021611-LEEM

COMPARISON BETWEEN AAR-INDUCED EXPANSION DETERMINED WITH AN ULTRA-ACCELERATED MICROBAR TEST AND A CONCRETE PERFORMANCE TEST

Andreas Leemann [1*], Christine Merz[2]

[1]Empa, Dübendorf, Switzerland

[2]TFB, Wildegg, Switzerland

Abstract

Aggregates consisting of one rock type and a mixture of different rock types were tested with the microbar test. Additionally, the expansion in the concrete performance test (CPT) was determined using selected aggregates. The variation of microbar values within similar rock types is high. However, some rock types as siliceous limestone generally exhibit higher expansions than others. The degree of quartz dissolution determined in the microbars after the test depends mainly on the total quartz content of the aggregates and shows a poor correlation to the microbar expansion value. The correlation between the expansions determined with the microbar test and the concrete performance test is also poor. Based on these results the significance of the microbar test has to be examined very critically.

Keywords: petrography, microbar test, concrete performance test, quartz dissolution

1 INTRODUCTION

The concrete market demands short test durations as the adaption of mix designs to meet the required criteria and the control of concrete production has to be possible within a relatively short time frame. Accordingly, acceleration of the alkali-aggregate reaction is achieved by adding alkalis and by elevating the temperature during the tests [eg. 1-5]. However, depending on the degree of acceleration needed, there are differences in the amount of added alkalis and in temperature. As a result, the correlation between different test methods can be unsatisfactory [6-9]. Even more important is the fact that this applies as well to the correlation between laboratory tests and the behaviour of structural concrete [10]. The transferability of the results obtained with different accelerated test methods may be compromised by differences in the reaction mechanisms. However, expansion is usually the only determined parameter and no data about leached alkalis or changes in the microstructure are usually collected, even if such studies would clearly benefit from an extension of the experimental program in this direction [10-12]. As such, the reason for a poor agreement between the results of different accelerated test methods and the behaviour of structural concrete often remains obscure.

In this study, the variations of microbar expansion obtained with different samples of similar rock types are examined to assess the influence of aggregate mineralogy on expansion. Furthermore, the microbar expansions of selected aggregates consisting of different rock types are compared with the degree of quartz dissolution determined with scanning electron microscopy. These selected aggregates are additionally used to produce concrete whose expansion potential is analysed with the concrete performance test (CPT) at 60 °C.

* Correspondence to: andreas.leemann@empa.ch

In addition, further microbar expansion values determined in other projects were added from the archives to the data generated in this study to extend the data base.

2 MATERIALS AND METHODS

2.1 General

Results about aggregate petrography, microbar expansion (including some microstructural data) and CPT expansion are presented in this paper. This study is part of a larger project that additionally includes a more in-depth analysis of the CPT and measurements of the residual expansion potential of concrete taken from structures.

2.2 Materials and mixture proportions

Aggregates

The aggregates selected and tested with the microbar test and the CPT are representative of different geological areas where the majority of the Swiss aggregates are quarried. The aggregates are named with an abbreviation of the location where they were quarried; aggregates MA, MAI, UR, GU, MS, ME, VI, WE, SG.

The majority of the aggregates are quarried in the Swiss Midland from alluvial deposits consisting of a variety of different rock types.

Test results from the archives of the TFB were added to investigate the variety of microbar expansion within one specific rock type. These aggregates were quarried in tunnel projects. The influence of the original grain size of the aggregates (0-4 and 8-16 mm) on the microbar expansion was measured on aggregates quarried from alluvial deposits in different regions of Switzerland.

Concrete

Aggregates MA, MAI, UR, GU, MS, ME and VI were used to produce and test concrete according to AFNOR P 18-454. All concrete mixtures were produced with a CEM I according to EN 197-1 (Table 1). Cements of different plants were used because the aim was to imitate concrete in structures showing AAR induced damages [13]. Therefore, each combination of cement and aggregate corresponds to one of the mixtures used in a specific structure. One series of concrete had a cement content of 300 kg/m^3, the other a cement content of 400 kg/m^3 to cover the usual range of cement content in structural concrete. NaOH was added to the mixing water, in an amount of 25% of the alkali content of the cement according to AFNOR P 18-454. Furthermore, data of CPT expansion from the archives of TFB were added for allowing the comparison between the microbar test and the CPT. In some of these concrete mixtures, CEM II/A-LL containing about 15% limestone powder was used besides CEM I but no other mineral admixtures such as fly ash, silica fume or slag were used.

