Methodology to Assess and Monitor the Condition of Concrete Components

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Abstract

The 5,000 bridges which are maintained by ASFiNAG (Austrian highway operator) are its main asset. Despite all maintenance efforts, these structures are still subjected to degradation, thus, leading to high expenses. Decisions for these maintenance actions are usually driven by the actual condition of the structure or deterministic (conservative) maintenance cycles proposed by guidelines. In order to provide high road net availability at moderate costs, the effectiveness of possible maintenance methods, as well as their maintenance intervals must be assessed. This forces the asset management to decide which maintenance measure is the best for a certain condition at certain time.

The aim of this paper is to determine condition and degradation (condition indices) by using objective indicators, like humidity, electrical resistivity, and corrosion potential. For the purpose of objectivity and the demand of an exact determination of the condition state, an overall performance index (CDI) is derived from the condition indices by using an analytic hierarchy process (AHP). Different levels of assessments are introduced over a lifetime of a surveyed structure, to assess the state of condition and to make the effort of an assessment as small and simple as possible.

Additionally, long-term monitoring from a reinforced concrete structure situated in the vicinity of Vienna are available. The monitoring data allows to continuously determine the degradation, as well as to show the methodology and the progress of the performance index over time.

Keywords: *Existing structures; degradation; corrosion; performance assessment; condition index; performance index; analytic hierarchy process; short time prediction.*

1. Introduction

The visual inspection is the first step necessary for the condition assessment of structures. By means of visual inspection an overall impression should be obtained of all forms of deterioration.
Primarily, condition assessments are made on a visual basis. This procedure is informative, fast and, if carried out by experienced engineers, sufficiently accurate. Nevertheless, the obtained data is discrete in time and cover only a small section of possible data for condition assessment. Condition surveys are mostly governed by national standards or internal guidelines. Nowadays Europe-wide affords are undertaken in standardization of indicators obtained during principal inspections, through a visual examination, a non-destructive test or a temporary or permanent monitoring system (COST ACTION TU1406, 2019).
It should be noted that currently the majority of condition assessments are based purely on visual inspections. At the same time, however, this means that damage tends to be detected too late, because it is not sufficiently visible visually, and, thus, the danger of systematically underestimating the condition is present. An objective condition assessment with easy-to-use condition survey techniques should support here and help to reduce the gap between visual inspection and real condition.
Prerequisite for a successful and sustainable repair of reinforced concrete structures is an exact knowledge of the state of preservation based on a detailed visual inspection of the components, as well

as results of non-destructive testing (NDT). All preliminary examinations together have the goal of showing as complete and as possible the current condition of the existing object.
In addition, it should be possible to use the condition analysis to predict future development in terms of a forecast of an optimal time for maintenance.
During the inspection, the visual apparent damage and defects are recorded and mapped. Next step is the sampling of those areas where high degradation can be observed. Common concrete technology surveys include (Hillemeier & Taffe, 2012; Küchler, 2013; Schickert et al., 1991):

- Determination of the depth of carbonation of concrete,
- Measurement of the concrete cover of the reinforcement,
- Determination of concrete compressive strength,
- Determination of the chloride content,
- Half-cell potential measurement of the reinforcement,
- Measurement of electrical resistivity of concrete,
- Documentation of cracks including widths.

In addition, other condition assessment techniques that increase the density of information especially about the reinforcement can be carried out, such as:

- Determination of the degree of corrosion on the reinforcement,
- Determination of cross-section loss of the reinforcement,
- Determination of the corrosion current of the reinforcement.

