SUSTAINABILITY OF LUMINOUS LIME IN ARCHITECTURE

[1]Robador González, María Dolores
[1]Dept Architectural Buildings II. University of Seville
Avda. Reina Mercedes, 4, 41012, Sevilla
e-mail: lolarobador@us.es

ABSTRACT

The concept of sustainability today is present in contemporary discourse, both in the intervention in architectural heritage and in new architecture.

The application of the term “sustainable” in architecture leads to the term "optimization" in the design and production process of the form for construction in the field of human, natural, and material resources.

The wise combination of sustainability, based on the material, construction and form, brings the true sustainability of architecture. In the study and definition of sustainable materials is where we discover the high value held by the noble lime and its derivatives: whitewash, mortar, stucco, etc. We define sustainable material as that which not only has minimal energy consumption in its extraction, manufacture, transportation, application in construction and in maintenance work for constructive, technical and aesthetic benefits during its lifetime, but also has the possibility of reuse or recovery with minimal energy consumption and, where appropriate, minimal or no toxic residues. Lime, when correctly employed, meets all these requirements and beyond, thereby providing us with a valuable building material.

Lime stands out due to its abundance as a raw material, its ease of application, and its high durability, while maintaining its technical, constructive and aesthetic benefits throughout his long life. Its thermal properties are also significant, as are its plasticity, air permeability, its slowing of the climate change, its decontaminating effect, and the fact that it generates and contains no toxic products, and is easily recycled. Its application in restoration should also be born in mind, since it can consolidate and protect other materials, such as stone and ceramics, and provides important coating in contemporary architecture. It is in the check protocol linings where its unique contribution to architecture lies: with lime mortar, stucco and “jabelga”, smooth textures, delicate or bold colours, which enables architecture, like life, to be in black and white or in vibrant colours.

Keywords: lime, mortar, stucco, durability, decontamination.

1.- Lime

Mies said you must guide students "…*a través del disciplinado camino de los materiales, más allá de los fines, hasta la formalización. Queremos guiarles hasta el sano mundo de las construcciones primitivas, allí donde cada hachazo significaba algo, y donde un golpe de escoplo era una auténtica declaración… los nuevos materiales no nos aseguran una superioridad, cada materia sólo vale lo que hacemos con ella, queremos por tanto conocer su esencia,… Queremos un orden que dé a cada cosa su sitio, y queremos darle a cada cosa lo que le corresponde según su esencia. Queremos hacerlo de modo tal, que el mundo de nuestras creaciones comience a florecer desde su interior"* [1].

Authenticity in sustainable architecture leads to its material condition, the use of materials that meet this feature. One material that gives full response is lime and all materials derived from it: pastes, mortars and concretes lime. Below is defined sustainable material and whys of compliance with all requirements set forth by the lime, according to its essence.

The lime, calcium hydroxide, mixed the carbon dioxide from the atmosphere and transformed into calcium carbonate, has been for centuries an integral and essential materials in construction, partly disappeared with the emergence of new materials, mainly cement and polymer industry products. The cement used in restoration of heritage and new architecture, and results seen no substantial improvement compared to lime mortar coatings. As happens in restoration use of products derived from polymers, which frequently produce adverse effects. And this has much to do with sustainability.

Efficient lime has great properties: abundance, easy to manufacture, easy pigmentation, luminosity, plasticity before and after setting, workable, bond to variety of walls, natural waterproofing, breathable, hardening to age, compatible iron and wood, insulation, surface protection, cost-effective and durable. Decreases climate change, contributes to environmental improvement and balance with nature (1 kg of applied lime removes 150 grams of CO_2).

Historically lime coatings express the architectural ideas and today continue doing: contribute character, light and color to buildings. Also, lime mortars due to its plasticity, allowing for a variety of finishes. Inorganic nature supported by its mixtures with mineral pigments, incorporating in its mass; this enables infinite colors and tones are achieved as mixed in varying proportions. This workable material, the architect can shape their ideas, customize your project giving it a uniqueness and providing outstanding durability.

In fact today lime mortars are fundamental properties among which sustainability and luminosity, color and plastic formal beauty. Contribute to architecture in its two main applications: restoration and coatings. Below in figure 1, the main types of limes, derivative products and the most important applications are discussed.

