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**CLUSTER 2:Production and Application of Blended Cements**

**<u>Research Activities</u>**


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ECO-Serve-C2-R-00xx

**EUROPEAN CONSTRUCTION IN SERVICE OF SOCIETY**

# ECO-SERVE NETWORK

## CLUSTER 2
## Production and Application of Blended Cements

**Research Activities**

# <u>Contract No. G1RD-CT-2002-00782</u>

5. Periodic Report

Period under review: 01.10.2003 - 30.09.2005

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# 1 Table of contents


1 Table of contents ..... 3
2 Executive Publishable Summary ..... 6
3 Objectives of the project ..... 8
4 Scientific and technical description of the results ..... 10
4.1 General ..... 10
4.2 Partner 1: VDZ ..... 12
4.2.1 General ..... 12
4.2.2 Granulated blast furnace slag (GGBS) ..... 12
4.2.3 Calcareous fly ash ..... 12
4.2.4 Limestone ..... 13
4.2.5 Characterization of the starting materials ..... 14
4.2.6 Cements ..... 17
4.2.7 Microstructure (Porosity and Pore size distribution) ..... 21
4.2.8 Concrete ..... 23
4.2.8.1 Fresh concrete properties ..... 25
4.2.8.2 Strength development ..... 26
4.2.8.3 Carbonation ..... 28
4.2.8.4 Penetration of chlorides ..... 30
4.2.8.5 Freeze-thaw resistance ..... 32
4.2.8.6 Freeze-thaw resistance with de-icing salts ..... 40
4.2.9 Summary and conclusions ..... 43
4.3 Partner 2: CTG ..... 45
4.3.1 General ..... 45
4.3.2 Starting materials ..... 46
4.3.3 Production of cements ..... 46
4.3.4 Cement properties ..... 48
4.3.5 Cement classification ..... 48

4.3.6 Cement composition refinement....50
4.3.7 Results on concrete....51
4.3.7.1 General....51
4.3.7.2 Compressive strength....52
4.3.7.3 Drying shrinkage....53
4.3.7.4 Freeze/thaw testing (beam test)....55
4.3.7.5 Freeze/thaw testing with de-icing salt (slab test)....56
4.3.7.6 Mercury intrusion porosity and sulphate/chloride penetration....57
4.3.7.7 Depth of carbonation....58
4.3.7.8 Concluding remarks....59
4.4 Partner 3: NORCEM....60
4.4.1 General....60
4.4.2 Workplan....60
4.4.3 Basic properties....63
4.4.4 Carbonation....65
4.4.5 Chloride penetration....66
4.4.6 Freeze thaw resistance....66
4.4.7 Freeze thaw resistance with de-icing salts....68
4.4.8 Conclusions....69
4.5 Partner 5: TITAN....70
4.5.1 General....70
4.5.2 Raw materials....70
4.5.3 Blended cements....71
4.5.4 Concrete....78
4.5.4.1 General....78
4.5.4.2 Rheological and mechanical properties....78
4.5.4.3 Carbonation....80
4.5.4.4 Chloride Permeability....82
4.5.4.5 Sulphate Resistance....84
4.5.4.6 Conclusions-Discussion....85
**5 List of deliverables....88**

**6 Comparison of initially planned activities and work actually accomplished ..... 89**

**7 Management and co-ordination aspects ..... 89**

**8 Results and Conclusions ..... 90**

8.1 Summary of the investigations ..... 90

8.2 Areas for furter research ..... 94

8.2.1 General ..... 94

8.2.2 Special items ..... 94

**9 Acknowledgements ..... 95**

**10 References ..... 95**

**11 Annex B: Minutes of the meetings ..... 96**

11.1 1. Meeting ..... 96

11.2 2. Meeting ..... 100

11.3 3. meeting ..... 104

11.4 4. Meeting ..... 108

## 2 Executive Publishable Summary

On November 15th 2002, the European Thematic Network "EUROPEAN CONSTRUCTION IN SERVICE OF SOCIETY" (ECOServe) was established. One of the technical clusters of the ECOServe Network, ***cluster 2***, deals with the ***production and application of blended cements***. The cement production process is intensive in energy as well as raw material demand. Limits of technical improvements to lower the environmental impact of the cement production have been reached in the European cement industry. Remaining potential to reduce environmental impacts is provided by the reduction of the clinker content in cement (blended cements). Other main constituents for cement like ground granulated blastfurnace slag, fly ashes from power plants, natural and industrial pozzolanas or limestone can be used. The production of blended cements results in lower emission and lower energy consumption of the clinker burning process. This reduction is obvious, because less clinker from the energy-intensive process is needed to produce such blended cements. Experience in the production of blended cements already exists. However, the new European cement standard EN 197-1 now allows more different types of these cements to be produced than before. The use of many of these cements in concrete is currently restricted only to a few climatic or environmental conditions in some of the various European countries respectively these cements have not been produced at all.