The scope of the condition analysis must always keep in mind the overall objective. In addition, the actual condition state also plays a major role, e.g. in the selection of suitable condition surveys methods. There are many different NDT methods used to identify and evaluate the deterioration of reinforced concrete. However, there is no single NDT method capable of identifying all aspects of reinforced concrete deterioration. For this reason, a multimodal NDT approach is a more effective one in terms of condition assessment. A multimodal approach provides a more complete condition assessment because it can identify different deterioration states simultaneously (Figure 1).
Figure 1 shows the efficiency of condition survey techniques as a function of the condition state. For example, a specific investigation for a specific problem, such as half-cell potential mapping, does not provide more accurate information about the state of preservation until parts of the reinforcement are already affected by corrosion and the concrete components are therefore already in the damage phase. Furthermore, the figure shows an important insight for the engineer, that with single visual condition assessment, damage is detected very late. Therefore, it is of enormous importance to know when and how accurate a possible degradation can be detected.

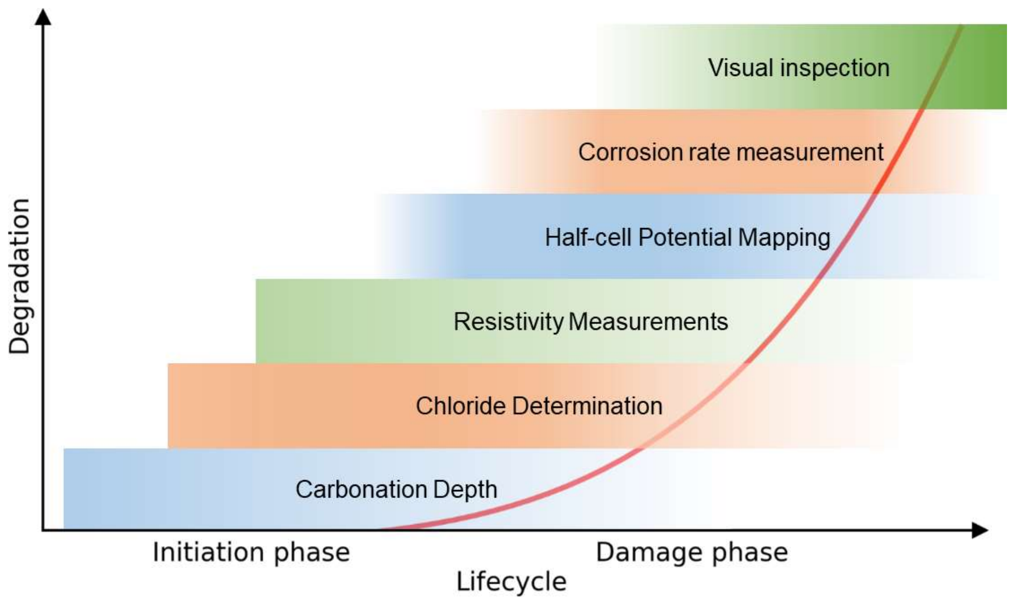

Figure 1: Effectiveness of different condition survey methods for condition assessment depending on the state of degradation based on (Pailes & Gucunski, 2015b).

The examination techniques mentioned in Figure 1 are established procedures and allow to obtain acceptable good and quantitatively sufficient results with sufficient monetary expenditure. It is always important that the procedures enable and support the increase of knowledge of the overall objective of the condition analysis.
As already mentioned, it is difficult to determine the true dimension of damage only based on visual appearance of the concrete component. Nevertheless, different condition survey techniques are available depending on the stage of degradation (see Figure 1) (Pailes & Gucunski, 2015).

2. Condition index

The decay of the durability and the evolution of damage are key aspects for a cost-effective maintenance. Later interventions, where the safety level is approached and strengthening, or repair methods are necessary, lead in most cases to considerable higher costs. For this reason, the need for adequate, (sufficient) precise and objective tools for assessing structures has become a subject of crucial economic interest. Several efforts for quantifying these effects have been undertaken (Andrade & Martinez, 2009; Furuya et al., 2011; R. Wendner, 2008; Schneck, 2012). The outcome of a structural assessment must contain at least the following points:

- Identification of the damage mechanism,
- Extent of damage,
- Dynamic of the degradation progress.

