CONTRIBUTION TO THE UNDERSTANDING OF THE BEHAVIOR OF VARIOUS CONSTRUCTION AND LINING MATERIALS IN DRINKING WATER TANKS: A WATER SUPPLIER'S EXPERIENCE.

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1. INTRODUCTION

As a rule, water suppliers don't build or rehabilitate reservoirs on a frequent basis. They may therefore lack the specific experience required to take the choices that will be critical for success. They are not always well advised, good projects are not always well implemented, and work with defects continue to appear, even if they could have been avoided. It therefore seemed worth reminding future contracting authorities of some basic technical principles. These are presented below based on the practical experience – successes and failures – of **eau**service, the water supplier of the city of Lausanne. With three water treatment plants, 21 reservoirs and 55 tanks due to geographical situation, **eau**service has had plenty of opportunity for experience.

2. GENERAL REQUIREMENTS

Drinking water tanks contain a food product and must in no way lessen its quality. They must therefore be designed to avoid contamination, which implies in particular the tightness of the structure. Moreover, Swiss law (ODAIOUs, SR 817.02, § 34) specifies that the materials may only release substances to food in quantities a) safe for human health, b) technically unavoidable, and c) changing neither its composition nor its organoleptic properties.
Water suppliers expect a service time of about 100 years for their reservoirs. Since the current standards for construction are intended for a 50 years lifetime, additional requirements are needed, as well as a strict compliance with the rules of the art (as stated in SIA 262, EN 206-1 and Directive W6 of SVGW: Guidelines for the design, construction and operation of water reservoirs, ed. 2004, for review). In new water tanks currently built with fair-faced formwork concrete without coating (according to W6) the concrete qualities achieved allow to expect a 100 years' service lifetime. As for coatings, applied in rehabilitations, a service time of 50 years or more is both practically and economically reasonable and technically possible. The quality of the water tanks inner surfaces, in constant contact with water, is one of the key factors for service lifetime without repair. By its own nature, water may strongly interact with the material that should therefore be designed and implemented to keep these interactions far below pathologic level.
Thus, health requirements as well as lifespan expectations imply a limitation of interactions and require water tightness of both the structure and materials. Water tightness is achieved by the choice of systems and their careful implementation. Materials based on hydraulic binders are perfectly appropriate for the task.

3. WHAT WORKED: MORTAR AND CEMENT SEALING

Many water tanks are coated with cement sealing, successfully carried out until 1989 (technique described in the 1975 edition of Directive W6). These coatings have very high cement content. Executed in 2 or 3 layers with a finishing layer of cement sealing, they show excellent durability. The sealing layer acts as a dense skin, whose low porosity strongly limitates water penetration and mineral leaching. Its high cement content implies a large hydration reserve and enables self-healing.

A great solution, but its implementation requires specialized expertise which, for want of being sufficiently used during the last decades, has been largely lost. A trend is generally observed since the 80's: with increasing costs for skilled workforce "know-how" has been transferred to higher technicality materials, whose intrinsic quality has to allow its implementation by less qualified staff.

Remark: In the process of normal aging, coloring and softening may affect cement sealings until the mortar locally appears (Fig. 1). When a sanding effect occurs, it generally evolves towards stabilization after the skin layer of the mortar has been removed. Sanding means that the skin layer was weakened by hard troweling, which may have generated an enrichment in water at the surface and thus increased porosity.

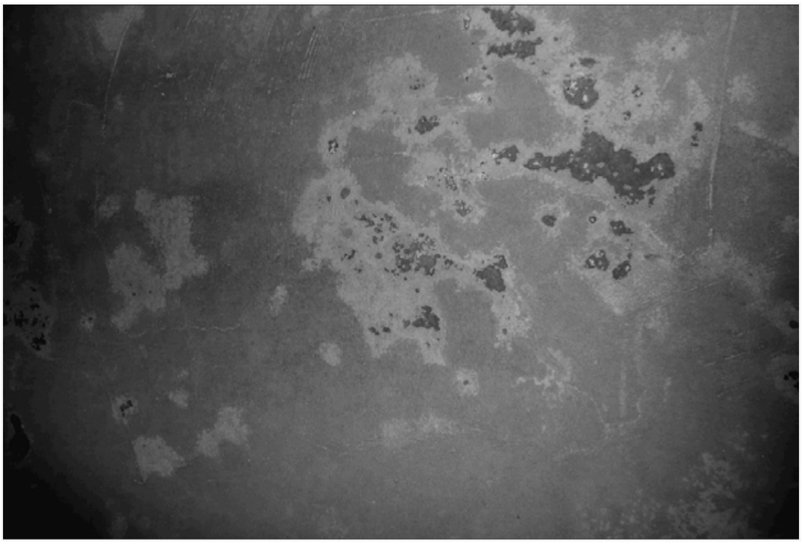


Fig. 1 different stages of alteration on cement sealing

4. WHAT DID NOT WORK, AND WHY

Some of the applied materials did not work, did not work properly or did not work at all. Part of the defects derived from the early times of the above-mentioned trend towards replacement of skilled labor force by more technical materials. In the 80's many kinds of more or less "miraculous" systems were put on the market that were later on proven to be unsuitable to water tank environment. Other defects have resulted from non-compliance with the rules of art during application. The use of less qualified workforce significantly enhances this risk and requires increased surveillance on site.
Systems that have shown defects can be grouped into 3 categories: either mixed, or purely organic, or purely mineral.

