The use of mortars in Palau Güell by Antoni Gaudi

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Abstract

In Catalonia during 19th century there was a process of industrialization following the Llobregat river. One of the traditional materials used historically in building had been lime mortar. Natural cement began to be used from the middle of the 19th century in order to improve quality and characteristics of mortar elements. Barcelona experimented a huge urban expansion during the second half of 19th century. In order to do new buildings it was necessary to develop new techniques and materials.

Antoni Gaudi finished his studies in 1876 and he began working in Barcelona since then. He had learned from traditional materials and techniques at his father workshop in his hometown. He also learned from new technologies at School of Architecture in Barcelona.

Güell family were a wealthy family who owned different industries around Catalonia, following Llobregat river. They were the founders of a Portland factory in Spain, at Castellar de N'Hug in 1904. Before that date some Portland cement shipments had arrived and had been used in Barcelona's buildings imported from France.

They asked to a young architect, Antoni Gaudi to build their family house in the centre of Barcelona, near the harbour. Palau Güell built from 1886 to 1890 was the first important project done by Antoni Gaudi. In this building, Gaudi was able of studying and experimenting different technologies and materials that he would later use in other buildings as Mila's House or Sagrada Familia.

Palau Güell is built during a period of confluence between traditional and industrial techniques. There are some traditional techniques as paintings or plaster coatings with other more industrialised as the use of pavements and finishing which they answer to a will of seriation and standardizing. There is a neat debate between technique and art and the relationship between production and design. Gaudi was focused in order to introduce new technologies to buildings and to enhance traditional ones.

In Palau Güell different mortars are used as binder materials and as fastening material for façades and pavements. This different way of using mortars lead us to do research in some areas of Palau Güell obtaining interesting results in the use of natural cements.

This lab research has allowed us to understand the development of mortars by Antoni Gaudi. This research proves how Gaudi was an architect related to traditional techniques but looking to its development through research and experimentation.

Introduction

Palau Güell is one of the masterpieces by Antoni Gaudi, nevertheless quite unknown until now. It is situated near Barcelona's harbour in one of the streets that crosses gothic district from Montjuich hill until Ramblas. As its name says it's a Catalan palace built to be the manor of Güell family. They were a wealthy family who had several industries around Catalonia. Palau Güell was built in the city centre of Barcelona in order to be the cultural and main centre for improving the social life of the family.

It was begun to be built on 1886 and finished on 1890. The parcel where it is situated it's a ground between other buildings in a quite narrow although important street. This kind of construction takes profit of patio as an architectonic element, creating the hall of the building inside. This palace should host a whole single family plus servants and it should be suitable for social parties and meetings. We can find important meeting spaces as halls and living-rooms. It has different floors from ground floor where it's the entrance until the roof. It has a total of 2.850 m2 divided in five different floors.

Antoni Gaudi travelled to Barcelona on 1869 in order to study architecture. In this recently created school of architecture he could learn from the best architects. He got an important knowledge on building techniques, drawing, physics and mathematics.

Gaudi was really attracted by Gothic architecture although he knew its lacks and he wanted to overcome it. He considered Gothic architecture had been an important challenge in the evolution of the architectonic techniques. He wanted to solve some of the technical problems experimented by this architecture that had not been solved yet. Gaudi was attracted from the Gothic architecture as a Christian artistic movement that had developed techniques and materials until its final step. He was interested by the improving solutions gotten by the Gothic architecture and its development towards perfection.

In order to improve building techniques, Gaudi knew he had to develop new technologies or to use the new ones that were being developed amongst Europe. Gaudi is an architect very interested in all the new technologies and materials developed by the industry. Although he was totally against serial production he wanted to improve traditional techniques. This is one of the reasons why Gaudi was never linked to a material not to a technology. He was using different materials and techniques getting the best of them and putting them to the limit. He used in his buildings timber, stone, iron, ceramics and all the different material and techniques he could. It's in the centre of this way of working that we can understand the use of mortars and cements by Antoni Gaudi.

The use of binders in Catalonia

The use of binders throughout history has always been linked to different aspects. It is not the same a façade coating, a supporting wall, an element subject to the effects of seawater or the need for a fast supporting when making a brick vault (Catalan vault). Each use implies that the properties of the binder to make mortar must be different. Therefore it is logical that the choice of the binder is based on the use that is given to him. Another aspect to consider is the availability of the raw materials and the distance between the production site and the market.