2.3 Methods for assessment and analysis

Petrography

The petrography of the aggregates was determined according to Swiss standard SN 670'115 [14] on the fraction 8/16 mm. The term “quartz-bearing limestone” was used for limestone containing detritic quartz.

Microbar test

The potential reactivity of the aggregates was measured with the microbar test according to [1]. In this test, the expansion of mortar bars is used to classify aggregates as non-reactive or potentially reactive. First, the aggregates were crushed and sieved to a grain size fraction of 16-63 µm and afterwards, mortar bars (1 ×

1 × 4 cm) with a ratio of cement to aggregate of 2, 5 and 10 were produced. The Na_2O-equivalent of the cement was increased to 1.5 % by adding NaOH. The curing included a vapour treatment above boiling water for four hours and a treatment in a 10 % KOH solution at 150 °C for six hours. The highest mean expansion of the microbars with different cement to aggregate ratios was used to classify the aggregate. An aggregate is classified as potentially reactive when the expansion is ≥ 0.11 %. The microbar test shows a good correlation to the NBRI test [2,15]. The microbar test was conducted on two different grain size fractions of the aggregates: 0/4 mm and 8/16 mm.

Concrete performance test

The potential alkali-aggregate reactivity of the concrete was determined according to AFNOR P 18–454 [3]. Three prisms (70 × 70 × 282 mm^3) were produced, stored at 20 °C and demoulded after 24 h. Afterwards, they were stored at 60 °C and 100% relative humidity for 20 weeks. Every four weeks, their mass and length was measured at 20 °C (cooling period of 24 h). When the expansion after 20 weeks exceeds 0.02% (mix designs with CEM I), the concrete is classified as unsuitable for the use in structures according to AFNOR FDP 18-456 [16]. This test method is very similar to RILEM AAR 4, which has been assessed in an extensive study conducted by a number of international laboratories as a very consistent method that clearly identifies alkali aggregate reactivity [17].

Electron microscopy

The microbars were cut along their length axis. Then, they were dried in an oven at 50 °C for three days, impregnated with epoxy resin, polished and carbon coated. Images were made with an environmental scanning electron microscope (ESEM-FEG XL30). The samples were studied in the high-vacuum mode (2.0-6.0 × 10^{-6} Torr) with an accelerating voltage of 15 kV and a beam current of 180-200 mA. Point analysis was conducted with energy dispersive X-ray spectroscopy (EDX) to identify the chemical composition of aggregates or minerals in aggregates. An EDAX 194 UTW detector, a Philips digital controller, and Genesis Spectrum Software (Version 4.6.1) with ZAF corrections were used. Based on the grey scale values, aggregates and voids within the aggregates were segmented with a software developed in Matlab (Figure 1). This software contains different filters facilitating image analysis. The voids were attributed to dissolved quartz. Occasionally, dissolution features were observed on feldspars. The feldspar dissolution was not accounted for as its extent was minor. Therefore, the total amount of dissolved minerals within an aggregate is referred to as the amount of "dissolved quartz". In some aggregates like gneiss, it was not possible to segment quartz properly as the grey scale values of the feldspars orthoclase and anorthite are too close to quartz. In such cases, the minerals were identified with EDX point analysis and the quartz content of the particular aggregates was assessed visually. In aggregates like limestone containing detritic quartz, a segmentation of the quartz was possible without problems. 100-150 particles were analysed per aggregate. In the microbar test, the reaction products usually extrude the aggregate leaving open voids. Reaction products in aggregates are mostly present as minor residues.

3 RESULTS

Petrography

The petrography of the aggregates is shown in Table 2.

Microbar test

The microbar expansion within a specific rock type and between the different rock types shows a significant variation (Figure 2). As an example, mean expansion of gneiss is relatively low, but the values vary from 0.03 to 0.28 %. The range of expansion measured with sandstone and siliceous limestone is similar. Siliceous limestone displays the highest mean value followed by quartzite, sandstone, gneiss and limestone. No significant expansion is expected from the limestone as it contains quartz only as impurities.

