Drinking water reservoirs – with controlled permeability formwork (CPF) liners: Analysis of the water tanks after 15 years of operation

Water supply, drinking water reservoirs, in-situ concrete, formwork (CPF) liners, low porosity surface, porosity, mercury porous-meter

For drinking water reservoirs, the governing standard EN1508 and DVGW (The German Technical and Scientific Association for Gas and Water) standard W 300 consider that a high quality low porosity surface is essential for hygienic reasons. A proven technique for optimizing the quality of concrete surfaces is the use of Controlled Permeability Formwork (CPF). The use of modern CPF liners such as Zemdrain® leads to significant reductions in surface porosity. CPF liners are specially engineered fabrics consisting of a filter and a drainage layer and have been in use worldwide for nearly 20 years. The filter fabric retains the majority of cement fines, whilst permitting the controlled removal of excess air and water from the concrete/formwork interface. Once attached to the formwork, concreting is performed in the normal way. Test cores taken from three drinking water reservoirs constructed in Germany in the early 1990's have been examined to assess concrete quality and porosity. The CPF liner cast surfaces were proven to have much lower porosity and to be virtually blowhole free when compared to surfaces cast against shotcrete/cement mortar coatings resp. steel or plywood faced formwork. From this it is concluded that the use of CPF is appropriate for the production of quality low porosity surfaces for drinking water reservoirs as defined by the standards.

1. Required profile for the internal surfaces of water reservoirs

Surfaces should be designed to enhance the quality of the stored water in accordance with EN 1508 *"Materials which meet appropriate test requirements and which will not cause the stored water to fail to comply with the requirements of appropriate EU Directives and EFTA Regulations shall be used in the structure of water compartments and in the surfaces in contact with the stored water. Concrete and cement mortar generally satisfy this requirement, but special care shall be taken if additives are used. In order to facilitate subsequent cleaning and to avoid bacterial growth, internal surfaces shall be as smooth and pore free as possible. This can be achieved by high quality concrete finishes or by the application of suitable coatings or linings"*.

In its Technical Regulations booklet W 300, the DVGW (German Technical and Scientific Association for Gas and Water), set the following requirements for reservoir [2] inner surfaces (fig. 1): *"When cleaning reservoirs, it is essential that they are as smooth as possible and of the lowest possible porosity. Rough surfaces, honeycombing and blowholes lead to the accumulation and deposit of substances that can promote micro-organic growth. Impermeable, low porosity concrete does not generally require any further surface treatment or inner lining"*

Therefore the construction of a low porosity, reinforced concrete surface [3,4,5] should be the preferred method.

Figure 1: *Drinking water reservoir of an older type – interior view*

2. Low porosity reinforced concrete surfaces with controlled permeability formwork (CPF) liners

The surface of concrete structures constitutes a weak point. A frequent reason for this is the poor quality of the concrete in the cover zone, as blowholes may appear or micro-organisms may grow on carbonated, porous concrete. Various causes can be attributed to this: The formwork is usually impermeable, which means that trapped air and excess water move towards the formwork during the compaction process and collect at the formwork/concrete interface. Blowholes, micro-cracks and a porous concrete surface are the visible consequence. During the compaction process necessary to achieve good concrete, vibration forces transport excess water to the cover zone, which for all concrete mixes leads to a poorer quality concrete due to an increased water cement (w/c) ratio. The structural life of any concrete structure to a large extent depends upon the quality of the cover zone, as this constitutes the main "line of defence". Special formwork systems with brand names such as AGEPAN, MAGNOPLAN, BETOPLAN, or ZEMDRAIN® document progress from smooth plywood formwork to CPF liners (leaving aside steel formwork for a moment). Report No. W 300 issued by the DVGW states with good reason in paragraph 6.7.1: *"The inner formwork surfaces should be as smooth as possible and of the lowest possible porosity. Water drainage and water-absorbent formwork (CPF) liners of synthetic filter fabric must be fitted without folds and firmly attached to the formwork panels. They must be replaced after each concrete pour as their efficiency decreases with each application."*