The XIXth century was a crucial period for these aspects. First, transport changed substantially thanks to the appearance and expansion of railway lines. This new transport mean allowed having materials manufactured at different points in the territory. Especially important were the train lines linking the north of Catalonia with Barcelona. The other aspect was the development of technology together with the advances that were being produced since the eighteenth century on the science and use of different kind of binders. This development was carried out especially in France and England. In Catalonia arrived at their peak during the nineteenth century, with the beginning of the making of a new binder, the natural cement. It was used at the same time that other ones as lime and gypsum, and even later with the Portland cement. Portland cement would be mainly used for a new constructive system, reinforced concrete, which it would prevail on all kind of constructions.

At the end of the nineteenth century there was an important inherited knowledge from the previous century in the use of the binders. In Spain, P. Madoz, in its Diccionario geográfico-estadísctico-histórico de España, publishes in one of the volumes in 1847 a detailed study of engineer PL Espinosa. It gives an explanation of the properties of the limestone from the quarries of the province of Vizcaya, with a careful classification of lime and natural cements, depending on the content of clays [1].

On one hand there was gypsum, used for very specific works, especially for coatings and interior decorations. In some areas where it was common to find deposits of gypsum (Pallars, Solsonès, etc.), it was common to use gypsum as mortar, for a variety of constructive elements, facade enclosures, pavements and others. In other territories where limestone was more abundant, the most used conglomerate was lime, aerial but also hydraulic one. It must be said that until hydraulic binders were not available, these were replaced by the addition of pozzolanic ash to the mortars. By this mean it was obtained a hydraulic mortar with an aerial binder, which supposed a faster support.

The other binder that would begin to be made in Spain in the mid-nineteenth century, it is the natural cement or also known in Europe as Roman cement. The knowledge of natural cement in Spain was initially brought by the English soldiers in 1837 in San Sebastián (Guipúzcoa). Some years later the first factories were established in Iraeta and Zumaya [2] and almost simultaneously in Catalonia, in the area of Girona (1858).

The natural cement sometimes was confused with the hydraulic lime due to its similarity. It is a hydraulic binder that proceeds from the burning of marls (limestone containing a significant amount of clay). Unlike lime, it has not to be extinguished before using it. It gets strong much faster and it has also more mechanical strength.

Finally, the last binder to appear in building technology was the artificial Portland cement. In Spain, the first Portland cement production, as we know it now, was in 1898 in Tudela Veguín, Oviedo. In Catalonia it was a little later, in 1903. This cement was an evolution and somehow an improvement of the natural cement. In the natural cement its hydraulic behaviour and its quality depended one hundred per cent of the marls rock and nothing more. Nevertheless in the Portland cement, since it is made from a mixture of limestone and clays (hence the name of artificial) their properties could be controlled. Even so we have to understand that the evolution from one binder to another was gradual. At the end of nineteenth century we can speak of the natural Portland cement that would be on between the natural and the artificial cement [9].

Antoni Gaudi was one of the first architects on using Portland cement on its works, as it has been widely reported on Sagrada Familia church [5] The use of this special cement it was due in part of its aim of researching for new materials and its better properties than traditional materials.

Thus, in the years that Palau Güell was built, Eusebi Güell, a manufacturer of Portland cement since 1904 at his factory ASLAND in Castellar de N'Hug, this cement could still not be used. It only could be used if it was imported, since some Portland cement shiploads are known at the port of Barcelona, from Newcastle (England) and others [9].

Therefore, the types of binders used by Antoni Gaudi at the Palau Güell could be different. He would probably took into account the benefits and properties of the different mortars. With the range of products that there were in the market, natural cement was an innovative material of the moment that could be found in this monumental complex.

Previous works carried out in Palau Güell

During the works on the Palau Güell between 1886 and 1890 it was the ideal moment to test different solutions. Palau Güell had different technical problems to be solved. Also the use of various building materials allowed Gaudi to try different mortars and compositions in order to check the benefit of them.

