Rehabilitation of Drinking Water Reservoirs – Requirements on Materials and Material Systems, Rehabilitation Principles

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1. Introduction

A lot of drinking water reservoirs are more than 50 years old. So they often have reached the end of their technical lifetime. Due to this and the necessity to recover the latest generally accepted engineering rehabilitation of drinking water reservoirs is in focus of many water suppliers.

For the rehabilitation of drinking water reservoirs made of concrete a variety of different material systems for linings and coatings are used. In addition to the hygienic requirements technical requirements are also important.

Therefore the user is confronted with complex issues that lead to the correct answer to the selection of a suitable material system.

Among this materials, all materials including construction materials and building materials have to be classified, that have direct or indirect contact with drinking water.

A distinction is made in three categories:

- Mineral, cementitious materials and material systems,
- Organic materials and material systems,
- Metallic materials and material systems

Often the lack of knowledge about the hygienic and non-technical suitability of used materials in drinking water is the cause of an (not in the sense of the European Drinking Water Directive) adverse change of the drinking water.

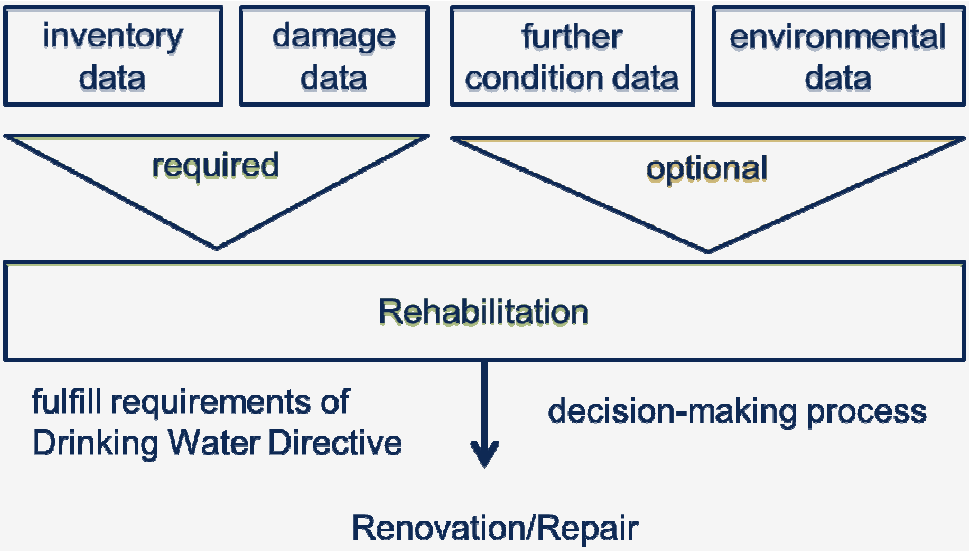
The selection of a suitable material or material system for the construction and rehabilitation of drinking water reservoirs is connected with a not inconsiderable effort. A thematic analysis and expertise are already entrusted with the planning engineer and therefore essential. The material-specific requirements for the hygienic suitability have an equally great importance, as the design-related requirements and must also be considered during the planning and construction phase.

The decision for "the right material system" requires detailed knowledge of the professional engineer. This is: The recording of the actual condition, determination of the stability of the structure, knowledge of the relevant exposure and the common principles of repair and rehabilitation as well as of suitable material systems. Limitations of the respective systems have to be reliably detected.

2. Decision criteria for selecting a material system

2.1 General

Basically, for each rehabilitation measure of a drinking water reservoir, a structural condition based maintenance analysis and plan has to be created, see picture 1.



Picture 1 – Data base for rehabilitation process

The decision process for estimating an appropriate rehabilitation method and the selection of a suitable material system can be divided into three levels:

- Level 1: Detection actual condition, stability of the structure
- Level 2: Determination of the relevant impact mechanism and exposure
- Level 3: Establish rehabilitation principles and ensure suitable material systems

2.2 Level 1

Level 1 reflects the detection of the status quo. Issues of this level are:

- Condition and stability of the structure
- Surface characteristics (such as tensile strength, porosity)
- Alkalinity (up to the reinforcement layer)
- Chemical composition of the concrete near the surface

Generally stability of the structure has to be ensured / examined before beginning rehabilitation. It has to be clarified further whether there may be a contamination with questionable substances of the primal concrete surface. If so, these are removed before applying a new material system so that no more adverse influence of the drinking water can be expected (e.g. removal of chlorinated rubber coatings).
For the subsequent selection of an appropriate repair principle studies on the surface characteristics and profile of alkalinity are necessary. To ensure durability and serviceability of the concrete structure is the appropriate determination of the concrete cover of utmost importance.

