MSc Final Dissertation

IMPLEMENTATION OF MICROENCAPSULATED PCM AS CONCRETE ADDITION IN PREFABRICATED RADIANT-WALL SOLUTIONS.

A feasibility study of the combination of Micronal & In-Therm Klimavæg, as an In-Space Thermal Energy Storage solution for heating applications.

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ABSTRACT.

Traditional heating and cooling solutions are currently being replaced with new low-temperature technologies, which reduce energy consumptions and reach a more sustainable approach. The current status of the European construction sector and the European energetic plans Europe 2020 and Europe 2050, present a potential market expansion in the energetic renovation area.

As one of the main emitter technologies, the implementation of radiant heating and cooling in constructive elements such as radiant floors, walls and ceilings has experienced a considerable growth during the last decade in Europe, and is highlighted as one of the most efficient heating and cooling solutions available.

The comparison of the principal radiant wall panel manufacturers in the European market shows a lack of products with high TES capacity, which opens a field for innovative products reaching greater thermal mass values. The implementation of PCM in construction products (latent heat) allows the improvement of the TES capacity of these materials without increasing the volume of the element or rising the element temperatures.

The present study analyses the feasibility of integrating BASF Micronal (microencapsulated PCM) in the concrete layer of a prefabricated radiant wall element (In-therm Klimavæg). This research is focused on the increase of the TES capacity of the element, in order to reduce heating costs by balancing the energy demand on electricity peak hours (Smart Metering).

The results of the present research showed that the addition of Micronal in the concrete layer of In-therm Klimavæg is technically feasible (mechanically and thermally), doubling the element TES capacity. Despite that the combination with smart metering solutions reaches small costs reductions, the results reached during the present study opens a vast range of applications for the thermal improvement reached on In-therm Klimavæg.

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LIST OF ABREVIATIONS.

CSS .... Combined Specific Surface.
DME .... Dansk Miljø Entreprise.
DTI .... Dansk Teknologisk Institut.
ePCM .... Macro-encapsulated Phase change Material.
EPS .... Expanded Polystyrene.
GSHP .... Ground Source Heat Pump.
HDD .... Heating Degree Days.
HRHC .... Hydronic Radiant Heating & Cooling.
HVAC .... Heating, Ventilation, and Air Conditioning.
IEB .... Intelligent Electricity Broker.
LTC .... Low Temperature Cooling.
LTES .... Latent-heat Thermal Energy Storage.
LTH .... Low Temperature Heating.
MDF .... Medium Density Fibreboard.
mPCM .... Microencapsulated Phase Change Material.
MP .... Melting Point.
MSS .... Modified Specific Surface.
MW .... Mineral Wool.
nPCM .... Nano-encapsulated Phase Change Material.
PCM .... Phase Change Material.
PE .... Polyethylene.
PEX .... Cross-linked Polyethylene.
PIR .... Polyisocyanurate.
RHC .... Radiant Heating & Cooling.
RWP .... Radiant Wall Panel.
SAHP .... Solar Assisted Heat Pump.
SD .... Standard Deviation.
SSD .... Saturated State Dry.
STES .... Sensible-heat Thermal Energy Storage.
TES .... Thermal Energy Storage.
WF .... Wood Fibres.
XPS .... Extruded Polystyrene.

1. INTRODUCTION.

In this section of the report, an initial description of the report background, aim and objectives and distribution can be found.

1.1. BACKGROUND.

The present research responds to a project proposed by the author, as a final dissertation topic for the finalization of the MSc in European Construction Engineering programme. The author had a first contact with PCM technology during the MSc programme, when developing a bibliographic research oriented to the implementation of PCM materials for solar-assisted floor heating solutions in Spain.

During the initiation phase of the research project (firstly oriented to radiant floor heating solutions), the author had the opportunity to contact DME BN Teknisk Aps director (Gunnar Bekker-Nielsen) and discover their prefabricated radiant wall product (In-therm Klimavæg).

The innovative concept of In-Therm Klimavæg, and the interest of DME on collaborating in a research including their product, lead to the orientation of the project into the enhancement of Klimavæg TES capacity using Phase Change Materials.

Once analysed the most relevant European manufactures, the author contacted BASF Denmark in order to show the project idea. The interest of the group to cooperate in the project, and the suitability of BASF Micronal with the research concept lead to the adhesion of BASF to the project.

The research project was then re-oriented to combine BASF Micronal with Klimavæg concrete in order to increase the volumetric heat capacity of the element in order to use it as an In-space TES element. At this point, the present research is initiated.

Further information regarding the characteristics and details of BASF Micronal and In-therm Klimavæg can be found along the report State of the Art section and Theoretical Research.

1.2. AIMS AND OBJECTIVES.

The aim of this research is to assess the technical feasibility, regarding the integration of the concept of In-space Thermal Energy Storage into a commercial prefabricated radiant wall module (In-Therm Klimavæg), by implementing microencapsulated Phase Change Materials.

Considering the current development in the academic and commercial area regarding radiant-wall heating solutions and mPCM, this study is focused on existing commercial products and patents available in the European market combined with the existing academic research carried out in two main areas: Radiant-wall heating solutions, and microencapsulated PCM in construction products.

The progress of this study can be enclosed in the accomplishment of four secondary aims, which would be divided as shown in the objective list:

FIRST. The analysis and synthesis of the current status of In-space Thermal Energy Storage in the European market, and the potential implementation benefits for a specific radiant-wall module (In-therm Klimavæg), oriented to marketing and technical aspects.

- Revise and classify the current academic and industrial development of radiant-wall heating technology in the European market.
- Analyse the status (academic and commercial) of PCM technology in the European construction market, focusing on combination of mPCM in concrete admixtures.

SECOND. The assessment of the technical implementation of In-space TES technology in In-therm klimavæg in the Danish market. This objective focuses on combining TES in radiant walls with the energy balance concept.

- Determine the variable hourly energy needs in an In-therm Klimavæg renovation project in Denmark.
- Set the principal thermal and mechanical properties of BASF Micronal DS 5038X in concrete admixtures based on bibliographic research.
- Calculate the theoretical TES potential of BASF Micronal in the previous case study.
- Analysis and description of the main mechanical and thermal properties of In-therm Klimavæg concrete.

THIRD. Develop a concrete admixture based on the theoretical research carried out, and following the main concrete design theories. The designed concrete admixture has been directed to achieve similar properties (workability, mechanical and thermal) to the ones specified in In-Therm Klimavæg technical documentation.

- Study the principal concrete and mortar design theories and develop an initial design theory based in similar previous researches.
- Cast and produce the concrete admixtures proposed and test the initial fresh concrete properties.
- Characterize the mechanical properties of the hardened concrete form the produced concrete admixtures.
- Characterize the thermal conductivity of the hardened concrete samples.

FOURTH. Compare the results gathered in the previous objectives and set the final recommendation regarding the feasibility of continuing with the project in a more detailed and extensive research.

- Determine the technical feasibility regarding the development of the project for industrial production, and set a list of recommendations for the future progress of the project.
- Enlist the potential research areas found during the development of this study, in order to facilitate the creation of new research branches in the matter for future investigators.

1.3. RESEARCH METHODOLOGY.

In this section, the research methodology followed along the evolution of this research will be described.

Starting with a global picture of the methodology and distribution, it has to be mentioned that the current research paper follows a structure divided by smaller sections or projects.

For some of these sections (Second area and third area), the former chapters have been treated as small studies or projects, which are linked together but reach individual conclusions and different approaches. The text showed in the report section refers just to the most relevant data and conclusions of these studies, and the full study can be found in the appendix named with the same numeration.

Once this organizational peculiarity has been clarified, the following list includes the former sections (areas) and the approach reached in each of them.

FIRST AREA. Theoretical bibliographic research, including the current status of radiant heating and PCM technology in the European market.

This section is based on the industrial and academic work available in digital and printed work, and follows the structure and patterns of a State of The Art.

SECOND AREA. Theoretical research, analysing the main critical points regarding the implementation of the concept of In-space TES in In-therm Klimavæg, by combining BASF Micronal as a concrete admixture.

For the development of this research area, the available technical information resultant from the first bibliographic research has been used.

This area follows the previously explained structure by projects, for each chapter in the report, a complete study can be found in the appendix section.

THIRD AREA. Development of a concrete admixture based on the theoretical research carried out, and following the main concrete design theories.

The designed concrete admixture has been directed to achieve similar properties (workability, mechanical and thermal) to the ones specified in In-Therm Klimavæg technical documentation.

- Characterization of the principal components of the future concrete admixture, including physical properties included in EN 1097.
- Study of the principal concrete and mortar design theories and development of an initial design theory based in similar previous researches. Development of a brief design guideline based on empirical validation of the proposed hypothesis.
- Cast and production of the concrete admixtures proposed, and testing of the fresh concrete properties, according to European regulations EN 12350.
- Characterization of the mechanical properties of the hardened concrete form the produced concrete admixtures, based on the procedures set on EN 12390 and EN 12504.
- Characterization of the heat conductivity of the hardened concrete, employing a linear transient method and following the procedures set on ATSM D5334-08.

This area follows the previously explained structure by projects, for each chapter in the report, a complete study can be found in the appendix section.

FOURTH AREA. Comparison and final analysis of the results and conclusions gathered from the previous research areas and set the final recommendation regarding the feasibility of continuing with the project in a more detailed and extensive research.

This area considers all the conclusions reached in the previous areas and establishes a condensed set of conclusions, more understandable and result-focused than the ones set in the previous sections.

1.4. LIMITATIONS AND SCOPE.

Once established that the aim of this research is the set of the technical feasibility for the implementation of mPCM products in concrete radiant walls as TES solution, the scope of the project can be established.

SCOPE.

As the main objective of this project is to establish the feasibility of investing in a further research line in the area of PCM technology for the In-therm Klimavæg model, the author has focused in the principal critical points regarding TES and PCM in concrete technology.

Despite that the research aim is not to establish any strong conclusion regarding the topic of PCM in concrete; some conclusions have been stated by the author regarding the achievement of high resistances in concrete mixes including Micronal in powder format.

It has to be remarked in addition, that the author is fully conscious of the theoretical approach taken in the TES theoretical calculations performed. The method used has to be considered as a mere approximation in a simplified way, which intends to illustrate the potential repercussions of the possible solutions proposed in a clear and simple way. The results obtained can be just considered as indicative and do not represent a tangible conclusion of the final performance of an element, which shall be simulated and tested in order to reach reliable TES (heat capacity and thermal inertia) values.

Regarding the electricity analysis performed, it has to be stated that the study represents a mere representation of some of the ideas and conclusions reached by independent projects (Intelligent Electricity Broker VIA UC project) as shown in Zavada et al. (2012). The author has studied briefly the daily evolution of electricity prices in order to establish a first rough number for the potential savings regarding the integration of the present research idea in the IEB concept.

LIMITATIONS.

Stating the former limitations of the project, the main boundaries have been divided into three groups, according to their nature. These limitations can be set as the following:

RESOURCES AND ORGANIZATIONAL LIMITATIONS.

It has to be accounted that the former project represents a part of an MSc programme, and accounts with 20 ECTS credits, which corresponds to a total workload of 500-600 hours distributed in 4 months. Considering this first statement, the following limitations have been identified:

- **Workload distribution along 4 months.** The distribution of the workload along time constricted the possibility of leaving longer periods for improving the networking or making the project more flexible along time.
- **Collaboration with third parties.** The cooperation with former organizations and enterprises (DME, BASF, DTI, VIA UC) regarding the procurement of technical, material and academic resources requires the development of a contact network. This networking process may take long periods.
- **Communicative limitations.** Considering that, the project is taking place in Denmark and that the author is still a novel user of Danish, the communicative process with the former collaborators may find important limitations.
- **Changes regarding research supervisor.** Due to administrative issues, the initial supervisor for the project (Bø Rijsbjerg Thomsen), was substituted by a group of two (Inga Sørensen and Regner Bæk Hessellund).
- **BASF Micronal DS-5038X availability.** Due to availability issues with Micronal DS-5038X in the BASF Danish division, and considering that the supply expenses were totally covered by BASF, a similar product (BASF DS-5040X) has been used for the conducted tests. The main difference between the two products refers to the melting point of the product (23ºC for Micronal DS-5040X against the 26ºC for Micronal DS-5038X), and it was not relevant for the performed tests (mechanical and heat conductivity), so the experimental results can be considered as valid.
- **CemFil-62 glass fibres supply.** Due to logistic issues, the delivery of the glass fibres suffered a considerable delay, which caused an alteration in the chronological development of the experimental process.

ACADEMIC LIMITATIONS.

Considering the background of the author (Building engineer) and former MSc in Construction Engineering, and without any specific professional experience regarding the studied fields, the following limitations have been found:

- **Available bibliography.** Considering the previous constraints, the author has been able to access information available on open digital databases and the ones available by University of Cantabria and VIA University College. Physical resources from VIA University College have been available furthermore.
- **Introduction to the author in the studied topics.** This project represents an initial contact of the author into the area of Phase Change Materials, radiant heating and concrete design.
- **Limited information regarding In-therm Klimavæg.** Considering that some information regarding the production process and characteristics of In-therm Klimavæg is confidential information that cannot be released, the study has to be redacted and conducted with a strong precaution in order to maintain the confidentiality agreement set.
- **PCM in concrete, lack of academic work.** The current development of Micronal in concrete admixtures can be considered as still incipient, especially when high resistances concrete gets into the picture. This fact and the lack of design guidelines for Micronal in concrete, complicates the development of a mix design by “traditional” methods.
- **PCM technology is an innovative field.** The fact that microencapsulated PCM represent a novel technology in construction industry turns into a lack of academic work in the area, especially when combined in concrete admixtures.
- **Lack of experience in concrete design and production.** It has to be accounted that the author is not an expert in concrete design and production, and as previously stated, the present work represents an introduction into the “practical” side of concrete technology.
- **Lack of experience in concrete mechanical and thermal testing.** As stated in the previous point, the current research represents the first contact for the author with concrete mechanical and thermal testing in a practical way.

TECHNICAL LIMITATIONS.

Taking into account the available technical means present in the facilities and owned by the author, several limitations have been found:

- **Concrete lab limited resources.** It has to be remarked that the facilities of VIA used (betonlab) have as main purpose the education of bachelor students, and counts with the most common resources regarding concrete testing. Nevertheless, the testing of fluid concrete consistence requires the use of shaking tables and fluidity-test methods not available, which were omitted from the original research organizational scheme.
- **Heat conductivity testing apparatus available.** Despite that using a transient line source method may not be consider the ideal method to test concrete specimens; the available means did not allowed using a more suitable method (hot plane, transient plane source method). Despite this limitation, a slight modification in the test procedure has been done to adapt it to the samples.
- **Heat capacity measurement.** The measurement of the heat capacity of the concrete samples has been considered in an initial phase of the process, but the lack of means to measure this property with the actual resources forced the use of theoretical approximate values.

1.5. REPORT OUTLINE.

This study has been divided in 3 main areas (including the first three objectives) and a fourth last conclusion (corresponding to the fourth objective). The following list includes these four research focus areas and enlists the internal subdivision:

FIRST AREA. Theoretical bibliographic research, including the current status of radiant heating and PCM technology in the European market.

- Revision of current academic and industrial development of radiant heating solutions in Europe, and combination with the concept of Thermal energy Storage.
    - Concept of radiant heating and cooling and current development in general technology.
    - Radiant wall heating and cooling. Including a European market research identifying the most relevant producers, and an overview of the current academic development in the area.
    - Description of In-therm Klimavæg, including an analysis of the main technical details and a subjective analysis of the potential strengths and weaknesses.
    - In-space short-term TES concept. Including an analysis of potential applications and the combination opportunities for In-therm Klimavæg.
- Revision of current academic and industrial development of PCM technology in Europe, focusing on construction industry applications.
    - Concept of Phase Change Material, general classification and European producers.
    - Status of microencapsulated PCM technology in Europe, commercial products and academic research.
    - BASF Micronal description, product description, research lines oriented to construction industry and commercial patents incorporating Micronal.
    - Microencapsulated PCM in concrete admixtures, current academic research and commercial evolution in European market.
    - Microencapsulated PCM in radiant heating solutions, current research areas and European producers.

SECOND AREA. Theoretical research, analysing the main critical points regarding the implementation of the concept of In-space TES in In-therm Klimavæg, by combining BASF Micronal as a concrete admixture.

- Determination of the variable hourly energy needs in an In-therm Klimavæg renovation project in Denmark.
- Setting of the principal thermal and mechanical properties of BASF Micronal DS 5038X in concrete admixtures.
- Calculation of the theoretical TES potential of BASF Micronal in the previous case study, and comparison with the storage potential in a set of different scenarios.
- Analysis and description of the main mechanical and thermal properties of In-therm Klimavæg concrete layer based on DME's technical documentation.

THIRD AREA. Development of a concrete admixture based on the theoretical research carried out, and following the main concrete design theories.

- Characterization of the principal components of the future concrete admixture, including physical properties included in EN 1097.
- Study of the principal concrete and mortar design theories and development of an initial design theory based in similar previous researches. Development of a brief design guideline based on empirical validation of the proposed hypothesis.

- Cast and production of the concrete admixtures proposed, and testing of the fresh concrete properties, according to European regulations EN 12350.
- Characterization of the mechanical properties of the hardened concrete form the produced concrete admixtures, based on the procedures set on EN 12390 and EN 12504.
- Characterization of the heat conductivity of the hardened concrete, employing a linear transient method and following the procedures set on ATSM D5334-08.

FOURTH AREA. Comparison and final analysis of the results and conclusions gathered from the previous research areas and setting of the final recommendation regarding the feasibility of continuing with the project in a more detailed and extensive research.

- Analysis and executive summary of the bibliographic research (First area).
- Executive summary of the thermal and electricity study, part of the theoretical research (Second area).
- Executive summary form the experimental test results (fresh concrete, mechanical and thermal) and conclusions (Third area).
- Solution overview and technical feasibility statement.

2. STATE OF THE ART.

The following section of this study will consist on a brief analysis on the current technological and intellectual development of Microencapsulated Phase Change Materials as concrete admixtures in radiant-heating solutions.

This section aims to introduce the reader into the current development of microencapsulated phase change materials as heat storage solutions in radiant-wall heating systems, and attempts to turn from a holistic picture of the current radiant heating technology into the specific field studied in this research.

2.1. INTRODUCTION.

Building industry, in its historical life cycle has represented a crucial factor in society welfare evolution. Current building uses, designs, materials and constructive solutions have been evolving through human history as a living creature. This evolution is clearly marked nowadays with "Energy efficiency" concept.

Closing this perspective to building industry in Europe, it could be painted as a mature sector with a vast representation of residential stock (Close to 75%). A considerable share of this stock is composed by constructions older than 50 years (40-50%), and just a 14-20% of this sector dates after 1990. If this picture is compared with past energetic regulations and constructive solution, a considerably old building stock with an excessive energy consumption can be clearly identified. Throwing some data to this picture, in 2009 European residential sector was responsible for a 68% of the total energy consumption in European buildings. Predominant energetic uses can be clearly identified, as space heating, which represents approximately a 70% of the total energetic consumption (Economidou et al. 2011).

Current European regulative efforts, such as "Energy Performance of Buildings Directive (EPBD, 2002/91/EC)" through energetic labelling, are steering the attention of nations, enterprises and users into the energy efficient construction field. Strategic plans such as Europe 2020 and Europe 2050, are pushing building market among others, to an energetic-focused planning and renovation of the existing market (European Commission 2010; European Union. Directorate-General for Research and Innovation 2012).

Once the idea of a growing energetic renovation filed is accepted as a reasonable scenario in the near future, the dimensions of this growing market could reach considerable sizes, reaching investments which would rise from 100- 180€ billion annually during the following 30 years (Economidou et al. 2011).

Even though these are estimated values, which depend on the implementation grade of this energetic renovation strategic plan and the market evolution predictions, the perspective set even by the most conservative theories reveal a rather positive prediction on future market trends.

The introduction of a radiant heating element, flexible enough to be implemented in new construction and renovation projects, and the possibility of being used as an insulation element plus a heating & cooling solution may result in an attractive product, which can reduce project costs when integrating radiant solutions in construction industry. The integration of the in-space TES concept into radiant technology, as intended in this project, may lead to a greater efficiency of the final installation, and a potential combination field with renewable energy sources.

2.2. RADIANT HEATING & COOLING.

In this chapter, the current development and basic principles of radiant heating & cooling (RHC) technology for building applications have been briefly analysed. Aiming to give an overall picture of the current development of this technology and serving as an introduction for RHC wall solutions.

PRINCIPLES.

When introducing the concept of radiant heating & cooling (RHC) systems in construction industry, this technology can be explained as a heat carrier/emitter element embedded into a constructive element. The heat exchange element usually consist on a piping distribution containing a heat carrier fluid (water, gases, oil). The main constructive elements in which these elements are casted are floors, ceilings and walls; existing an extensive variety of in-situ and prefabricated modular solutions (Watson & Chapman 2002).

Considering the extensive product and technologic solutions available, and in order to focus this research on a narrower field, the author will focus from now on in hydronic RHC solutions (HRHC) which use water as carrier fluid, which may be considered as the most popular technology over the international market, and specially the European (Bean, Olesen & Kim 2010).

The basic working principle consist on the uniform temperature increase/reduction of the constructive element by the emitter, due to heat conduction. Depending on the fluid or resistance temperature the element will gain thermal energy or lose it allowing the use as a heat release solution or heat absorption solution (Watson & Chapman 2002).

Further information regarding the basic principles and solutions for this technology can be found in Watson & Chapman (2002) and Çengel (2003), which the author recommends as a complete guide in the matter. Furthermore, in Crocker & Higgins (2012) an interesting summary review of the evolution of this technology in the last decades can be found, giving an accurate and short overall image of this technology.

For further information regarding RHC systems, the author recommends ASHRAE (2012) as an essential guideline in which concerns not just radiant elements but the whole installation required.

Regarding the effect of RHC in building temperature and thermal comfort in (Watson & Chapman 2002) temperatures ranging from 25-21ºC are recommended on the surface layer radiant elements depending on external conditions, building characteristics and element disposition. While surface layer temperatures of 17-19ºC are recommended in cooling elements varying with the same parameters.

Due to the low working temperature of the fluids these heating solutions are considered low temperature heating & cooling solutions (LTH / LTC), being able to use low consumption heating and cooling generators including renewable sources such as solar thermal and solar passive, or any type of heat-pump system including ground source solutions (GSHP) (Watson & Chapman 2002).

CURRENT DEVELOPMENT.

The actual development of this technology can be considered as fully integrated in the European market, representing a 50% of the heating solution market in new building projects, and can be assessed (Bean, Olesen & Kim 2010). It has to be remarked that the main market share is hold by floor heating solutions, being the most implemented technology nowadays.

In Anastaselos et al. (2011) an interesting evaluation of the integration of RHC solutions is carried out considering the European market as scenario, this study may give the reader a general overview of the implementation possibilities from an economical point of view.

