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AAR-prevention for the world's longest tunnels – AlpTransit Gotthard and Lötschberg in Switzerland

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ABSTRACT:

The construction work for new railway tunnels through the Swiss Alps (Alptransit Gotthard and Lötschberg) with a length of 57 respectively 42 km has been in progress since 1996. The world's longest tunnel Gotthard is expected to be in service in 2013. The Lötschberg in 2007. A issue of the project is the reuse of the suitable excavated rock for the aggregate production. The service life time requirement of 100 years for the tunnel construction induced profound studies of the concrete aggregates and the concrete systems.
Additionally to the rock strength, petrographic analysis the potential reactivity of the excavated rock and aggregates is continually measured with the microbar test AFNOR P18-588. This test gives a result in reasonable time (5 – 7 days). The concrete behaviour itself is determined by the performance test AFNOR P18-454.
About 50% of the required concrete aggregates have to be classified as potentially reactive in regard to AAR. Therefore precautions and measures have to be taken. The risk and prevention level for each concrete and shotcrete type will be discussed. Furthermore, the constructive and concrete measures taken will be presented. The results of the performance test will be presented and discussed.

Key words: Alkali-aggregate reaction, Underground construction, AAR prevention, Microbar, Performance test

1 INTRODUCTION

The construction work for new railway tunnels through the Swiss Alps (Alptransit Gotthard and Lötschberg) with a length of 57 respectively 42 km has been in progress since 1996. A major issue of the project is the reuse of the suitable rocks excavated during construction of the tunnel [1]. This aim provides not only a viable alternative to the diminishing natural resources of sand and gravel, but it is also of ecological and economical interest During the construction of the tunnel around 42 million tons of rock will be excavated. Around 10 million tons will be reused as concrete aggregates which are prepared in six different processing plants.

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This amount covers practically 100% of the concrete aggregate required for the main tunnels. The service life time requirement of 100 years for the tunnel construction induced profound studies of the concrete aggregates and the concrete systems.

1 PRELIMINARY STUDIES

Before 2000 AAR damages were not recognised in Switzerland by the major concrete industry. The AAR topic came up at a late phase of the project planning of the AlpTransit tunnels where the concrete concepts were already defined without any AAR requirements. The first preliminary study dated from 2000 showed that about 50% of the required concrete aggregates produces out of suitable rock excavation material have to be classified as potentially reactive in regard to AAR [2].

A further study was engaged by AlpTransit Gotthard in 2002 to examine the AAR behaviour in existing tunnel concrete [3]. In this study 19 to 44 years old concrete and shotcrete were studied. Although reactive aggregates and signs for AAR are present in the microstructure of the majority of the concrete samples, the visual inspection of the tunnels and the physical properties of the concrete and shotcrete indicate no substantial damage. The minor climatic fluctuations in the tunnels might be one of the reasons that AAR did not develop as expected. The results of this study indicate that reactive aggregates might be used for concrete in tunnels without causing substantially damage due to AAR.

Based on this studies the project management decided to use the potentially reactive rock material for the aggregate production and to take AAR preventions. The project management decided further to commission an AAR expert group. Due to the different type of raw material (petrography of the aggregates, cement types, admixtures, etc) for the concrete the AAR prevention are slightly different for the tunnels Gotthard and Lötschberg.

3 AAR PREVENTION FOR THE GOTTHARD

Some of the construction sites of the AlpTransit tunnel project are situated in high mountain areas or are situated in small valley regions, with difficult transportation access. A secure provision of non reactive aggregates from others parts in Switzerland to the construction sites are not practicable because the supply cannot be guaranteed. The separation of non reactive an reactive rock material during the excavation work is not possible because of the small depot space situation and due to logistic problems.

The expert group proposed to fellow the Canadian AAR standards CSA for the preventive measures against AAR in new concrete structures [4]. The AAR test procedures are based on the French ARNOR procedure because they allowed rapid results.

3.1 Reactivity of the aggregates

For the preparation of the aggregates only the suitable rock excavation material with a moderate reactivity of <0.2% expansion measured with the microbar test AFNOR P18-588 [5] will be used for the aggregates production. Expansion values under 0.1% are classified as non reactive. Highly reactive rock material will not be used for the aggregate production. This test procedure was chosen because this test gives result within 5 to 7 seven days.

