45.99	37.58	36.74	37.43	23.17
	(6.70%)	*(19.76%)*	*(6.91%)*	*(13.62%)*	*(21.21%)*	*(7.29%)*	*(3.92%)*	*(29.81%)*
28	51.47	51.36	45.84	53.05	41.11	47.75	44.77	45.72
	(3.37%)	*(5.79%)*	*(20.11%)*	*(10.71%)*	*(6.73%)*	*(3.09%)*	*(3.35%)*	*(4.02%)*
60	51.41	59.01	52.93	48.14	45.67	49.02	43.03	44.07
	(1.99%)	*(3.81%)*	*(11.54%)*	*(20.45%)*	*(4.99%)*	*(3.68%)*	*(8.60%)*	*(4.56%)*



Development of compressive strength in time

Compressive strength results (MPa)

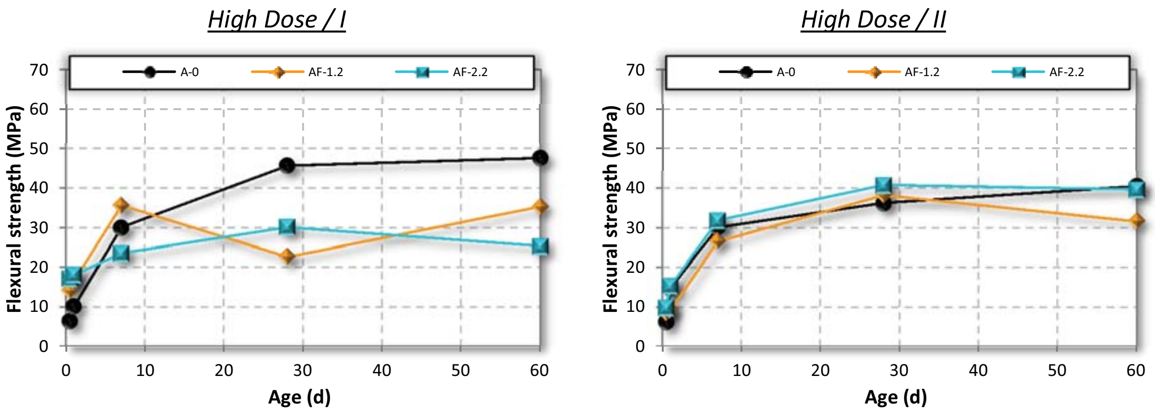
	Medium Dose							
Age (d)	**A-0_3_I**	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**A-0_3_II**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
0.5	4.52 *(20.17%)*	15.67 *(6.87%)*	19.32 *(3.95%)*	20.05 *(4.48%)*	7.05 *(5.61%)*	8.60 *(7.39%)*	9.71 *(7.50%)*	10.57 *(7.14%)*
1	13.68 *(3.52%)*	20.71 *(18.58%)*	25.30 *(12.74%)*	28.08 *(29.80%)*	15.28 *(5.72%)*	13.11 *(9.11%)*	13.62 *(15.64%)*	15.41 *(7.84%)*
7	32.97 *(13.31%)*	42.78 *(12.02%)*	46.53 *(5.63%)*	47.56 *(11.62%)*	33.66 *(7.81%)*	34.71 *(8.37%)*	34.51 *(5.56%)*	34.68 *(3.37%)*
28	46.61 *(2.83%)*	44.78 *(24.07%)*	47.58 *(10.57%)*	42.16 *(26.49%)*	40.21 *(2.82%)*	40.91 *(14.36%)*	35.50 *(22.10%)*	39.66 *(3.53%)*
60	50.92 *(2.96%)*	45.44 *(15.34%)*	45.72 *(13.55%)*	40.72 *(19.81%)*	45.90 *(3.99%)*	46.35 *(11.37%)*	42.64 *(12.74%)*	38.75 *(5.31%)*



Development of compressive strength in time

Compressive strength results (MPa)

	High Dose					
Age (d)	**A-0_4_I**	**AF-1.2_9_I**	**AF-2.2_9_I**	**A-0_4_II**	**AF-1.2_9_II**	**AF-2.2_9_II**
0.5	6.56 *(38.77%)*	14.23 *(14.15%)*	17.28 *(29.59%)*	6.47 *(5.64%)*	8.63 *(5.59%)*	9.89 *(4.79%)*
1	10.23 *(31.06%)*	16.68 *(17.95%)*	18.21 *(31.69%)*	14.93 *(3.40%)*	9.36 *(16.44%)*	15.46 *(15.58%)*
7	30.15 *(13.47%)*	35.63 *(28.47%)*	23.66 *(57.59%)*	30.27 *(5.50%)*	26.62 *(18.66%)*	31.97 *(17.41%)*
28	45.83 *(2.94%)*	22.74 *(23.08%)*	30.20 *(31.38%)*	36.29 *(5.22%)*	38.33 *(20.01%)*	40.87 *(7.38%)*
60	47.77 *(1.89%)*	35.34 *(48.64%)*	25.46 *(67.56%)*	40.63 *(3.09%)*	31.71 *(13.69%)*	39.76 *(18.71%)*



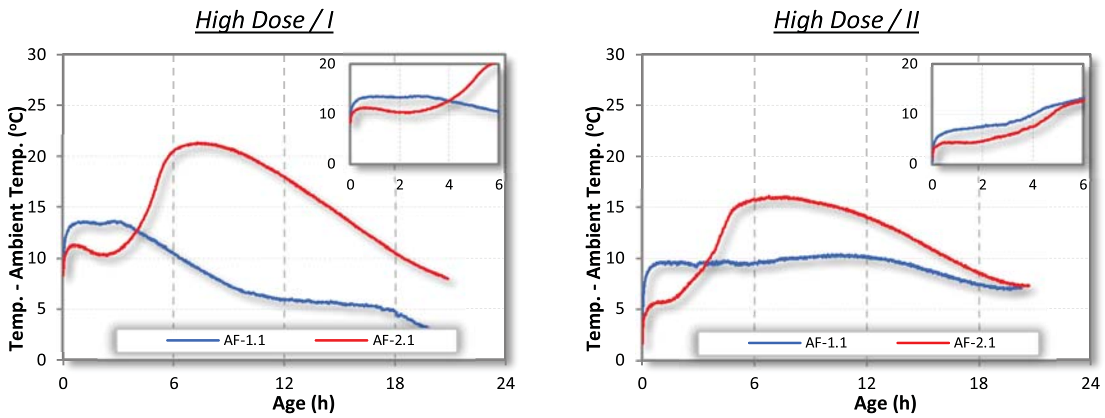
Development of compressive strength in time

APPENDIX C- EXPERIMENTAL ANALYSIS OF SPRAYED CONCRETE

Appendix C presents the results of the experimental program of sprayed concrete referred to the mixes with high dose of accelerator AF-1.1, AF-2.1 and AF-3.1, and all doses of accelerator AF-1.2, AF-2.2 and AF-3.2. The results are divided on early and long ages. Firstly, the results of evolution of temperature, penetration needle test and stud driving method are presented. Subsequently, the result of compressive strength and modulus of elasticity are shown.

EARLY AGES

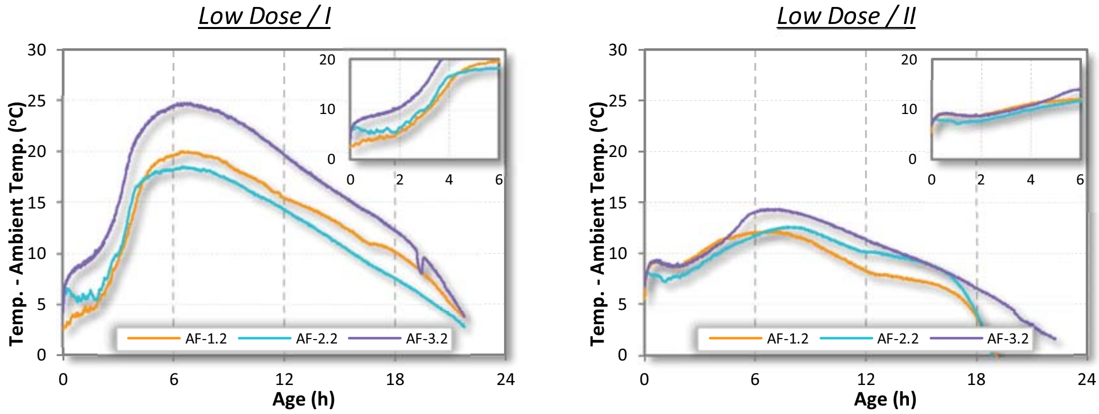
Evolution of temperature



Evolution of temperature considering type of cement and dose of accelerator

Evolution of temperature characteristic points

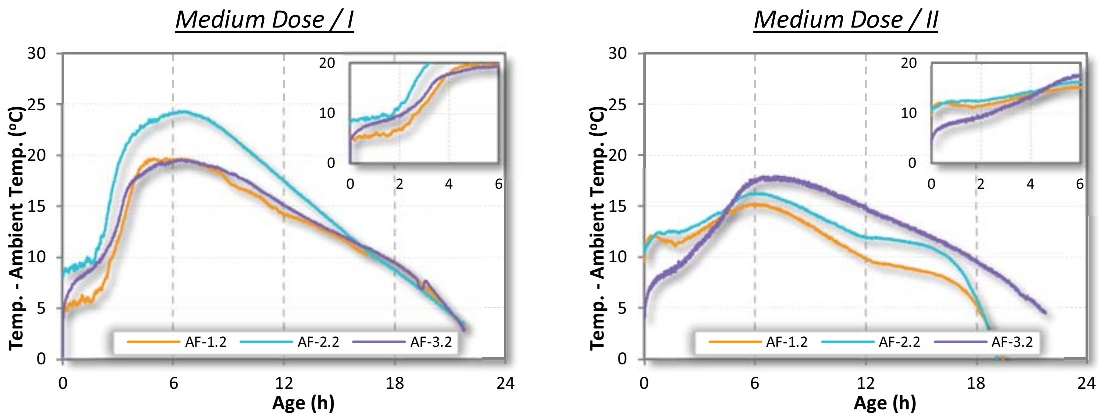
	High Dose			
Reference	**AF-1.1_9_I**	**AF-2.1_9_I**	**AF-1.1_9_II**	**AF-2.1_9_II**
T_{max} (°C)	13.64	21.33	10.40	16.10
t_T_{max} (h:min:s)	2:48:00	7:15:00	10:37:00	6:46:00
Et_T_{max} (h·°C)	2240.60	6245.85	6163.63	4187.45
T_{1P} (°C)	13.58	11.30	9.72	5.94
t_T_{1P} (h:min:s)	0:50:00	0:36:00	1:27:00	1:26:00
Et_T_{1P} (h·°C)	652.79	398.88	793.61	465.78
T_{2P} (°C)	11.67	21.33	10.40	16.10
t_T_{2P} (h:min:s)	5:00:00	7:15:00	10:37:00	6:46:00
Et_T_{2P} (h·°C)	3917.33	6245.85	6163.63	4187.45
$T_{min1P-2P}$ (°C)	11.56	10.27	9.16	5.83
$t\_T_{min1P-2P}$ (h:min:s)	4:59:00	2:25:00	2:53:00	1:31:00
$Et\_T_{min1P-2P}$ (h·°C)	3905.70	1567.85	1610.37	495.09