Regarding the relation of radiant temperature a thermal comfort, several studies have been developed in the matter (Atmaca, Kaynakli & Yigit 2007; Fanger 1970; Kalmár & Kalmár 2012; Rizzo, Beccali & Nucara 2004), (Oseland 1994; Schellen et al. 2013), even though this is a too extensive field to be studied into this research.

The development of RHC solutions has had an important evolution in the informatics modelization field, where different physical calculation models for general radiant elements may be found (Laouadi 2004; Strand & Pedersen 2002). Strand & Baumgartner (2005) develops study regarding the integrated simulation with a whole-building simulation software, pointing towards in which may be in the opinion of the author the future development line in this field.

When mentioning the development of calculation and design models for floor RHC systems, several studies can be found drawing a general outline of the current evolution of this system (Olesen 2002; Wu et al. 2013; Zhang, Cai & Wang 2013). In Cho & Zaheer-uddin (1999) an experimental study of using heat cycles of 2-3h in RHC floors was compared to a continuous heat solution reaching a better overall performance. Furthermore in Woodson (2009) a complete design manual and guideline can be found merging the main calculation and design methods used in this technology.

Regarding the design and calculation of RHC ceilings, in Causone et al. (2009) a study of heat transfer coefficients between radiant ceilings and the room environment was carried out, reaching interesting values for future calculation methods, moreover in Kilkis, Sager & Uludag (1994) and Kilkis, Eltez & Sager (1995) two simplified calculation models for radiant ceilings are proposed with interesting perspectives for informatics modelization.

Several studies have been developed in the area of wall radiant solutions; however, these ones have been studied in more depth in the following chapter of this study (chapter 2.3).

Several studies may be found regarding the combination of RHC solutions with renewable energy sources, as in Athienitis (1997) where a solar passive construction with radiant floor heating is proposed using thermal mass as the main temperature control element recommending 5cm as the ideal concrete mass thickness when using solar solutions. Where in Kilkis (1999) the reader may find a simulation based on the heat/cool supply of a family house, using a ground-source heat pump heating & cooling installation supplied by a 6KW wind turbine, and choosing a radiant floor system as an in-space thermal storage solution, reaching positive conclusions for the implementation in rural areas.

Even though the literature in this area is very extensive, the author will focus on the combination of RHC wall elements with renewable energy sources in more depth in the next chapter (chapter 2.3).

2.3. RADIANT WALL HEATING & COOLING.

Once given a first picture regarding the evolution of RHC technology on construction industry, the author will focus on the RHC wall panels sector.

The following chapter will start giving a first picture of the current development of this heating & cooling technology, focusing on the current commercial solutions. Following with a brief analysis of the selected solution for this study (In-therm Klimavæg), and finishing with the concept of in-space short-term heat storage in combination with renewable energy sources.

2.3.1. INTRODUCTION.

As previously mentioned RHC wall panel solutions can be assessed as one of the less developed and implemented solution in the RHC market (Bean, Olesen & Kim 2010).

Even though it is considered as the most versatile element in this author's opinion, as it can be implemented either as an external envelope element or even in internal partitions allowing a greater modularity and a higher surface range where being installed. Even allowing a great range of implementation solutions either in prefabrication or in-situ techniques, and allowing the use of a great range of materials such as concrete, mortars, plasters, even metals and composites as base material for the emitter (Watson & Chapman 2002).

2.3.2. GENERAL RESEARCHES AND COMMERCIAL PATENTS.

It is interesting anyway, to draw a rough picture of current development of radiant wall technology, not just in the technical side, which concerns mainly industrial patents linked to specific products, but also in the academic area with the current research lines. This study will focus on the European market regarding developed products.

ACADEMIC AND SCIENTIFIC RESEARCH.

In which concerns current research lines, the following fields have been considered interesting for the author:

Regarding informatics modelling and software simulations, EnergyPlus may be considered as one of the most implemented and extended solutions (Crawley et al. 2000), even though several alternative simulation methods have been proposed (Díaz & Cuevas 2010; Djuric et al. 2007; Hanibuchi & Hokoi 2000; Kilkis 2012; Myhren & Holmberg 2008; Tye-Gingras & Gosselin 2011, 2012). Unfortunately, a deeper study into this field may require an entire bibliographic research work, and cannot be carried out on this research.

In what concerns the comparison between different HRHC solutions, numerous studies can be found, even though the author will expose the ones resulting most interesting in his opinion:

Starting with Bojić et al. (2013) where floor, ceiling and wall heating solutions are compared in energetically, being the wall heating solution the second best option, just overcame by a floor-ceiling combined system by a slight (10%) benchmark percentage. In Bojić et al. (2012) an evaluation of the substitution or a traditional radiator system with a radiant wall panel system is conducted using EnergyPlus, showing that a radiant wall solution with additional insulation in the external walls gives the best energetic and emissions results.

In relation to innovative designs and new product development Kilkis (2006) has to be mentioned, regarding the development of a hydronic composite radiant wall panel (RWP) with a porous constitution which combines air-conditioning and ventilation in one element, whose technical, energy efficiency and economic variables are analysed for a Midwest USA single house with positive results. In Roulet, Rossy & Roulet (1999) a two layered steel hydronic panel is designed and tested under real conditions.

COMMERCIAL PATTENTS AND PRODUCTS.

Once the main areas of the academic development related to this technology have been enlightened, the author will focus on setting a general picture of the current European market state regarding radiant wall patents and producers. A selection of 11 of the main European manufacturers has been carried out, and a summary chart with the main relevant aspects of their products can be found below.

The following European manufacturers have been selected as the most relevant ones.

- WEM (Germany) – Climate Panel; Climate Grid (WEM Wandheizung 2008)
- Viega (Gernamy) – Fonterra side 12; Fonterra side 12 (Clip) (Viega 2012a, 2012b)
- BEKA (Germany) – Prefabricated Units; Capilarity tube-mats (BEKA 2006a, 2006b)
- Variotherm (Austria) – DryWall; Plastered Wall (Variotherm 2009a, 2009b)
- Fantoni (Italy) – RW (Fantoni 2010).
- Rossato Group (Italy) – EcoWall; EcoWall Dry (Rossato Group 2013a, 2013b)
- Eurotherm (Italy) – Eco Wall; Leonardo (Eurotherm 2004a, 2004b)
- KERMI (Italy) – Xnet (KERMI 2011)
- KME (Italy) – Hypoplan (KME 2013)
- Proterimex (Italy) – Protenwand WKGM; Protenwand WKIP(Proterimex 2013a, 2013b)
- RDZ (Italy) – B!Klimax (RDZ 2010)

* Two further radiant wall producers (EBB; Lebast Lehmbaustoffe) have been excluded from the present analysis as their product includes Phase Change Materials as a TES solution. These products have been analysed in Chapter 2.7.2.

As it can be appreciated from the previous enumeration, Germany and Italy can be assessed as the main manufacturers in Europe. It has called the attention of the author the important development of most of the Italian products, not just in the technical side but either in design and marketing aspects.

In the following chart, a summary of the most relevant aspects from these manufacturer's products is showed, it has to be pointed that the author has focused on the relevant aspects for the current study.

Brand and product	Production	Matrix layer material	Piping Material	Insulation material	Thickness (mm)
WEM [Germany]					
Climate Panel	Pref.	Clay	ALU-PE (multi)	NO	25,0
Climate Grid	In-situ	Clay	ALU-PE (multi)	NO	30,0
VIEGA [Germany]					
Fonterra side 12	Pref.	Plasterboard	Polybutylene	NO	18,0
Fonterra side 12 (clip)	In-situ	Plaster	Polybutylene	NO	26,0
BEKA [Germany]					
Prefabricated Units	Pref.	Plasterboard	Polypropylene	XPS (30mm)	(+30) 12,5
Capilarity Tube-mats	In-situ	Plaster	Polypropylene	NO	20,0
VARIOTHERM [Austria]					
Dry Wall	Pref.	Plasterboard	ALU-PE (multi)	NO	17,0
Plastered Wall	In-situ	Plaster	ALU-PE (multi)	NO	31,0
FANTONI [Italy]					
RW	Pref.	MDF	XPE	YES	7,0
ROSSATO GROUP [Italy]					
Eco Wall Dry	Pref.	Plasterboard	ALU-PE (multi)	XPS (3mm)	(+30) 15,0
Eco Wall	In-situ	Plaster	ALU-PE (multi)	NO	25,0
EUROTHERM [Italy]					
Eco Wall	Pref.	Plasterboard	XPE	WF (20mm)	(+30) 10,0
Leonardo	In-situ	Plaster	XPE	NO	25,0
KERMI [Italy]					
Xnet	In-situ	Plaster	ALU-PE (multi)	EPS (25mm)	(+25) 18,0
KME [Italy]					
Hypoplan	In-situ	Plaster	Cooper	NO	25,0
PROTERINEX [Italy]					
Protenwand WKGM	Pref.	Plasterboard	Cooper	NO	20,0
Protenwand WKIP	In-situ	Plaster	Cooper	NO	25,0
RDZ [Italy]					
B!Klimax	In-situ	Plaster	Polybutylene	PS (40mm)	(+40) 15,0

Table 2.3.2-1, Summary chart of European hydronic radiant wall manufacturers

As it can be concluded from this overall picture, most existing product are based on light construction elements using mainly plaster as matrix layer. Piping materials vary from plastic to cooper and multilayer, using sections from 6-10mm.

However, the main conclusion the author is willing to remark is the low thermal inertia of most of the constituent layers, which opens a gap in the market for high thermal inertia solutions.

In the following chart, a brief summary of the matrix-layer materials and their estimated thermal inertia per square meter of element is shown. (International Organization for Estandarization 2007). For further information regarding this estimated calculation, follow to (Appendix 2.3.).

Brand and product	Production	Matrix layer material	Heat Capacity (per m2) [J/(m2 ºK)]	Thermal Inertia (per m2) [W/(m2 ºK √s)]
		WEM [Germany]		
Climate Panel	Pref.	Clay	26.000	1.530
Climate Grid	In-situ	Clay	31.200	1.836
		VIEGA [Germany]		
Fonterra side 12	Pref.	Plasterboard	12.600	414
Fonterra side 12 (clip)	In-situ	Plaster	15.600	513
		BEKA [Germany]		
Prefabricated Units	Pref.	Plasterboard	8.750	288
Capilarity Tube-mats	In-situ	Plaster	12.000	394
		VARIOTHERM [Austria]		
Dry Wall	Pref.	Plasterboard	11.900	391
Plastered Wall	In-situ	Plaster	18.600	611
		FANTONI [Italy]		
RW	Pref.	MDF	4.760	110
		ROSSATO GROUP [Italy]		
Eco Wall Dry	Pref.	Plasterboard	10.500	345
Eco Wall	In-situ	Plaster	15.000	493
		EUROTHERM [Italy]		
Eco Wall	Pref.	Plasterboard	7.000	230
Leonardo	In-situ	Plaster	15.000	493
		KERMI [Italy]		
Xnet	In-situ	Plaster	10.800	355
		KME [Italy]		
Hypoplan	In-situ	Plaster	15.000	493
		PROTERINEX [Italy]		
Protenwand WKGM	Pref.	Plasterboard	14.000	460
Protenwand WKIP	In-situ	Plaster	15.000	493
		RDZ [Italy]		
B!Klimax	In-situ	Plaster	9.000	296

Table 2.3.2-2, Summary chart of European hydronic radiant wall thermal properties.

As can be appreciated from the chart, WEM 's solution reaches a tangible higher heat capacity and thermal inertia value, in the opinion of the author is the only solution between the ones exposed which may be considered as a medium-high thermal inertia solution.

When these values are compared with the thermal capacity of a traditional element, (e.g. an average hollow-brick division-wall (7-10cm), whose heat capacity would vary from 90.000-120.000J/m2) (ATECYR 2009), it can be appreciated that current heat capacity values hold by the products are much lower in comparison.

In the end, this lower heat capacity can be translated into a lower thermal inertia of the internal envelope, which may affect in terms of excessive overheating of the elements in long heating cycles, and a bad response to cyclic occupation periods (Scheatzle 2006).

This conclusion leads to the next chapter, which will study a medium-high thermal inertia radiant wall solution, *In-therm Klimavæg*.

2.3.3. IN-THERM KLIMAVÆG.

The following chapter will focus on the description of the specific product object of this research, In-Therm Klimavæg. As a brief situation, the product has been developed by the Danish company Dansk Miljø Enterprise (DME), and is currently commercialised in Denmark and the Nordic region

However, in order to protect the secrecy of the current patent and private information, just the commercial information available for any user have been directly mentioned (Dansk Miljø Enterprise 2003).

INTRODUCTION.

Following the previous descriptive summary made to the current main products, this solution may be labelled as a hydronic radiant wall panel element with a concrete matrix main layer, a PEX piping as heat exchanger and a rear XPE insulation layer.

As the main difference when compared the previously studied elements, it can be appreciated that the matrix layer material changes from a light construction product (such as plaster or MDF), to a higher density material (fibre-concrete) solution.

Even though this detail may not seem relevant in terms of performance at first sight, the election of a material with a higher heat capacity and density may lead to a solution with a greater thermal inertia per square meter, which may lead to a solution to the previously exposed problems.

COMPOSITION.

To describe briefly the element object of this study, a brief analysis of its constituent layers and elements have been carried out, all the exposed information is available at the manufacturers technical brochure (Dansk Miljø Enterprise 2003).

Starting from the concrete superficial layer, the available information shows a 10-12mm glass-fibre reinforced concrete coating, which is performed as a finishing surface either for direct application of paint or plastering.

The first insulation layer consists on a Polyurethane foam projected over the concrete back surface; the PU foam is moulded and fits to the concrete back layer embracing the pipes shape distortion created in the concrete back layer.

The piping circuit is constituted by a PEX Ø8mm continuous pipe, with a separation of 200mm between conducts.

The connexion between modules and heat distribution pipes can settled either on the upper or lower side of the element, forming a longitudinal skirting.

When installing the solution on a refurbishment case, a PIR-MW or EPS insulation board with variable thickness is installed, allowing the designer to reduce the wall U-value down to the required one. As stated by DME, this panels ranges from thicknesses from 50-100mm.

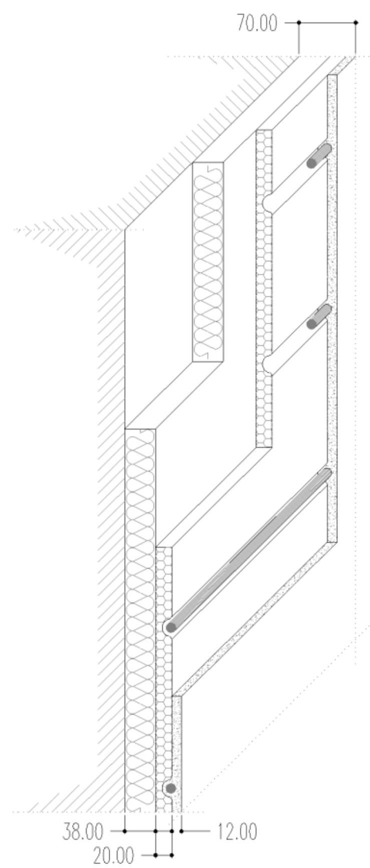

Figure 2.3.3-1, In-Therm Klimavæg module description.

The panel is installed by screwing to a resistant surface (existing walls in case of renovation) or an auxiliary structure in case of new building. Further information regarding the fixing system cannot be accessed openly and may not be released in this study, as is protected information from DME and is not relevant for the studied matter.

TECHNICAL SOLUTIONS.

Regarding the technical solutions available, the author will make a brief analysis showing the most interesting fields and applications exposed by the manufacturer.

Mentioning renovation of existing buildings, the manufacturer clearly focuses the application of its product on this field, especially in residential constructions. Technical information is focused on using the solution to insulate external walls, implementing a radiant heat solution simultaneously.

The solution has been studied for the implementation in different cases depending on the insulation level and age of the construction. A comparative analysis between *In-therm klimavæg* and traditional heating solutions is also exposed in the technical brochure, defending the thermal efficiency of the solution in comparison.

The following chart and diagram represent a study of the different layer temperatures on the installed element. These values belong to the study carried out by the producer DME, and can be accessed at the available technical brochure.(Dansk Miljø Enterprise 2003)

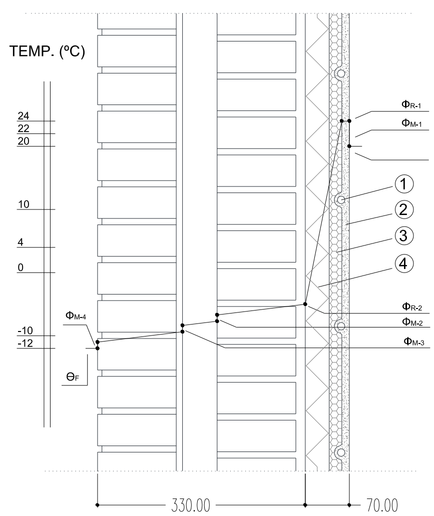

Figure 2.3.3-2, In-Therm Klimavæg module (temperatures and composition).

The studied solution is constituted by the following elements:

1- Casted in concrete PEX pipes.
2- Glass-fibres reinforced concrete (10-12 mm).
3- Polystyrene insulation board EPS 80 (20mm).
4- PIR Titan Slim Line (40mm).

The following temperatures values are shown in the chart.

Θ_I - Room temperature.
Θ_E - Outdoor temperature.
ϕ_{M-1} - Surface temperature on the internal wall surface.
ϕ_{M-2} - Surface temperature on the internal air chamber.
ϕ_{M-3} - Surface temperature on the external wall air chamber.
ϕ_{M-4} - Surface temperature in the surface of external wall.
ϕ_{R-1} - Transition-temperature, fibre-concrete / insulation.
ϕ_{R-2} - Transition-temperature, insulation / external wall.

The next chart includes the temperature evolution along the different layers of the element:

Symbol	Designation	Values
Θ_I	Room temperature	19_21ºC
ϕ_{M-1}	Surface temperature (Internal wall)	23_24 ºC
ϕ_{R-1}	Transition temperature	24_28ºC
ϕ_{R-2}	Transition temperature	-5_6 ºC
ϕ_{M-4}	Insulation surface temperature	-11.2 11.5 ºC
Θ_E	Outside temperature	-12ºC
Θ_F	Circuit-system temperature	Max: 35 ºC

Table 2.3.3-1, In-therm Klimavæg layers and temperatures.

As a brief summary for this study, it can be appreciated how the temperature evolution of the element, leaves the radiant matrix layer core at a temperature of 24-28 ºC. The surface temperature for the radiant element is 23-24 ºC, similar to the values studied previously for radiant wall applications. Moreover, in a general overview, the performance of the solution can be considered as similar to the previously studied systems.

The following chart summarizes the heat capacity and thermal inertia values per square meter of the element, as done with the previously studied products (section 2.3.2). For further information regarding the calculations, see (Appendix 2.3.)

Brand and product	Production	Matrix layer material	Heat Capacity (per m2) [J/(m2 ºK)]	Thermal Inertia (per m2) [W/(m2 ºK √s)]	Thermal Inertia [W/(m2 ºK √s)]
		DME [Denmark]			
In-therm Klimavæg	Pref.	Concrete	24.000	1.183	98.590

Table 2.3.3-2, In-therm Klimavæg summary chart.

Summarising the values showed in the previous chart, it could be appreciated that the heat capacity of the concrete layer in higher than the plaster ones, even though the thickness is lower. The thermal inertia of the element is even higher than the one achieved by WEM's solution, even though the heat capacity is lower, this is due to the high density of the concrete compared to clay and gypsum (section 2.3.2)

PRODUCT ANALYSIS.

Once analysed the main characteristics of *In-therm klimavæg*, the author will show a brief analysis, stating the main personal conclusions and outlooks gathered from the study.

Beginning with the intellectual development of the solution, and comparing with the actual research areas which mainly focus on software design and simulation solutions. The author identifies here a potential improvement area, in which de development of an informatics thermodynamic model may have an important place; it also shall be considered the integration with BIM allowing the implementation for designers.

Continuing the integration with renewable energy sources, the product represents a low-heating solution which is in the opinion of the author the actual and future trend in the matter of heat supply allowing the use of heat pumps, high performance boilers and even solar-thermal solutions.

As for the clear direction of the manufacturer towards building renovation sector, the author finds it an excellent choice, as this sector points to represent in future years an important market share in the European construction sector (Huber et al. 2011).

To finish with a brief comparison with the European competitors previously studied (section 2.3.2); the author would like to highlight two main points in terms of development in the industry.

- As stated previously, in the author's opinion, Italian manufacturers seem to have reached the most attractive commercial presentation of their products. Despite marketing analysis is by far not the expertise of the author, it has to be remarked that is a crucial aspect of a product that has to be cautiously studied and enhanced.
- Regarding the technical aspects of the different products, *In-therm klimavæg* belongs to the group of the higher thermal inertia and heat capacity elements. This property has a great distinguishing potential, giving the product the opportunity of filling a gap in the European market in terms of high thermal inertia solutions.
- The clear orientation of *In-therm klimavæg* to the refurbishment market, opens also a potential leading opportunity considering the technical aspects of the solution, which can be implemented in the

refurbishment process of old buildings without affecting in a great extent to the internal thermal inertia of the external envelope.

The main potentials of a high thermal inertia constructive element have been analysed in the following chapter of this research.

2.4. IN-SPACE SHORT-TERM TES IN RADIANT WALLS.

In this chapter, an introduction on the concept of heat storage and particularly in-space heat storage have been exposed. This introduction have been followed by the application of this concept to the studied solution, reaching the inception of the core idea of this research, which is the implementation of a latent-heat storage solution on the product. The chapter will conclude with a brief analysis of the current renewable heat supply solutions that can be boosted by combining with an in-space heat storage solution.

2.4.1. INTRODUCTION.

The concept of Thermal energy storage (TES) represents a widespread solution in heating and cooling applications in building industry. The following section will focus on bringing the reader closer to the existing concepts of TES according to the main theoretical currents (Cabeza 2012; Dincer 2004; Hasnain 1998), but also including the opinion of the author regarding the main classifications that could be done:

On a first approach to the concept and as an overview of the current research areas, the author would establish a first classification according to the physical reaction experienced by the heat storage media, leaving the following groups:

- Sensible Thermal Energy Storage (STES); where the energy is stored by increasing or lowering the temperature of a specific material or element. This storage could be subdivided among the different states of the matter (solid, liquid, gaseous).
- Latent Thermal Energy Storage (LTES); where an important part of the energy is stored taking profit of the phase change of a certain element or compound. A deeper subdivision could be done in relation to the phases intervening on the phase change process (solid-liquid, liquid-gas…)

As a second classification, not alternative but combinable with the previous one, the author would like to suggest a classification based on the disposition or constructive nature of the TES element, leaving the following groups

- Storage tank solutions; these systems would be based in a confined TES compound insulated from the exterior by a protection envelope. These solutions may use either solid, liquid or gaseous products as TES, and can combine STES or LTES compounds.
- Heat/cool sink solutions; in this case, the TES element would be usually an external medium separated from the internal ambient but devoid of a tangible insulation from the external ambient. These solutions usually take profit from natural resources such as ground (GSHP) or aquifers, but also from
- In-space solutions; this third group would embrace all TES solutions based on the use of constructive elements to store energy, having these elements usually a direct connection with the internal space in the building. The main idea is to give a “second use” to the main constructive elements of a building, usually by taking profit of high thermal inertia materials. The use of this solution can be considered in the opinion of the author the one that gets closer to the concept of passive construction.