The geological zones with potentially reactive rock material are roughly known based on the preliminary study [2]. During excavation the microbar test is done with the excavated rock from the first tube of the two parallel tubes every 250 tunnel meter in reactive zones and all 500 tunnel meter in non reactive zones. Also the prepared aggregates are tested every 20’000 to 40’000 tones, depending on the reactivity. 20’000 tones correspond to the production capacity of one week. Unfortunately it could not be verify if the AAR reactivity level of 0.1 to 0.2% measured by the AFNOR microbar correspond with the moderately reactivity level of the CSA (CSA A23.214A or CSA A23.2-25A).

3.2 Determination of the AAR risk level

Based on the CSA [4] the value of the AAR risk level is set by 1 and 3. The value 1 is for the non massive and dry concrete element. The terms ‘massive’ and ‘dry’ are defined as follow: A massive Element has a least dimension of one meter or more. A dry environment corresponds to ambient average relative humidity condition <60%, normally found in buildings. The value 3 results for the tunnel concrete which is exposed to humid air, buried or immersed.

3.3 Determination of the need for prevention level

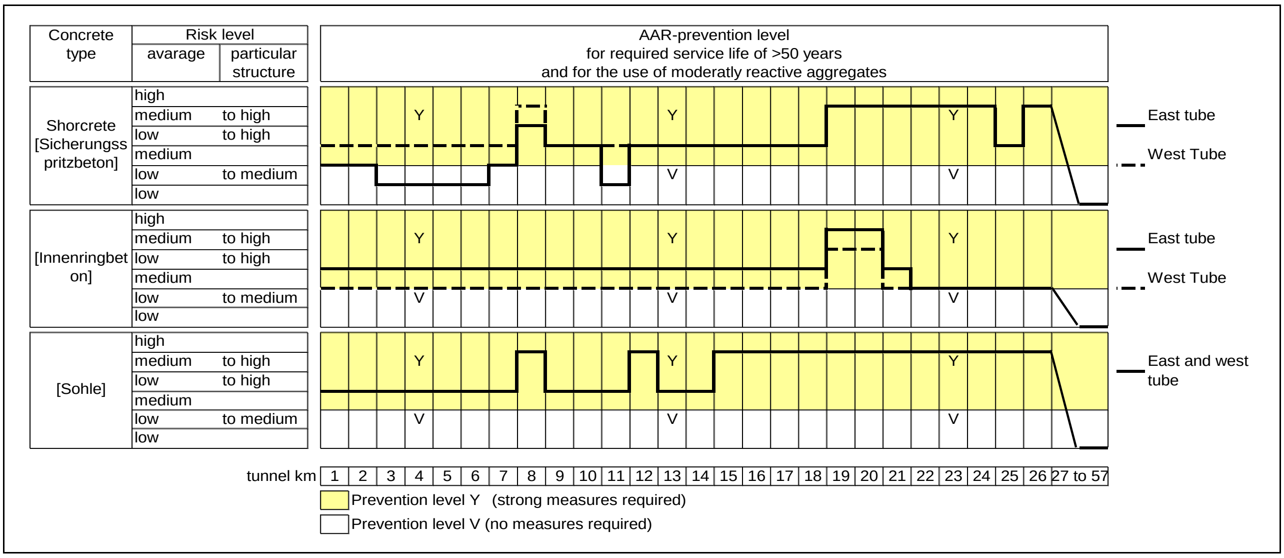
The required service life for these tunnels is 100 years. Based on the CSA [4] the level of prevention is V and Y. The level V is for the use of the non reactive aggregates where no preventive AAR measure is needed. The level Y requires a strong preventive measure for the use of moderately reactive aggregates.

3.4 Preventive measures for the concrete

Following measures are described for prevention level V [4]: Accept the proposed aggregate without any preventive measure but periodically ensure that the reactivity of the aggregate extracted has not changed. Prevention for level Y: Strong preventive action required; use one of following approaches: Y1) Reject the proposed aggregate, or Y2) Limit the alkali content contributed by the Portland cement to the concrete <1.8kg/m^3 Na_2O-equivalent, or Y3) Use a sufficient amount of an effective supplementary cementing material SCM or combination of effective SCMs.

The mixture for the tunnel concrete has high cement content. The Na_2O-equivalent of the used portland cement lies between 0.9 and 1.0%. The allowed content of 1.8kg/m^3 Na_2O-equivalent is greatly exceeded. Therefore only a solution with SCM is possible.

