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Eco-efficiency of plasters for rehabilitation and new buildings

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Abstract

A review of the current state of art for air-lime, gypsum and earth based plasters for rehabilitation and new buildings, in terms of eco-efficiency, is presented. These mortars belong to Portuguese traditional architecture, responding to compatibility criteria most of the time. This factor, combined with a possible positive response to eco-efficiency evaluation, would bring interest for their application in rehabilitation as well as in new construction. To assess eco-efficiency of plasters, the considered factors are linked to the environmental impact of these products and to their contribution for occupants well-being. Some qualitative results concerning embodied energy for these mortars in a "cradle to gate" approach analysis are shown. The lack of a common, standardized and shared procedure for this evaluation seems an evidence, above all when the attempt of comparing results from different studies is made. Furthermore, common and specific characteristics mostly related to contribution for indoor comfort conditions are presented, as indicators of technical efficiency of those plasters. The potential for behaving as moisture regulators and passive removal materials not only affect users, but can also have an important role in energy savings. Lastly, durability is considered a key factor of eco-efficiency mainly to meet the purpose of minimising exploitation of raw materials. For this reason it is important to consider protective treatments or finishing system, for improving durability, always keeping in mind all the elements of the equation.

Keywords: air-lime; gypsum; earth; embodied energy; hygroscopicity; IAQ; durability

1. Introduction

Plaster is an interior coating system for walls and ceilings made of mortar that can be applied in one or more layers. The surface of the exterior layer can be finished differently, being generally soft. Alternatively, specific finishing systems can be applied to consolidate, protect and decorate the plaster surface.

Commonly a plaster system has to meet requirements linked with the building but those requirements should not overlook the well-being of occupants. In case of new construction but mainly in intervention on existing buildings, compatibility with the materials in contact should be checked in terms of chemical, mechanical and physical properties [1]. Therefore, considering that traditional architecture is a significant part of the building stock of European countries, it seems possible to reduce the palette of materials used for plasters, so that compatibility criteria are respected also for traditional architecture. Air lime mortars were commonly employed in construction until the first decades of the 20th century performing such protective as decorative functions. Each air-lime based mortar can differ, depending on composition (the type and preparation of the air lime [2] and the aggregates used, the volumetric proportion between them, the water ratio, the use of mineral or organic additions, such as pozzolans or fibers, and admixtures such as natural fats), on the system, application technology and environmental conditions (number, type and thickness of mortar layers, manual or mechanical mixing and application, weather before and after application, which can strongly influence carbonation process) [3,4,5], to eventual application of a finishing system, its type and application technology. Several of the previous involve human factor. Even if there are many parameters to take into account when using air lime plasters, they are still the most adequate solution in many cases of rehabilitation [6]. In Portugal, as reported from Damas et al. [7] on a study on cases from the 1st to the 20th century, the presence of air lime as a binder for structural or protective function was often verified. In Roman times lime mortars were enriched with natural or artificial pozzolans, such as ceramic dust from crushed bricks to obtain hydraulic characteristics [8], whereas during Arabic domination of Iberian Peninsula, gypsum was mixed with air-lime and used for plastering [9]. In Portugal the period in which traditional gypsum plaster was mostly widespread was when *stucco* technique became popular. Actually, from the Enlightenment movement during the second half of the 18th century passing through Baroque and Romanticism until the ending of the 19th century, gypsum plaster was responding the most to decorative style needs of the period. Traditional gypsum plaster was prepared mixing air lime, gypsum and sand/marble powder in different volumetric proportions, varying from 3:1:1 to 1:0:0 (gypsum: putty lime: sand) depending on the coat to be applied (undercoat, preparation or finishing coat), the architectural and artistic period and the local know-how [10]. Apart from these binders, most of the vernacular architecture in Portugal refers to earth as main construction material. This can be seen in different regions of the country, following the different forms earth was used as a building material. Rammed earth and adobe masonry are the most common techniques from the southern coast of Portugal between Faro and Vila Real de Santo António, to the norther one that connects, with continue presence of adobe, the Lisbon southern area to Aveiro [11]. Where stone was available, stone masonry and rubble stone masonry were also common. In this scenario earth based mortars were used as well as air lime mortars, both compatible with the substrates. Earth-based mortars not only are compatible with earth and stone walls broadly present in those areas, but also to common masonry [12] but also have many advantages as efficient indoor plasters. For these reasons these plasters are awaking the interest of many studies addressed to improve their use for new construction, together with rehabilitation. Thus, plastering mortars based on air lime, gypsum or earth could fit the restoration requirements and, at the same time, perform well in modern or contemporary architecture.