4.1. BACKGROUND IN ORGANICS

Whether natural or synthetic, organic components are made of the constitutive elements of the living world. Some of them are biodegradable and can therefore provide a nutrient supply supporting the growth of microorganism or even biofilm.

Biofilms are organized "consortia" formed by microorganisms attached to a support and wrapped by a gel constituted principally of exopolysaccharides. This gel stabilizes the microorganisms and provides them efficient protection

particularly against disinfection agents. The proliferation of microorganisms required to form a biofilm implies the presence of a source of nutrients.

The decisive importance of nutrient supply by the substrate rather than by water was proven in our case for each occurrence of biofilms: in a very tank they only develop on surfaces coated with materials including organic components. Biofilms are presenting a risk, being themselves a nutrient source and harboring more or less unwanted organisms (bacteria, yeasts, fungi, protozoa, nematodes, etc.). Their eradication requires both mechanical cleaning and disinfection.

4.2. MIXED SYSTEMS: MODIFIED MORTAR

Technical datasheet extracts: "*Powder based on hydraulic and special synthetic binder with addition of selected quartz sand. Due to composition, the product is completely harmless and binds very well to the cement. It has a good aging resistance.*"

Used between 1991 and 1993 for the rehabilitation of 3 tanks totaling 11'200 m^3 in a reservoir built in 1946, the coating has shown since 1995 severe blistering and delamination (Fig. 2), together with biofilm formation (Fig. 3). However, gluing tests were performed beforehand, with one year waiting time and good results at pull tests.

Fig. 2: Delamination on modified mortar

Fig. 3: Biofilm on modified mortar

Analyses were carried out, showing the presence of a polyvinylacetate polymer in the coatings. In alkaline conditions, this polymer is hydrolyzed to acetic acid which then reacts with the calcium available in the mortar to form soluble and hygroscopic calcium acetate. Two situations can result: if the coating is intact, the induced osmotic pressure forms blisters containing a concentrated (0.1 molar) solution of calcium acetate, smelling typically of the traditional photo labs. If the coating is perforated, calcium acetate seeps out of, forming a local nutrient source on which a biofilm begins to grow (Fig. 3).

Applied in 1994 as local rehabilitation in another tank, the product shows the same defects. Interestingly, the biofilms host a different combination of microorganisms, which supports the assumption that in our case the primary cause of biofilm development has to be linked with nutrient supplied by the support rather than with the presence of a particular bacterial species in the water.

Remark: Here, the main source of problems is the bad conception of the material. A definitive solution requires its replacement. On a temporary basis, pluriannual cleaning and disinfection limit biofilm growth.

4.3. MIXED SYSTEMS: ADHESION LAYER UNDER CLASSICAL CEMENT COATING

In a reservoir built in 1970, the two tanks, totaling 15'532 m^3, have been coated with a conventional mortar with cement sealing, underlain by an adhesion layer. The walls show locally delamination as well as biofilm growth on fissures or humidity haloes (Fig. 4). Analyses show that the adhesion layer releases organic components into the water seeping through cracks in walls and coating. The resulting solution, highly concentrated in organic components, causes blisters or delamination by osmotic pressure, or oozes through local defects feeding the biofilms.