To conclude this classification, the author would like to propose a third organisation depending on the time-constraint of the TES, by dividing these solutions into three main groups:

- Short-term TES; this group would be enclosed by the solutions in which the charge-discharge cycle takes place in a time-limit in the order of 0-12h, so the element can be considered as a thermal buffer more than as a TES solution ad-hoc.
- Medium-term TES; this second group would group the solutions in which the charge-discharge cycles take place in the order of hours to days, these elements can be considered as a proper TES solution and represent the larger and most developed solutions group.

- Long-term TES; or seasonal TES solutions, would include the systems focused on storing energy for long periods in the timespan of months, and are usually focused on taking profit of seasonal weather conditions being coupled with renewable systems such as solar thermal in combination usually with GSHP.

As previously exposed, the author will focus in this research in an in-space short-term TES solution, based on the combination of sensible and latent heat storage.

2.4.2. IN-SPACE SHORT-TERM HEAT STORAGE.

Once a general picture of the concepts in energy storage has been set, this chapter will study in more depth the concept of in-space heat storage applied to short-term TES solutions.

As a start point on the immersion of the concept of Short-term TES with In-space solutions, the author will set on a brief explanation of some important concepts directly related with this topic:

- Heat capacity (J $^{o}K^{-1}$). The physical quantity that specifies the amount of energy required to vary the temperature of a body by a given amount. The concept of heat capacity can be related to any dimension of the body: specific heat capacity (J/kgºK), volumetric heat capacity (J/m3ºK), or linear heat capacity (J/m º K).
- Thermal mass. This concept is considered as the equivalent to heat capacity, when used in construction and engineering. It can be referred also to any dimension of the element.
- Thermal inertia ($J\ m^{-2}\ K^{-1}\ s^{-1/2}$). This concept can be defined as a measure of the heat capacity of an element in relation with the velocity of the thermal wave that controls the surface temperature of the body. A higher thermal inertia represents a longer time of the body to reach thermal equilibrium with the environment.

2.4.3. POTENTIAL APPLICATIONS.

Once set the basic concepts this chapter will work with, the main application possibilities for an in-space short-term TES have been exposed. The author will divide these possibilities between two main groups:

Starting with temperature control applications. This group would integrate all the solutions oriented to control or balance the temperature of a space or element by giving to certain elements a high thermal inertia. The basic principle consist on storing the thermal energy during peak occupation or heat periods to release this energy during valley periods. This solution can be linked directly to a huge range of traditional constructive solutions, usually based on massive elements which collaborated passively in the indoor temperature control of the building by rising the thermal mass of the construction (Coch 1998).

Focusing now in current solutions, the use of high thermal inertia elements in building applications reaches a vast collection of fields. Going from overheating control in external elements as façades (Fallahi, Haghighat & Elsadi 2010) or in integrated solutions including (Orme, Palmer & Irving 2003; Scheatzle 2006). To indoor temperature balancing either in residential constructions (Kazanavičius et al. 2006) or in office buildings where these peaks tend to be more pronounced (Chowdhury, Rasul & Khan 2008; Pfafferott, Herkel & Wambsganß 2004).

Continuing with "proper" thermal energy storage applications. The combination of high thermal mass elements combined with heating and cooling solutions touches directly the field of radiant heating and cooling solutions explained previously (section 2.3.1). This combination obeys to the fact that the radiant element usually represents an extensive surface, and as usually, having a considerable mass can be used to store energy directly during short time periods.

The combination of these two technologies in the different radiant elements has been studied, such as in Athienitis & Chen (1993) where an electric floor heating solution with integrated thermal storage is designed and tested experimentally. Or in Olesen (2002) where an analysis of the thermal storage and regulation effect of concrete radiant floors has been developed, considering the most important design factors and studying the relation between thermal comfort and the floor temperature and thermal mass.

The implementation short-term TES in traditional radiant panels, such as wall and ceiling panels does not reaches sufficient notoriety to leave any track for the author during this research, so it could be concluded that may be still a slightly developed research field.

Once arrived at this point of this research, most part of the bibliography takes a common direction: the introduction of the concept of latent heat storage in constructive elements to increase their thermal mass, to use them either as passive temperature balancing elements or as short-term TES radiant elements (Tyagi & Buddhi 2007). Is at this instant, where the concept of phase change materials (PCM) comes on the scene: the combination of materials with its phase change point on a particular temperature with traditional solutions to increase radically the heat capacity of an element without varying its volume.

Furthermore, and due to the dynamic variation of the heat capacity of a PCM, this thermal mass will fluctuate depending on the temperature of the element, allowing the creation of new materials with a selective thermal mass(Zalba et al. 2003). In any case, the current development and main aspects of PCM technology related to in-space TES have been studied in more depth in the following chapter of this research (chapter 2.5).

2.4.4. CONSIDERED APPLICATION FIELDS.

Once reached the concepts of in-space short-term TES and enhancement of thermal capacity with PCM, and after observing a potential knowledge gap in the implementation of short-term TES in radiant wall elements, the author will propose which could be in his opinion, two interesting research fields in the matter in relation with new solutions:

The first considered option would be the enhancement of the thermal inertia of In-therm klimavæg radiant wall panel solution (chapter 2.3.3), in order to increase the thermal regulation effect of the solution, providing a second passive utility to the radiant panel. This concept would be based on maintaining a room comfort temperature by combining a PCM with its melting point in the order of 21-23ºC with the concrete layer of the element.

The second option would be oriented to the concept of TES for energy consumption balancing, deepening into the idea of using the radiant element as a TES buffer, and combine the solution with an intermittent heat supply in order to compensate this heat supply variation with the TES. Two main intermittent heat sources comes to the author’s mind:

The first one, a solar assisted heat pump system, which would vary the main source of supply from day to night according to the radiation variation, and also depending on the electricity price variation for the heat pump (Chwieduk 2012).

The second option, could be oriented to the field of air-air heat pumps or GSHP, and may consider the potential benefits of electric net metering, and the balancing of electricity consumption depending on the market price (Poullikkas 2013).

Once weighed the possibility of following any of this alternatives proposed, the author will continue this study following the research line related with TES in combination with renewable heat supplies. This decision has been taken considering the current development of net metering in the Danish market, with important research lines in the area of energy balancing solutions and smart metering (Zavada et al. 2012). The following section of this chapter will go in more depth into these concepts and the combination with In-therm Klimavæg solution.

2.4.5. IN-THERM KLIMAVÆG AND RENEWABLE HEAT SUPPLIES.

Once exposed the two main development opportunities found by the author, and selected the study of the combination of In-therm Klimavæg as TES and an intermittent renewable heat solution. This section of the study will focus on giving a more accurate picture of the current possibilities for the two renewable options proposed in the Danish market, and will end by selecting one of these two branches for the further development of the research.

SOLAR ASSISTED HEAT-PUMPS.

Starting with the implementation of a solar assisted heat pump, several research lines may be found regarding this concept, but in Chwieduk (2012) a complete and understandable general overview may be found. Despite the current development of the technology in the Danish market, especially in the area of central solar heating plants with seasonal energy storage, the particular climatology of Denmark during winter has to be considered, and the implementation of a SAHP with short-term TES may be considered feasible unless the system is oversized (Heller 2000).

NET METTERING & HEAT PUMPS.

In the other hand, the combination of a short-term TES solution with a heat pump heating system may lead to a successful solution if the concept of smart metering gets into the picture. The analysis of this combination does not limit to the use of a specific heat pump system, and any solution from air-water heat pumps to water-water GSHP could be implemented.

The main concept to take into account in this coupling is the concept of net metering, where the user would buy and sell electricity to the net at a variable price depending on the electricity market price set by offer and demand (Darby 2010). This solution has led to an important research field in the Danish electricity market, and the design of intelligent buy-sell devices is starting to take off, as an example the Intelligent Electricity Broker project being developed by two Danish Universities (Danske Klimaministeriet, Danske Energiministeriet & Danske Bygningsministeriet 2013; Zavada et al. 2012).

The combination of a smart metering solution with a radiant element with a TES lag of 2-4h may lead to important savings in the final electricity bill of the consumer, leaving the opportunity of reducing consumption during peaks hours, and compensating these with the consumption of electricity during valley hours (Zavada et al. 2012).

Due to the implementation flexibility that gives this solution, and the current development potential of smart metering in the Danish market (Danske Klimaministeriet, Danske Energiministeriet & Danske Bygningsministeriet 2013).

The author will study the rise of the heat capacity of the previously exposed radiant-wall solution oriented to the combination with Smart Metering solutions to optimize the electricity costs of the final user. Considering the extent of this report, the author will not get into deep details of the heat pump system, and will focus on the TES concept. A deeper study of electricity costs and savings potential have been carried out in further chapters of this study (Chapter 3.4).

2.5. MICROENCAPSULATED PCM.

During the previous analysis on the area of short-term heat storage, the concepts of thermal inertia and heat capacity of a solid element have been explained. The following section of this chapter has been related to the idea of rising the heat capacity of a solid material without increasing its volume but introducing the physical concept of latent heat storage, described in the previous section.

2.5.1. PHASE CHANGE MATERIALS (PCM).

As a summarized definition of Phase Change Material as an engineering concept in the construction field, is any substance that can be used to store energy temporary by using the energy required to change its phase (latent heat).

Narrowing the concept to the field of solid building materials such as concrete, these substances absorb and release energy during their melting /solidification phase change. (Zalba et al. 2003). Moreover, in Zalba et al. (2003) the main groups of materials that have been investigated for this purpose with their physical and chemical properties can be found.

This research will focus on paraffin-based compounds with melting points ranging from 4 to 70ºC, due to their high chemical stability and degree of implementation in the market (Zalba et al. 2003). The second main group of compounds would be the one grouping hydrated-salts, these compounds have melting points ranging from -1 to 100ºC, with higher heat storage capacity compared to paraffin bases but a greater chemical and volumetric instability (Zalba et al. 2003). Further compound bases can be found in the market and research filed, such as fatty acids, polyglycols, eutectic solutions and oils; nevertheless their current technical development oriented to construction industry is less pronounced compared to the previous exposed groups (Zalba et al. 2003).

Going back to paraffin-based compounds, these products have been studied previously as a raw material directly combined in the admixture, nevertheless problems regarding exudation and flammability were found (Lee & Choi 1998). In Hawes & Feldman (1992) a recommendation on using a encapsulation to avoid the exudation effect with the resultant reduction of thermal properties of the material is done.

Current researches divide the encapsulation of paraffin-based PCMs in three main groups (Salunkhe & Shembekar 2012):

Macro-encapsulated Phase Change Materials (ePCM), these encapsulation solutions are based in small to large sized containers (>1mm), and are usually combined with hydrated salt based compounds.
Several researches have been conducted in this field related to the implementation of this solution in construction as single elements or parts of complex installations (Wang, Zhang & Wang 2009), (Rady et al. 2009), and (Zheng et al. 2013).

Concerning the commercialization of these products, European producers such as the Swedish company Climator (2013), the German Rubitherm (2013a), or the British PCM Products (2013) have made an important bet in relation with macro-encapsulated hydrated-salt products, and paraffin mPCMs also in the case of Rubitherm©.

Micro-encapsulated Phase Change Materials (mPCM), these encapsulation solutions are based on small to micro capsules (1-1000µm), the use of micro encapsulations is directly related with paraffin-based compounds due to the great chemical stability they offer (Zhao & Zhang 2011).

This encapsulation solution has been studied in more depth in the following section of this chapter (chapter 2.5.2).

Nano-encapsulated Phase Change Materials (nPCM), these encapsulation solutions are based on the use of nano-capsules (1-1000nm), this technology is still in experimental phase and several projects are being conducted aiming the implementation of this technology into industrialized products.

Several researches have been conducted following this line, like in Fang et al. (2008), Dong & Shuo (2009) and Zhang, Bon & Zhao (2012) where three studes of different nPCM emulsions are carried out, reaching better thermal capacities compared with mPCM. Similar researches have been conducted also aiming to reach new nPCM compounds to be implemented in miniemulsions, with encouraging results (Fuensanta et al.) (Wu et al. 2011). These researches are opening a totally new technological field, where PCM could be implemented as heat-transport fluid increasing the heat storage capacity of heating and cooling installations with important reductions in storage unit's dimensions.

2.5.2. MICROENCAPSULATED PHASE CHANGE MATERIALS (mPCM).

As previously exposed, microencapsulation solutions have been the studied in more depth in this section, since it has been the product type used to conduct the theoretical and empirical research in this work.

Furthermore, considering the development timeline in PCM technology, encapsulation solutions have been evolving from macroencapsulations to nanoencapsulation, and mPCM can be assumed as the most recent technology really applicable to construction industry, considering the early development stage of nPCM (Tyagi & Buddhi 2007).

GENERAL DESCRIPTION.

As previously explained, microencapsulation solutions gather particle sizes ranging from 1-1000μm, usually gathering paraffin PCM encapsulated by polymeric dispersions.

PARAFFIN-BASED MPCM PRODUCTS.

In Zhao & Zhang (2011) a general overview of the different microencapsulation and production methods is presented. In this overview, encapsulation solutions are divided among core-shell models where the encapsulation represents an external layer or layers that covers the PCM and matrix models, where the encapsulation consists on a crystalized matrix combined with the PCM. Further researches may be found in this area, either in the development of solid products (Qiu et al. 2013; Sarı, Alkan & Karaipekli 2010), and liquid dispersions and emulsions (Delgado, Lázaro, Mazo & Zalba 2012).

In relation with the main properties of paraffin-based mPCM, the author would like to highlight some significant characteristics present in this product range, in accordance with the overviews given by Zhao & Zhang (2011) and Zalba et al. (2003):

- Mechanically resistant material. Due to the small diameter of the particles and elastic behaviour of the polymeric encapsulations, mechanical efforts experimented as a compound of a resistant matrix (concrete, plaster, polymers) do not break the particles but deform them, creating a virtually nor destructible product with a plastic behaviour against mechanical efforts.
- High latent heat. As paraffin-based products, mPCMs reach latent heat values ranging from 130-170 kJ/kg, with a lower specific heat (from 1.400-1.800 kJ/kgºC).
- Low conductivity. Considering that the main constituent compound of mPCMs is paraffin, the thermal conductivity of the material does not reach high values, in the range of 0,130-0,300 W/mºC.
- Wide temperature range. Considering the design flexibility when dealing with paraffin, the
- Low density. In accordance to the main compound properties, the density of mPCMs usually ranges from 900-1100 kg/m3, which makes it a material usually less dense than water with a low bulk density.

- Fire behaviour. According to its reduced particle size and polymeric-paraffin nature, mPCMs in bulk state can be considered as highly flammable, even though when casted in a stable matrix this issue is totally avoided.

COMERCIALIZATION AND EUROPEAN MANUFACTURERS.

Once enlisted the main characteristics of this product range, and as this research is focused on the commercial implementation of PCM technology in an existing product in Denmark. The study will focus on commercialized mPCM products in the European Union and current researches related to direct implementation of this technology.

As the main European mPCM producers, two world-leading companies in microencapsulation technology may be clearly identified.

The first one, the previously mentioned Rubitherm©. The German Rubitherm© represents in the opinion of the author one of the largest PCM world producers, as previously stated this manufacturer produces PCM based on hydrated salts and paraffin with different macroencapsulation solutions. In another product line, Rubitherm© produces microencapsulated paraffin based products under the product line PX, this product line counts with a wide melting point range from 10ºC to 82ºC, including the possibility of including products from their raw material line RT. This product line reaches heat capacities in the order of 80-100kJ/k in the temperature range of (10-30ºC), with a particle size of 0,1-0,5mm (Rubitherm 2013a).

As the second main producer in the European market, BASF with Micronal project can be clearly stated as an important agent. BASF Micronal offers a product line based on paraffin with three melting points groups (21 ºC, 23 ºC, 27ºC), with two different presentations of the product. On one hand a water suspension line with a mPCM concentration close to 50% and a particle size of 2-20μm, and on the other hand a powder format with a greater particle size in the order of 0.1-0.3mm. This product line accounts with a heat capacity in the order of 125-145kJ/kg in the temperature range of (10-30ºC) (BASF - Micronal 2010).

MICROENCAPSULATED PCM IN BUILDING APPLICATIONS.

In this section of the chapter, the main research fields related with the implementation of mPCMs in construction industry has been analysed, offering a background to the reader regarding the current background in the area.

To start with, the author will focus on the academic research area. In Baetens, Jelle & Gustavsen (2010) and Tyagi et al. (2011) a general overview of the application of PCMs in construction industry may be found with the main research fields, while in Tyagi et al. (2011) a review focused in the mPCM technology for construction industry can be found. In any case, the author will give his own overview of the current development of the microencapsulation technology in the main research branches:

MATHEMATICAL MODELLING.

To start with, in the modelling field several research lines may be found. Even though, as stated in Dutil et al. (2012) there is a lack of standardization in the matter, which leads to a great impediment when assessing and comparing results from different researches. In any case, works in the numerical modelling field may show the reader the current knowledge potential and implementation level in simulation software, such as BSim (Rose et al. 2009), or mathematical finite elements analysis methods (Derradji et al. 2013), which open a great development field for commercial products and its corresponding testing and simulation process.

INTEGRATION WITH BUILDING FACILITES.

Continuing with the development of integration with building facilities, the combination of mPCM slurries in hydronic and liquid storage circuits has been studied in a great depth as may be appreciated in the review carried out in Youssef et al. (2013). Two important studies related to the direct use of mPCM slurries as a TES fluid shall be remarked by the author: In Delgado, Lázaro, Mazo, Marín, et al. (2012) a satisfactory experimental analysis using a 10% mPCM concentration was carried out with a performance increase in the systems close to 25%. And in Zhang, Rao, et al. (2012) a study of the natural convection in storage tanks was experimented also with positive heat transfer results. Further studies in the order of numerical simulation may be found, showing a profound interest in the technology by the scientific community (Chen et al. 2008; Song, Liao & Shen 2013; Song et al. 2013), in any case this field are should be studied in more depth in other context more related with fluid physics. To finish with, a direct application of mPCM slurries to nocturnal radiative cooling has been studied in Zhang & Niu (2012), and an application to solar energy heating solutions in Huang et al. (2011). The results obtained in these works can be considered as a successful implementation of mPCM slurries into HVAC solutions, and should encourage HVAC industry to invest in the future development of this technology.

INTEGRATION IN CONSTRUCTION PRODUCTS.

When research lines turn into the direction of construction products, the combination of mPCM in gypsum products takes a clear leading in comparison with other binding base materials (cement, polymers, clay, wood). In this field, a strong knowledge basis in relation to the effect of these compounds in plaster admixtures can be found and a successful characterization process of the main thermal properties has been achieved (Su et al. 2012; Toppi & Mazzarella 2013). Once the behaviour of mPCM in plaster admixtures has been fixed in an acceptable extent, most research works are currently focusing on the properties of plasterboard solutions usually oriented to retrofitting industry (Eddhahak-Ouni, Colin & Bruneau 2013; Oliver, Neila & García 2010; Rodriguez-Ubinas et al. 2013; Zhang, Xu, et al. 2012).

Focusing the sight of the reader to the integration of mPCM into cementitious materials, the comparison work carried out on Barreneche et al. (2013), between gypsum and cementitious mixes incorporating mPCM showed a great potential in the development of mPCM enhanced cementitious products in terms of greater conductivities and thermal inertias when compared with gypsum. This research area has been studied in more depth in the following chapter (chapter 2.6).

Further isolated applied research areas may be found in the area of implementation in construction products, as in the work of Castellón et al. (2010) where a metallic sandwich panel was enhanced with mPCM comparing the effect of the addition in the different layers of the panel.

Following with the combination of mPCM in other construction materials, in Jeong et al. (2012) the enhancement of a wood-based flooring was studied combining Rubitherm© RT31 with the epoxy adhesive, showing a moderate thermal mass improvement. Continuing in the area of wooden solutions, in de Gracia et al. (2011) a mPCM enhanced wooden panel was designed and tested using a one-dimensional heat flow under controlled environment test method, which would be interesting for validation of numerical methods due to its flexibility.

When broadening the scope to direct implementation in constructive solutions, in Castell et al. (2009) and Castell et al. (2010), an experimental research related to the effect of macro and microencapsulated PCM (Rubitherm© RT27, SP25) in the envelope of traditional constructive solutions in Spain was carried out showing a great potential in the area of passive cooling applications. In the area of LCA, a reduction of the overall environmental impact by over a 10% was observed in a Spanish case study conducted in de Gracia et al. (2010).

MACROSCALE OVERVIEW.

Broadening the sight to the macroscale, a great implementation potential for mPCM can be identified in the European market, reaching not just a tech-effective but also a cost-effective solution, with primary energy demand reductions ranging from 15-32% depending on the country of study (Warsaw, Frankfurt, Paris, London, Rome and Seville), as shown in the residential house study done in Origgi (2006).

BASF MICRONAL IN CONSTRUCTION INDUSTRY.

Once established a general overview of the current academic development of mPCM in construction, and as this paper is focused on the commercial implementation of mPCM-enhanced products, the author will focus on the commercial development of mPCM technology, focusing on BASF Micronal product line (BASF - Micronal 2010).

The following commercial products directed to the final user have been selected:

- Rigips Saint-Gobain (Switzerland) – Alba Balance (Rigips Saint-Gobain 2013).
- National Gypsum (USA) – Thermal Core (National Gypsum 2013).
- Weber Saint-Gobain (Germany) – Mur Clima 26 (Weber Saint-Gobain 2013).
- Grupa CSV (Poland) – Klima 544 (Grupa CSV 2013).
- Scheicher (Austria) – K.Wand (Scheicherwand 2013).
- EBB (UK) – Eco Building Boards (EBB 2013).
- Lebast Lehmbaustoffe (Germany) – Lehmbauplatte (Lebast Lehmbaustoffe 2013).
- Armstrong (UK) – Cool Zone (Armstrong 2013).
- Monodraught (UK) – Cool Phase (Monodraught 2013).

In the following chart, the main characteristics of the product lines incorporating BASF Micronal have been enlisted.