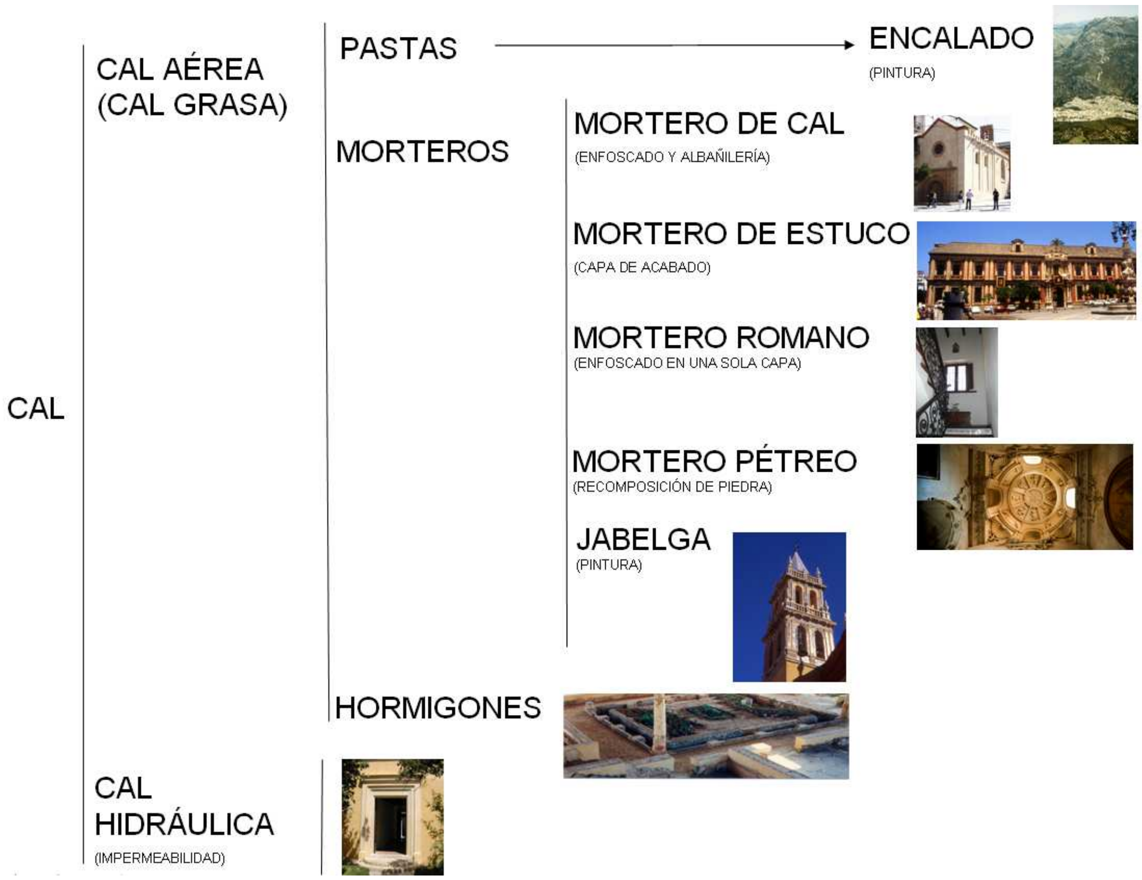

Figure 1. Types of lime, derivative materials and their applications.

The bibliography allows further research in lime, their derivatives and applications. Highlights the article *La noble cal en la restauración del patrimonio histórico. Materiales y aplicaciones* [3], by describe each of the products and their applications and to clarify the distinction between *cales aéreas y cales hidráulicas. Las cales aéreas son las que se combinan y endurecen con el dióxido de carbono presente en el aire. De ellas las más puras son las denominadas cales grasas. Las cales hidráulicas tienen la propiedad de fraguar y endurecer cuando se mezclan con agua y/o bajo el agua* [4].

La cal es el producto blanco natural, pulverulento, sólido, con elevado punto de fusión y alta densidad, que se produce por cocción a cerca de mil grados de las piedras calizas que se obtienen de las canteras calizas [5]. *Para la elaboración de los morteros de restauración y de revestimientos la mejor cal es la cal grasa, cal procedente de la cocción de calizas de alto contenido en carbonato cálcico. La cal necesaria para la fabricación de estucos ha de ser de gran pureza, que a veces llega a contener aproximadamente un 99% de hidróxido cálcico al ser apagada con agua.*

A partir de la cal se elaboran pastas, morteros y hormigones. Es sabido que el encalado es cal con agua, pudiendo incorporar pigmentos minerales. Los morteros, además de la cal, el agua y los posibles pigmentos minerales, contienen árido, pudiendo ser silíceo, calcáreo, cerámica triturada u otros. Los hormigones incorporan a la composición del mortero árido de mayor tamaño.

