TESTING OF AGGREGATES REGARDING ALKALI-AGGREGATE-REACTIVITY - PROPOSAL FOR RECOMMENDATIONS IN SWITZERLAND

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Abstract

In the year 2004 the Association of the Swiss Cement Industry (cemsuisse) and the Association of the Swiss Aggregate and Concrete Industry (FSKB) initiated a study about the AAR-Situation in Switzerland in collaboration with the Swiss Federal Laboratories for Materials Testing and Research (Empa) and the Büro für Ingenieurgeologie AG (B-I-G). In this project, data were collected to assess the severity of deleterious AAR in Switzerland. The existing data base was expanded with an experimental part consisting of laboratory tests.

Based on the results of the project, recommendations to prevent AAR were established. A procedure was proposed taking into account the existing experience in regard to AAR, the type of structure and its exposure.

The report of the project will be used as the base of an official guideline containing recommendations to prevent AAR in Switzerland.

Keywords: alkali-aggregate-reaction, microbar and performance test, guideline

1 INTRODUCTION

Since about 1998, the number of structures in Switzerland damaged by alkali-aggregate reaction (AAR) appears to be increasing [1-6]. This increase may be a fact or a consequence of the increased awareness of the problem. Nevertheless, a variety of structures such as dams, bridges and walls are affected today. Most of the structures display damage 20 to 40 years after construction. However, there are a few cases where damage has already appeared five to ten years after construction.

So far, there are no national guidelines or standards dealing with AAR. In 2004, the Association of the Swiss Cement Industry (cemsuisse) initiated a project in cooperation with the Association of the Swiss Aggregate and Concrete Industry (FSKB), in order to propose guidelines on the basis of the existing experience with AAR in Switzerland [7].

In the laboratory part (chapter 2), the potential reactivity of two typical Swiss aggregates was tested using the microbar test (AFNOR P18-594 [8]). Various concrete mixtures have been produced with these aggregates varying the type and dosage of cement. The potential reactivity of these mixtures was measured using a concrete performance test (AFNOR P18-454 [9]). These results were compared with the existing database consisting of 79 microbar test and 93 concrete performance test results (chapter 3).

Based on the results of the project recommendations to prevent AAR are established. A procedure is proposed taking into account the existing experience in regard to AAR, the type of structure and its exposure (chapter 4).

2 CONCRETE TESTS

The goal of the experimental part is to assess the effect of the different cements used in Switzerland on AAR induced expansion and to possibly define a maximum alkali content for concrete.

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2.1 Materials and mix design

A total of 46 mixtures were produced with cements of three different producers (Table 1). Concrete mixtures were produced with cement contents of 300, 350 and 400 kg/m^3, respectively. For additional concrete mixtures mineral admixtures were used; 50 and 100 kg/m^3 of low CaO fly ash or 15 and 30 kg/m^3 of silicafume. The composition of the cements and admixtures is listed in Table 2. Al concrete mixtures were made with two different types of aggregate.

Water-to-cement-ratio (w/c) was 0.45 for the mixtures with 400 kg/m^3 of cement, 0.50 for the ones with 350 kg/m^3 of cement and 0.55 for ones with 300 kg/m^3 of cement. The superplasticizer content (SP: based on polycarboxylate ether) ranged from 0.8 to 1.0% for 400 kg/m^3, 0.6 to 0.8% for 350 kg/m^3 and 0.4 to 0.6 for 300 kg/m^3 cement.

2.2 Methods for assessment and analysis

Petrography

The petrography of the aggregates was determined according to Swiss standard SN 670'115 [10].

Microbar test

The potential reactivity of the aggregates was measured with the microbar test according to AFNOR P 18-594 [8].

Concrete performance test

The expansion of the concrete was measured according to AFNOR P18-454 [9]

2.3 Results

Petrography

Aggregate 'd' mainly consists of metamorphic and igneous rocks, gneiss being the most frequent rock type. In contrast, aggregate 'e' mainly consists of sediments dominated by sandstone and limestone (Table 1).

