Possible Utilization of Used Precast Building Elements Through Consideration of Concrete Carbonation Degree

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Abstract. Significant changes in the strategic goals of the construction sector at the global level have been visible in recent years. By implementing the fundamental principles of sustainable development and circular economy, the modern construction industry tries to contribute to a healthier environment by reducing CO2 emissions, minimizing waste landfills, and preserving non-renewable natural resources. The possibilities of reusing prefabricated concrete elements of existing buildings instead of their traditional recycling on a material level or disposing of them in landfills are analyzed in this paper. Special attention in the research was placed on the carbonation of prefabricated reinforced concrete elements of buildings, as it is one of the most frequent processes that accelerate the deterioration of RC structures. Long-term carbonation processes inevitably result in reinforcement corrosion and accompanying damage to the concrete cover, therefore some constrains for the further use of prefabricated RC building elements must be precisely defined. In this study, the potential use of prefab RC building elements was determined by calculating the depth of carbonation while taking into account the age of buildings and environmental conditions (relative air humidity, position of prefab element). Depending on the thickness of the carbonized concrete and the type and intensity of damage to the reinforcement and concrete, various variants for further use of the dismantled prefabricated RC building elements were proposed (reuse without restrictions, use in the interior of new buildings, use in less demanding facilities, reuse after application of a protective coating, replacement of the protective cover and reuse etc.).

Keywords: Concrete · Buildings · Service Life · Carbonation · Reuse · Circular Economy

1 Introduction

Concrete is the most consumed material in the world, with almost 30 gigatons of annual demand. In Europe, concrete waste alone contributes about 30% of the total mass of solid waste [5]. With an ever-growing demand, concrete production today accounts for a high share of air pollutants [7], and both the extraction of its raw materials and the landfilling of its waste threaten landscapes, biodiversity and ecosystems.

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There are several well-known strategies to reduce the Detrimental Environmental Impact (DEI) of the concrete industry, but more stringent application of these strategies and the development of new ones are needed as the direct CO_2 intensity of cement production globally increased by 1.8% per year between 2015 and 2020 [5].

The utilization of Circular Economy (CE) strategies can contribute to further limitation of waste accumulation, prolong the use of concrete, and introduce material recovery loops (Fig. 1). CE strategies should be implemented as follows:

– Extend the use of structures as long as possible without modification,
– Repair or rehabilitate them if needed,
– If building removal is unavoidable, deconstruct it and reuse its pieces in another project with minimal reprocessing,
– If components are not reusable, recycle them into the manufacture of a similar or different product by crushing and downcycling it as backfilling material in excavated areas and engineering works [11] or as replacement of natural aggregates in recycled aggregate concrete.

Extending the use and/or reuse are strategies to prioritize over recycling as they prolong the service life of existing products. Reusing reduces the demand for new ones and waste generation.

Strategic reuse of demounted concrete elements in new buildings may be one of the solutions that will support the transition to circular construction. To ensure wider application of concrete reuse, it is necessary to develop a methodology for the assessment of the structural condition of existing buildings, and the selection of elements suitable for reuse, including guidelines for their disassembly, storage, and installation. However, one of the main obstacles for wide application of concrete reuse is the uncertainty concerning the remaining service-life of concrete elements and evaluation of quality over the future service-life in a new building. [9].

All structures must maintain their key performance indicators like load-bearing capacity, fire resistance and etc. over time. The service life is obviously affected by the material/product quality which is decided at the design and production stage in relation to the intended use, target environment conditions and the expected level of performance required over the service life. The end of service life can be detected by the loss of performance that results from aging, frequent failures, and increased repair expenses [9].

Because of their durability, most concrete and masonry buildings are demolished due to functional obsolescence rather than deterioration. However, a concrete shell or structure can be repurposed if a building use or function changes or when a building interior is renovated. Concrete, as a structural material and as the building exterior skin, has the ability to withstand nature's normal deteriorating mechanisms as well as natural disasters [8].

Obsolete buildings are often structurally sound before their transformation or demolition, and the same is true for their load-bearing components once extracted. Indeed, buildings, especially in urban areas with high land pressure, are typically demolished for reasons unrelated to material grade and structural performance [5]. Their load-bearing systems are generally well protected from weathering during their service life, and their components, mostly concrete, could be used longer, that is, reused in new projects.