On recent years as the restoration of the building was going on, some studies on the mortars used in Palau Güell have been done. It is very interesting the research carried out by the lab of heritage research from University of Barcelona [7]. In a report of this lab done on July 27th 2002 they tested one piece of mortar from the ceiling of the noble room. This test was done taking profit of the falling down of one of the pieces of crystalline lime that are coating the ceiling of the noble floor (Figure 1). In this test they considered that it was not Portland cement but they didn't conclude which binder it was. In order to advance in the characterization of the mortars used on Palau Güell the following research has been carried out.

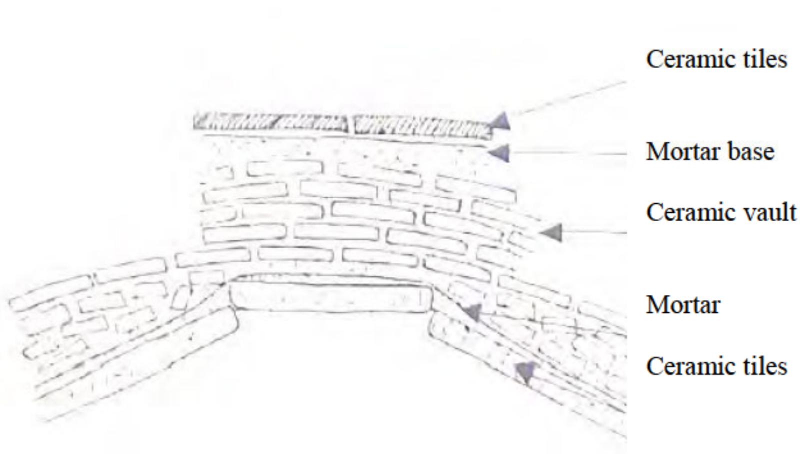


Figure 1. Detail extracted from this report [7] "Section of the disposition of different materials forming the vault in the studied area"

Methodology of study

In order to do a right research on this building a plan of visits was held. The first goal was to recognize the different kind of mortars being used in Palau Güell. After doing different research visits they were identified approximately 30 mortars in the building.

We should be especially careful with the mortars used in different elements on the roof. During the restoration held between 2004 and 2011 lots of these elements were affected and part of the original mortars removed and changed for some other modern ones.

In order to begin the research we chose two different elements in the same area of the building, the noble floor where it was the living room of the building. We took one sample from the mortar used in the ceiling (Figure 3) and another from the mortar used in on the ground in this area (Figure 4). We chose two small areas that we were sure they hadn't been restored, the ground of the inner part of the chimney and the ceiling of a small staircase that begins in the living room.

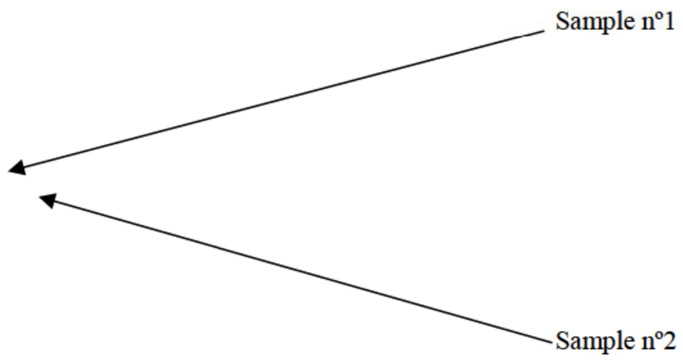


Figure 2. Plan of the noble floor drawn by Joan Alsina Arús on 1910.

Figure 3. Collection area sample 1

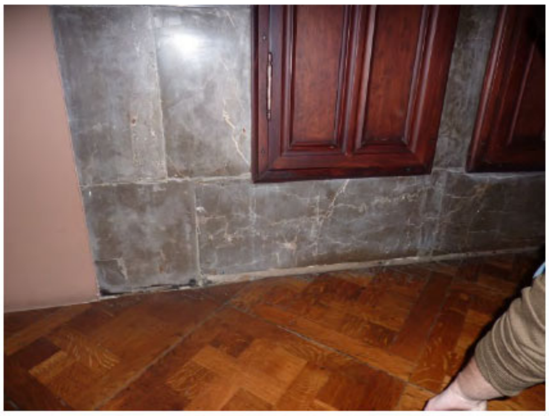


Figure 4. Collection area sample 2

We decided to try different methods to test these samples. We took different samples with a measure of 2 cm per 5 cm approximately. The goal of these two samples was to find amongst them some rests of natural cement that could prove our initial thesis.