Evolution of temperature considering type of cement and dose of accelerator

Evolution of temperature characteristic points

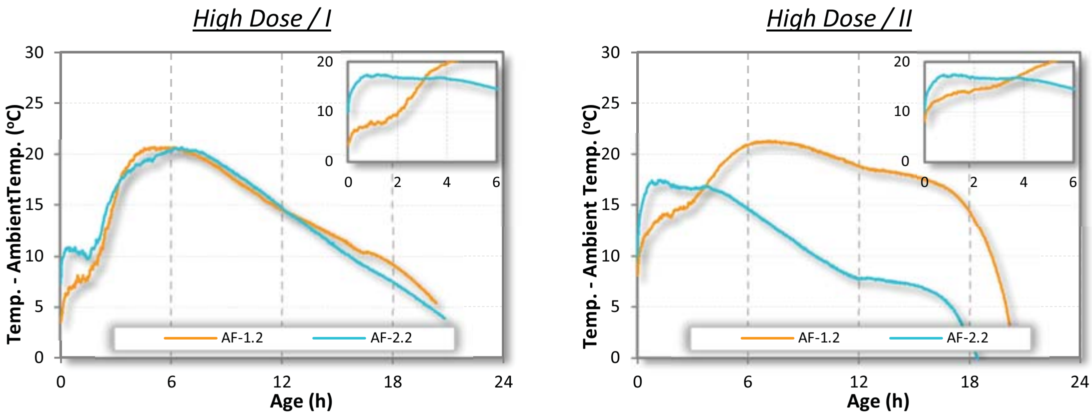
	Low Dose					
Reference	**AF-1.2_5_I**	**AF-2.2_5_I**	**AF-3.2_9_I**	**AF-1.2_5_II**	**AF-2.2_5_II**	**AF-3.2_9_II**
T_{max} (°C)	20.08	20.00	26.42	12.24	12.66	14.40
t_T_{max} (h:min:s)	6:29:00	24:00:00	24:00:00	6:31:00	7:48:00	6:39:00
Et_T_{max} (h·°C)	4487.36	15406.38	21649.91	4060.83	4658.08	4320.12
T_{1P} (°C)	4.86	6.64	9.77	9.29	8.15	9.40
t_T_{1P} (h:min:s)	1:29:00	0:13:00	1:30:00	0:27:00	0:08:00	0:48:00
Et_T_{1P} (h·°C)	353.58	86.98	771.13	236.38	70.55	436.46
T_{2P} (°C)	20.08	20.00	26.42	12.24	12.66	14.40
t_T_{2P} (h:min:s)	6:29:00	24:00:00	24:00:00	6:31:00	7:48:00	6:39:00
Et_T_{2P} (h·°C)	4487.36	15406.38	21649.91	4060.83	4658.08	4320.12
$T_{min1P-2P}$ (°C)	4.57	4.61	8.42	8.62	7.22	8.68
t_$T_{min1P-2P}$ (h:min:s)	1:35:00	1:49:00	1:41:00	1:35:00	1:03:00	1:51:00
Et_$T_{min1P-2P}$ (h·°C)	381.59	531.25	951.23	848.99	499.85	997.81



Evolution of temperature considering type of cement and dose of accelerator

Evolution of temperature characteristic points

Medium Dose						
Reference	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
T_{max} (°C)	20.00	24.43	25.62	15.29	16.36	18.02
t_T_{max} (h:min:s)	24:00:00	6:17:00	24:00:00	5:50:00	6:23:00	7:14:00
Et_T_{max} (h·°C)	16552.24	6561.25	17302.08	4541.26	5327.71	5562.60
T_{1P} (°C)	6.36	10.09	8.84	12.18	12.66	8.99
t_T_{1P} (h:min:s)	1:02:00	1:20:00	1:30:00	0:20:00	1:29:00	1:29:00
Et_T_{1P} (h·°C)	344.06	739.29	684.12	241.93	1091.01	693.55
T_{2P} (°C)	20.00	24.43	25.62	15.29	16.36	18.02
t_T_{2P} (h:min:s)	24:00:00	6:17:00	24:00:00	5:50:00	6:23:00	7:14:00
Et_T_{2P} (h·°C)	16552.24	6561.25	17302.08	4541.26	5327.71	5562.60
$T_{min1P-2P}$ (°C)	8.52	9.46	8.49	11.11	12.43	8.59
t_$T_{min1P-2P}$ (h:min:s)	1:29:00	1:35:00	1:29:00	1:39:00	1:53:00	1:30:00
Et_$T_{min1P-2P}$ (h·°C)	701.25	884.41	700.99	1171.45	1391.82	702.34



Evolution of temperature considering type of cement and dose of accelerator

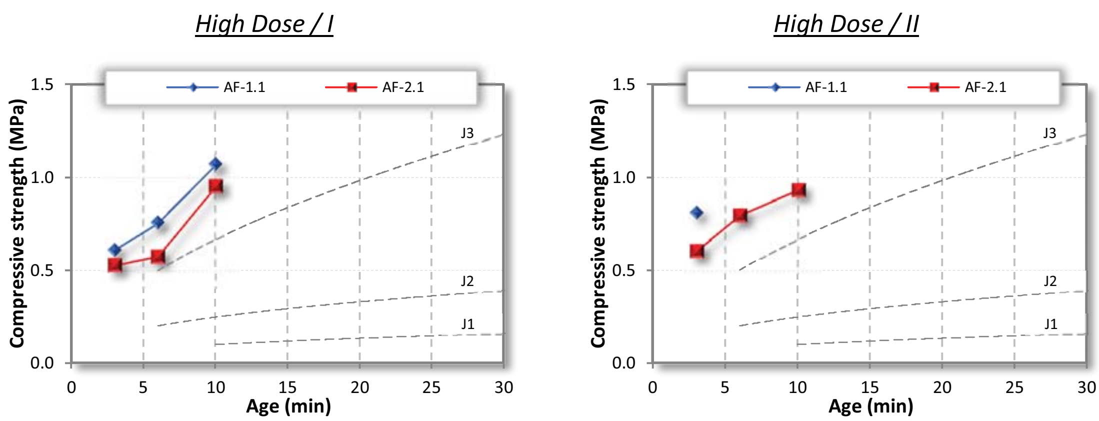
Evolution of temperature characteristic points

High Dose				
Reference	**AF-1.2_9_I**	**AF-2.2_9_I**	**AF-1.2_9_II**	**AF-2.2_9_II**
T_{max} (°C)	20.70	20.67	21.31	17.47
t_T_{max} (h:min:s)	5:06:00	6:32:00	7:03:00	1:11:00
Et_T_{max} (h·°C)	4125.69	6222.63	7140.07	1162.34
T_{1P} (°C)	8.16	10.93	14.16	17.47
t_T_{1P} (h:min:s)	1:13:00	0:24:00	1:29:00	1:11:00
Et_T_{1P} (h·°C)	501.20	254.14	1130.07	1162.34
T_{2P} (°C)	20.70	20.67	21.31	15.82
t_T_{2P} (h:min:s)	5:06:00	6:32:00	7:03:00	5:03:00
Et_T_{2P} (h·°C)	4125.69	6222.63	7140.07	5031.02
$T_{min1P-2P}$ (°C)	7.58	9.74	13.81	15.78
t_$T_{min1P-2P}$ (h:min:s)	1:21:00	1:28:00	1:48:00	5:00:00
Et_$T_{min1P-2P}$ (h·°C)	563.57	921.97	1395.97	4983.62

Penetration needle test

Compressive strength (MPa) obtained by the penetration needle test

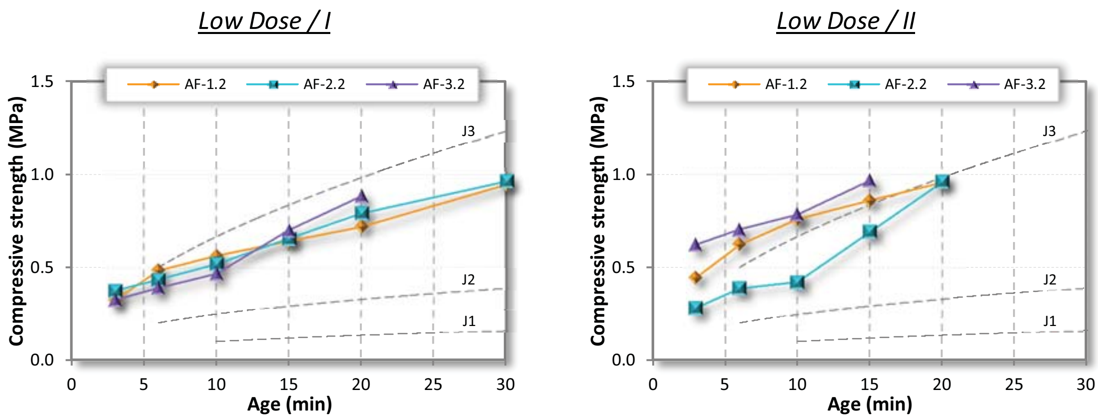
	High Dose					
Age (min)	AF-1.1_9_I	AF-2.1_9_I		AF-1.1_9_II	AF-2.1_9_II	
3	0.61	0.53		0.81	0.61	
	(16.56%)	*(19.69%)*		*(11.59%)*	*(17.44%)*	
6	0.76	0.58		-	0.80	
	(22.03%)	*(13.10%)*		-	*(21.21%)*	
10	1.07	0.95		-	0.93	
	-	*(19.94%)*		-	*(23.39%)*	
15	-	-		-	-	
	-	-		-	-	
20	-	-		-	-	
	-	-		-	-	
30	-	-		-	-	
	-	-		-	-	



Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained by the penetration needle test

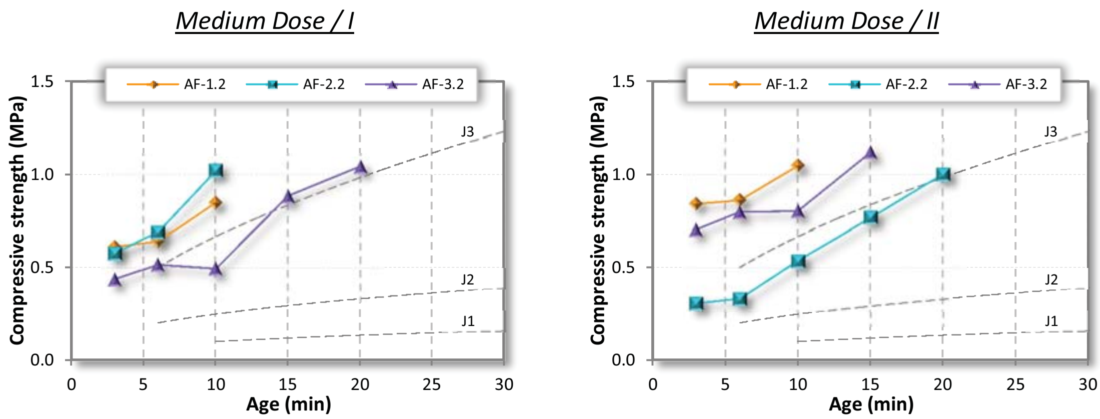
	Low Dose					
Age (min)	AF-1.2_5_I	AF-2.2_5_I	AF-3.2_9_I	AF-1.2_5_II	AF-2.2_5_II	AF-3.2_9_II
3	0.33	0.29	0.33	0.45	0.29	0.63
	(10.73%)	*(9.21%)*	*(57.13%)*	*(12.83%)*	*(49.28%)*	*(28.19%)*
6	0.49	0.39	0.39	0.63	0.39	0.71
	(23.03%)	*(16.13%)*	*(16.80%)*	*(13.81%)*	*(21.85%)*	*(21.35%)*
10	0.57	0.42	0.47	0.76	0.42	0.79
	(21.79%)	*(10.16%)*	*(20.93%)*	*(18.55%)*	*(17.14%)*	*(10.73%)*
15	0.64	0.69	0.70	0.86	0.69	0.97
	(0.09%)	*(16.25%)*	*(13.65%)*	*(0.19%)*	*(0.05%)*	*(13.71%)*
20	0.72	0.96	0.89	0.96	0.96	-
	(15.26%)	*(5.23%)*	*(12.08%)*	*(9.10%)*	*(9.10%)*	-
30	0.95	-	-	-	-	-
	(9.84%)	-	-	-	-	-



Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained by the penetration needle test

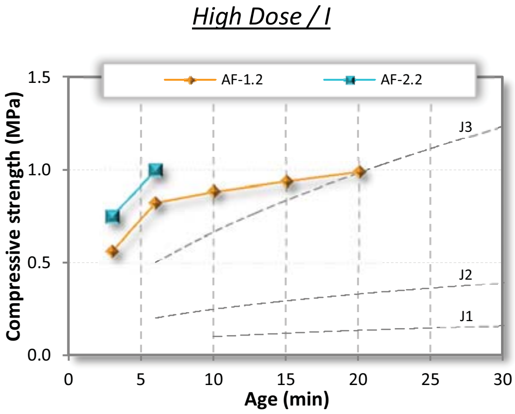
	Medium Dose					
Age (min)	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
3	0.61	0.58	0.44	0.84	0.31	0.71
	(17.03%)	*(12.48%)*	*(38.79%)*	*(13.82%)*	*(9.27%)*	*(23.27%)*
6	0.64	0.69	0.52	0.86	0.33	0.80
	(17.15%)	*(9.60%)*	*(19.47%)*	*(11.61%)*	*(9.99%)*	*(16.55%)*
10	0.85	1.02	0.50	1.05	0.54	0.81
	(13.30%)	*(2.76%)*	*(28.04%)*	*(3.87%)*	*(32.75%)*	*(17.71%)*
15	-	-	0.89	-	0.77	1.12
	-	-	*(10.20%)*		*(0.22%)*	*(0.00%)*
20	-	-	1.04	-	1.00	-
	-	-	*(0.00%)*	-	*(10.64%)*	
30	-	-	-	-	-	-
	-	-	-	-	-	-

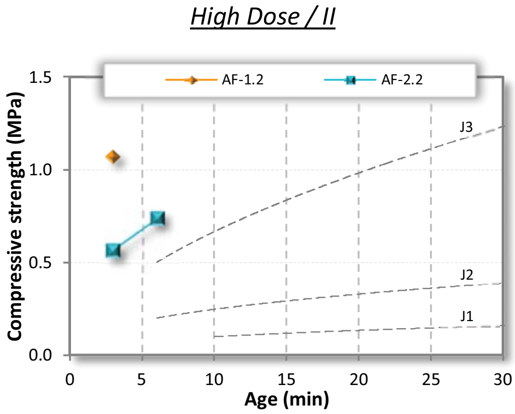


Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained by the penetration needle test

	High Dose			
Age (min)	AF-1.2_9_I	AF-2.2_9_I	AF-1.2_9_II	AF-2.2_9_II
3	0.56 *(17.92%)*	0.75 *(0.05%)*	1.07 *(0.19%)*	0.57 *(19.02%)*
6	0.82 *(17.92%)*	1.00 *(10.23%)*	- -	0.74 *(17.42%)*
10	0.88 *(12.07%)*	- -	- -	- -
15	0.94 *(11.38%)*	- -	- -	- -
20	0.99 *(7.16%)*	- -	- -	- -
30	- -	- -	- -	- -





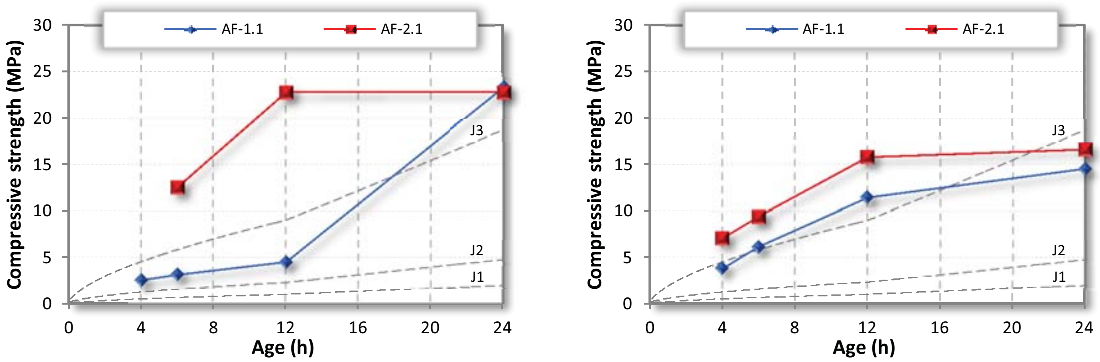
Compressive strength results considering type of cement and dose of accelerator

Stud driving method

Compressive strength (MPa) obtained by the stud driving method

	High Dose			
Age (h)	AF-1.1_9_I	AF-2.1_9_I	AF-1.1_9_II	AF-2.1_9_II
4	2.62	-	3.89	7.13
	(17.74%)	-	*(15.03%)*	*(11.84%)*
6	3.22	12.63	6.21	9.45
	(16.95%)	*(15.50%)*	*(8.95%)*	*(12.32%)*
12	4.55	22.80	11.48	15.81
	(26.57%)	*(14.17%)*	*(38.17%)*	*(11.34%)*
24	23.36	22.83	14.55	16.66
	(20.88%)	*(21.52%)*	*(22.08%)*	*(30.83%)*

High Dose / I *High Dose / II*

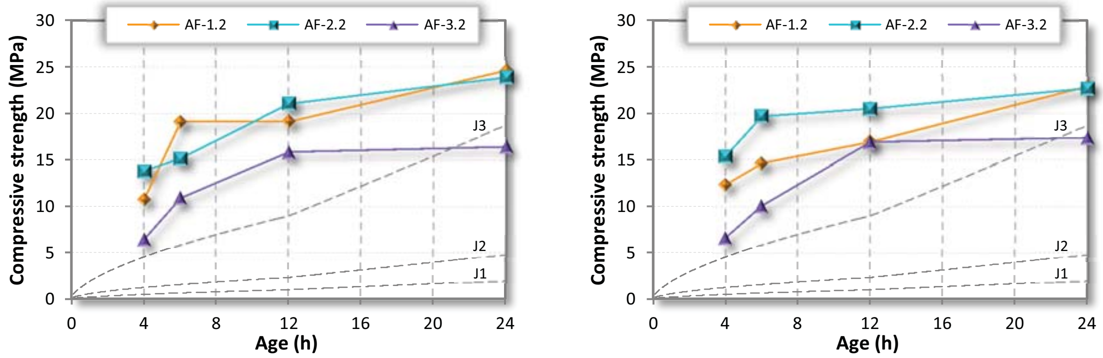


Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained by the stud driving method

	Low Dose					
Age (h)	AF-1.2_5_I	AF-2.2_5_I	AF-3.2_9_I	AF-1.2_5_II	AF-2.2_5_II	AF-3.2_9_II
4	10.81	13.87	6.54	3.18	-	-
	(11.84%)	*(13.39%)*	*(7.48%)*	*(12.38%)*	-	-
6	19.16	15.23	10.98	5.53	4.13	5.95
	(22.44%)	*(12.14%)*	*(21.41%)*	*(13.99%)*	*(10.08%)*	*(11.09%)*
12	19.21	21.14	15.91	9.88	7.96	9.96
	(15.57%)	*(21.79%)*	*(18.29%)*	*(18.05%)*	*(29.09%)*	*(21.82%)*
24	24.68	23.97	16.52	20.41	15.54	16.96
	(24.39%)	*(9.99%)*	*(13.91%)*	*(9.82%)*	*(19.48%)*	*(20.54%)*

