PORTLAND-SLAG CEMENTS - REDUCTION OF THE RESIDUAL RISK OF AGGREGATES CONTAINING REACTIVE COMPONENTS

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Abstract

National guidelines ensure that using local available raw materials e.g. aggregates or cements, and with the observance of acknowledged rules of technology and methods of execution future damages on concrete structures could be prevented. Due to a systematic approach both clients and engineers could be supported which measures have to be taken to prevent harmful Alkali-reactions in a certain region. In addition to concrete technological and structural measures the methods of execution and maintenance are important to be looked at, especially for concrete pavements.

Results of a set of testing methods expose, that a residual risk of the tested aggregates could be covered with cements which have higher granulated blastfurnace slag contents (additional requirement in Austria: „reduced expansion - VD"). The amount of slag has to be defined in a normative prescribed approval test. Based on this research programme a new Austrian standard for prevention of AAR has been established.

Keywords: Portland-slag cement, granulated blastfurnace slag, concrete pavements, Austrian standard, external enrichment of alkalis

1 INRODUCTION AND PURPOSE OF THE STUDY

A set of studies and experiences on buildings and construction elements during the past years have shown, that the potential for a possible damage caused by Alkali-Aggregate Reaction (AAR) depends on regional determining factors. Therefore national guidelines can be used to assess and ensure the qualification of measures and raw materials for minimizing the risk of a harmful AAR.

Aggregates which are used for concrete constructions in Austria show a minor content of reactive components. These sand and gravel types usually arise from the sedimentation of rivers. Therefore damages in Austria actuated by Alkali-Aggregate Reaction (AAR) are almost unknown. Otherwise thin sections of aggregate particles of some construction elements which have been produced several decades ago show characteristic AAR-damages (air voids filled with gel; gel in and around aggregate particles[1]). On this account the topic of AAR had also been discussed in Austria.

As a result of a possible potential presence of alkali-silica reactivity in Austrian aggregate deposits research work was necessary to develop and provide a set of rules to minimize the residual risk and to prevent possible damages. Due to the geological variety of the Austrian aggregates it is not predictable which type of aggregate contains reactive constituents and would cause AAR.

Examinations with different cements and aggregate types result in, that Austrian CEM II/A-S cements, which have been used for concrete pavements since several decades, show a similar performance compared with a foreign Low-Alkali-Cement. Expansions are importantly lower and even for critical aggregate types insignificant if a CEM II/B-S was used. The use of CEM II/A-S cements for concrete pavements over decades is definitely a reason for the absence of serious AAR-damages in Austria [2]. Pavements constructed with CEM II/A-S and CEM II/B-S show also no damages due to freeze-thaw-attack.

A research programme has been designed according to above mentioned results. The aim of this programme was to create cements for concrete pavements with higher contents of granulated blastfurnace slag which reduce on one hand the residual risk of aggregates containing reactive components and ensure otherwise the durability of concrete pavements. [1]

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[1] Some countries use CEM III cements with a slag-content > 50 % to obtain resistivity against AAR. These cements are inappropriate for concrete pavements and bridges due the fact that e.g. the risk of damages due to freezing and thawing will be enlarged.

2 RESEARCH PROGRAMME

In total, 25 cements with different slag contents of 8 Austrian cement producers have been used for the tests. Beside this large number of cements, different types of natural aggregates were used for the analysis. Some of them have shown a certain residual risk regarding AAR. In addition to these natural aggregates, also recycled materials and respectively drilling cores from existing concrete pavements have been used to evaluate testing methods for the assessment of recycled materials and for the re-use in new concrete pavements.

The aim of the study was to assess the performance of cements with different slag contents. A set of aggregates both containing reactive components and, as a reference material one non reactive type of aggregate, has been used for testing.