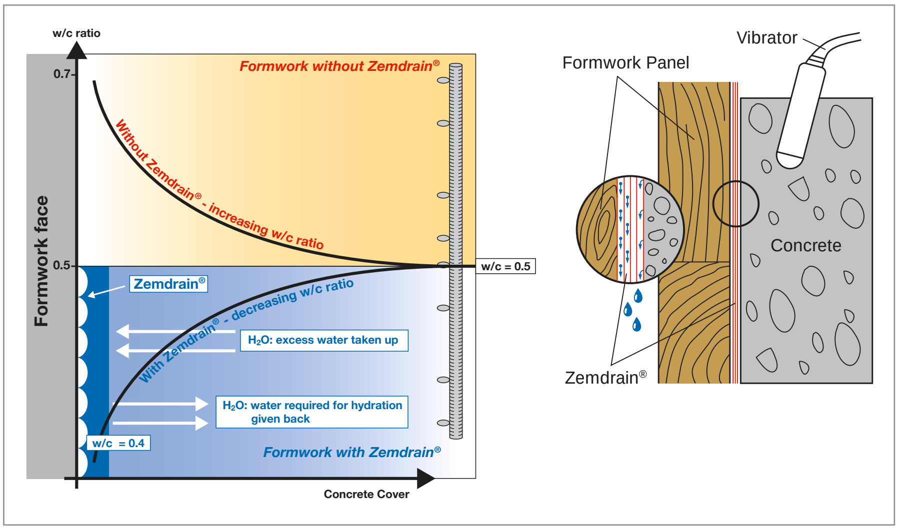

Figure 2: *Drainage system of Zemdrain® formwork (CPF) liners for demanding boundary zones*

The exemplary properties of Zemdrain® formwork (CPF) liners (a trademark of market leader DuPont) are available in two types MD or Classic with a filter fabric of fine polypropylene (PP) fibres with a controlled permeability and a drainage side composed of coarse fibres or a net. When affixed to the formwork, the filter layer allows excess air and mixing water to escape from the concrete surface under vibration energy (fig. 2). On the formwork side, air and excess water are collected at the contact surface with the formwork and removed using a textured surface with coarse fibres, whilst on the concrete side the finer fibres retain the cement fines thus leading to a denser concrete surface. At the base of the attached formwork, the formwork (CPF) liners are directed outward, which permits excess water to drain off harmlessly by gravity since no vacuum effect is involved. This drainage means the cement fines are retained at the concrete surface while the water cement ratio in the cover zone is reduced to w/c < 0.4 (fig. 2). Some mixing water remains stored in the filter fabric and is returned to the concrete surface within the first hours of concrete setting and thus seals the concrete during the curing process (meaning quicker and more complete cement hydration). This should result in smoother, very dense concrete, with fewer blowholes, lower porosity and increased surface hardness and durability. MD is approximately 1.7 mm thick with a special drainage grid on the formwork side, double application is standard in general construction, whereas Classic (fig. 3) is approximately 0.7 mm thick and recommended for once-only applications. Considering the high quality required of water tanks however, MD (fig. 3) should also only be recommended/tendered for once-only applications, whereby the cost effectiveness of both types of material remains the same due to other advantages. When concrete is used together with formwork (CPF) liners, the concrete is generally of a darker colour than usual due to continual drainage.

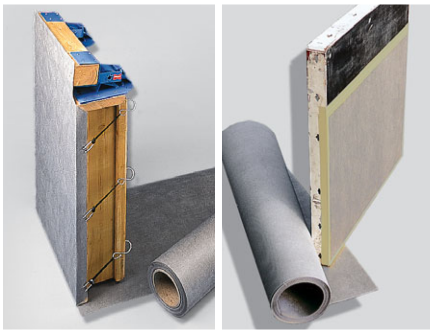

Figure 3: *Zemdrain® Classic (left) and Zemdrain® MD (right)*
Both types are different in the materials and also for application on various shutterings.

3. In-situ examination of three long-operating water reservoirs constructed with Zemdrain® CPF liners

3.1 General information

When using reinforced concrete, the liner type, the use of release agents and the concrete installation should be accorded particular importance. In report W 347 issued by the DVGW (May 2006) it says: *"Concrete surfaces inside drinking water reservoirs must be equipped with liners that do not require the use of release agents (liners without release agents, drainage liners). As-struck surfaces still showing traces of such substances may not come into contact with drinking water (and/or any dripping water/condensation)"* [3].