Low Dose / I　　*Medium Dose / I*

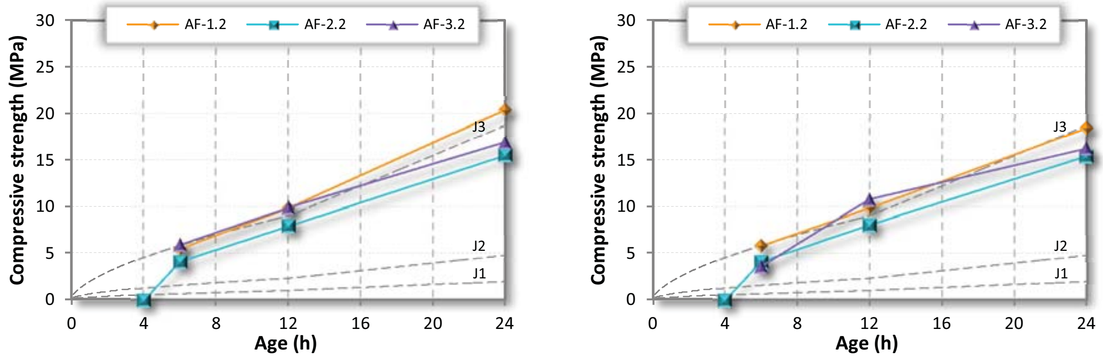


Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained by the stud driving method

	Medium Dose					
Age (h)	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
4	12.39	15.39	6.67	4.06	-	-
	(15.78%)	*(12.21%)*	*(17.65%)*	*(15.75%)*	-	-
6	14.69	19.75	10.14	5.84	4.14	3.65
	(26.79%)	*(14.40%)*	*(20.10%)*	*(16.92%)*	*(12.40%)*	*(14.16%)*
12	17.00	20.55	16.97	9.91	8.06	10.81
	(25.36%)	*(26.77%)*	*(13.47%)*	*(15.58%)*	*(17.80%)*	*(18.17%)*
24	22.96	22.76	17.44	18.46	15.45	16.29
	(17.07%)	*(15.34%)*	*(27.30%)*	*(14.82%)*	*(16.88%)*	*(25.05%)*

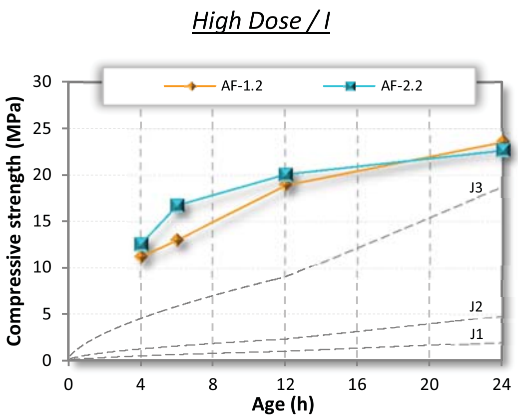
Low Dose / II　　*Medium Dose / II*

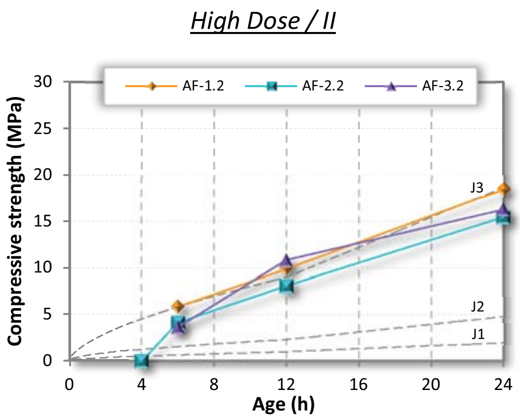


Compressive strength results considering type of cement and dose of accelerator

Compressive strength (MPa) obtained by the stud driving method

	High Dose			
Age (h)	**AF-1.2_9_I**	**AF-2.2_9_I**	**AF-1.2_9_II**	**AF-2.2_9_II**
4	11.24 *(14.51%)*	12.60 *(10.19%)*	4.04 *(16.26%)*	- -
6	13.05 *(19.40%)*	16.76 *(13.08%)*	6.06 *(16.89%)*	3.19 *(12.13%)*
12	18.92 *(13.49%)*	20.06 *(16.24%)*	9.52 *(12.14%)*	4.72 *(24.17%)*
24	23.54 *(16.36%)*	22.64 *(13.16%)*	16.09 *(7.47%)*	12.20 *(15.15%)*





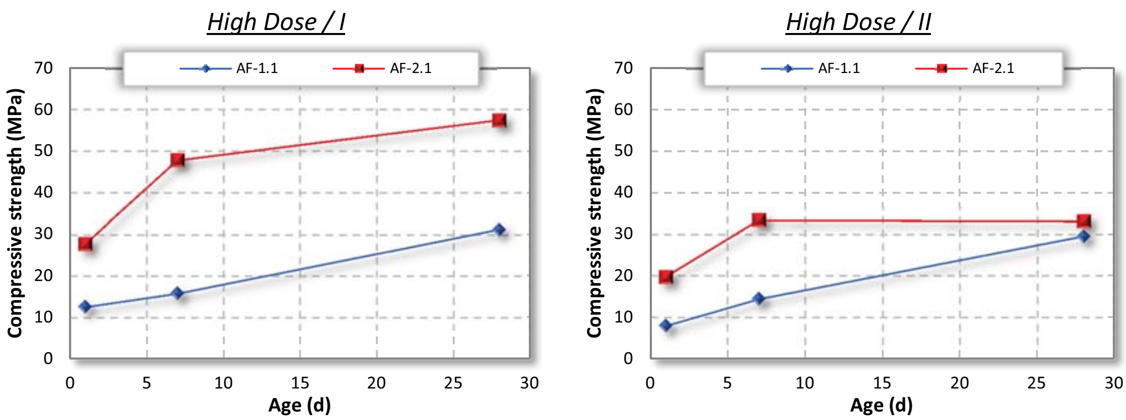
Compressive strength results considering type of cement and dose of accelerator

LONG AGES

Compressive strength

Compressive strength (MPa)

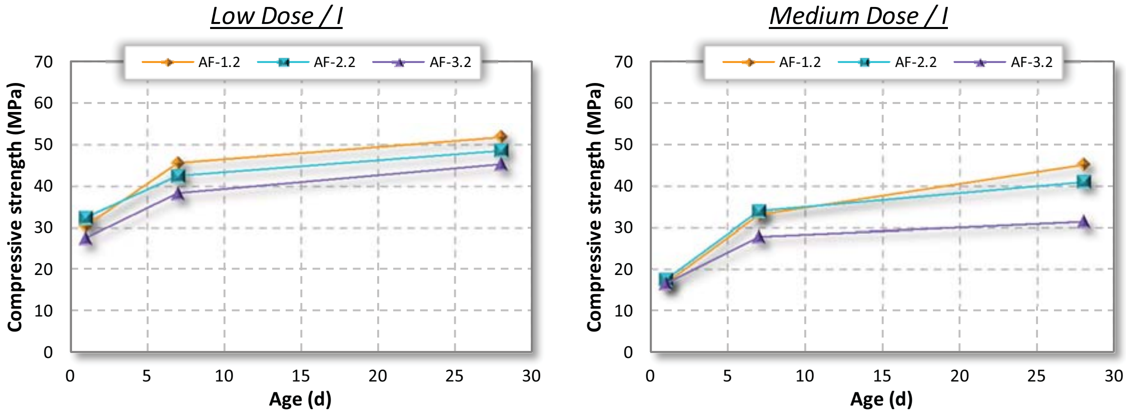
	High Dose			
Age (d)	AF-1.1_9_I	AF-2.1_9_I	AF-1.1_9_II	AF-2.1_9_II
1	12.59 -	27.84 *(9.65%)*	7.98 *(9.88%)*	19.81 *(5.34%)*
7	15.84 *(31.13%)*	47.79 *(8.24%)*	14.48 *(15.37%)*	33.42 *(6.90%)*
28	31.17 *(14.31%)*	57.39 *(2.05%)*	29.52 *(15.68%)*	33.09 *(30.10%)*



Compressive strength results at long ages considering type of cement and dose of accelerator

Compressive strength (MPa)

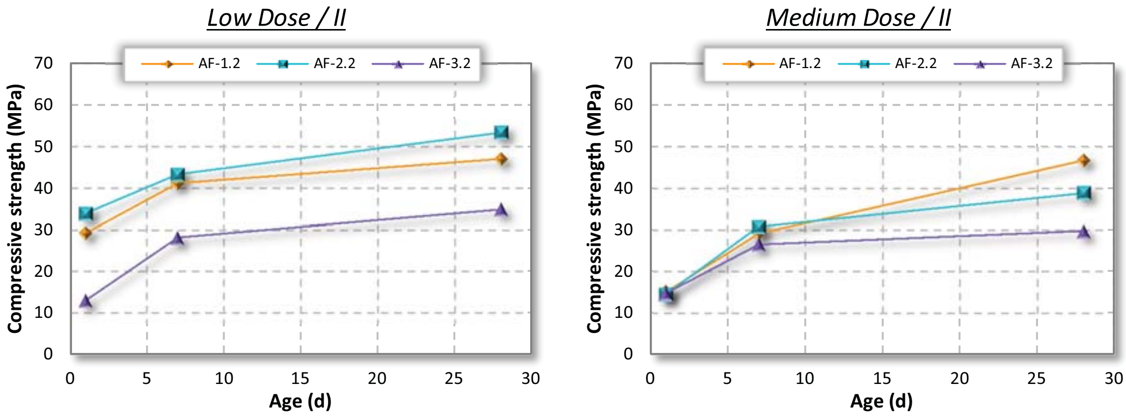
	Low Dose					
Age (d)	AF-1.2_5_I	AF-2.2_5_I	AF-3.2_9_I	AF-1.2_5_II	AF-2.2_5_II	AF-3.2_9_II
1	30.56 *(9.18%)*	32.61 *(3.30%)*	27.67 *(7.46%)*	16.87 *(8.49%)*	17.70 *(9.96%)*	16.74 *(15.58%)*
7	45.71 *(7.00%)*	42.60 *(11.40%)*	38.43 *(9.13%)*	33.23 *(7.57%)*	34.09 *(6.46%)*	28.03 *(7.53%)*
28	51.96 *(1.94%)*	48.73 *(4.66%)*	45.44 *(4.07%)*	45.34 *(9.48%)*	41.15 *(13.49%)*	31.55 *(12.13%)*