Brand and product	Product industry	Solution type	Base product	Active / Passive
Rigips Saint-Gobain [Switzerland]				
Alba Balance	Plasterboard	Prefabricated	Gypsum	Passive
National Gypsum [USA]				
Thermal Core	Plasterboard	Prefabricated	Gypsum	Passive
Weber Saint-Gobain [Germany]				
Mur Clima 26	Plaster dry-mix	In-situ	Gypsum	Passive
Grupa CSV [Poland]				
Klima 544 TYNK	Cement dry-mix	In-situ	Cement + Lime	Passive
Scheicher [Austria]				
K.Wand	Clay-board	Prefabricated	Clay	Passive
EBB [UK]				
Eco Building Board	Clay-board	Prefabricated	Clay	Passive
Eco Building Board	Clay-board (Radiant)	Prefabricated	Clay (Electric)	Active / Passive
Eco Building Board	Clay-board (Radiant)	Prefabricated	Clay (Hydronic)	Active / Passive
Lebast Lehmbaustoffe [Germany]				
Lehmbauplatte	Clay-board	Prefabricated	Clay	Passive
Lehmbauplatte	Clay-board (Radiant)	Prefabricated	Clay (Electric)	Active / Passive
Lehmbauplatte	Clay-board (Radiant)	Prefabricated	Clay (Hydronic)	Active / Passive
Armstrong [UK]				
Cool Zone	Ceiling panel	Prefabricated	Metal + Plaster	Passive
Monodraught [UK]				
Cool Zone	Cooling Unit	Mechanical	HVAC Unit	Active

Table 2.5.2-1, BASF Micronal in construction products.

As a conclusion from this section, it can be appreciated how the thermal improvement of their products represents an important side for certain powerful European producers such as Saint-Gobain or Armstrong, and ever the American National Gypsum. In the other side, some smaller producers have reached highly developed products as in the case of Monodraught. In relation to clay products lines as Scheicher's, and specially EBB and Lebast, a close relationship with the final aim of this research can be clearly identified, and these producers may be considered clear competitors in the area of wall-radiant heating with in-space heat storage.

As an overall conclusion, a clear involvement of European construction industry in mPCM technology can be appreciated, which leads to think that may be a potential area in present and future construction industry.

2.6. mPCM IN CEMENTITIOUS ADMIXTURES.

As previously mentioned, the addition of mPCM in concrete admixtures has a considerable relevance in the research field, despite its low implementation level in the construction industry as appreciated in previous chapters (chapter 2.5.2).

PCM IN CONCRETE ADMIXTURES (NON-MICROENCAPSULATED SOLUTIONS).

To start with, the author would like to highlight two important research line in relation with the addition of PCM in concrete admixtures, even though the concept of microencapsulation is not contemplated. As the first one, the study regarding the impregnation of paraffin to porous lightweight aggregates, reaching PCM proportions up to 350kg per cubic meter of concrete (Bentz & Turpin 2007; Zhang et al. 2004). The second one is related to the production of a Paraffin enhanced silica fume composite using a vacuum impregnation method, the final product showed a great implementation potential in the concrete industry (Jeong et al. 2013). In any case, as these two solutions are not commercially available for concrete industry, except in the case of Rubitherm© GR which cannot be considered as suitable as a concrete aggregate. Therefore the author cannot considerate them for the empirical research conducted, even the potential benefits are considerable.

MPCM IN CONCRETE & MORTAR ADMIXTURES.

Continuing with researches in the area of microencapsulation technology, the author will now focus on projects integrating mPCM in cementitious admixtures (concrete, mortar, and cement paste); it has been found that all the studied projects have focused in a particular mPCM commercial product when choosing in the available market options, BASF Micronal.

MPCM-CONCETE FOR PASSIVE OVERHEATING PROTECTION AND HEAT BALANCING.

Starting with the implementation of mPCMs in external constructive elements, in (Cabeza et al. 2007; Castellón et al. 2007) a combined research under the European MOPCON project was conducted, in order to develop a high thermal inertia concrete panel enhanced with a 5%w/w Micronal (melting point 26ºC). The concrete reached compression resistances of 25MPa and tensile strengths of 6MPa, which made it suitable for structural purposes. The project reached interesting conclusions in the area of overheating protection and thermal energy balancing, but also encouraging results in the area of high resistances concrete with mPCM.

MPCM-CONCETE FOR SOLAR PASSIVE HEATING IN FLOORS.

Following with the concept of in-space TES, in Entrop, Brouwers & Reinders (2011) an experimental research studying the thermal storage capacity of a concrete floor with a 5%w/w Micronal DS5008X (melting point 23ºC) was studied under a passive-solar solution based on a vertical glazed surface. The study found a greater efficiency potential for thin concrete layers (below 50mm); due to a faster load/unload process during the cycles.

This study finds a strong support in the mPCM-mortar design and characterization research conducted in Hunger et al. (2009), where a 5%w/w Micronal DS5008X (melting point 23ºC) is studied from the design, mechanical, rheological, and thermal point of view. This study has been used by the author in the further development of this project due to its strong background and methodology used (chapter 3.2).

MPCM-CONCETE FOR ACTIVE AND PASSIVE COOLING IN SLABS.

To finish with, the author will highlight which has been the initial basis for the development of the mortar-mix design in this project (chapter 3.2). This research line conducted, studied the concept of using a prefabricated concrete slab element with an integrated heating/cooling system (Spæncom 2005), combined with a latent heat storage material as BASF Micronal DS 5040X (melting point 23ºC) (Danish Technological Institute 2013).

The research is initiated in Pomianowski, Heiselberg & Jensen (2011) with a numerical simulation of the performance of the PCM enhanced deck using COMSOL Multiphysics as simulation software with a 2D model. This simulation studies the behaviour of a concrete-PCM layer placed below the slab element, using four different thicknesses (1-4cm) and Micronal concentrations in the range of (1-4-6-10-15-20-40%w/w). The study takes into consideration the implementation of the solution in two different scenarios, the first one using the slab element as a passive solution, the second one as an active hydronic cooling solution. The study concluded with very positive results, showing an optimum concrete-PCM layer of 2-3cm attached to the bottom surface of the element, with an important role on the surface heat transfer for the thermal mass activation of the deck element.

Considering the positive results achieved in the previous research, a further experimental investigation is conducted in Pomianowski, Heiselberg & Jensen (2012), where a characterization of 6 different mortar admixtures (0-1-2-4-6%w/w PCM) was carried out, determining its heat capacity and thermal conductivity using a modified Hot Plate apparatus (Pomianowski et al. 2011). The paper compares the theoretical results previously obtained with the experimental ones for the four different thicknesses (1-4cm), showing a reduction on the cooling capacity of the final solution when using PCM, even though the thermal capacity and thermal inertia of the element in the melting point range was demonstrated considerably higher in the experimental results.

In a further development of the research line (Pomianowski, Heiselberg & Jensen 2013), a full-scale modelling is carried out using different tiles surface areas (grooved finishing) with area factors of (1-2-3 as flat and two extended areas). The new full-scale solution was tested in five decks, covered with 1200x550x30mm tiles using a fixed Micronal DS 5040X addition of 6%w/w. The experiment consisted on a large-scale modified hot-plate apparatus which tested the full scale elements, a previous numerical simulation was carried out. The experimental setup showed a slight improvement in grooved surfaces, and a lack of performance improvement when using mPCM in an active cooling solution if the final purpose is activating a second element (concrete deck).

Despite the discouraging results from this research line main objective, the author has found a great improvement and application potential if this knowledge is applied in light concrete wall elements. The development of a proper concrete with mPCM ratios close to 7-10%w/w may open a new concept of high thermal inertia radiant elements. Due to the great potential and relation of this research with the present study, this project has been studied in more depth in further sections (Chapter **¡Error! No se encuentra el origen de la eferencia.**).

SUMMARY.

As a summary of the previous information, it can be concluded that the increase of the heat capacity and thermal inertia of a cementitious admixture is perfectly doable, and workable admixtures can be reached with Micronal proportions up to 6%w/w. The main complications faced by all the authors were usually regarding concrete production and conductivity reductions in the final admixtures. It can be appreciated that final resistances close to 25MPa were troublesome to be reached due to the weakening effect of the mPCM, also workability problems were found due to the high filler content required when dealing with high mPCM proportions (close to 15% in volume basis).

Facing these main problems, the author will focus the empirical part of this research on studying a mortar mix with a high mPCM ratio (7%w/w), and looking for mechanical resistances over 30MPa, which can be assumed as a realistic and acceptable limit for a non-structural prefabricated element layer.

2.7. mPCM IN RADIANT HEATING SOLUTIONS.

Once established which would be the main area of this research, the author will give a final overview considering the implementation level of mPCM in radiant heating solutions, focusing specially in prefabricated radiant-walls.

2.7.1. RADIANT FLOORS ENHANCED WITH mPCM.

Even though the field of radiant floors is not the main topic of this research, the greater development in PCM technology in this area and the technical similarities makes an interesting field to set on an overview.

Several related research lines can be found in the area of PCM enhanced floor heating solutions, as reviewed by Jisoo et al. (2010). In the area of alternative solutions to concrete slabs, in Ansuini et al. (2011) a lightweight radiant floor heating solution is proposed using Rubitherm© GR27 as thermal mass layer, reaching a thermal buffer of 2-3 days. As an overview in the simulation field, in Jin & Zhang (2011) a double layer PCM floor heating and cooling system is modelled applying the concept of heat & cool storage in the same element.

As a close approach to the taken in this research, in (Mazo et al. 2012) a PCM enhanced radiant floor is integrated into EnergyPlus simulation software and analysed with the idea of developing an off-peak electricity consumption system, coupling the radiant floor with a heat-pump and using this first one as a thermal buffer. A total energy consumption economic savings of 18% was achieved, considering the use of a night electric tariff (electric consumption limited from 22-12h). This concept reached in this work gets really close to the net-metering solution the author will study in further sections of this research (chapter3.4).

In the area of commercial products, an underfloor heating system based on Rubitherm® GR41 is currently commercialized, combining the solution with an electric heating mat which can be combined with an night electric tariff to reduce electricity costs (Rubitherm 2013b). A similar approach is taken in Net Green Solar (2013), where a solar floor heating solution is proposed, the concept integrates the use of vacuum-pipes solar collectors combined with an in-space TES based on Rubitherm® GR41 embedded on a mortar floor heating element.

2.7.2. PREFABRICATED RADIANT WALLS ENHANCED with mPCM.

Once given an overview of the current development in microencapsulation technology in radiant floors, the author will get into deeper research regarding PCM technology in radiant wall solutions.

Starting with the academic field, a slight development in this area can be found, considering that most works do not consider microencapsulation technology and usually focus in macroencapsulation or theoretical simulations, as in Shi Guan (2009) where a numerical model of a radiant wall incorporating PCM is studied. Further researches focus on passive solutions, as in Evers, Medina & Fang (2010) where a frame wall insulation is enhanced with paraffin and hydrated salts and tested using a dynamic wall simulator. Further academic research in the area of radiant wall solutions does not seems to be available up to the date.

When the research is focused on the commercial side, two European producers previously named (BASF Micronal in construction industry. page 34) can be identified.

The solution proposed by Lebast Lehmbaustoffe (2013) and EBB (2013) combines a 22mm patented clayboard on modules of 1250x625mm screwed on a lightwall structure (metallic, wooden). The solution has been combined with BASF Micronal in a proportion of 3kg/m2, with the melting point set on 26ºC the panel's high thermal inertia prevents overheating and keeps a stable radiant temperature during winter, in summer the panel's high inertia could be used to absorb overheat during the day and release it during night hours (nightly ventilation).

This product line is designed for new construction and retrofitting projects, and aims to be as flexible as possible, being sold either as a radiant ceiling solution.

No further commercial development for this technology has been found in the European market, the presence of a clear development patent in the prefabrication market into high-inertia products can be identified considering the information gathered in previous sections of this research (BASF Micronal in construction industry. page 34).

Potential leading competitors can be found in the area of wall-radiant technology, which leads the author to contemplate an important development potential for the studied product In-Therm Klimavæg in this area.

In further sections of this research, the concept of enhancing In-Therm Klimavæg's concrete layer with BASF Micronal has been studied, focusing on the smart-metering concept previously explained (chapter 3.3).

3. THEORETICAL RESEARCH.

The current section of this study will focus on gather and calculate the essential aspects required to carry on with the empirical research proposed. These calculations have moreover an analytical purpose, and take part into the theoretical feasibility study of the solution proposed.

Considering the aim settled previously in this report, this section will analyse the following areas and concepts of the idea in order no assess the feasibility of the potential development project.

1. Building Energetic analysis. In this chapter of the study, the author will analyse an In-Therm Klimavæg existing project in Denmark, this study has been used as a realistic support for the assumptions taken when focusing on TES.
2. BASF Micronal in concrete admixtures. This chapter has been focused on analysing the thermal, mechanical and rheological properties of BASF Micronal DS 5040X in concrete admixtures. Due to the limitations of this research, a theoretical study based on the available literature has been made.
3. Theoretical thermal properties analysis. In this chapter, the results obtained in sections 1 (building energetic analysis) and 2 (BASF Micronal in concrete admixtures) have been combined, and the energy storage potential of the solution has been studied.
4. Electricity costs analysis. The purpose of this chapter is to analyse briefly the electricity price fluctuation in Denmark. The analysis will consider a scenario with a smart metering installation, which will turn on the heating system (heat pump) depending on the electricity price.
5. In-Therm Klimavæg concrete properties. The main objective of this chapter is the analysis and understanding of the main properties regarding In-Therm Klimavæg concrete layer, this study will serve as a basis when developing the concrete dosage and experimental part of this research.

Once these points are fulfilled, the theoretical feasibility of the project (Implement mPCM in concrete radiant wall elements) will be analysed in the conclusion of the research (Section 6). The results obtained have been compared with the studied literature in the state of the art (Section 0). As a final step, the theoretical properties of the concrete have been validated in the experimental research section (Section 4).

3.1. BUILDING ENERGETIC ANALYSIS.

In this chapter, a brief energetic analysis form an existing In-therm klimavæg refurbishment project has been carried out. The aim of this chapter is to set the real heat demand of an In-Therm Klimavæg project. After fixing this data, the heat storage requirements for the mPCM enhanced concrete layer proposed in this study have been calculated.

The present script consists on a summary of the conclusions reached from the study performed in the Appendix 3.1. of this research. For further details and a complete explanation see (Appendix 3.1.).

3.1.1. HEATING DEGREE DAYS (HDD) ANALYSIS.

Along the present section, the summarised results obtained from the HDD analysis performed in (Appendix 3.1.) will be exposed. The following graphics show the selected scenario for the TES study performed in (section 3.3) of this research.

The next chart includes the HDD variations on a weekly basis, considering the average values for the year 2012 (including the end of 2011 and start of 1213).

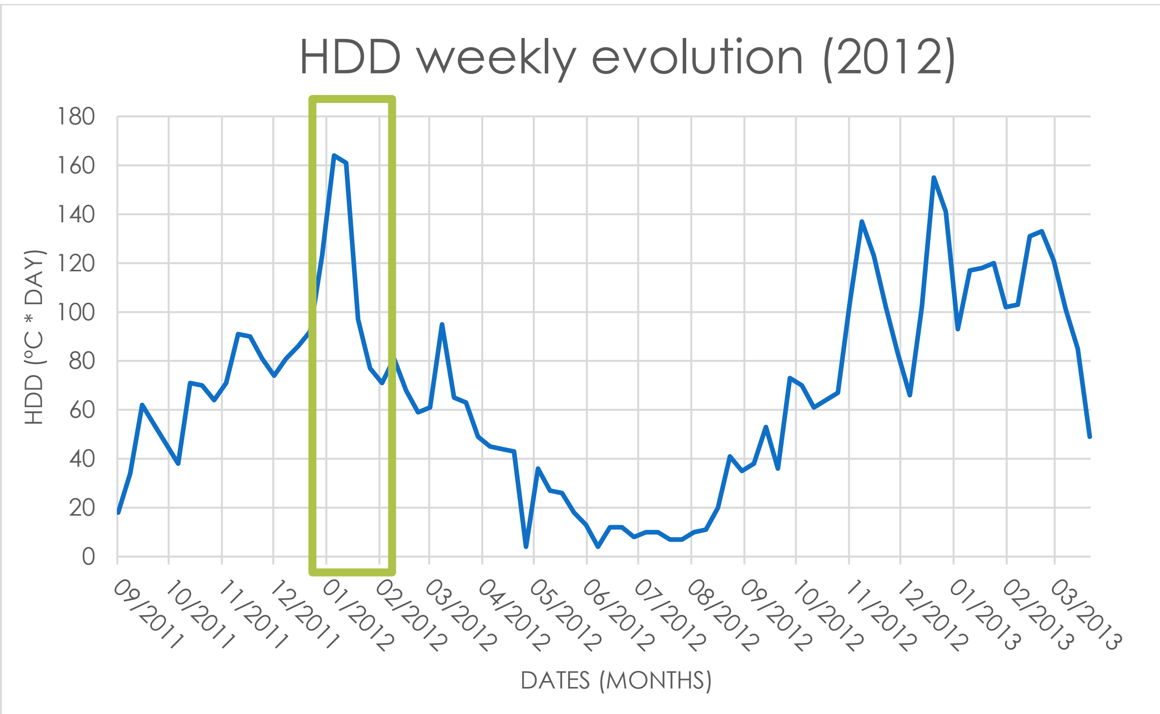

Figure 3.1.1-1, HDD weekly evolution (2012).

Concluding the information present in the previous graphic, the month of January has been chosen as the most adverse month regarding thermal loads. For the present study, this scenario (Scenario 3 MAM) has been selected as the thermal loads basis in order to size the TES system.

The chart below follows with an analysis of the HDD loads by ranges, linking the thermal loads with the average HDD in the selected range.

In the chart below, an analysis of the distribution of the HDD along 5ºC ranges is shown. This division among ranges allows a better comprehension of the demand distribution and heating needs along the year.

SCENARIOS	DAYS	DAYS %	DAYS C%	HDD	HDD %	HDD C%	HDD AVERAGE
Range [0-5)	130	36%	36%	250,5	8%	8%	1,927
Range [5-10)	110	30%	66%	840,0	28%	37%	7,636
Range [10-15)	78	21%	87%	941,1	32%	69%	12,065
Range [15-20)	**30**	**8%**	**95%**	**506,5**	**17%**	**86%**	**16,883**
Range [20-25)	12	3%	98%	262,2	9%	95%	21,850
Range [25-n)	6	2%	100%	161,3	5%	100%	26,883
TOTAL	366			2961,6			8,092

Table 3.1.1-1, HDD analysis by ranges (2012)

The range of 15-20ºC has been selected as the studied range, according to the hypothesis set on the appendix study (Appendix 3.1.). This range can be linked to the HDD values reached in the most adverse month scenario proposed (Scenario 3 MAM).

3.1.2. IN-THERM KLIMAVÆG TES NEEDS.

The present section includes the summary chart from the thermal needs estimation according to the previous HDD analysis and the energy consumption records available from the original project (Appendix 3.1.)

SCENARIO	ENERGY NEEDS PER HOUR (KWH)	ENERGY STORAGE PER HOUR (KWH/M3)	ENERGY STORAGE PER HOUR (KWH/M2)
Most adverse day	5,07	5,788	422,500
Most adverse week	4,53	5,171	377,500
Most adverse month	**2,75**	**3,139**	**229,167**
Most adverse trimester	2,72	3,105	226,667
Most adverse semester	2,25	2,568	187,500
Yearly average	1,42	1,621	118,333

Table 3.1.2-1, In-Therm Klimavæg project, energy storage needs.

The energy needs per hour and the TES requirements per hour for the different scenarios proposed, will be used in the following sections (Section 3.3) for the estimation of the TES time-lag potential (Hours of service) of the PCM solution proposed in this research.

3.2. BASF MICRONAL IN CONCRETE ADMIXTURES.

In the following section, an analysis the thermal and physical properties from BASF Micronall DS-5038X has been carried out. A previous introduction to BASF Micronal product range has been made in (Chapter 2.5.2).

The present summary is focused on the conclusions reached from the study performed in the Appendix 3.2. of this research. For further details and a complete explanation, see (Appendix 3.2.).

3.2.1. BASF MICRONAL DS-5038X.

The following chart enlists the main thermal and physical properties of the product BASF Micronal DS-5038X.

PROPERTY	VALUE
Peak melting temperature	25 ºC
Peak crystallization temperature	24 ºC
Enthalpy of fusion (Latent heat cap.)	100 kJ/kg
Total heat capacity (range 10-30ºC)	142 kJ/kg
Bulk density	300-400 kg/m3

Table 3.2.1-1, Micronal DS 5038X properties.

The following properties and characteristics form all the BASF Micronal (Powder product line) have been extracted as relevant for the present study.

- The MPCM addition will be considered as a filler addition, when mixing it in cementitious admixtures.
- Micronal dry particles have a size ranging from 50-300 µm.
- Micronal particles can be considered mechanically indestructible during the mixing process due to their small shape, and can be considered as chemically stable when combined in concrete admixtures.
- Micronal particles have a flexible structure and will deform when bearing mechanical stress.
- Durability of Micronal has been secured by BASF with 10.000 charge-discharge cycles, and its properties can be maintained during periods of up to 30 years.

3.2.2. DTI PCM-CONCRETE MIX-DESIGN.

The following list summarize the conclusions reached in the DTI collaborative research regarding PCM technology in concrete admixtures, these conclusions have been gathered from the concrete mix produced:

- The final Micronal proportion was set to a value of 7.5% in mass (15% volume basis). It was found that rising the PCM content over this value lead to rheological problems in the wet admixture.
- A high rate of superplasticizer had to be added to the admixture to get to a workable admixture.
- During the mixing process, the PCM particles were not broken but deformed by the aggregates.
- The chemical stability of the PCM capsules was studied, and it was shown that the alkaline environment of the concrete did not affect them.
- Due to the mixing process, the mortar admixtures reached high air contents, which lowered the heat capacity and conductivity compared to the theoretical values.
- The final admixture reached two days strengths of 10MPa when produced industrially.

The previous conclusions will be considered during the experimental part of this research (Section 4.2, section 4.3), a replica of the DTI concrete mix will be produced in order to compare it with the actual designed mixes.

3.3. THEORETICAL THERMAL PROPERTIES ANALYSIS.

In this section, the TES properties of a set of concrete admixtures (including Micronal DS-5038X as addition) have been studied following a theoretical simplified approach. The aim of this section is to serve as an initial guideline in order to pre-dimension the concrete properties according to the TES requirements, or estimate the TES time-lag for a specific concrete admixture (PCM ratios, element thickness).

The present section represents a summary of the conclusions reached along the study carried out in the Appendix 3.3. of this research. For a more detailed description of the analysis process, consult the full study in (Appendix 3.3.).

3.3.1. IN-THERM KLIMAVÆG TES TIME-LAGS (ORIGINAL THICKNESS)

The following chart summarizes the TES time-lags reachable in the different proposed scenarios, considering the proposed Micronal ratios.

