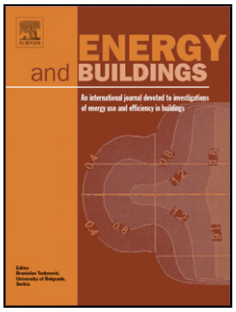

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# Effectiveness of mortars composition on the embodied carbon long-term impact

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## Abstract:

Refurbishment activities represent more than 17% of the saving potential of the EU up to 2050. However, studies on buildings structure and finishing reparation of rendering mortars using LCA are still lacking. An innovative design approach is required to drive the minimisation of embodied carbon using objective performance information of buildings behaviour. This research work is focused on the reparation of rendering mortars and intends to demonstrate that the choice of mortars for buildings affects the maintenance actions needed and can increase the construction environment liability and embodied carbon expenditure. A new leaching risk analysis combined with LCA of different mortars composition (cement and lime based) was implemented enabling to predict the longevity of the rendering and the embodied carbon expenditure on 20th century buildings. It is demonstrated that some mortars may have a higher impact at the outset, such as cement-based mortars, but result in a much lower impact across the building service life. The embodied carbon of repair actions of mortars similar to OPC are expected to reduce the environmental impact of rendering repair actions at least in 10 times in comparison to less hydraulic mortars.

**Keywords:** performance based-design; embodied carbon expenditure; rendering mortars; LCA

## 1. Introduction

40% of the total energy consumption in the EU is consumed by the buildings. The rate of new construction will remain generally low and the existing buildings will be working for the next 30 years. The oil crisis forced the implementation of buildings energy saving measures and in a near future, they shall be nearly zero-energy consumption buildings. However, the slow renewal rate of the buildings makes vital their rehabilitation.

Currently only at 1.2% of the European building stock is renovated per year, meaning that the biggest challenge reducing energy use in buildings is to increase the rate, quality and effectiveness of building renovation. To do this it is necessary to reduce the costs and to increase the speed to minimise disturbance for occupiers and city users – highly associated with the effectiveness of maintenance actions. To achieve an ambitious increase of the renovation rate (up to 2 - 3 % per year until 2030, according to the European Performance Building Directive (EPBD)), effective solutions need to be extensively demonstrated and replicated [1,2].

Regarding the high levels of carbon dioxide in the atmosphere, the European Commission target is to reduce the $CO_2$ emissions by 90% for the building sector by the year 2050 [3].This would mean retrofitting 80% of the 25 billion $m^2$ of the current useful floor space in EU-27, Switzerland and Norway around the European territory [4]. Therefore, it is demonstrated that the renovation of buildings has a high capacity to influence the environmental impacts and global objectives of climate change mitigation. In fact, the refurbishment of existing buildings represents more than 17% of the saving potential of the EU up to 2050 [4].

From a rehabilitation point of view, the energy requirements for buildings is obviously a function not only of the users and standards/regulations requirements, but also a function of each building rehabilitation technique used. Special attention must be paid to the environmental impact of each constructive solution and embodied energy consumed during construction and operational phases, without neglecting aspects associated with the durability and the service life of the construction [5- 7].

Currently, buildings account for some 45% of carbon emissions and it has been estimated that 80% of the buildings that will be occupied in 2050 have already been built [6-8]. However, EU does not have regulation on embodied energy/carbon. Nevertheless, there are some countries that intend to achieve a substantial reduction in carbon emissions by 2050. In Portugal, for example, there is an effort to reduce carbon emissions, where a decrease of 1 million tonnes of $CO_2$ emissions resulted from the reduction in the use of coal-fired electricity (between 2012 and 2013) [9].

To achieve the goal of reducing $CO_2$ emissions, a life cycle approach is required to quantify the potential environmental impact of a product or a service. The life cycle assessment (LCA) is defined in the ISO 14040:2006 [10] and ISO 14044:2006 [11] standards.

The importance of a LCA analysis, to select the optimum constructive material/system, increases when it is correlated to the energy use of the building. This is particularly important as buildings use larger quantities of materials and systems to achieve minimum energy consumption or even “zero energy” in operation. It also enhances the need of a new design approach to drive the minimisation of embodied carbon through objective performance information of building behaviour, meaning that the effectiveness of a low carbon project should be judged by its energy in use together with the specific needs of the buildings[6, 8, 12,13].