In (Rodriguez & Andrade, 2008), two procedures are described to establish these three aspects of the assessment in case of concrete structures affected by corrosion. In this paper a procedure, that excludes the factor for exposure, is applied and described in the following.

2.1. *Indicators for corrosion*

Nearly all measurements in the condition survey, used in this paper (see also discussion in section 4), can be classified with respect to damage or potential damage due to corrosion. Threshold and limits for classification of damages were gathered from standards, guidelines and literature (Baumann et al., 2014; fsv, 2011; ÖNORM B4706, 2015; Polder, 2000; R. Wendner, 2008; Raupach & Büttner, 2014) and are given in Table 1. If a measured value exceeds the threshold documented in the literature, the index jumps to the next higher level. This leads to a stepwise indication of damage over time (abrupt changes in condition), which assumed to be accurate enough for such a condition assessment.

2.2. *Condition index*

The Condition Index (CDI) is obtained by first transferring measured values to Corrosion indicator levels, see Table 1. The mean value of the corrosion indicator levels results in the “Condition Index” (see Eq. 1).

$$CDI_{Mean} = \sum_{i}^{n} \frac{Degradation\ indicator\ level_i}{n} \qquad (1)$$

The procedure in Equation 1, together with the levels for the individual degradation indicators in Table 1, lead to the condition index, which can be subdivided in the following four classes:

1. = negligible or no corrosion,
2. = low corrosion,
3. = medium corrosion,
4. = high corrosion.

Table 1. Indicator for degradation and their levels.

Degradation Indicator	Akr.	Unit	Indicator level 1 Negligible	 2 Low	 3 Moderate	 4 High
Carbonation depth	X_{CO2}	[mm]	0% C	≤ 75% C	> 75% C	≥ C
Chloride content	X_{Cl}	[M%]	≤ 0,2	0,2 - 0,6	0,6 - 1,0	> 1,0
Crack width due corr.	w	[mm]	no	< 0,3	≥ 0,3	Spalling
Concrete resistivity	ρ	[Ωm]	> 1000	500 - 1000	100 - 500	< 100
Corrosion potential[1]	E_{corr}	[mV]	> -200	-200 - -350	-350 - -500	< -500
Corrosion current	i_{corr}	[μA/cm²]	< 0,1	0,1 - 0,5	0,5 - 1	> 1

[1] using Cu/CuSO4 reference electrode
C means thickness of the concrete cover

2.3. *Condition index using the Analytical Hierarchy Process (AHP)*

Here the higher importance of individual corrosion indicators, such as direct corrosion current measurements are considered. To determine the prioritization or weighing of individual corrosion indicators, the analytical hierarchy process (AHP) or Saaty method (Saaty, 1977) is used. The method enables transparent traceability of how prioritization was calculated and, thus, strengthens the understanding and acceptance in decision making. Thus, a comprehensible and expert based weighting is achieved. The approach of the method is to simplify the problem by breaking it down into a hierarchical system and to form a systematic procedure to structure and solve the decision processes. Which indicators are used in particular and how they are ranked and prioritised can be seen in Table 1. The corrosion indicator chloride content is two times more important than the corrosion potential (X_{Cl}) and seven times more influential than the carbonation depth (X_{CO2}). This additional information is processed in the AHP algorithm and derives the weighting in percent, which is given in the last column of Table 2 labeled as priority. The CDI derived by using AHP is:

$$CDI_{AHP} = \sum_{i}^{n} Degradation\ indicator\ level_i \cdot w_i \quad (2)$$

where w_i is the derived weight seen in Table 2.
By using AHP the decision problem is decomposed into a hierarchy of more easily comprehensive sub-problems, which can be analysed independently. Once the hierarchy is built, the process consists of systematically evaluate the elements and determine their interrelations and by comparing them to each other with respect to their impact on an element above them in the hierarchy. In making the comparisons, concrete data about the elements can be used to enhance the judgments about the elements' relative meaning and importance. The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the proposed problem. Finally, a numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared in a rational and consistent way. After incorporating these judgments this yields to a set of overall priorities for the hierarchy. With every kind of pairwise comparison, inconsistencies can also occur. For the examination of these inconsistencies a so called Consistency Ratio (CR) is used, where CR < 10 % is considered to be acceptable (Saaty, 1990).