Compressive strength results at long ages considering type of cement and dose of accelerator

Compressive strength (MPa)

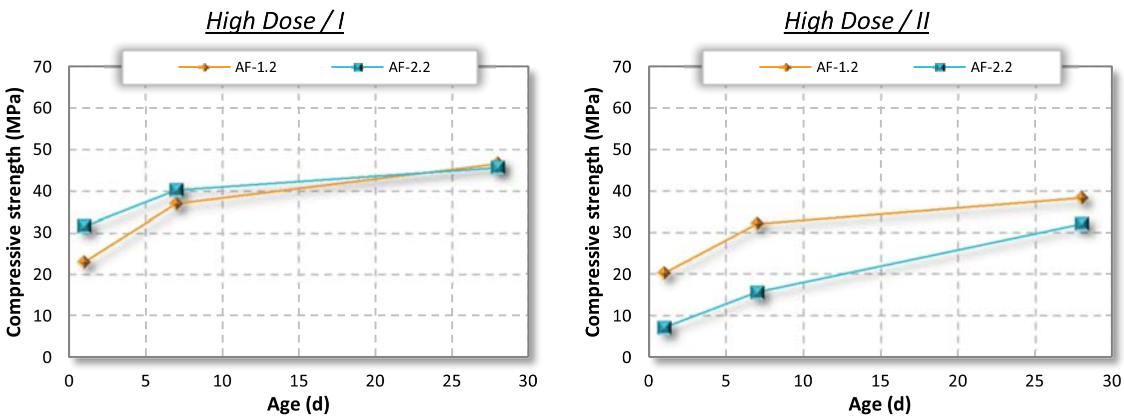
Medium Dose						
Age (d)	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
1	29.25 *(10.80%)*	34.00 *(13.13%)*	13.12 *(8.15%)*	15.21 *(8.75%)*	14.69 *(2.18%)*	14.92 *(7.95%)*
7	41.26 *(14.76%)*	43.37 *(10.18%)*	28.24 *(21.50%)*	29.27 *(8.72%)*	30.87 *(4.74%)*	26.66 *(4.72%)*
28	47.07 *(7.46%)*	53.49 *(3.17%)*	34.97 *(12.68%)*	46.75 *(8.54%)*	38.98 *(5.65%)*	29.84 *(16.36%)*



Compressive strength results at long ages considering type of cement and dose of accelerator

Compressive strength (MPa)

High Dose						
Age (d)	**AF-1.2_9_I**	**AF-2.2_9_I**		**AF-1.2_9_II**	**AF-2.2_9_II**	
1	23.20 *(20.19%)*	31.73 *(8.65%)*		20.35 *(6.47%)*	7.32 *(10.78%)*	
7	37.09 *(10.42%)*	40.34 *(7.79%)*		32.20 *(8.08%)*	15.75 *(29.78%)*	
28	46.73 *(6.51%)*	45.79 *(13.66%)*		38.45 *(9.49%)*	32.19 *(10.98%)*	



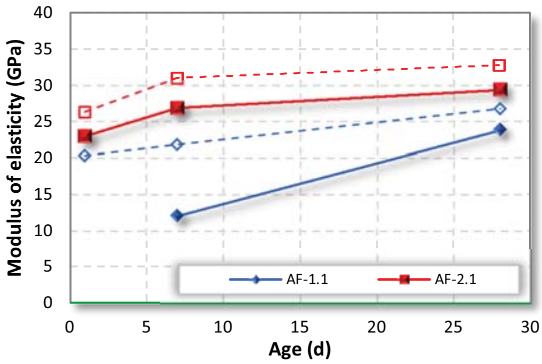
Compressive strength results at long ages considering type of cement and dose of accelerator

Modulus of elasticity

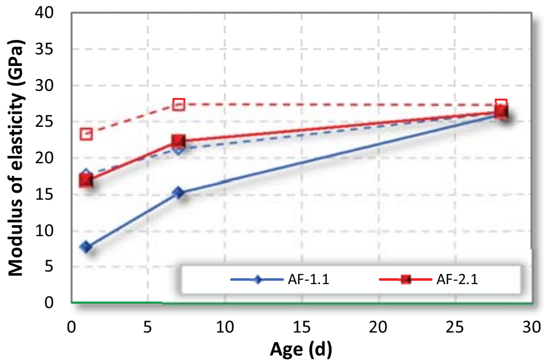
Modulus of elasticity obtained in the Laboratory (GPa)

	High Dose					
Age (d)	AF-1.1_9_I	AF-2.1_9_I		AF-1.1_9_II	AF-2.1_9_II	
1	-	23.02		7.78	16.89	
	-	*(5.82%)*		*(15.91%)*	*(7.02%)*	
7	12.08	26.89		15.29	22.34	
	(8.84%)	*(4.08%)*		*(12.91%)*	*(9.43%)*	
28	23.87	29.40		26.00	26.39	
	(5.15%)	*(5.33%)*		*(16.82%)*	*(6.78%)*	

High Dose / I



High Dose / II

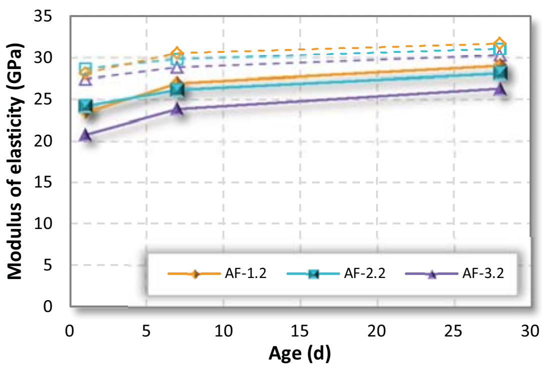


Modulus of elasticity measured (continuous lines) and estimated with EHE-08 equations (discontinuous lines) considering type of cement and dose of accelerator

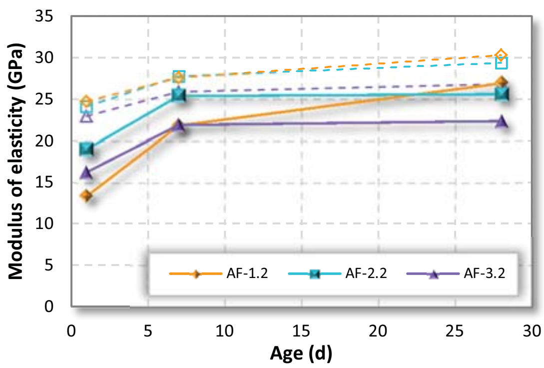
Modulus of elasticity obtained in the Laboratory (GPa)

	Low Dose					
Age (d)	AF-1.2_5_I	AF-2.2_5_I	AF-3.2_9_I	AF-1.2_5_II	AF-2.2_5_II	AF-3.2_9_II
1	23.44	23.44	23.44	23.44	23.44	23.44
	(23.56%)	*(23.56%)*	*(23.56%)*	*(23.56%)*	*(23.56%)*	*(23.56%)*
7	26.92	26.92	26.92	26.92	26.92	26.92
	(1.67%)	*(1.67%)*	*(1.67%)*	*(1.67%)*	*(1.67%)*	*(1.67%)*
28	29.04	29.04	29.04	29.04	29.04	29.04
	(2.70%)	*(2.70%)*	*(2.70%)*	*(2.70%)*	*(2.70%)*	*(2.70%)*

Low Dose / I



Low Dose / II

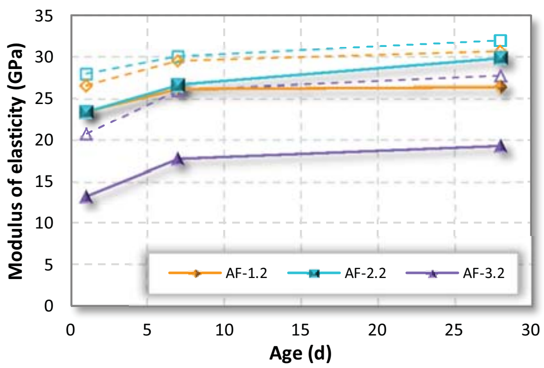


Modulus of elasticity measured (continuous lines) and estimated with EHE-08 equations (discontinuous lines) considering type of cement and dose of accelerator

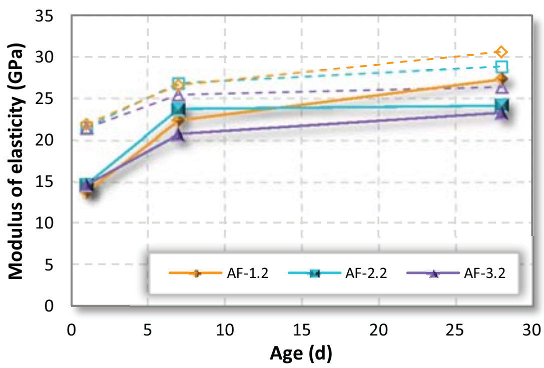
Modulus of elasticity obtained in the Laboratory (GPa)

	Medium Dose					
Age (d)	**AF-1.2_7_I**	**AF-2.2_7_I**	**AF-3.2_11_I**	**AF-1.2_7_II**	**AF-2.2_7_II**	**AF-3.2_11_II**
1	23.55 *(4.28%)*	23.53 *(20.54%)*	13.33 *(12.33%)*	13.84 *(0.80%)*	14.77 *(4.86%)*	14.71 *(13.51%)*
7	26.26 *(0.83%)*	26.71 *(7.82%)*	17.81 *(8.01%)*	22.37 *(1.60%)*	23.78 *(5.93%)*	20.75 *(1.47%)*
28	26.48 *(4.59%)*	29.89 *(3.24%)*	19.35 *(6.35%)*	27.36 *(5.75%)*	24.19 *(7.30%)*	23.32 *(3.01%)*