From the LCA point of view, most of the studies are carried out in buildings that have been designed and constructed as low energy buildings, but there are very few studies on “traditional buildings”, such the ones from the 20th century, which are the most common buildings in cities. Thus, this enhances the importance of studies related to the application of LCA in current buildings, together with their building energy analysis from a rehabilitation purpose [8, 12]. Those techniques are only efficient and effective if an integrated design process approach is used and optimised.

Recent LCA advances indicate that the global tendency is to build buildings with lower energy demands in the operation stage, which means that the relationship between the materials embodied energy and the operational energy (20%–80%) is changing in such a way that 40% of the impact is related to materials and 60% is related to the operational stage [13].

The comparison of the environmental impacts before and after refurbishment is made by the majority of LCAs focused on refurbishment. From the other side, almost none of the LCAs study the environmental impact of building system repairs, such as structural or finishings. The more frequently studied life cycle stages are those related to the manufacturing and use phases. Studies on building refurbishment using LCA are still lacking [6; 14-16].

Many buildings have rendered facades. Sometimes renders are protected by paint systems, with low durability, exposing the render and increasing refurbishment needs. Therefore, the use of rendering mortars, a product which needs frequent repair and is largely used by the construction segment, causes significant environmental impacts. Starting by its composition, formed by non-renewable raw-materials (cement, lime and sand), and, secondly, by the reduction of its service life -which increases maintenance actions need - due to the environmental exposure and subsequent weathering, with lack of adherence to the substrate or leaching phenomenon, increasing the civil construction environmental liability. For that reason, the repair, maintenance and sustainable use of mortars is very important when it comes to building preservation.

Hence, maintenance of building fabric must be undertaken to address the perspective of environmental impact and economic costs of existing built environment. Besides this, the protection must be undertaken since it is reflected in the fact that 50% of Europe’s national wealth is condensed within its existing built environment [17]. Lack of regular maintenance leads to early deterioration and can widely reduce the value of these existing assets.

In fact, one material may have a higher impact at the outset but result in a much lower impact across the building service life. Therefore, this research work intends to demonstrate that the choice of rendering mortars is a function of the long-term environmental impact, from a longevity of maintenance intervention perspective and embodied carbon expenditure. An innovative leaching risk analyses of different mortars composition was implemented, enabling to predict the longevity of the rendering and the embodied carbon expenditure of each solution on 20th century buildings. The justification for the interest on the correlation of maintenance and environmental impact is the fact that refurbishment activities represents more than 17% of the saving potential of the EU up to 2050.

## 2. Longevity of repair and embodied carbon expenditure

Figure 1 presents the broad areas of a building's life cycle, with the proportion of $CO_2$ emissions the construction industry can influence. A substantial proportion of these carbon emissions have been attributed to the operation as well as the maintenance and repair of existing buildings.

The Figure shows that operation stage represent 82% and design stage plus prescription of construction materials represent 16% of the overall proportion of $CO_2$ emission in the construction sector [19].

The choice of coating materials for walls such as ordinary cement or lime based mortar renders can influence embodied impacts (energy and carbon), but also construction methods, operational use, maintenance cycles and building service life, and all these issues should be considered. In the maintenance context, the service condition and expended embodied carbon ($CO_2$ emission) for each mortar repair action of a generic model are illustrated in Figure 2. Each maintenance intervention is characterized by its longevity (l) (red line) and embodied carbon (Ce) (blue stepped dotted lines). Therefore, repairs with high life expectancy are of low carbon impact and are "green" maintenance type [17].
The cumulative effect of "non-green" maintenance increases the total embodied carbon expended far more quickly than "green" maintenance and does not attain required longevity.

