vdz.

W. Neufert, I. Reuken, Spenner Zement GmbH & Co. KG, Erwitte;
Ch. Müller, S. Palm, Research Institute of the German Cement Industry, VDZ gGmbH,Duesseldorf;
C.-A. Graubner, T. Proske, M. Rezvani, Technische Universität Darmstadt, Institut für Massivbau, Darmstadt, Germany

SUMMARY

Cements lying within an extensive range of compositions in the ternary system consisting of clinker (K), granulated blastfurnace slag (S) and limestone (LL) were investigated in a research project sponsored by the DBU. Tests were carried out on the durability of concretes made with cements within the composition limits of the currently envisaged extension of DIN EN 197-1 and beyond. It was found that cements with a Portland cement clinker content of about 50 mass % using granulated blastfurnace slag and limestone as the other main constituents are suitable, in principle, for producing structural concretes. These cements gave fresh concrete properties as used in practice, good mechanical properties and, with the exception of freeze-thaw resistance, admissible durability properties within the framework of the currently valid descriptive rules of DIN 1045-2. Concretes made with cements lying outside the range of the currently envisaged extension of DIN EN 197-1 with a Portland cement clinker content of about 20 to 35 mass % with granulated blastfurnace slag and limestone as the other main constituents can also exhibit admissible durability properties provided not only granulometric matching of the main constituents but also exacting concrete technology measures (low-water concrete with low water/cement ratio and corresponding addition levels of admixtures) are applied in the concrete production.

ZUSAMMENFASSUNG

In einem DBU-geförderten Forschungsvorhaben wurden Zemente innerhalb eines umfangreicheren Zusammensetzungsfelds im Dreistoffsystem Klinker (K) – Hüttensand (S) – Kalkstein (LL) untersucht. Die Dauerhaftigkeiten von Betonen mit Zementen in Grenzzusammensetzungen der derzeit vorgesehenen Erweiterung der DIN EN 197-1 und darüber hinaus wurden geprüft. Es zeigte sich, dass Zemente mit einem Portlandzementklinkergehalt von rd. 50 M.-% unter Verwendung der weiteren Hauptbestandteile Hüttensand und Kalkstein prinzipiell zur Herstellung von Konstruktionsbetonen geeignet sind: Diese Zemente führten zu praxisgerechten Frischbetoneigenschaften, guten mechanischen Eigenschaften und, mit Ausnahme des Frost-Widerstands, zu zulassungsfähigen Dauerhaftigkeitseigenschaften im Rahmen der heute gültigen deskriptiven Regeln der DIN 1045-2. Betone mit Zementen jenseits des Bereichs der derzeit vorgesehenen Erweiterung der DIN EN 197-1 mit einem Portlandzementklinkergehalt von rd. 20 bis 35 M.-% und den weiteren Hauptbestandteilen Hüttensand und Kalkstein können ebenfalls zulassungsfähige Dauerhaftigkeitseigenschaften aufweisen, wenn neben der granulometrischen Abstimmung der Hauptbestandteile anspruchsvolle betontechnologische Maßnahmen (wasserarmer Beton mit einen geringen Wasserzementwert und entsprechenden Zusatzmitteldosierungen) in der Betonherstellung zur Anwendung kommen.

CONCRETE TECHNOLOGY
REPORTS

(Translation by Robin B.C. Baker)

Performance of clinker-efficient cements containing granulated blastfurnace slag and limestone

Leistungsfähigkeit klinkereffizienter Zemente mit Hüttensand und Kalkstein

1 Introduction

The investigations in this research project are based on the results of the completed project entitled "Reducing the environmental impact of concrete construction by using cements with high limestone contents" [1, 2] and provide suggestions with respect to the use of new cements in compliance with the revised European cement standard EN 197-1.

It was established in [1, 2] that cements containing up to 50 mass % limestone as the main constituent can be used for producing concretes with admissible durability properties, for which it was necessary to lower the water/cement ratio to w/c = 0.35. In order to achieve a workability as used in practice the key to success was not only selective matching of the cement main constituents in the cement plant but also the use of concrete admixtures matched to the cement with adequate paste content.

It was also found that for certain durability properties (e.g. for resistance to chloride penetration) there is further potential for optimization with respect to particularly exposed ambient conditions. The environmental impact (ecobalance considerations) can also be improved further. Specifically with respect to the chloride penetration resistance this can be achieved by using granulated blastfurnace slag as the third main constituent. In contrast to [1, 2] a correspondingly more extensive range of compositions in the ternary system consisting of clinker [K], granulated blastfurnace slag [S] and limestone (LL) was investigated in this research project (see ❱ Fig. 1). The compositions of the cements are orientated towards the corner points of the planned extension of EN 197-1. The durability of the concretes was investigated using the methods that had proved successful in the previous research project and, in addition, would be relevant in the context of approvals. These were supplemented with accelerated carbonation and testing for resistance to freeze-thaw with de-icing salt.

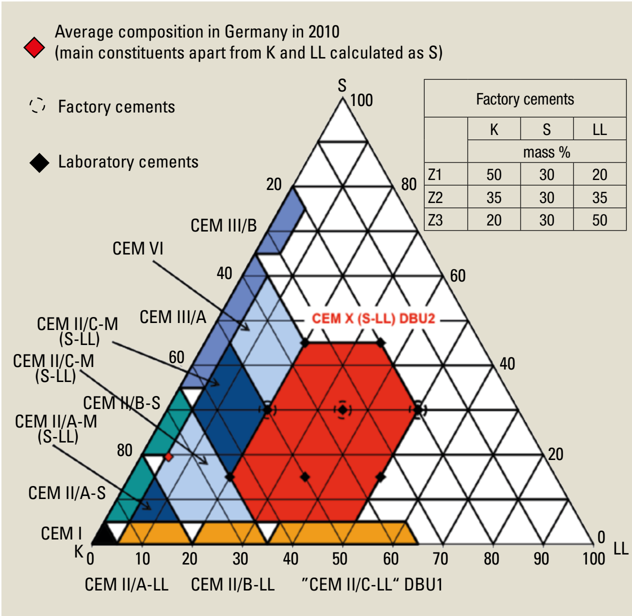


Figure 1: Framework of the investigation, shown as a ternary cement system consisting of Portland cement clinker (K), granulated blastfurnace slag (S) and limestone (LL)

2 Trials

2.1 Cements and main cement constituents

A CEM I 52,5 R, a CEM I 42,5 N and a CEM III/A 42,5 N cement from Spenner Zement were used as the reference and starting cements. The test cements were produced by mixing a CEM I 52,5 R cement with four separately ground granulated blastfurnace slags or a ground limestone. The cements are designated on the following principle: CEM (50 K, 30 S, 20 LL) – 50 mass % CEM I 52,5 R, 30 mass % granulated blastfurnace slag, 20 mass % limestone.