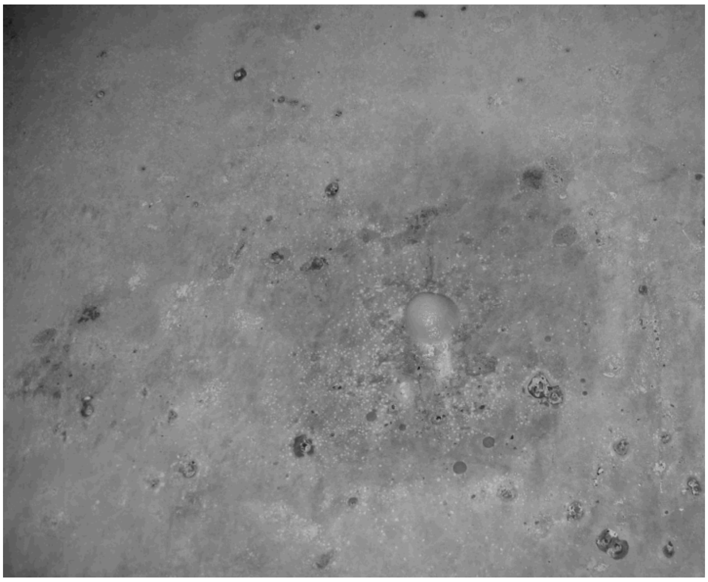


Fig. 4: Moisture and biofilm on cement sealing underlain by an adhesion layer

Note: No adhesion layer should be needed at the interface between two products based on hydraulic binder. However adhesion layers are sometimes used whereas the surfaces to be coated are too smooth and badly absorb water (excessive smoothing and metal forms that produce such surfaces should therefore be avoided in this case). The present example shows that a mechanical preparation is far better than the use of a adhesion layer.

Remark: Due to the use of an adhesion layer under a suitable and classical mortar coating with cement sealing, these water tanks will still show throughout their entire service life delaminations and biological issues requiring repeated local repairs and frequent cleaning and disinfection.

4.4. PURELY ORGANIC SYSTEM: EPOXY COATING

Two water tanks totaling 5'400 m^3 have been covered during construction with an epoxy coating. The product had been successfully applied beforehand in a smaller tank (500 m^3). However, isolated problems like soft or oily spots as well as perforations were observed in the new reservoir after only 8 months, quickly followed by blistering. Despite repairs, blistering (Fig. 5) became widespread enough to jeopardize coating adhesion. A complete renovation of the two water tanks had to be carried out.

The problems encountered here and studies undertaken have shown that, basically, the material does not appear to be really adapted to the coating of large concrete water tanks. The substrate must be dry during implementation (< 4% residual moisture), which is hard to achieve while being possible as shown by the results in the small tank. The product is also potentially sensitive to the alkalinity of the concrete in case of polymerization defects. This appears to have been the case here.

Laboratory trials carried out on epoxy samples taken from the tanks have confirmed that the material is hydrolysable in the presence of KOH, which serves as catalyst. Now the pore solution of the concrete of the walls contains around 1.5% KOH and the fluid in the blisters too!

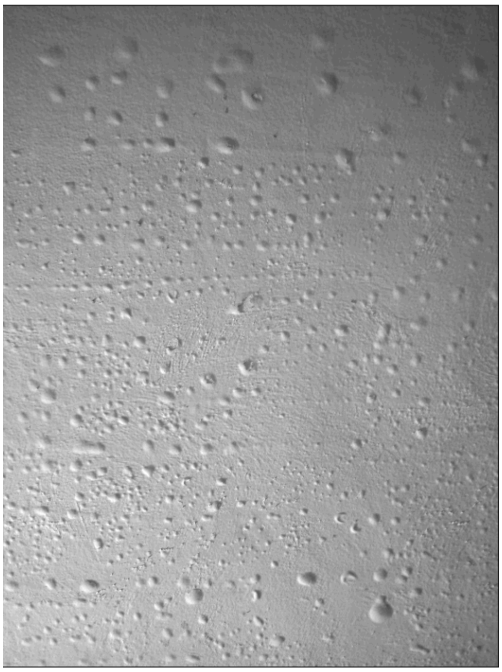


Fig. 5: Blistering on epoxy coating

Remark: Failure in the respect of the requirements of implementation has undoubtedly played an aggravating role.

4.5. PURELY ORGANIC SYSTEMS: SEALING ON BUILT IN AND DOOR

Repair sealings are frequently made of organic material. They may show a high risk of bacterial growth and biofilm formation (Fig. 6). A careful placement during concreting will generally spare the use of these products (Fig. 7).

Fig. 6: Biofilm growth on door sealing

Fig. 7: Well built in door

4.6. PURELY MINERAL SYSTEM: THIN MINERAL COATING

A ready to use cement based thin coating has been applied concrete by wet spraying (without pressure) in three water tanks. It has been applied in two layers totaling 3 to 5 mm, with a so-called orange peel finish. This finish requires expertise, but was said to provide improved surface characteristics by avoiding the water enrichment and the destruction of the early hydraulic bonds induced by troweling.

Applied 17 years ago, as local repair in a large tank, by a firm trained by the supplier, the coating is currently undamaged. The same coating, applied by two different firms in two significantly smaller tanks (300 m^3 each), shows defects of two different kinds.

In tank 1, the coating has a wild roughcast aspect with fragile, binder depleted peaks. Alteration of the asperities was observed within two years after application. The weathered zones have softened and spread, forming numerous brown spots (Fig. 8). The depletion of binding, and the ensuing alteration, could be due to local dilution by a punctual supply of water during the early phases of curing, as a result of condensation for example. The material is known to be sensitive to water films throughout implementation and curing.