The more frequent the maintenance intervention, the higher the embodied carbon expended.
By multiplying the total repaired mortar area ($m^2$) with the embodied carbon expenditure for repairing $1m^2$ wall for each repair technique, within a selected maintenance period (lets say 100 years), it is possible to obtain the cumulative embodied carbon expenditure (SUM Ce) (eq. 1). The expected carbon emission is calculated assuming that no major advance of manufacturing technology of mortars is going to be implemented in the future.

$$SUM\ Ce = \sum_{i}^{n} Ce_i \quad (1)$$

Where:
n = number of interventions for an arbitrary value of 100 years;
$Ce_i$ = embodied carbon expenditure for the $i^{th}$ maintenance intervention ($kg.CO_2e/(kg/m^2)$) evaluated within selected "cradle-to-gate" boundary of LCA.

The reduction of mortars service life increase maintenance actions need mainly due to the lack of adherence to the substrate or due to the leaching phenomenon [20; 21].
Several factors influence adherence such as nature of the substrate (roughness, capillary suction and initial moisture content) and type of coating material (materials composition, thickness, age, and weather conditions during application). The loss of adherence leads to mortar detachments and this may affect service life [22].
Furthermore, rendering materials used in building walls are exposed to higher risk of binder leaching and consequent deterioration, because they could be saturated for longer periods [23;24]. Therefore, it is expected a substantial increase of maintenance actions and cumulative embodied carbon expenditure for an increasing leaching phenomenon.

## 3. Minimisation of embodied carbon through objective performance data

### 3.1 Leaching effect and the expected embodied carbon expenditure

Binder leaching (Figure 3) studies only started very recently and the authors of these research works [25-29] present a quantification of the rate of deterioration in uncarbonated and carbonated lime and cement mortars.

Several authors reported the beneficial effect of ultra-fine particles of pozzolanic silica on the leaching behaviour of Portland cement and consequent deterioration [25; 26]. However, most experimental studies of the leaching effect on the mechanical properties of cementitious materials are investigated for bulk materials and show that the strength of the samples is significantly reduced after dissolution of the hydrates [27-29]. The effect of leaching on the interfacial transition zone (ITZ) (Figure 4) - an additional phase introduced by the presence of aggregates - remains little studied in the scientific literature even though the presence of aggregates should influence the leaching process and mechanical behaviour of leached concrete [27; 28].

Currently, it is known that the binder components vulnerable to dissolution are mainly portlandite ($Ca(OH_2)$) and calcite ($CaCO_3$) [30]. This means that higher hydraulic lime binders should be less susceptible to dissolution [31].
Since the facades covered with mortars (rendered) could be subjected to leaching phenomena, it is necessary to find the best rendering solution that can minimise maintenance repair interventions by increasing the mortar service life.

In general, it is expected an increase of mortars mechanical strength with the decrease of open porosity [27-29]. A higher cement ratio and a higher tensile and compression strength could indicate a lower proportion of $Ca(OH)_2$ and $CaCO_3$ available in the hardened mortar, minimising the potential for binder loss due to leaching effects. However, regarding the interfacial transition zone (ITZ) it is known that the porous transition zones formed at the aggregate-paste interfaces affects the pore size distribution and the mortars permeability [32]. ITZ is characterized by a higher porosity in comparison with the bulk paste and a high concentration of portlandite.
Jebli et al. [27] demonstrated that there is a strong impact of chemical degradation on mechanical behaviour, more marked in the case of tensile soliciting the paste-aggregate interface. Regarding the compression test, the force at rupture is less affected.

### 3.2 Cross-correlation between leaching effect and LCA

Based on experimental tests values and existing state of the art regarding the potential for binder loss from several mortars and its effect on properties and performance [25-29], different mortars compositions based on cement and lime where studied from a leaching perspective: NHL2, NHL3.5 and NHL5 mortars; Ordinary Portland Cement (OPC) mortars with and without silica fume. The effect of leaching at the ITZ interface between aggregates and cement paste in a mortar (ITZ-OPC) was also analysed. The optimum solution was selected in face of its expected leaching depth in 100 years.

The authors presented several test results and determined the rate of portlandite leaching in a range of mortars, using ammonium nitrate, and assessed the effect on strength and moisture handling characteristics.
If the leaching process is diffusion controlled, then the leached depth h is proportional to the square root of time, according to equation 2.

$$h = kt^{1/2} \quad (2)$$

Where:

h is the leaching depth (mm);

k (mm/day½) is an index of resistance to leaching that is a function of the materials composition the chemical environment;

t is the time (days).