The microbar expansions of the grain size fraction 8/16 mm is on average slightly higher than the values obtained from the grain size fraction 0/4 mm (Figure 3).

The amount of dissolved quartz in aggregates seems to increase along with the increasing quartz content of the aggregates (Figure 4). In relation to their quartz content, quartz dissolution in the two gneiss aggregates (SG and MS) is relatively low.

Concrete performance test

Four of the six concrete mixtures with aggregates used in damaged structures are exceeding the limit value of 0.02 % at a cement content of 300 kg/m^3 (Table 3). The expansion of the CPT is higher with a cement content of 400 kg/m^3; all concrete mixtures except the non-reactive reference concrete GU exceed the limit value. However, the relative increase going along with the increase in cement content is specific for each aggregate.

4 DISCUSSION

The significant variations in microbar expansion within a specific rock type could be attributed to the heterogeneity in regard to texture (presence of cleavage/layering, grain size and spatial distribution of quartz). Furthermore, the differences in quartz properties can be expected especially because aggregates of the same rock type originate from different geological and tectonic units (so-called "nappes"). In particular, the mechanical stress conditions in the geological history of the rocks can have a significant influence on quartz reactivity; they govern the frequency of defects in the lattice structure of the mineral and with it the proneness to hydroxide attack [eg. 18-20]. The differences between the different rock types are likely caused by differences in texture and quartz properties and, at least in the case of limestone, quartz content as well. Based on these variations it is obvious that petrography is insufficient to identify potentially reactive aggregates. The identification of potentially reactive rock types is mostly based on experience rather than on the identification of quartz features indicating high reactivity.

Aggregate preparation for the microbar test includes crushing to achieve the required grain size distribution. As the degree of crushing is higher for the grain size fraction of 8/16 mm compared to the one of 0/4 mm, a higher amount of freshly cracked aggregate surfaces can be expected. Moreover, the obtained particles may contain a higher amount of internal microcracks. This could explain the slightly higher microbar expansion of the grain size fraction 8/16 mm.

The relation between quartz content of the aggregates and dissolved quartz in the microbar test seems reasonable. However, the variation in the results, especially in regard to gneiss, indicate that specific quartz properties as discussed above and aggregate texture have an influence on the extent of quartz dissolution.

The correlation between dissolved quartz and microbar expansion is poor (Figure 5) clearly indicating that the amount of degree of quartz dissolution, and with it the amount of reaction products formed, is not the governing parameter for expansion. In fact, the potential of the reaction products to take up water by either osmosis or capillary suction is influenced by their Ca/Si-ratio [e.g. 21-23]. Moreover, in order to generate stress and strain, the reaction products need a certain viscosity that seems to be dependent on their composition [24,25]. The composition of the reaction products may be influenced by the availability of calcium that could depend on the texture of the aggregates, the permeability of the aggregates and the distance of the reacting sites to $Ca(OH)_2$ in the cement paste. The reason for the poor correlation is, however, not entirely clear.

The aggregate-specific increase of expansion in the CPT caused by the increase in cement content from 300 to 400 kg/m^3 clearly shows that quartz dissolution, formation of the reaction products and subsequent expansion are not a linear process. The cause is most likely the varying quartz properties and the composition of the reaction products as discussed above.

The correlation between microbar expansion and expansion in the CPT is poor (Figure 6). The studied aggregates and concrete mixtures even seem to indicate that a high expansion in the microbar test decreases the probability for high expansions in the CPT. The extension of the data set with results from the archives containing various aggregates and mix designs (only concrete produeced with CEM I or CEM ll/A-LL) does not significantly improve the correlation (Figure 7). Whereas the majority of the aggregates is classified as potentially reactive in the microbar test, about half of them are below the limit value in the CPT. However, non-reactive concrete can be produced with potentially reactive aggregates. More worrisome is the fact that three of the six concrete mixtures produced with aggregates classified as non-reactive exceed the limit value in the CPT. For these reasons, the meaningfulness of results obtained with ultra-accelerated test methods in general and of the microbar test in particular has to be examined critically. The amount of dissolved quartz in the microbar test is significantly higher than in the CPT [12]. Moreover, quartz dissolution in ultra-accelerates tests is mainly governed by the amount of quartz present in the aggregate (Figure 4). However, in the CPT and in concrete structures with the same or similar aggregates as tested with the microbar test in this study, the expansion is mainly caused by the frequently reacting quartz-bearing limestone and siliceous limestone [13].