Microbar test

Both aggregates exceed the limit value of 0.11% and are to be classified as potentially reactive (Table 1). The difference between aggregate 'd' and 'e' is substantial; the microbars produced with aggregate 'd' expand (mean value 0.31%) twice as much as the one produced with aggregate 'e' (mean value 0.15%).

Concrete performance test

The results of concrete performance tests with aggregate 'e' and cement from producer 'a' are shown in Figure 1. The concrete mixtures without mineral admixtures show a continuous expansion with time. The concrete with the highest cement content (400 kg/m^3) exceeds the limit value of 0.02% after 20 weeks. All other mixtures containing 350 kg/m^3 of cement are below the limit value. The use of mineral admixtures or CEM III/B leads to a negative length change during the first eight weeks most likely due to autogenous shrinkage.

Figure 2 shows the expansion after 20 weeks versus the cement content of concrete mixtures with aggregate 'e' and cement of producer 'a'. The mixtures with CEM I and CEM II without mineral admixtures show a steady expansion with increasing cement content. The concrete mixtures with mineral admixtures exhibit less expansion than the ones without.

The expansion of the concrete mixtures with identical mix design but with CEM I and CEM II/A-LL from the two producers 'a' and 'b' and with aggregates 'e' and 'd' is shown in Figure 3. The mixtures with aggregate 'e' exhibit a greater expansion rate after 20 weeks then the mixture with aggregate 'd'.

2.4 Discussion

The concrete mixtures shown in Figure 1 exhibit the expected behaviour; the higher the cement content the higher is the expansion. The mixture with 400 kg/m^3 cement has a total alkali content of 3.60 kg/m^3 (Na_2O-equivalent) and exceeds the limit value of expansion. CEM II/A-LL mixtures expand less the CEM I mixtures because of the 15% lower clinker content of the former. A significant reduction of expansion is possible by using fly ash or silicafume. The lowest expansion behaviour is shown by concrete produced with CEM III/B. The concrete mixtures containing mineral admixtures or CEM III/B during the first four to eight weeks.

Figure 2 shows that the expansion rate after 20 weeks can be reduced by increasing the mineral admixture content. The use of 15 and 30 kg silicafume combined with 350 kg/m^3 cement leads to the same reduction of expansion as using 50 respectively 100 kg/m^3 of fly ash.

Concrete expansion is higher with aggregate ‘e’ compared to the same mixtures with aggregate ‘d’ (Figure 3). This behaviour seems contradictory because aggregate ‘e’ with lower microbar value (0.15%) expand more in the concrete performance test than aggregate ‘d’ with higher microbar value (0.31%). Leemann et al. [11] suggest that these differences must have a relation to the characteristics of the quartz present. Quartz in aggregate ‘d’ dissolves under the conditions present in the microbar test but is more or less stable in the conditions present in the concrete performance test. In contrast quartz in aggregate ‘e’ dissolves in both tests. A reason of this behaviour might be the differences in the crystal structure of quartz resulting from differences in the geological history of the aggregates. Aggregate ‘e’ was subjected to a retrograde metamorphosis of the greenschist facies while the majority of the rock types present in aggregate ‘d’ are not metamorphic.

3 FIELD EXPERIENCE

The number of structures in Switzerland damaged by alkali-aggregate reaction (AAR) appears to be increasing during the last ten years [1-6]. The damage present shows the typical features of AAR. On a microscopic scale, cracked aggregates and gel deposits occur. On a macroscopic scale, typical crack patterns appear on the concrete surface in combination with deposits of gel and calcite along the cracks.

3.1 Aggregates

The situation in Switzerland with regard to aggregates is very complex. There are a wide variety of aggregates used for concrete production. These aggregates include sedimentary and igneous rocks in various states of metamorphosis. There are five different geological regions that have to be distinguished: Jura, Middle-Land, Pre-Alpine Area, Central Alps and the Southern Alps. Structures affected by AAR are concentrated in the region where aggregates of the Pre-Alpine area, Central Alps and Southern Alp are used. In the Middle-Land and Jura the number of AAR related damages is minor.