For the mortar trials the components were mixed in the laboratory. Cements produced in the plant were used for the concrete trials. The cements investigated are recorded in Fig. 1.

2.2 Mortar properties

The mortar strengths of the cements marked with diamonds in Fig. 1 were measured and the full results can be found in the final report. The compressive strengths of both the standard mortars and the mortars with divergent cement contents and water/cement ratios were tested after 2, 7, 28 and 91 days as specified in DIN EN 196-1 (❱ Fig. 2). Standard mortars with a water/cement ratio of w/c = 0.50 were all produced in accordance with DIN EN 196-1 with a cement content of 450 g per mix, basically without the use of superplasticizers. Mortars with a water/cement ratio of w/c = 0.40 were produced with a cement content of 500 g per mix and mortars with w/c = 0.35 were produced with 535 g cement per mix to maintain a constant paste content of about 420 l/m^3. A PCE-based superplasticizer was used to achieve a constant flow table spread of 160 ± 10 mm. The results from cements 1-3 produced in the plant (cf. Fig. 1) that had been selected for the concrete trials are shown below by way of example. The cements were selected on the basis of the following criteria:

- In a standard mortar with w/c = 0.50, cement CEM (50 K, 30 S, 20 LL) "Z1" exhibited strengths comparable with those of the reference cements CEM I 42,5 N and CEM III/A 42,5 N in the standard mortar with w/c = 0.50. The cement marked with "1" in Fig. 1 represents the "boundary composition" between the cements CEM II/C-M (S-LL) and CEM VI to be standardized in future in EN 197-1 and the new range of compositions shown in red in Fig. 1.
- In a mortar with w/c = 0.40, cement CEM (35 K, 30 S, 35 LL) "Z2" exhibited strengths comparable with those of the reference cements CEM I 42,5 N and CEM III/A 42,5 N in the standard mortar with w/c = 0.50.
- Cement (20 K, 30 S, 50 LL) "Z3" with a limestone content of 50 mass % has the maximum limestone content

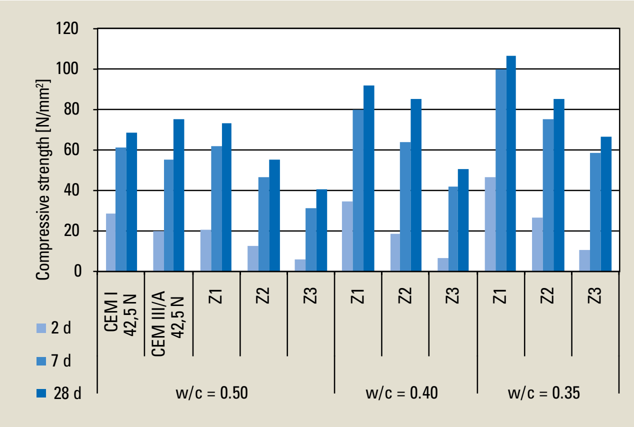


Figure 2: Mortar compressive strengths

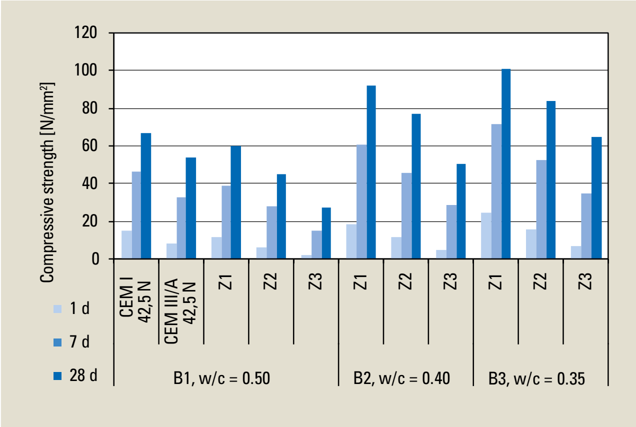


Figure 3: Compressive strength development of concretes B1 to B3

established in [1, 2] for such cements and, with adapted concrete technology, exhibited admissible durability properties in the concrete.

2.3 Concrete trials

2.3.1 General

The water/cement ratios of the concretes were varied while maintaining the paste content, and a flow table spread of 500 ± 20 mm was set by using superplasticizers. ❱ Table 1 shows the concrete compositions used. Rhine sandy gravel with the A16/B16 grading curve was used as the aggregate.

2.3.2 Concrete compressive strength

The compressive strengths of concretes B1 to B3 were measured as specified in DIN EN 12390-3 at 1, 7 and 28 days on cubes of 150 mm edge length after 6 days' water storage (with the exception of the 1-day value). The results are shown in ❱ Fig. 3.

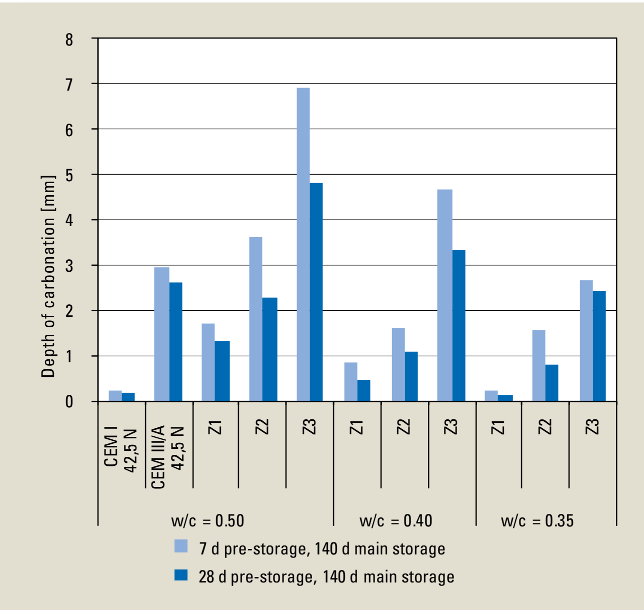
Concrete B1 made with cement Z1 (50 % CEM I) exhibited strengths comparable with those of the B1 concretes made with the reference cements. As expected, strengths fell at all test ages with decreasing clinker content. The B2 concretes made with cement Z2 and the B3 concretes made with cement Z3 did in fact exhibit somewhat higher strengths than the reference concretes, but the strength of the concrete alone is not an adequate indication of all the durability properties.