Table 1: Concrete risk analysis based on the CSA [4] for the Gotthard tunnel section with reactive rock material (non reactive material is expected for the tunnel km 27 to 57).



3.5 Risk analysis for the concrete types

The project engineer made a risk analysis for the three main concrete type's shotcrete, arch and invert concrete (table 1). The risk level was defined for the first 26 of the totally 57km and for each tunnel tube. The tunnel section between km 26 and 57 consists of none reactive rock material. Table 1 show that the invert concrete has the highest AAR risk level due to the possible tunnel water exposure. The risk level for the shotcrete is low up to high depending on the expected tunnel water inflow. The arch concrete shows a moderate risk level. The east tube has slightly higher risk level than the west tube due to higher humidity condition. The concrete elements for the tunnel km 19 to 20 have a grater dimension and therefore a higher risk level.

3.6 AAR preventive measures

Based on these studies the project management decided following AAR measures for the Gotthard base tunnel: the use of moderately reactive aggregate (microbar test AFNOR P15-855 <0.2%).
The whole tunnel will be protected against inflowing water by means of a water proofing system.
Strong AAR measures are taken for the invert concrete and the construction sections where only shotcrete is applied.

3.7 Cement concept for the strong preventive measure required

The supplementary cementing material SCM which is applied consist of blast furnace slag (CEM III) with a cement replacement over 50% or a silica fume content of minimum 7% (CEM II/A-D). The combination of these elements as ternary blends is also used. The requirements of CSA [4] are fulfilled with these mix designs. Fly ash is only use as filler admixture to increase the finest content in the sand but not as SCM. Most of these concrete concepts were at origin designed for high sulphate attack resistance.

3.8 Control system of al concrete elements

In praxis usually only the aggregates are controlled systematically. To control the efficiency of concrete mixture against AAR the tunnel contractor has to declare the amount of the Na_2O-equivalent of al concrete elements regularly (cement, CMS, adjuvant). The Engineer office takes samples regulary which can be analysed if thought necessary. The contractor fulfils his obligation with the observance of the CSA [4] concerning the use of supplementary cementing material for the strong prevention level Y.

3.9 Performance Test

To control the efficiency of the AAR measures the AAR performance test AFNOR P18-454 [6] will be conducted regularly for the main concrete types. Preliminary performance tests with shotcrete shows that a lot of mixtures have a greater expansion value of 0.02% after 5 month (figure 1). The only shotcrete mixtures which have lover expansion are those with non reactive aggregates B3 and C3). With reactive aggregates only mixture A1 with CEM IV/A 42.5R with 5.6% silica fume and D2 with CEM III/A 32.5 indicates a sufficient AAR resistance. All other shotcrete mixture shows an insufficient AAR resistance.

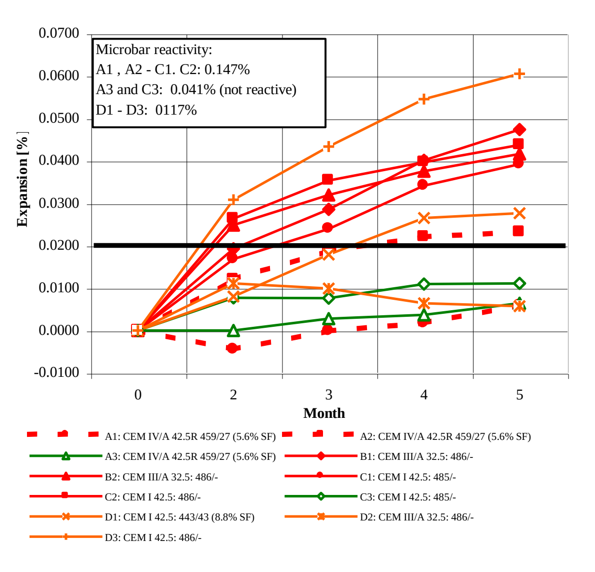


Fig 1: Perfomance tests with shotcrete mixtures.

This expansion behaviour does not astonish because of the high cement content which are used for these mixtures. The alkali content of the portland cement lies between 3 and 4 kg per m^3 shotcrete.

The study in underground construction [3] and based on the experience of other projects it could be shown that this laboratory behaviour doesn't correspond with the real behaviour of the shotcrete which is exposed to natural or tunnel climatic exposures.