Medium Dose / I



Medium Dose / II

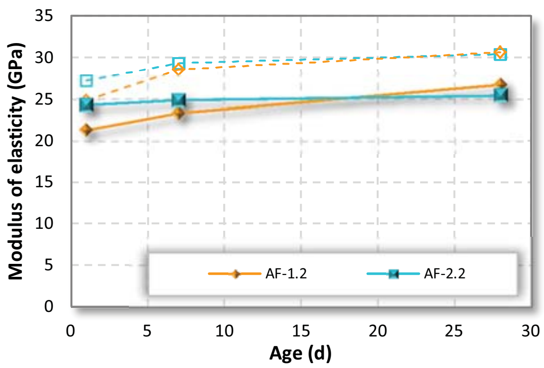


Modulus of elasticity measured (continuous lines) and estimated with EHE-08 equations (discontinuous lines) considering type of cement and dose of accelerator

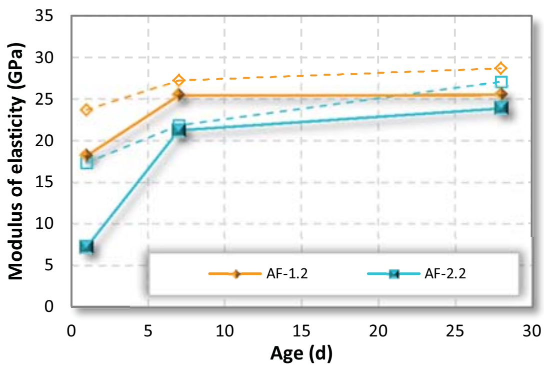
Modulus of elasticity obtained in the Laboratory (GPa)

	High Dose					
Age (d)	**AF-1.2_9_I**	**AF-2.2_9_I**		**AF-1.2_9_II**	**AF-2.2_9_II**	
1	21.29 *(19.46%)*	24.28 *(0.86%)*		18.17 *(20.99%)*	7.22 *(11.11%)*	
7	23.30 *(4.20%)*	24.86 *(0.64%)*		25.45 *(6.42%)*	21.22 *(11.18%)*	
28	26.72 *(4.02%)*	25.43 *(1.93%)*		25.51 *(2.58%)*	23.88 *(4.89%)*	

High Dose / I



High Dose / II



Modulus of elasticity measured (continuous lines) and estimated with EHE-08 equations (discontinuous lines) considering type of cement and dose of accelerator

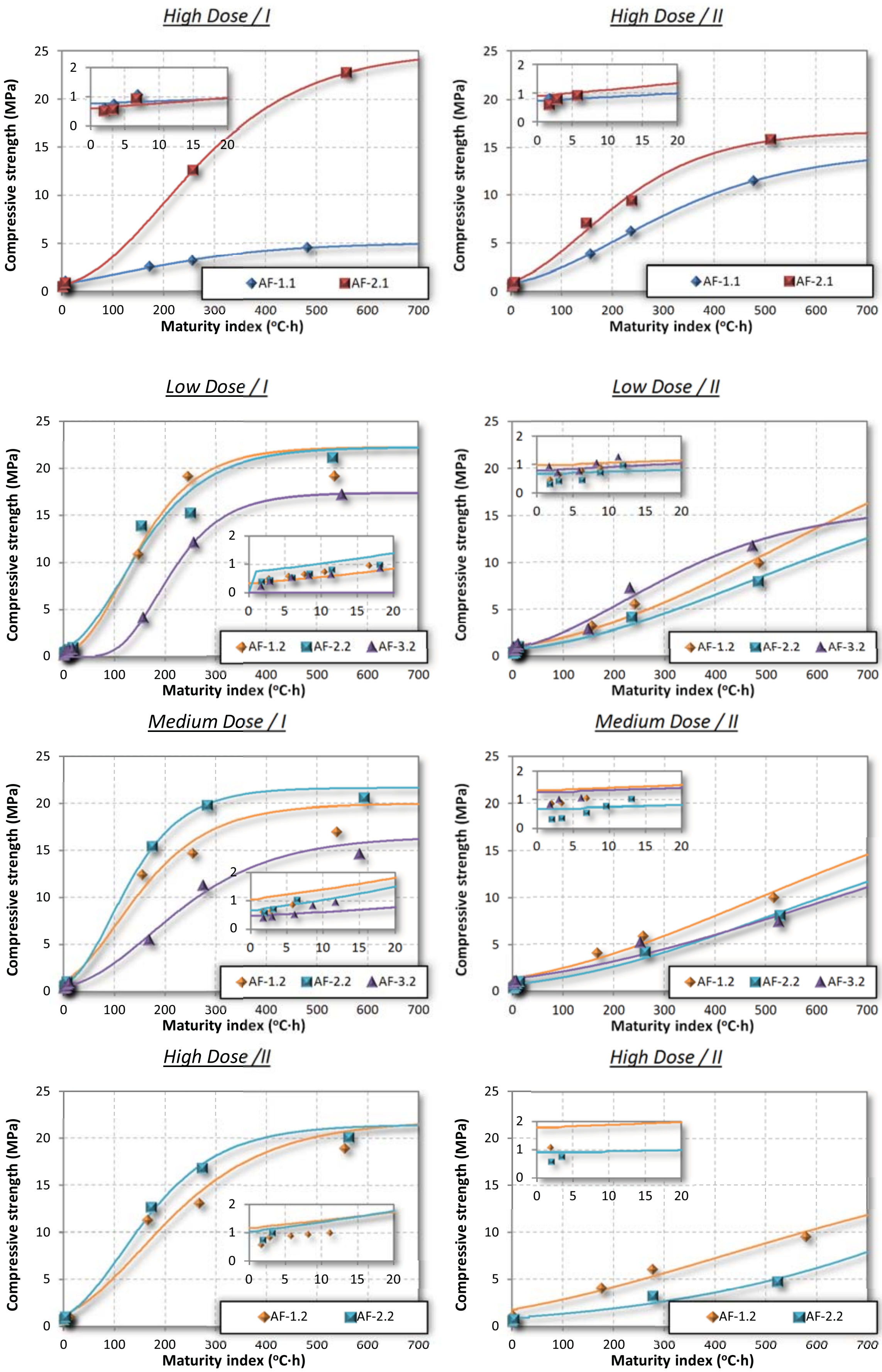
APPENDIX D- MATURITY CURVES

The relationships between the maturity index and the compressive strength obtained with the experimental results of the mixes with high dose of accelerator AF-1.1 and AF-2.1 and all doses of accelerators AF-1.2, AF-2.2 and AF3.2 are presented in this appendix. Furthermore, the parameters of the Equation 8.2 in Chapter 8 are gathered together with the result of the R^2.

Maturity curves

Parameters obtained by LAB Fit

Accelerator	Cement	Dose	A	B	C	R^2
AF-1.1	I	High	5.104	-1.869	-0.006	0.992
	II	High	14.758	-2.974	-0.005	1.000
AF-2.1	I	High	25.094	-3.688	-0.007	1.000
	II	High	16.761	-2.901	-0.007	0.993
AF-1.2	I	Low	22.252	-4.179	-0.012	0.982
		Medium	19.958	-2.940	-0.010	0.959
		High	21.902	-2.921	-0.007	0.979
	II	Low	31.531	-3.468	-0.002	0.994
		Medium	26.501	-2.995	-0.002	0.992
		High	20.444	-2.433	-0.002	0.989
AF-2.2	I	Low	22.267	-3.386	-0.011	0.982
		Medium	21.633	-3.474	-0.013	0.996
		High	21.461	-3.014	-0.010	0.993
	II	Low	21.350	-3.446	-0.003	0.995
		Medium	21.791	-3.451	-0.002	0.996
		High	209.986	-5.432	-0.001	0.991
AF-3.2	I	Low	17.454	-12.508	-0.014	0.999
		Medium	16.534	-3.568	-0.007	0.991
	II	Low	16.140	-3.019	-0.005	0.991
		Medium	25.776	-3.013	-0.002	0.985



Relationship between the maturity index and the compressive strength

APPENDIX E- THERMAL MODEL CODES AND RESULTS

This Appendix gathers the modelling codes for the Thermal model developed in Chapter 8. Firstly, it presents the code for the study of the evolution of temperature of the concrete sprayed on a panel test with 150 mm of thickness. Then, the one used to study the concrete sprayed on a 100 mm-thickness test panel. Finally, the code use to study the evolution of temperature in time of concrete directly sprayed on ground is shown. Notice that only the code for a layer of 100 mm-thickness on clay is presented since the other combinations thickness-ground entail slightly changes in the code.