Zemdrain® formwork (CPF) liners have meanwhile been used in the niche business of drinking water reservoirs for almost 15 years. Reason enough to instigate an examination of wall surfaces under hydraulic stress during this period. Consequently, a search for water supply companies and planners that commissioned new reservoirs of different sizes using Zemdrain® at the beginning of the 1990's and that were prepared to allow an inspection of the wall surfaces in a drained down reservoir and also to permit a hygienically impermeable drilling core to be extracted for detailed examination (fig. 4) as inconspicuously as possible was initiated. Instead of using mortar, nowadays the drill hole (fig. 5) can be closed up elegantly and easily using a gasket (test certificates KTW [6], W 270 [7] available) fitted with blank flanges according to "diameter normal DN 100".
Service reservoirs were selected more or less randomly: the headquarters of Zemdrain®'s licensee (company Max Frank in Leiblfing) are in Bavaria, suggesting locations in Bavaria would be appropriate. A somewhat unusual set of inspection dates from the end of April to May was set and a rather "inconspicuous and convenient drilling core extraction point" was requested. From these criteria three reservoirs of different sizes were selected with capacities of 2 x 106 m^3 (ZV WV-group P.), 2 x 500 m^3 (Markt F.) and 2 x 3,250 m^3 (Bad W.). However, the construction details are not always still kept on record and it was therefore not possible to interview all the people or companies involved after such a long period of time since construction.

