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Deterioration Mechanisms Active in Reinforced Concrete Structures

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Abstract

The extent of necessary repair of damaged reinforced concrete structures is of major concern in most industrialized countries today. Attempts to raise the quality standards showed limited success in this context. Monitoring techniques may have a decisive input to limit expenditures for maintenance and repair of existing structures. In this contribution an overview on various deterioration mechanisms is presented. In this way a basis for a systematic choice of monitoring systems for reinforced concrete structures under different environmental conditions may be provided.

Keywords: deterioration, maintenance, repair, monitoring

Schädigende Mechanismen in Stahlbetontragwerken

Zusammenfassung

Heute ist das Ausmass an notwendigen Instandsetzungsmassnahmen an bestehenden Stahlbetontragwerken in den meisten industrialisierten Ländern Besorgnis erregend. Bisher zeigten die Bemühungen auf diesem Gebiet, die Qualität hinreichend zu verbessern, nur bescheidenen Erfolg. Leistungsfähige Überwachungssysteme können deshalb ganz wesentlich dazu beitragen, die Ausgaben für Unterhalt und Instandsetzen der Tragwerke zu begrenzen. In diesem Beitrag wird ein allgemeiner Überblick über relevante schädigende Mechanismen gegeben. Damit wird eine Grundlage geschaffen für eine systematisch und zielgerichtete Auswahl von *tauglichen Überwachungssystemen für Stahlbetontragwerke unterschiedlicher Belastungen.*

Stichwörter: *Schädigung, Unterhalt, Instandsetzen, Überwachen*

Prof. Dr. F.H. Wittmann, Member of WTA, first studied physics at the universities of Karlsruhe and Munich, Germany, and in 1969 habilitated in civil engineering at University of Technology in Munich. Since 1976, he has been holding the position of professor for building materials, first at Delft, Netherlands, subsequently at EPF Lausanne, Switzerland, and presently at Swiss Federal Institute of Technology (ETH) Zürich, Switzerland. His main interest and experience are in the fields of cement-based materials and application of fracture mechanics.

1 Introduction

This is rather an introductory note and not a comprehensive contribution on deterioration mechanisms. In the literature we can find a wealth of data on deterioration of concrete under various conditions. A selection will be made in the following sections and the emphasis will be laid upon mechanisms which might be at the origin of damage and therefore may ask for health monitoring [1].

Application of sensors in concrete structures is at its infancy. Due to the enormous amount of money spent for repair measures which are frequently necessary on comparatively new structures, this field, however, will most probably experience rapid growth. It is generally acknowledged that damage can be repaired at low cost or even prevented if detected at an early stage.

In the following sections the huge number of different types of deterioration will be subdivided into four groups characterizing the major origin: (a) thermally induced damage, (b) hygral damage, (c) chemical interactions, and finally (d) mechanical deterioration. There are, however, no clear border lines and often real damage is originated by a combination of different mechanisms.

2 Damage induced by thermal action

Especially in massive concrete structures heat liberated by the hydration of cement leads to severe thermal gradients. Simple and approximate calculations show that the risk for crack formation is very high. Numerical models are available to predict precisely the temperature evolution in large concrete structures. If the material properties are known the occurance of cracks can be predicted in a realistic way [2]. The numerical models then may serve as a tool to avoid early thermal cracking. Experimental determination of the evolution of thermal gradients by means of thermocouples or other thermal sensors is certainly a good example of early application of health monitoring.

Thermal gradients may also be at the origin of damage in the matured state of concrete structures. Solar radiation may heat up the surface of structural concrete elements depending on their colour up to 70°C [3]. Whenever the risk of thermal damage exists, thermal sensors will give an early warning and prevent progressive crack formation.

In industrial applications concrete elements may be close to powerful heat sources. In this case it is possible to check by means of thermal sensors if the gradients and the maximum temperature remain under tolerable limits. Quite obviously the result of this type of monitoring becomes meaningful only in conjunction with a rigorous mechanical analysis. But this is true for many other monitoring systems. Numerical mechanics has become a wide field of application in this context.

Another application of thermal monitoring is the control of frost action. Frost action may result in spalling but also in a progressive decrease of resistance and elastic modulus. For this reason thermal monitoring may help to determine the time when thermal deterioration begins to jeopardize durability or integrity of a reinforced concrete structure.

3 Damage induced by moisture changes

Normal concrete with a water-cement ratio around 0,5 is in equilibrium with nearly 100% RH at the moment when the formwork is being removed. In most cases the surface of concrete elements is exposed however, to a drier environment and therefore a long lasting drying process begins. The time-dependent water loss can be described in a realistic way by non linear diffusion equation. Drying induces a time-dependent moisture profile in the material.