The aggregate (Agg. 1) which is used for concrete constructions for decades shows an expansion of 1.4 ‰ with CEM I 52.5 R cement according to the ultra-accelerated mortar bar test-method described in the Austrian standard [3] which is related to the RILEM AAR-2 test-method [4].[2] The reactive aggregate (Agg. 2) which is not used for concrete constructions in Austria is a siliceous limestone. This material shows an expansion of 1.7 ‰ tested according to the ultra-accelerated mortar bar test method [3]. [3]

The third tested aggregate has been used for some 40 years for concrete pavements and bridge-constructions without damages due to AAR. This aggregate is indicated as non-reactive (Agg. NR) due to the practical experience and passed ultra-accelerated mortar bar and long-term concrete prism tests.

To assess the effect of different common cement compositions, in total 25 cements, with variable slag contents, have been used for the tests.

AAR-reactions occur if an aggregate includes reactive silica but also some other preconditions e.g. moisture or additional enrichment of alkalis have to be met. The simulation of durability and long-term behaviour of AAR in the laboratory is highly demanding. Present common European test methods allow simulating only some relevant parameters at a time. Due to this below mentioned tests, besides fracture mechanical and chemical determinations were performed:

Aggregate 1 (Agg. 1):

Ultra-accelerated mortar bar test method [3]
Long-term concrete prism test method with additional enrichment of alkalis [3]

Aggregate 2 (Agg. 2):

Ultra-accelerated mortar bar test method [3]
Long-term concrete prism test method with additional enrichment of alkalis [3]
Long-term concrete prism test method without additional enrichment of alkalis (test method according to RILEM AAR-3 [5])

Non-reactive aggregate (Agg. NR):

Ultra-accelerated mortar bar test method [3]
Long-term concrete prism test method with additional enrichment of alkalis [3]

3 REQUIREMENT FOR COMPARABILITY OF CEMENT

For the appraisal of aggregates normally CEM I cements with a fineness (Blaine) of 4500 cm^2/g are prescribed. These cements show generally an early strength of about 30 N/mm^2 after one day and of about 40 N/mm^2 after two days. The CEM I 52.5 R cement used for testing had an early strength of 31 N/mm^2 after one day and of 42 N/mm^2 after two days. The explorative CEM II/..-S cements showed a compressive strength of 6 to 14 N/mm^2 after one day and 16 to 23 N/mm^2 after two days.

The rate of hydration is essential for the durability against chemical reactions especially at the beginning of the exposure. For a comparative assessment of different cements, they have to be tested with comparable rates of hydration, this means at similar early strength.

After demoulding the prisms for the ultra-accelerated mortar bar tests (specimen size: 4/4/16 cm^3) according to [3, 4] at the age of 24 ± 2 hours they will be placed in water of 20°C and heated up to 80°C ± 2°C. At the age of two days the specimen will be relocated in a 1 M NaOH-solution at a

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[2] Aggregate 1 contains a critical number of reactive constituents due to petrographic determination. A large number of long-term concrete prism tests according to the Austrian test method have been conducted with this material. As a result of the variation of the test results this material is considered to have a residual risk regarding AAR.

[3] According to the Austrian long-term concrete prism test method this material is considered to be reactive.

temperature of 80°C ± 2°C. Cements with a slower hardening rate show also a slower hydration when heating up to 80 ± 2°C compared with cements with a higher hardening rate. Therefore the demoulding of the prisms took place when they had reached an early strength of (0.7 $ß_{D1}$ + 0.3 $ß_{D2}$) of the CEM I 52.5 R cement (reference cement).

After demoulding the prisms for the long-term concrete prism tests according to [3], [5] at the age of one day, they will be stored at 20 ± 2°C and min. 95 % relative humidity (r. h.) until the age of seven days. Subsequently the storage took place in a 1 M NaOH-solution of 38 ± 2°C. Therefore the demoulding of the prisms took place when the tested cements had reached an early strength after 24 hours of the CEM I 52.5 R cement (reference cement).