The results for the leaching tests of several mortars are presented in Table 1. Carbonated and uncarbonated lime based mortars are compared to cement based (bulk zone and ITZ). It was adopted an acceleration factor of 100 for cement based mortars and 20 for the leaching tests of NHL based mortars [25].

The results suggest that hydraulic mortars such as Ordinary Portland cement mortars (OPC) present the highest resistance to leaching and that feebly hydraulic mortars such as NHL2 or NHL3.5 had the lowest resistance. Furthermore, it is observed a proportion between the resistance to leaching and compressive strength, which according to the previous references could indicate a lower proportion of $Ca(OH)_2$ and $CaCO_3$ available in the hardened mortar, minimising the potential for binder loss due to leaching effects.

In the leaching phenomenon, the assumption made was that mortar compositions had the objective to achieve a service life of 100 years. To select the best repair solution using one of those mortars, the probability of reaching a leaching depth of 10 mm was calculated as a function of the mortar service life. Therefore, it was assumed that k presents a lognormal distribution with a CoV (coefficient of variation) equal to 20%, as the majority of construction materials physical characteristics. Then, the Monte Carlo method was implemented by assigning a probability distribution to each input parameter under consideration. The objective is to ensure higher mortar durability by controlling the leaching depth and this behaviour could be improved throughout the intended mortar selection and optimisation.

The implementation of the cited method was carried out with new values randomly selected and 100000 generated values for each random variable.

In this method, it was adopted the following limit state function g(x) (eq. 3):

$$g(x) = t_L - t_g = \frac{\left(\frac{h}{k}\right)^2}{365} - 100 \quad (3)$$

Where:

h is the leaching depth (mm);

k (mm/day½) is the index of resistance to leaching;

$t_L$ is the design life time of each mortar in years;

$t_g$ is equal to 100 years (the target value).

The probability of failure may be expressed as the probability that the limit state function is negative: $Pf=P[g(x)<0]$. Figures 5 and 6 present the probabilistic calculus of the design service life of different mortars for a leaching depth of 10 mm.

From Figs. 5 and 6 there are significant differences for each mortar composition if the effect of leaching is regarded. The previous results demonstrate that cement mortars present enhanced performance when compared to natural hydraulic lime-based mortars. Considering the same level ofPf, there is an increase in the design service life values for an increasing hydraulicity which means that cement based mortars present an expected service life 10 times higher than NHL mortars.

Figure 6 shows the expected service life to achieve a leach depth of 10 mm in 10% of the situations for a NHL5 mortar, a mortar where the interface between the cement paste and the aggregate has influence on the leaching effect (ITZ-OPC) and the service life of an ordinary cement mortar (OPC). If the porous transition zones formed at the aggregate-paste is relevant, NHL mortars will present a decrease of service life in comparison with OPC mortars.

Table 2 present the time to achieve a leach depth of 10 mm in 10% of the situations (Pf= 10%) and the expected number of severe repair actions.

Based on existing detailed LCA tools such as SIMAPRO [33] and on Bath Inventory of Carbon and Energy (ICE) [34] a wide range of environmental aspects of building materials could be aggregated and quantified in the inventory analysis into a limited set of recognizable impact categories (e.g. global warming, ozone depletion, acidification). Cement, natural hydraulic lime, aggregates and water data were adapted from the Ecoinvent v.2.2 database, by switching into the Portuguese energy grid, since such processes were considered as sufficiently adherent to national practice.

Because of the lack of temporal information, LCA here relies on restricted steady-state models – the ones adopted for the current research. However, this dependence is considered to be an important limitation of LCA because it could decrease its accuracy. One simple example is the fact that releasing a big amount of pollutant instantaneously generally does not have the same impact as releasing the same amount of pollutant at a small rate over several years [35]. Based on this information, Table 2 also present, for each mortar, the expected Embodied Carbon expenditure for the all maintenance interventions (kg $CO_2$ equiv./ $m^2$) evaluated within selected “cradle-to-site”.

In this situation, the comparison took into account the average values of LCA since the bridge between mortars service life and LCA was made using average values of expected maintenance/repair actions for a period of 100 years. The previous results show that rendering mortars used to coat external walls by being saturated for longer periods are exposed to higher risk of binder leaching and, therefore, a substantial increase of maintenance actions and cumulative embodied carbon expenditure is expected.