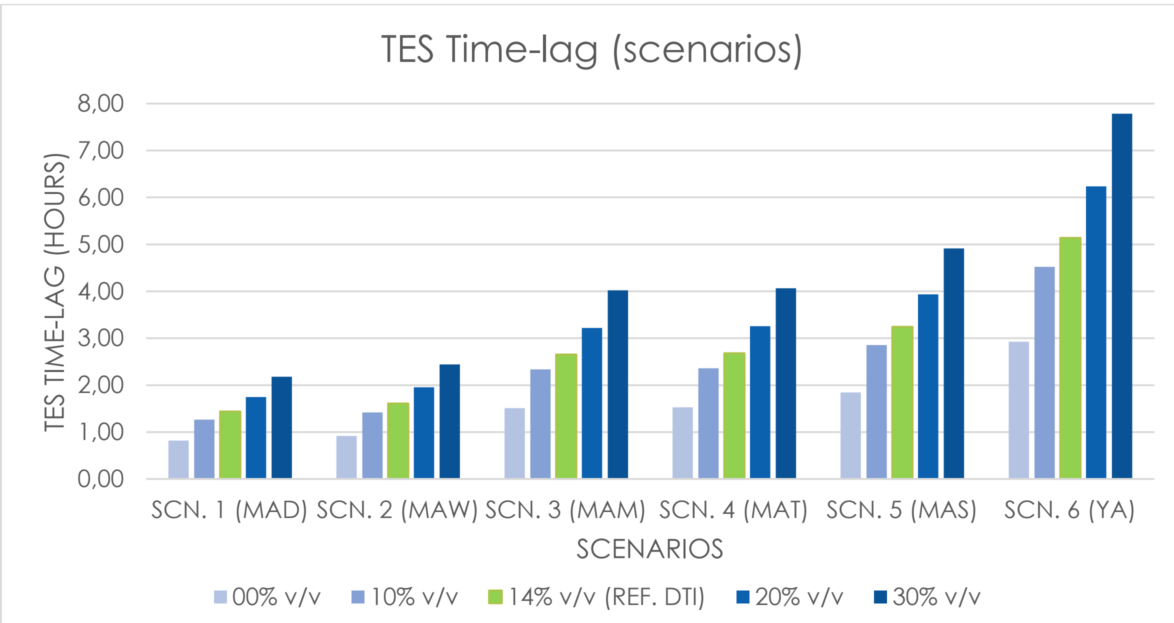

Figure 3.3.1-1, Thermal Energy Storage time-lags for the scenarios and Micronal proportions proposed.

Once the results gathered in this section have been analysed and compared, the following conclusions can be taken:

- Considering the Scenario 3 (MAM), a strong increase in TES time-lag (+1h) can be appreciated when introducing Micronal in a 14% v/v. Despite this relevant energy storage increase, a final time-lag of 2,65h does not seem a strong enough value to consider the use of the element as a TES device combined with smart-metering solutions.
- When the element is studied with a Micronal addition of 20% v/v, the TES time-lags for the current project reach values of 3,22h, this solution almost duplicates the original value, and could be considered as an interesting option which could be used in combination with smart-grids.

  Despite this improvement in TES, it has to be accounted that introducing a 20% v/v of Micronal in a concrete admixture will affect negatively in the mechanical and rheological properties of the admixture.

- The introduction of a high content of Micronal (30% v/v), despite throwing interesting TES values (4 hours of TES time-lag), cannot be considered as reachable considering the hardened concrete mechanical requirements in In-therm Klimavæg.

3.3.2. IN-THERM KLIMAVÆG TES TIME-LAGS (VARIABLE THICKNESS)

The present section includes a study of the TES repercussions regarding the oversizing of In-Therm Klimavæg concrete layer. The study focuses on the effect of slight thickness increases (1-8mm) in the TES performance of the product integrated in the project.

In the following graphic, a numbered distribution of the previously exposed data can be found. The graphic shows the values calculated for Scenario 3 (MAM).

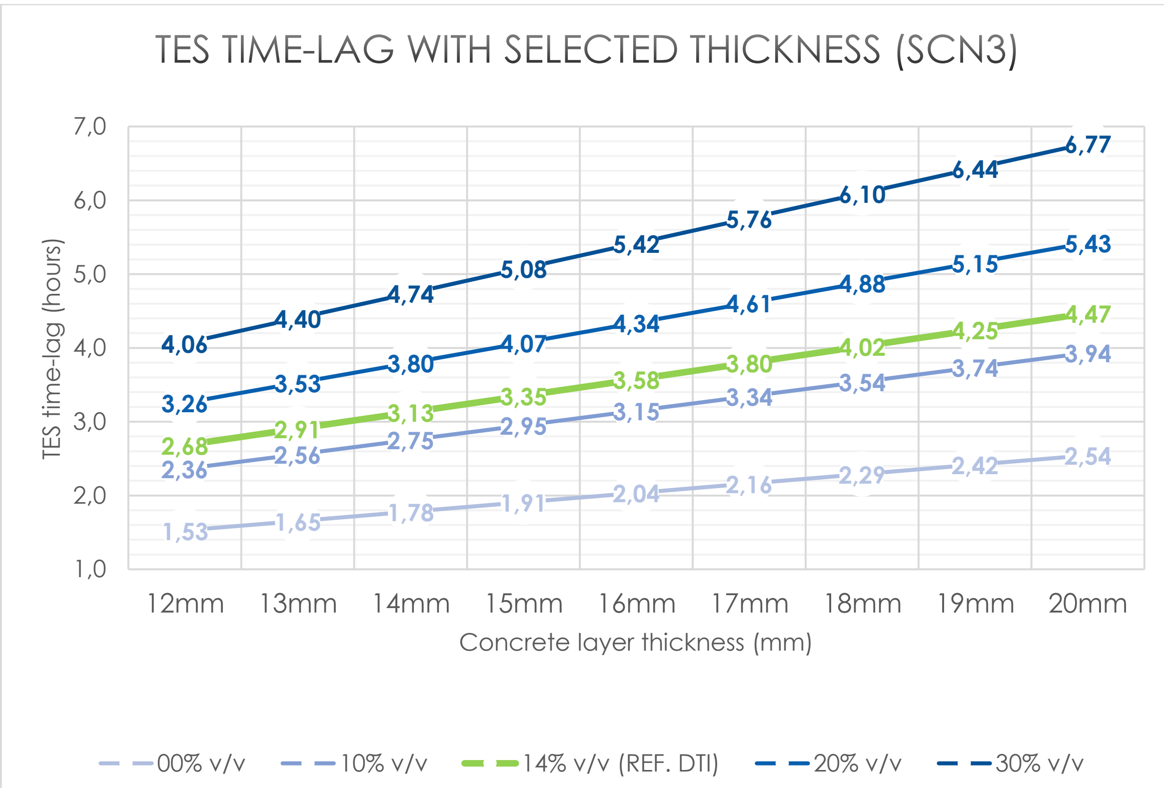

Figure 3.3.2-1, TES time-lag for thicknesses between 12-20mm (Scenario 3).

Once analysed the previous data, a final set of conclusions regarding the possibility of oversizing In-therm Klimavæg concrete layer are exposed:

- If the original concrete admixture is analysed, a slight TES increase can be appreciated. Due to the lack of heat capacity of the element, an increase in thickness on the element leads to slight TES increases (0,12h per mm). Values of 1,9h of TES time-lag are found with 15mm thicknesses.
- When the concrete admixture including a 14% v/v of Micronal is considered, a more relevant increase of TES against thickness can be appreciated (0,23h per mm). This admixture reaches values of 3,4h with 15mm thicknesses.

- If greater Micronal proportions are considered, the potential TES improvements grow higher. With Micronal proportions of 20% v/v, TES increases of 0,27h per mm can be found. Final TES time-lag values reach 4,1h with 15mm thicknesses.
- Despite that, high Micronal additions (30% v/v) reach the greatest improvement ratios when TES is compared with the thickness increase (0,34h per mm), the implementation of such high addition proportion may affect the final resistance and thermal conductivity of the concrete, which can lead to counterproductive results.

In order to summarize the previous conclusions, and develop a design tool able to assist the decision process, a summary line-graphic has been developed.

This graphic can be used when having two of the variables (TES time-lag, Concrete thickness and PCM concentration) set in order to determine the third one. Furthermore, the graphic allows a clear understanding of the effect of adding Micronal in concrete when varying the section of the elements.

The next graphic shows the previous evolution proposed plotted between 0-25mm of concrete layer thickness, the graphic aims to serve as a design guideline.

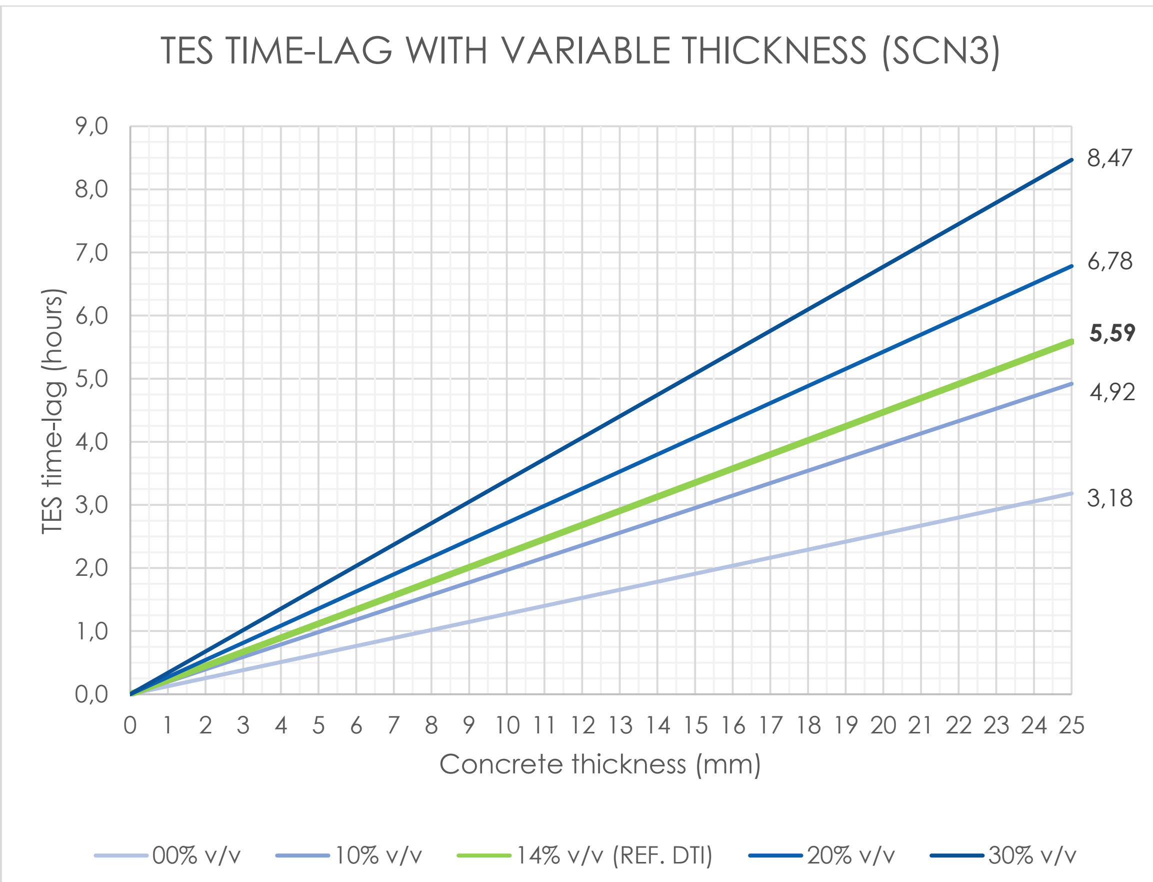

Figure 3.3.2-2, TES time-lag for thicknesses between 0-25mm (Scenario 3). GUIDELINE.

3.4. ELECTRICITY COSTS ANALYSIS.

The following chapter will focus on the study of the daily and monthly evolution of electricity prices in Denmark. The aim of this chapter is to evaluate the economic profitability of the solution for the final user.

This study is linked to the net-metering concept exposed on (section 2.4.5). It has to be remarked that this analysis will not take the matter in depth and may be considered as a preliminary analysis to set the feasibility of the solution.

This chapter represent a summary of the study performed in the homonymous appendix included in the back section of the report (Appendix 3.4.). For further information regarding the logical analysis process and the analysed data refer to this annex.

3.4.1. MONTHLY ELECTRICTY COSTS EVOLUTION.

Previous to the analysis of the hourly electricity prices evolution, a representative month from the year 2012 has been selected. Further information

Considering that, this process represents an auxiliary analysis performed in order to back up the former study. Just the main conclusions reached along the monthly electricity cost evolution study will be showed (for further information see appendix 3.4.):

- January 2012 has been selected as the most representative month for the present study. This situation helps furthermore to boost the correlation between the energetic analysis section (Chapter 3.1) and the present section, as in both January has been selected as the studied period.
- There is a great variability in electricity prices along a monthly and daily basis; this variability is greater than the one observed in an hourly basis under a one-day analysis. This leads the author to a first indicator that a short-term energy balancing may not represent a considerable costs reduction.

The following graphic shows the daily electricity cost evolution for the most representative months selected, including the studied scenario (January 2012).

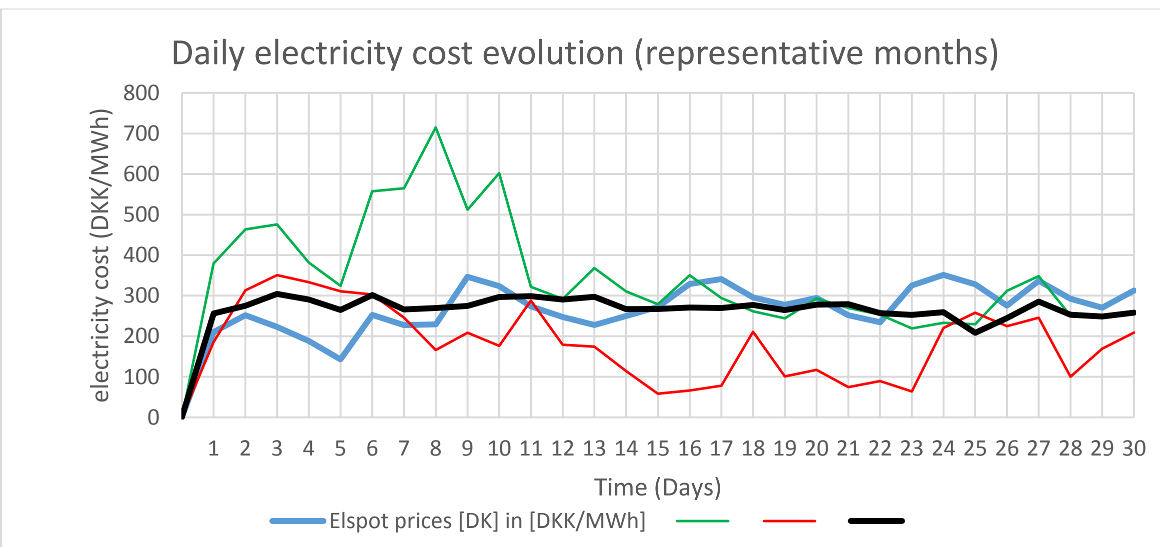

Figure 3.4.1-1, Daily electricity cost: JAN), FEB, JUL, AVG (2012).

3.4.2. HOURLY ELECTRICITY PRICE EVOLUTION ANALYSIS.

The present section summarizes the energetic balancing hypothesis set, and shows the results of the present analysis.

This analysis has been performed compensating the discharge cycles of the elements (cost peaks, red) with the loading cycles of them (cost valleys, green). A limit TES time-lag of 3 hours has been set, the periods where energy balancing is not possible have been considered under a steady consumption. Further information regarding the assumptions taken can be reached in (Appendix 3.4.).

The following graphic shows the "common" distribution of electricity price peaks and valleys, extracted from the average hourly evolution of January. The sections in red represent the energy release periods, while the ones in green represent the energy storing periods.

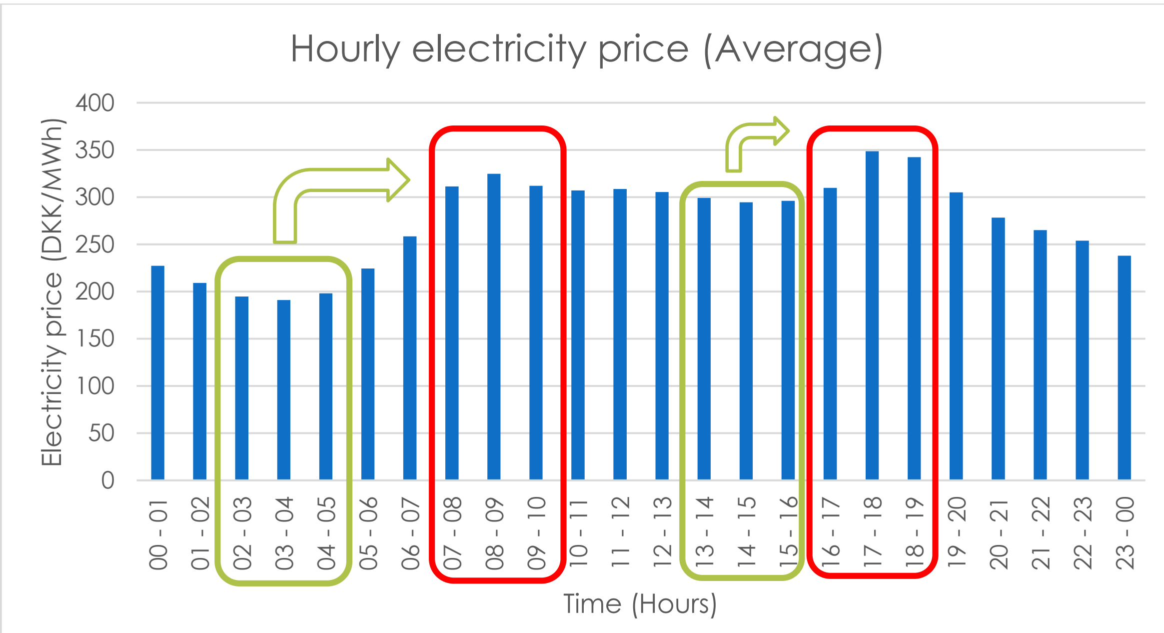

Figure 3.4.2-1, Hourly electricity price evolution (Average). Explanation of energy balancing hypothesis.

Once the hourly analysis has been performed, the conclusions from the study can be summarised in a set of numerical indicators, as shown in the following chart.

The next chart summarizes the most relevant indicators regarding the analysis performed:

	MAX	**MIN**	**MEDIAN**	**AVERAGE**
AVERAGE PRICE (DKK/MWh)	322	65	265	**265**
OPTIMIZED PRICE (DKK/MWh)	351	143	274	**274**
PRICE REDUCTION (DKK/MWh)	77	3	20	**20**
PRICE REDUCTION %	54%	1%	7%	**7%**

Table 3.4.2-1, Electricity price analysis, indicators summary chart.

In the following graphic, a summary of the average and optimized electricity prices can be found. This summary includes the prices reductions calculated expressed in absolute value and percentage.

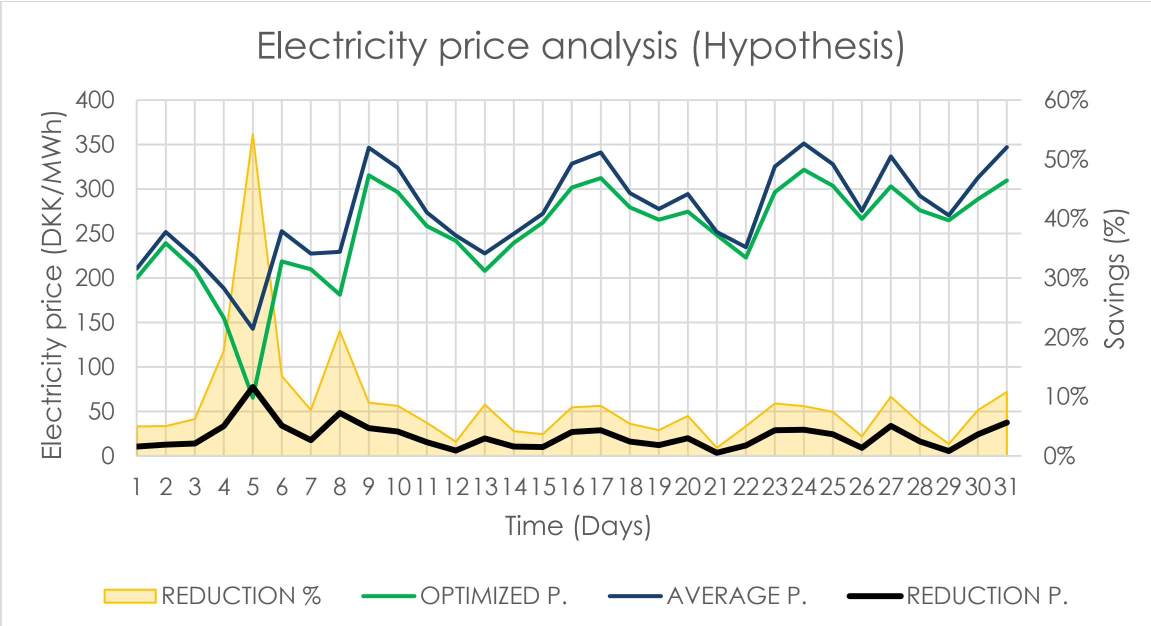

Figure 3.4.2-2, Electricity price analysis (Hypothesis). January 2012 daily evolution.

CONCLUSIONS.

As a final summary section for the present chapter, and considering the most relevant factors, which may affect the implementability of the present solution, the following conclusions have been taken:

- A greater electricity costs variation has been observed along daily and weekly cycles, the concept of medium-term TES solutions should be considered as a more interesting application of TES in smart-metering electricity networks.
- The moderate potential savings of the idea proposed does not make it interesting for implementation in small projects, as the possible cost reduction will be lower than the required investment.
- The implementation in greater projects (collective residential buildings, office buildings, district heating networks) may result profitable, even more when considering the possibility of combine an energy balancing for the heating installation with a electricity broker solution.

  Despite that the combination of these two concepts reaches an interesting approach, the development of this combination idea may require a complex research line, which has to be considered as a long-term project.
- The increase of the TES potential, either adding a storage tank or increasing Klimavæg TES capacity (Chapter 3.3.) can be considered as a viable option for further research areas. The increase of the TES time-lag would allow the covering of a greater peak section, which for an ideal savings potential should be not lower than 8-10 hours.

Despite the discouraging results of this study, the idea of using the heating installation as an energy balancing solution reaches an interesting approach for the use of TES in heating/cooling applications. A study of alternative options in the future regarding this idea represent an interesting and beneficial research area, which shall be studied.

3.5. IN-THERM KLIMAVÆG CONCRETE PROPERTIES.

In the following chapter of the study, the technical properties of the concrete layer form In-therm Klimavæg have been analysed.

The present text is a summary of the conclusions reached in the Appendix analysis linked to this chapter (Appendix 3.5.). For a more detailed description, consult the information available at (Appendix 3.5.).