4 PREVENTION FOR THE LÖTSCHBERG

The AAR standards and test procedure for the Lötschberg base tunnel rely basically on the French system [7]. The rock material control concept to evaluate the suitable rock material is similar to the Gotthard base tunnel project [1]. The construction work for the base tunnel started already in 1999, so that the conclusions of the preliminary study [2] could not be awaited. The concrete concept foresees also mixtures with high sulphate resistance which prove to have also an high resistance against AAR.

4.1 AAR preventive measures

The protection of the tunnel concrete against inflowing water by means of a water proofing system is an efficient measure.
Strong AAR measures are taken for the invert concrete and construction sections where only shotcrete is applied.

4.2 Reactivity of the aggregates

The reactivity of each geological zone is measured as well as the prepared aggregates regularly by the microbar test AFNOR P18-588 [5] and with petrographic examination.

4.3 Limiting the alkali content of the cement

In imitation of the French standard [7] the alkali content in the concrete should not exceed 3 kg per m^3 concrete. By use of maximum 380 kg portland cement for the concrete mixture the Na_2O-equivalent of the cement has to be theoretically less than 0.8%.

4.4 Use of supplementary cementing material

The use of supplementary cementing material was planned for the concrete with sulphate resistance. The shotcrete of the northern part of the tunnel is build with a CEM II/A-M 52.5 containing 8% silica fume. The invert and arch concrete for the whole tunnel is prepared with CEM I and fly ash in a ratio 70/30 to 80/20. Two different cement producers are furnishing the cements.

4.5 Control system of al concrete elements

To control the efficiency of the concrete mixtures against AAR the Na_2O-equivalent of the cements and admixtures are controlled regularly.

4.6 Performance Test

The AAR resistance of the concrete mixtures are measured by the performance test AFNOR P18-454 [6].

5 RESULTS LÖTSCHBERG TUNNEL

5.1 Preliminary performance test

The cement supplier for the northern part of the tunnel project has made a preliminary study to estimate the efficiency of his cements types against AAR [8]. The AAR resistance were measured by the Performance Test AFNOR P18-454 [6] with highly reactive aggregates (microbar: 0.35%).

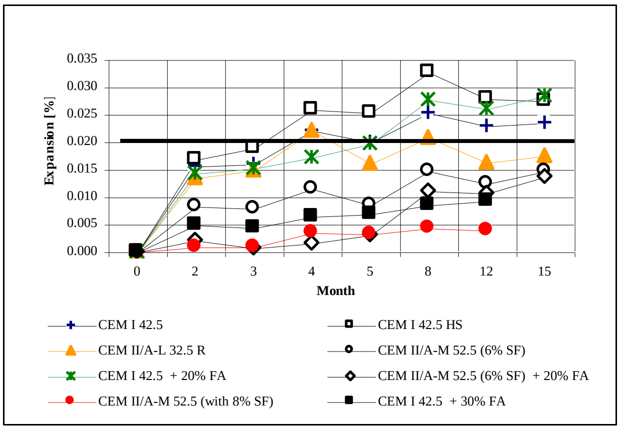


Fig 2: Performance test with different binder types and strong reactive aggregates

The performance tests in figure 2 were made without alkali addition and were measured over one year instead of maximum 5 month. Concrete expansion values under 0.02% after 5 month are considered as to be resistant against AAR. Figure 2 shows that the concrete with CEM II/A-M 52.5 including 8% silica fume gives the lowest expansion values. Also the binder with CEM I 42.5 and 30% Fly ash shows a low expansion. 20% of fly ash seems to be not efficiency enough.

5.2 Performance test during construction period

Different performance test were conducted to test their AAR behaviour with different cement types and content, different fly ash content and reactivity of the aggregates (Figure 3).