Fig. 8: Spotted alteration in tank 1

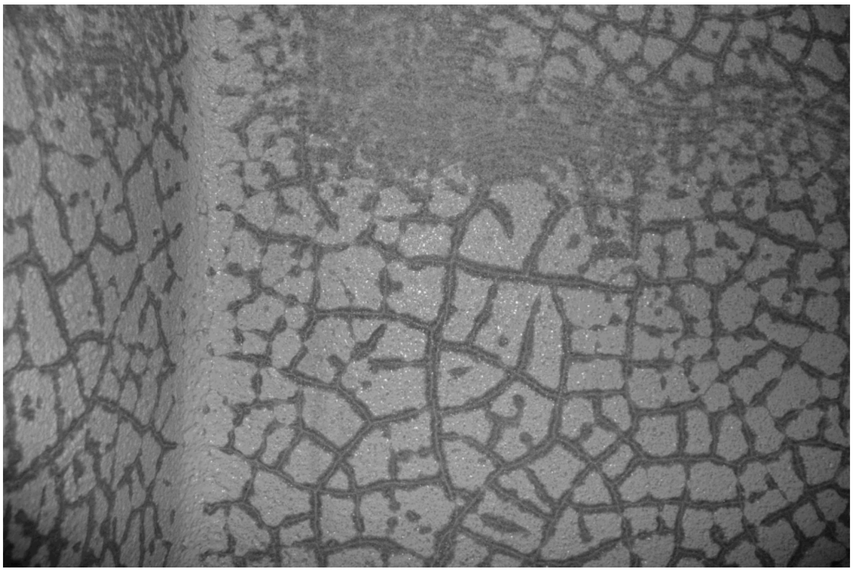


Fig. 9: Alteration following desiccation cracks in tank 2

In tank 2, implementting hasn't been optimal either, the undertaker using the technique for the first time. The coating shows a polygonal network cracking, probably desiccation cracks made visible two years after application by the beginning of alteration. Desiccation cracks are caused by a superficial moisture deficit during setting, i.e. insufficient curing proven here. In the submerged zone of the walls alteration continues on both sides of the healed fissures (Fig. 9).

Microscopic examination (Fig 10 and 11) shows in both cases a severe superficial deterioration, sharply delimited, including: binder loss, loosening of aggregates and increase in porosity. Underneath, a second area shows a digressive destruction of cement matrix. The two deteriorated areas represent together 20 to 30 % of the thickness of the product. Cracking through the top coating doesn't affect the base coating.