La alta calidad de una cal no presupone una buena calidad del mortero, ya que la mediocridad del árido puede dificultar la cohesión total. Es importante no desligar el valor porcentual de la cal en un mortero en relación con el porcentaje del árido y la naturaleza de éste. Históricamente las condiciones locales primaban en la elección de las materias primas de los morteros, elegidos en razón de su disponibilidad; hoy es posible contar con las materias primas idóneas tanto de cal como de los demás componentes del mortero, tan sólo es necesario saber reconocer cuáles son los *idóneos para cada aplicación y emplearlos. Si se quiere un auténtico mortero de cal, que es el bueno para restauración* y para revestimientos de la arquitectura contemporánea*, es importante que todo sea mineral y no contenga cemento portland, ni sustancias acrílicas, sintéticas, ni otro tipo de aditivos* [3].

After this introduction to lime, their derivatives and applications, then develop the aspects that make it sustainable, describing in detail in the following sections define sustainability. Sustainable material is the one with energy consumption is minimized in its extraction, manufacturing, transportation, building and maintenance work, for constructive, technical and aesthetic features, during his useful life, and possibility of reuse or recovery with minimal energy consumption and, appropriate, minimal or no toxic residues. And so, lime, rightly applied, meets all these requirements and many others allowing us to have a valuable building material. As we can see, lime meets all the requirements mentioned and even more.

2.- Minimum energy consumption in mining, manufacturing, transportation, building and maintenance work

2.1.- Minimum energy consumption in mining, manufacturing and transportation

The raw material for the manufacture of lime is limestone, calcium carbonate, extraordinary abundance in nature. Lime is a natural product and, therefore, like all natural products, there is not a constant and homogeneous composition.

Located quarry -for the ideal type of lime manufactured- is normally operated in strip mining, with an energy consumption similar to the extraction of stone for other applications. Lime kilns are usually next to the quarries, reducing the energy consumption of transport.

Manufacturing is done by cooking in traditional kilns [5] or industrial cements, but at a lower temperature, approximately 1000 °C compared to 1500 °C required for cement, so the energy consumption is considerably lower.

The calcination process starts with the evaporation of water contained in the rocks, then the calcium carbonate is converted to quicklime, according to the following chemical reaction (Re.1):

$CaCO_3$	+	Heat	→	CaO	+	CO_2
(calcium carbonate) (pure limestone)		(tª ≈ 1.000 ºC)		(calcium oxide) (quicklime)		(carbon dioxide)

(Reaction 1. Calcination lime)

When limestone is cooked and transformed into vivid lime or calcium oxide, it has many applications. Sometimes quicklime is used and in the case of applications to build, slaked lime is used. Lime is slaked when the quicklime wet with water, and the calcium oxide is converted to calcium hydroxide. The reaction that occurs during slaked is as follows (Re. 2):

CaO	+	H_2O	→	$Ca(OH)_2$	+	Heat
(calcium oxide) (quicklime)		(water)		(calcium hydroxide) (lime slaked)		

(Reaction 2. Slaked lime)

The slaked lime is mixed with other raw materials for the products to be applied: pastes, mortars or concretes. For each application the lime is mixed with the aggregates (mainly siliceous, calcareous or crushed ceramic) and inorganic pigments if required color change. When the product is ready -mortar, “jabelga” or concrete- is transported to construction. There the product is applied with dosing requirements, size gravel aggregate and color required.

2.2.- Minimum energy consumption building and maintenance work

The application of lime is easy to be very workable, outstanding quality of lime mortars for workability. Its application requires low energy consumption. The greasy lime, as it is also called, indicates its "buttery" consistency, docility, very easy to apply. Proper professionals use lime mortars for ease of application, unlike other less workable and less workable in its application, especially cement mortars.

Lime hardens, as binder material, and slowly carbonizes by reaction with carbon dioxide of atmosphere. Finally, it solidifies as calcium carbonate by the chemical reaction of carbonation, and is evolved heat and water.