5 CONCLUSIONS

Microbar expansions of different aggregates including several ones consisting of only one rock type have been determined. The extent of quartz dissolution in the aggregates during the microbar test has been determined combining electron microscopy with image analysis.

- There is a wide variation in microbar extension of the same rock type originating from different sources.
- The grain size fraction 8/16 mm results in slightly higher expansion in the microbar test than the grain size fraction 0/4 mm.
- The amount of dissolved quartz mainly depends on the total quartz content of the aggregates. However, the properties of the quartz present seem to have an influence as well, as indicated by gneiss aggregates.
- The amount of dissolved quartz shows a poor correlation to microbar expansion.

Some of the aggregates tested with the microbar test were used to produce concrete investigated with the concrete performance test.

- The increase of expansion in the CPT caused by an increase in cement content from 300 to 400°kg/m^3 is non-linear and aggregate-specific.
- There is no correlation between microbar expansion and expansion in the CPT. Even the use of aggregates classified as non-reactive in the microbar test can result in concrete expansion exceeding the limit value.
- Ultra-accelerated expansion tests have to be examined very critically.
-

6 ACKNOWLEDGEMENT

The authors would like to thank the federal road authorities (ASTRA) for the financial support of the project (AGB 2005/023, AGB 2006/03).

7 REFERENCES

[1] AFNOR XP 18-594 (2004): Méthods d'essai de reactivité aux alcalis. Association Française de Normalisation, Paris.
[2] SABS 1245 (1994): Potential reactivity of aggregates with alkalis (accelerated mortar prism method), South African Bureau of Standards, South Africa.
[3] AFNOR P18-454 (2004): Réactivité d'une formule de béton vis-à-vis de l'alcaliréaction (essaie de performance). Association Française de Normalisation, Paris.
[4] ASTM C 1260-01(2004): Standard test method for potential alkali reactivity of aggregates (mortar-bar method). Annual book of ASTM standards (04.02), 680-684.
[5] ASTM C 227-03 (2004): Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method) Annual book of ASTM standards (04.02), 141-145.
[6] Lane, S (1999): Comparison of results from C 441 and C 1293 with implications for establishing criteria for ASR-resistant concrete. Cement, Concrete and Aggregates (21): 149-156.
[7] Sanchez, L, Kuperman, SC, Helene, P, and Kihara Y (2008): Trials to correlate the accelerated mortar test, the standard and the accelerated concrete prism tests. In: Broeckmans, MATM, Wigum BJ (editors): Proceedings of the 13th ICAAR, Trondheim, Norway: 1154-1165.
[8] Shayan, A, Xu, A, and Morris, H (2008): Comparative study of the concrete prism test (CPT 60°C) and other accelerated tests. In: Broeckmans, MATM, Wigum BJ (editors): Proceedings of the 13th ICAAR, Trondheim, Norway: 412-421.
[9] Einarsdóttir, SU, and Wigum, BJ (2008): Alkali-aggregate reaction in Iceland - new test methods. In: Broeckmans, MATM, and Wigum, BJ (editors): Proceedings of the 13th ICAAR, Trondheim, Norway: 340-349.
[10] Leemann, A, Hammerschlag, JG, and Thalmann, C (2008): Inconsistencies between different accelerated test methods used to assess alkali-aggregate reactivity. In: Broeckmans, MATM, and Wigum, BJ (editors): Proceedings of the 13th ICAAR, Trondheim, Norway: 944-953.
[11] Thomas, M, Fournier, B, Folliard, K, Ideker, J, and Shehata, M (2006): Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete. Cement and Concrete Research (36): 1842-1856.
[12] Ben Haha, M, Gallucci, E, Guidoum, A, and Scrivener, KL (2007): Relation of expansion due to alkali silica reaction to the degree of reaction measured by SEM image analysis. Cement and Concrete Research (37): 1206-1214.
[13] Leemann, A, and Merz, C. (2012): An attempt to validate the concrete performance test with the degree of AAR-induced damage observed in concrete structures. Submitted to the 14th ICAAR.
[14] SN 670'115 (2005): Gesteinskörnungen: qualitative und quantitative Mineralogie und Petrographie. Swiss Standard, VSS Zürich.
[15] Hammerschlag, JG, and Zgraggen, P, (2000): Beurteilung der Alkali-Zuschlag-Reaktion der Zuschläge und einzelner Betonrezepturenfür die Alptransit Tunnelprojekte Gotthard und Lötschberg. TFB-Bericht, Projekt 998055, Ref. 05.001/2.
[16] AFNOR FD P18-456 (2004): Réactivité d'une formule de béton vis-à-vis de l'alcaliréaction. Association Française de Normalisation, Paris.
[17] Nixon, P, and Lane, S (2006): Experience from testing of the alkali reactivity of European aggregates according to several concrete prism test methods. Partner report 3.3 (n SBF52 A06021). Trondheim: SINTEF.
[18] Monteiro, PJM, Shomglin, K, Wenk, HR, and Hasparyk, NP (2001): Effect of aggregate deformation on alkali-silica reaction. ACI Materials Journal (98): 179-83.