2.3 Level 2

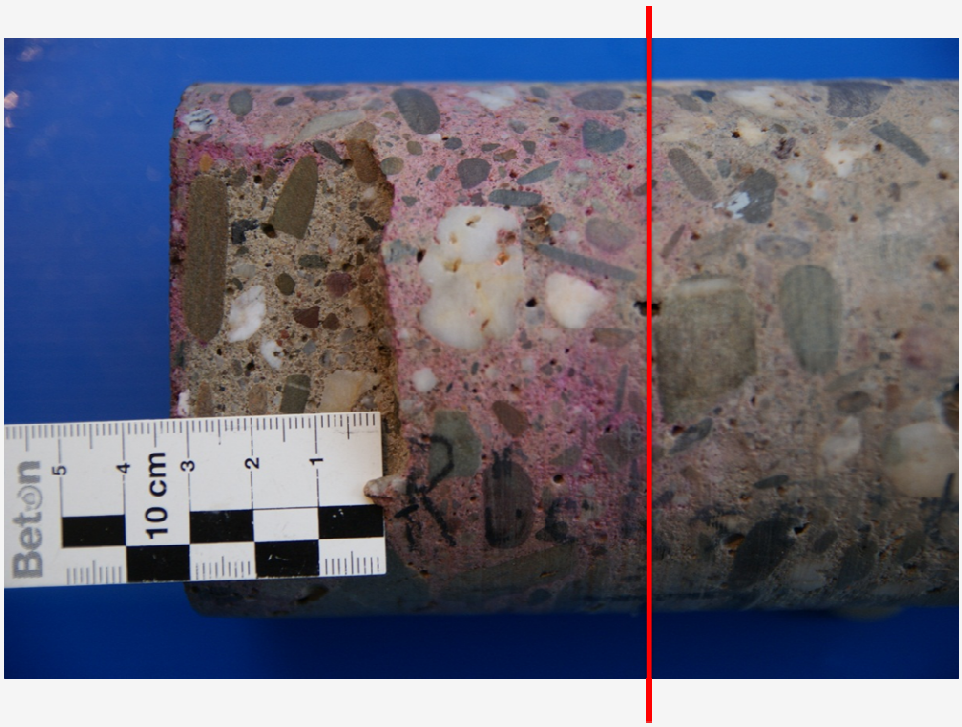
The second level is the determination of relevant impact mechanisms. The governing damage mechanism in the case of a drinking water reservoir is the leaching process, which reduces the alkalinity of the concrete and is known as hydrolysis (local and flat release of calcium from lime-dissolving carbonic acid), see picture 2. Calcium carbonate is getting under the formation of calcium bicarbonate in solution in water.

The process is increased due to water pressure changes and the resulting pumping action on the concrete pores.

$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow 2H^+ + CO_3^{2-}$

$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2\ H_2O$

$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2 \rightarrow$ Leaching Process



Picture 2 - Phenolphthalein test for identification the alkalinity border

Because there is no separate exposure class fixed in EN 206 (only by carbonation) for this impact mechanism, a new exposure category is required. In past for the construction and rehabilitation the exposure classes X_{C2} and X_{M1} were required. For determination of the required concrete cover, this is considered to be accurate, but only the impact by carbonation (formation of calcium carbonate) is assumed.

The creation of a new exposure class for constant contact with water/concrete to regard hydrolysis especially for diffusion open coatings will therefore need to be taken into consideration:

- (w/c)eq ≤ 0,50
- Content of cement (c) ≤ 320 kg/m^3
- Content of cement in recognition of additives ≤ 270 kg/m^3
- Powder content ≤ 400 kg/m^3
- Level of water penetration ≤ 30 mm
- Compressive strength class ≥ C 30/37
- Aggregate, free from organic impurities, no wood and no swellable and less solid particle fractions
- Aggregate grading A/B 16 or A/B 32
- Consistence class F3 middle

- Flow diameter a = (45 ± 2) cm
- Concrete covering
  - c_{nom} ≥ 45 mm, ≥ 55 mm (pre stressed steel)
  - c_{min} = 20 mm
  - Δc ≥ 25 mm (reinforcing steel)

The exposure class to be chosen will depend on the choice of the rehabilitation principle, so in the following decision-making level 3 is also the correctness of the chosen exposure class to be reconsidered.