2.4. *Levels of assessment (LOA)*

The objective of a condition assessment is to determine the current condition and estimate the future performance of a structure or only of a component with high accuracy and minimal effort. From this arises the need for an objective method for assessing the extent of damage over the life of road infrastructure components.
However, at different stages in the life cycle, different dynamics are at work with respect to damage mechanisms. With focus on Figure 1, it becomes clear that during the initiation phase, hardly any phenomena of degradation are visually detectable. During the task to determine the condition index (CDI) over the service life of a reinforced concrete component, it is not always necessary to determine a large number of indicators. It must be considered that it is very likely while the structural component passes the initiation phase, negligible corrosion rates and corrosion potentials can be determined. Thus, over the entire life cycle, it is obvious to focus on those indicators where the most information can be

Table 2. Levels of assessment and their priority over the lifecycle.

LOA 1		LOA 2		LOA 3	
Degradation indicator	Priority	Degradation indicator	Priority	Degradation indicator	Priority
Cracks	75.0	Chloride content	38.3	* Corrosion rate	33.0
Visual appearance	25.0	Corrosion potential	25.3	Chloride content	23.3
		Rebar corrosion level	16.0	* Corrosion potential	16.0
		Cracks	10.0	* Concrete resistivity	10.7
		Carbonation depth	6.3	Rebar corrosion level	7.0
		Visual appearance	4.2	Cracks	4.6
				Carbonation depth	3.1
				Visual appearance	2.2

* Data obtained from in-situ corrosion monitoring system.

obtained. Thus, determining the condition index CDI as precisely as possible depends, on one hand, on the phase (see Figure 1) in which the reinforced concrete component is currently located and on the other hand which degradation level the component can be associated.
In (Šomodíková et al., 2020) three levels of assessment are described to act as a basis for the application of accurate degradation models for chloride and carbonation. The assessment levels depend on life cycle phase and level of degradation. Furthermore, the level of degradation should also set the depth and number of corrosion indicators to be determined.
A typical lifecycle of condition assessment is starting with a simple quantification based on visual inspection during periodic condition assessments. This obligatory regime can be found in the Austrian guideline RVS 13.03.11 (fsv, 2011). Higher assessment levels using preliminary tests of usual scope, such as chloride, carbonation, half-cell potential mapping. The highest level, where extensive tests are made on site and in the laboratory, enable a detailed and more accurate damage classification.
The Figure in Table 2 shows which corrosion indicators should be used at which stage and damage class. In addition, in Table 2 each corrosion indicator is assigned a survey stage.
These levels are not clearly separated from one another, neither in terms of time nor depending on the condition state (see Figure 2). Thus, LoA 1 does not necessarily have to end at the beginning of degradation, at the same time, LoA 2 does not exactly starts here, especially since this point in time is also difficult to catch precisely. This level of assessment represents more likely areas in which associated indicators are used which are available under economic and efficiency reasons.

2.4.1. Level 1

At this assessment level, no NDT surveys are initiated, and only visual indicators are used to form the condition index (CDI). If there are no signs of accelerated degradation evident, this survey stage is primarily suitable in the initiation phase. In addition, it represents a basic principle of many assessment regimes among of high-priority infrastructure operators. Visually detectable indicators, such as wear or cracks on the surface, are used to infer the condition of the component at the time of assessment. This method is intended as completely non-destructive. The great weakness in this stage is certainly the unreliable formation of the CDI, because only few imprecise indicators are available at this time. For the purpose of a better and more accurate assessment of the condition, the authors recommend the use of higher levels as standard assessments.