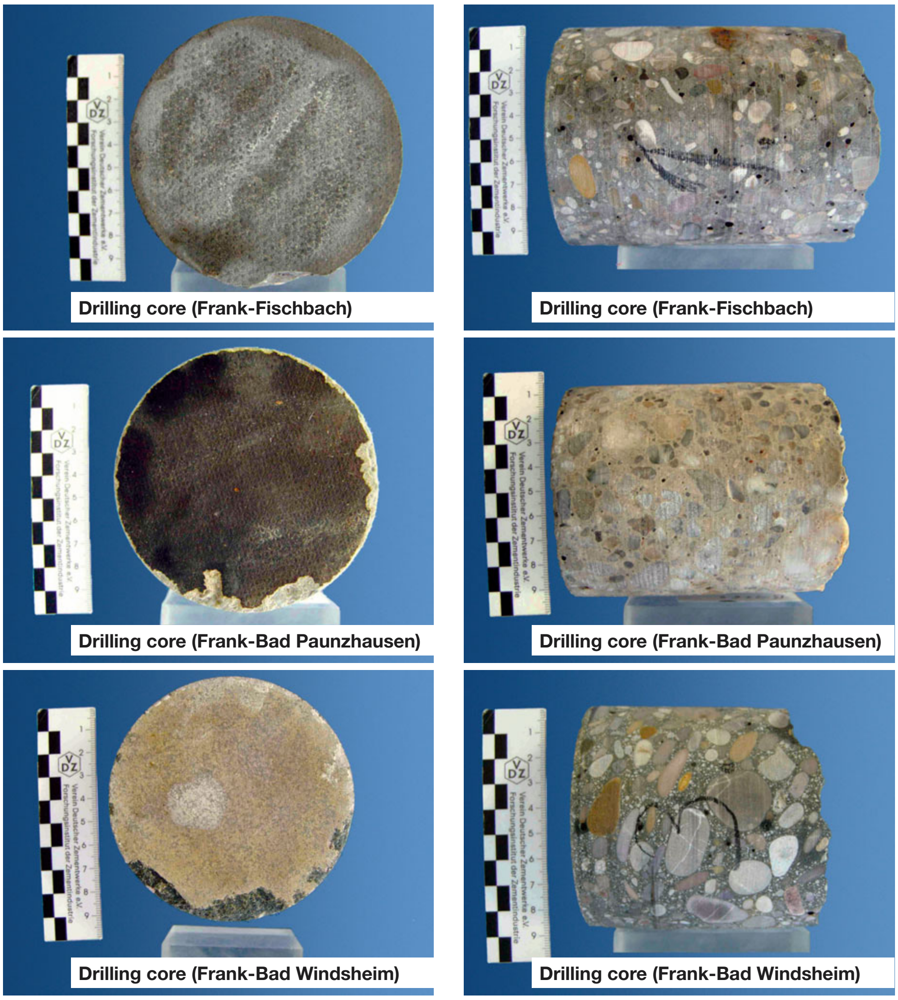

Figure 4: *drilling cores*

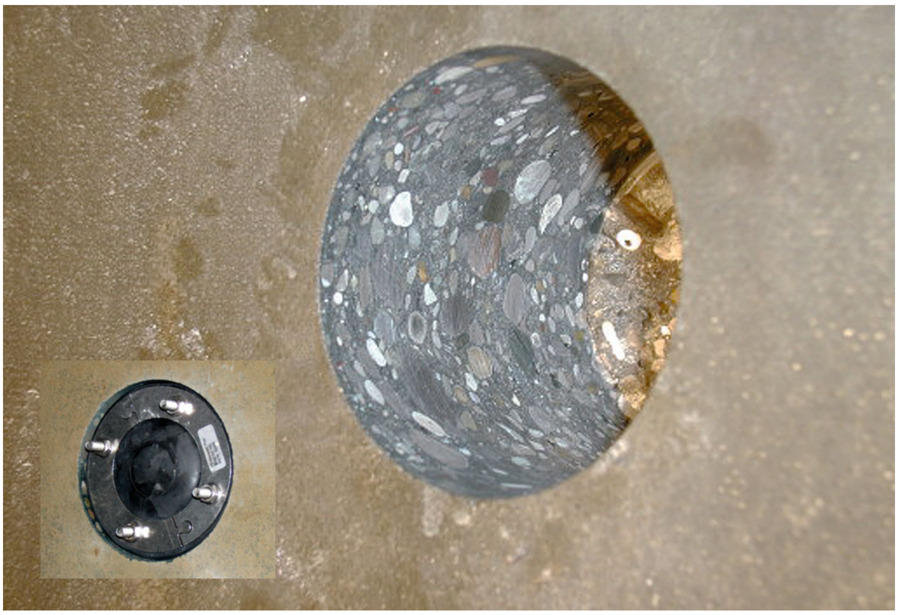

Figure 5: *Borehole open and borehole sealed (blind seal used)*

Inspection of and drilling core extraction from drinking water reservoirs with Zemdrain® wall surfaces

3.2.1 Elevated reservoir "Weinturm" – Bad Windsheim Water Authority

This elevated water reservoir with a total capacity of 6,500 m³, consisting of 2 compartments (2 x 3,250 m³) each with inner dimensions of 40 m length/ 13.5 m width/ max. 7.64 m height and water depths of 6.28-6.64 m, was made in 1993/94 by the contractor Dyckerhoff & Widmann, Nuremberg branch, of reinforced concrete without expansion joints and with walls, soffit slab and floor slab 40 cm, columns 50 cm Ø thick, of impermeable concrete quality B 35, workability KR, blast-furnace cement 35L-NW/HS (new CEM III/ B 32.5 NW/HS), 1 % admixture FM 25, w/c set value 0.45 (a very modern type of concrete), all inner surfaces – walls, and columns were cast with Zemdrain® CPF liners, the base of vacuum concrete and soffit slab underside with fair-faced plywood panels. As can be seen in a test certificate for concrete blocks 150 mm edge length with a concrete content of 400 kg/ m³, aggregates of grading curve AB 32, the 28 day tensile strength measurements before conversion from three samples are 45/48/51 N/mm² and therefore above standard levels. Generally, water analyses (in addition to the water meters of a large-scale consumer) show that the neutral water (pH-value 7.52), of average mineralization (570 µS/cm at 20° C) and water hardness of 16.9° dH has balanced lime and carbon dioxide levels, meaning no lime sediments or solutions should appear and, due to the water composition, no increased risk of corrosion or change in drinking water quality is likely.