The following tests were realized to these samples:

- Visual observation
- Thin section study with polarizing petrographic microscope (Optika microscope with 4X, 10X, 20X and 40X lenses) and image capture
- Binder elemental composition determination with electronic microscope (Scanning electron microscope SEM Brand JEOL Model JSM-7001F, Energy Dispersive X-ray spectroscope EDX)
- Mineralogical composition of the binders (fraction size under 0,063 mm) with a powder diffractometer (PANalytical X'Pert PRO MPD Alpha) with copper radiation.
- Binder hydraulic properties with Differential Thermal Analysis (TG)

Lab research carried out

Sample nº1: Main floor ceiling mortar

The mortar found is grey-brown colour and it's very cohesive. The maximum size of aggregate is 3 mm and they are mainly of silica composition (polycrystalline and monocrystalline quartz grains, orthoclase feldspar- some of them altered with sericite- fragments of metamorphic rocks tipus schist) and with subangular form (Figure 5). Also there are some limestone grains (fragments of limestone rocks and marble rocks) with subrounded form.

In the fine fraction (size under 0,063 mm) there is also clay (phyllosilicate minerals of the kaolinite, illite and biotite type) and belite crystals non-hydrated at the grains of slaked lime or at the large grains of overburnt cement stones were found (Figure 6).[1]

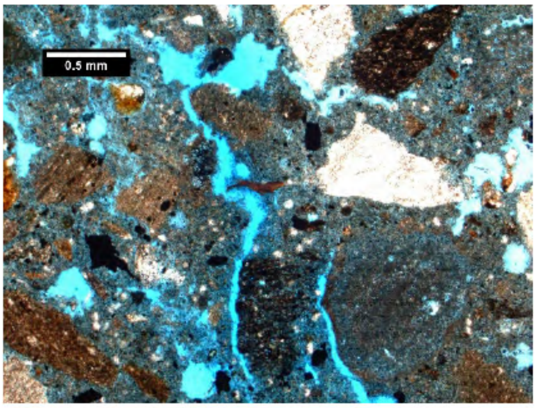


Figure 5. Microphotography with plain light where it can be seen quartz grains, fragments of metamorphic rocks and limestone grains. Also there can be seen retraction cracks and rounded pores.

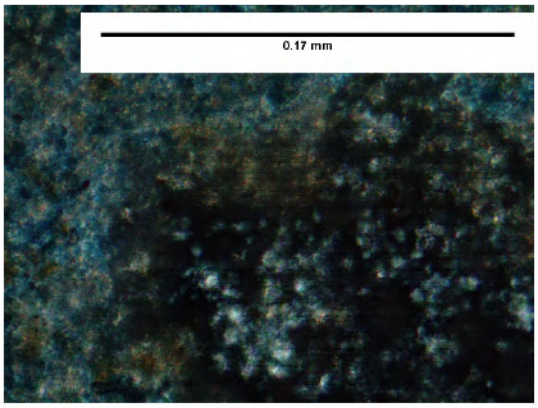


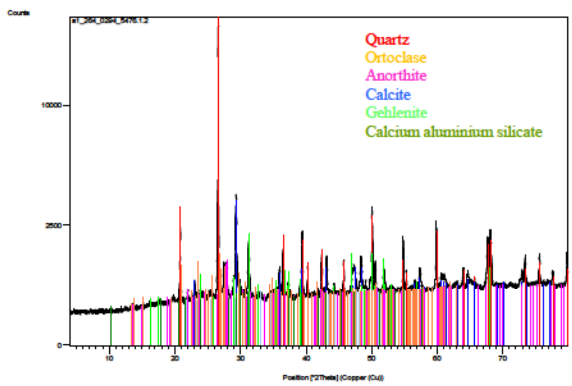
Figure 6. Microphotography with crossed-polarized light of a burnt limestone grain where it can be seen belite crystals.

The elemental composition of the binder has been obtained by electronic microscope and EDX elemental analysis (Table 1). The presence of silicon oxide and calcium oxide is noteworthy, although the presence of alumina oxide has also been detected in percentages higher than 4%. Sodium, magnesium, chlorine and potassium oxides were detected as minor components.