Modelling

Code for 150 mm-panel test

```
!* ***************
!* White Background
!* ***************
!*
/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX, 0, 0, 0,15

!* *********************
!* Choosing Thermal Analysis
!* *********************

/NOPR
/PMETH,OFF,0
KEYW,PR_SET,1
KEYW,PR_STRUC,0
KEYW,PR_THERM,1
KEYW,PR_FLUID,0
KEYW,PR_ELMAG,0
KEYW,MAGNOD,0
KEYW,MAGEDG,0
KEYW,MAGHFE,0
KEYW,MAGELC,0
KEYW,PR_MULTI,0
KEYW,PR_CFD,0
KEYW,LSDYNA,0
/GO
!*
/COM,
```

```
/COM,Preferences for GUI filtering have been set to display:
/COM,  Thermal

!* ******************
!* Choosing Elemnt type
!* ******************

/PREP7
!*
ET,1,PLANE35

!* **************
!* Materials Models
!* **************

!* Steel

MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,1,,154
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,1,,0.49
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,1,,7600

!* Concrete

MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,2,,6.12
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,2,,0.75
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,2,,2000

!* *******
!* Creating
!* *******

!* Key Points

!*   Nombre,     X,               Y,              Z
k,       1,     0.0000000,       0.0000000,     0.0000000
k,       2,     0.0016905,       0.0036252,     0.0000000
k,       3,     -0.1905664,      0.0932761,     0.0000000
k,       4,     -0.1937585,      0.0903511,     0.0000000
k,       5,     -0.2019498,      0.5631224,     0.0000000
k,       6,     -0.3615765,      0.5631224,     0.0000000
```

```
k,        7,       -0.3653353,          0.5617543,       0.0000000

!* Lines

!*        K1       K2
l, 2,     5
l, 5,     6
l, 6,     3
l, 3,     2
l, 6,     7
l, 7,     4
l, 4,     1
l, 1,     2

!* Areas

!*        L1,      L2,      L3,      L4,      L5,      L6
al,       1,       2,       3,       4
al,       4,       3,       5,       6,       7,       8

!* ***************
!* Material definition
!* ***************

!*Steel

CM,_Y,AREA
ASEL, , , ,     2
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
AATT,     1, ,  1,     0,
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1

!*  Concrete

CM,_Y,AREA
ASEL, , , ,     1
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
AATT,     2, ,  1,     0,
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1

!* ***********
!*  Meshing (Tri)
```

```
!* ***********

SMRT,6
MSHAPE,0,2D
MSHKEY,0
!*
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2

!* **********************
!* Type of solution : TRANSIENT
!* **********************

FINISH
/SOL
!*
ANTYPE,4
!*
TRNOPT,FULL
LUMPM,0

!* **************************
!* Definition of steps Time-Tiem Step
!* **************************

TIME,12
AUTOTS,1
DELTIM,0.01,0.001,0.25,1
KBC,0
!*
TSRES,ERASE

!* show results for all steps

/SOL
!*
OUTRES,ALL,ALL,

!* ******
!* Arrays
```

```
!* ******

!* Room Temperature

*DIM,RT,TABLE,13,1,0,Time,Temp,
!*
*SET,RT(0,1,1)    ,    291.15
*SET,RT(1,0,1)    ,    291.15
*SET,RT(1,1,1)    ,    291.15
*SET,RT(2,0,1)    ,    291.15
*SET,RT(2,1,1)    ,    291.15
*SET,RT(3,0,1)    ,    291.15
*SET,RT(3,1,1)    ,    291.15
*SET,RT(4,0,1)    ,    291.15
*SET,RT(4,1,1)    ,    291.15
*SET,RT(5,0,1)    ,    291.15
*SET,RT(5,1,1)    ,    291.15
*SET,RT(6,0,1)    ,    291.15
*SET,RT(6,1,1)    ,    291.15
*SET,RT(7,0,1)    ,    291.15
*SET,RT(7,1,1)    ,    291.15
*SET,RT(8,0,1)    ,    291.15
*SET,RT(8,1,1)    ,    291.15
*SET,RT(9,0,1)    ,    291.15
*SET,RT(9,1,1)    ,    291.15
*SET,RT(10,0,1)   ,    291.15
*SET,RT(10,1,1)   ,    291.15
*SET,RT(11,0,1)   ,    291.15
*SET,RT(11,1,1)   ,    291.15
*SET,RT(12,0,1)   ,    291.15
*SET,RT(12,1,1)   ,    291.15
*SET,RT(13,0,1)   ,    291.15
*SET,RT(13,1,1)   ,    291.15


!* Heat Generation Rates

*DIM,HG,TABLE,9,1,0,Time,Heat,
!*
*SET,HG(0,1,1)  , 0
*SET,HG(1,0,1)  , 0.0000
*SET,HG(1,1,1)  , 6000
*SET,HG(2,0,1)  , 0.0100
*SET,HG(2,1,1)  , 10000
*SET,HG(3,0,1)  , 2.0000
*SET,HG(3,1,1)  , 5000
*SET,HG(4,0,1)  , 3.0000
*SET,HG(4,1,1)  , 10000
*SET,HG(5,0,1)  , 4.0000
*SET,HG(5,1,1)  , 13000
*SET,HG(6,0,1)  , 5.0000
*SET,HG(6,1,1)  , 6500
```

```
*SET,HG(7,0,1)  , 6.0000
*SET,HG(7,1,1)  , 3500
*SET,HG(8,0,1)  , 7.0000
*SET,HG(8,1,1)  , 2000
*SET,HG(9,0,1)  , 8.0000
*SET,HG(9,1,1)  , 300

!* ****************
!* Boundary Conditions
!* ****************

!* Ambient temperature
!* Film coefficient Concrete

FLST,2,2,4,ORDE,2
FITEM,2,1
FITEM,2,-2
/GO
!*
!*
SFL,P51X,CONV,0.10, , %RT%

!* Film coefficient Steel

FLST,2,4,4,ORDE,2
FITEM,2,5
FITEM,2,-8
/GO
!*
!*
SFL,P51X,CONV,19, , %RT%


!* Heat Generation

FLST,2,1,5,ORDE,1
FITEM,2,1
/GO
!*
!*
BFA,P51X,HGEN, %HG%

!* **********************
!* Specifying initial conditions
!* **********************

!* Initial temperature Concrete

APLOT
ASEL,S, , ,      1
ALLSEL,BELOW,AREA
NPLOT
```

```
FLST,2,997,1,ORDE,6
FITEM,2,1
FITEM,2,-4
FITEM,2,8
FITEM,2,-291
FITEM,2,530
FITEM,2,-1238
IC,P51X,TEMP,291.15,

!* Initial temperature Steel

NSEL,INVE
NPLOT
FLST,2,490,1,ORDE,6
FITEM,2,5
FITEM,2,-7
FITEM,2,292
FITEM,2,-529
FITEM,2,1239
FITEM,2,-1487
IC,P51X,TEMP,291.15,
ALLSEL,ALL
GPLOT

!* ********
!* Solution
!* ********

/STATUS,SOLU
SOLVE

!* *************
!* Results review
!* *************

/PNUM,KP,0
/PNUM,LINE,0
/PNUM,AREA,0
/PNUM,VOLU,0
/PNUM,NODE,1
/PNUM,TABN,0
/PNUM,SVAL,0
/NUMBER,0
!*
/PNUM,ELEM,0
/REPLOT
!*
EPLOT
*SET,cp1 , node (-0.3055880,0.4239138,0.0000000)
*SET,cp2 , node (-0.2397965,0.4478200,0.0000000)

FINISH
```

```
/POST26
FILE,'file','rth','.'
/UI,COLL,1
NUMVAR,200
SOLU,191,NCMIT
STORE,MERGE
FILLDATA,191,,,,1,1
REALVAR,191,191
!*
NSOL,2,954,TEMP,, TC_L
STORE,MERGE
!*
NSOL,3,637,TEMP,, TC_H
STORE,MERGE
XVAR,1
PLVAR,2,3,
```

Code for 100 mm-panel test

```
!* ****************
!*  White Background
!* ****************
!*
/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX, 0, 0, 0,15

!* ******************
!* Choosing Thermal Analysis
!* ********************

/NOPR
/PMETH,OFF,0
KEYW,PR_SET,1
KEYW,PR_STRUC,0
KEYW,PR_THERM,1
KEYW,PR_FLUID,0
KEYW,PR_ELMAG,0
KEYW,MAGNOD,0
KEYW,MAGEDG,0
KEYW,MAGHFE,0
KEYW,MAGELC,0
KEYW,PR_MULTI,0
KEYW,PR_CFD,0
KEYW,LSDYNA,0
/GO
!*
/COM,
/COM,Preferences for GUI filtering have been set to display:
/COM,  Thermal

!* ******************
!* Choosing Elemnt type
!* ******************

/PREP7
!*
ET,1,PLANE35

!* ***************
!* Materials Models
```

```
!* ***************

!* Steel

MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,1,,154
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,1,,0.49
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,1,,7600

!* Concrete

MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,2,,6.12
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,2,,0.75
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,2,,2000

!* ********
!* Creating
!* *******

!* Key Points

!*   Nombre,     X,              Y,              Z
k,       1,      0,              0,              0
k,       2,      0.0016905,      0.0036252,              0
k,       3,      -0.1905664,     0.0932761,      0
k,       4,      -0.1937585,     0.0903511,      0
k,       5,      -0.0623952,     0.0335089,      0
k,       6,      -0.3615765,     0.5631224,      0
k,       7,      -0.3653353,     0.5617543,      0
k,       8,      -0.2551587,     0.5631224,      0

!* Lines

!*       K1      K2
```

```
l, 1,      2
l, 2,      5
l, 5,      8
l, 8,      6
l, 6,      7
l, 7,      4
l, 4,      1
l, 6,      3
l, 3,      5

!* Areas

!*      L1,     L2,     L3,     L4,     L5,     L6,     L7
al,     3,      4,      8,      9
al,     1,      2,      9,      8,      5,      6,      7

!* **************
!* Material definition
!* ***************

!*Steel

CM,_Y,AREA
ASEL, , , ,    2
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
AATT,    1, ,  1,    0,
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1

!*  Concrete

CM,_Y,AREA
ASEL, , , ,    1
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
AATT,    2, ,  1,    0,
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
```

```
!* ************
!*  Meshing (Tri)
!* ***********

SMRT,6
MSHAPE,0,2D
MSHKEY,0
!*
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2

!* ****************
!* Type of solution : TRANSIENT
!* ******************

FINISH
/SOL
!*
ANTYPE,4
!*
TRNOPT,FULL
LUMPM,0

!* *****************************
!* Definition of steps Time-Tiem Step
!* *****************************

TIME,12
AUTOTS,1
DELTIM,0.01,0.001,0.25,1
KBC,0
!*
```

```
TSRES,ERASE

!* show results for all steps

/SOL
!*
OUTRES,ALL,ALL,

!* *******
!* Arrays
!* ********

!* Room Temperature

*DIM,RT,TABLE,13,1,0,Time,Temp,
!*
*SET,RT(0,1,1)    ,     273.15
*SET,RT(1,0,1)    ,     273.15
*SET,RT(1,1,1)    ,     288.03
*SET,RT(2,0,1)    ,     274.15
*SET,RT(2,1,1)    ,     290.07
*SET,RT(3,0,1)    ,     275.15
*SET,RT(3,1,1)    ,     291.31
*SET,RT(4,0,1)    ,     276.15
*SET,RT(4,1,1)    ,     291.91
*SET,RT(5,0,1)    ,     277.15
*SET,RT(5,1,1)    ,     292.03
*SET,RT(6,0,1)    ,     278.15
*SET,RT(6,1,1)    ,     291.79
*SET,RT(7,0,1)    ,     279.15
*SET,RT(7,1,1)    ,     291.31
*SET,RT(8,0,1)    ,     280.15
*SET,RT(8,1,1)    ,     290.70
*SET,RT(9,0,1)    ,     281.15
*SET,RT(9,1,1)    ,     290.02
*SET,RT(10,0,1)   ,     282.15
*SET,RT(10,1,1)   ,     289.35
*SET,RT(11,0,1)   ,     283.15
*SET,RT(11,1,1)   ,     288.71
*SET,RT(12,0,1)   ,     284.15
*SET,RT(12,1,1)   ,     288.13
*SET,RT(13,0,1)   ,     285.15
*SET,RT(13,1,1)   ,     287.61
```

```
!* Heat Generation Rates

*DIM,HG,TABLE,9,1,0,Time,Heat,
!*
*SET,HG(0,1,1) , 0
*SET,HG(1,0,1) , 0.0000
*SET,HG(1,1,1) , 6000
*SET,HG(2,0,1) , 0.0100
*SET,HG(2,1,1) , 10000
*SET,HG(3,0,1) , 2.0000
*SET,HG(3,1,1) , 5000
*SET,HG(4,0,1) , 3.0000
*SET,HG(4,1,1) , 10000
*SET,HG(5,0,1) , 4.0000
*SET,HG(5,1,1) , 13000
*SET,HG(6,0,1) , 5.0000
*SET,HG(6,1,1) , 6500
*SET,HG(7,0,1) , 6.0000
*SET,HG(7,1,1) , 3500
*SET,HG(8,0,1) , 7.0000
*SET,HG(8,1,1) , 2000
*SET,HG(9,0,1) , 8.0000
*SET,HG(9,1,1) , 300

!* ******************
!* Boundary Conditions
!* ******************

!* Ambient temperature
!* Film coefficient Concrete

FLST,2,2,4,ORDE,2
FITEM,2,3
FITEM,2,-4
/GO
!*
!*
SFL,P51X,CONV,0.10, , %RT%

!* Film coefficient Steel

FLST,2,5,4,ORDE,4
FITEM,2,1
FITEM,2,-2
FITEM,2,5
```

```
FITEM,2,-7
/GO
!*
!*
SFL,P51X,CONV,19, , %RT%

!* Heat Generation

FLST,2,1,5,ORDE,1
FITEM,2,1
/GO
!*
!*
BFA,P51X,HGEN, %HG%

!* *******************
!* Specifying initial conditions
!* **********************

!* Initial temperature Concrete (293.70 oC)

APLOT
ASEL,S, , ,      1
ALLSEL,BELOW,AREA
NPLOT
FLST,2,997,1,ORDE,6
FITEM,2,1
FITEM,2,-4
FITEM,2,8
FITEM,2,-291
FITEM,2,530
FITEM,2,-1238
IC,P51X,TEMP,293.70,

!* Initial temperature Steel (292.15 oC)

NSEL,INVE
NPLOT
FLST,2,490,1,ORDE,6
FITEM,2,5
FITEM,2,-7
FITEM,2,292
FITEM,2,-529
FITEM,2,1239
FITEM,2,-1487
```

```
IC,P51X,TEMP,292.15,
ALLSEL,ALL
GPLOT

!* *********
!* Solution
!* ********

/STATUS,SOLU
SOLVE

!* *************
!* Results review
!* *************

/PNUM,KP,0
/PNUM,LINE,0
/PNUM,AREA,0
/PNUM,VOLU,0
/PNUM,NODE,1
/PNUM,TABN,0
/PNUM,SVAL,0
/NUMBER,0
!*
/PNUM,ELEM,0
/REPLOT
!*
EPLOT
*SET,cp1 , node (-0.3055880,0.4239138,0.0000000)
*SET,cp2 , node (-0.2632974,0.4392931,0.0000000)

FINISH
/POST26
FILE,'file','rth','.'
/UI,COLL,1
NUMVAR,200
SOLU,191,NCMIT
STORE,MERGE
FILLDATA,191,,,,1,1
REALVAR,191,191
!*
NSOL,2,916,TEMP,, TC_L
STORE,MERGE
!*
NSOL,3,648,TEaMP,, TC_H
```

```
STORE,MERGE
XVAR,1
PLVAR,2,3,
```