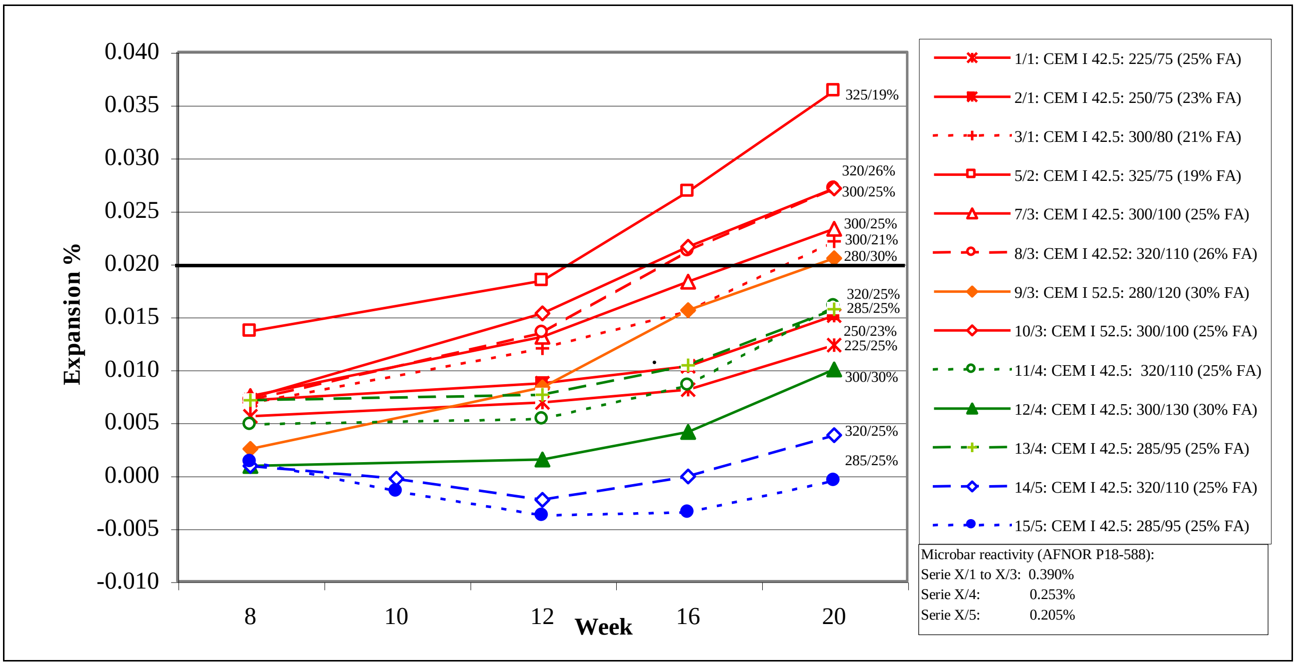


Fig. 3: Performance test AFNOR P18-454 for cement CEM I and different aggregates reactivity. Concrete expansion values under 0.02% after 5 month are considered as to be resistant against AAR (legend: 1/1: test series, EM I 42.5: cement type, 225/75: cement content / fly ash content kg/m^3, FA: fly ash in mass-%)

The reactivity of the aggregate for the concrete series 1/1 to 10/3 with a microbar expansion of 0.390% is very high. These aggregates consist of pure fine grained siliceous limestone. The concrete series 11/4 to 13/4 were made with a mix of aggregates which consist of around 70% limestone without siliceous matrix and about 30% of the high reactive siliceous limestone. The reactivity of this aggregates mixture is 0.253%. The concrete series 14/5 and 15/5 were also made with an aggregate mixture which consist beside two limestone types also of non reactive gneiss. The microbar reactivity of these aggregate mixtures amount to 0.205%. The used portland cement has a constant Na_2O-equivalent of 0.76%. The alkali input from the portland cement ranges from 2.66 to 1.71 kg/m^3.

Figure 3 shows that the expansion behaviour of the performance test is controlled by the quantity of the portland cement and the reactivity of aggregates.

Figure 4 shows that a correlation between the content of the same portland cement type (CEM I 42.5) and aggregate from the same petrography and reactivity is possible. The maximum portland cement content for the use of high reactive aggregates should not exceed 270 kg which means 2.0 alkalis kg per m^3 concrete.

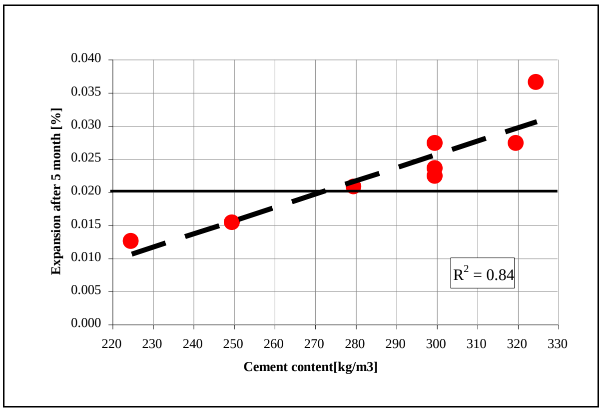


Fig 4: Performance test and correlation between the different cement content (CEM I 42.5) but same aggregate family and expansion value after 5 month (microbar reactivity of aggregate: 0.39%)

The fly ash seems to be only a replacement of the portland cement content without visible effect against AAR expansion. Some of the concrete mixtures measured by the performance test show that the shrinkage behaviour overlays the expansion for the measurement after 10 and 12 weeks.