The process of preparing the lime is started from calcium carbonate, $CaCO_3$, and the cycle closes lime reconstituting the same calcium carbonate according to the following (Re. 3):

$$\underset{\substack{\text{(calcium hydroxide)}\\ \text{(slaked lime)}}}{Ca\,(OH)_2} + \underset{\text{(carbon dioxide)}}{CO_2} \rightarrow \underset{\text{(calcium carbonate)}}{CaCO_3} + \underset{\text{(water)}}{H_2O} + \text{Heat}$$

(Reaction 3. Carbonation)

In hardened and carbonation reactions, limes are losing their workable properties and are slowly hardening.

During maintenance, energy consumption is reduced by the high durability of lime mortars, if the application is successfully and resolved constructively water tightness and structural strength.

Require almost no maintenance. On rare occasions, mortars and stuccoes may require cleaning, with water.

3.- Technical performance during his long useful life

3.1- Durability

3.1.1. Durability of lime mortars

The useful life of the building is essential to talk about sustainability, coupled with durability. If durability is reduced energy consumption, present needs are met without compromising future generations, maintaining the architecture and its value of permanence. If no durability, the concept of sustainability is unhelpful and even dyed banality.

Lime mortars have very good performance over time. They do not degrade with age, but dignify and bring more beauty to the building.

The durability of a lime mortar depends on its quality. This turn of the materials used in it: a good lime, aggregate and proper dosage and correct mixture. In durability influences the proper execution, there are small details that have to care for the coating is durable, as the walls are pre-wet and wet to prevent the mortar mixing water loses necessary for setting and hardening.

When building the solutions are correct, appropriate raw materials and the application made by people who know the craft, mortars getting harder as the days passed, will carbonating, according to reaction 3 above. Mortar properties improve over time, as will the carbonating calcium hydroxide with carbon dioxide in the atmosphere. And this results in a long life, eternal, without having to go periodically replacing the mortar for its poor condition and the harmful effects.

3.1.2. Collaboration lime mortars in the durability of stone

Lime mortars are durable and also contribute to other materials are durable. This applies to the protection of stone, ceramics and other materials with thin layers of lime mortar. If we focus on the stone, deteriorates to the destructive actions. Applying a thin layer of micro lime on stone, it protects against atmospheric CO_2, SO_2 and SO_3 before, to the water and its effects, to mechanical, solar and biological destructive actions, strengthens and consolidates, beautify, and is a material tested by time, ensuring good behavior.

Indeed, this treatment has been applied in stone facades and published in articles *Restauración de la singular fachada renacentista de la Casa Consistorial de Sevilla* [6] and *Restauración de la Puerta de Marchena del Real Alcázar de Sevilla* [7].

The stones composed by calcic carbonate, lime or calcarenite, insoluble, ($CaCO_3$), when mixing with water that contains the carbonic anhidrate of the air dissolved, (CO_2), change into calcium bicarbonate $(CaCO_3H)_2$, which disolves very well in water, with wich the lime and calcarenite stones start to degrade.

If the stone is calcarenite it loses the cementing element, silicic anhidrate ($CaCO_3$), with which its resistance is reduced, losing mass and consequently magnificent sculptures disappear irreversibly. If the stone is limestone, when the rain water arrives with a great amount of carbonic anhidrate, it transforms into calcium bicarbonate, that dissolves very well in water, according to the following chemical reaction:

$$\underset{\text{(calcium carbonate)}}{Ca\,CO_3} + \underset{\text{(carbon dioxide)}}{CO_2} + H_2O \rightarrow \underset{\substack{\text{(calcium bicarbonate)}\\ \text{(water-soluble)}}}{Ca\,(CO_3H)_2} + H_2O$$

$$\underset{\text{(calcium carbonate)}}{Ca\,CO_3} + \underset{\text{(carbonic acid)}}{H_2CO_3} \rightarrow \underset{\substack{\text{(calcium bicarbonate)}\\ \text{(water-soluble)}}}{Ca\,(CO_3H)_2} + H_2O$$

(Reaction 4. Action CO_2 in stone)

This chemical phenomenon was sensed by the sculptors, so they covered the buildings with a fine layer of lime mortar, very rich in lime. This lime mortar protected the stone from the corrosion of the carbonic gas in the atmosphere, and for this are known of old as "sacrifice mortars".