[19] Broekmans, MATM (2004): Structural properties of quartz and their potential role for ASR, Materials Characterization (53): 129-140.
[20] Locatia, F, Marfilb, S, and Baldoa, E (2010): Effect of ductile deformation of quartz-bearing rocks on the alkali-silica reaction. Engineering Geology (116): 117-128.
[21] Wieker, W, Hubert, C, Heidemann, D, and Ebert, R (1998): Alkali–Aggregate Reaction- A Problem of the Insufficient Fundamental Knowledge of its Chemical Base. In: Cohen M, Mindess S, Skalny J (editors): Proceedings of the Sidney Diamond Symposium on Materials Science and Engineering of Concrete and Cementious based Composites. Materials Science of Concrete, American Ceramic Society, Westerville, OH: 395-408.
[22] Mansfeld, T (2008): Das Quellverhalten von Alkalisilikatgelen unter Beachtung ihrer Zusammensetzung (Expansion behaviour of alkali silicate gels considering their composition), Doctoral Thesis, Bauhaus-Universität Weimar, Germany.
[23] Leemann, A, Le Saout, G, Winnefeld, F, Rentsch, D, and Lothenbach, B (2011): Alkali–silica reaction: the influence of calcium on silica dissolution and the formation of reaction products. Journal of the American Ceramic Society (94): 1243-1249.
[24] Krogh, H (1975): Examination of Synthetic Alkali–Silica Gels. In: Symposium on Alkali–Aggregate Reaction. Icelandic Building Research Institute, Reykjavik, Iceland: 133-163.
[25] Iller, RK (1979): The chemistry of silica. Wiley, New York.

TABLE 1: Concrete mixtures.

concrete	cement content [kg/m^3]	Na_2O-equ [mass-%]	w/c
GU	300 / 400	0.79	0.45
MAI	300 / 400	0.78	0.45
UR	300 / 400	0.80	0.50
MA	300 / 400	0.90	0.45
MS	300 / 400	0.77	0.50
ME	300 / 400	0.83	0.45
VI	300 / 400	0.83	0.45

TABLE 2: Petrography of the aggregates.

	MA	MAI	UR	GU	MS	ME	VI	WE	SG
ophiolithe	0.0	0.0	0.0	0.0	19.1	0.0	0.0	0.0	0.0
gneiss	17.0	23.5	18.2	18.6	72.3	17.9	29.4	4.5	100.0
quartzite	8.5	8.3	6.5	20.5	8.6	4.2	23.0	4.5	0.0
sandstone	16.5	11.0	31.7	39.6	0.0	37.7	14.1	35.0	0.0
dolomite	0.0	17.1	0.0	0.0	0.0	0.0	0.0	17	0.0
siliceous limestone	11.2	19.6	21.6	15.1	0.0	17.8	15.1	15.5	0.0
quartz-bearing limestone	18.2	17.2	8.4	3.0	0.0	9.6	12.4	14.5	0.0
limestone	28.6	3.3	13.7	3.2	0.0	12.7	6.0	9.0	0.0
SUM total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 3: Expansion in the concrete performance test.