By using aggregates with a microbar reactivity about 0.25% a cement content of maximum 300 kg or 2.3 kg alkalis per m^3 concrete seems to have sufficient AAR resistance (Figure 3, mixtures 11/4 to 13/4). With a less aggregate reactivity of about 0.20% a cement content of 320 kg or 2.4 kg alkalis per m^3 concrete shows still small performance expansion value (Figure 3, mixtures 14/5 and 15/5).

In figure 5 different mixture with CEM II/A-L 32.5 were conducted with different reactive aggregates. Two mixtures (4/1 and 6/2) has no fly ash the other three consist of 20% fly ash. Again the influence of the fly ash of the AAR behaviour is not recognisable.

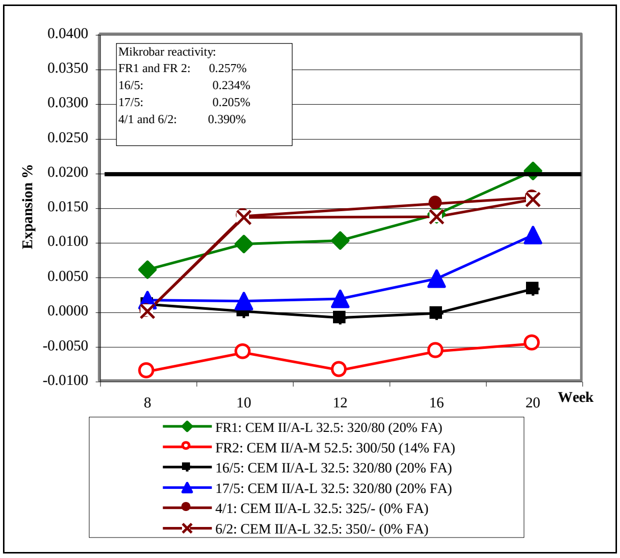


Fig 5: Performance test AFNOR P18-454 for cement CEM II/A-L 32.5, CEM II/A-M 52.5 and different aggregates reactivity.