3.5.1. CONCRETE PROPERTIES.

The following chart summarizes the relevant concrete properties according to the infor

SPECIFICATIONS	FIBRE-CONCRETE
Dimensions	t = 10-12 mm.
Density (d)	2.000 kg/m3
Compressive strength (Fc)	60 MPa.
Tensile strength (Ft)	8 MPa.
Modulus of elasticity (E)	25.000 MPa
Thermal Conductivity (λ)	0,75 W/m.ºC.

Table 3.5.1-1, In-Therm Klimavæg concrete specifications.

From these specifications, it can be concluded that it is required a high-resistance concrete, especially regarding compressive and bending strengths. The aim of this description is to have a reference point in terms of final properties to achieve with the further proposed admixtures in the empirical section of this research (Section 4)

3.5.2. CONCLUSIONS AND RECOMMENDATIONS.

Once analysed the main technical aspects related to the concrete, the author will give a list of the main hypothesis and considerations gathered.

- During the casting process, the piping element is embedded in the mass, so fluidity and workability have to be taken into account when measuring the wet concrete properties.
- The casting process of the element includes a vibrant table as compacting method; this has to be considered when designing admixtures with low tendency to segregation.
- It has to be remarked that the thickness of the layer (10-12mm) and the surface finishing represent an important aspect on the final product quality and a regular and flat surface without impurities has to be obtained.
- The high mechanical strengths required for the hardened concrete may suppose inconvenient, as such high resistances may not be reached when adding an additional compound to the admixture.
- It has to be remarked either the high cement ratio for the admixture, which represents a 50% of the total weigh, and may lead to rheological problems.
- Regarding the wet concrete properties, the absence of any chemical addition has to be taken into account, and gives the author an improvement opportunity regarding the final properties of the concrete if superplasticizer is added.

These considerations have been taken into account when starting the first concrete design and production phases, even though during the development of the experimental process (Section 4.3) further conclusions have been obtained.

4. EMPIRICAL RESEARCH.

In the following section of this study, the empirical tests and its results will be presented. This section is dedicated to the design, production and testing of a concrete admixtures set, in order to reach a proper mix-design suitable for In-therm Klimavæg (considering the properties stated in Section 3.5).

Along this section, an executive summary of the experimental process will be performed. The former summaries will include the main results from the tests carried out and the conclusions reached through the analysis of them. A more detailed report regarding each of the constituent chapters can be found in the appendix section (Appendixes have the same number as the chapters).

To ease the comprehension of the experimental process carried out, a list including a brief explanation of each chapter is shown. This section has been divided into 4 different chapters, following the logical process of concrete production and testing:

1. **Components characterization.** This chapter involves the analytical testing of the former components of the concrete admixtures produced.
2. **Concrete dosage and corrections.** In this chapter, a series of concrete trial mixes incorporating BASF Micronal have been produced and tested. The aim of this chapter is to establish a theoretical approach for the concrete design, using present concrete mix theories.
3. **Concrete production and casting.** This chapter includes the empirical process of concrete production. The mixing, wet concrete tests, casting and curing process of the studied concrete samples is incorporated.
4. **Testing of hardened concrete.** This chapter involves the testing process of the hardened concrete samples, being divided into mechanical and thermal tests.
   - **4.1. Hardened concrete Mechanical testing.** This chapter includes the mechanical tests performed to the hardened concrete samples, including compression, tension, density, elasticity and sound velocity characterization along a set of different concrete ages.
   - **4.2. Hardened concrete Thermal testing.** This chapter includes the thermal tests performed over the hardened concrete samples, consisting in the heat conductivity characterization.

For further information regarding the experimental setup and the experiments distribution. A detailed guideline can be reached in the Testing programme appendix (Appendix 4.).

*** NOTE:** Due to logistic issues, Micronal DS-5038X was not available for the performance of the study. Instead of using this one, Micronal DS-5040X has been used. Fortunately, the basic difference between these two products is the melting point (26ºC for DS-5038X vs 23ºC for DS-5040X), which is not truly relevant for the experimental study performed. The author will assume during the testing process that Micronal DS-5040X performs identically to DS-5038X in the studied fields (mechanical, rheological and in term of heat conductance).

4.1. COMPONENTS CHARACTERIZATION.

The next chapter summarizes the information regarding the tested properties from the main components of the admixture. This analysis includes the characterization of the following components:

- Gravel (A) 4mm and Sand (B) 2mm, Fine and medium aggregates.
- BASF Micronal DS-5040X (C), Microencapsulated PCM.
- CemFil 62, Glass fibres.
- BASF Glenium ACE 425, Superplasticizer.

The present section includes the analysis of the physical properties of the materials, relevant for the design of a concrete admixture. This properties include:

- Specific and Bulk density.
- Aggregates grain sizes and grading curves. Including the determination of the Modifies Specific Surface.
- The Ph and chemical properties of the additions used.
- The dimensions and mechanical properties of the glass fibre reinforcement used.

It has to be accounted that the present text is a summary including the most relevant conclusions for the present study. A more detailed analysis can be reached in the former appendix (Appendix 4.1.).

4.1.1. COMPONENTS PROPERTIES SUMMARY.

After the complete characterization of the components, the following statements can be considered as an overall summary of the components properties:

- The gravel (A), represents a discontinuous aggregate with angular shape, the low MSS and filler content makes it interesting to be used as a grading fineness module reducer for the mixes.
- The sand (B) can be considered as a common sand without any special characteristic to highlight. In any case this aggregates can be considered as very suitable as a base aggregate for a mortar.
- BASF Micronal (C) represent a particularly fine compound, with smooth particles and very low densities. Considering these properties, the effect of Micronal in the admixture would have to be corrected by adjusting the two main aggregates.
- CemFil 62, can be included in the proportions set by the producer brochure. The small size and average density suggest an effective combination with a high filler concrete admixture.
- BASF Glenium ACE 425, could be defined as a high-range superplasticizer, allowing high proportions in concrete, and having properties (PH, density) that make it suitable for the proposed use. It has to be remarked that this addition is the one used in the DTI research with Micronal which showed a good response along the project (Danish Technological Institute 2013).

* The properties of the air inclusor SIKAair, have not been included in the study, as it has been used in the trial admixture (P0S0), and does not have a strong relevance in the study.

The following pictures show a microscopic view (10x) of BASF Micronal and CemFil 62. This pictures have been used to understand the internal appearance of both materials, as can be considered innovative in a sort of way for concrete technology.

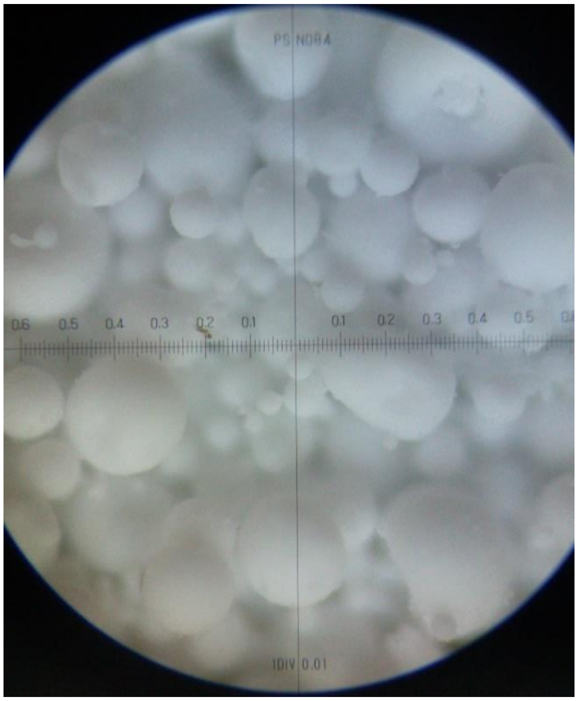

Figure 4.1.1-1, Microscopic image (10x) of BASF Micronal DS 5040x

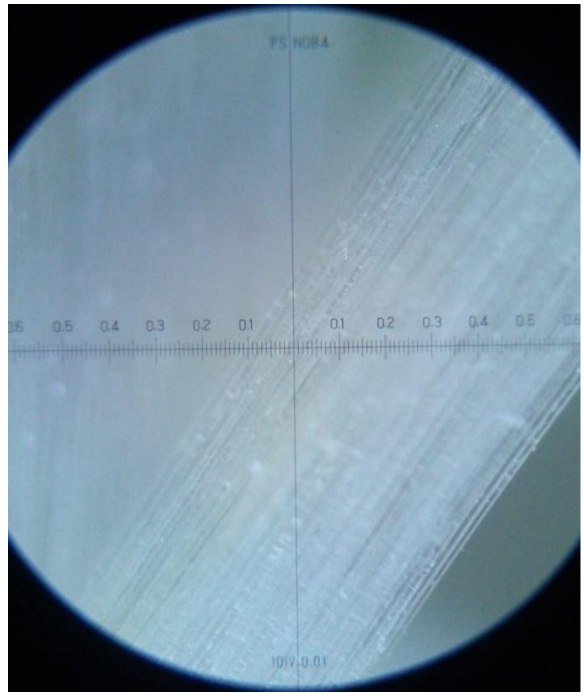

Figure 4.1.1-2, Microscopic image (10x) of CemFil 62 strand.

In the first image, the granular distribution of BASF Micronal can be appreciated. It shows a smooth surface in the particles, free of any crack of impurity. The great difference between particles can be clearly appreciated.

The second image shows the glass fibres structure composing CemFil strands. The micrometric thickness of the glass fibres can be appreciated in a very clear way.

4.2. CONCRETE DOSAGE AND CORRECTIONS.

In the following chapter, the theoretical study of the produced concrete admixtures has been exposed. Further information regarding the different admixtures can be found in the appendix linked to this chapter (Appendix 4.2.)

4.2.1. CONCRETE DOSAGE CONSIDERATIONS.

A detailed analysis of the most relevant concrete design methods and theories has been performed in (Appendix 4.2.); the following statements consist on the summary of the conclusions reached along this study. For further information and a more detailed analysis of the different theories examined, see (Appendix 4.2.).

Considering the current technological and academic means available for the author and once carried out a bibliographic revision of the actual replicable concrete mix design methods for a new concrete mix, the author has selected the Conad Mixture method (Day 2006) as the main design solution.

This method consists on a flexible design solution based on Combined Specific Surfaces (CSS), the prediction of mechanical strengths has not been used due to the particularities of the concrete admixtures designed. A study of the cement paste thickness and cement content per CSS unit has been carried out in order to compare the experimental results.

4.2.2. CONCRETE MIX DESIGN.

The mix design process has be conducted according to the previously mentioned design method (See appendix 4.2.). For further information regarding the proportions and design process, see (appendix 4.2.).

The following list includes the resultant concrete admixtures, dividing them into four different phases:

- **PHASE 0**, which includes an initial trial admixture proposed as an introduction for the author into high cement ratios concretes.
  - **SERIES 0,** Trial admixture including high cement ratios and high air contents.
- **PHASE 1,** in which the author has developed a study form two concrete replicas, the first one from an original Klimavæg admixture and the second one from a DTI project regarding Micronal concrete admixtures.0
  - **SERIES 1,** Original In-Therm Klimavæg concrete admixture (See section 3.5.).
  - **SERIES 2,** DTI concrete admixture including BASD Micronal (See section 3.2.).
- **PHASE 2,** which represents the first concrete admixture proposed, designed as a first concrete mix with a 7,5% w/w of Micronal into three series. The first one without glass fibre addition and the next two ones studying the addition of fibres on it at short and long term resistances.
  - **SERIES 3,** First admixture, including BASF Micronal.
  - **SERIES 4,** Second admixture, including BASF Micronal and CemFil glass fibres.
  - **SERIES 5,** Adjustment of second admixture, tested for short-term resistances.
- **PHASE 3,** which improves the concrete admixture, prosed on phase 2, varying cement and w/c ratios. It includes as well 3 concrete series following the same premises as phase 2.
  - **SERIES 6,** Third admixture, including BASF Micronal.
  - **SERIES 7,** Fourth admixture, including BASF Micronal and CemFil glass fibres.
  - **SERIES 8,** Adjustment of third admixture, tested for short-term resistances.

4.3. CONCRETE PRODUCTION AND CASTING.

This chapter includes the main aspects regarding the mixing, casting and curing process of the different series. The section includes also the wet concrete tests performed (Density, slump and air content). A study of the curing temperature evolution has been performed too, in order to control the chamber temperature as a variable.

The present text represent a summary of the conclusions section available in (Appendix 4.3.). For a deeper analysis and further information regarding the production process, see (Appendix 4.3.).

4.3.1. CONCRETE PRODUCTION SUMMARY.

Once all the data proceeding from the experimental process has been gathered and analysed, the most relevant information for the present study has been summarised in the present chart:

	P0S0	P1S1	P1S2	P2S3	P2S4	P2S5	P3S6	P3S7	P3S8
Corrections	YES	YES	NO	YES	YES	YES	YES	YES	NO
Vibration (min)	3	4	4	2	4	4	1,5	5	4
Density (g/dm3)	-	2077	1767	1848	1780	1830	1707	1850	1853
Air cont. (%)	7,6	3,9	8,0	5,7	7,9	6,0	5,1	6,6	5,5
Slump (mm)	>240	109	>240	>240	>240	>240	>240	>240	>240
Quality (0-10)	9	3	5	9	9	8	8	8	9
Curing t. (ºC)	21,0	20,7	20,6	20,5	21,0	22,7	20,2	21,3	22,7

Table 4.3.1-1, Average curing temperatures and deviations against 20ºC.

The following set of charts included, represent a comparison along the different properties. The graphic representation is a visual aid to understand the effect and variability of the density, air content and vibration energy compared.

The following graphic includes the density values against the air content for the different series produced.

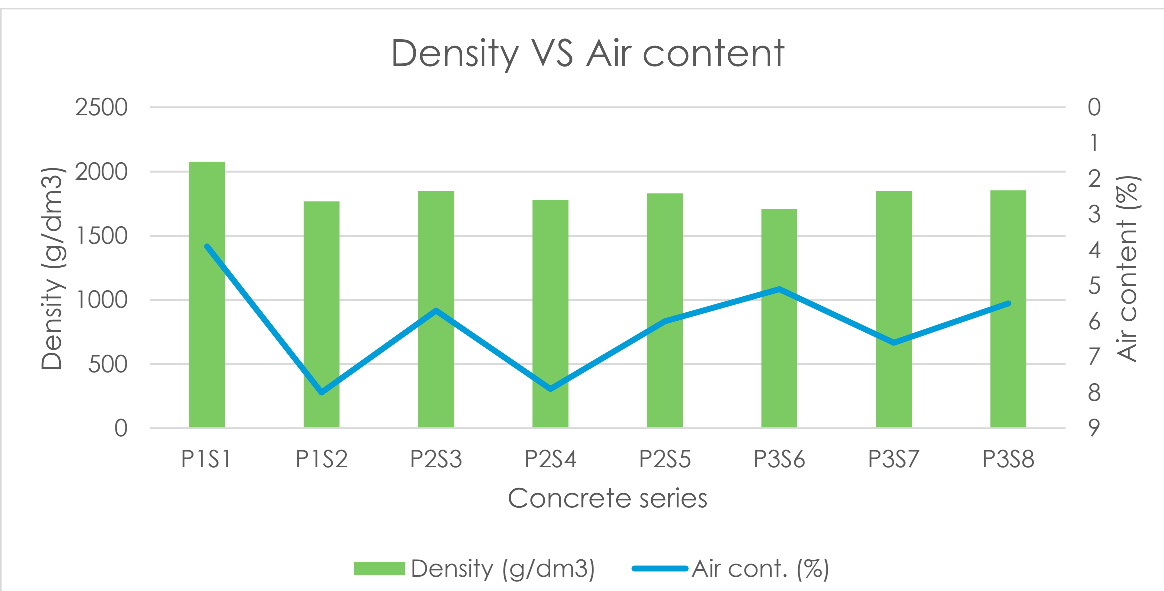

Figure 4.3.1-1, Density of fresh concrete versus air content.

The following graphic includes the air content values against vibration times for the different series produced.

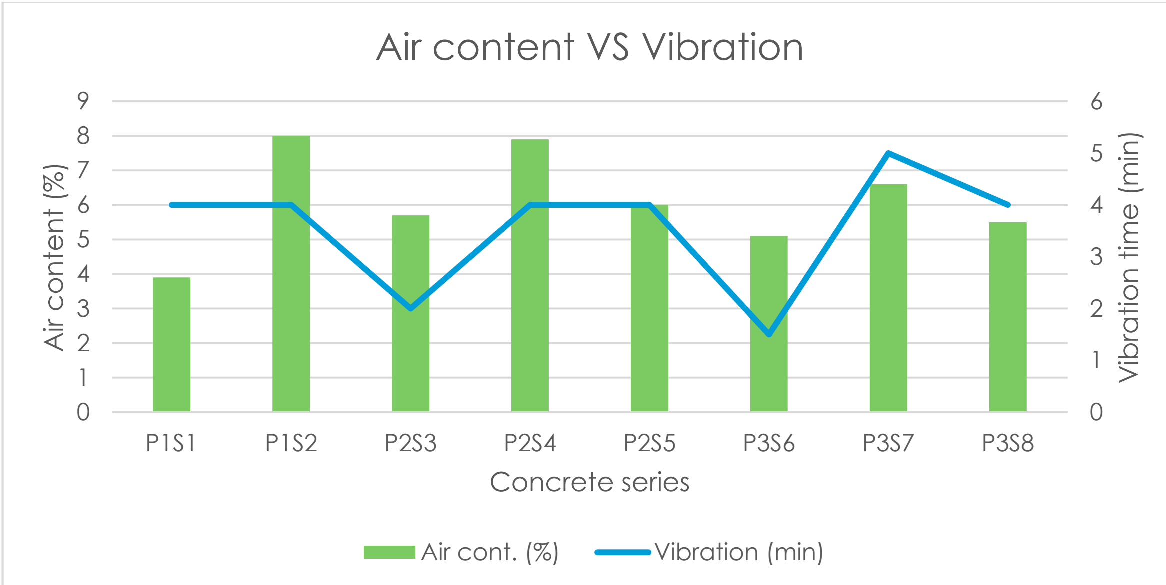

Figure 4.3.1-2, Air content versus vibration times.

From the present study, the following conclusions have been set. A further explanation form these conclusions can be reached in (Appendix 4.3.).

- The study showed fluid concrete admixtures, the behaviour against vibration was observed as satisfactory, reaching very low or null segregation problems.
- The density difference between P1S1 and the rest of the samples can be clearly linked to the absence of Micronal in the first one.
- The addition of Micronal represents a more important factor in the variation of the fresh concrete density than the cement ratio used.
- The addition of Micronal to the admixture is followed by an important air occlusion (Close to 5-7%). The air inclusion was in the form of very small bubbles (less than 1mm) which could not be released by vibration.
- The variation in vibration (from 1 to 5 minutes) cannot be clearly linked with an air content reduction.

This assessment has showed acceptable samples with appropriate finishing for precast elements, and a proper consistence and flowability to cast elements including casted-on pipes.

4.4. TESTING OF HARDENED CONCRETE.

This chapter includes the main aspects regarding the hardened concrete tests performed; the chapter has been divided between the two testing areas studied: Mechanical testing, and thermal testing.

The present text represent a summary of the conclusions section available in (Appendix 4.4.1. and Appendix 4.4.2.). For a deeper analysis and further information, refer to the two remarked appendixes.

4.4.1. HARDENED CONCRETE MECHANICAL TESTING.

From the concrete series produced in the experimental section of this research (section 4.3.), three different mechanical tests has been carried out, in accordance with the European standard EN 12390, being the following ones:

- Compressive strength test. (EN 12390-3:2009).
- Tensile splitting strength test. (EN 12390-6:2009).
- Determination of the elasticity modulus in compression. (ISO 1920-10:2010).

In order to correlate the values obtained from the different tests and asses the overall quality of the concrete, the following properties of the concrete have been established:

- Density of hardened concrete. (EN 12390-7:2001).
- Ultrasonic pulse velocity test. (EN 12504-4:2004).

In the following chart, a holistic view of the average results obtained during this phase can be identified.

PHASE	SERIES	DENSITY (kg/m3)	TENSILE STRENGTH (MPa)	E-MODULE (MPa)	SOUND VELOCITY (Km/s)	COMPRESSIVE STRENGTH (MPa)	AGE (days)
PHASE 1	SERIES 1	2182	6,88	18500	4,087	28,88	7 d
					4,174	**36,52**	**28 d**
	SERIES 2	1784	1,43	5900	2,456	7,05	7 d
					2,805	**12,34**	**28 d**
PHASE 2	SERIES 3	1901	2,41	12000	3,348	26,81	7 d
					3,472	**32,93**	28 d
	SERIES 4/5	1854	3,59	12000	2,360	7,29	1 d
					2,882	16,33	2 d
					3,007	19,62	3 d
					3,157	25,04	7 d
					3,304	**28,84**	**28 d**
PHASE 3	SERIES 6	1898	3,85	12500	3,304	29,79	7 d
					3,478	38,02	28 d
	SERIES 7/8	1891	4,52	13500	2,686	14,03	1 d
					3,000	21,96	2 d
					3,133	25,10	3 d
					3,298	29,18	7 d
					3,488	**35,58**	**28 d**

Table 4.4.1-1, Average values mechanical properties, summary table.

The previous data has been used to plot a series of graphics which will allow the understanding and comparison of the final mechanical properties of the concrete mixes object of this study.