Code for ground (example: Clay 100 mm-thickness)

```
!* ****************
!*  White Background
!* ****************
!*
/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX, 0, 0, 0,15

!* **********************
!* Choosing Thermal Analysis
!* **********************

/NOPR
/PMETH,OFF,0
KEYW,PR_SET,1
KEYW,PR_STRUC,0
KEYW,PR_THERM,1
KEYW,PR_FLUID,0
KEYW,PR_ELMAG,0
KEYW,MAGNOD,0
KEYW,MAGEDG,0
KEYW,MAGHFE,0
KEYW,MAGELC,0
KEYW,PR_MULTI,0
KEYW,PR_CFD,0
KEYW,LSDYNA,0
/GO
!*
/COM,
/COM,Preferences for GUI filtering have been set to display:
/COM,  Thermal

!* *******************
!* Choosing Element type
!* ********************

/PREP7
!*
ET,1,PLANE35

!* ***************
!* Materials Models
```

```
!* ***************

!* Clay

MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,1,,5.4
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,1,,0.92
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,1,,800

!* Concrete

MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,2,,6.12
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,2,,0.75
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,2,,2000

!* *******
!* Creating
!* *******

!* Key Points

!*   Nombre,    X,      Y,      Z
k,      1,      0.00,   0.00,   0.00
k,      2,      1.50,   0.00,   0.00
k,      3,      1.60,   0.00,   0.00
k,      4,      1.60,   3.00,   0.00
k,      5,      1.50,   3.00,   0.00
k,      6,      0.00,   3.00,   0.00

!* Lines

!*      K1      K2
l, 1,   2
l, 2,   3
```

```
l, 3,      4
l, 4,      5
l, 5,      6
l, 6,      1
l, 5,      2

!* Areas

!*      L1,     L2,     L3,     L4
al,     1,      7,      5,      6
al,     2,      3,      4,      7

!* ***************
!* Material definition
!* ****************

!* Clay

CM,_Y,AREA
ASEL, , , ,     2
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
AATT,     1, ,  1,     0,
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1

!*  Concrete

CM,_Y,AREA
ASEL, , , ,     1
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
AATT,     2, ,  1,     0,
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1

!* ***********
!*  Meshing (Tri)
!* ***********
```

```
SMRT,6
MSHAPE,0,2D
MSHKEY,0
!*
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CMSEL,S,_Y
CMDELE,_Y
!*
!*
AREFINE,_Y1, , ,1,0,1,1
CMDELE,_Y1
!*

!* ***********************
!* Type of solution : TRANSIENT
!* ***********************

FINISH
/SOL
!*
ANTYPE,4
!*
TRNOPT,FULL
LUMPM,0

!* ***************************
```

```
!* Definition of steps Time-Tiem Step
!* ****************************

TIME,12
AUTOTS,1
DELTIM,0.01,0.001,0.25,1
KBC,0
!*
TSRES,ERASE

!* show results for all steps

/SOL
!*
OUTRES,ALL,ALL,

!* ******
!* Arrays
!* ******

!* Heat Generation Rates

*DIM,HG,TABLE,9,1,0,Time,Heat,
!*
*SET,HG(0,1,1)  , 0
*SET,HG(1,0,1)  , 0.0000
*SET,HG(1,1,1)  , 6000
*SET,HG(2,0,1)  , 0.0100
*SET,HG(2,1,1)  , 10000
*SET,HG(3,0,1)  , 2.0000
*SET,HG(3,1,1)  , 5000
*SET,HG(4,0,1)  , 3.0000
*SET,HG(4,1,1)  , 10000
*SET,HG(5,0,1)  , 4.0000
*SET,HG(5,1,1)  , 13000
*SET,HG(6,0,1)  , 5.0000
*SET,HG(6,1,1)  , 6500
*SET,HG(7,0,1)  , 6.0000
*SET,HG(7,1,1)  , 3500
*SET,HG(8,0,1)  , 7.0000
*SET,HG(8,1,1)  , 2000
*SET,HG(9,0,1)  , 8.0000
*SET,HG(9,1,1)  , 300

!* ****************
```

```
!* Boundary Conditions
!* ****************

!* Temperature ground (inifinite)

FLST,2,3,4,ORDE,3
FITEM,2,1
FITEM,2,5
FITEM,2,-6
!*
/GO
DL,P51X, ,TEMP,291.15,0

!* Ambient temperature
!* Film coefficient Concrete

FLST,2,1,4,ORDE,1
FITEM,2,3
/GO
!*
SFL,P51X,CONV,0.1, ,291.15,

!* Heat Generation

FLST,2,1,5,ORDE,1
FITEM,2,2
/GO
!*
!*
BFA,P51X,HGEN, %HG%

!* *********************
!* Specifying initial conditions
!* *********************

!* Initial temperature Concrete

APLOT
ASEL,S, , ,       2
ALLSEL,BELOW,AREA
NPLOT
FLST,2,309,1,ORDE,9
FITEM,2,2
FITEM,2,-5
FITEM,2,16
```

```
FITEM,2,-42
FITEM,2,65
FITEM,2,-91
FITEM,2,261
FITEM,2,264
FITEM,2,-513
IC,P51X,TEMP,291.15,
NSEL,INVE
NPLOT

!* Initial temperature Clay

FLST,2,810,1,ORDE,11
FITEM,2,1
FITEM,2,6
FITEM,2,-15
FITEM,2,43
FITEM,2,-64
FITEM,2,92
FITEM,2,-260
FITEM,2,262
FITEM,2,-263
FITEM,2,514
FITEM,2,-1119
IC,P51X,TEMP,291.15,
ALLSEL,ALL
GPLOT

!* *********
!* Solution
!* ********

/STATUS,SOLU
SOLVE

!* *************
!* Results review
!* *************

/PNUM,KP,0
/PNUM,LINE,0
/PNUM,AREA,0
/PNUM,VOLU,0
/PNUM,NODE,1
/PNUM,TABN,0
```

```
/PNUM,SVAL,0
/NUMBER,0
!*
/PNUM,ELEM,0
/REPLOT
!*
EPLOT
*SET,cp1 , node (1.55,1.50,0.00)

FINISH
/POST26
FILE,'file','rth','.'
/UI,COLL,1
NUMVAR,200
SOLU,191,NCMIT
STORE,MERGE
FILLDATA,191,,,,1,1
REALVAR,191,191
!*
NSOL,2,384,TEMP,, TEMP
STORE,MERGE
XVAR,1
PLVAR,2,
```