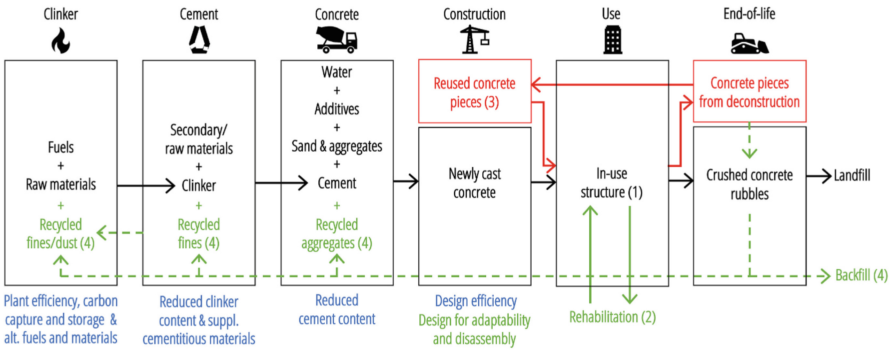

Fig. 1. Concrete value chain. In black, conventional concrete production and service cycle. In colors, trategies to lower the DEI of concrete: direct strategies in blue, circular strategies in green, circular reuse strategies in red. Numbers indicate the circular strategy priority to lower DEI. Adopted from [5].

Reuse is the second step in the waste pyramid after prolongation of the service-life due to preservation of the embodied value and, as such, it has minimal impact on the environment. To accelerate the transition from a linear to a circular economy, it is essential to ensure the quality of the concrete elements for reuse in terms of mechanical performance, physical properties, and longevity required by building standards. There are numerous obstacles to implementation of "reuse" strategies in the construction industry [6]. Some of them are:

– A lack of enthusiasm, as architects and engineers currently still prefer to build based on their ideas and do not want to be influenced by the design, structure, and size of previous reusable elements;
– Inability to use a standard template for planning reuse in each specific construction project. Individual measures and designs are required to ensure a construction process with reused concrete elements, and these extra activities increase the construction cost;
– Documenting the quality of building materials. The problem is occurs in documenting and tracking concrete quality in reused elements. The challenge is especially linked to the responsibility for the material quality.

On the base of carried out interviews [6] concluded the regulations and standards have a major impact on the development of increased reuse. That is, without more political incentives that force companies to build with reuse, improved development of reused concrete elements will be difficult to achieve. Therefore, current building norms and standards have to be updated to meet the challenges posed by circular economy [9].

In this paper the authors tried to predict possible utilization of used precast building elements through consideration of concrete carbonation degree.

2 Service Life

The design process of structures for the service life takes into consideration three main factors [9]:

- Limit values for performance indicators (in Eurocodes called limit states),
- Required period for the service life (in Eurocodes expressed as structure class),
- Reliability level of not passing over the limit values in the defined service life period (accounted for by safety factors applied on loads and material properties).

The durability of the structure is ensured by prescribing classes of expose (from XC to XA). They are necessary to define a depth of concrete cover and concrete important performances, from material with specific quality (cement, aggregate, additives, and admixtures), to cement content, water to cement ratio etc.

2.1 Service Life Calculation Tool for Reused Elements

The following approach to assessing the remaining service life of reused concrete elements will help real estate owners and structural engineers make decisions regarding their reuse. The approach started with:

- Analysis of existing documentation,
- Visual and full field surveys to check correspondence between the actual geometry of the structure with the available outline construction drawings or production of structural drawings that describe the geometry of the structure, allowing for identification of structural components and their dimensions, as well as the structural system to resist both vertical and lateral actions.
- Non-destructive testing; usually covers the evaluation of compressive strength (e.g. with Schmidt hammer), reinforcement scanning (e.g. with georadar), and determination of concrete cover (e.g. by reinforcement detector),
- Site sampling of built-in materials (taking concrete cores and reinforcement samples) for laboratory testing of their main properties (e.g. concrete compressive strength, carbonation depth, chloride ion content, steel tensile strength, etc.) and
- Field visual - condition inspection (detection of damages and defects, like cracks, spalling or surface decomposition of concrete, honeycombs, reinforcement corrosion etc.).

The estimation of residual service life (Lres) of concrete structures continues with following steps:

- Determining the condition of the materials (on the base of testing results) and defining the end of service life of each material in the structure, and
- Assessment of the damage degree according to results of visual inspection, and
- Making some type of time extrapolation from the present state to the state that characterizes the end of service life.

The calculation tool is used utilizing data from the condition assessment. The element was always given two lives: (I) Degradation of concrete cover (initiation based on the Fick's 2nd law) and (II) Corrosion of steel (propagation based on corrosion rate in certain atmosphere). In the first life the diffusion coefficient was calculated based on status achieved from the laboratory tests and the age of the structure. The user is asked to define the target environment (e.g. exposed to chlorides or just to carbonation and relative humidity). Using the procedure presented in [9], the reference service life (Lref) could be calculated, as well as the residual service life, Lres.