The mineralogical composition of the binder was established using X-ray diffraction analysis (Figure 7). The following components were identified:

- The quartz, the anorthite and the orthoclase are due to the thin section arid size (size under 0,063 mm)
- The calcite is due to the carbonated part of the binder.
- The gehlenite and the calcium aluminium silicate are the definite elements to show that the cement used is natural cement. There are still some non-hydrated areas.

Observing the conglomerate with electron microscopy, hydrated grains have been detected with an unhydrated central nucleus (Figure 8).



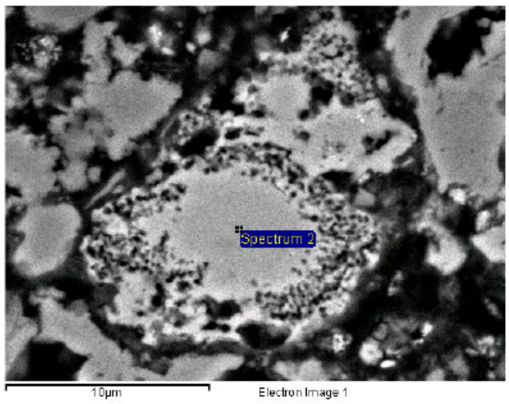


Figure 7. DRX spectrum of the binder Figure 8. Grain of the original binder showing a hidrated ring around an unhydrated core (image with back scattered electrons)

Table 1. Elemental composition

Element	O	Na	Mg	Al	Si	Cl	K	Ca
%	56.86	0.64	0.84	4.80	21.10	0.47	1.69	13.60

Differential Thermal Analysis allows checking that with a difference of temperatures of 950ºC a 28% of the sample is lost. This fact means that there are few composites that are decomposed in this range of temperatures (Figure 9). The highest peaks are found at 300ºC, which it fits with the loss of water of some clay and at 800ºC matches with the calcite decomposition.

If we compare the loss of weight produced by the decomposition of calcium carbonates (decomposition of CO_2) at more than 600ºC and the quotient between this loss and the water that decomposes between 200 and 600ºC, we can determine the degree of hydraulicity of the analysed mortar [8] (Figure 10). So we can conclude that it is a mortar with hydraulic binder, of the type of the roman cement totally carbonated. There are nodules of gehlenite hydrate, and silicic aggregate, maximum size of 3 mm.

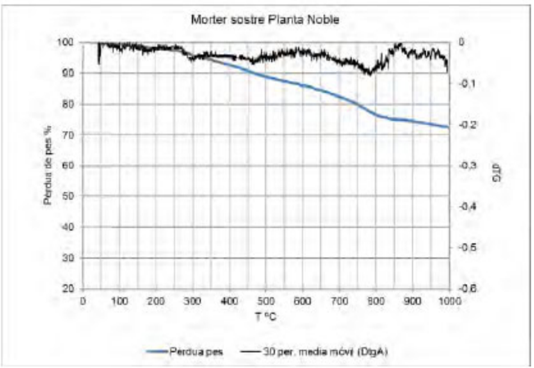


Figure 9. Shows the termogravimètric line in blue and black represents derivation of termogravimètric.

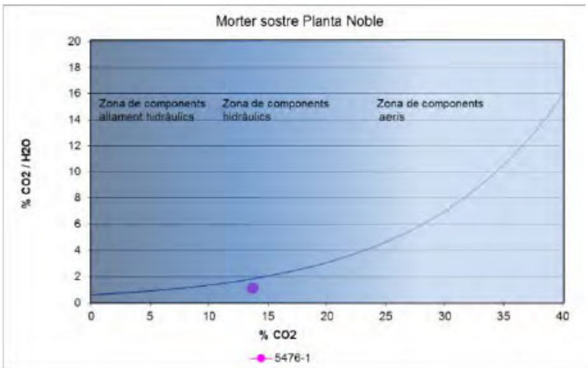


Figure 10. CO_2 to structurally bound water ratio in relation to % CO_2

Sample nº2: Main floor pavement mortar

The mortar found is grey-brown colour and it's very cohesive. Maximum size of aggregate is 2 mm and they are mainly of silica composition (fragments of metamorphic rocks tipus phyllite) and with subangled form (Figure 11). Also there are some limestone grains (fragments of limestone rocks) with subrounded form. There are some limestone fragments not enough burnt. In the inner parts we can find belite crystals non-hydrated (Figure 12).