The LCA results show that NHL-based mortars present at least 15% less embodied carbon than cement based mortars. However, the leaching resistance of cement mortars is more than 10 times higher than NHL-based, which means that the Total Embodied Carbon of lime based during a period of 100 years is not an advantage. The embodied carbon of repair actions of mortars similar to OPC are expected to reduce the environmental impact of these actions at least in 10 times in comparison to NHL-based mortars, which means that this traditional solution must be preserved and included as a green solution for masonry rendering.

Of course, this is valid for rendering mortars applied on compatible supports – mainly buildings built in the cement era (mainly since the beginning of the 20th century). The compatibility of cement mortar renders with older buildings could not be achieved easily and reversibility of interventions would be jeopardized [36].

## 4. Conclusions

Almost none of the LCAs studies the environmental impact of building system repairs, such as on structure or finishings. Studies on building refurbishment using LCA are still lacking. The authors address critical issues to enable more robust comparisons of mortars selection for rendering purpose. Therefore, this research work intends to demonstrate that the choice of rendering materials is a function of the long-term environmental impact, from a longevity of maintenance intervention perspective and embodied carbon expenditure. It was implemented an innovative leaching risk analyses combined with LCA of different mortars composition enabling to predict the longevity of the rendering and the embodied carbon expenditure of each solution. In this context, the following facts may be highlighted:

- The repair, maintenance and sustainable use of mortars is very important when it comes to buildings´ preservation.
- The more frequent the maintenance intervention, the higher the embodied carbon expended.
- It is demonstrated that the application of mortars that have a higher impact at the outset, such as cement based, may result in a much lower impact across the building service life. Furthermore, if the porous transition zones formed at the aggregate-paste interfaces is relevant, it may affect the pore size distribution of the mortars and their service life.
- It is shown that there are significant differences for each mortar composition if the effect of leaching is regarded. The results demonstrate that cement mortars present enhanced performance when compared to natural hydraulic lime-based mortars.
- Considering the same level of probability of failure Pf, there is an increase in the design service life values for an increasing of the hydraulicity.
- The embodied carbon of repair actions of mortars like OPC on compatible substrates are expected to reduce the environmental impact of rendering repair actions at least in 10 times in comparison to less hydraulic mortars.
- However, it should be highlighted a dynamic LCA could increase the accuracy of the results and further work must be developed.

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Figures

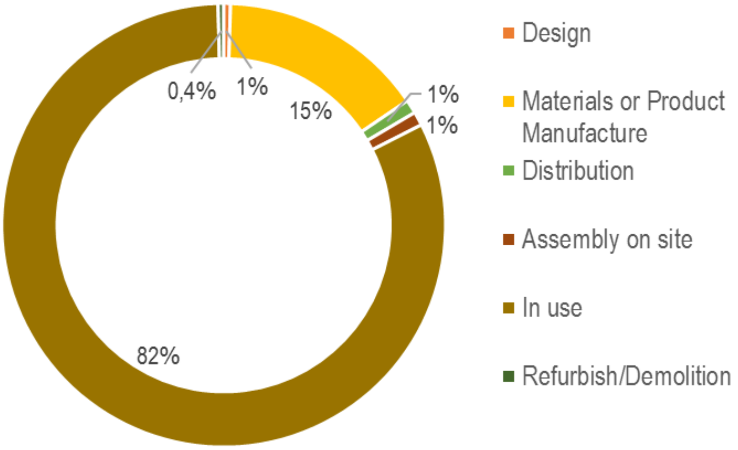

**Figure 1** - Broad areas of a building's life cycle, with the proportion of $CO_2$ emissions the construction industry can influence [18].