The mortar not only does not get spoiled but also gets harder and stronger the more the amount of carbonic there is in the atmosphere. The process is very slow, and while it goes on, the stone keeps its properties. Lime combines with carbonic gas, neutralizing, making it dissapear, in a way that it cannot get to the surface of the stone upon which the mortar is placed, reason by which it is recommended to be rich in lime. Carbonatation reaction is slow and it is done according to the following formulation:

$$\underset{\text{(calcium hydroxide)}}{Ca(OH)_2} + \underset{\text{(carbon dioxide)}}{CO_2} \rightarrow \underset{\text{(calcium carbonate)}}{CaCO_3} + H_2O + \text{Heat}$$

(Reaction 5. Stone protection against CO_2)

The defensive lasting of the lime mortar depends on many factors: of the pureness of the lime in the mortar, the amount it contains in its dosage, the humidity, atmospheric *gases, compactness, etc., but it normally lasts for more than fifty years, even centuries. When the lime is totally carbonated, it has finished its protection mission, having to replace it with a younger mortar, in the important building maintenance work and especially of the great buildings.*

The fine lime mortar layers protect against SO_2 and SO_3.

The lime that forms part of the lime mortars and stucco ones, for its alchaline nature, forms a natural barrier, a filter that avoids the acids contained in the atmosphere that causes so much damage on the limestones. The sulfur oxides contained in the atmosphere, degrade the stone quickly: they produce loss of stone mass, wipe out artistic figures, etc.

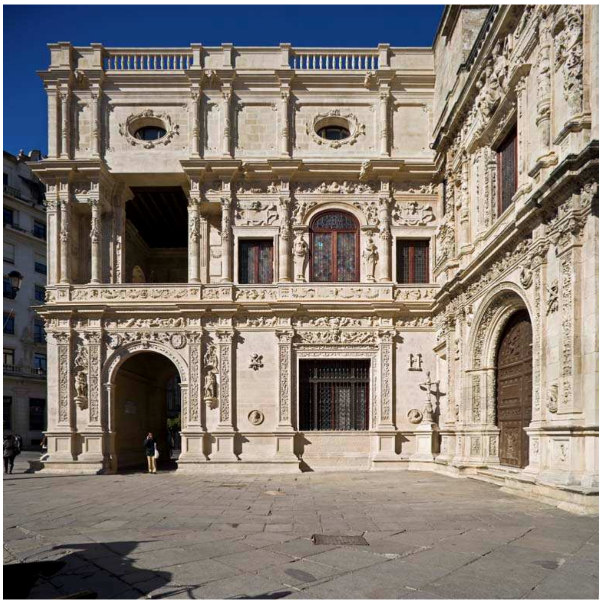

Figure 2. City Hall Seville facade. In the restoration were cleaned, reinforced, protected and consolidated masonries and stone sculptures by applying thin layers of lime mortars.
Designer and project manager: Architect PhD María Dolores Robador

If the stone has no lime based protection, calcium carbonate would transform in a nonresistant hydrated plaster, which supposes its total degradation.

The stone changes into calcium sulfate, because of the increase of the relative humidity in the air or by the rain water which precipitates a hydrated form of plaster, which makes it crumble, as it is not resistant when it suffers an aggressive weather.

And so, if these aggressive agents get to the stone and find a barrier that avoids their penetration and further reaction, the stone is not impaired, its impairment is stopped by this sacrifice skin, and when this is spoilt, it will be easy to repair in the obliged maintenance that these buildings require. The lime contained in the fine layers of lime mortars and "jabelgas" reacts changing into plaster, avoiding the stone to be attacked and impaired.

The neutral products formed, are not alien to the building, that when in formation close even more the pores of the protection layer, the more the pollution, the best it protects it [6].

It is also important to use in protecting the stone material of the same nature, because that does not change the subject, critical to preserving the authenticity of heritage. The art object, as Cesare Brandi, include material consistency (structure and appearance) and image. The first support of the second. Whenever one of these aspects is altered, the integrity of the building is affected. Preserve the essential characteristics that define image and matter, integrity [8]. By using thin layers of lime mortar in protecting the stone you are using a product of the same nature, of the same materials consistency, does not alter the composition of the asset. If other products are used as polymer industry products; the matter alters and often do not have the compatibility and durability needed with the original materials. So that the protective effect is less and harmful to destructive agents, and also the original material of heritage is not preserved.