This moisture profile is a dominant origin for damage of the sensitive surface near zones which are to protect the steel reinforcement. It can be shown that in the dry outer zones high tensile stresses are generated. In most cases this leads to crack formation [4]. But at the same time the drying process opens the porous system and makes it susceptible for ingress of aggressive solutions and gases. If the diffusion coefficient has been determined the moisture profile can be predicted for any duration of drying. In most real structures the drying process lasts for several decades. For this reason in sensitive structural elements moisture sensors which allow to determine the moisture gradient with the necessary accuracy should be foreseen.

In modern high-strength concete endogenous drying plays an important role. This internal moisture „loss“ differs from drying in several aspects. First, very low moisture gradients are generated only. Therefore, global eigenstresses can be neglected as an origin of damage. Local eigenstresses, however, are built up around the stiff aggregates in the composite structure of concrete [5]. Second, the time evolution of endogenous drying is linked with the rate of hydration. This means that the process is very rapid at the beginning and slows down considerably after about two weeks. Therefore, endogenous drying provokes rapid endogenous shrinkage at an early stage. This process may lead to early cracking in statically indetermined systems and restrained elements [6,7]. By means of moisture gauges it is possible to control endogenous drying and to avoid unexpected crack formation.

4 Chemial reactions

Hydration products of Portland cement form a meta-stable system. Depending on the environmental conditions a series of reactions may take place. Here a few of them will be mentioned briefly. CO_2 of the surrounding air reacts with $Ca(OH)_2$, which is originally liberated during the hydration of cement. This form of carbonation lowers the pH-value of the pore solution and as a consequence reinforcement steel is not protected any longer by passivation in high alkalinity. Carbonation of concrete also induces additional shrinkage which may cause additional crack formation. SO_2 may form sulfate compounds in concrete. Sulfates are water soluble and may quickly be leached out. If rewetting with sulfate containing water takes place or concrete is exposed to elevated temperatures damage may be originated by sulfate expansion [8].

If concrete is in permanent contact with water $Ca(OH)_2$ may be leached out at a first stip of deterioration. As a consequence the Ca^{2+}-ion concentration in the pore solution decreases and CSH-phases become chemically unstable. Hydrolysis is particularly important if the porosity is high and the concrete surface is in permanent contact with water. Water soluble salts such as chlorides may penetrate the porous structure of concrete. This may lead to damage in the concrete itself or to accelerated corrosion of reinforcement.

More recently it has been observed that a combination of chemical and mechanical load is at the origin of stress corrosion [9,10]. If mechanically loaded elements are simultaneously in contact with agressive chemical compounds crack formation may be strongly enhanced.

Another example of chemical degradation of concrete is the well-known alkali aggregate reaction. Swelling due to this reaction may cause crack formation but it may also finally lead to complete destruction of concrete elements. In order to get a reliable warning at an early stage strain measurements ought to be carried out.

5 Damage under mechanical load

In case concrete is temporarily loaded beyond a characteristic limit the remaining load bearing capacitiy decreases. Concrete is a material with characteristic strain softening [11]. Cyclic load may induce fatigue failure and a sustained load beyound 70% of the short-term load may eventually lead to static fatigue failure. With appropriate monitoring the probability of damage and the risk of failure can be determined under arbitrary loading conditions.

A most important issue is the stability of existing cracks in reinforced or unreinforced concrete structures. The evolution of cracks has to be determined in all critical cases. Again, the result becomes meaningful only if it is supplemented by a numerical structural analysis based on non-linear fracture mechanics.

In prestressed reactor vessels acoustic emission has been used to monitor and localise crack formation or damaged microcracked zones.

6 Conclusions

One aim of this brief contribution is to point out that monitoring of reinforced concrete structures means more than corrosion mapping. In the following table typical mechanisms of deterioration are compiled. The actions are subdivided into four different groups.

Monitoring of most degradation mechanisms is possible [1]. For any sensitive structure a careful selection is to be made. The costs even for sophisticated monitoring systems are negligible when compared to costs for avoidable repair measures.

Interdisciplinary co-operation is needed in order to develop reliable monitoring systems in a reasonable lapse of time. More work is needed for a proper evaluation of measured data. Standard solutions are to be developed for typical structures.

Results of monitoring systems become meaningful if used in numerical analysis of reinforced concrete structures. Therefore, monitoring has to be supplemented with experimental studies to determine all relevant material properties.

Table 1: Typical deterioration mechanisms subdivided according to their major origin.

Major origin of damage	Typcial Mechanisms	Possible Monitoring
Thermal action and thermal gradients	Dehydration Frost action Thermal cracking	Temperature gauges
Hygral action and hygral gradients	Shrinkage cracking Endogenous drying	Humidity gauges Strain gauges
Chemical reactions	Carbonation Sulfate interaction Chloride penetration Hydrolysis Alkali Aggregate reaction Stress corrosion	pH-sensors Cl^--sensors Corrosion potential Corrosion rate Strain sensors Ultrasound velocity
Mechanical actions	Strain softening Crack growth Dynamic fatigue Static fatigue Wear	Fibre optics Ultasound velocity Acoustic emission Strain gauges

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