The collection of data within the network activities should lead to an Europeanwide exchange of knowledge on the properties, the capability, the availability and the application of blended cements with the objective of a broader application of blended cements in Europe. In addition the production and testing of cements with maximum amounts of main constituents besides clinker acc. to EN 197-1 and the production and testing of cements with a composition beyond the limits of EN 197-1 will lead to a broader knowledge about the behaviour of such cements in mortar and concrete an therefore can contribute to a broader application of blended cements in Europe.

Partners from Germany, Greece, Italy and Norway used constituents, which are relevant for the particular part of Europe. The work with blended cements in cluster 2 comprises cement types included in and beyond the limits of EN 197-1. Some of the cements according to EN 197-1 would, however, be new in a particular region, containing a new constituent (e. g. limestone in Norway), or greater quantities of substitutes (more fly ash), or mixes of additional constituents (fly ash <u>and</u> limestone). Ground brick has been successfully used as pozzolanic material in Italy. Nevertheless mortars and concretes in which the cement has been partially substituted by ground brick showed high water demand and low durability. The use of a third recycled pozzolanic material will be investigated in order to reduce the aforesaid problems. For the greek market 2,5 million tons/a of fly ash from power plants are of special interest. The high CaO content of these fly ashes (> 10%) renders them unsuitable for the manufacturing of concrete, according to the EN 450. Currently, they are being used for the production of cement but their implementation requires some precaution because they exhibit problems regarding inhomogenity and high $SO_3$ values. Investigations within the cluster should give hints, to what extend these fly ashes can be used for the production of blended cements. Building practice experience with Portland-limestone cements of up to 35 mass.% is not available in Germany. Currently they may not yet be used for concrete with high resistance to freeze thaw or freeze thaw with de-icing salt. Investigations should give hints, to what extend the limestone qualities available in the region, can be used for the production of blended cements. For the comparability and the reproducibility of the investigations and their results, partners agreed on some mortar- and concrete compositions as well as the test methods.

All constituents where characterized with regard to there chemical and physical properties. Cement properties have been determined. Concrete tests mainly on workability, strength development, chloride penetration and the resistance against freezing and thawing have been carried out.

As the applicability of cements is regulated in the various national annexes to EN 206-1, the results on cements with maximum amounts of main constituents besides clinker acc. to EN 197-1 can partly be used to achieve an extension of the national application rules for these cements.

The results on cements with a composition beyond the limits of EN 197-1 – as a further step – might be used as the basis for a future extension of EN 197-1. The investigation showed, that there are some potentials.

## 3 Objectives of the project

On November 15th 2002, the European Thematic Network “EUROPEAN CONSTRUCTION IN SERVICE OF SOCIETY” (ECOServe) was established. One of the technical clusters of the ECOServe Network, ***cluster 2***, deals with the ***production and application of blended cements***.

The cement production process is intensive in energy as well as raw material demand. Limits of technical improvements to lower the environmental impact of the cement production have been reached in the European cement industry. Remaining potential to reduce environmental impacts is provided by the reduction of the clinker content in cement (blended cements). Other main constituents for cement like granulated blastfurnace slag, fly ashes from power plants, natural and industrial pozzolanas or limestone can be used. The production of blended cements results in lower emission and lower energy consumption of the clinker burning process. This reduction is obvious, because less clinker from the energy-intensive process is needed to produce such blended cements. Experience in the production of blended cements already exists. However, the new European cement standard EN 197-1 now allows more different types of these cements to be produced than before. The use of many of these cements in concrete is currently restricted only to a few climatic or environmental conditions in some of the various European countries respectively these cements have not been produced at all.

The cluster consists of network (N) and research activities (R) in 6 inter-related tasks. In the network part, the exchange of knowledge about the production and especially the application of blended cements ist the main objective. The expected outcome of the network acivities is a Europeanwide exchange of knowledge on the properties, the capability, the availability and the application of blended cements with the objective of a broader application of blended cements in Europe. The collection and evaluation of application rules for blended cements is one of the integral parts of the work in cluster 2 of the network.

Besides the data collection investigations on blended cements and their behaviour in mortar and concrete and consequential new perceptions about the influence of blended cements especially on the durability can enhance the use of these cements. As the use of many of the blended cements with the maximum content of main constituents besides clinker according to EN 197-1 in concrete is currently restricted only to a few climatic or environmental conditions in some of the European countries respectively these cements have not even been produced, the innovative aspects of the research activities in cluster 2 are

- the production and testing of cements with maximum amounts of main constituents besides clinker acc. to EN 197-1 and
- the production and testing of cements with a composition beyond the limits of EN 197-1.