Figure 3. Marchena facade in the Real Alcázar of Seville. In the restoration, previously the cleaning process and structural consolidation is performed, lime mortar is applied in stone joints, stone mortar and stone recomposition, and finally the masonry and stone sculptures were protected and consolidated with thin layers of lime mortars. Designer and project manager: Architect PhD María Dolores Robador

Paolo Marconi also stresses the need to consolidate with high durability materials: *Los intentos actuales para propugnar la consolidación con materiales especiales, proceden en realidad de interesadas campañas de venta de productos que, por lo demás, vienen de uno de los sectores industriales más comprometidos en su aspecto científico, sin tener en cuenta en lo más mínimo el problema de la degradación progresiva e inexorable que cualquier impregnación, aunque eficaz, no podrá jamás anular. Se trata por tanto de aplazar por algún año de degradación, pero no ciertamente de eludirla de forma definitiva* [9]. And even cause irreparable damage to the future, changing the structure of matter maintaining its look.

Therefore, applying these thin layers of lime mortar to protect and restore the stone masonries, sustainable restoration is done with great durability, protection and safeguarding of the authenticity of the architectural heritage.

3.2- Reducer of climate change. Lessening pollution

In the carbonation reaction (Re.3), is proved how the calcium hydroxide will carbonating to mix carbon dioxide from the atmosphere, it clears the atmosphere and transforms it into stone, thus demonstrates how lime mortars lower the pollution. It is estimated that environmental improvement is 150 g of CO_2 per kilo of lime.

3.3- Efficiency. Thermal Properties

The thermal properties of materials lime contribute to the sustainability of architecture. Lime contributes to climate control.

As we discussed in the inaugural lecture *La Luz y el color de Sevilla* [10], the facades colors influence the absorption of solar radiation. The black color absorbs 90-100 per cent solar radiation, and white color 0-10 per cent, within these limits are other colors that absorb 10-90 per cent. The absorption increases the temperature of the facade, and if it is not well insulated, the heat is transmitted to the interior, also originates dimensional variations of the buildings elements -expansion and contraction- which can cause damages. Therefore the white color of lime: limed, “jabelgas”, mortars and plasters, reduces the amount of energy required for thermal comfort inside the buildings, assuming energy savings. The cities like Seville, through the centuries have carefully the effects of intense solar radiation and folk knowledge has protected their buildings with local materials and experiences. Therefore, defend lime is defending the architectural heritage, and materials that are part of its good properties, apology of the inherited. We have to improve and not lose our heritage, both to develop restoration work to incorporate into future buildings.
Other lime properties that contribute to sustainability are breathability, compatibility with other materials, economy, etc.

4.- Constructive benefits for long useful life

Today lime has an important role to play in the restoration of architectural heritage and the new architecture, mainly in coatings
Historically lime was present in all the constructive elements of architecture, as shown in figure 4. Today lime still has its place in the restoration of these building elements.