2. Embodied energy

Nowadays there are important concerns with the environmental impact of each building material and the energy efficiency of building products and elements. The total energy of a building is defined as the sum of operational plus embodied energy. Embodied energy represents a significant amount of the total life cycle energy of a building, in some cases overcoming the operational energy. This phenomenon is often linked with the requirements for nearly zero energy buildings that low down the energy request during the operative life of a building, so that embodied energy is taking the larger role of total estimation. Thus, the need of a protocol to evaluate embodied energy is increasing [13]. Even if this indicator for buildings materials can be calculated through various tools, as a part of Life Cycle Assessment (LCA) supported by Standards ISO 14000 family, according to Dixit et al. [13], there are still many difficulties in obtaining comparable results due to the lack of standardization for energy measurement process. Some of the parameters of still uncertain calculation figured out from the researchers are: system boundaries, methods of measurement, geographic location, primary and delivered energy, age of data sources, sources of data, data completeness, technology of manufacturing processes, feedstock energy consideration, temporal representativeness. Due to the complexity and uncertainties still associated with LCA, Giama et al. [14] considered eco-labelling as a simple instrument which can play an important role in giving a direct awareness of the environmental impact of a product. Carbon Footprint Analysis (CFA), an analysis "cradle to gate" with the objective of mapping greenhouses gas emissions, according to the study, could be easier to apply to small and medium enterprises and speed up the process of eco-labelling.

In this scenario each binder, as the composites produced with it, has a different impact on the environment. Taking into account only the energy used in the manufacturing process plus the possibility of reuse, it appears as an evidence that earth-based plasters respond to requirements of low environmental impact and low embodied energy. According to Melià et al. [15] from the measurement of different indicators of the environmental impact of an earth based plaster compared with hydraulic lime and cement based ones, a big difference between those plasters exists. From data reported, for example, for 1 Functional Unit (FU) - as defined in the study - of plaster, the Cumulative Energy Demand (CED) calculated is 22.7 MJ for earth while for hydraulic lime and cement corresponds to 52,8 MJ and 45,5 MJ respectively. CED is the measure of direct and indirect energy requested for the entire cycle of the product, which in this case corresponds to an analysis *cradle to gate* for the boundaries chosen. Gypsum plasters also present low embodied energy mostly due to the low calcination temperature of the binder (120-180ºC). However, there are many factors influencing this evaluation. For example in Spain a research stands out how a higher volume of production can lower the environmental impact per ton of material [16][7]. Same researchers compared environmental impact of gypsum production in case of choosing raw material rather than recycled from plasterboard waste or from gypsum powder dust. As a result of this analysis *cradle to gate* the recycled gypsum powder results the less impactful even without considering the benefits that recycling could bring in the *end of life phase*. In comparison to earth and gypsum, air lime plasters show higher embodied energy, depending on the higher temperatures required for production (~900ºC), but still lower than cement [17]. However, the durability and predicted life time of these plasters are different and these differences should be taken into account in a complete LCA. The existing methods for running the analysis are still inaccurate and incomplete and the obtained results are often not comparable one another. In Table 1 are reported data of the previously referred studies which analyse the environmental impact and energy demand for production of these coating. Boundaries correspond to a *cradle to gate* scenario and producers are the sources of data. The age of data sources, the functional unit (F.U.) chosen, the methods of measurements and impact categories are all different, so that the output of the analysis are not comparable.

Table 1. Comparison of studies on environmental impact for the production of coatings based on lime, gypsum and earth, all conducted after the ISO LCA standards update.

Year	Ref.	Coatings	F.U.	Unit	Methods	Indicator/Impact category	Software
2006	[17]	Mortar based on: Hydrated Lime; Hydrated Lime plus Metakaolin.	1 ton	kg CO_{2eq} kg SO_{2eq} kg PO_{4eq} kg SPM_{eq}	Eco-Indicator95	Global warming effect, acidification, eutrophication, winter smog.	unknown
2014	[15]	Base / Finishing plaster based on: Earth; Hydraulic Lime.	1m^2 x 15 mm	MJ	CED 1.08	Energy from renewable and non-renewable sources.	SimaPro7.3.3
				kg CO_{2eq}	GGP 1.01	Greenhouse gases in atmosphere.	
				m^2 x year	EF 1.01	Land occupation.	
				Point	ReCiPe	Human health, ecosystem diversity, resource availability.	
2015	[14]	Plasterboard.	1 kg	kg CO_{2eq} kg SO_{2eq} kg PO_{4eq} kg C_2H_{4eq} MJ	CML 2 baseline 2000	Climate change, acidification, eutrophication, photochemical oxidation, embodied energy.	SimaPro, GEMIS
				%	Eco-Indicator95		
2020	[16]	Gypsum plaster made with: Natural gypsum; Recycled gypsum from plasterboard; Recycled gypsum from powder.	1 ton	%	IMPACT 2002+	Carcinogenic and non-carcinogenic effects, photochemical ozone formation with respiratory organic effects, abiotic depletion due to mineral extraction, global warming, ozone depletion, acidification, eutrophication, land occupation, non-renewable energy, respiratory inorganics.	SimaPro8.5
				milliPoint		Human health, ecosystem diversity, climate change, resource availability.	

3. Indoor performance

The optimization of multifunctional plasters is a topic of big innovation, even if these composites have been used in construction for millennia. For some decades, mortars used for plastering are rousing researchers' interest with the aim to profit from technical characteristics that were not considered in the past, such as hygroscopic behaviour [18] and contribution for indoor comfort and occupants' health.