4 ULTRA-ACCELERATED MORTAR BAR TESTS

Preparation of the prisms

From each deposit 35 % of the fraction 0/4 mm, 20 % 4/8, 10 % 8/16 and 35 % 16/32 were used for testing. The fraction 0/4 had been sieved into the size ranges 0.125/0.25, 0.25/0.5, 0.5/1, 1/2 and 2/4. The fractions 4/8, 8/16 and 16/32 had been crushed and afterwards also been sieved in the above mentioned size ranges. The specimen (4/4/16 cm^3) had been composed of 15 % 0.125/0.25, 25 % 0.25/0.5, 25 % 0.5/1, 25 % 1/2 and 10 % 2/4 of the above mentioned size ranges of the single fractions.

Storage and measurements of prisms produced with different cements

Storage in moulds at 20 ± 2°C and 95 % r. h. until an early strength of 0.7 β_{D1} + 0.3 β_{D2} (β_{D1} early strength after one day and β_{D2} early strength after two days of CEM I 52.5 R) had been reached after demoulding.

After demoulding: storage in water for 24 ± 2 h (heated up from 20°C to 80 ± 2°C).

Subsequently storage in 1 M NaOH-solution at 80 ± 2°C.

Measurements: 2, 7, 9, 14 and 28 days after initial measurement.

5 LONG-TERM CONCRETE PRISM TEST METHOD

Concrete prisms (10/10/36 cm^3) have been demoulded at an age of an early strength of cement of 31 N/mm^2 and stored at 20 ± 2 °C and min. 95 % r. h. for six days. Subsequently the prisms have been stored in 1M NaOH-solution at 38 ± 2°C to obtain well-defined test results regarding the alkali-sensitivity of aggregates for concrete structures. The storage in NaOH-solution shows improved significance due to the fact that a larger quantity of alkalis is available for a possible reaction.

In addition to the above described test method, concrete prisms (7.5/7.5/25 cm^3) have been produced and after identical pre-storage these prisms have been stored according to the RILEM AAR-3 test method [5].

6 RESULTS ULTRA-ACCELERATED MORTAR BAR TESTS

Effect of slag content on expansion

Figure 1 shows the expansions of prisms according to [3, 4] with CEM I 52.5 R cement and with for concrete constructions common aggregate (aggregate 1, aggregate with residual risk), the non reactive aggregate and exemplary aggregate 1 with a CEM II/B-S cement. The positive effect of the CEM II/B-S on the gradient and the magnitude of the expansion are clearly noticeable.

The gradient of the expansion of the prisms produced with CEM I 52.5 R cement increase strongly after 10 days both for aggregate 1 (Agg. 1) and the non-reactive aggregate (Agg. NR). The magnitude of expansion of the non-reactive one amounts only to 70 % of aggregate 1 (Agg. 1).

In contrast the prisms produced with CEM II/B-S cement and aggregate 1 (Agg. 1) show no acceleration of the expansion with increasing time of storage. The magnitude of the expansion is considerable lower than the expansion of the non-reactive aggregate produced with CEM I 52.5 R cement. Because of the gradients of expansion, the assessment of cements on their effect of the expansion has to be based on storage in NaOH-solution for 27 days.

Figure 2 shows the expansions after 27 days for all assessed cements with aggregate 1 (aggregate with residual risk) in NaOH-storage in relation to the slag content of the different cements. The expansion of aggregate 1 with CEM I 52.5 R cement has been taken as 100 %. The correlation between expansion and slag content is clearly visible. Higher slag contents reduce noticeable the expansions of the specimen. The expansion of the non-reactive aggregate (Agg. NR) with CEM I 52.5 R cement is achieved by Portland-slag cements with a content of blastfurnace slag above about 12 to 15 %. These Portland-slag cements show an expansion equivalent to 70 % of the expansion of the aggregate 1 and CEM I 52.5 R. This "70 % criterion" corresponds to the criterion of the additional requirement "VD" ("Verringerte Dehnung" - reduced expansion) as described in chapter 8.

Visual verification with uranyl acetate

Uranyl acetate dihydrate ($C_4H_6O_6U{\times}2H_2O$) is used for verification several elements [6], [12], [13]. Uranyl acetate solution has been applied on fresh fractured surfaces of prisms. After drying of the surface a yellow-green fluorescence is observable under ultraviolet light (254 nm).