Table 1: Concrete mix formulations

	Concrete B1	Concrete B2	Concrete B3
Cement content [kg/m³]	320	365	390
Water/cement ratio	0.50	0.40	0.35
Content of air voids [%]	No specification		
Paste content incl. aggregate fraction < 125 µm [l/m³]	290 ± 5	290 ± 5	290 ± 5
Flow table spread [mm]	500 ± 20	500 ± 20	500 ± 20

2.3.3 Carbonation

The depths of carbonation were measured on fine concrete prisms with dimensions of 40 mm x 40 mm x 160 mm and an A8/B8 grading curve. This corresponds to the conditions in the approval procedure for cements specified by the DIBt (German Institute of Structural Engineering). Mortars with a water/cement ratio of w/c = 0.50 were produced with a cement content of 450 g per mix (as specified in DIN EN 196-1) without the use of superplasticizers. Mortars with a



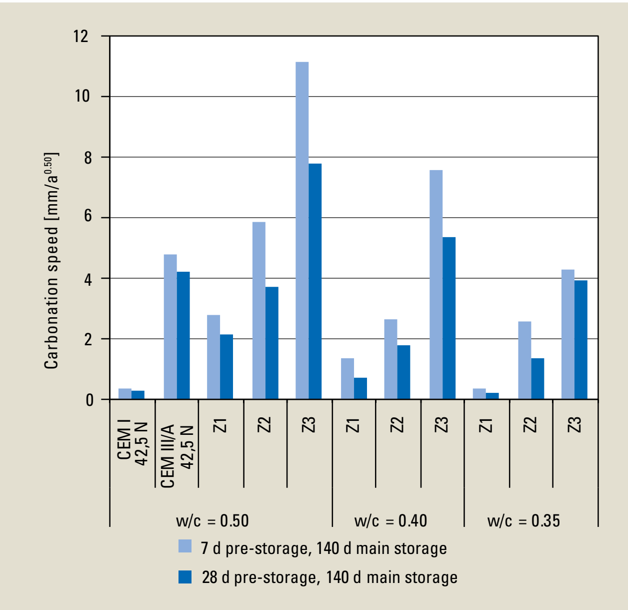


Figure 4: Depths and speeds of carbonation in fine concretes after 140 days of main storage

CONCRETE TECHNOLOGY REPORTS

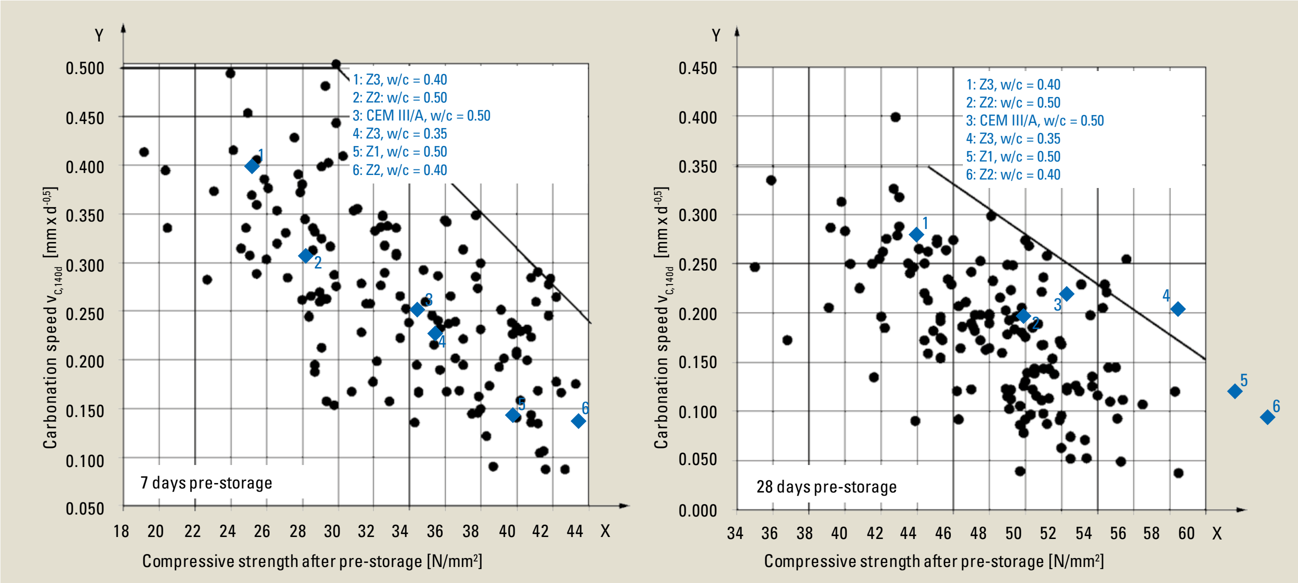


Figure 5: Classification in the evaluation background in accordance with Appendix B in [3]

water/cement ratio of w/c = 0.40 were produced with a cement content of 500 g per mix to maintain a constant paste content. 535 g cement per mix were used for the mortars with w/c = 0.35. In each case half of the prisms were placed in preliminary storage for 7 days in water at a temperature of 20 ± 1 °C and the other half were stored for 28 days in water

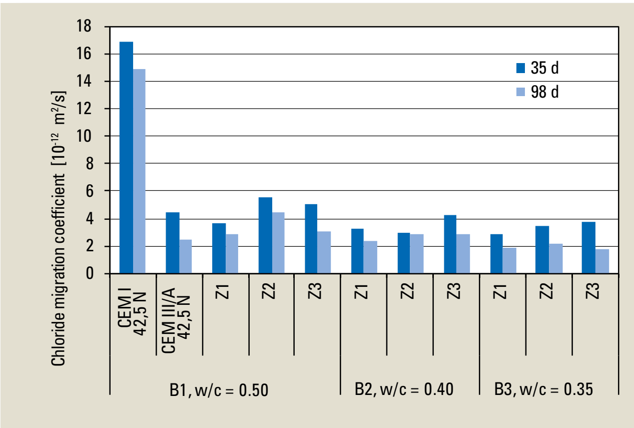


Figure 6: Chloride penetration resistance of concretes B1 to B3

at a temperature of 20 ± 1 °C. The test pieces were then stored at a temperature of 20 ± 1 °C and relative humidity of 65 ± 5 %. The depths of carbonation after 140 days' storage at a CO_2 concentration of 0.04 % are shown in ❱ Fig. 4. The carbonation speeds are given in mm/a$^{0.5}$. This unit corresponds to the current status of the debate on the definition of possible carbonation classes in the European standard.