2.4.2. Level 2

This level of assessment is applied by allocating more detailed data, such as as-built drawings. Mandatory preliminary surveys are carried out to increase the density of information. The most important information about the condition of a structure or an individual component are collected and confirmed or verified by preliminary NDT. Exact data and a well-documented structural component are beneficial in terms of determining the concrete cover or compressive strength of the concrete. Control measurements should be applied to confirm the documented data or to reveal deviations.

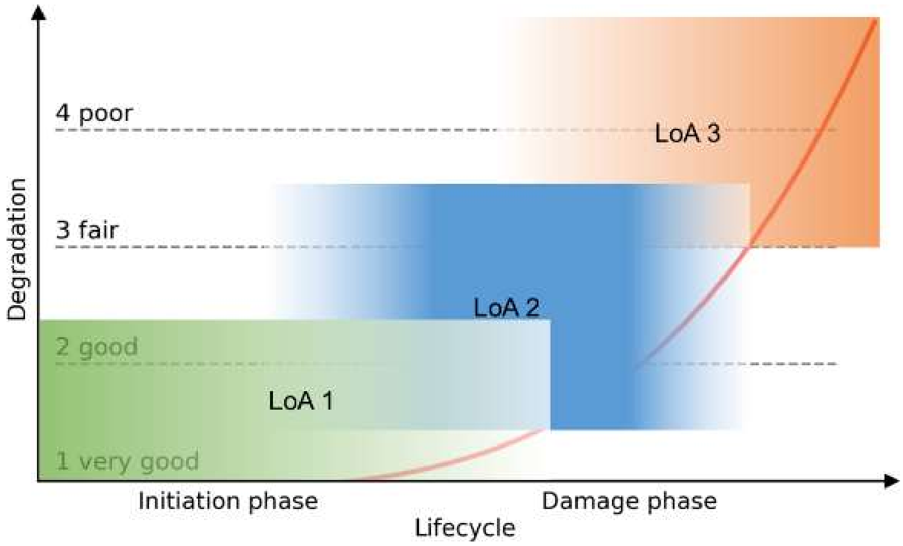

Figure 2. Graphical manifestation in time and degradation scale of the three Levels of Assessments

In fact, it is useful and cost-effective to use the knowledge observed at assessment level one to set up a targeted and suitable testing regime and to determine what needs to be tested additionally.
In LoA 2 investigations are typical for the condition assessment of concrete structures in bridge construction when repair is required.
It is intended that the LoA 2 is performed during preliminary surveys for upcoming maintenance measurements and also when first signs of degradation on the component are visible.
The preliminary surveys used are quasi non-destructive. During the half-cell potential mapping, a connection to the reinforcement must be installed. At this time, it is also possible to visually assess the condition of the reinforcement with respect to the degree of corrosion or cross-section loss. In practice, the determination of the cross-section loss is very difficult and may the inaccurate to perform in-situ. Imagine a drilled hole and roughly chiselled in the concrete cover, which reaches up to the reinforcement. In this hole, after removal of the rust layers, the measurement has to be carried out at several points, preferably with a sliding gauge. The authors consider that a reliable determination of the cross-section by means of this method is not satisfactory.
Nevertheless, the additional information obtained from these tests are directly incorporated into the assessment in order to finally eliminate any doubts remaining at the end of LoA 1.
It is recommended to determine the indicators LoA 2 periodically over the life of the structure. In principle, there is a significant benefit in performing periodic condition surveys. With respect to the obligatory in-depth inspections every six years, this rhythm appeals to be suitable (fsv, 2011). During the inspections, almost all concrete surfaces of the infrastructure are inspected and evaluated as close to hand as possible. Therefore, it is possible to carry out NDT to determine the degradation indicators. Additionally, it is an advantage to determine other concrete parameters too, that can serve as essential input parameters for degradation models (Šomodíková et al., 2020).
In most cases preliminary investigations are performed in the summer, but it has to be considered, that the data for the condition assessment are also subject to a significant cyclical and seasonal variability (Binder et al., 2018).

