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Durabilité accrue du béton exposé à des eaux agressives

Verlängerung der Lebensdauer von aggressivem Grundwasser ausgesetzten Beton

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SUMMARY

The Swiss Federal Railways now requires a planned service life of 100 years for its new "Rail 2000" tunnels. With normal maintenance, no basic repair work should be necessary during that period of time. These very stringent standards place equally high quality demands on the materials and the structure, together with high project design quality. For such important structures, questions of testing methods and construction materials must be answered in order to ensure satisfactory long-term quality.

RÉSUMÉ

Les Chemins de Fer Fédéraux Suisses exigent, pour les nouveaux tunnels du projet "Rail 2000", une vie de service de 100 ans sans travaux de réparation et de restauration majeurs. Cette exigence sévère présuppose une qualité élevée des matériaux utilisés, de la main d'oeuvre et du projet. En présence de projets importants, le problème du choix des méthodes d'essai appropriées et des matériaux se pose, afin de garantir la longévité exigée des ouvrages.

ZUSAMMENFASSUNG

Die Schweizerischen Bundesbahnen fordern für die neuen Tunnel der "Bahn 2000 " ein Nutzungsziel von 100 Jahren, d.h. bei sichergestelltem, üblichem Bauwerksunterhalt soll in der geforderten Zeitspanne keine grundlegende Sanierung notwendig werden. Diese sehr hohen Ansprüche setzen eine entsprechende hohe Qualität der Baustoffe und der Projektgestaltung voraus. Für bedeutende Bauwerke stellt sich somit die Frage nach der geeigneten Prüfmethode und Baustoffwahl, um eine genügende Langzeitqualität zu sichern.

1. CONCRETE STRUCTURES WITH A PLANNED SERVICE LIFE OF 100 YEARS

Economy is the key issue for practically all construction projects.Relevant for the economy of a project are not only the original construction costs but also the long-term costs accumulating during its service life. For large tunnel projects in Switzerland, the risks deriving from heaving anhydrous gypsum and clay rock formations, as well as the effects of sulfate and chloride containing underground waters, have to be accounted for already in the design stage and when letting the contract.

For the tunnels of the multi-billion project "Rail 2000", the target set by the Swiss Federal Railways (SBB) Administration is the following:[1]

"No basic restoration work should become necessary during the planned service life of 100 years, provided that normal maintenance is guaranteed."

Such exacting demands require adequate quality of materials and workmanship.

2. THE CORROSION OF CONCRETE

The durability of concrete is mainly determined by its resistance against the penetration of liquid and gaseous substances, i.e. the denser the cement stone, the higher the resistance of the concrete against chemical or mechanical attacks.[2] Most Standards therefore demand high watertightness besides the specific project-related requirements. Corrosion of concrete and masonry in Swiss tunnels is caused mainly by:[1]

- Soft water, above all if it is carbonated.
- Water with an aggressive amount of carbonic acid.
- Water containing sodium-, magnesium- or calcium sulfates.
- Water containing chlorides corroding re-bars and steel parts of the installations.
- Chlorides from de-icing salts and water containing polluants from agriculture or other remains from "civilization".

Evaporation of water on the free surface of the structure leaves the harmful substances of the underground waters inside the concrete and leads to an increasing concentration of such substances. Highly corrosive solutions may result from this, or cristallizing mineral salts may cause spalling.

3. STATE OF THE ART IN CONSTRUCTION PRACTICE

To improve the durability of concrete various measures are taken in practice to cope with the types of attack described above.

- The **dissolving attack** by soft and aggressive carbonated waters can quite successfully be countered by a very dense concrete matrix, i.e. decrease of the w/c ratio by means of high-range water reducers and addition of latent hydraulic silica fume.[3]
- As a rule, a cement with an as low as possible content of tricalciumaluminate (C_3A-content < 3%) is prescribed whenever there is a danger of **swelling attack** by sulfate containing water.[4] This should prevent the formation of ettringite ($3CaO\bullet Al_2O_3\bullet 3CaSO_4\bullet 32H_2O$), which increases 8 times in volume in the cement stone.

  In spite of such precautionary measures, considerable damages have shown up in several tunnels in Switzerland, caused by sulfate-swelling from thaumasite ($CaO\bullet SiO_2\bullet CaSO_4\bullet CaCO_3\bullet 14H_2O$). Thaumasite can develop independently from the C_3A contents. Cements with a low C_3A content may therefore in future not any more be considered as being sulfate resistant without further investigations. For important projects arises now the need for suitable materials selection criteria and test methods, which can give reliable results within acceptable time to guarantee a sufficient long-time durability of the project.