COMPRESSIVE STRENGTH VS SOUND VELOCITY

In the next graphic the compressive strength and sound propagation values along the different ages of the concrete series is shown:

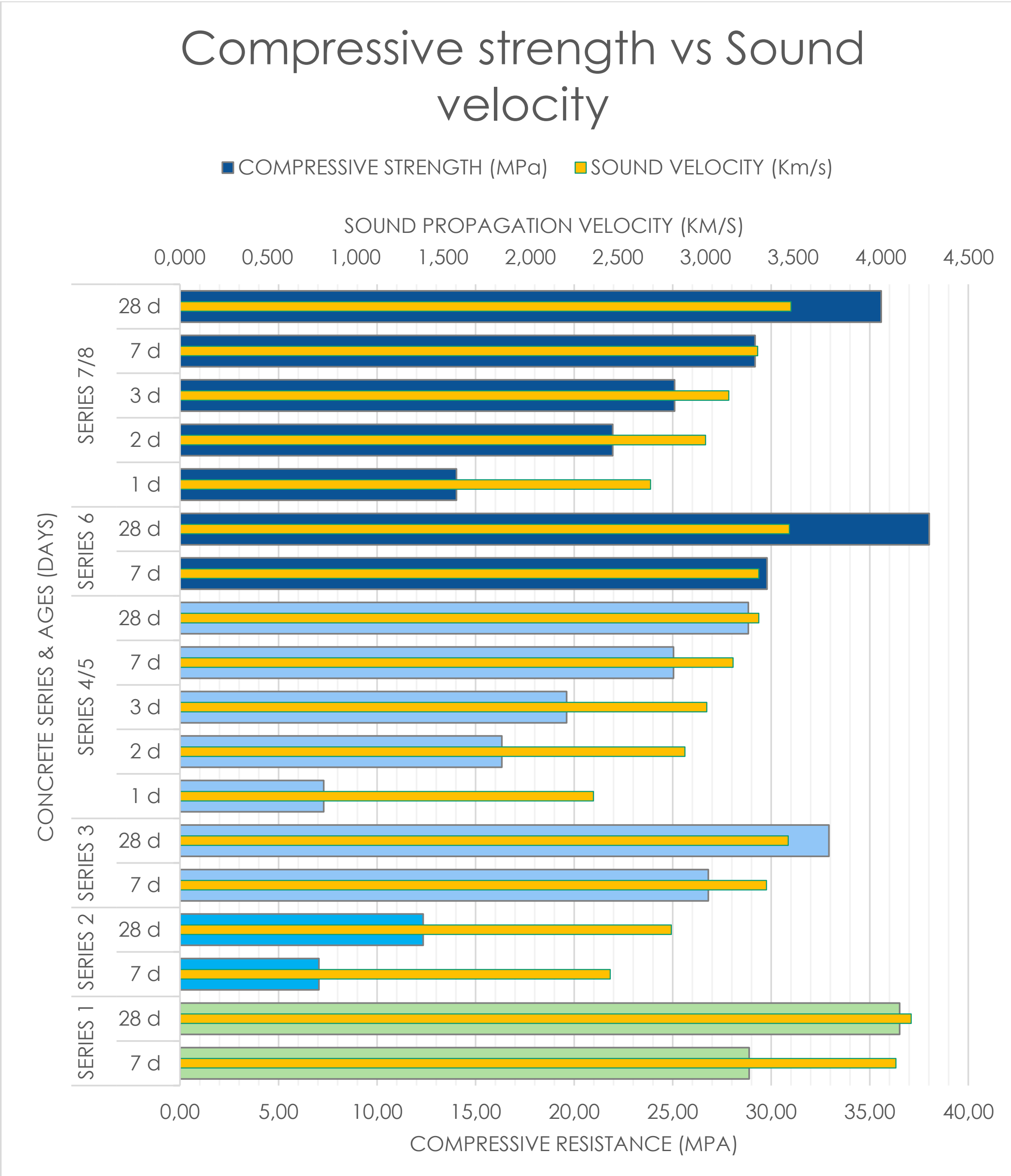

Figure 4.4.1-1, Compressive strength against Sound velocity.

When comparing the two developed concrete admixtures (P2 & P3) with the original admixtures replicated (P1), the following conclusions regarding compressive strength evolution can be taken:

- Sound velocity values tend to show a direct relationship with compressive resistances.
- Phase 3 concrete mix (Series 6/7/8) reached the greater compressive resistance values, with resistances at 1 day greater than the original Micronal concrete (series 2) studied.
- Compressive resistances of Phase 3 mix reached final values at 28 days of 35,5MPa, close to the values reached with Series 1 36,5MPa.
- Final compressive resistance values for Series 1 and 2 were found lower than expected, considering the information available from DTI and DME.
- Mechanical resistances of Phase 2 concrete reached values at 28 days close to the values in Phase 3 at 7 days in comparison. Nevertheless, it has to be considered that Phase 2 mix had lower cement ratios than Phase 3 (750 vs 850 kg/m3).
- The addition of glass fibres to the concrete mixes created (Phase 2, Phase 3), resulted in a slight lowering of compressive resistances (close to 3-4MPa). This compressive strength reduction may be linked to discontinuities caused by the fibres over the concrete macrostructure.
- Initial resistances of concrete highlight the potential of the current concrete admixture for precast industry, with resistances over 40% at 1 day. These values will allow a fast demoulding, and proper resistances to deliver the product at 7 days.

COMPRESSIVE STRENGTH & TENSILE STRENGTH VS SOUND VELOCITY (28 DAYS).

The next graphic shows the compressive strength and tensile strength values plotted against sound velocity values at 28 days.

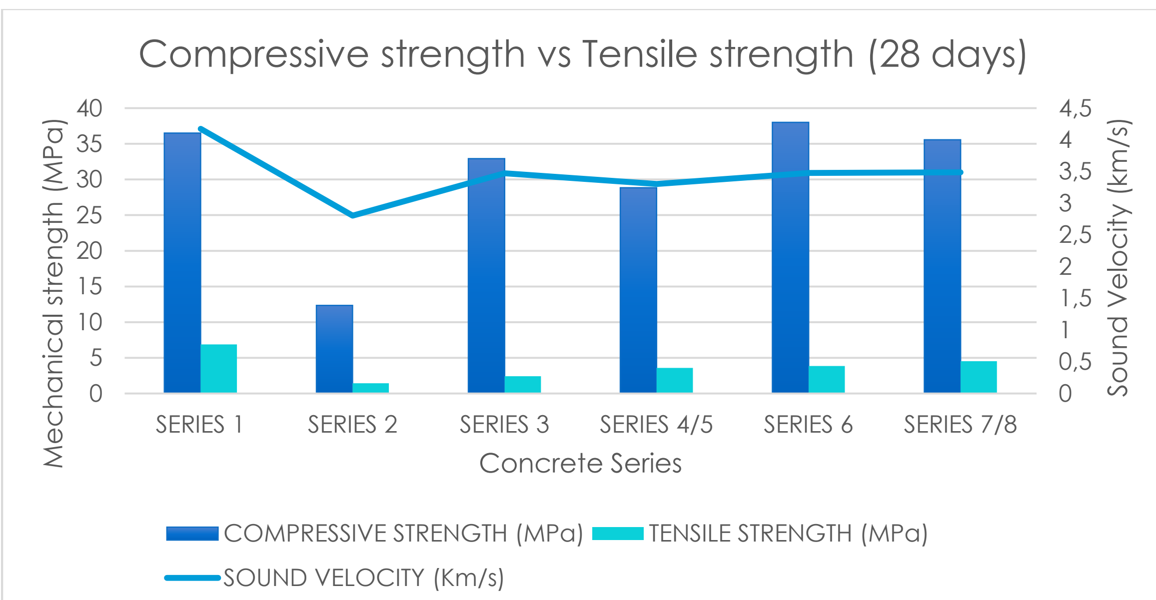

Figure 4.4.1-2, Compressive strength & tensile strength against Sound velocity (28 days)

When comparing the two developed concrete admixtures (P2 & P3) with the original admixtures replicated (P1), the following conclusions regarding compressive and tensile strengths can be gathered:

- Phase 3 mix reached the greater tensile strengths at 28 days, when compared with Phase 2 mix (close to 1MPa higher).
- Aimed tensile strengths at Series 1 (6,8MPa vs 4,5MPa) were not reached.
- The addition of fibres to the designed concrete mixes entailed an increase on tensile strengths in the order of 1MPa. Despite the low increase in tensile strength of the concrete, it has to be remarked the achievement of reduced fragility in the breakage under tensile strength.
- Sound propagation velocities do not show direct relationship with tensile strengths in concrete when adding glass fibres.

COMPRESSIVE STRENGTH & TENSILE STRENGTH VS E-MODUE (28 DAYS).

The next graphic shows the compressive strength and tensile strength values plotted against sound velocity values at 28 days.

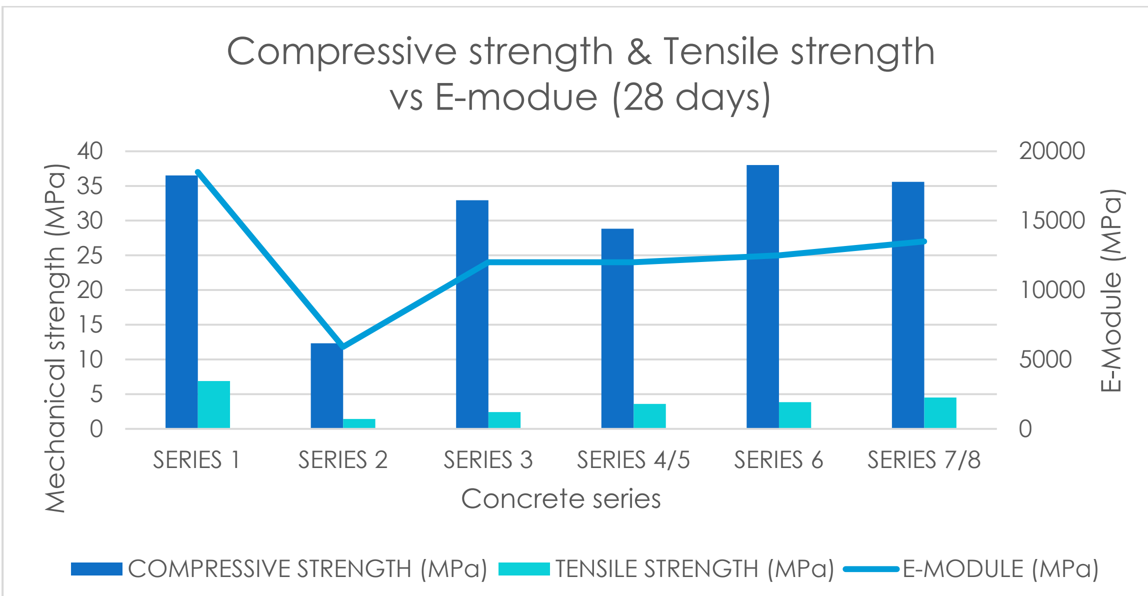

Figure 4.4.1-3, Compressive strength & tensile strength against E-Module (28 days)

Comparing the two developed concrete admixtures (P2 & P3) with the original admixtures replicated (P1); the following conclusions regarding mechanical strengths and elasticity have been set:

- A considerable decrease in the elastic modulus of concrete series including Micronal can be appreciated. The comparison between series 1 linear elastic modulus (18.500MPa), and Series 2 E-module (5.900MPa) shows a drastic decrease in the elastic modulus that can be a result of a combination of the lower cement ratios, the absence of glass fibres and the addition of Micronal.
- Comparing E-module values from Phase 2 and Phase 3 (12.000-13.000MPa) with the original Klimavæg concrete (Series 1) (18.000MPa); a significant reduction in the elastic modulus can be identified. If the two designed mixes are compared with Series 2 (5.900MPa) a considerable increase can be appreciated.
- When comparing Phase 2 and Phase 3 mixes, a slight increase in the Elastic modulus can be appreciated in the second one, which can be linked to the increased cement ratio in Phase 3.

- If an internal comparison in Phase 2 and Phase 3 mixes is done, a slight increase of the Elastic modulus can be appreciated when adding glass fibres to the admixtures.
- Comparing tensile strengths and linear elastic modulus a direct relationship can be found, where greater tensile strengths can be linked to higher E-modules.

COMPRESSIVE STRENGTH & TENSILE STRENGTH VS DENSITY (28 DAYS)

The next graphic shows the compressive strength and tensile strength values plotted against sound velocity values at 28 days.

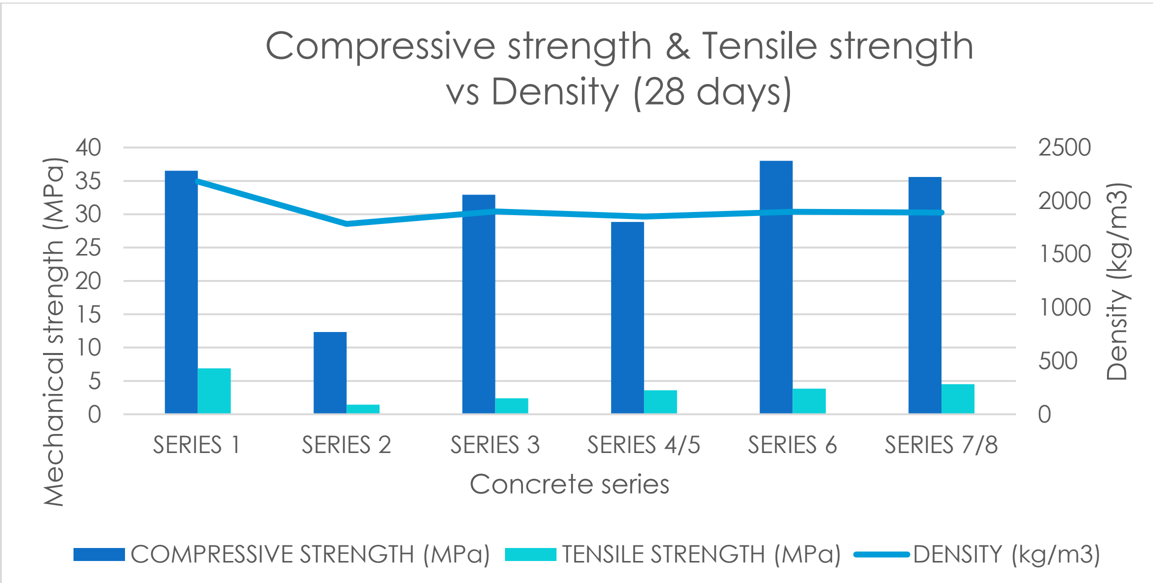

Figure 4.4.1-4, Compressive strength & tensile strength against Density (28 days)

Comparing the two developed concrete admixtures (P2 & P3) with the original admixtures replicated (P1), the following conclusions regarding mechanical strengths and hardened concrete density can be set:

- Comparing the original concrete mixes replicated, a considerable reduction in density can be identified when adding Micronal to concrete admixtures.
- The decrease of mechanical strengths can be linked in a certain way with the density reduction, as the Micronal concrete may have lost part of its compactness and the internal cement paste structure has been drastically reduced.
- When analysing Phase 2 and Phase 3 mixes a density value of 1900kg/m3 can be set as an average value, which can be considered as representative for all the series casted.
- The comparison between the designed mixes (Phase 2 & Phase 3) and the original klimavæg admixture (Series 1), leaves the conclusion that the designed ones (Phase 2 Phase 3) can be considered as lighter concrete mixes (13% lighter).
- If these density values are compared with the original PCM admixture (Series 2), an increase on the density values in the order of 7% can be identified. Despite this density increase, the mechanical resistances increase (+280%) compensates this density increase leaving a considerable stronger concrete.

4.4.2. HARDENED CONCRETE THERMAL TESTING.

In the present section, a summary of the conclusions reached during the performance and analysis of the thermal conductivity values for the hardened concrete samples has been conducted. Further information regarding the details of the test and the analysis process can be reached in (Appendix 4.4.2.).

Considering that, this experiment represents a small portion of the study, and the aim of the author is not the establishment or validation of this method, but the characterization of a series of concrete samples. In any case, further information related to these procedures can be found in their respective references.

The measurements have been conducted using a Huxeflux TPSYS02 Thermal needle equipment. To conduct the experiments, the procedures set on ATSM D5334-08 standard have been followed, even this is an USA normative it is considered the reference standard in this kind of test.

SUMMARY.

The present section includes a summary of the average thermal conductivity values calculated in the previous section can be found. This chart includes the Standard deviation values obtained, and the average conductivity value considering the sample state.

The next chart includes the conductivity values measured at 28 days with the sample in dry condition, these values will be the ones used for the characterization of the concrete as represent in a more reliable way the final state of the material when used.

SERIES	SAMPLE STATE	THERMAL CONDUCTIVITY (λ) (W/mK)	Lambda SD (%)
P1S1	28D (Dry)	1,433	2,72%
P1S2	28D (Dry)	1,109	1,86%
P2S3	28D (Dry)	1,031	0,30%
P2S4	28D (Dry)	1,051	1,67%
.P3S6	28D (Dry)	1,029	2,23%
P3S7	28D (Dry)	1,010	1,42%

Table 4.4.2-1, Thermal conductivity summary chart.

The next graphic shows the previous data as a graphical representation with the SD values plotted, the graphic includes the values at 7 and 28 days at saturated and dry condition. The values colured in green (28 days) represent the values considered as characteristic heat conductivity (λ) values.

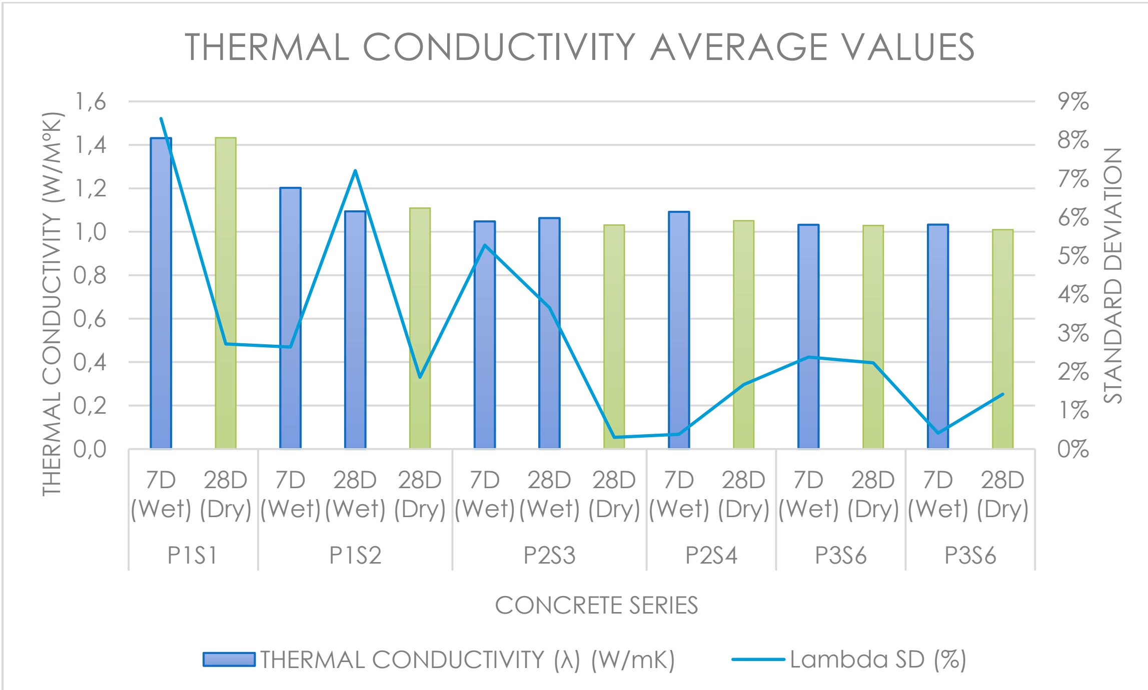

Figure 4.4.2-1, Thermal conductivity average values, summary graphic.

The following statements represent a summary of the most relevant conclusions reached through the analysis process of the results reached during the experimental research.

- Thermal conductivity values obtained from saturated testing samples at 7 and 28 days showed slight variations compared to the values determined at 28 days with dry samples.
- The variance of thermal conductivity linked to the concrete age did not show a strong pattern, and the variations obtained can be assumed as testing uncertainties dependent on the number of measurements done.
- The variations on thermal conductivity observed when changing from saturated samples to dry samples (ambient humidity), show a slight decrease in the second value (1-2%). This hypothesis can be considered as acceptable as humidity content in a porous element increases the thermal conductivity.
- The concrete admixtures including Micronal showed a lower thermal conductivity compared with the original concrete admixture P1S1 (values close to 70% of P1S1).
- The proposed admixtures showed similar conductivity values (range of 1,01-1,05W/mºK), the variations experimented (3% in comparison) are to slight to represent a tangible difference in the thermal performance of a radiant heating construction element.
- The addition of glass fibres to the concrete did not showed a pattern in the variations suffered, and considering the low proportion of glass fibres used, the hypothesis that the glass fibres structure may not affect the final thermal conductivity of the concrete gains strength.

5. RESULTS ANALYSIS AND CONCLUSIONS.

The present section of the report has been set as a final summary section, which will be directed to synthetize the conclusions from the previous sections and elaborate a clear set of statements which define the result of the research process from a particular and holistic point of view.

5.1. BIBLIOGRAPHIC RESEARCH ANALYSIS.

Regarding the bibliographic research conducted, the following statements can be considered as relevant for the present study and a further R&D research:

1. **Introduction (Chapter 2.1.).**

   The current situation of the European building sector is leading to the development of an important market field for the energetic renovation of buildings. This market represent a potential investment area for radiant solutions (predictions set values around 100-180€ billion annually from 2015 to 2050, in the European market). (Chapter 2.1.).

2. **Radiant heating and cooling (Chapter 2.2.).**

   Current development of radiant technology in the European market points to implementation levels up to a 50% of the heating & cooling solutions. Radiant floors and chilled ceilings accounts with the greater implementation rate in the commercial and academic field. (Chapter 2.2.)

   The present development includes the existence of a fully developed academic field, and the presence of design and simulation tools, including the effect of thermal comfort eases the design and creation of new products. (Chapter 2.2.2.)

   Regarding the combination with renewable energy solutions, the combination with ground source heating systems and solar thermal installations is found very common. This area counts with a vast number of theoretical (simulations) and empirical studies. (Chapter 2.2.2.)

3. **Radiant wall heating and cooling (Chapter 2.3.).**

   The present status of radiant wall solutions in the European and global construction sector present this solution as what seems to be a “forgotten option”. This situation is counteracted with the fact that this solution reaches some of the best energetic efficiencies compared to radiant floors and ceilings. Fortunately, this technology seems to be attracting more attention in the commercial and academic field. (Chapter 2.3.2.)

   Comparing a selection of some of the most important European radiant wall manufacturers, a predominance of low-inertia solutions has been identified. The presence of plaster as the main matrix material leaves most of the products as light and flexible solutions, but with an important lack of thermal mass. Italy and Germany, but specially the first one, excel in the presence of leading enterprises in the radiant wall area. (Chapter 2.3.2.)

When the radiant wall solution object of this study (DME In-Therm Klimavæg) is analysed and compared with its European competitors, a clear improvement in the thermal mass of the element can be clearly noticed. Furthermore, the flexibility reached in the product design, and the combination of external wall insulation and radiant element makes this product a very interesting option for energetic renovation on buildings, in addition to the evident applications in new construction projects. (Chapter 2.3.3.)

4. In-Space Short-term Thermal Energy Storage (In-space ST-TES). (Chapter 2.4.)

The use of high thermal inertia elements for the control of the internal environment comfort represents one of the current interest fields in the international academic sphere. Studies in this field go from overheating control application to passive heating and cooling, and a vast collection of research lines covering the integration of thermal inertia in radiant elements can be found. (Chapter 2.3.4.2.)

The presence of mathematical models and specially software simulations regarding the study of the effect of integrated TES in active (radiant) and passive solutions, allows a fast an effective modelization of current market products. This know-How can result very useful if is implemented in the analysis of THES solutions in radiant wall panels (slight developed area). (Chapter 2.3.4.2.)

The combination of an In-space Short-term TES solution with renewable energies opens an interesting research field when combining it with Net-Metering (Very developed in Denmark). (Chapter 2.3.4.3.)

5. Microencapsulated PCM. (Chapter 2.5.)

The implementation of mPCM products, based on paraffin as latent heat element appear to be the most effective solution if the combination in a thin concrete layer is considered. (Chapter 2.5.1.)