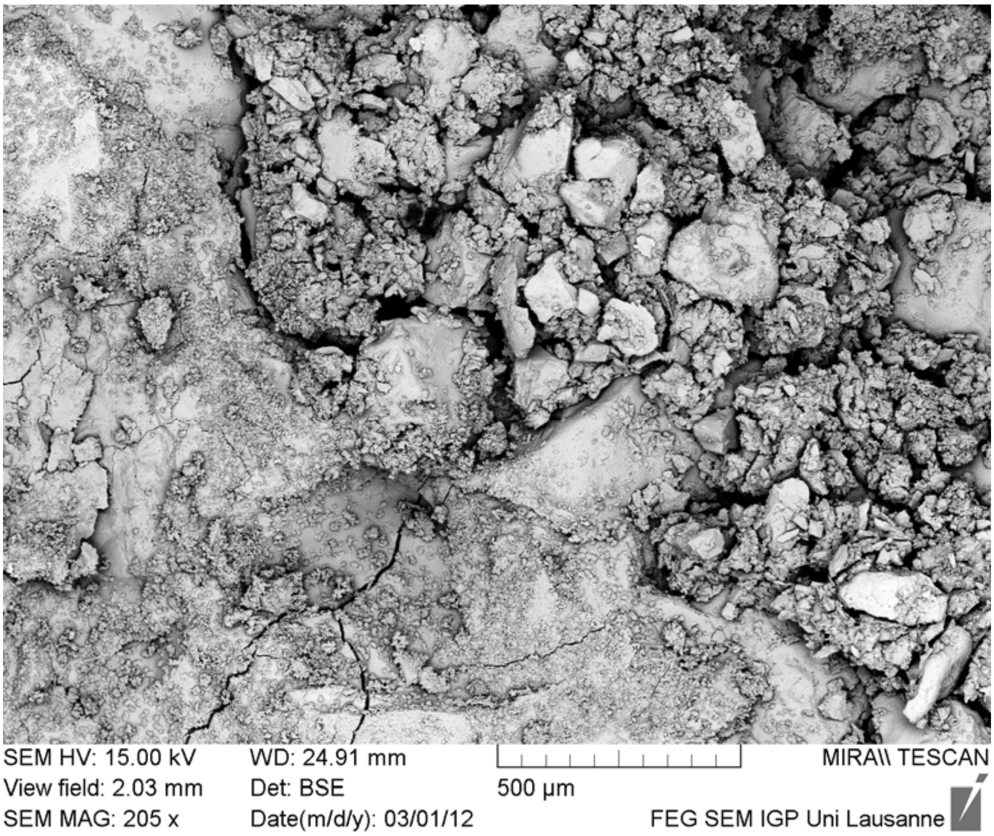


Fig. 10: SEM of thin mineral coating, altered (top right) and sound surface

Remark: Sensitive both to condensation and moisture deficit, this product requires a good control of local conditions. Moreover, thin layers induce specific fragilities when improperly implemented.

Existing fragilities have furthermore been enhanced during the first years of service by acidic cleaning, which is abandoned today.

Nevertheless, microscopic examination has shown that rehabilitation is premature at the time, in spite of the impressive appearance of the alterations, and thanks to the absence of organic compounds and the related risks.

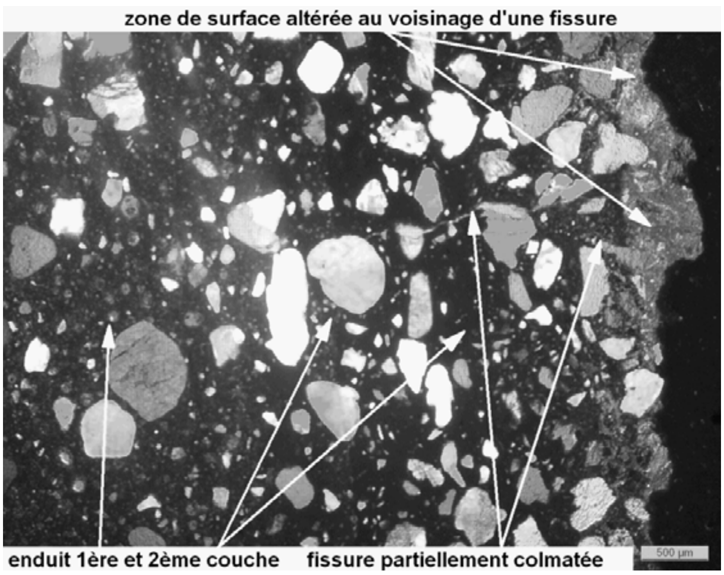


Fig. 11: Microscopic view of mineral coating

4.7. OTHER CAUSES OF DEFECTS

All possible causes of defects have not been mentioned here. Especially the "electric" issue, causing rapid onset of characteristic local damages, has not been met by **eau**service. Here, like in every other investigation for damage causes, the intervention of a materials expert and microscopic analysis on thin section and / or by scanning electron microscopy (SEM), help to confirm the diagnosis. If the electric influence is proven, identification of the causes by a global expertise of the reservoir, followed by their removal, must be undertaken before any other action.

4.8. CLEANING AND CLEANING AGENTS

The cleaning agent used since 1988 by **eau**service for the maintenance of water tanks has been blamed for some of the premature deterioration of the thin mineral coatings. A survey was therefore initiated to determine the aggressiveness of cleaning agents on the one hand, the hygienic necessity to use them on the other hand. The cleaning agent used, a descaling agent, was mostly meant to eliminate colorations on the waterlines. Effective on hydraulic based surfaces, it was without effect on synthetic materials, which suggests that removal of the coloring succeeded by attack of the underlying surface. A set of lab test has confirmed the hypothesis. Bacteriological analyses of the colorations have shown that their removal is not required. Chemical cleaning has therefore been dropped in 2004.

5. NEW SYSTEMS

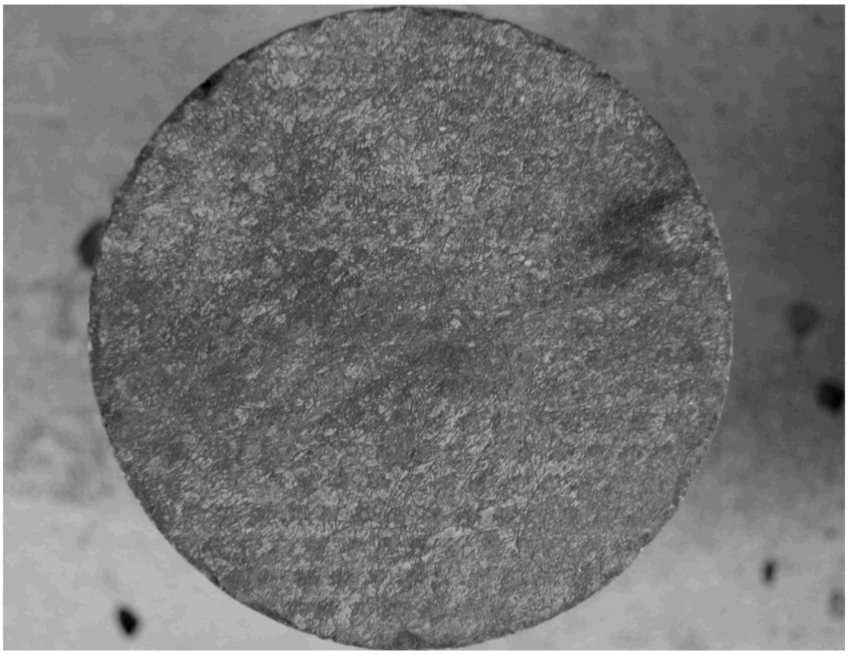
The new systems are the answer to the specific shortcomings encountered with the diverse materials experienced; they are well adapted to local conditions.