Finally, all the collected results are evaluated, and recommendations on element classification for reuse are made.

3 Durability

The durability properties of concrete have an important role in assessing residual service life and defining the potential ways of reusing RC structural elements. Durability is defined as the ability of material to last a long time without significant deterioration. A durable material helps the environment by conserving resources and reducing wastes and the environmental impacts of repair and replacement. Concrete is considered as a building material with good durability properties. The durability of concrete may be defined as the capability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties [1]. Different concretes require different degrees of durability, depending on the exposure environment and properties desired. For example, concrete exposed to tidal seawater will have different requirements than an indoor concrete floor. Concrete, as a structural material and as the building exterior skin, has the ability to withstand nature's normal deteriorating mechanisms as well as natural disasters.

The main reason for the deterioration of reinforced concrete (RC) structures and the reduction of their durability is the corrosion of steel reinforcement. Reinforcement is protected by the surrounding concrete which is a highly alkaline environment with a pH value approximately 13 [2]. This ensures chemical protection of steel reinforcement with a thin oxide (passivation) layer. Two processes can cause reinforcement corrosion: concrete carbonation and chloride ion ingress in concrete. Carbonation-induced corrosion has been reported as a major durability problem in urban environment, considering a large number of buildings that are exposed to a CO_2-rich environment.

3.1 Concrete Carbonation

Carbonation is the process where CO_2 from the atmosphere penetrates through concrete pores and with pore solution forms weak carbonic acids (H_2CO_3). These acids react with portlantide ($Ca(OH)_2$) in the pore solution and are deposited as calcium carbonates ($CaCO_3$) which line the internal surfaces of the concrete pores. Described reaction leads to the decrease of the pH value in concrete. Depletion of hydroxyl ions (OH^{-1}) lowers the pore water pH from above 12.5 to below 9.0 where the passive layer becomes unstable, allowing general reinforcement corrosion to occur if sufficient oxygen and water are present in the vicinity of the rebar [2]. The carbonation depth in natural conditions directly influences the concrete cover depth required for the desired service life.

Evans [12] defined the reinforcement corrosion types as general corrosion, localized corrosion, and pitting corrosion. Also, the microcell and macrocell corrosion mechanisms may exist in RC structures. Microcell corrosion occurs when anodic and cathodic half-cell reactions take place at adjacent parts of the same metal. On the contrary, macro-cell corrosion takes place when the actively corroding rebar is coupled to another rebar, which is passive, either because of its different composition or because of different environment. Through a 3-year monitor program, Hansson et al. [12] concluded that microcell corrosion is the major mechanism of corrosion in RC.

A variety of interrelated factors influence the carbonation depth in concrete, such as: effective CO_2 diffusion coefficient, curing condition, age, cement type, presence of mineral admixtures, surface concentration of carbon dioxide, time of wetness, ambient temperature, relative humidity, etc. Environmental conditions, such as sheltered versus exposed and underground versus atmospheric, also have an important impact on concrete carbonation process.

The carbonation process occurs in almost all concrete structures but at different rates depending mainly on the humidity level. The most severe conditions accelerating carbonation occur in around 50–70% RH which in practice often means wetting and drying cycles (ex. buildings facades). However, the process happens also at lower pace in drier environments (e.g., in-house).

Concrete carbonation and carbonation-induced corrosion occur naturally in RC structures at a rather slow yet invasive rate. Carbonation-induced reinforcement corrosion usually affects a wider range of RC structures at a larger scale and belongs to general corrosion. There are lot examples of serious rebar carbonation induced corrosion even in hot and dry climate regions, such as North Africa.

Carbonation exposure class (XC) is the only one of the 5 classes of exposure according to EC 1992 (XC, XD, XS, XF and XA), which is always analyzed and defined for each element of RC structure, because carbonation is a spontaneous process that takes place in all environments (from dry to aquatic environments). The exposure carbonation classes, according to EN206, are shown in Table 1.

Table 1. Exposure classes related to carbonation (adapted from EN 206, 2013)

Class designation	Description of the environment	RH (%)	Informative examples
XC1	Dry or permanently wet	<40	Concrete inside buildings with low air humidity
XC2	Wet, rarely dry	>80	Concrete surfaces subject to long-term water contact
XC3	Moderate humidity	50–70	Concrete inside buildings with moderate or high air humidity
XC4	Cyclic wet and dry	-	Concrete surfaces subject to water contact

To determine the residual service life of concrete elements when their reuse is planned, the carbonation class must be redefined.