In the in-situ examination of the reservoirs on 25.04.2006, no blowholes could be detected in the walls but some small pinholes were seen under magnifying glass that were probably due to the blast-furnace cement; there was some iron/ manganese discolouration in the reservoir walls/base; manganese silt could be rinsed off the base during cleaning; chemical cleaning agents were sometimes used. There were some folds along liner joints and some cracks from the bottom slab up to 4 m height, which were injected. Some folds had been filled in and revealed partial debonding. Distance tubes made of fibre concrete were plugged and in good condition. The soffit slab had not been worked on and the joints between plywood sheets could be seen, some of them displaced, and some fibre cement snake type bar spacers were visibly crooked. The joint between the soffit slab and the wall was partially repaired. The reservoir started operation in spring 1996. Altogether, these deficiencies in the constructional quality have no structural effect, however they do not reflect well on the construction company, even allowing for the need to tension long lengths of CPF liners and to erect high level formwork towers for the soffit slab. At this point we would like to note that it is not necessary to carry out remedials on folds in concrete as the concrete quality is assured and blemishes become even more noticeable due to differences in colour. The core hole was drilled below the maintenance catwalk in the reservoir ca. 2 m from the corner of the middle wall / sump pit and ca. 1.18 m from the bottom slab at the outside wall, ca. 40 cm above a visible pour line.

3.2.2 Suction reservoir in Paunzhausen – communal water supplier for Paunzhausen, Schweitenkirchen, Kirchdorf

This low level service reservoir for untreated water, with a total capacity of ca. 212 m³, consisting of 2 compartments (2 x 106 m³) each with inner dimensions of 9.47 m length/4.67 m width / max. 2.80 m height and water depth of 2 m started operation in 1994. It supplies ten boroughs and 87 villages with over 3,000 water connections. Construction details were not available. The in-situ examination of a reservoir on 15.05.06 revealed a completely sealed concrete surface, probably due to the Portland cement (CEM I) or Portland metallurgical cement (CEM II), with very visible iron and manganese deposits at water surface level (inlet above water); chemical cleaning agents were sometimes used; there were no cracks in the walls but some remnants of Zemdrain® fibres (Zemdrain® 1st generation; harmless; test certificate KTW [6] and W 270 [7]); two continuous folds from floor to soffit slab; the joint between the bottom slab and the wall was bevelled with mortar at 45°, the poorly sealed joint between soffit and wall formwork resulted in cement flow-marks on the wall; the as-struck soffit had not been shotcreted, the soffit is supported by cross beams 20 x 35; these beams were also constructed with Zemdrain®, but there were folds here; the joints between plywood formwork panels sometimes revealed an open structure. Schmidt hammer results of 41-45 can be converted to concrete tensile strengths of 42-50 N/mm². Snap-readings of water analyses show that the untreated water from the three wells exceeds the threshold value for iron in well II and slightly exceeds the limit for manganese in well II, and that the treated water, pH-value 7.6, of average mineralization (510 µS/cm at 20°C) and water hardness of 16.9° dH is within the neutral zone, tending to lime scale. The borehole was scarcely visible and was drilled below the access door in the end wall about 1 m from the corner and ca. 1.30 m above the bottom slab.

3.2.3 Elevated reservoir in Markt Fischach

This elevated water reservoir, consisting of 2 compartments of 2 x 500 m³ capacity, each with inner dimensions of 15 m length/ 7.5 m width / 5.40 to max. 8.65 m height and water depths of 4.85-5.70 m, of reinforced concrete with (Zemdrain®) walls, soffit slab, floor slab all 40 cm thick, of impermeable concrete quality B 35, started operation in 1993 to supply 3,000 units. After completion, "charcoal" was found in some areas of one wall; it was removed and the sites repaired, which can still be seen by differences in colour (paler areas). This phenomenon has been well-documented [3]. The in-situ tests on the left reservoir on 22.05.2006 show a cured concrete surface (probably CEM I), with slight iron and manganese deposits at the wall/base water level; chemical cleaning agents were sometimes used and the reservoir is usually cleaned by steam. Folds are visible on five formwork elements, the formwork joints are sometimes closed, sometimes open and worn. Schmidt hammer results of 42-46 can be converted to concrete tensile strengths of 44-52 N/ mm². The borehole was drilled in the left reservoir below the maintenance catwalk in the reservoir ca. 4 m from the corner of the middle wall and ca. 1.60 m from the soffit slab in the outside wall.