3.2 Test methods

In Switzerland, the microbar test according to AFNOR P18-594 [8] and the concrete performance test according to AFNOR P18-454 [9] are in use since ten years and are accepted by the building industry. The results of 79 aggregate production plants indicate that 85 % of the Swiss aggregates are potentially reactive according to the microbar test. However, there are some inconsistencies when the results of the microbar and the concrete performance test (concrete produced wit CEM I, CEM II and various mineral admixtures) are compared (Figure 4). The microbar expansion does not correlate with the expansion of the performance test.

3.3 Alkali content

In Figure 5 the expansion of the concrete performance test is compared with the alkali content of the cements in 38 concrete mixtures commonly used in the building industry. A wide variety of cement and mineral admixture combinations are used. The aggregates are from different geological areas.

Based on concrete produced with CEM I and CEM II but without mineral admixtures, the maximum alkali content leading to expansion below the limit value should be around 3.0 kg/m^3. But there are also some mixtures with CEM II and fly ash which reach the expansion limit with an alkali content of less than 2.5 kg/m^3. The lacking correlation between concrete expansion and alkali content is due to the great variation of mix designs and aggregates.

3.4 Discussion

The results of the concrete performance test correlates significantly better with the distribution and frequency of AAR affected structures in Switzerland than the results of the microbar test. However, the use of the microbar test seems to be justified, when results have to be obtained within a couple of days. However, the test is not suited to assess the degree of reactivity. To assess the degree of aggregate reactivity a more suitable test method has to be used.

The relation between alkali content and concrete expansion is dependent on the type of aggregate used and its reactivity. Based on the existing data a limitation of alkali content seems not to be a useful because of the wide range of aggregates used in Switzerland.

4 GUIDELINE

Based on existing data and experiences with AAR in Switzerland the Association of the Swiss Cement Industry (cemsuisse) has developed a guideline for AAR prevention in new structures.

4.1 Risk assessment

The risk assessment is made by the owner in cooperation with the contractor according to the following classes:

- R1 - low risk: AAR damages: acceptable - structures with a service life <50 years or replaceable components
- R2 - normal risk: AAR damages: hardly acceptable - structures with service life between 50 and 100 years
- R3 - high risk: AAR damages: not acceptable - important structures with a service life > 100 years

The risk class is based on the planned service life and the acceptability of damages due to AAR.

4.2 Exposure assessment

The classification of exposure is based on the concrete's expected moisture content (Table 3):

- B1: Structures in dry conditions with low moisture content
- B2: Structures with frequent changes wet and dry or structures that are often wet
- B3: Structures always wet with high moisture content, may be exposed to alkalis (de-icing salts)

4.3 Level of prevention

The level of prevention is derived from a combination of risk and exposure assessment:

- P1 - low level of prevention
- P2 - normal level of prevention
- P3 - high level of prevention

The level of prevention is set in the planning stage by the owner.

Example 1: A supporting wall at a hillside is classified as B3 (exposure class) and as R1 (risk class). The resulting level of prevention is P1.

Example 2: The column of a bridge of a minor road is classified as B2 (exposure class) and R2. The concrete producer can not prove the long term suitability of the concrete used for similar applications. The resulting level of prevention is P2.

Example 3: The bridge deck of a motorway is classified as B2 (exposure class) and R3. The level of prevention is P2. As a result the bridge deck receives a polymer coating.

4.4 Approval of concrete

The level of prevention sets in place the necessary steps to take for approving a specific concrete mixture:

P1 - no approval necessary
P2 - approval necessary
P3 - approval necessary (as at level P2) and additional consulting of experts

Figure 6 shows the sequence of the necessary steps. The owner approves a concrete mixture when it meets the specified requirements.

4.5 Concrete Producer

If the producer knows that the concrete has not caused problems in the past, he can put together a documentation substantiating this long-term situation. This includes information about structures for which concrete was supplied and information about the mix design used. If this is not possible, tests have to be conducted.