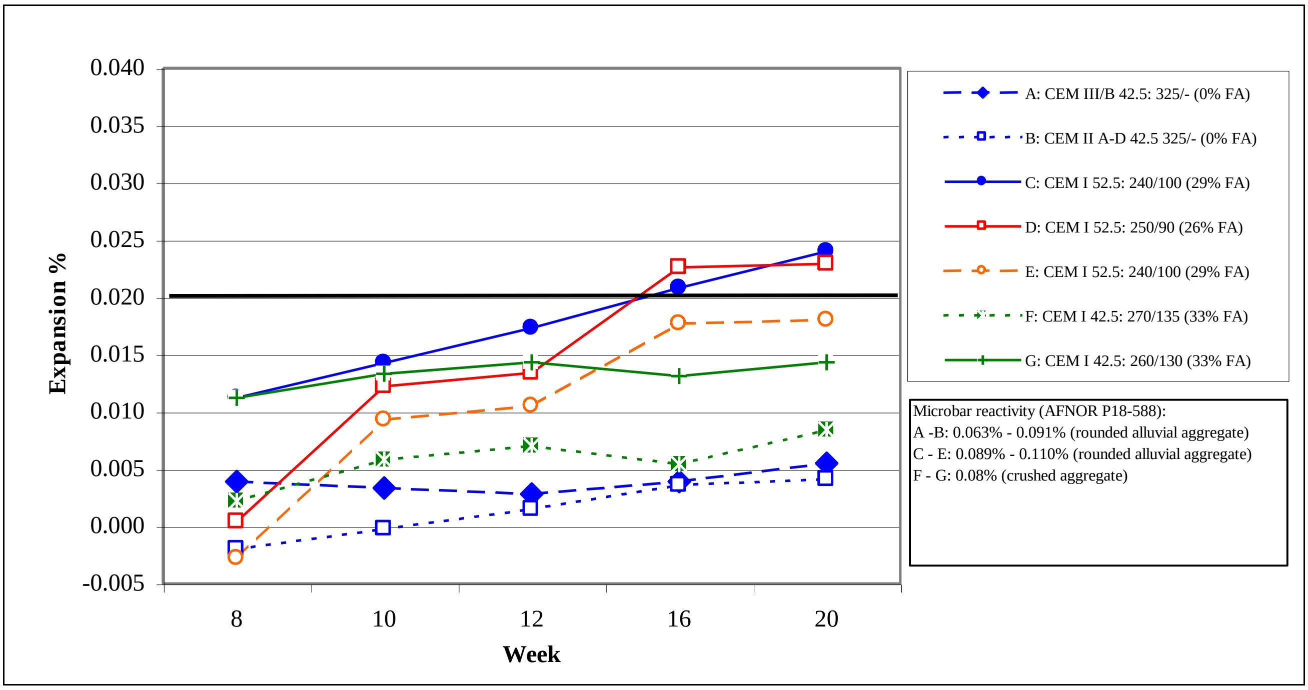


Fig 6: Performance Test with different cement types and non reactive aggregates

The concrete with CEM II/A-M 52.5 (FR 2 in figure 6) which consists of 8% silica fume and with 14% fly ash show even after 5 month a grater shrinkage than expansion value. The fly ash here was used to increase the workability of the fresh concrete. In the southern part of the Lötschberg tunnel the suitable excavation material for the aggregate production has a lower reactivity (maximum 0.20% microbar expansion) than the northern tunnel section (up to 0.40% microbar expansion).

The rock material of the south consists mainly of gneiss and granite with microbar expansion lower than 0.11% which is classified as non reactive material. Nevertheless performance test were conducted with ‘non reactive’ aggregates (Figure 6). The concrete mixtures A to E are for the tubings. The mixture F and G are linings.

Figure 6 gives contradictory AAR behaviour. In to cases (C and D) the performance test shows an expansion over 0.02% after 5 month although non reactive, rounded alluvial aggregate were used which consists mainly of different gneiss types.

The lowest performance expansion has the concrete B with CEM II/A-D 42.5 and the concrete A with CEM III/B 42.5. Al mixture (C to E and G) with 240 kg to 250 kg CEM I and 26% to 33% fly ash show a considerable expansion after five months. Only the behaviour of concrete F corresponded to the expectation. In the cases C and D a non AAR resistant concrete was made with non reactive aggregates.

To explain this behaviour different samples of the cement and fly ash which where collected regularly during the construction time by the Engineer were analysed.

5.3 Fly ash and cement analysis

The fly ash which is directly ordered by the tunnel constructer shows significant quality differences (figure 7). The quality of the producer nr 1 shows a relatively large variation in the Na2Oe and the LOI (loss of ignition). Also the fines content <0.045mm varies between 20 and 50 mass-%. The microscopic examination of this product show also a high percentage of none identified by-products in the coarser fraction.

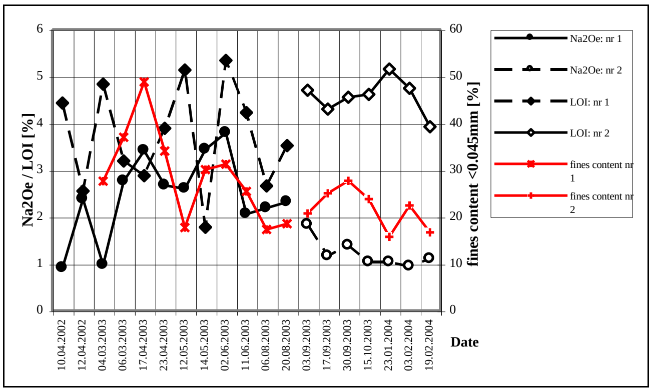


Fig 7: Na_2Oe, LOI (loss of ignition) and fines content (< 0.045mm) of two fly ash types used.

It could also be observed that this fly ash tends to absorb a certain amount of water. The tunnel constructer decided to appoint fly ash supplier (figure 7 nr 2) which guarantees a more or less constant quality. Microbar tests which were conducted with the coarse fraction (0.16 – 0.63mm) of this two fly ash types shows that nr 1 has a grater reactivity than nr 2 (figure 8).