2.4.3. Level 3

At the third and final assessment level, supplemental and frequently sophisticated surveys are required to accurately determine the condition index. Data from monitoring systems can provide additional time-continuous data to quantify the condition at this state of degradation. Data from the corrosion monitoring applied in this study are tagged with an Asterisk (*) in Table 2.
All available relevant information to the actual state of condition should be collected. This allows a more accurate determination of the condition. In this process, it will be essential to use non-destructive testing as well. At this level invalid data that origin from as-built information should be evaluated. The majority of the results from the examinations carried out at this time are made directly in situ on the concrete component. These tests provide the most accurate results with statistically small deviations.

Environmental parameters such as temperature or air and humidity conditions as well as (de-icing salt) exposure of the component can be incorporated from the closest weather station, respectively. In principle, average ambient temperatures measured at the component to be analysed should be used (Schiessl, 2013).

3. Case study

The structure for this case study was built in 1980 and designed as an overpass over a motorway. The overpass has a length of about 100 m and shows a tunnel-like characteristic. The beams are supported by the abutment and the columns are situated between the direction lanes of the motorway. In 1994, concrete spalling was noticed for the first time. A patch repair of the substructure with surface protection up to a height of 2.00 m was executed. In 2013 the abutment walls, but mainly the columns show massive damage of the concrete structure. Spalling and cracks greater than 0.3 mm width and traces of rust up to the splash zone are visible. Carbonation depth has reached a mean value of 9.3 mm, whereas the maximum values are 22 mm. More detailed information about the outcome of the condition assessment can be read in (Binder, 2013).
The chloride content of the concrete cover is very high in the contact zone and decreases with height. This is also confirmed by the half-cell potential mapping. The concrete resistivity was determined by surface resistivity meter based on the Wenner-principle. The measurement results are in the range from 7 to 2000 Ωm. The average value is 454 Ωm.
Since installation of the monitoring system in 2010, trends could be observed, that indicate a gradual corrosion damage. The monitoring data used for the investigation were

- Electrolytic resistance,
- Potential of the reinforcement,
- Corrosion current.

The monitoring data is now available for 10 years. For this time range the chloride content and the carbonation were assumed to be constant. Thus, the progress and the variation of the indicators can be mapped across all recorded indicators.

As can be observed in Figure 3, the condition of the concrete component seems to build plateaus over time. In particular this can be observed after erecting and the first maintenance intervention (marked as grey bar in Figure 3). This is due to the fact that since LoA 2 is applied for the condition assessment, no