3.2.4 Essential inspection results

In general, after 15 years of operation, the wall surfaces at water surface level show more or less visible reddish-black-brown iron and manganese discolouration but otherwise they are characterized by smooth, dense, low-porosity concrete surfaces, even if the filter fabric structure of the 1st Zemdrain® generation can sometimes be detected under a magnifying glass. There are some signs of visible formwork joints and folds which might point to initial construction difficulties, although such blemishes cannot be totally eliminated today if technical instructions are not followed correctly. In the final analysis, these blemishes have no real negative effect as the areas concerned were of the same dense concrete structure and quality without pores and had no contaminative effect on the water quality.

3.3 Tests on drilling core samples from Zemdrain® wall surfaces related to the latest scientific information

3.3.1 Preliminary note

Mineral paint coats/thin coatings (3 mm) were very common in the decades following World War II – at least regionally – partly because of the term „mineral“: there was a general consensus among planners, authorities and building constructors that this procedure was advisable – on the one hand because reservoirs were required to be impermeable, on the other hand because of the frequently unsatisfactory construction methods used (blowholes in the concrete) and visible blemishes. Since the beginning of the 1980's, however, cases of damage to thin (3 mm) shotcrete inner coatings of reservoirs in Germany and Switzerland have been recorded [4].

The damage typical to the coatings – brown patches with funnel-shaped areas of softened material and degradation, abrasion, or yellowish-brown streaking with corresponding softening of the material below the water surface, whether the coatings were white or grey – has frequently been described and the previous standard of knowledge outlined in the cause study sponsored by the DVGW (1995-2002) has been comprehensively summarized [4]. For the main part, changes in mortar products through the years were/are characterized by high porosity (clearly > 20 vol. %), and therefore a low hydrolysis resistance and at coating thicknesses of 3 mm a short structural life or even claims made during the guarantee period. Based on these findings, the DVGW laid down technical requirements [2] that should also be respected for in-situ concrete [4]:

- Equivalent water/cement value $(w/c)_{eq} \leq 0.50$
- Total porosity after water storage $P_{28d} \leq 12$ vol. % or $P_{90d} \leq 10$ vol. % (tested by mercury porous-meter to DIN standard 66133:1993-06)
- Design value for prism tensile strength $ß_{D\ 28d} \geq 45$ N/mm^2

However, these findings were not common knowledge in the construction industry and only gradually emerged into tougher requirements. In the studies by the DVGW on the construction of drinking water reservoirs, in 1965 talk was of B 225 with 300 kg/m^3 cement, in the year 1976 of concrete B II or concrete 350 with 350-400 kg/m^3 cement and water/cement value w/c < 0.60, in 1988 of concrete B II with cement of minimum 25 N/mm^2 tensile strength (B 25) and water/cement values of maximum 0.55, preferably lower than 0.5, while today we speak of former B 35 or C 30/37 with cements (hardness cat. 32.5) and additives of ca. 360-380 kg/m^3 and $(w/c)_{eq} \leq 0.50$. These types of concrete made with a generous water/cement factor have a higher degree of porosity so it is also interesting to see the effect of Zemdrain® formwork (CPF) liners on the upper concrete surface compared with the total porosity measured by mercury-porous-meter testing. The drilling cores were sent to the cement industry's research institute in Düsseldorf for this examination (technical report TB-BTe B 2000-Frank/2006), not least because a lot of drilling cores from cement-based coatings have also been sent for mercury-porous-meter testing up to 2,000 bar according to the DVGW report W 300 [4], thus enabling direct comparison.