The carbonation speeds are shown in ❱ Fig. 5 against the evaluation background described in Appendix B in [3]. The unit used here is mm/d$^{0.5}$. The mortars with compressive strengths that are too high for the given scale are not shown (cf. Fig. 2). With a pre-storage of 7 days the mortars – in some cases with adjusted water/cement ratios – lie below the limit function marked with a black line. With a pre-storage of 28 days the results lie in the region of the limit value or, in one case, above it. In most cases the mortars or cements exhibit admissible carbonation speeds.

2.3.4 Resistance to chloride penetration

The resistance of concrete to penetrating chlorides was determined with the aid of a rapid test (migration test: [4, 5]). ❱ Fig. 6 shows the test results at 35 days and 98 days.

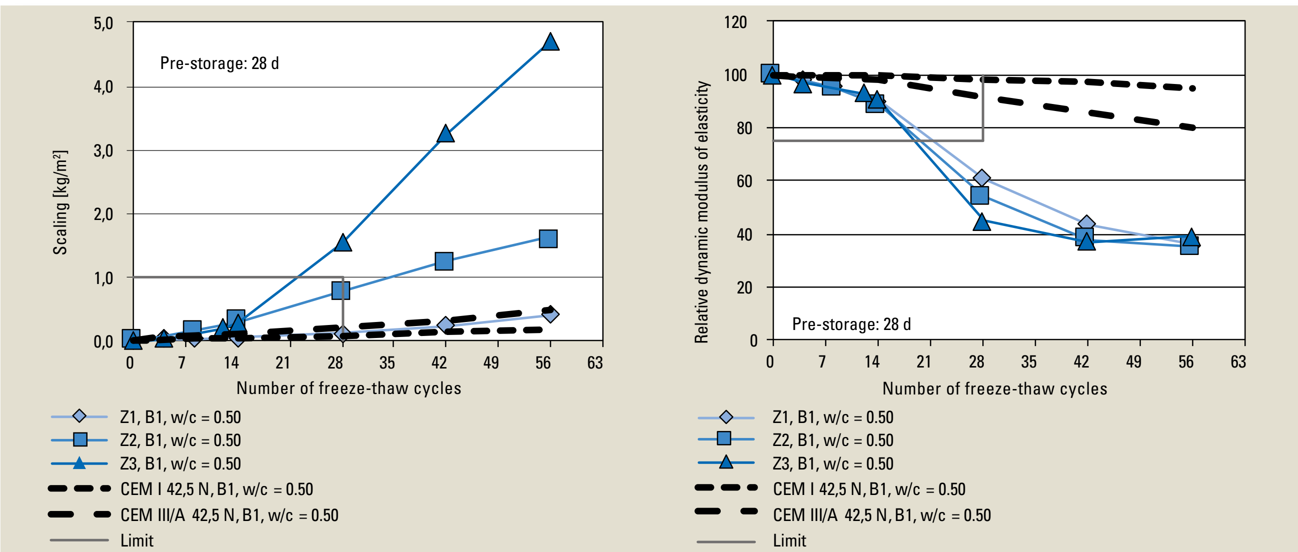


Figure 7: Scaling and relative dynamic elastic modulus of concretes with water/cement ratios w/c = 0.50; 28 d pre-storage

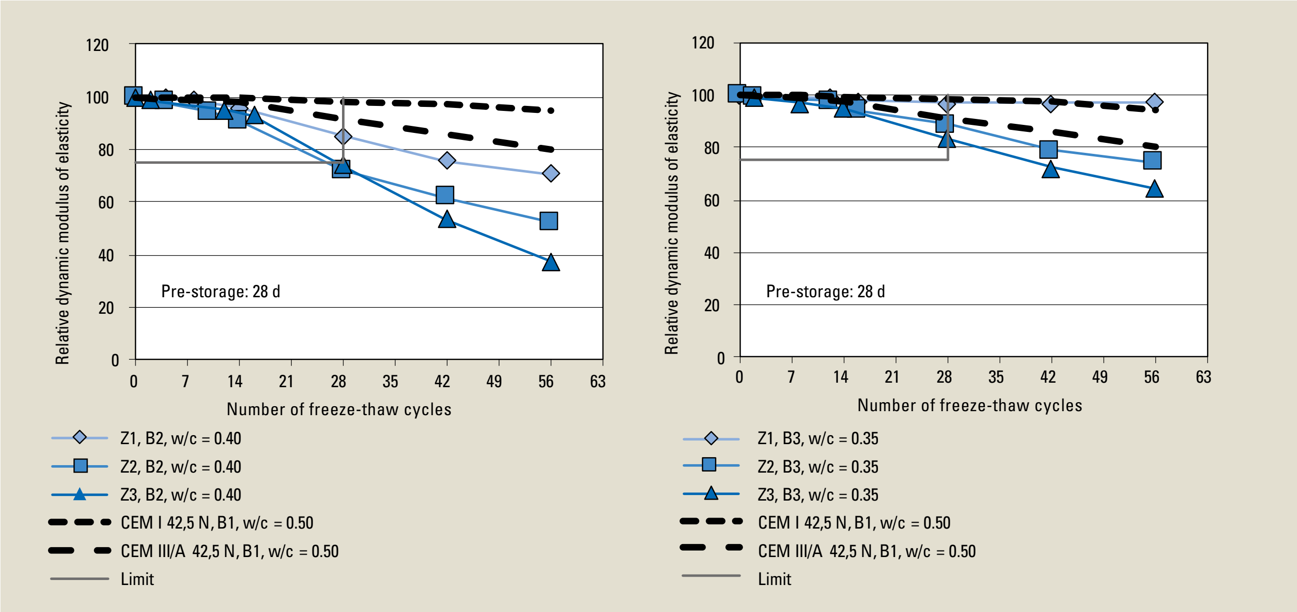


Figure 8: Relative dynamic elastic modulus of concretes with water/cement ratios w/c = 0.40 and w/c = 0.35; 28 d pre-storage (reference concretes with w/c = 0.50); 28 d pre-storage

Regardless of the water/cement ratio all the concretes made with the test cements exhibited low chloride migration coefficients – i.e. high resistance to penetration by chlorides. This eliminates an important "weakness" of the cements investigated in [1, 2] that contained only limestone as a further main constituent. For the cements investigated in the research project a granulated blastfurnace slag content of 30 mass % was sufficient to ensure a high chloride penetration resistance for applications in, for example, hydraulic engineering ($\leq 10 \times 10^{-12}$ m/s^2 for XS1-2, XD1-2) or $\leq 5 \times 10^{-12}$ m/s^2 for XS3, XD3 as described in [6]).