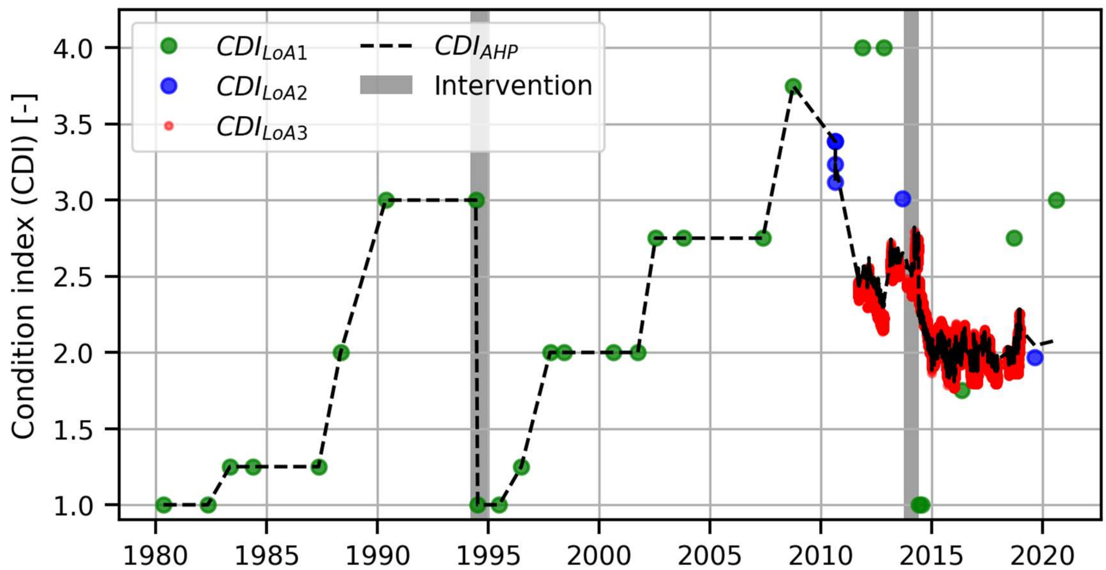

Figure 3. Course of the condition index (CDI) over the past lifecycle obtained from different levels of assessment (LoA). Gray areas indicate interventions in terms of maintenance measures.

accurate data on the condition of the structural component will be included in the recordings as visual perceptions and cracks. The progress of the condition ten years after the construction reveals that the CDI reaches a plateau that drops to best condition due to the first maintenance intervention.
Previously the increase of the CDI is comparable to that shown in Figure 1.
Thereafter, a fifteen-year progressive increase of the CDI begins, which is further interrupted by plateaus. With the beginning of the in-depth preliminary investigations, the CDI_{LoA1} (indicated as green points in Figure 3) already deviates significantly from the over-all CDI (indicated as dashed black line in Figure 3). Before the second maintenance intervention in 2013, the structure is visibly assumed to be in a worse condition than actually given. After the intervention, again the phenomenon of an underestimation appears inverted. The implementation of further time-continuous assessment data by the monitoring system increases and condenses the accuracy of the CDI_{LOA3} (indicated as red dots in Figure 3). The state determined from the data of the preliminary investigation (CDI_{LoA2} indicated as blue points in Figure 3) represents the state in a good approximation. There can be minor differences observed from CDI_{LOA3} to CDI_{LoA2} in the Figure. By including assessment level 2 earlier, a more accurate condition data can be obtained over the entire life cycle.

4. Conclusions

The paper presented a methodology to assess and monitor the condition of concrete components. The condition is determined from real and therefore objective values which are suitable to indicate degradation. The obtained data is mainly derived from condition surveys and monitoring data, like humidity, electrical resistivity, and corrosion potential.
The demand of an exact as possible determination of the condition state is a key mission for the asset management to decide which maintenance measure is the best for a certain condition at certain time. This is considered by using objective indicators (degradation indices) to derive an overall performance index. This condition indicator (CDI) is handled through an analytic hierarchy process (AHP) for the sake of objectivity and comprehensibility. Different levels of assessments are used over a lifetime of a surveyed structure to assess the state of condition and to show that effort of an assessment can be kept as small and simple as possible.
The methodology was evaluated, proofed, and demonstrated within the case study. If data from assessment level 2 is available earlier or if these examinations are carried out at regular intervals, this assessment level can provide a more accurate condition over the lifecycle and so serve-for more profound decisions in terms of maintenance management.
The strict rely on only visual inspection data for condition assessment to manage repair measures is considered as critical by the authors.
The paper presents a comprehensive methodology for structural monitoring with the aim of showing how directly usable results from monitoring can be, obtained in the long term for service life prognosis, asset management and maintenance with acceptable effort.
In addition, with the application of this approach on a larger, representative building stock, the perspective of an even more reliable service life prognosis will take place. Therefore, the data already acquired, but also future data, can be described as valuables. In the future better forecasts will be possible based on more precise condition assessments on higher levels. An important point is that uncertainties on both the impact and the resistance side can be concretised or reduced through monitoring and a previously set level of assessment. In future, the results can be transferred from individual structures to entire types of structures.

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