3.3.2 Test results

Three "100 drilling cores" were extracted, characterized by the designation diameter/height: 1-F 93.6/119 mm; 2-P 93.5/111 mm; 3-W 94.4/88 mm and the following measurements taken:

- Rebound values of the drilling core sample using a sclerograph
- Rebound values of a surface area test portion and of a sample from the lower drilling core zone using a sclerograph
- Water absorption in a surface area test portion and in a sample from the lower drilling core zone according to leaflet 422 DAfStb issued by the German reinforced concrete commission
- Depth of damage to a surface area test portion
- Total porosity of a surface area test portion and a sample from the lower drilling core zone

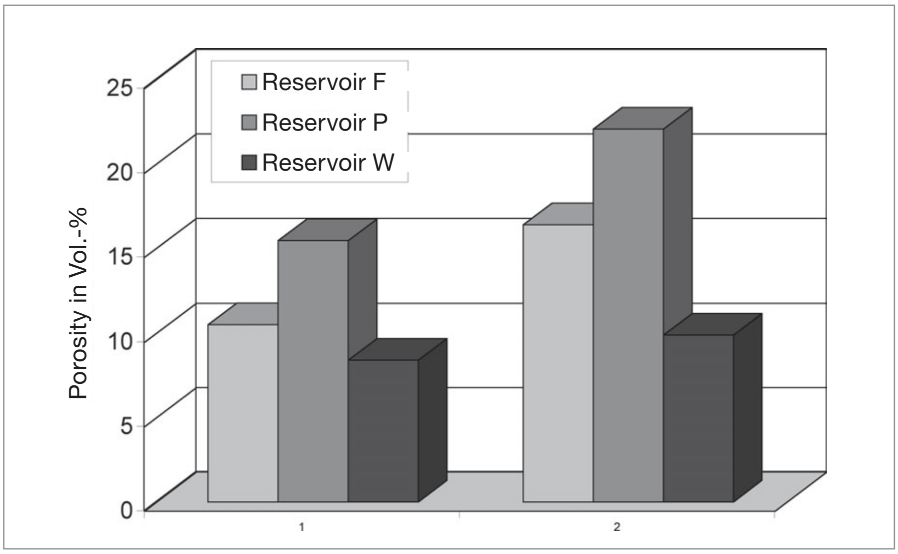

Figure 6*: Results of the mercury intrusion tests: porosity in vol. % of test portion 1 (Zemdrain® top section) and test section 2 (bottom drilling core section)*

The two last points are the most interesting, whilst the first three allow comparisons to be made but do not permit any absolute conclusions. Due to the limited sample material (one sample/drilling core per structure), only basic trends regarding the efficiency of Zemdrain® can be ascertained. The rebound values were measured by sclerograph, an instrument normally used to determine steel hardness at non-specific locations; it was modified to test concrete (a bar was dropped onto the surface of the sample and rebounded to a particular height depending on surface hardness, thus enabling comparisons to be made). The conclusion drawn from the rebound values on the drilling core sample surface (test 1) was that reservoirs F and W tend to show similar levels of hardness, whereas reservoir P was of a lower hardness. After the first test, a portion was cut from the surface area of the drilling core (top section) and a portion from the lower part (bottom section) for further tests (section height 15 mm). The surface area test portion "top section" therefore corresponded to Zemdrain® concrete surface whilst the lower portion „bottom section" corresponded to normal concrete. The results of rebound tests on surface area test portions and lower drilling core portions tend to reveal that the top sections of Zemdrain® concrete show up to 20% higher rebound values (hardness) than the lower areas of normal concrete, which demonstrates that even during the introductory phase of Zemdrain®, boundary zone concrete was of a better quality, thus reflecting what is now known today about Zemdrain® formwork (CPF) liners. Water absorption in mass percentages or vol. % is a further characteristic of dense concrete. The volume is determined by underwater weighting. A similar result can be seen in leaflet 422 DAfStb, issued by the German reinforced concrete commission in which the water absorption of a surface area test portion and a lower drilling core portion was determined. Another indication for the quality of Zemdrain® cover zone concrete can be deduced from the depth of damage from hydrolysis determined in a surface area test portion (top section). After completion of the above-mentioned tests, drilling core test portions were split in the direction of extraction and the fracture surfaces sprayed with an indicator solution of 1% phenolphtalene solution. At pH values under pH 9, the colour changes from reddish-mauve to colourless. As all the areas were coloured and the pH value therefore over 9, no damage from hydrolysis processes or from carbonation (construction phase) could be ascertained in the concrete surface of any of the three test portions over this period of time. After determining water absorption, other test portions were taken from the surface area (top section) and from the lower drilling core zone (bottom section) to determine the total porosity of a surface area test portion and a lower drilling core test portion according to German government norm DIN 66133:1993-06 "Determining pore volume distribution and the specific surface of solids by mercury intrusion". The final pressure measured was ca. 2,000 bar according to DVGW report W 300, the data was evaluated using the cylindrical pore model. This is of particular interest since the standard of knowledge and construction requirements [2] dated from more than a decade ago. The porosity values incl. macro-pores in vol. %, rounded to a decimal place, are for both test portion 1 (top section Zemdrain® concrete) and test portion 2 (bottom section concrete) from reservoir F at 10/16, reservoir P 15/22, reservoir W 8/10 (fig. 6). The average pore radius was constant at ≤ 0.1 µm. The porosity values of the lining mortar, required to be below P ≤ 12 Vol. % in the DVGW-German Associations for Gas and Water report W 300, were well below in two reservoirs at values of 8 and 10 („they could not be better"). This data also leads us to conclude that Zemdrain® formwork (CPF) liners mean a definite improvement in porosity (of 20 – 50 % related to the core area) in all reservoirs (fig. 6).