In this sample we cannot find so much porosity associated with fissure systems and there are more spherical pores, due to the gasification during the setting of the mortar.

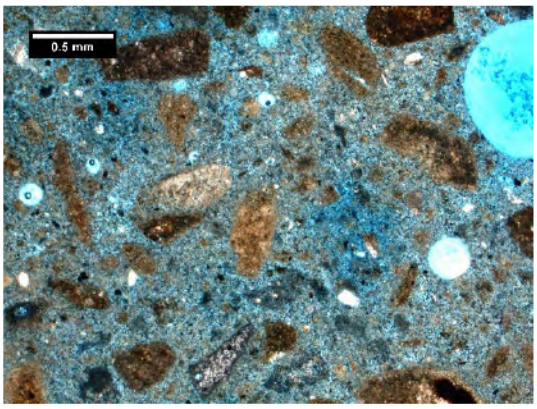


Figure 11. Microphotography with plain light where it can be seen fragments of metamorphic rocks and limestone grains. Also there can be seen rounded pores.

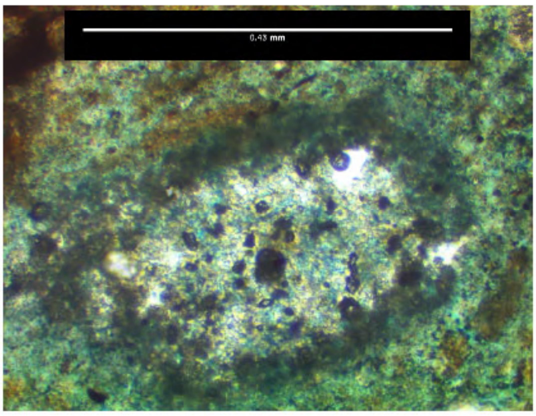


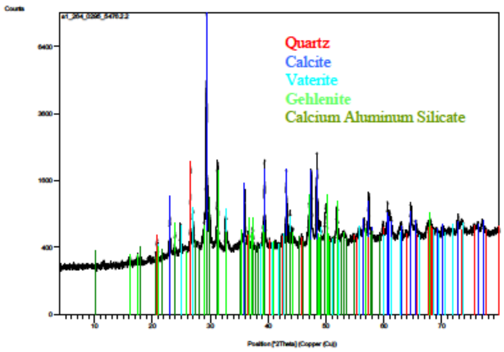
Figure 12. Microphotography with crossed-polarized light of a burnt limestone grain where it can be seen belite crystals.

The elemental composition of the binder has been obtained by electronic microscope and EDX elemental analysis. (Table 2). The presence of silicon oxide, iron oxide and calcium oxide is noteworthy, although the presence of alumina oxide has also been detected in percentages higher than 2%. Magnesium, sulphur and potassium oxides were detected as minor components.

The mineralogical composition of the binder was established using X-ray diffraction analysis (Figure 13). The following components were identified:

- The quartz is due to the thin section arid size (size under 0,063 mm)
- The calcite and the vaterite are due to the carbonated part of the binder
- The gehlenite and the calcium aluminium silicate are the definite elements to show that the cement used is natural cement. There are still some non-hydrated areas.

Observing the conglomerate with electron microscopy, hydrated grains have been detected with an unhydrated central nucleus (Figure 14).



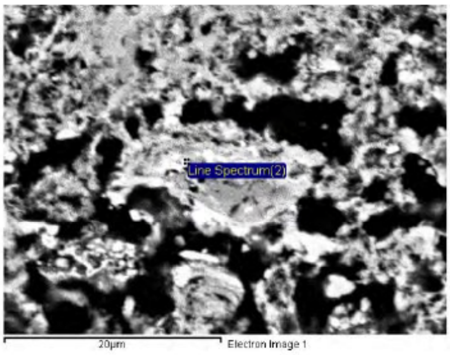


Figure 13. DRX spectrum of th binder Figure 14. Grain of the original binder showing a hidrated ring around an unhydrated core (image with back scattered electrons)

Table 2. Elemental composition

Element	O	Mg	Al	Si	S	Fe	K	Ca
%	44.05	1.22	2.11	7.37	0.5	12.33	0.53	31.89

Differential Thermal Analysis allows checking that with a difference of temperatures of 950ºC a 38% of the sample is lost. This fact means that there are more composites that are decomposed in this range of temperatures than in the ceiling one (sample nº1) (Figure 14). The highest peaks are found at 300ºC, which it fits with the loss of water of some clay and between 750ºC and 800ºC that matches with the vaterite decomposition (first peak) and calcite.