5.1. FAIR-FACED CONCRETE (WITH CONTROLLED PERMEABILITY FORMLINER - CPF)

Fair-faced concrete without coating, according to W6, is a successful example of the trend to more technical solutions. It allows excellent surface qualities.

The W/C (water/cement) ratio is an important criterion for concrete quality. Cement requires water for its hydration, but the water in excess, which isn't used in hydration, creates a porosity that is most harmful when it communicates. A high durability concrete will therefore have a W/C ratio <0.5 while maintaining the necessary workability for implementation.

Current formwork may cause an accumulation of entrapped air and excess water at the surface. W/C ratio and porosity are locally increased, weakening concrete properties on the surface. In contrast, draining formliners reduce the W/C ratio at the surface, which becomes particularly dense and thus resistant and durable. Surface quality, in particular porosity closure, is similar to that obtained by cement sealings of the past, while not requiring additional post-concreting operation by a specialized mason. The knack for the implementation of the different existing sheet types can rapidly be acquired; excellent results have been achieved by a small careful contracting firm which made first tries on walls not meant for contact with water before proceeding successfully with the concreting of the water tanks.



Resulting surfaces are characteristic (Fig. 12) and may astonish. As they are dark, marked by the structure of the draining formliner, the obturations of the spacer holes remaining visible, they appear less flattering than smooth cement sealing or the less durable light coatings.

Fig. 12

Since 1996 several structures totaling fifteen tanks, were carried out by **eau**service with this system. The first reservoir was completed in 1996 with a CEM II A-LL 32.5 cement. The concrete shows good quality characteristics. This tank is a good example of watertight concrete, ranking above the average civil engineering concrete. The surface quality is almost comparable to that achieved by cement sealings of the past.

Remark: Nevertheless, surfaces have locally displayed beige areas reflecting slightly more capillary areas of concrete skin (Fig. 13). Microscopic examination shows that they are resulting from local conservation of cement slurry at the surface, resulting either from local incorrect concrete internal vibration, or from a locally insufficient or impeded drainage (formliner locally soiled prior to use, incompletely cleaned in case of reuse, etc.). The defect remains minor.

Fig. 13: Local cement slurry conservations

Based on tests carried out by **eau**service in order to understand interactions between water and concretes made with different cements, all the following structures were carried out with concretes made with a CEM I 32.5 cement

incorporating 4% silicafume (SF). The use of cement with SF significantly improves the water tightness of concrete, through filler effect (fine grain) and pozzolanic effect (inducing reduction of capillary size in the cement paste). Unfortunately this cement is no longer produced and it is hoped for an equivalent, the addition of SF during concrete manufacturing sometimes not being easy to realize.
The resulting concretes show characteristics of quite remarkable quality (Fig. 14): surface with low capillarity of cement paste, good bonding between cement paste and aggregates, low cracking content. They were well implemented and compacted and are successful examples of watertight concretes, matching with concretes for civil engineering structures subjected to high solicitations and requirements. Surface qualities are similar to those obtained by the cement sealing of the past.