Figure 3 shows characteristic fracture surfaces of mortar bars produced with aggregate 1 and cements with a slag-content of about 10 %, about 20 % and about 30 %. The decline of the intensity of the fluorescence with increasing slag content is noticeable visible.

7 RESULTS LONG-TERM CONCRETE PRISM TEST METHOD

Effect of slag content on expansion

Figure 4 shows the expansions of concrete prisms according to [5] with CEM I 52.5 R cement and with the for concrete constructions common aggregate (aggregate 1, aggregate with residual risk), the non reactive aggregate and exemplary aggregate 1 with a CEM II/B-S VD cement.

The positive effect of the CEM II/B-S VD on the gradient and the magnitude of the expansion are clearly noticeable. By using a CEM II/B-S VD cement and aggregate 1 the same gradient and magnitude of expansion as a non-reactive aggregate and CEM I 52.5 R cement can be achieved.

Figure 5 shows the expansions of concrete prisms (10/10/36 cm^3) after 52 weeks in NaOH-storage for all assessed cements with aggregate 2 (reactive aggregate - siliceous limestone) in relation to the slag content of the cements.

The expansion of aggregate 2 with CEM I 52.5 R cement has been taken as 100 %.

The correlation between expansion and slag content is clearly visible. Higher slag contents reduce noticeable the expansions of the specimen.

The expansions of concrete prisms (10/10/36 cm^3) after 52 weeks for all assessed cements with both aggregate 1 and aggregate 2 in NaOH-storage related to the Na_2O-equivalent of the cements show absolutely no correlation. Ultra-accelerated mortar bar tests show exactly the same behaviour.

Visual verification with uranyl acetate

Uranyl acetate solution applied on fresh fractured surfaces of concrete bars (10/10/36 cm^3 - storage in NaOH-solution) show the same effect as applied on fractured surfaces of mortar bars. The decline of the intensity of the fluorescence with increasing slag content is noticeable visible.

8 CEMENT "VD" FOR CONCRETE PAVEMENTS

The additional requirement "VD" ("Verringerte Dehnung" – reduced expansion) for cements used for concrete pavements has been standardised on the basis of the above mentioned research results. This requirement is regulated in the Austrian standard ÖNORM B 3327-1 [7].

A test method of cements for verification of the additional requirement "VD" (reduced expansion) for aggregates containing reactive silica is prescribed in the ÖNORM B 3327-1. This test method is based on a comparative test between a reference cement (CEM I 42.5 R EHZ (mixture of all Austrian CEM I cements) with a Na_2O-equivalent of 1.0 ± 0.1 %) and the tested cement. The type of aggregate which has to be used is also defined [7]. The prisms size is according to the RILEM AAR-2 test method 4/4/16 cm^3.

The requirement which has to be met by the tested cement and the prescribed aggregate is an expansion after 27 days storage in NaOH-solution of ≤ 70 % of the expansion of the reference cement and the prescribed aggregate in this time period.

9 IMPLEMENTATION IN ÖNORM B 3100 „ASSESSMENT OF THE ALKALI-SILICA REACTIVITY IN CONCRETE" [11]

For the assessment of the alkali-silica reactivity in concrete the produced concrete construction elements will be classified in levels of exposure according to Table 1.

9.1 Classification of aggregates

Level of exposure 1

Aggregates can be used without information regarding alkali-silica reactivity.

Level of exposure 2

Aggregates for buildings according to level of exposure 2 (and 3) require information about their AAR-behaviour. This information has to be primarily obtained from practical operating experience with this type of aggregate.

Existing practical operating experience is determining and further testing (ultra-accelerated mortar bar tests and/or long term concrete prism tests) is not required.

A documented building component of level of exposure 2 with an age of min. 10 years is required for an assessment due to practical operating experience. Location and production period has to be stated. This building component must consist of an aggregate of comparable geological age and pedogenesis. In addition to that, damages due to AAR are not permitted. The assessment "harmless" results from the practical operating experience.