It is recommended that the concrete producer determines the potential reactivity of the aggregates as the first step. When the aggregates are not reactive, the producer does not have to proceed with testing. However, when the aggregates show a potential reactivity one has to take a second step and test the potential reactivity of a concrete mixture. The producer should choose a mixture within the production range with high cement content. When the concrete performance test shows that the concrete tested is not potentially reactive, no further testing is necessary.

The result is valid for all mixtures with the same or lower cement content than the mixture tested. Consequently, the process has to be verified when an aggregate of a different source is used or when the cement content is increased. A change of grain size distribution of the aggregate is allowed without retesting as long as the different fractions come from the same quarry. If the results indicate a potential reactivity, the mix design has to be adapted and the concrete has to be retested.

5 SUMMARY

AAR is a problem present in Switzerland that has to be dealt with accordingly. Since measures for affected structures are limited, the focus is on prevention. The proposed measures offer the following benefits:

- tool for owner/engineer and concrete producer
- take into account national conditions and local experiences
- no limits to cement content or Na_2O-equivalent
- acceptance of concrete performance test

Because there are still some gaps with regard to the understanding of AAR, national guidelines and standards have to be adapted to new findings. As AAR proceeds very slowly, the effectiveness of the preventive measures has to be reevaluated during the next years.

6 REFERENCES

[1] Regamey, JM, and Hammerschlag, JG (1995): Barrage d'Illsee - assaintment. Research and Development in the Field of Dams, Proceedings of the ICOLD-Symposium (Crans-Montana, Switzerland).

[2] Leemann, A, Thalmann, C, Kruse, M (1999): Gebrochene Zuschlagstoffe. Schweizer Ingenieur- und Architektenverein, SI+A (24): 4-8.

[3] Thalmann, C, Zingg, J, Rytz, G, Strahm, K, and Wyss, C (2001): Verhinderung von Betonschäden infolge Alkali-Aggregat-Reaktion. Schweizer Ingenieur- und Architektenverein, tec 21 (15): 2-8.

[4] Leemann, A, Thalmann, C, and Studer, W (2005): AAR in underground structures of Switzerland - a survey. In: Tang, M, and Deng, M (editors): Proceedings of the 12th ICAAR, 2004, Beijing, China, 1071-1077.

[5] Leemann, A, Thalmann, C, and Studer, W (2005): Alkali-aggregate reaction in Swiss tunnels. Materials and Structures (38): 381 – 386.

[6] Thalmann, C, Pralong, J, Burdin, J, Schmid, H, and Weiss R (2004): AAR-prevention for the world’s longest tunnels - Alptransit Gotthard and Lötschberg in Switzerland. In: Tang, M, and Deng, M (editors): Proceedings of the 12th ICAAR, 2004, Beijing, China, 651-658.

[7] Frenzer, G, Hammerschlag, JG, Henoch, T, Leemann, A, Lunk, P, Pilloud, C, Rytz, G, Romer, M, Spicher, G, Thalmann, C, and Widmer, H (2005): Alkali-Aggregat-Reaktion (AAR) in der Schweiz. cemsuisse, Bern: pp. 55.

[8] AFNOR P18-594 (2004): Granulats: Méthodes d’essais de réactivité aux alcalis, Association Française de Normalisation, Paris.

[9] AFNOR P18-454 (2004): Béton: Réactivité d’une formule de béton vis-à-vis de l’alcali-réaction (essaie de performance). Association Française de Normalisation, Paris.

[10] SN 670'115 (2005): Gesteinskörnungen: qualitative und quantitative Mineralogie und Petrographie. Swiss Standard, VSS Zürich.

[11] Leemann, A, Hammerschlag, JG and Thalmann, C (2008): Inconsistencies between different accelerated test methods used to assess alkali-aggregate reactivity. Proceedings of the 13th ICAAR, 2008, Trondheim, Norway.

[12] SN EN 196-21 (1989): Determination of chloride, carbon dioxide and alkali content of cement. Schweizerischer Ingnieur- und Architekten-Verein. Zürich.

TABLE 1: Mix design of the concrete.