4. Summary of evaluation – conclusions drawn

The special tests on three randomly selected drinking water reservoirs, whose water compartment surfaces were constructed with Zemdrain® formwork (CPF) liners and which started operation almost 15 years ago, show that they exceed or at least conform to the latest requirements set out in the DVGW/ DIN-German technical regulations. It is particularly worth noting the total pore volume after water storage of $P_{28d} \leq 12$ Vol. % (tested by mercury-porous-meter to DIN standard 66133:1993-06) [2]. In the DVGW report W 300, paragraph 6.1, it says „concrete that is impermeable and of the lowest possible porosity requires no further surface treatment or inner lining. For this reason, drinking water reservoirs of reinforced concrete without coatings or lining have proven especially reliable" [2]. In general, a pure concrete surface is also the simplest and most cost effective solution for the construction of new drinking water reservoirs. In fact, in-situ concrete with a formwork liner, known internationally as Controlled Permeability Formwork (CPF liner), as shown in the introduction or in [5], shows significantly improved qualities in comparison to in-situ concrete with so-called absorbent or non-absorbent liners and is longer-lasting and more hygienic; quite different types of concrete are improved by liners such as Zemdrain® [5], to the extent that the quality of cover zone concrete can be classed satisfactory or good, even when under hydraulic/hydrolytic/corrosive stress. All these advantages have also meant that the use of CPF is now recommended in the new "United Kingdom Guidelines" and in the latest "British Standards" [5]. Even if handling regulations are not adhered to, resulting in shortcomings such as avoidable folds and visible formwork joints, the concrete in these areas remains hard and of low-porosity, meaning there is no need to polish or repair. As can be seen in the tests carried out, Zemdrain® concrete cover zones show significantly improved qualities compared to the core concrete (fig. 6), although the latter was of a good quality, as can be seen in the drill holes and drilling cores. After 15 years of operation, the wall surface joints were still very dense and showed no signs of abrasion or hydraulic/ hydrolytic/corrosive wear and tear and will therefore probably continue serving their constructional and operative purpose for decades to come. When technical guidelines are adhered to, the desired result of a smooth, dense, low-porosity reinforced concrete surface is assured. Due to the general experience of the last 20 years and the above-mentioned series of tests [5] on Zemdrain® CPF liners, this can be assumed to be the most cost-effective form of in-situ concrete available for achieving a low-porosity, long-lasting concrete surface in drinking water reservoirs.

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Among teaching and research activities over long years, in between construction industry and construction site activities (8,000 m^3 drinking water reservoir) with Dyckerhoff+Widmann Munich (KB div. Bomhard) he is well known for the 28 water technical seminars organised by him at the Technical University Munich. Main focus of his more than 85 papers is for drinking water reservoirs (text books “drinking water reservoirs” and “technic water supply” Oldenbourg publisher. In 2003 he was decorated with the new raised DVGW-award for his long cooperation in the board of the DVGW for example since 1978 in the technical committee TK 2.2 water storage. Consultant since pensioned off in 2007.

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