Tests have to be carried out if an aggregate has a lack of practical operating experience. This testing is required before the aggregate is used the first time for buildings of that level of exposure. The assessment by means of the long-term concrete prism test lasts 12 months and the criterion which has to be met is 0.5 ‰ [11]. Instead of the long-term concrete prism test an ultra-accelerated mortar bar test can be carried out. The criterion of this test method is 1.0 ‰ [11].

Level of exposure 3

The procedure of assessment is the same as for level of exposure 2. A documented building component of level of exposure 3 (concrete pavement) with an age of min. 20 years is required for an assessment due to practical operating experience.

The classification of concrete components according to the different levels of exposure is compiled in table 2.

10 DISCUSSION

Portland-slag cements reduce the residual risk of a harmful AAR. This could be shown with the use of a lot of different test methods. As in chapter 6 and 7 stated the use of Portland-slag cements reduces the expansion of prisms tested both with the ultra-accelerated mortar bar test method and the long-term concrete prism test method. Fracture mechanical and chemical determinations also approve these results. Especially the visual verification with uranyl acetate shows clearly the positive effect of Portland-slag cements.

The reason for lower expansions at higher slag-contents of cements could be seen in a probably smaller amount of silica gel inside the mortar bar or concrete prism. The use of Portland-slag cements reduces the concentration of alkali-ions in the pore-solution compared to OPC. A mix of phases consisting of CSH-phases and phases similar to hydrotalcite which sorbs alkalis is produced due to the presence of slag [14]. Furthermore a dilutive effect is occurring (lower content of soluble alkalis compared to OPC) and the impermeability at the contact zone between aggregate and hardened cement paste (reduction of the velocity of diffusion) will be increased.

A recently conducted survey of concrete pavements in Austria (up to 35 years old) shows no evidence of damages due to AAR [15]. This can be attributed both to the use of CEM II/A-S cements and to for concrete pavements used types of aggregates. The alkali-sensitivity of these aggregate-types has been tested in a different research programme [16]. The obtained results approve both the conclusions described in the present paper and assumptions and requirements respectively prescribed in ÖNORM B 3100. Furthermore the use of CEM II/B-S cements does not enlarge the risk of damages due to freezing and thawing [17].

The use of recycled aggregates is, besides the treatment and assessment of natural aggregates, an important factor regarding the production of concrete traffic areas. Recycled materials are important for Austrian construction methods and therefore an adaptation of the present standard ÖNORM B 3100 for that application is probably necessary. A research programme which deals with the problem of recycled aggregates is currently conducted on the Research Institute of the Austrian Cement Industry (VÖZFI).

Existing results (practical experience of concrete pavements with recycled aggregates and laboratory trials with recycling material) indicate, that recycled aggregates used in Austria do not increase the threat of a harmful AAR, compared with in the primary concrete pavement used natural aggregates.

11 CONCLUSIONS

The recently published Austrian standard ÖNORM B 3100 [11], which is mainly based on the above shown results, contains measures to prevent the risk of a harmful AAR. This standard is embedded in international committees and experience e.g. RILEM and round-robin tests. The risk of appearance of a harmful AAR can be reduced especially by the use of cements with the additional requirement "VD" (reduced expansion). This type of cement leads to a significant reduction of the expansion of aggregates containing reactive components. This requirement which is demanded for certain concrete constructions is achieved e.g. by cements with higher slag contents (CEM II/B-S). Tested Low-Alkali-cements do not meet the criterion (≤ 70 % of expansion of the reference cement with a defined aggregate after 27 days of storage in NaOH-solution) of this additional requirement.

Besides the use of cements containing blastfurnace slag a multiplicity of parameters have to be preserved e.g. for concrete pavements to minimise the risk of a potential AAR.