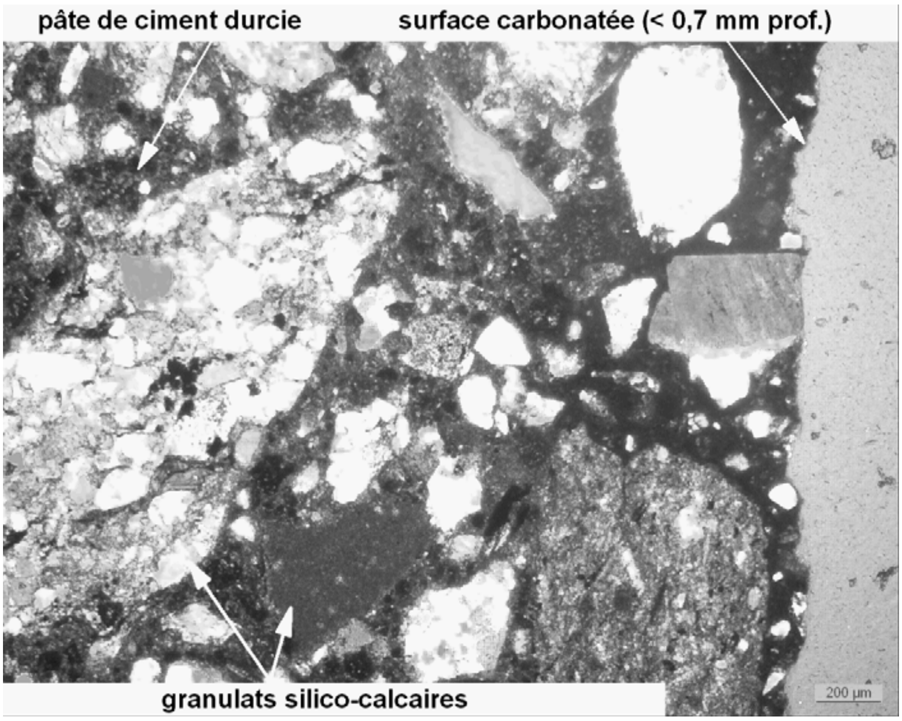


Fig. 14: Microscopic view of excellent fair-faced SF concrete with CPF

Even here surface irregularities happen. Areas of a lighter shade of grey in the first reservoir show a slightly higher capillarity due to locally poorer draining effect. A second reservoir locally shows voids (1 mm) in the surface region, which could be due to small variations in vibration during implementation, without being a default, all microstructure parameters being similar. In any case, local irregularities affect only the concrete skin, the concrete's intrinsic qualities remaining untouched underneath. Consumption of the first millimeters may eventually occur and surfaces evolve into a lightly sanded but healthy and sustainable concrete.

Important remark: The system, confirmed by 16 years hindsight, does not however eliminate the risks of faulty workmanship, failure to observe the rules of art sadly remaining possible. A major defect has thus been brought about in one of the described structures by a brutal and premature stripping, carried out by a hurried subcontractor, despite a reminder of the standards of SIA stripping conditions and the explicit ban of shocks. This unfortunate action created microcracks around the water-parks. During the leak test it became apparent that in all 10 tanks virtually all water-parks were leaking. The concrete was remarkably watertight, but the tanks were not! The internal controls of both the contracting firm and the local management were insufficient. This case highlights the need for independent supervision, performed by contracting authorities or delegated by them.

5.2. REPAIR BY DRY PROCESS SPRAYED MORTAR (SHOTCRETE)

Tests were conducted by **eau**service, together with a company and two control laboratories in order to develop a system for the rehabilitation of existing tanks. The resulting system shows all the advantages of the dry spray process such as high performance and high durability properties of the material and its surface.

This system requires detailed invitation to tender and specifications and a good knowledge of the technique of dry shotcrete, both from the contracting authority and the executing company. The competence of (the) workman(s) is essential for a good result: it is he who regulates distance, pressure and angle of application as well as the amount of water mixed with the dry mortar at the nozzle. These reasons have led to awarding the construction in two steps. 1) Pre-selection of contracting firm based on the technical file: estimation of skills in the area of shotcrete, experience of staff and adequacy of the proposed product. 2) Final award on the basis of a test on site: application of shotcrete on two surfaces, by the staff known by name, and using the proposed product.

The system was implemented in 2004 (Fig. 15). The mortar was made with a CEM I cement with an addition of SF and carefully selected and controlled aggregate (a bad surprise with a ready to use mortar may be noted here: during the tests it has shown significant but unannounced changes in composition between batches). Our dry process sprayed mortar was applied in a single layer, 12-16 mm thick (3 to 5 times the maximum diameter of the sand, beyond which there is a risk of cracking) and troweled.

Fig. 15: Successful rehabilitation with dry process sprayed mortar, on walls, stairs, gully and over-flow