The Na_2Oe of the Portland cement increased regularly from 0.75 – 0.85% in the year 1998 up to 0.98% in 2004 due to natural variation in the raw material sources. The consequence therefore is that the alkali content of the concrete with Portland cement (CEM I) increased from about 2.0 kg up to 2.5 kg alkalis per m^3 concrete.

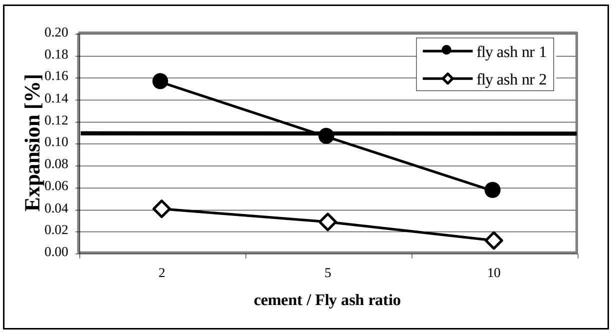


Fig 8: Microbar test of the two fly ash types used.

4 DISCUSSION

For the longest tunnel in the world which is in construction actually AAR prevention is applied consequently by using potentially reactive aggregates. For the AAR prevention not only concrete but also constructive measures were taken by protecting the concrete for water contact with a water proofing system. For the Gotthard base tunnel the Canadian AAR standard is applied basically but with French test procedure (microbar and performance test) because they are the quickest method which is a major criteria during an on going construction. The Lötschberg base tunnel refers to the French AAR recommendations and test procedures.

The preliminary studies show that the expansion values of the performance test for shotcrete mixtures does not corresponds with the real shotcrete behaviour. Even if some AAR signs can be observed in microscopic scale no substantially AAR damages can be observed on the real shotcrete. The reason might be that the microstructure and the pore size of the real shotcrete correspond not with the laboratory mixture.

One of the main problem concerning the Na_2Oe determination is the analysis method itself and the availability of the date. Although an official test analyse is given by CEN 196-21 [9] the alkali contents are measured by different methods. The different test methods can reach significant differences up to 30% and therefore leads to endless discussion. An international homogenisation of the alkali analyse is indispensable.

The reactivity of the aggregates plays an important role for the expansion behaviour of the concrete. Significant correlation between portland cement content and therefore alkali content is only possible with the same aggregate type and with the same reactivity level (figure 4). The analyses show that the amount of alkali of the portland cement should not exceed 2.0 kg per m^3 concrete with high reactive aggregates (microbar >0.25%). For aggregates with a reactivity between 0.20 and 0.25% an alkali content of 2.3 kg m3 concrete is acceptable.

With an aggregate reactivity under 0.20% the alkali content of 2.4 kg shows still a high AAR resistance. The maximum alkali content for these aggregates could yet not be determine exactly but can be estimated based on other projects between 3.0 and 3.3 kg per m^3 concrete.

The fly ash seems to be only a replacement of the portland cement content without visible effect against AAR expansion. Experience shows that the influence of the fly ash can even be contradictory (figure 6). Fly ash with great quality variation, higher alkali content and certain level of reactivity seems to induce an AAR expansion even if non reactive aggregates are used (figure 8).

The expansion behaviour of certain concrete with fly ash shows a increasing tendency only after 4 to 5 month (figure 3). A prolongation of the test shows that certain concrete exceed the limit after 6 to 7 month. If this expansion behaviour can still be judged as AAR resistant can not be verified actually.

5 CONCLUSIONS

An online AAR test procedure during the tunnel construction work is possible by using the French microbar test (AFNOR P18-588) with an analysis time of 5 to 7 days to measure the aggregate reactivity. The AAR resistance of the concrete can be controlled by the alkali amount and the performance test with an analyse time of 5 maximum month (AFNOR P18-454).

The performance test can not be used to predict the AAR behaviour of shotcrete mixtures because the shotcrete micro structure is different to the laboratory concrete.

The testing time for the performance test with fly ash has eventually to be extended.

A valid and reproducible test procedure for the determination of the alkali content has to be harmonised so that only one reference method is accepted.

Some fly ash types might induce AAR expansion even if non reactive aggregates are used.

The fly ash quality criteria proposed by prEN 450-1 is not strong enough. They should be complete with shape requirement tested by microscopic analysis. Not only the SiO_2 content but also the potential reactivity (in example with microbar test) should be analysed.

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