Cement					
Type	Strength class				Producer
CEM I	42.5 N				a
CEM II/A-LL	42.5 N				a
CEM II/A-LL	32.5 N				b
CEM III/B	32.5 N				a
CEM III/B	42.5 N				c
Mineral admixture					
Type	Abbreviation				Producer
Low CaO fly ash	V				g
Silicafume	D				f
Superplasticizer					
Type	Abbreviation				Producer
Polcarboxylate	FM-VZ				f
Aggregates					
Area Grain size [mm]	Microbar expansion (≥ 0.11 = potentially reactive)				Producer
Middle-Land					
0/4	0.286				d
4/8	0.304				
8/16	0.334				
16/32	0.325				
Pre-Alpine area					
0/4	0.125				e
4/8	0.174				
8/16	0.157				
16/32	0.138				
Petrography of aggregate					
Rock types [weight-%]	Grain size [mm]				Producer
	1/4	4/8	8/16	16/32	
Quartzite	8	3	4	2	d
Igneous rocks	1	1	2	2	
Sandstone	46	31	24	30	
Dark limestone	8	12	17	11	
Bright limestone	34	52	50	52	
Porous sandstone and limestone	3	1	3	2	
Porous conglomerate	0	0	0	1	
Fine grained gneiss	63	62	64	61	e
Strongly foliated gneiss	7	6	8	5	
Granite	10	12	17	22	
Quartzite	4	2	2	4	
Limestone	16	18	9	8	

TABLE 2: Composition of cements and admixtures used in the concrete tests.

Cement	Type	CEM I	CEM II/A-LL	CEM II/A-LL	CEM III/B	CEM III/B	Fly ash	Silica-fume	SP
Producer	-	a	a	b	a	c	g	f	f
Blaine	cm^2/g	3029	3449	3092	4340	4180	-	-	-
SiO_2	%	20.87	18.50	18.18	30.96	28.41	46.72	96.50	-
Al_2O_3	%	4.53	4.05	4.57	7.93	8.69	30.85	0.50	-
Fe_2O_3	%	2.64	2.37	2.52	1.16	1.39	8.28	0.20	-
CaO	%	63.29	61.51	62.09	45.12	49.60	2.44	0.00	-
Na_2O	%	0.19	0.17	0.12	0.33	0.25	1.07	0.17	0.37
K_2O	%	1.08	0.95	0.93	1.11	0.60	3.99	0.34	0.01
MgO	%	1.74	1.59	1.71	6.53	5.00	2.75	0.30	-
SO_3 total	%	2.87	2.78	1.93	4.20	3.45	0.60	0.10	-
Mn_2O_3	%	0.06	0.05	0.05	0.74	0.23	0.00	0.00	-
TiO_2	%	0.23	0.21	0.28	0.74	0.74	0.00	0.00	-
P_2O_5	%	0.38	0.36	0.39	0.17	0.08	0.00	0.00	-
CL	%	0.03	0.02	0.04	0.01	0.03	0.01	0.06	-
SrO	%	0.08	0.08	0.08	0.09	0.09	0.00	0.00	-
LOI	%	2.49	6.93	6.93	0.69	1.30	2.90	1.70	-
total	%						99.61	99.87	-
Na_2O-equ(1)	%	0.90	0.79	0.73	1.06	0.64	3.69	0.39	0.38
Na_2O-equ(2)	%	0.87	0.77	0.73	0.64	0.47	-	-	-

(1): Total alkali content SN EN 196-21 [12]
(2): Content of soluble alkalis AFNOR P18-454 [9]

TABLE 3: Classification of preventive measures for individual structures.