3.4 Level 3

The third level represents the rehabilitation principles itself. Only a certain choice of rehabilitation principles of EN 1504 in the field of drinking water storage is useful:

Damage to the concrete

- Protection against ingress of substances
  - Coating
  - filling cracks
  - Installation of attachment plates
  - application of membranes

- Regulation of water balance of the concrete
  - coating
  - Installation of attachment plates
  - application of membranes

- Concrete Replacement
  - mortar application
  - section supplemented by concrete
  - concrete and mortar application by spraying
  - Replacement of components

Reinforcement corrosion protection

- Maintaining or restoring passivity
  - Increasing the concrete cover with additional mortar or concrete
  - Replacement of harmful substances or carbonated concrete
  - Electrochemical re-alkalization of carbonated concrete (see cathodic corrosion protection)

- Cathodic protection (CP)
  - impressed current
  - using sacrificial anode

The above-mentioned principles have to be weighted differently because not all material systems related the necessary performance characteristics to be needed. On this decision-making level requirements to the appropriate exposure and to meet the best result for choosing the right material system have to be reconsidered.

At first at the beginning of the decision process is to be proved that the stability of construction is warranted. In answering this fragment position may already decide for

or against a cement-based system. For example, are the principles *concrete repair* and *restoration for corrosion protection* and *ensure the stability* necessary, the decision can be made rather in favor of a pure cement-based system.

If the principle *regulation of water balance* and *protect against the entry of "pollutants"* (drinking water) is in the foreground, the decision may be made for a coating or lining system. Provided the requirements of *stability* and *corrosion protection* are not required.
It is important in the evaluation and selection of material systems to meet the goals of rehabilitation with the chosen rehabilitation principle.

3. Overview of materials and material systems

3.1 General

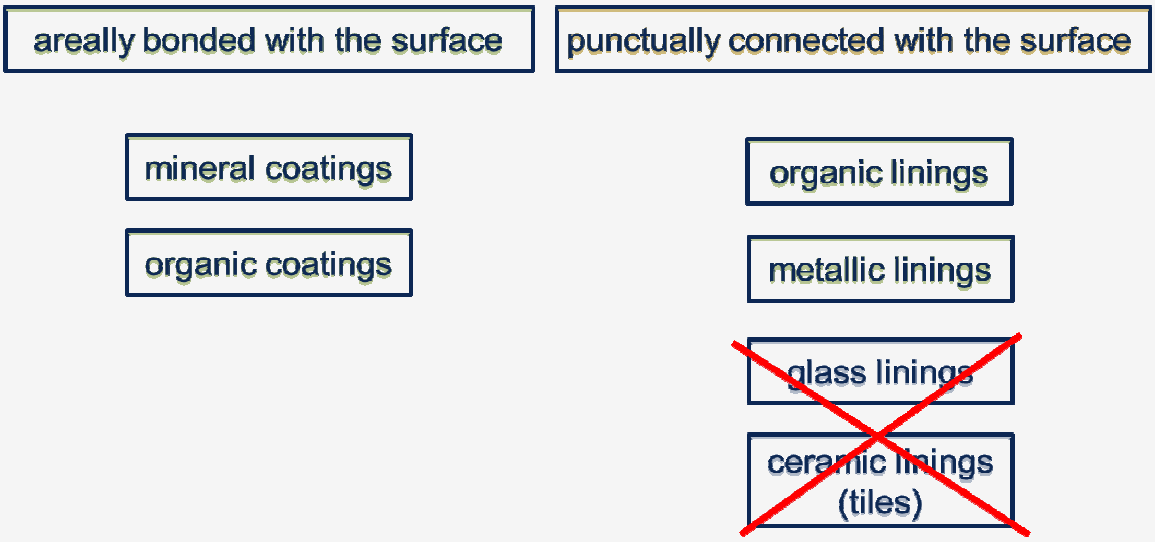
The various material systems differ both constructive and on the material behavior itself. There are systems which are connected over the entire surface with the substrate, and those that are connected only punctually with the ground. A distinction is made between mineral (cement based), organic, metallic and ceramic materials. Systems with full surface connection to the substrate material, are essentially the coating systems. The punctually connected systems are represented by the linings, see picture 3. The following material systems are generally used:

Coatings:

- Mineral, cement-bound materials
  - Purely cement-bound materials, Cement Concrete (CC)
  - Cement mortar with polymer additives, (sprayable) Polymer Cement Concrete (PCC/SPCC)
- Epoxy coatings

Linings:

- Membranes (Flexible PO, PE)
- Synthetic liner panels (PE, PP)
- Stainless steel



Picture 3 - Overview of materials and material systems

3.2 Mineral cementitious coatings

Pure mineral cement-based materials (CC and SCC) without addition of polymers can fulfill all the necessary rehabilitation principles for water reservoirs equally. They are also used as a base coat, as a concrete substitute or to ensure the corrosion protection.