Constructive measures as a protection against damages due to AAR are relevant and therefore to apply. These measures are e.g. securing of drainage, conservation of tightness by appropriate joint-constructions, proper and adequate dimensioning of the concrete pavement, execution as prescribed in the particular standards and monitoring of the concrete raw materials.

Admixtures are also a part of the concrete raw materials and they provide also an additional contribution of alkalis, which can react with reactive constituents of the aggregate. Therefore the use of admixtures with limited alkali contents is advised.

An accurate realisation of the concrete pavement is also required. The concrete has to be cast without segregation and a dense concrete texture has to be achieved to prevent the transport of moisture and consequently the enrichment of external alkalis. The curing of the concrete is relevant for the concrete quality especially for a dense texture near the surface. Dense concrete constructions (e.g. low water/cement-ratios, use of additives) minimise the risk of an AAR considerably.

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TABLE 1: Levels of exposure.

Level of exposure		Building component	Environmental conditions [1)]
1	Low	- Inside buildings Temporary building components (also level of exposure 2 and 3)	- Dry to moderate moisture penetration - Service life: max. 15 years
2	Moderate	All building components with exception of building components of level of exposure 1 and 3	- Exposed to weather conditions - Moderate to high moisture penetration - Building component temperature: < 20 °C
3	High	Concrete pavements (sub concrete and concrete topping)	- External alkali supply (e.g. de-icing agents) - Moderate to high moisture penetration - Surface temperature: alternating and > 25 °C - Dynamic loading

) In each case one of the informative stated environmental conditions has to be met to divide building components into the appropriate levels of exposure.

TABLE 2: Classification of concrete components.

	Level of exposure		
	Level of exp. 1	Level of exp. 2	Level of exp. 3
Classification of cement	Cements for particular concrete specifications acc. to ÖNORM B 4710-1 [8]		Cement "VD" (reduced expansion acc. to ÖNORM B 3327-1 [7]
Classification of admixtures	Admixtures for particular concrete specifications acc. to ÖNORM B 4710-1 [8]		Admixtures acc. to ÖNORM EN 934-2 [9]; declared alkali content < 1 %
Classification of additives	Additives for particular concrete spedifications acc. to ÖNORM B 4710-1 [8]		Additives acc. to ÖNORM B 3309 [10]
Measures of design and execution of building components	No additional measures required		Prevention of water-penetration Measures of drainage Adequate and satisfactory curing

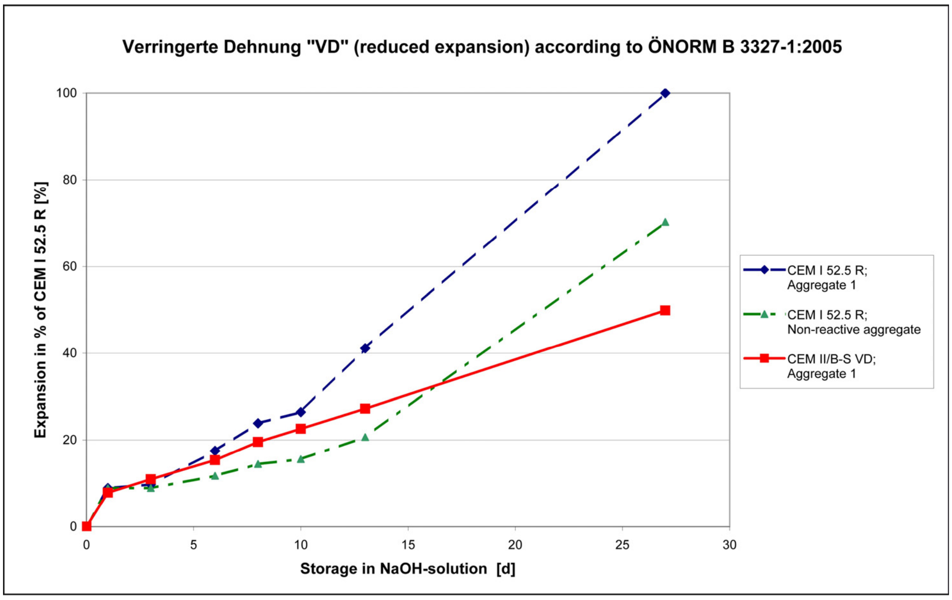

Figure 1: Expansions of mortar bar prisms with aggregate 1 (CEM I 52.5R, CEM II/B-S) and non-reactive aggregate (CEM I 52.5 R)