	GU	MAI	UR	MA	MS	ME	VI
expansion with 300 kg/m^3 cement [%]	0.0027	0.0238	0.0094	0.0299	0.0637	0.0115	0.0217
expansion with 400 kg/m^3 cement [%]	0.0050	0.0357	0.00268	0.0401	0.0893	0.0200	0.0755

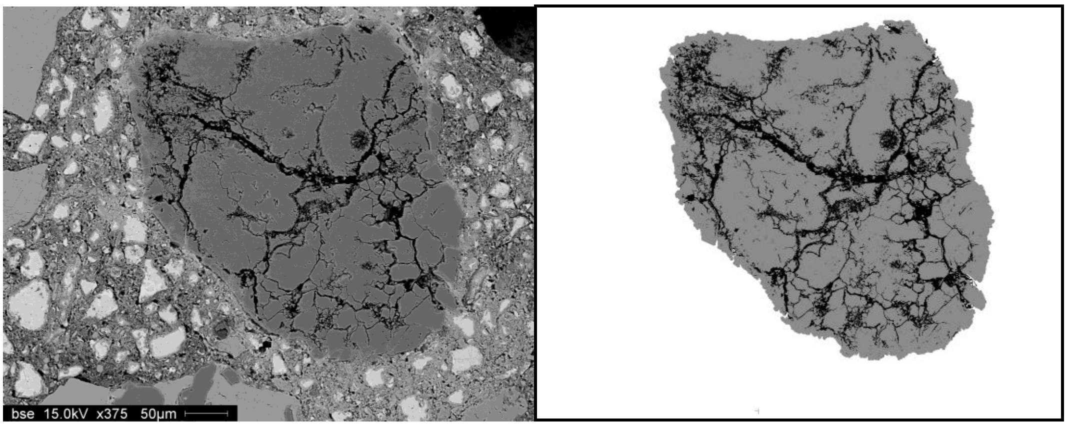

FIGURE 1: Quartzite aggregate displaying dissolved quartz as black voids (left side) and a segmentation of this image (grey = aggregate, black = dissolved quartz, content of dissolved quartz = 18%, right side).

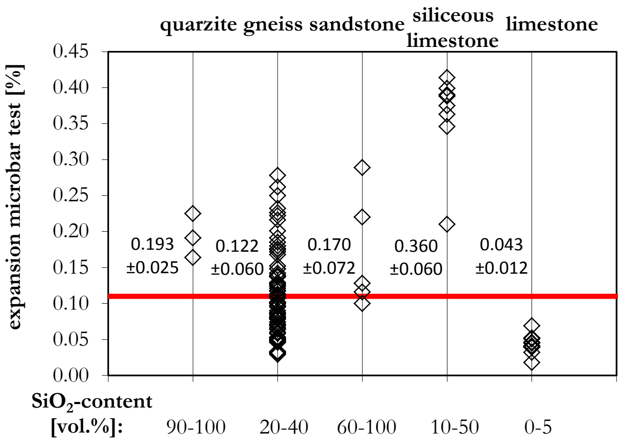

FIGURE 2: Microbar expansion of specific rock types (101 aggregates: 3 quartzites, 74 gneiss, 5 sandstones, 8 siliceous limestones, 11 limestones / numbers on the left side of the symbols: mean value and standard deviation). The horizontal line represents the limit value for the microbar test.

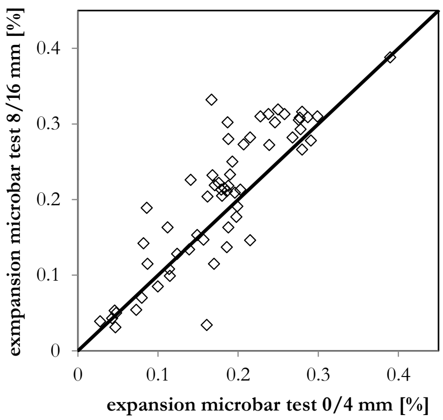

FIGURE 3: Microbar expansion of the grain size fraction 8/16 mm as a function of the grain size fraction 0/4°mm (mean values: 0/4 mm = 0.180 %, 8/16 mm = 0.203 %).