Research activities focus on concrete durability.

Participants in the resarch activities of cluster 2 are:

| Partner No. * | Name | Short name |
|---|---|---|
| 1 | Verein Deutscher Zementwerke | VDZ |
| 2 | CTG SpA | CTG |
| 3 | Norcem A.S. | Norcem |
| 5 | Titan Cement Company | Titan |
| *: ref. to Annex 1 „Description of work“ to Contract No. G1RD-CT-2002-00782 | | |

# 4 Scientific and technical description of the results

## 4.1 General

Experience in the production of blended cements already exists. However, the new European cement standard EN 197-1 now allows more different types of these cements to be produced than before. The use of many of these cements in concrete is currently restricted only to a few climatic or environmental conditions in some of the various European countries (table 1) respectively these cements have not been produced at all.

The applicability of cements according to various national annexes to EN 206-1 is shown in table 1 by the example of an exposed vertical surface of inland concrete with no significant levels of external chlorides.

Table 1: Applicability of cements according to various national annexes to EN 206-1 [15] – ***partly corrected by cluster members***

| **CEN member** | **Exposure class** | **Minimum compressive strength class, maximum w/c ratio, minimum cement content, permitted cement types** | | | **Other requirements** |
|---|---|---|---|---|---|
| Austria | XC1+XF1 | -- | 0,55 | 300 | Cements in yellow need testing |
| | I II/A-S II/B-S II/A-D II/A-V II/B-V II/A-W II/A-L II/B-L II/A-M II/B-M III/A III/B | | | | |
| Belgium | EE3 (XC4+XF1) | C30/37 | 0,50 | 320 | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-W II/B-W II/A-T II/B-T II/A-L II/B-L II/A-LL II/B-LLII/A-M II/B-M III/A III/B III/C | | | | |
| Czech Republic | XC1 to 4 orXF1 | C30/37 | 0,50 or 0,55 | 300 | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-W II/B-W II/A-T II/B-T II/A-L II/B-L II/A-LL II/B-LLII/A-M II/B-M III/A III/B | | | | |
| Denmark | (XC2,XC3,XC4 XF1, XA1) | C25/30 | 0,55 | 150 | 375 minimum filler |
| | I II/A-V II/B-V II/A-L II/A-LL Minimum strength class 42,5 | | | | |
| Finland | XC3 or 4, XF1 | C25/30 | 0,60 | 250 (270 if XC4) | |
| | I II/A-S ~~II/B-S~~ II/A-D II/A-V ~~II/B-V~~ II/A-LL II/A-M ~~II/B-M~~ ~~III/A III/B~~ (Strikeout used to delete cements not approved for XC4) | | | | |
| France | XC4+XF1 | | | | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-W II/B-W II/A-T II/B-T II/A-L II/B-L II/A-LL II/B-LLII/A-M II/B-M III/A III/B III/C IV/A IV/B V/A V/B | | | | |
| Germany | XC4+XF1 | C25/30 | 0,60 | 280 | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-T II/B-T III/A III/B | | | | |
| Ireland | XC2 orXC4+XF1 | C30/37 if XC4+XF1 | 0,55 | 320 | |
| | I (no guidance provided on other cements) | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Italy | XC1,<br><br>XC2+XF1 | C25/30 if XC1<br>C32/40 | 0,60<br><br>0,50 | 300<br><br>320 | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-W II/B-W II/A-T II/B-T II/A-L II/B-L II/A-LL II/B-LLII/A-M II/B-M<br>III/A III/B III/C IV/A IV/B V/A V/B | | | | |
| Luxembourg | XC4+XF1 | C25/30 | 0,60 | 280 | |
| | I II/A-S II/B-S II/A-D II/A-V II/A-T II/A-L II/A-LL II/A-M (S-V, S-D, S-T, S-LL) III/A III/B | | | | |
| Netherlands | XC3,<br>XC4+XF1 | --<br>-- | 0,55<br>0,50 | 280<br>300 | |
| | I II/A-S II/B-S II/A-V II/B-V II/A-T II/B-T III/A III/B | | | | |
| Norway | ***XC4 + XF1*** | ***--*** | ***0,60*** | | |
| | ***I II/A-S II/A-D II/A-V II/A-L II/A-LL*** | | | | |
| Portugal | XC2/XC4/XF1/XF2<br>Assume XC4+XF1 | C30/37 | 0,60 - I, II/A<br>0,55- other | 280 – I, II/A<br>300 - other | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-W II/B-W II/A-T II/B-T II/A-L II/B-L II/A-LL II/B-LLII/A-M II/B-M<br>III/A* IV/A* IV/B V/A* (* not less than 50% PC clinker) | | | | |
| Slovenia | XC4+XF1 | | | | |
| | I II/A-S II/B-S II/A-D II/A-P II/B-P II/A-Q II/B-Q II/A-V II/B-V II/A-W II/B-W II/A-T II/B-T II/A-L II/B-L II/A-LL II/B-LLII/A-M II/B-M<br>III/A III/B III/C IV/A IV/B V/A V/B | | | | |
| Sweden | XC4, XF1 | -- | 0,55 | 200 | |
| | I II/A-S II/A-D II/A-V II/A-LL II/A-M II/B-M (Min strength class 42,5) | | | | |
| Switzerland | XC4+XF1 | -- | 0,50 | 300 | Min. fines |
| | I II/A-S II/A-D II/A-LL II/A-M (D-LL) III/A III/B | | | | |
| United Kingdom | XC3/4+XF1 | C28/35 | 0,60 | 280 | |
| | I II/A-S II/B-S II/A-D II/A-V II/B-V II/A-L II/B-L II/A-LL II/B-LL<br>III/A III/B | | | | |