For mineral cement-based coatings it is differed between purely cementitious materials (CC) without addition of synthetic polymers and polymer-modified materials.

Synthetic polymer-modified materials can be classified as follows:

- cement mortar / concrete with synthetic polymer additives (PCC), sprayed mortar/concrete with synthetic polymer additives (SPCC)
- Reactive resin mortar / reaction resin concrete (PC) (without water)

For drinking water reservoirs the so-called PC materials (percentage greater than 90% plastic) are not used. There the application is limited to use of CC and PCC materials.

Polymer modified coatings (PCC) cannot be used to increase the concrete cover and as concrete substitute. To ensure corrosion protection PCCs have to be proved due to their re-alkalization potential. If the principles *concrete repair* and *corrosion protection* are not necessary, they can also be used as a base coat to increase the resistance to penetration.

3.3 Organic two-component reaction resin systems (epoxy coatings)

In general, no problems are seen to use epoxy coatings as an effective corrosion protection for concrete and reinforcement, if the reinforcement is still under alkaline conditions and measures to enhance the static are not necessary. The protective effect is due to the high chemical resistance and the high diffusion resistance to carbon dioxide.

Provided, however, is always that there is sufficient protection against corrosion of reinforcement (alkalinity) and the carbonation is not yet well advanced. A re-alkalization potential of carbonated concrete of epoxy coatings is limited. Local corrosion of reinforcement problems that have no relevance to stability can be protected and re-profiled with alkaline or resin-bound systems.

By increasing the resistance of drinking water touched surfaces with impermeable epoxy coating materials the main use is for protection *against ingress of substances* and *regulation of water balance* of the concrete. Benefit from this material is the high resistance to hydrolysis.

3.4 Linings of membranes, plates and stainless steel

Different from coatings lining systems are connected only punctually with the ground. Because these systems are diffusion-tight (in cold water) these materials are used for the rehabilitation principles *protect against ingress of substances* and *regulation of water balance of the concrete*. Precondition here is still a sufficient corrosion

protection of reinforcement (alkalinity) and not a far advanced carbonation. A re-alkalization of carbonated concrete is not possible with these systems.
Measures to ensure the long-term corrosion protection and stability are often required previously (e.g. sealing of voids, concrete replacement, increasing the concrete cover). Mandatory for such systems is a necessary sealing against outside pressing water to prevent an accumulation of non-potable water between the construction and the lining.
It is also important to note that there are other exposures for linings as for coating systems.

4. Hygienic requirements

The 4MS (MS Member States: France, Germany, the Netherlands and UK) have committed themselves to work towards common practices for the assessment and approval of products in contact with drinking water. Principles have already been established for use with metallic materials and for the organic materials by control of constituent substances and risk-based testing of finished products against defined acceptance criteria. These principles have been applied – insofar as they are relevant - to cementitious products and are based on an analysis of established national practices. The aim is to reach a position where assessment and approval in one country allows a product to be accepted in the other three MS without further testing. Thus common practices are required for products which are placed on the market within the 4MS. They are expected to cover factory made products (but not specialist items intended only for one particular use in one MS) and coatings and packaged products for site application. Users of such products are entitled to rely on third party testing and certification to demonstrate that they meet national regulatory requirements.

Materials prepared on site from primary constituents, or ready-mixed off site and transported to the point of use, will not be the subject of common regulatory practices at this time. National regulators will continue to specify the requirements to be met by such materials, and it will be the responsibility of the constructor and the client to make the arrangements needed to ensure compliance. There will, however, be elements of the arrangements for factory made products that will also be relevant for site prepared materials e.g. use of approved constituents. It will be for each MS to decide on the extent of their use in relation to site prepared materials.

It has to be distinguishes between requirements for use from raw materials/constituents and the requirements for the finished product made from these materials:

- requirements for the individual constituents:
  - Technical requirements
  - Toxicological requirements (substances accepted - Positive List)

- Requirements for the final product:
  - External appearance, boundary
  - Migration behavior
  - Microbiology

In addition to the hygienic suitability of the materials requirements on the structural design to avoid contamination are necessary. Especially, ensure that an unintended

intrusion will be excluded from non-potable water. In view of the chosen rehabilitation system, therefore, the principle weaknesses of each system are considered (e.g. stagnation areas with risk of inadvertent occurrence of defects especially under changing pressure fluctuations / pumping effects)

5. Declaration of Performance (DoP) in relation to the essential characteristics of construction products and materials (CE Marking)