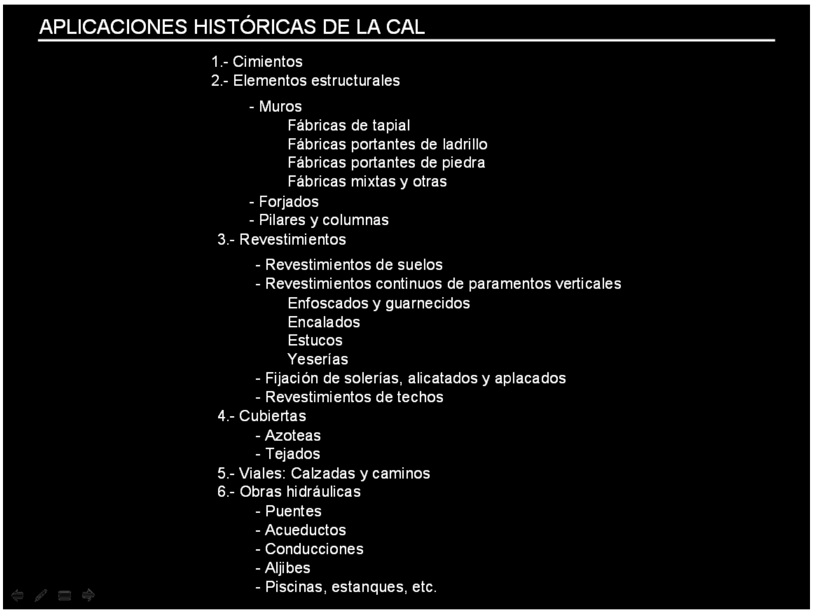

Figure 4. Historical lime applications

In contemporary architecture, the highlight of the application of lime mortars, stuccoes and “jabelgas” locate in the coatings.
We analyze architectural awards in recent years and coatings buildings have been resolved with lime. The Cordoba bus station by the architect César Portela, interior and exterior walls are covered with stuccoes, or Panorama Housing in Madrid by the architect Jerónimo Junquera, where stuccoes cover the concrete panels. This building which highlights the variety of colors of the stucco received the following awards: 1st National Architectural Prize, 2007, 1st prize best building built collective housing, 2006 and 1st prize for best performance in free housing, 2004.

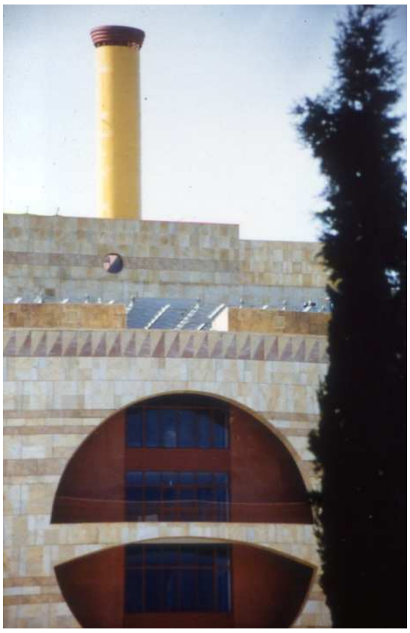

Figure 5. *Torre Triana* building. Architect Francisco Javier Sáenz de Oiza. Stucco coating

5.- Aesthetic benefits during his long useful life

Lime mortars - for its inorganic nature, the beauty of arid and mineral pigments, variety of colors and natural tones, variety of textures -bring a luminosity and aesthetic characteristics of unparalleled beauty. You just have to look at stucco or “jabelga” wall, in façade or inside, to be fascinated.

The different colors and shades of lime mortar, stucco mortar and “jabelgas”, are almost endless, because the color depends on mixtures of mineral pigments and proportions.

The finished textures are varied, playing with light and shadow, and can get to thrill.

Another feature of mortars, “jabelgas” and stuccoes, is that light is reflected colored; due to the internal structure of arid, siliceous or marmolina, plus the mineral pigment and lime. This quality causes the luminous and lifelike walls, unlike acrylic or synthetic paints that have a dull, appear dead. Therefore when using lime materials, architecture and the city has luminosity, which varies with the angle of incidence of the solar radiation, by hour of day and changing season. These materials are durable, and remain the colored luminosity over time, while contributing to sustainability. Do not repaint the dull walls, chipped, every so often to replace them.

It has to return to the beauty and luminosity had our cities when these materials were used. Today unlike the city has facades subdued, without luminosity, that deteriorate the city. Hopefully this fact is not a metaphor for the state in which we find those who live in them. By the way, change our facades, which affect us much.

6.- Potential for reuse

A lime mortar is also sustainable because it is recyclable. A mortar when it has served its purpose, its waste can be reused.

7.- Null toxic products

Lime mortar has no toxic products, since their raw materials are minerals and inorganic: lime, aggregate, mineral pigment and water.

8.- Epilogue

Lime eligible to verify if the architecture is sustainable and therefore also lime mortar, stucco and “jabelga”.

- Low energy of the materials provided to the work (extraction, manufacturing: the lower oven temperature does consume less than the cement manufacture. Transportation: that so abundant does not require long distances to transport. Application: Easy application, with a cost-efficiency, because is buttery, easy to apply).
- Durability. Is so durable that is sustainable, throughout the process in which the fine calcium hydroxide or lime mortar becomes “jabelga” calcium carbonate; to its degradation, last hundreds of years if lime is good.
- Do not generate waste or toxic emissions, moreover, is an environmentally friendly material that keeps balance with nature: 1 kilo of lime placed 150 grams of CO_2 removed, lessening pollution. Retrieves the CO_2 carbonated removing it from the contaminated atmosphere.
- It is sustainable because complete cycles, recyclable, a mortar when it has served its purpose, its waste can be reused.

In conclusion, lime and all their derivatives are excellent materials for restoration and building sustainable contemporary architecture.

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