4. PRELIMINARY INVESTIGATIONS OF THE SBB FOR THE "RAIL 2000" PROJECT

Differences in the concrete mixes, the test solutions and the exposure durations made it impossible to directly compare the sulfate resistance tests done so far.
Therefore, in 1990, the Swiss Federal Railways initiated an extensive test programme with the aim to develop the necessary technology.The following conditions were stipulated:

A) **The concrete mix shall be designed to allow the continuous production of a consistent concrete quality on site without requiring excessive additional measures;**
i.e. Spread-table size of 45 ± 2 cm (slump ≈ 12 cm) has been determined for optimal workability.

B) **The requirements for the properties of the hardened concrete shall account for the nature of the chemical aggressors identified by trial borings as well as for the degree of importance of the different structural parts in the project;**
i.e. The final compressive strength on cubes shall be B55/45N/mm^2 (mean/min. value).

C) **High early strength shall allow economical production of precast tubbings;**
i.e. the compressive strength for demoulding of tubbings has been set at 15 N/mm^2 after 4.5 h. Standard test cubes have to develop f_{cw} > 10 N/mm^2 after 6 hours at 30°C in the laboratory for qualification.

D) **Testing of sulfate resistance shall account for the characteristics of underground water in Switzerland as well as for the high service life expectations for the project;**
i.e. ASTM C 1012-89 Standard Test [5] describes the testing of sulfate resistance (5% Na_2SO_4) of cement mortar. By analogy to this, an aggressive test solution of 5% Na_2SO_4 + 1%$MgSO_4$ has been selected for the testing of concrete .This corresponds to about 40 times of what was found in trial borings for different tunnels in Switzerland.[1]

For sulfate resistant concrete the Critical Length Change has been defined in due consideration of the smaller amount of cement paste in concrete and of the long service life expectations for the projects:

ASTM:	$\Delta l \leq 0.5‰$ after 1 year	⇒ high sulfate resistance
SBB:	**$\Delta l \leq 0.25‰$ after 2 years**	**⇒ high sulfate resistance**

The following test criteria have to be observed for qualification-testing of sulfate resistant and durable concrete in the laboratory:

- Laboratory mixes shall be prepared with materials (cement,aggregates...), which are representative of those available on site.
- Concrete mixes with insufficient workability shall be eliminated.
- Mix designs, which do not develop sufficient early or final strength shall not be considered any further.
- SBB requirements for sulfate resistance shall be met (6 test specimens per mix design).
- After each Length Change measurement the prisms shall be checked visually for cracks, spallation and deformation.

- If even only one out of six test specimens of a test series fails, the test shall be discontinued.
- Test series shall be followed by microscopic examination of thin sections to detect changes of the matrix and formation of ettringite/thaumasite. Strengthes shall be tested and compared to those of a virgin specimen.

5. SELECTION OF MATERIALS AND CONCRETE MIX DESIGN

89 different mix designs have been tested to gain confirmation that the chosen test method is correct.The large number of mixes came from the combinations of:

- 11 different cement types of Swiss and German origin (Portland cements, sulfate resistant cements, blast-furnace cements)
- 3 different aggregate gradings optimised to suit different uses (pumped concrete, heated concrete for precast tubbings, etc.).
- 2 different high-range water-reducers for w/c reduction and improved workability.
- 4 specially designed concrete additives based on silica fume for improved strength, watertightness and sulfate resistance.

Out of these 89 mixes, 61 had to be eliminated because of insufficient fresh concrete properties and poor workability.The remaining 28 mixes permitted to appraise the different materials as follows:[1], [6]

A) Strength development

The various types of cement differ above all in the development of early strength. The **finely ground Portland Cements** (Type III) in combination with high-range water-reducers develop sufficient early strength, whereas "**Sulfate Resistant Cements**" (Type V) need special measures such as accelerators to reach the target. **Blast-Furnace Cements** do not develop sufficient early strength, not even with accelerators.

The required final strength is developed by **Portland** as well as **low C_3A Cements** (Type V) in adequate combination with high-range water-reducers, whereas **Blast-furnace Cements** do not gain sufficient final strength, not even if silica fume is added.

B) Sulfate resistance.

Concrete produced with **Portland Cement** and high-range water-reducing admixture have only a very modest sulfate resistance, even with very low w/c ratio (< 0.43). Top sulfate resistance results have been obtained only when specially designed Sikacrete additives were used. (Fig.1) The measured Length Changes (without swelling caused by storage of the specimens in water) remain very modest and the standard deviation of the compressive strength is small. The cracking on the test specimens after 2 years exposure to sulfates is minimal.