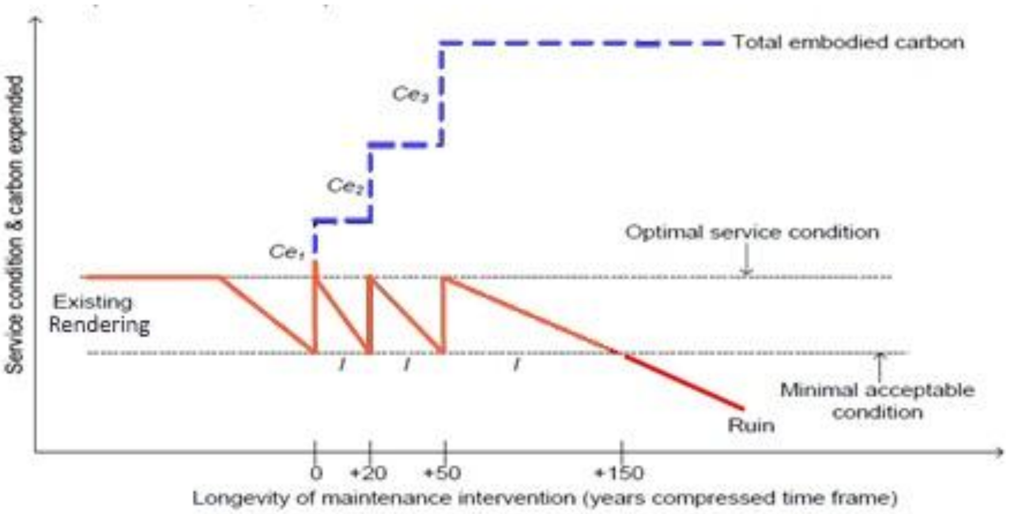

**Figure 2 -** Relationship between longevity of repair and embodied carbon expenditure (based on [17]).

**Figure 3 –** Example of mortar binder leaching in a building.

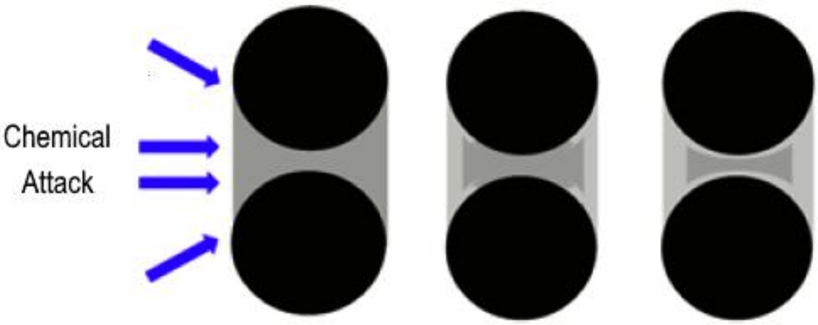

**Figure 4 -** Diagram of the degradation evolution of the composite at the ITZ and the bulk paste (based on[27]).

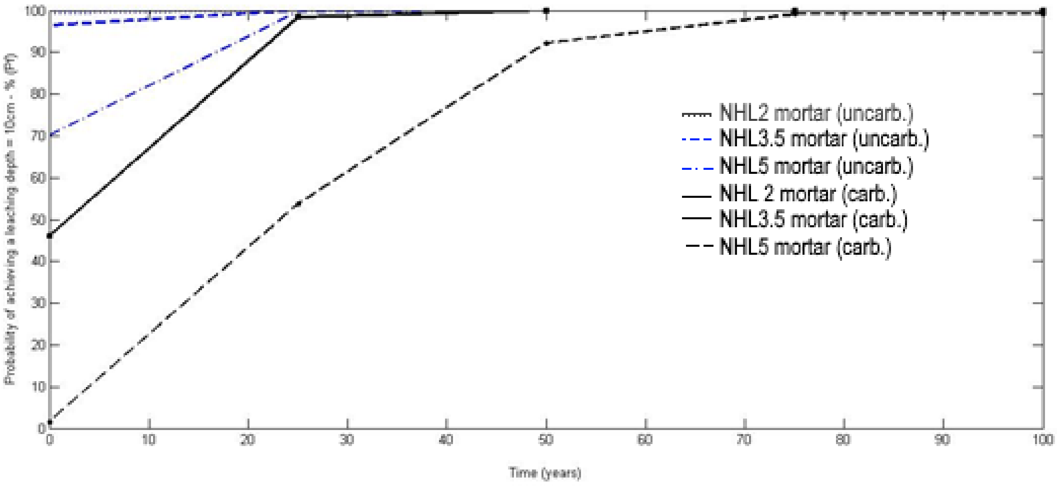

**Figure 5 -** Design service life of natural hydraulic lime mortars (uncarbonated NLH represented by the blue lines and carbonated NHL represented by the black lines) for a leaching depth of 10 mm.