2.3.5 Freeze-thaw resistance

The freeze-thaw resistance of the concretes was determined by the CIF process as described in CEN/TR 15177. The scaling and the relative dynamic elastic modulus were measured and the results are shown in ❱ Figs. 7 and 8 as average values of five test pieces.

As a rule, internal structural damage can be expected during freeze-thaw attack without the action of de-icing agents if unsuitable starting materials or unsuitable concrete compositions are used. According to [5] this damage can be described by the relative dynamic elastic modulus.

Fig. 7 shows that when used in concrete B1 the test cements Z1-Z3 lead to scaling and a relative dynamic elastic modulus that lie respectively above and below the evaluation criteria. Lowering the water/cement ratio to w/c = 0.40 led to a significantly smaller drop in the relative dynamic elastic modulus. The concrete made with cement 1 lies above the evaluation criterion. With a further reduction in the water/cement ratio to w/c = 0.35 the concretes made with cement 2 and cement 3 also lay above the evaluation criterion (Fig. 8). The scaling criterion was met in all cases for water/cement ratios w/c < 0.50.

2.3.6 Tensile splitting strength and elastic modulus

The results of testing the elastic modulus as specified in DIN 1048-5:1991-06 and the tensile splitting strength as specified in DIN EN 12390-5:2009-07 are shown in ❱ Figs. 9 and 10. The tests were carried out at a concrete age of 28 days. The elastic moduli and the tensile splitting strengths

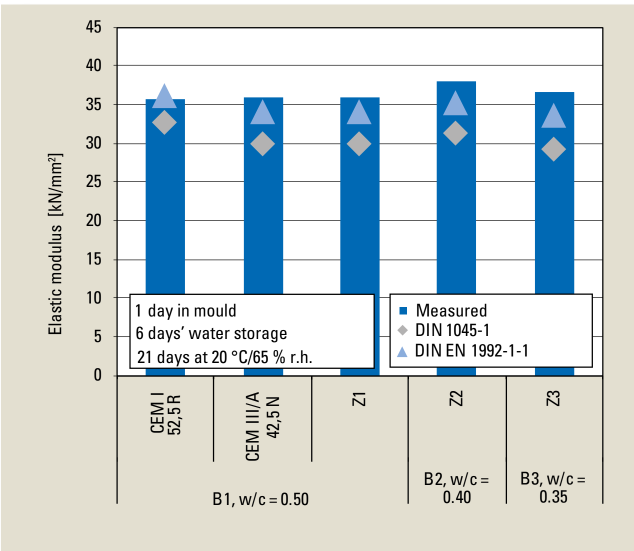


Figure 9: Elastic modulus

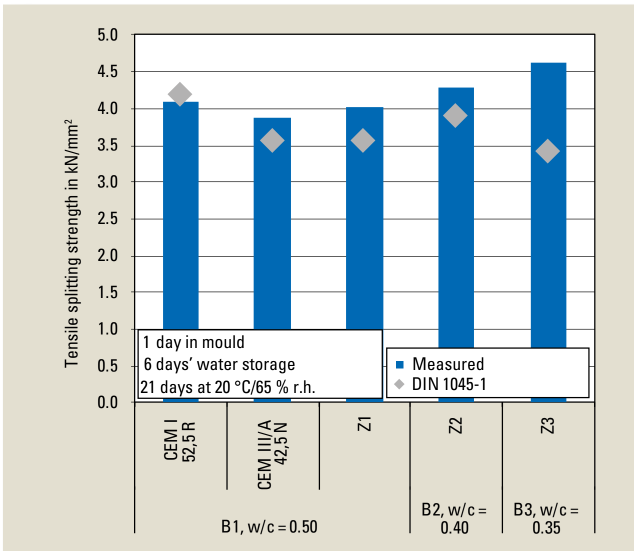


Figure 10: Tensile splitting strength

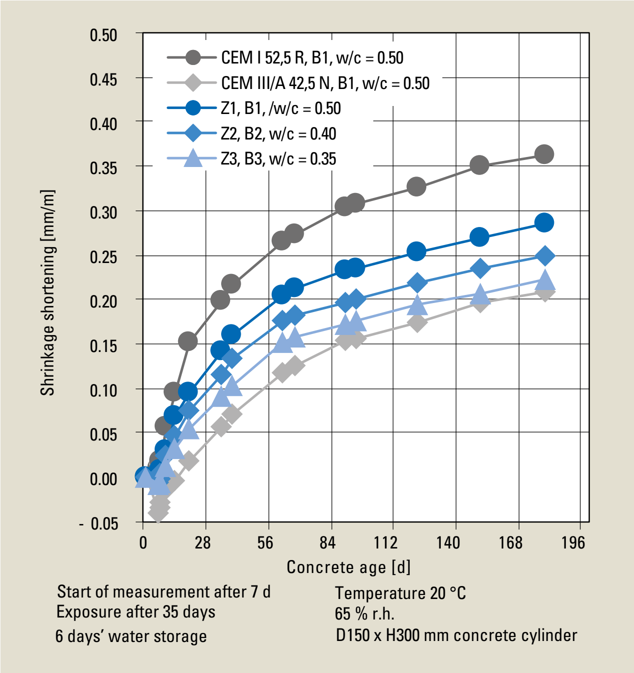


Figure 11: Behaviour pattern of the shrinkage deformation of the reference concretes and of the concretes made with clinker-efficient cements