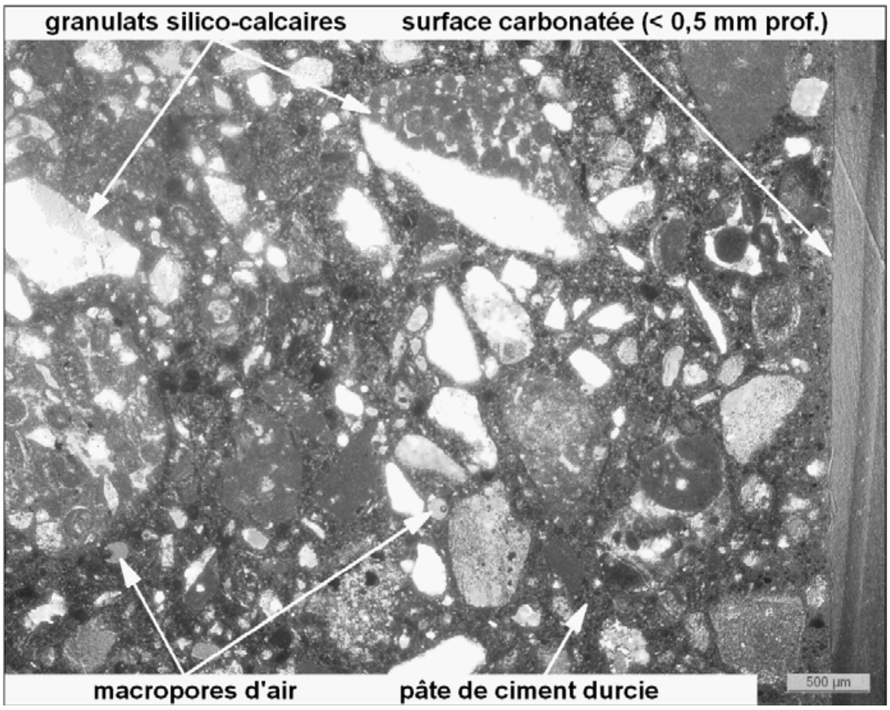


Fig. 16: Microscopic view of dense shotcrete

Microscopic examination (Fig. 16) shows that the mortar was well implemented and applied in a compact manner on the concrete support. It has outstanding quality characteristics: low capillarity of the cement paste up to the surface, particularly good bonding between cement paste and aggregates (due to the impact force of the projection on a rough and moist concrete surface), low cracking content. This is a good example of successful application of a watertight system on a concrete which isn't, but is sufficient for the mechanical stresses to which it is subjected. The dry sprayed mortar corresponds to that applied on engineering structures exposed to bad weather and subjected to high solicitations and requirements. The quality of the surface, in particular the closure of porosity, is greater than that obtained by the cement sealing of the past, while being obtained by mechanical means ensuring a rapid advance the work. The expected service lifetime exceeds the one of the structure.

6. WHAT IT TAKES TO MAKE IT WORK

Other critical points have to be considered in addition to those raised in the examples (requirements, material types, conditions of implementation, surveillance). They refer to construction but can be adapted to rehabilitation.

At project start, the water supplier needs to store water. He has to transpose this function in terms of structure (civil engineering) and material (concrete specifications). To do this he appoints an engineering office (project specifier), to which he usually attaches an expert who will define the materials to be implemented (concrete, mortar) taking into account the standard EN 206-1 (ch. 6.2 and 6.3) and Directive W6 (to be amended to fit the new standards for concrete and mortar).

In agreement with the contracting authority, the project specifier and the expert will define the specifications of concrete. This has to be done either on the basis of successful initial concrete tests, or on the basis of data taken from successful experiences with reservoirs whose concrete tanks have shown exemplary behavior over time and provide profitable inspiration for a new construction. Initial trials must be carried out quite early, some tests, such as resistance to alkali-silica reaction, can take months.

This approach to initial project design has been gradually implemented and systematized by **eau**service with growing experience. Other elements have been formalized over time. At the stage of tender, the contracting authority has to set out clear rules and apply them - especially those relating to:
- The applicable standards
- The criteria for award
- The experience of the company in the field of construction of water reservoirs or equivalent (list of similar objects constructed)
- Subcontracting (what is allowed and what is not)
- The controls during work (by the laboratory of the company and by the outside laboratory of the contracting authority)
- What is defined in case of bad control results (replacement, ...)

Remark: The contracting authority keeps part of direct surveillance and has to check that everything is done according to the tender, by practicing a strict and continuous supervision, with the help of his expert whenever needed.

7. CONCLUSIONS

Drinking water tanks must meet requirements concerning health issues and sustainability. Both involve minimizing the interactions between material and stored water. Successes and failures reported here, resulting from a long experience with a range of construction systems and coatings, illustrate the basic principles coming into play during the implementation of the materials. Their understanding has lead to specifying criteria for selection and requirements to be met in order to get optimal and lasting results in operating conditions. Appropriate use of suitable materials based on hydraulic binders allows reaching the objectives.
The said basic principles have been applied in an exemplary way during the construction of fair-faced concrete without coating, and in the rehabilitation of tanks with dry process sprayed mortar, both providing remarkable surface qualities.
In addition to the choice of system, professional conception, tender, award and supervision are essential for good results, not forgetting explicit mention of performances such as arising from the SIA standards supplemented by Directive W6 of SVGW.