The present development of microencapsulated PCM products in the European market leaves a clear leadership of BASF and Rubitherm (both Genrman enterprises). In which refers to building applications, BASF Micronal takes a clear advantage against Rubitherm, having an important range of commercial products and projects integrating the product successfully. (Chapter 2.5.2.1.)

The presence of current researches in the area of mathematical (purely numerical and software based) models including the performance of mPCM combined in building elements, opens the possibility of using the present know-how in a R&D project regarding this technology. (Chapter 2.5.2.2.).

Following with the implementation in the experimental area, an important number of applied researches can be found in the area. The research lines the implementation in plaster-based products, sandwich panels, and composite elements. Furthermore, concrete technology represent an important field of study. (Chapter 2.5.2.2.)

The presence of Micronal in the commercial area is clearly focused in gypsum-based products. Most products are oriented to the passive control of indoor temperature (melting points of 23ºC), and just two smaller producers have set their view in the enhancement of radiant elements (clay based) with Micronal. (Chapter 2.5.2.3.)

6. **mPCM in Cementitious admixtures. (Chapter 2.6.)**

All the mPCM-concrete combination projects found have been developed using BASF Micronal as the mPCM selected product. This fact leads to the conclusion that BASF is offering a strong support to the R&D field in this area. (Chapter 2.6.2.)

The analysed projects included the following fields: The use of Micronal-concrete as an overheating protection in external elements (MP 26ºC). The addition of Micronal (MP 23ºC) to a concrete under-flooring using it as a passive solar heating element. Finally, the combination of Micronal (23ºC) in an active cooled concrete slab. (Chapter 2.6.2.)

The addition of Micronal in concrete admixtures reached a maximum concentration of 14% in volume basis (Cooled slab project), with low mechanical resistances. This issue opens a potential research are in high-resistant concretes incorporating Micronal. (Chapter 2.6.2.)

7. **mPCM in Radiant heating solutions. (Chapter 2.7.)**

The presence of PCM solutions in radiant elements is limited to a small number of studies and a few commercial products. In the area of floor heating systems, a research line (energetic simulation) regarding the combination of TES (enhanced with PCM) and a nightly heat-pump installation can be found, reaching positive results. (Chapter 2.7.1.)

Regarding the presence of mPCM (Micronal) in radiant-wall technology, a holding of a UK and a German producer is currently developing a clay radiant wall incorporating Micronal (MP 26ºC) in order to boost the TES capacity of the element during active heating periods. This solution can be considered as the present competitor in the area of TES enhanced radiant solutions. (Chapter 2.7.2.)

5.2. THEORETICAL RESEARCH ANALYSIS.

Through the evolution of the theoretical research performed, two important fields can be remarked along the chapters composing the section. The TES analysis performed (Chapter 3.3) and the Electricity-costs analysis (Chapter 3.4) are included.

Along this summary, a solid statement will be set in accordance to the viability of using In-Therm Klimavæg (enhanced with Micronal) as a TES solution, and the possibilities of combining it with the Danish Smart-metering electricity network.

TES ANALYSIS, IN-THERM KLIMAVÆG TES TIME-LAG.

The former summary, consist on a conclusion regarding the statements performed in theoretical thermal properties analysis (Chapter 3.3).

The present graphic represents the considered options; this graphic includes the original Klimavæg concrete, and two more options (14% and 20% Micronal addition v/v). The chart includes the values for the Scenario 3 (MAM). For further information, see (Chapter 3.3).

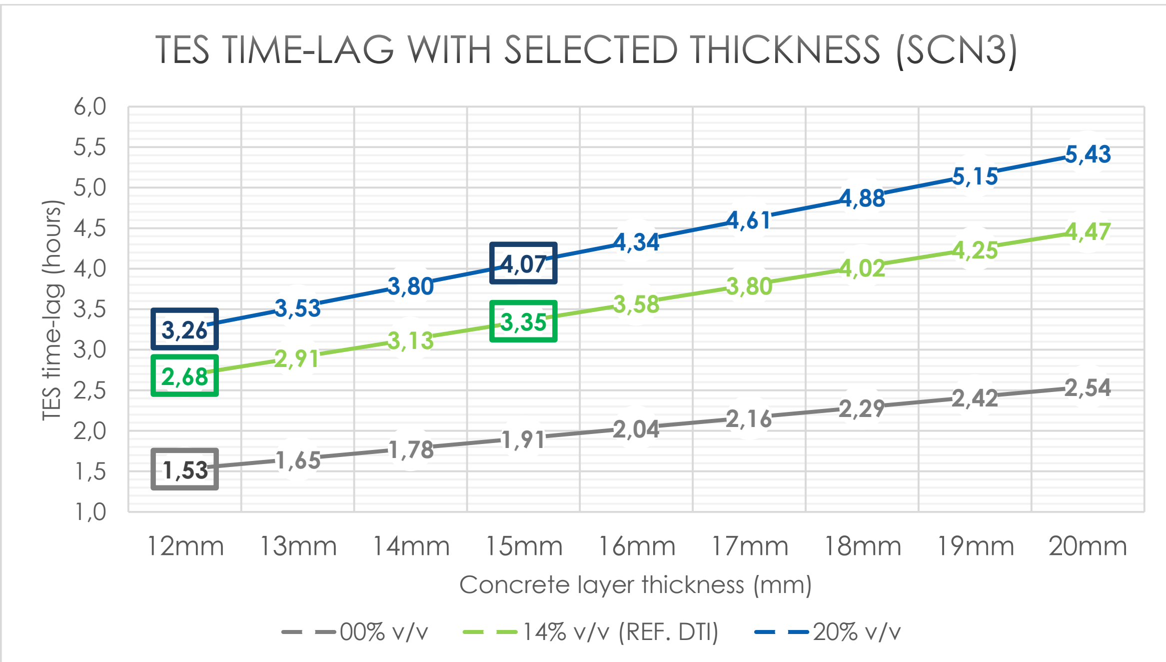

Figure 4.4.2-1, TES time-lag for considered options (Scenario 3).

The present set of conclusions represents the most relevant ideas and assumptions to consider, in the hypothesis of enhancing Klimavæg with Micronal:

- The addition of a 14% v/v of Micronal, may increase the TES capacity of the original element up to 2,7 hours. (This admixture has been actually designed and may accomplish Klimavæg requirements).
- The increase of sections up to 15mm, leads to TES values of 3,4 hours (14% v/v Micronal addition). These TES values are considered sufficient for combination with Danish Smart metering solutions).

- The increase of Micronal proportions up to a 20% v/v, may lead to important improvements in the TES time-lags reached (3,3h with 12mm and 4,1h with 15mm). The addition of Micronal in such proportions can be considered for further research lines.

ELECTRICITY COSTS ANALYSIS.

The present summary includes the most relevant conclusions reached from the electricity costs study performed in the electricity cost analysis section of this report (Section 3.4).

Regarding the combination of a TES enhanced in-therm Klimavæg with an Intelligent-metering solution; the following final conclusions have been stated:

- The moderate potential savings of the idea proposed does not make it interesting for implementation in small projects, as the possible cost reduction will be lower than the required investment.
- The implementation in greater projects (collective residential buildings, office buildings, district heating networks) may result profitable, even more when considering the possibility of combine an energy balancing for the heating installation with an electricity broker solution.
- Despite that the combination of these two concepts reaches an interesting approach, the development of this concept may require a complex research line, which has to be considered as a long-term project.
- The increase of the TES potential can be considered as a viable option for further research areas. The increase of the TES time-lag would allow the covering of a greater peak section, which should be at least of 8-10 hours.
- A study of alternative options in the future regarding this idea represent an interesting and beneficial research area, which shall be studied.

As a final statement to agglutinate all the previous assertions, it can be concluded that: The investment in the development of a Klimvavæg product line oriented to TES Smart-metering applications does not present promising results, and would requires a strong research in the area. As there are promising research lines in progress in this area, is advisable to follow up the evolution of them until a stronger basis is established in the matter.

5.3. EXPERIMENTAL RESEARCH ANALYSIS.

Through the evolution of the experimental analysis performed, two different mix designs have been performed (following two parallel hypothesis). This summary will focus on the complete description of the most appropiate concrete mix-design reached (Series 8). This admixture can be considered as a valid one for the integration in In-Therm Klimavæg.

The following chart represents the concrete dosage to cast one cubic meter of concrete incorporating a 15% v/v of Micronal and a 2% w/w of CemFil glass fibres. (Chapter 4.2)

COMPONENT	DOSAGE M (kg)	M (%)	DOSAGE V (dm3)	V (%)
CEM I 52,5	835,0	44,58%	269,4	26,94%
Gravel 4mm (A)	227,0	12,12%	87,5	8,75%
Sand 2mm (B)	338,0	18,04%	126,9	12,69%
PCM Micronal (C)	143,0	7,63%	150,1	15,01%
Water	250,5	13,37%	250,5	25,05%
Glass Fibres 60/2-12mm (Cem-fil)	37,5	2,00%	20,4	2,04%
Superplastizier (Glenium)	42,2	2,25%	40,3	4,03%
*** Air (5,5% v/v)**			55,0	5,50%
TOTAL	**1873,2**		**1000,0**	

Table 4.4.2-1, SERIES #8, corrected admixture.

The following chart includes the tested properties of SERIES 7/8 concrete mix. This summary can be considered as the specification chart for the hypothetical Klimavæg concrete layer. The former values are compared with the ones from the original Klimavæg concrete. (Chapter 4.3, chapter 4.4.1, chapter 4.4.2)

PROPERTY	VALUE	AIM (Original)
FRESH CONCRETE PROPERTIES		
Wet concrete density (kg/m3)	1853 Kg/m3	-
Air content (%)	5,5%	-
Slump (mm)	>240mm (Fluid)	100mm (Plastic)
HARDENED CONCRETE PROPERTIES		
Density (Kg/m3)	1.890 Kg/m3	2.000 Kg/m3
Compressive strength 28d (MPa)	35,60 MPa	60 MPa
Compressive strength 7d (MPa)	29,20 MPa	-
Compressive strength 1d (MPa)	14,03 MPa	-
Tensile strength 28d (MPa)	4,50 MPa	8 MPa
Elasticity Module 28d (MPa)	13.500 MPa	25.000 MPa
Heat conductivity 28d (W/mºK)	1,010 W/mºK	0,750 W/mºK

Figure 4.4.2-1,SERIES 7/8 concrete specification chart.

As a conclusion for the present section, the evolution of the compressive strengths against the concrete age has been plotted. This graphic may be used to determine the unmoulding and storage times for the precast elements once they are produced.

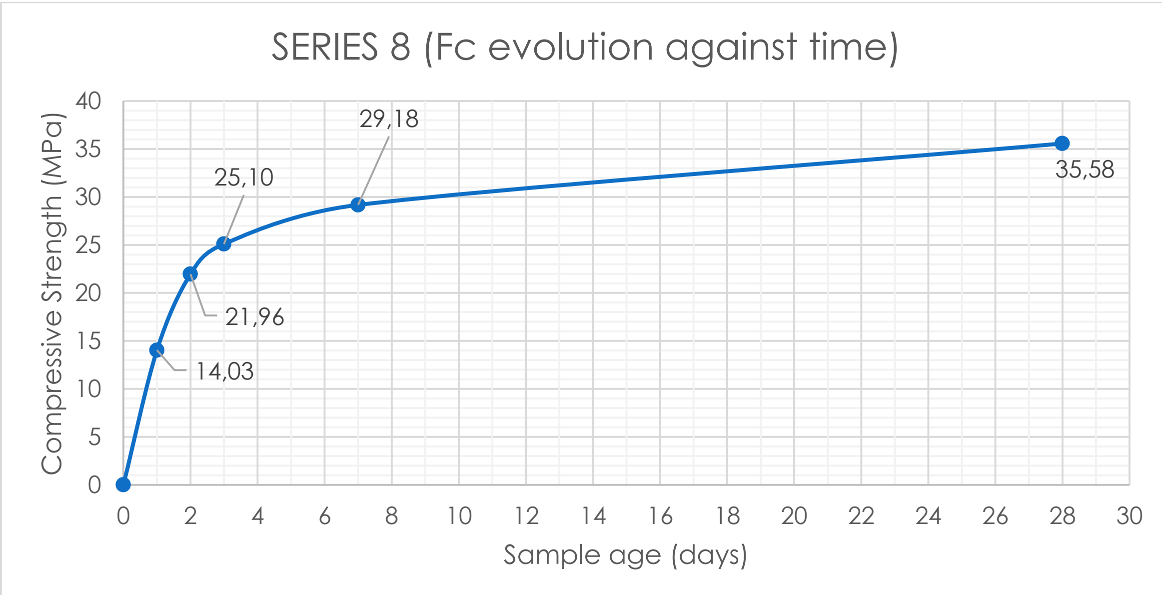

Figure 4.4.2-2, Compressive strength evolution of SERIES 7/8 concrete.

As a final conclusion, despite that the final mechanical properties of the concrete do not reach the original Klimavæg ones (compressive strength, tensile strength), some of the properties of the concrete have been improved by the addition of Micronal.

- A lower Elastic modulus value represents a higher deformation level in the concrete when submitted to stresses. This fact leaves a concrete with a lower tendency to crack, and a reduced fragile breakage. These two characteristics can be considered as very interesting for a non-structural precast element.
- A greater thermal conductivity value would improve the thermal inertia of the element, rising the efficiency of the solution either being used as a TES solution or not.
- A lower density value leads to lower element weighs, which is very positive if the element has to be lifted and installed. This reduction will also conclude into lower loads in the structural elements holding the Klimavæg modules.
- The currently obtained properties may be improved if the concrete recipe is adjusted, and the production process is improved. It has to be remarked that the concrete design and production has been developed by an amateur in the area, the experience of a concrete expert may improve the final properties in a sensible quantity.

5.4. SOLUTION OVERVIEW AND ALTERNATIVES.

The present chapter presents the potential benefits and a brief analysis of the implementation of Micronal in Klimavæg concrete under a holistic point of view.

Concluding the previous analysis (Section 5.), the present assumptions can be considered as valid according to the results and conclusions reached:

- The present status of the European building market, is leading to the substitution of traditional heating solutions by new ones more efficient and environmental friendly. This energetic renovation sector is predicted to expand in the former years under a considerable rate.
- Radiant heating and cooling solutions represent a solution field of great interest for renovation and new construction sectors. Radiant walls have a great growth potential in this area due to their flexibility and high performance ratios.
- The combination of Micronal in In-therm Klimavæg, can improve the TES capacity of the original element up to a 190% (considering volumetric heat capacities increase).
- The combination of a TES enhanced Klimavæg installation with an Intelligent electricity metering system does not reach sufficient initial benefits to be considered for a present research in the area.
- The addition of Micronal into concrete admixtures under ratios of 15%v/v can be considered as feasible. The designed concrete can reach compressive resistances over 35MPa.
  This combination leaves concrete admixtures with acceptable Heat Conductivity values (1,0 W/mºK) for radiant heating and cooling purposes.

5.4.1. PCM ENHANCED RADIANT PRODUCTS COMPARISON.

Considering the previous assumptions, and using a theoretical estimation of the thermal properties of the proposed New Klimavæg product-line, and the potential European competitors (Appendix 2.3). The present chart has been elaborated to illustrate the TES improvement of adding Micronal to In-Therm Klimavæg:

Brand and product	Matrix layer material	Heat Capacity (per m2) [J/(m2 ºK)]	Thermal Inertia (per m2) * [W/(m2 ºK √s)]	Thermal Inertia [W/(m2 ºK √s)]
EBB [UK]				
Eco Building Board	Clay	60.480	1.197	85.495
Eco Building Board	Clay	95.040	1.181	85.495
LEBAST LEHMBAUSTOFFE [GERMANY]				
Lehmbauplatte	Clay	60.480	1.197	85.495
Lehmbauplatte	Clay	95.040	1.181	85.495
DME [Denamrk]				
Klimavæg	Concrete	24.000	1.183	98.590
Klimavæg (PCM 15%v/v)	Concrete	45.360	1.407	117.235
Klimavæg (PCM 15% v/v) 15mm	Concrete	56.700	1.759	117.235
Klimavæg (PCM 20%v/v) 12mm	Concrete	52.391	1.427	118.935

* The concept of thermal inertia per square meter does not represent a proper physical property, but the author has included it in order to introduce the thickness variability of the different products. This value gives an intuitive

idea of the effect of a thickness increase in the thermal stabilization effect of the element along the working temperature range (melting point ±2ºC).

Following the results from the previous chart, a clear improvement in the thermal inertia and heat capacity of the final Klimavæg solution can be appreciated:

When the original product is compared with EBB and Lebast solutions, a clear reduction in the TES capacity of the element can be observed. This situation leads to a lack of competitively in this field, which could be "closing" this market for In-therm Klimavæg.

If the "improved" TES solutions are compared with the studied competitors, it can be appreciated how the product reaches a more competitive position, reaching similar characteristics when compared.

5.4.2. CONCLUSIONS AND ALTERNATIVES.

From the previous global summary performed, a final group of future recommendations and ideas can be set. It has to be mentioned that the following statements represent the professional opinion of the author, and have to be considered as mere professional advice.

1. The implementation of Micronal into In-Therm Klimavæg seems to be feasible considering the results obtained, and a further study regarding the industrialization of this concept represents an interesting option.

2. The increase of the heat capacity and thermal inertia of the element, turns the PCM-enhanced Klimavæg concept into an interesting option regarding In-space TES solutions.

3. The analysis performed in the area of Smart-metering showed a lack of potential benefits to consider a research in the area, at least taking into account the incipient development in the matter.

4. The comparison of the proposed Klimavæg concept with the present competitors in the European market shows a similar performance reaching close TES performance with lower thicknesses.

5. The potential applications for this idea are not enclosed just in the Smart-grid application, and the following development options should be considered:

   A. PCM with melting points in the range of (21ºC).
      - **A.1. Overcooling protection and cooling passive control.** The increase of the thermal inertia in this temperature range may reduce overcooling issues when connecting the element to refrigeration installations. This solution will maintain a more stable temperature improving the thermal comfort, and reducing energy losses due to overcooling.
      - **A.2. TES for active cooling installations.** Higher heat capacity of the element in cooling installations allows steadier working periods in the chillers and may reduce consumptions. Furthermore, the combination with renewable cooling solutions (Ground source heat pumps, solar absorption cooling) can be considered.

   B. PCM with melting points in the range of (23ºC).
      - **B.1. Passive indoor thermal energy balancing.** The increase of the thermal inertia in the range of 23ºC can be used to balance the indoor temperature during warmer periods (the heater is turned off). This combination would produce to an active and passive element, improving the annual efficiency of the system, and reducing consumptions.

C. PCM with melting points in the range of (26ºC).

C.1. Overheating protection and heating passive control. The increase of the thermal inertia in this temperature range may reduce overcooling issues when connecting the element to refrigeration installations. This solution will maintain a more stable temperature improving the thermal comfort, and reducing energy losses due to overcooling.

C.2. TES for active heating installations. The increase of heat capacity of the element, combined in heating installations allows steadier working periods in the heating units, and may reduce consumptions. Furthermore, the combination with renewable cooling solutions (Ground source heat pumps, solar assisted heat pumps) shall be considered.

C.3. TES for district heating applications. The increase of the thermal inertia of the element along its working temperature range can be used in order to reach a constant heat flux in combination with district heating networks (which in some occasions work under intermittent periods).

From the previous research lines showed: A1, B1 and C1 can be considered the research areas with the greatest opportunity of success in a shorter-term research. Solutions A2, C2 and C3 reach a more complex approach, and should be considered as an evolution of the previous ones. Choosing a more flexible approach along the R&D phase may increase the probability of success and reduce failure risks.

6. FINAL RECOMMENDATIONS.

In this final section of the present study, a final statement summarising the project conclusion and a list of future research lines and development areas for the TES enhancement of In-therm Klimavæg have been set. The aim of this concluding section is to assist executives and future researchers along the understanding of the subjective opinion of the author in the matter, and enlighten parallel and alternative research branches identified along the research process.

RESEARCH CONCLUSION.

Once reached a global and particular overview of the concept of In-space TES applied to In-therm Klimavæg, and understanding the limitations and possibilities given by the addition of BASF Micronal into concrete admixtures:

The enhancement of the TES properties of In-therm Klimavæg with Micronal is considered as feasible from this author viewpoint.

Despite that the combination of the TES concept with Smart metering solutions do not throw very encouraging results, **the evolution of the present research lines in the area should be monitored** in order to consider future research lines in combination with this technology.

The improvement of In-therm Klimavæg heat capacity and thermal inertia can be applied to **alternative TES applications such as passive thermal loads control and overheating protection**, as showed in (Chapter 5.4.2).

The enhancement of In-therm Klimavæg TES properties **may increase the competitiveness of the product when compared with its potential European competence**, by creating a second Klimavæg product line oriented to new markets.

FURTHER RESEARH LINES AND RECOMMENDATIONS.

In this final section, a list of potential research areas found during the development of the present research has been performed. The conclusions and R&D lines proposed in the conclusions and alternatives section (Chapter 5.4.2) have been taken into account when proposing the next academic research areas:

THERMAL MODELLING AND ANALYSIS (In-therm Klimavæg).

- The development of a numerical (software) model including PCM additions as an active and passive TES component in the element.
- The thermal characterization of the hardened concrete mix including PCM additions, in order to establish accurate values for the heat capacity and thermal diffusivity.
- Using the results obtained in a software modelization an experimental setup based in the Hot Plate method shall be performed. This experimental process would be used to validate the previous simulation and would allow the analysis of the real performance of the element.
- The numerical and experimental modelization of a full-scale prototype of the solution, including a performance test under realistic conditions (load-unload cycles).

M-PCM IN CONCRETE ADMIXTURES (In-therm Klimavæg).

- The development of a concrete design guideline for concrete admixtures including mPCM as addition. The design guideline presented in this research can be used as a starting point for a deeper study in concrete technology.
- Using the previous guideline, a study regarding the substitution of Micronal with a traditional filler (clay or limestone). This replacement would avoid the use of Micronal for the mechanical characterization of the concrete, in order to reduce the costs of the experimental process.
- The evolution of resistances varying the Micronal and cement proportions shall be characterized in order to establish a relationship among these factors and ease the concrete design process.
- A deep study of the air inclusion effect in the heat conductivity of concrete admixtures including Micronal.
- The production of a full-scale prototype in order to adjust the concrete properties to an industrialized production process, and identify potential critical points and improvement areas in the new material.

OTHER ALTERNATIVE RESEARCH AREAS.

- Current heat capacity characterization methods require complex and expensive laboratory equipment. The development of a simplified method, including an easily produced equipment (Do it yourself concept) could represent a very beneficial research area. A research project in this area can ease the access to heat capacity characterization with educational purposes (Bachelor students, small projects), where a very reliable method is not necessary.
- A research line in the area of PCM technology applied to radiant floorings can be a very interesting and beneficial research area. Specially it this concept is studied in combination with solar assisted heat pumps or energy balancing with longer TES time lags (10-20 hours).

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