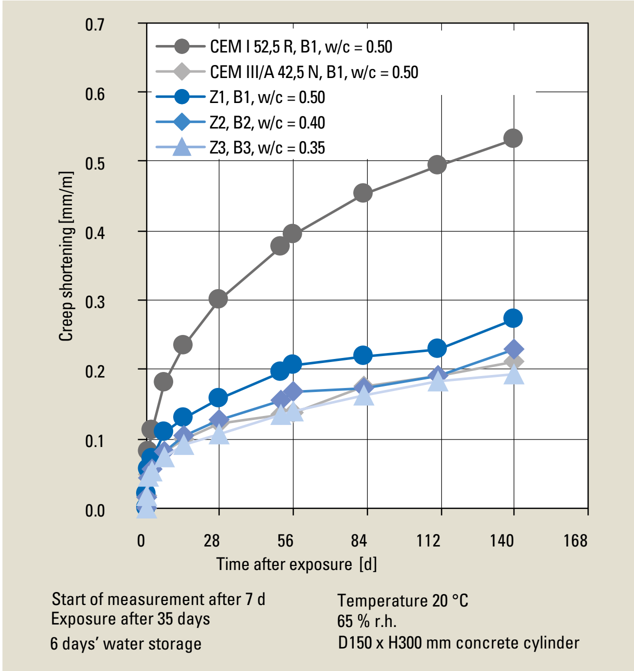


Figure 12: Creep deformation of the reference concretes and of the concretes made with clinker-efficient cements

of the concretes lay in the expected range as specified in DIN EN 1992-1-1.

2.3.7 Creep and shrinkage

The shrinkage and creep measurements on cylinders with dimensions of Ø = 158 mm, h = 300 mm were each carried out on two cylinders in accordance with DAfStb No. 422, Section 2.6. After the test pieces had been cast they were left for one day in the mould, then stored until the 7th day under water and finally stored at a temperature of 20 °C and relative air humidity of 65 ± 2 %. After six days' water storage the shrinkage measurements were carried out up to an age of 168 days after exterior storage.

The creep stress of $\sigma_u = 1/3_{fc,cyl}$ was applied at the age of 28 days. The creep measurements were carried out up to an age of 140 days after application of the load.

The measured shrinkage deformation curves are shown in ❱ Fig. 11. It can be seen that at first there was a certain amount of swelling of the concrete made with granulated blastfurnace slag during the water storage. For a water/cement ratio w/c = 0.50 the changes in length of the concrete made with Z1 lay "centrally" in the value range "spanned" by the concretes made with the reference cements CEM I and CEM III/A. The shrinkage deformations of the concretes with reduced water/cement ratios made with cements Z2 and Z3 lay between those of CEM I and CEM III/A with w/c = 0.50.

The measured creep deformation curves are shown in ❱ Fig. 12. This deals with pure creep shortening – it does not include elastic shortening or shrinkage shortening. The shortening is relative to the first measurement directly after the initial load application. The creep shortening of the concretes made with cements with several main constituents was in all cases less than the creep shortening of the concrete made with the CEM I Portland cement. For the same water/cement ratio w/c = 0.50 the creep shortening of the concrete made with Z1 lay in the same range of values as the concrete made with CEM III/A. Both cements have a comparable clinker content of about 50 mass %.

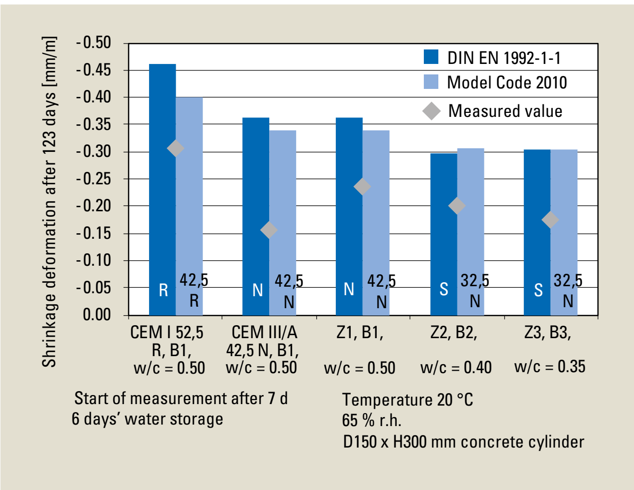


Figure 13: Comparison of the test results for shrinkage with the procedures specified in Model Code 2010 and Eurocode 2

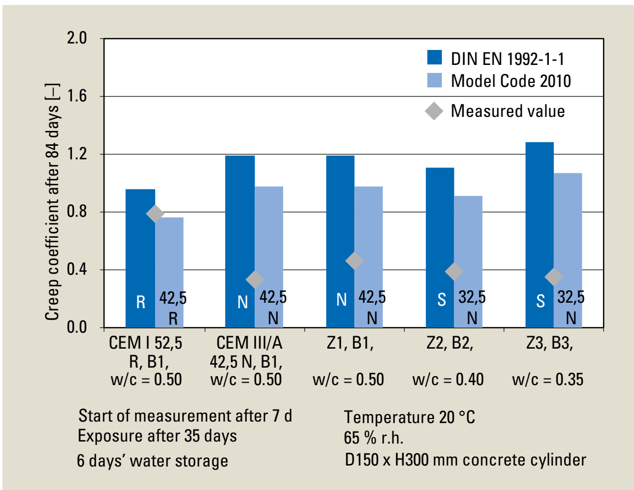


Figure 14: Comparison of the measured creep coefficient with the procedures specified in Model Code 2010 and Eurocode 2