<table>
<tr><td rowspan="2">Risk Class</td><td colspan="3">Exposure Class</td></tr>
<tr><td>B1 (dry)</td><td>B2 (dry-wet)</td><td>B3 (wet)</td></tr>
<tr><td>R1 (low)</td><td colspan="3">P1: no measures</td></tr>
<tr><td rowspan="2">R2 (medium)</td><td rowspan="2"></td><td></td><td rowspan="2"></td></tr>
<tr><td rowspan="2">P1*: no measure or
P2: measures needed</td></tr>
<tr><td>R3 (high)</td><td></td><td>P3: experts</td></tr>
<tr><td colspan="4">*: The concrete producer has to prove the long term suitability of the concrete for similar applications.</td></tr>
</table>

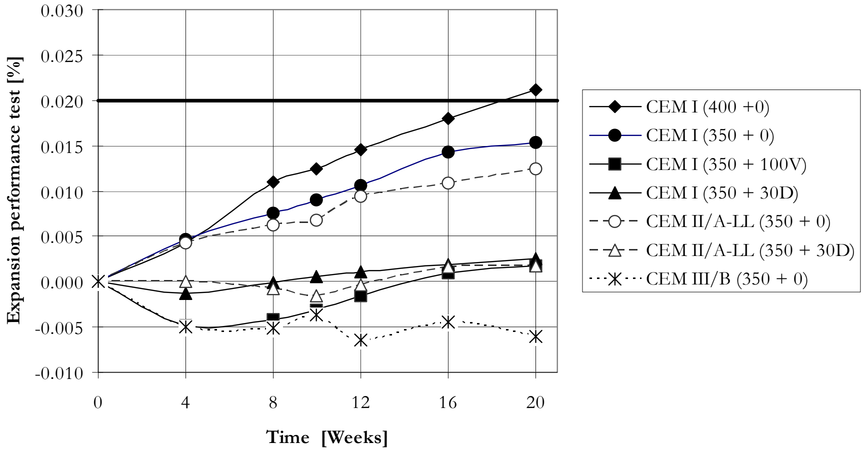

Figure 1: Expansion of concrete versus time; 0.02% = limit value; legend: cement type (cement and mineral admixture content in kg/m³); V = fly ash; D = silicafume).

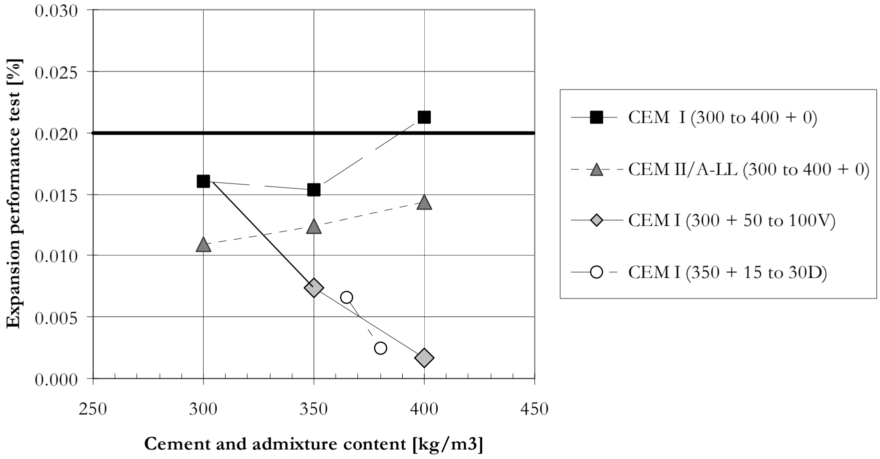

Figure 2: Expansion of concrete versus cement and admixture content after 20 weeks; 0.02% = limit value; legend: cement type (cement and mineral admixture content in kg/m³); V = fly ash; D = silicafume.