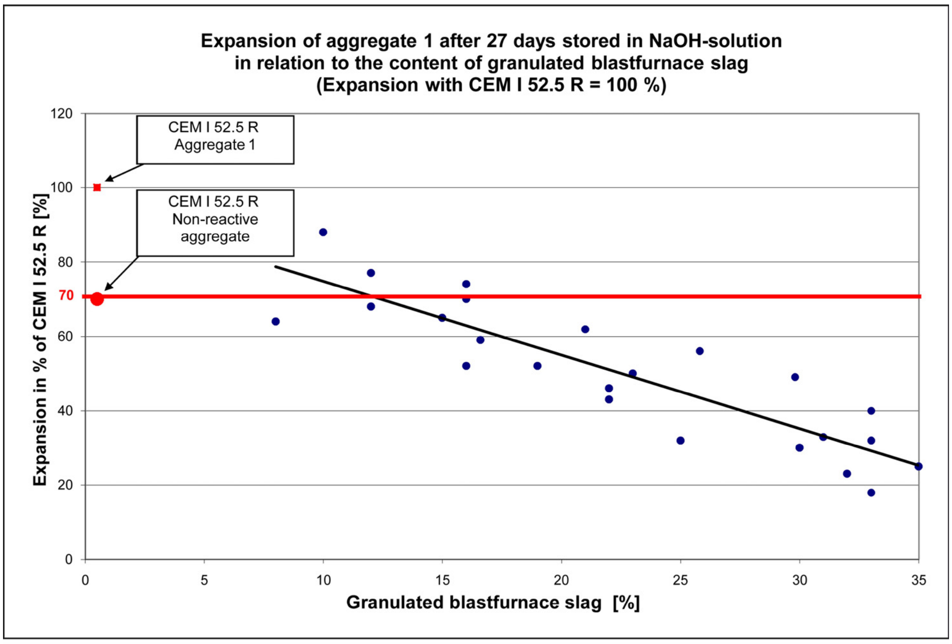

Figure 2: Expansions of mortar bar prisms after 27 days with aggregate 1 and different cements in relation to the slag content of the cements.

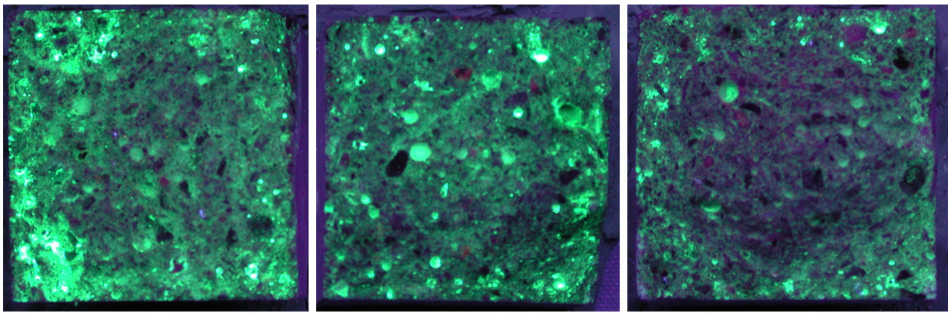

Figure 3: Fracture surfaces of mortar bars with aggregate 1 and cements with a slag-content of about 10%, 20% an 30% (from left to right).