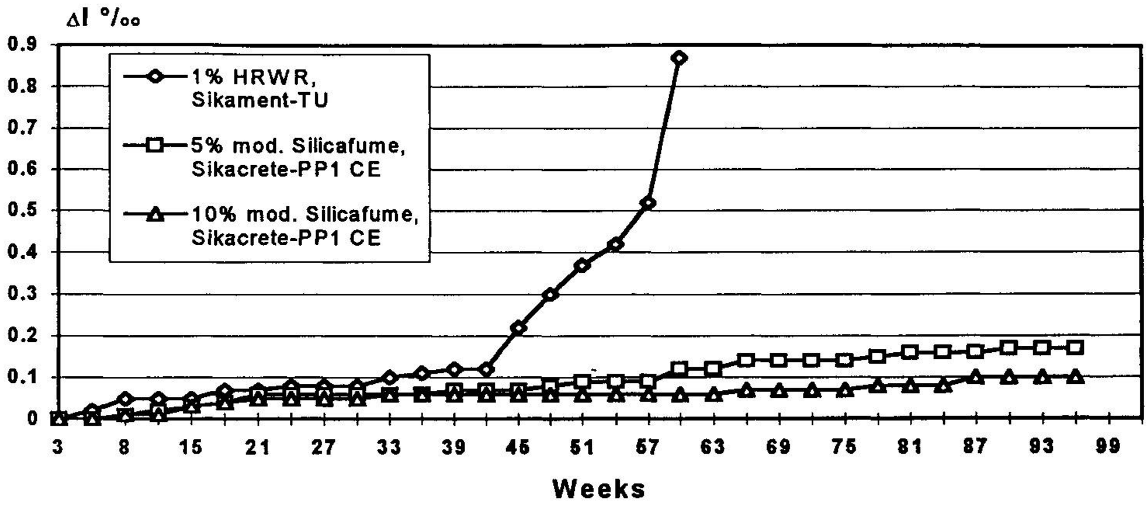

Fig.1 SBB Sulfate Resistance Test (modified ASTM C 1012-89)

Concrete mixed with the so-called **"Sulfate Resistant Cements"** gain only high sulfate resistance together with silica fume and the appropriate amount of high-range water-reducers. New accelerator technologies (aluminium-free) permit nowadays to compensate for insufficient early-strength development.

Water-reduction by means of appropriate admixtures has a beneficial effect on concretes produced with **Blast-Furnace Cements**. Addition of silica fume increases the sulfate resistance insignificantly only. Although many test specimens showed very little inner deterioration (little length change) their outer surfaces had been eroded by sulfate attack in such a way that the tests could not be carried on.

6. PRACTICAL RECOMMENDATIONS.

It has been established by the tests that High Early Strength Portland Cements (Type III) together with a specially designed additive (blend of silica fume, high-range water-reducers etc),give the highest sulfate resistance, higher even than low-C_3A Cements (Type V) together with the same additive.This fact is altogether very much in favour of precast-concrete production on site, because the required high early strength can be obtained without any problems.

To reach with the highest possible certainty the very high target of a 100 years service life for concrete structures under sulfate attack, the following recommendations must stricly be adhered to:

- The concrete matrix shall be very dense, i.e. continuous sieve curve with sufficient amount of very fines and a minimum of mixing water.
- The w/c ratio shall be < 0.42. In spite of all measures taken for sulfate resistance, the good workability of the concrete shall be guaranteed.
- Sulfate resistance is increased by the presence of a large number of micro-pores. Such pores, of the correct size (0.02 - 0.3mm), shall be introduced in an appropriate manner.
- Additives, specially designed to fit specific requirements, combining silica fume, plasticisers and air-entrainers, shall be used.

- Concrete shall be cured with utmost care to guarantee a tight surface and prevent early shrinkage cracks.
- In presence of underground waters containing sulfates **and** chlorides, re-bars shall need additional protection by impregnations, coatings or addition of integral corrosion inhibitors in the concrete. Appropriate coatings applied after demoulding, assure proper curing. Under no circumstances do such measures compensate for bad concrete mix design.
- ASTM C 1012-89 is suitable in principle for the testing of sulfate resistance, if complemented by a visual inspection of the test specimens (see Blast-Furnace Cement Tests under 5.B). The concentration of the test solution as well as the duration of exposure have to be chosen in accordance with the service life requirements of the project in question. The difference between the amounts of cement paste contained in mortar and concrete shall be duly taken into account.

7. FROM LABORATORY TESTS TO PROJECT SITE

Results and experience gained from several years of testing will be put to use for the first time on site for the construction of the 4.3 km long tunnel "Adlertunnel"of the "Rail 2000" project. The tubbings will be precast in a site factory, specially erected for that purpose. In order to increase production output, the concrete will be heated to 32 - 35°C by using hot water and steam and the elements will be steam-cured for 4 - 5 hours at 40°C. Compressive strength for demoulding shall be 15 N/mm^2 after 5 hours.

Laboratory testing as per SBB Specifications is completed.Tubbing production started early 1995. First results are not yet available at the time of printing of this paper, but will be presented at the time of the Symposium.

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