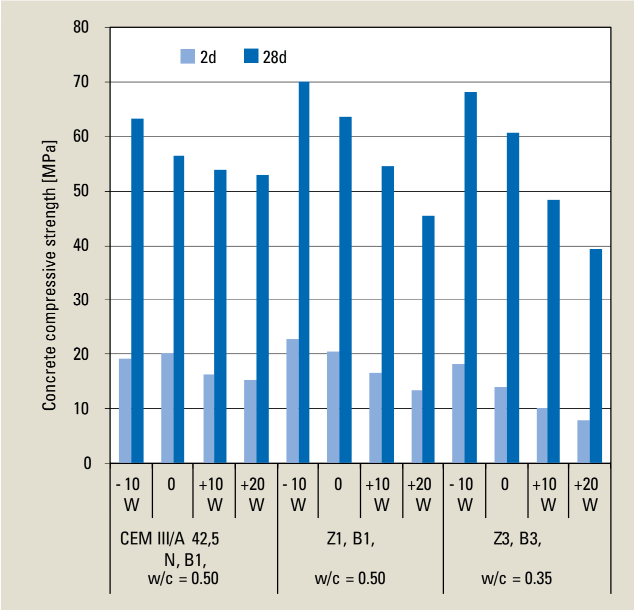


Figure 15: Compressive strength in relation to water content

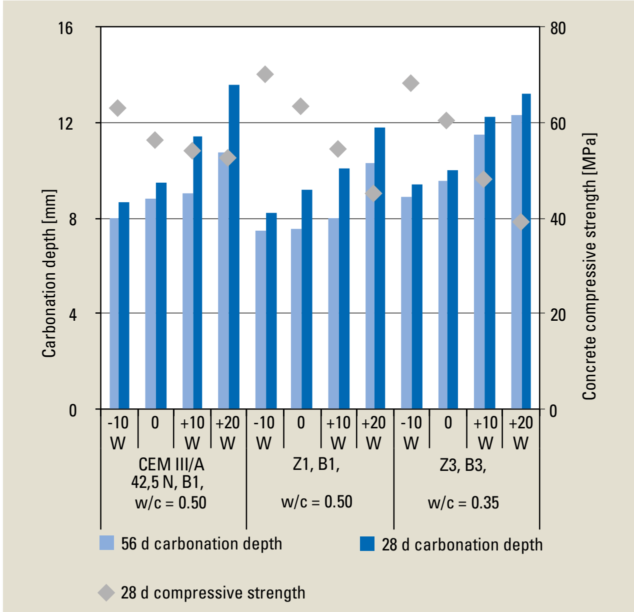


Figure 16: Depth of carbonation in relation to water content

Comparison of the measured values with the calculated shrinkage deformation and creep coefficients of the concretes under investigation (see ❱ Figs. 13 and 14) showed that the measured shrinkage deformation and creep coefficients of all the concretes were significantly lower than specified in Eurocode 2 and Model Code 2010.

2.3.8 Robustness

"Robust concrete properties in accordance with good site practice" is currently one of the predominant topics in the onward development of the regulations for concrete construction. The influence of the fluctuations in water content that occur in practice on selected properties of the hardened concrete were checked as part of this project.

The extent to which the variation in water content (ΔW = -10, 0, +10 and +20 l/m^3) affects the compressive strength and carbonation resistance was examined. The tests were carried out on concretes made with two test cements (B1 with cement Z1 and B3 with cement Z3) as well as on reference concrete B1 made with CEM III/A 42,5 N. All twelve concretes were set to a flow table spread of 500 ± 20 mm by appropriate addition of superplasticizer.

The effect on compressive strength was investigated by testing the 2- and 28-day compressive strengths of cubes with edge lengths of 150 mm. The effect on durability with respect to carbonation was quantified by measuring the depth of carbonation (storage at 20 °C, relative humidity of 65 % and elevated CO_2 concentration of 2 vol. %).

❱ Figs. 15 and 16 show the absolute values and ❱ Figs. 17 and 18 show the values relative to concrete with ΔW = 0. The compressive strengths of the concretes made with the test cements reacted more sensitively to the change in water content than did the compressive strengths of the reference concrete made with CEM III/A. Appropriate care is therefore required in practice when adding the water. When the test

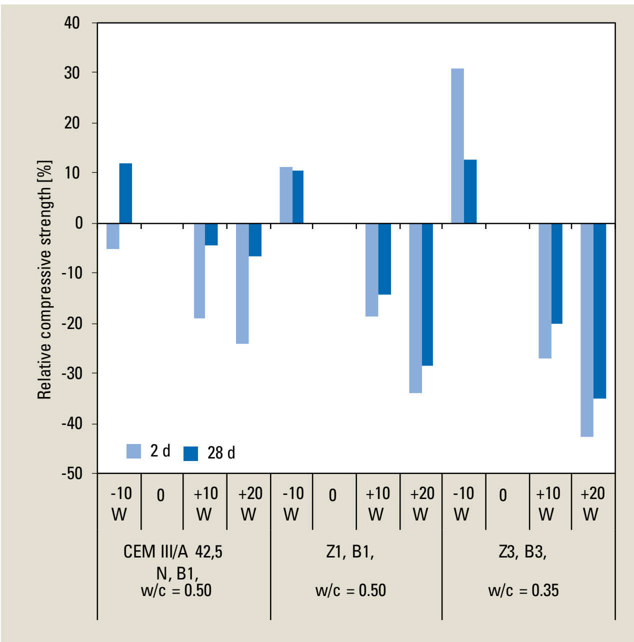


Figure 17: Compressive strength in relation to water content, relative to ΔW = 0

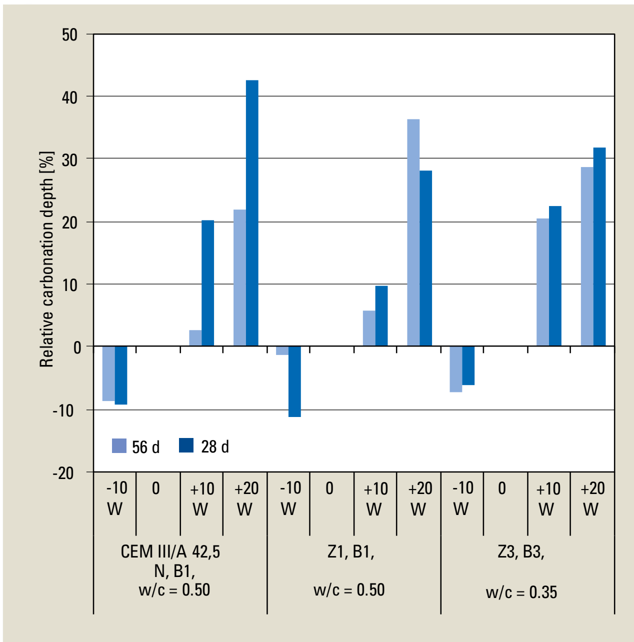


Figure 18: Depth of carbonation in relation to water content, relative to ΔW = 0

cements were used, the changes in the relative depths of carbonation were comparable with those when using CEM III/A.

3 Ecobalance

3.1 General

The environmental impact of the cements and concretes investigated in the research project is calculated and plotted below. The base data of the GaBi 5 software from the life cycle costs network and the EPD (Environmental Product Declaration) for the average German cement (VDZ) were used for the calculations [7]. The transport distances from the plant to the user were ignored for the evaluation of the cements and concretes.

3.1.1 Balances for the concretes

The respective capabilities (compressive strength and durability) were taken into account when drawing up the balances for the environmental impact of the concretes. Concretes made with the test cements were compared with reference concretes and with a concrete made with limestone-rich cement (CEM 50 % LL) investigated in the previous research project [1, 2]. The results of the ecobalances for concretes with comparable capabilities with respect to compressive strength and carbonation speed are shown in ❱ Figs. 19 and 20. The 28-day concrete compressive strengths of the concretes under consideration were 65 ± 10 N/mm^2.