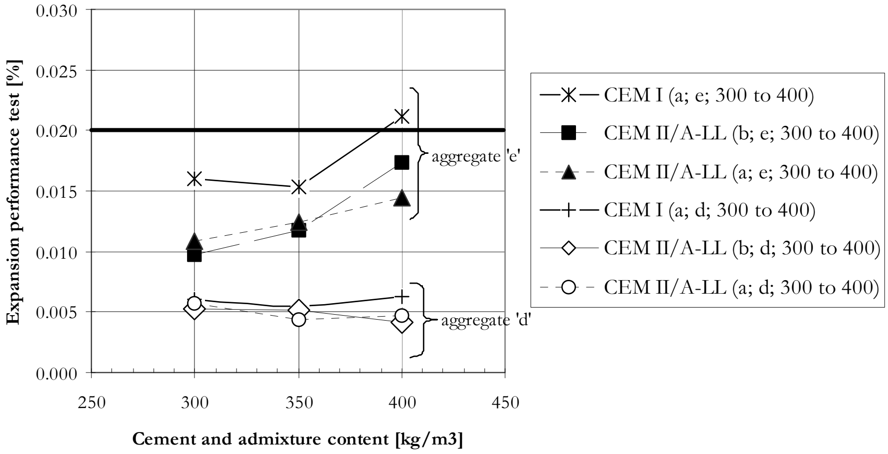

Figure 3: Expansion of concrete versus cement content after 20 weeks; 0.02% = limit value; legend: cement type (b/a = cement producer; e/d = aggregate type; cement content in kg).

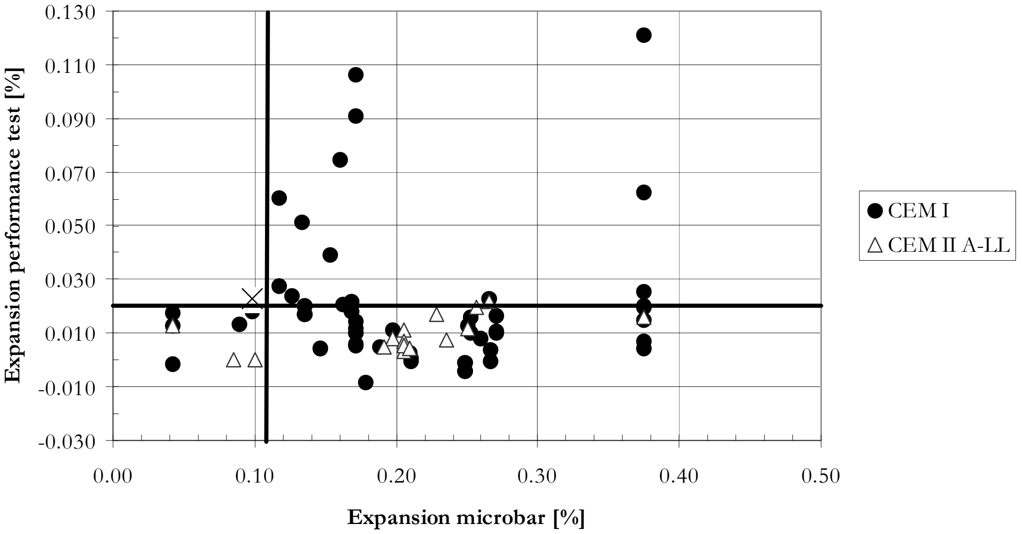

Figure 4: Concrete expansion (20 weeks) versus microbar expansion; 0.02% = limit value for the concrete performance test; 0.11% limit value for the microbar test; legend: cement typ, X = concrete mixture with insufficient fly ash quality.