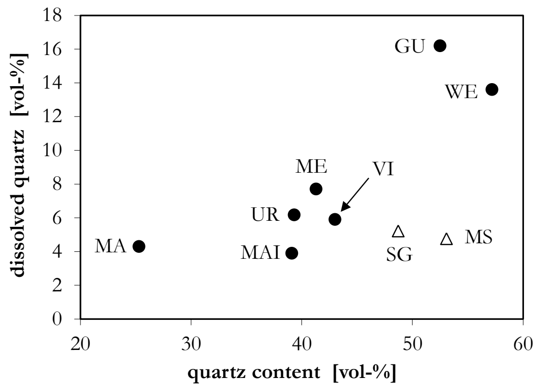

FIGURE 4: Amount of dissolved quartz within aggregates as a function of the quartz content of the aggregates (circle: aggregate consisting of various rock types, triangle: aggregate consisting mainly of gneiss).

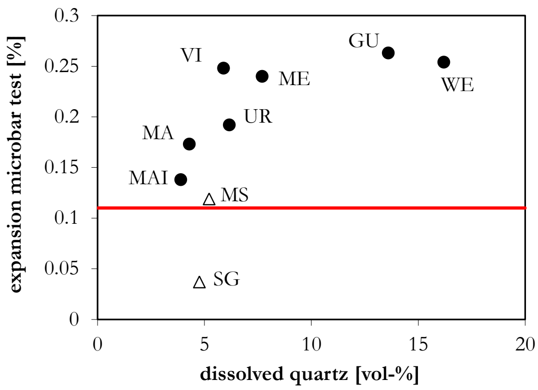

FIGURE 5: Expansion in the microbar test as a function of the amount of dissolved quartz within the aggregates (circle: aggregate consisting of various rock types, triangle: aggregate mainly consisting of gneiss). The line represents the limit value for the microbar test.

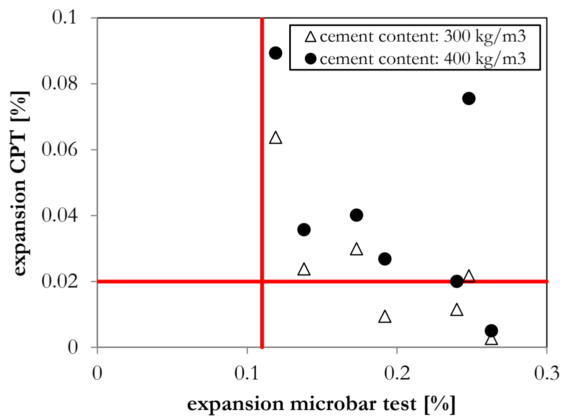

FIGURE 6: Expansion in the CPT as a function of the expansion in the microbar test (data from this study).

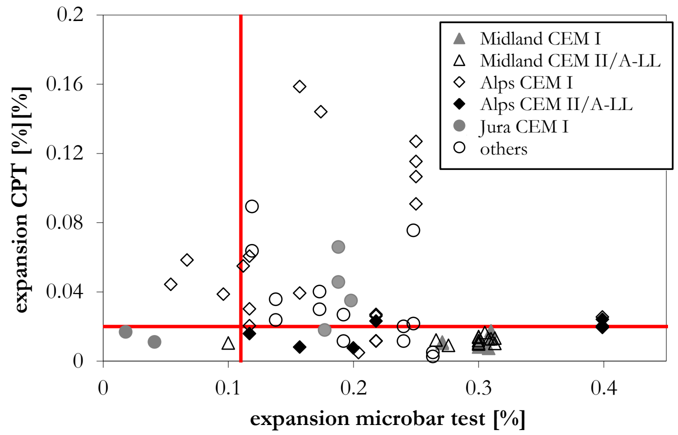

FIGURE 7: Expansion in the CPT as a function of the expansion in the microbar test (64 data sets from the archives representing different regions).