3.2 Cracks in Concrete

Cracks are characteristic for all brittle materials, especially for concrete. They occur when the internal stresses exceed tensile strength of material. They may appear regardless of the concrete age or state: before and after hardening, in unloaded concrete, or in concrete elements under the load According [10], 18 different causes induce cracking occurrence. They are classified into physical, chemical, thermal, and structural groups based on their origin. Cracks generally reduce the mechanical properties and endanger the durability of concrete. They reduce the shear capacity of the cross-section, allow the penetration of moisture, oxygen, carbon dioxide, and chloride into the concrete, and, over time, the corrosion of the reinforcement can be initiated. Due to their width limits, cracks are conditionally permitted in most reinforced concrete structures. The key issue in cracked concrete is obtaining the required durability since the steel reinforcement continues to transfer loads even after cracking. The maximum allowed crack width depends on the reinforcement type (normal reinforcement or prestressing) and the reinforcement grade. Since most prestressed constructions are designed to resist decompression (cracking), their limits are often tougher.

According to the requirements of Eurocode 2, the acceptable crack widths range from 0.4 to 0.3 mm for structures with an expected service life of 50 years. The maximum design cracks with (wmax) is 0.4 mm for exposure classes X0 and XC1, wmax = 0.3 mm for reinforced concrete in XC2, XC3 and XC4, and wmax = 0.2 mm for prestressed concrete regardless the classes of exposure. If the cracks are large enough, they accelerate the rate of carbonation [4]. However, the rate of carbonation is not only affected by the surface crack width, but also by its depth, interconnection with other cracks or voids, and the location of cracks with respect to reinforcement. In general, it is agreed that cracks finer than 0.05 mm do not affect the diffusion properties, due to self-healing process. The crack width has also to be included as a criterion for disassembled element quality classification.

4 Assessment of Concrete Carbonation Degree

The degree of carbonation can be easily evaluated through concrete and reinforcement damage analysis. The following damages are characteristic:

- Cracking and spalling of concrete,
- Reduction in rebar property (cross section area and bearing capacity), and
- Loss in interfacial bond strength.

They together may cause a significant reduction in the load-bearing capacity of structure elements individually or of the whole structure.

The authors of the paper propose three degrees of concrete carbonation based on the severity and type of damage:

I - Initiation period; the carbonation process has started, but it is sufficiently reliably estimated that it progresses slowly and that the carbonation front is $<<$ than the thickness of the concrete cover. The reinforcement still has satisfactory protection against the electrochemical corrosion of the steel in the alkaline environment surrounding it.

II - Propagation period; the carbonation process is in progress so that the carbonation front has reached close to the reinforcement ($d_{carb}. </\approx d_{cover}$) The reinforcement gradually loses its passive protection against corrosion. Cracking of concrete is possible.

III - Developed period; the carbonation process is fully developed and the carbonation front has passed behind the reinforcement bars. The reinforcement does not have the necessary corrosion protection and the electrochemical corrosion of the steel has already advanced. Possible visual manifestations are cracking and spalling of concrete, flaking and "enlargement" of rebar volume, and loss of interfacial bond strength.

5 Possible Utilization of Used Precast Building Elements Through Consideration of Concrete Carbonation Degree

The following five utilization scenarios for used precast building elements are given based on the degree of concrete carbonation:

Reuse - use of existing concrete structure elements in origin state.

Upgraded reuse - adding new layers such as thermal insulation, fire protective cover, applying protective materials to prolong durability, etc.

Repair and reuse - repair of concrete and reinforcement damages.

Recycling - production of aggregate for partial or total replacement of natural aggregates in concrete.

Downcycling - crushing and usage as backfilling material.

The possible utilization scenarios of used precast building elements regarding their concrete carbonation degree, are suggested in Table 2.

Table 2. Utilization scenarios versus concrete carbonation degree

Concrete carbonation degree	Reuse	Upgraded reuse	Repair and reuse	Recycling	Downcycling
I - Initiation period	✓	✓	-	-	-
II - Propagation period	-	✓	✓	-	-
III - Developed period	-	-	-	✓	✓

6 Conclusion

In this paper the authors tried to predict possible utilization of used precast building elements through consideration of concrete carbonation degree in line with CE strategies in construction industry.

Three degrees of concrete carbonation based on the severity and type of damage are proposed: I - Initiation period, II - Propagation period and III - Developed period.

Five utilization scenarios for used precast building elements are analyzed based on proposed degrees of concrete carbonation.

If reuse scenarios are chosen, the residual service life of concrete elements should be determined, in which the carbonation class is among the major factors that endangered concrete durability.

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