The concretes B1 made with cement Z1, B2 made with cement Z2 and B3 made with cement Z3 exhibited comparable results to the reference concretes. Concrete B3 made with CEM 50 % LL from [1, 2] had a significantly higher chloride migration coefficient.

When compared with a concrete prepared with the notional use of the EPD average cement there is a reduction in greenhouse potential of about 35 % when using concrete B1 made with cement Z1. Greater savings of up to 40 % and 55 % can be achieved when using concretes B2 made with cement Z2 and B3 made with cement Z3.

The limiting factor with respect to energy consumption in the comparison with concrete made with the EPD average cement was the increased fineness of grinding of the test cements.

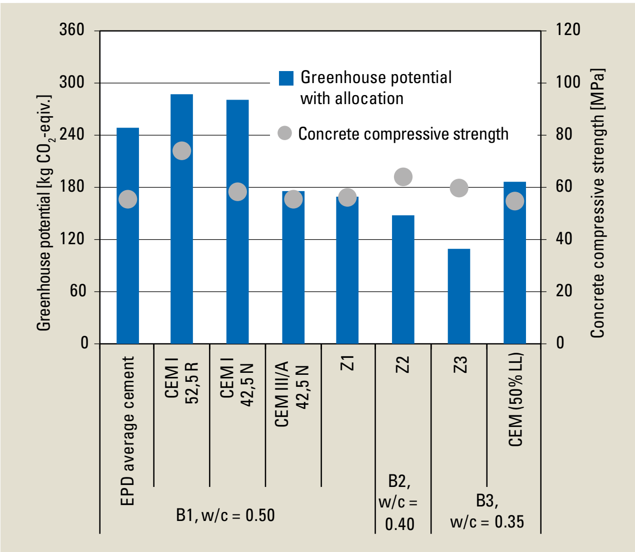


Figure 19: Greenhouse potential of the concretes under investigation made with factory cements

4 Summary

The tests have shown that cements containing Portland cement clinker, granulated blastfurnace slag and limestone as the main constituents taken from the area shown in Fig. 1 with a clinker content of about 50 % are suitable, in principle, for producing structural concretes.

Cements in the transition region to the currently envisaged extension of DIN EN 197-1 are of particular interest. These cements give fresh concrete properties as used in practice, good mechanical properties and, with the exception of freeze-thaw resistance, very good durability properties that lie within the framework of the currently valid descriptive rules of DIN 1045-2. A precondition is chemical and mineral optimization as well as granulometric optimization of the cements. There is potential for optimization with respect to the freeze-thaw resistance.

For cements that lie outside the range of the currently envisaged extension of DIN EN 197-1 the findings of the previous cement research project into cements containing high levels of limestone [1][1, 2] apply in principle. Cements with Portland cement clinker, granulated blastfurnace slag and limestone as the main constituents and with clinker contents of, for example, 35 or 20 mass %, are also suitable for producing structural cements provided not only granulometric matching of the main constituents but also exacting concrete technology measures (low-water concrete with low water/cement ratio and corresponding addition levels of admixtures) are applied. The robustness of these concretes during construction work requires further verification. If these conditions are met then the limit of 50 mass % clinker in the cement defined in the previous research project can, where appropriate, be lowered further. This would also optimize the greenhouse potential and the total energy consumption for producing a cubic metre of concrete still further (see Figs. 19 and 20).

5 Further results

Further investigations, for example with respect to resistance to freeze-thaw with de-icing salt, bearing capacity tests and robustness of the concretes with regard to temperature fluctuations, have been carried out. The final report can be accessed at www.vdz-online.de.

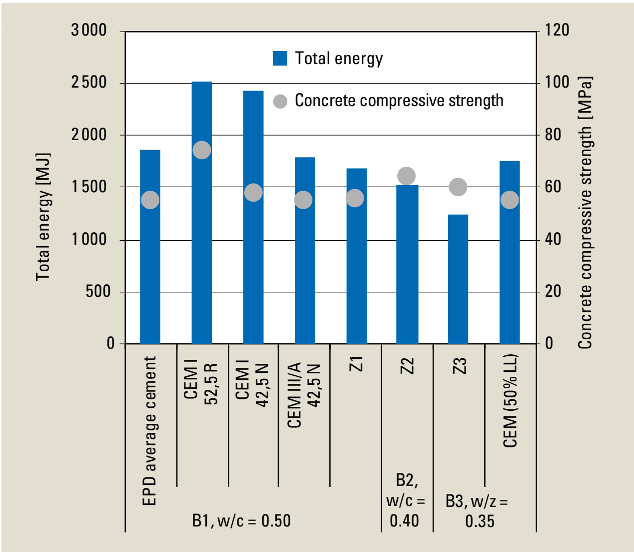


Figure 20: Total energy consumption of the concretes under investigation made with factory cements

Acknowledgement

The authors would like to thank the BDU (German Foundation for the Environment) for sponsoring the project.

LITERATURE

[1] Müller, Ch.; Palm, S.; Graubner, C.-A.; Proske, T.; Hainer, S.; Rezvani, M.; Neufert, W.; Reuken, I.: Zemente mit hohen Kalksteingehalten Dauerhaftigkeit und praktische Umsetzbarkeit. beton 64 (2014) H. 1+2, pp. 43–50.

[2] Palm, S.; Proske, T.; Rezvani, M.; Hainer, S.; Müller, Ch; Graubner, C.-A.: Cements with a high limestone content – Mechanical properties, durability and ecological characteristics of the concrete. Construction and Building Materials (2016), pp. 308–318.

[3] 2013. CEN/TR 16563:2013: Principles of the equivalent durability procedure (Verfahrensgrundsätze zum Nachweis gleichwertiger Dauerhaftigkeit).

[4] Tang, L.: Chloride Transport in Concrete – Measurement and Prediction. Dissertation, Chalmers University of Technology, Göteborg 1996.

[5] BAW-Merkblatt „Chlorideindringwiderstand". Bundesanstalt für Wasserbau, Karlsruhe 2004.

[6] BAW-Merkblatt „Chlorideindringwiderstand". Bundesanstalt für Wasserbau, Karlsruhe 2012.

[7] Umwelt Produktdeklaration des Vereins Deutscher Zementwerke e.V. Zement. Verein Deutscher Zementwerke e.V., Institut Bauen und Umwelt e.V., Düsseldorf, März 2012.