Besides the applicability of cements according to various national annexes to EN 206-1 the availablity of cements per country and the regional availability of blended cements is different. Due to the availability of main constituents besides clinker, not every cement plant is able to produce any kind of blended cement in a cost-effective and ecologically way (transport etc.). The same aspects have to be considered concerning the combination of cements and concrete additions. Therefore partners aggreed to investigate cements, which are or might be of relevance for their national cement market in the future. This does not mean, that benefits from the results of the investigations can only be taken in the respective country. The investigations are – to some extend – repesentative for the different regions in Europe and it is most interesting to compare the results of these cements made from constituents form different regions throughout Europe using the same test methods. Investigations of the four partners will be discussed in the following chapters in detail by every partner. On overal summary is given in chapter 8.

## 4.2 Partner 1: VDZ

### 4.2.1 General

Accordung to the objectives of cluster 2 the investigations included

- the production and testing of cements with maximum amounts of main constituents besides clinker acc. to EN 197-1 and
- the production and testing of cements with a composition beyond the limits of EN 197-1.

Besides clinker (K), granulated blastfurnace slag (GBFS), calcareous fly ash (W) and limestone (LL) were planned to be used as main constituents.

### 4.2.2 Granulated blast furnace slag (GGBS)

In the year 2000, more than 66 % out of 7,53 Mio t blastfurnace slag were granulated and almost completely used as cementitious materials in Germany [19]. Middle European granulated blastfurnace slags usually consist of more than 95 % glassy particles. The EN 197-1 requires a glassy slag content of at least two-thirds by mass. Chemically, the slag has to consist of at least two-thirds of CaO, MgO and $SiO_2$, while the ratio of (CaO + MgO)/($SiO_2$) shall exceed 1,0. The fulfilment of these requirements is seen to be the prerequisite for the slag to possess latent hydraulic properties and so be suitable for cement production.

Additional chemical parameters have been established in practice as hydraulic activity indexes to describe slag properties. The application experience reveals that a simple consideration of the CaO, MgO and $SiO_2$ content is not always sufficient. High amounts of $Al_2O_3$ can enhance the reactivity of slag, whereas high $TiO_2$ and MnO contents can reduce its hydraulic properties. Moreover, the glass content of GBS plays a key role in view of the reactivity. Evidently, not only the absolute glass content but also the glass structure, which can be influenced by the chemistry as well as by the quenching conditions during granulation, are of importance.

### 4.2.3 Calcareous fly ash

Due to their chemical composition, German lignite fly ashes basically correspond to the category of calcareous fly ash according to EN 197-1. They may be utilized as cement main constituents, if they contain at least 10,0 mass.-% reactive CaO. If the proportion of reactive CaO does not exceed 15,0 mass.-%, the ash has to contain at least 25,0 mass.-%. reactive $SiO_2$. Calcareous fly ash containing more than 15,0 mass.-% reactive CaO has to achieve a compressive strength of 10,0 MPa according to EN 196-1. For this test the fly ash has to be adequately ground and must replace the cement in the mortar by 100 %. The soundness of calcareous fly ash shall not exceed 10 mm when tested in accordance with EN 196-3 using a mixture of 30 wt-% of fly ash and 70 mass.-% of a CEM I cement.