3.1. Hygroscopic behaviour

By its hygroscopic behaviour, a plaster can comply with double function since, on one hand, can contribute to avoid the growth of fungi and moulds, guaranteeing a better indoor air quality and, on the other hand, can integrate a passive regulation of temperature and relative humidity (RH), with the target of minimising the energy request to meet this purpose. The cyclic adsorption/desorption mechanism can allow a passive control of the RH in the interior ambient which can improve also thermal sensation of comfort. Already many researches have been run in this direction with calculation of moisture buffering value of building materials, for example as defined by the NORDTEST protocol [19], under controlled conditions of temperature (23°C) and RH variations (33%-75%). But still these tests are set with laboratory control. What happens in real conditions? In the study from Liuzzi et al. [20] the same scenario, with or without HVAC system, is modelled. Various systems are tested as plaster for a reference room, placed in a Mediterranean climatic area, with established boundary conditions. Numerical simulation run with WUFI+ points out that in free running conditions an earthen plaster with addition of straw can significantly reduce the amplitude of fluctuation of indoor RH both in summer and winter, providing important benefits, whereas with HVAC system not big differences are registered in terms of contribution to energy savings and indoor comfort. Hygroscopic behaviour of gypsum plaster was also tested by WUFI+ model and by real validation experiment [21] showing in both cases a good moisture buffering behaviour, with a reduction of the peak with maximum moisture production from 70% to about 50% RH. However, a laboratory study [22] shows that the impact of gypsum plasters on hygroscopicity may be lower than earth plasters.

3.2. Indoor Air Quality contribution

After the discovery of the connection between some illnesses and a poor Indoor Air Quality (IAQ), a big focus has been given to the emission of Volatile Organic Compounds (VOCs) from buildings' materials. Primary and secondary emissions have been tested for many common materials to classify them in terms of toxicity and eventual capacity to act as passive removal materials. Plasters based on clayish earth, air lime and gypsum are considered as low emitting (primary) sources and, in terms of secondary emissions, results seem to be also good, allowing to consider their eventual application for contributing to the well-being of occupants. Da Silva et al. [23] tested many coating materials and, among them, a lime plaster. The lime plaster showed a good sink effect, which is the capability of capturing formaldehyde or VOCs, justified by its porous microstructure and interaction between silicon dioxide (from the aggregate) and analysed compounds, concluding that this composite has good potential for acting as a passive IAQ improver. There are many factors to consider in this kind of analysis as deposition velocity and reaction probability [24], but researchers have been studying this phenomenon since long time [25]. Earth based plaster [26] also present a really good aptitude to be used as Passive Removal Material (PRM) of ozone such as unpainted gypsum [27]. Those materials could implement a control strategy for indoor pollutants, allowing to decrease ventilation rates and, therefore, saving energy.

4. Plaster system and durability

Low embodied energy plasters with different binders, especially earth-based ones, are awaking more and more interest in construction practice especially due to those aspects listed above, even if there are still some characteristics that is possible to improve for guaranteeing a greater durability, as well as superficial cohesion, surface hardness or resistance to liquid water. It should be considered, in case of analysing earth based mortars, that there are many factors influencing their properties, above all clay mineralogy, but also microstructure linked to the type of sand added, in terms of particle size distribution and chemical nature, and amount of mixing water needed [28].

To increase predicted life time of plasters it is possible to resort to the use of additions in formulation or complementary finishings, such as paintings or protective treatments (to consolidate the surface or to provide other characteristics such as a different colour) [29] or thin paste layers. Bio-treatments have been interesting researchers for the past years with the aim of improving the properties of many building materials. Also bio-treatments for lime plaster [30] and earth plaster have been studied [31] with very good results in terms of surface cohesion and resistance to water absorption, combined with no significant visual alteration of the final appearance. The finishing systems or the additions can have a strong influence on the plaster system characteristics, namely on hygroscopic behaviour, capture of pollutants and LCA.

5. Conclusions

Plaster based on gypsum, air lime and clayish earth mortars respond to eco-efficiency parameters presented in this review. These mortars show high compatibility with actual building stock, always to be checked from case to case, together with good expectation for new applications. Due to the low, relatively low or null temperature required for production, the availability on the territory and their potential of being recycled, environment impact of these mortars seems to be significantly low. Apart of this it has been proved that all the plasters made with these mortars are low emitting products which, together with some specific properties as hygroscopic behaviour and capability to remove pollutants, may turn them in multifunctional plasters. In this context not only well-being of occupants is considered, but also the possibility of energy savings.

Durability is considered as an important characteristic since nowadays, to extend the expected life of construction products has a big relevance for eco-efficiency evaluation. There are, however, still many issues that need more investigation, particularly linked with the use of finishings (surface treatments such as paints or thin coating) or addition in formulation, once that could modify the behaviour of the new system and increase or reduce the benefits here reported. Therefore, further investigation is needed.

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