5.1 General

The Declaration of Performance (DoP) is the key concept in the Construction Products Regulation (CPR) [12]. The DoP gives the manufacturer the opportunity to deliver the information about the essential characteristics of his product he wants to deliver to the market.
The manufacturer shall draw up a Declaration of Performance when a product covered by a harmonised standard (hEN) or a European Technical Assessment (ETA) is placed on the market. The manufacturer, by drawing up his DoP, assumes the responsibility for the conformity of the construction product with the declared performance.
On the basis of the information contained in the DoP, the user will decide to buy, amongst all the products available on the market, the one which is fit for the use he intends to give to such product and he assumes the full responsibility of such decision.
The DoP constitutes then the key element in the functioning of the Internal Market for construction products by providing it with the necessary transparency and by establishing a clear system of allocation of the responsibilities between actors. The CE marking follows the DoP and means that the manufacturer has strictly followed all the applicable procedures for drawing up his DoP and, consequently, the DoP is accurate and reliable.

The difficulty is, that for the so called hygienic requirements (characteristics) fixed by the 4MS, a European acceptance scheme under the CPR has not established yet. In conclusion a CE marking for products in contact with drinking water does not exist. Never the less the 4MS has adopted a declaration of intent to establish a co-operation in the field of approval of products in contact with drinking water. This declaration intent also to set common requirements for the factory production controls to be put in place by manufacturers and system of assessment and verification of constancy of performance for DoP for products in contact with drinking water.

5.2 Systems of assessment and verification of constancy of performance

The intention of the 4MS is to establish a system which has been already approved for CE marking in accordance with CPR. This system is the so called System 1+:
System 1+ – Declaration of the performance of the essential characteristics of the construction product by the manufacturer on the basis of the following items:

- the manufacturer shall carry out:
  - factory production control (FPC);
  - further testing of samples taken at the factory in accordance with the prescribed test plan;
- the notified product certification body shall issue the certificate of constancy of performance of the product on the basis of:

- determination of the product-type on the basis of type testing (including sampling), type calculation, tabulated values or descriptive documentation of the product;
- initial inspection of the manufacturing plant and of factory production control;
- continuous surveillance, assessment and evaluation of factory production control;
- audit-testing of samples taken before placing the product on the market.

This system will be adopted for all hygienic characteristics for products in contact with drinking water. For all other essential technical characteristics it is the responsibility of the European Standardization process to fix systems of assessment and verification in the harmonized standards. One possibility could be System 2+:

System 2+ – Declaration of the performance of the essential characteristics of the construction product by the manufacturer on the basis of the following items:

- the manufacturer shall carry out:
  - determination of the product-type on the basis of type testing (including sampling), type calculation, tabulated values or descriptive documentation of the product;
  - factory production control;
  - testing of samples taken at the factory in accordance with the prescribed test plan;
- the notified production control certification body shall issue the certificate of conformity of the factory production control on the basis of:
  - initial inspection of the manufacturing plant and of factory production control;
  - Continuous surveillance, assessment and evaluation of factory production control.

Table 1: System 1+ and 2+ of assessment and verification of constancy of performance

Essential Characteristics		**Hygienic Characteristics: System 1+**	**Technical/other Characteristics: System 2+**
Manufacturer	**FPC**	X	X
	testing of samples with a test plan	X	X
	Type Testing	-	X
Notified certification body	**Type Testing**	X	-
	initial inspection of manufacturing plant and FPC	X	X
	surveillance, assessment and evaluation of FPC	X	X
	audit-testing of samples	X	-

A lot of products are already covered by a harmonised standards (hEN) or a European Technical Assessment (ETA) without respecting hygienic characteristics.

Picture 4 shows what steps are necessary to cover the whole process of assessment and verification of constancy of performance with the aim of a marking (certificate) for products in contact with drinking water.

Picture 4 - CE marking in accordance with CPR with respecting/including hygienic characteristics

6. Conclusions

The choice of materials and material systems for the rehabilitation of water reservoirs is varied. The system must comply with both structural and hygiene requirements. Here, a detailed knowledge of the systems is necessary. Decision-making and a structured approach is a basic requirement.

The design engineer should be added in a position to handle this task and make the right decisions. These are characterized from the three levels of decision making process. Each level of decision requires different professional detailed knowledge. This is especially the detection, identification of the actual condition of stability of the structure, knowledge of the relevant impact mechanism (exposure), the common principles of rehabilitation and suitable material systems. Limitations of each system have to be detected reliably. In Addition it is necessary to have the knowledge of hygiene requirements of the materials, which are dependent on the material of varying complexity. A clear and European wide accepted declaration of the performance of all essential characteristics in accordance of the CPR should be a necessary method for the engineer to simplify the selection of suitable materials and material systems in future.

Literature

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