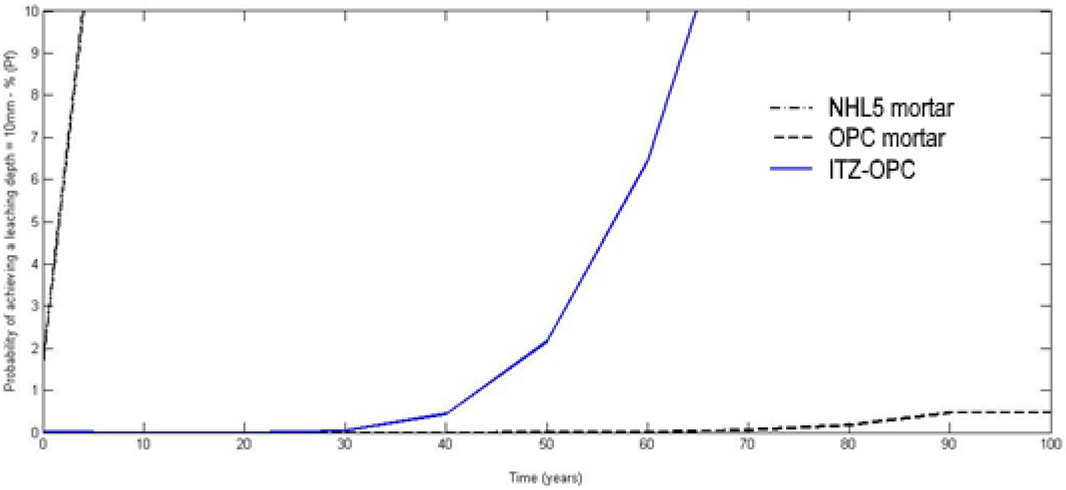

**Figure 6 -** Design service life of NHL5 mortar (left side, almost superimposed with Y-axis), ITZ-OPC (middle) and OPC (right side) for a leaching depth of 10 mm.

**Table 1 -** Resistance to leaching of lime and cement based mortars (uncarbonated * and carbonated **) (based on data from [25-29]).

| Mortar | k (mm/day$^{1/2}$) | Compressive strenght (MPa) | Flexural strenght (MPa) |
|---|---|---|---|
| * NHL 2 | 3,1 | 0,72 | 0,27 |
| * NHL 3.5 | 2,8 | 2,72 | 1,02 |
| * NHL 5 | 2,3 | 2,45 | 0,94 |
| ** NHL 2 | 2,09 | 1,42 | 0,1 |
| ** NHL 3.5 | 2,09 | 2,2 | 0,18 |
| ** NHL 5 | 1,52 | 2,45 | 0,51 |
| ITZ-OPC | 2 | 27,1 | 3 |
| OPC | 1,46 | 52 | _ |
| OPC- 0.8% sílica | 1,37 | 53 | _ |
| OPC- 3.8% sílica | 1,13 | 60 | _ |

**Table 2 -** Resistance to leaching, expected number of repair actions and total embodied carbon for all mortars repair action.

| Mortar | Time to leach depth of 10mm in 10% of the situations (Pf= 10%) | Nº important repair actions | Total Embodied Carbon (kg |
|---|---|---|---|

| | | | **CO$_2$ equiv./ m$^2$)** |
|---|---|---|---|
| * NHL 2 | 2 years | 50 | 600 |
| *NHL 3.5 | 8 years | 13 | 169 |
| * NHL 5 | 10 years | 10 | 150 |
| ** NHL 2 | 10 years | 10 | 120 |
| ** NHL 3.5 | 10 years | 10 | 130 |
| ** NHL 5 | 10 years | 10 | 150 |
| ITZ-OPC | 65 years | 2 | 26 |
| OPC | 100 years | 1 | 13 |
| OPC- 0.8% sílica | >100 years | 1 | 13 |
| OPC- 3.8% sílica | >100 years | 1 | 13 |