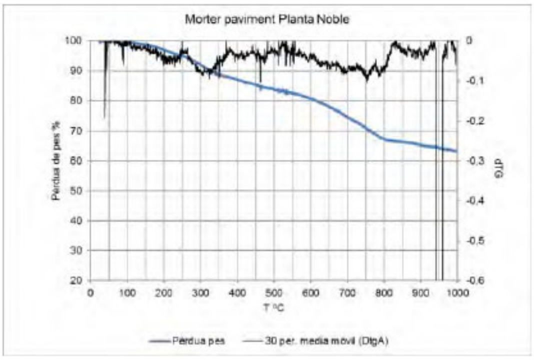


Figure 14. Shows the termogravimètric line in blue and black represents derivation of termogravimètric.

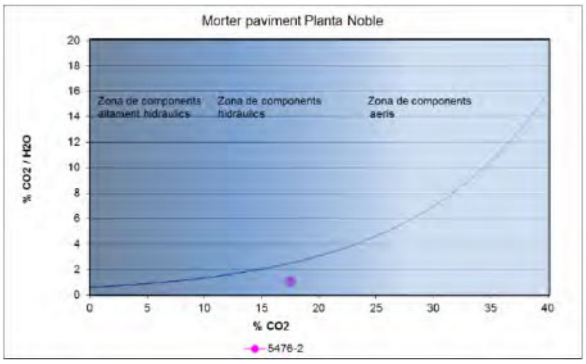


Figure 15. CO_2 to structurally bound water ratio in relation to % CO_2

If we compare the loss of weight produced by the decomposition of calcium carbonates (decomposition of CO_2) at more than 600ºC and the quotient between this loss and the water that decomposes between 200 and 600ºC, we can determine the degree of hydraulicity of the analysed mortar (Figure 15). So we can conclude that it is a hydraulic binder mortar, cement type naturally carbonated by now, but no nodules gehlenite hydrate, and silicic arid, maximum size of 2 mm.

Conclusions

The two samples studied are just the beginning of a more wide research about the use of materials and innovative building technology by Antoni Gaudi. These studies carried out in the materials laboratory of the EPSEB in UPC are the beginning of a more wide research. These first examples that we have been able to analyse thanks to the Servei de Patrimoni Arquitectònic of the Diputació de Barcelona are showing us the way to continue in our research. The two selected samples are an interesting selection of the noble floor of Palau Guell, one of the ceiling and one from the floor. These samples were selected as we were totally sure they were non-altered areas. The one of the ceiling it was under one small staircase and the one on the floor under the original pavement, never touched until now. Also these two samples they belong to two different building techniques, as one it is coating (ceiling) and the other has a supporting goal (floor). As we already knew from other studies carried out about Antoni Gaudi [3], he was an architect with an important knowledge of the traditional techniques but with also a highly innovative look. His innovation aims were focused on the improvement of his architecture and the technology he needed to improve it.

In this goal it is where we can find its innovation in building materials. Along his career he was using different and innovative building techniques and materials as other studies have already demonstrated with the use of reinforced concrete [4]. But it has not been yet studied his evolution in order to get to these materials from the traditional materials he had learnt and used until then. Palau Güell was the building in which he could try and search different methods and materials.

The use of natural cement in different areas of Palau Güell as it has been already shown in our study it's an important step in this knowledge about the evolution of the technical knowledge by Gaudi. What we have found proves how Gaudi was trying different new materials that were beginning to be used at this time at Catalonia in order to test its properties and behaviour. The use of natural cement is a clear explanation of this evolution from Gaudi. As he was innovative in his designs and forms, he was innovative in his building techniques trying to get the best materials he could in order to carry out his projects.

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