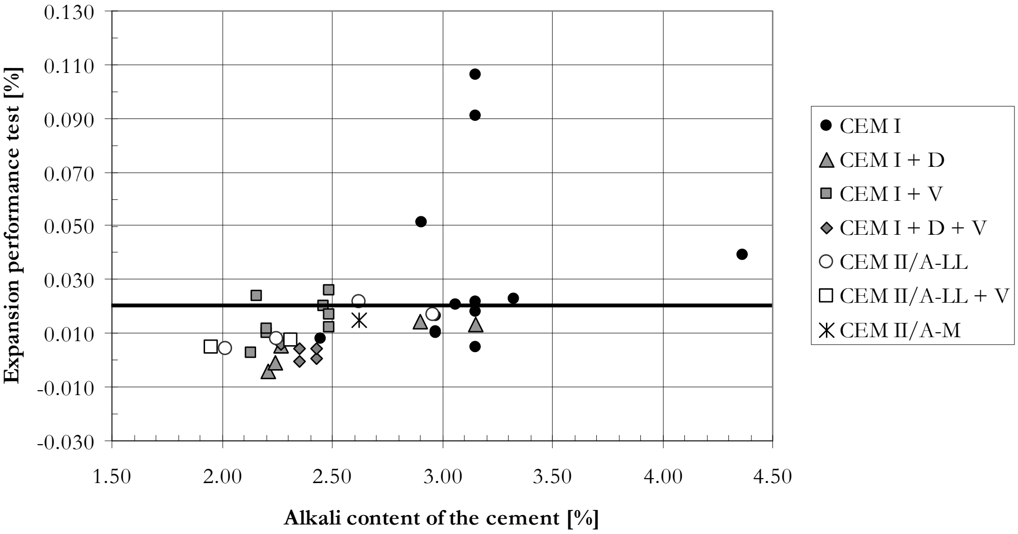

Figure 5: Concrete expansion (20 weeks) versus alkali content of the cement; 0.02% = limit value for the concrete performance test; legend: cement type + admixture: V = siliceous fly ash; D = silicafume.

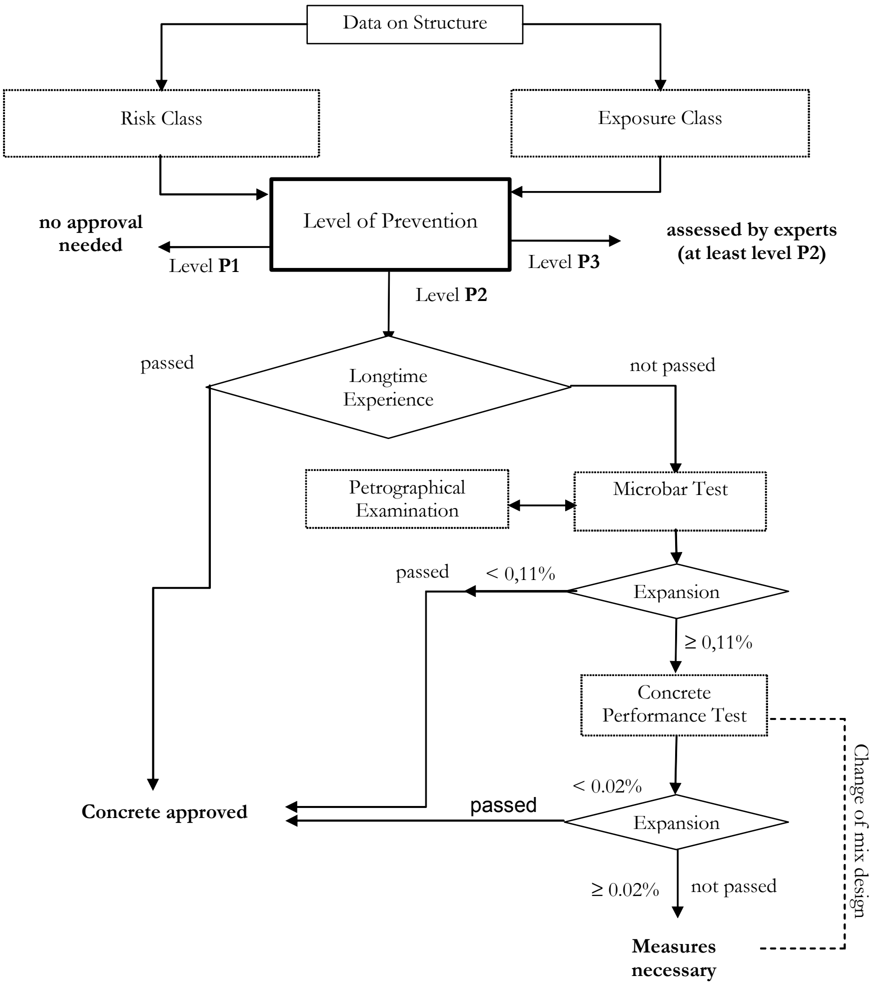

Figure 6: Flow chart of the necessary steps to take for approving a specific concrete mixture.