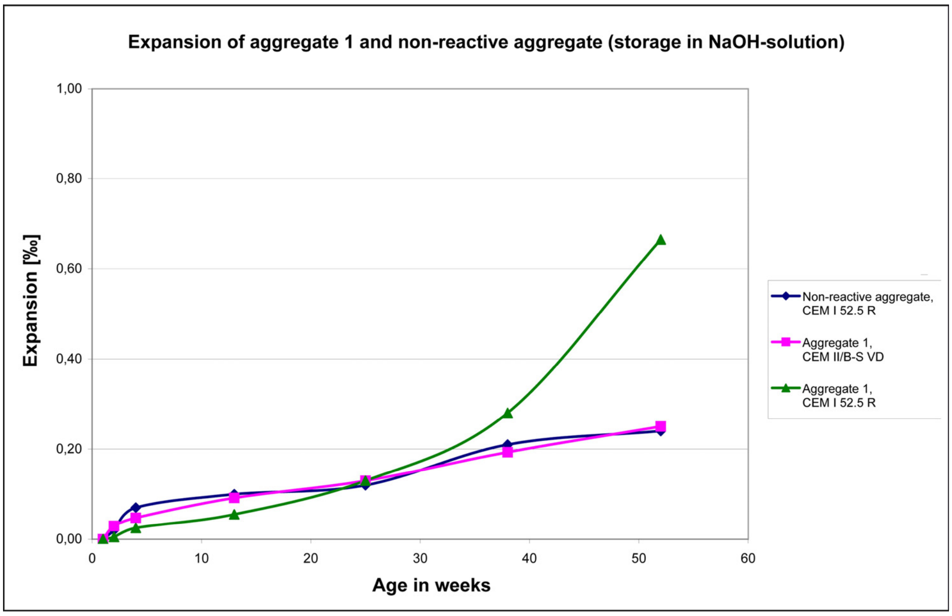

Figure 4: Expansions of concrete prisms (storage in NaOH-solution) with aggregate 1 (CEM I 52.5R, CEM II/B-S) and non reactive aggregate (CEM I 52.5R).

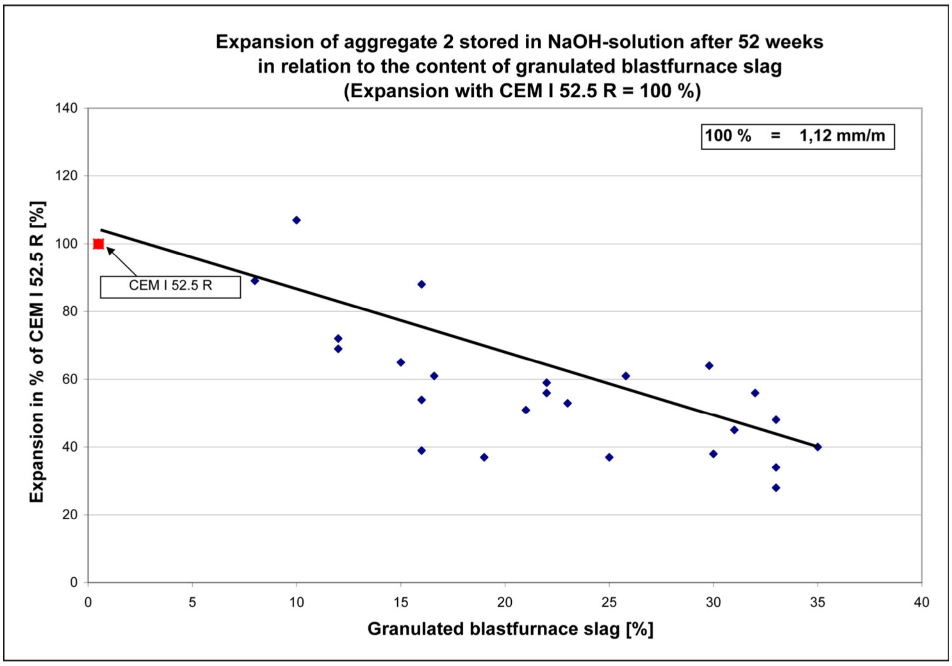

Figure 5: Expansions of concrete prisms after 52 weeks with aggregate 2 and different cements in relation to the slag content of the cements (storage in NaOH-solution).