In Germany 8 Mio t calcareous fly ash per year are produced, which are predominantly used to recultivate the exploited coal mining fields and mines. About 10 % of the ashes are available for alternative uses. Actually, German lignite fly ashes play only a minor role as cement main constituents, although developments of cementitious binders containing CFA have been in progress during the past five decades in Germany. In 1972 fly ash was established as a cement component by the standards of Eastern Germany [16, 17]. For the past years, selected calcareous fly ashes have been certified as concrete additions [6].

### 4.2.4 Limestone

In Germany Portland-limestone cements with a limestone content up to 20 wt-% were developed by the cement manufacturers during the 1980ies and were established then as cements with technical approval. After a practical experience of more than 10 years in building construction and structural engineering they were included in the national standard DIN 1164-1:1994 as CEM II/A-L. Limestone used in these cements meets the following requirements according to EN 197-1:2000:

The calcium carbonate ($CaCO_3$) content calculated from the calcium oxide content shall be at least 75 % by mass.

The clay content, determined by the methylene blue test in accordance with EN 933-9, shall not exceed 1,20 g/100 g. For this test the limestone shall be ground to a fineness of approximately 5000 $cm^2/g$ determined as specific surface in accordance with EN 196-3 (Blaine).

The total organic carbon (TOC) content shall not exceed 0,20 mass.%. This type of limestone is marked with the letter „LL“ according to EN 197-1:2000. Therefore these Portland-limestone cements are now called CEM II/A-LL.

The performance of concrete manufactured from Portland-limestone cement CEM II/A-LL, in terms of fresh and hardened concrete properties and durability, has been verified by extensive laboratory investigations and practical experiences. In particular the freeze-thaw resistance of concretes, which fulfil the minimum requirements of the exposure class XF4 (freeze/thaw attack on concrete with high water saturation with de-icing salt or sea water) according to the German concrete standard DIN 1045-2, is generally high and can be compared to that of Portland cement concrete. In road construction Portland-limestone cement CEM II/A-LL may be used for the same applications as Portland cement. In general the strength development of concretes using Portland-limestone cement CEM II/A-LL is comparable to concretes with Portland cement CEM I of otherwise identical composition [18].

With the introduction of EN 197-1 further Portland-limestone cements have been standardized in addition to the CEM II/A-LL cements. Now it is possible to use limestone contents of up to 35 mass.% (CEM II/B-LL) as well as limestone with TOC contents of up to 0,50 mass.%. Portland-limestone cement with increased TOC contents in the limestone is labelled with the letter „L“.

Building practice experience with Portland-limestone cements of up to 35 mass.% is not available in Germany. Currently they may not yet be used for concrete with high resistance to freeze thaw or freeze thaw with de-icing salt.

### 4.2.5 Characterization of the starting materials

Laboratory cements on the one hand will be produced by mixing clinker, sulphate agent and the other main constituents. On the other hand, cements will be produced using Portland cements usual in the market mixing with the other main constituents.

The final selection of the two calcareous fly ashes has not yet been finished. Table 2 shows the chemical composition of representative calcareous fly ashes from the Rhenish and the Lusatian area (VDZ-data) and from the Mitteldeutsches Revier (literature). Particulary the Rhenish fly ash contains higher amounts of free lime. Also free magnesia (perclase) can be detected by X-ray diffraction. Probably the fly ash from the Lusatian area and onother fly ash from the Mitteldeutsches Revier will be used for further investigations.

Table 2: Chemical composition of two representative calcareous fly ashes from the Rhenish (R) and the Lusatian (L) area (VDZ-data) and from the Mitteldeutsches Revier [1]

| Parameter | Unit | R1 | L1 | Mitteldeutsches Revier [1] |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| $SiO_2$ | mass.-% | 34,8 | 38,8 | 40 – 60 |
| $Al_2O_3$ | | 3,80 | 8,41 | 7 – 16 |
| $TiO_2$ | | 0,39 | 0,73 | n. s. |
| $P_2O_5$ | | 0,02 | 0,03 | n. s. |
| $Fe_2O_3$ | | 11,9 | 22,8 | 6 – 14 |
| CaO | | 31,7 | 18,8 | 12 – 33 |
| MgO | | 8,52 | 6,53 | 1 – 6 |
| $SO_3$ | | 7,04 | 2,70 | 1 – 7 |
| $K_2O$ | | 0,35 | 0,72 | n. s. |
| $Na_2O$ | | 1,21 | 0,17 | n. s. |
| loss on ignition | | 1,76 | 0,66 | n. s. |
| reactive CaO | | 27,0 | 17,3 | n. s. |
| reactive $SiO_2$ | | 7,79 | 12,8 | n. s. |
| free lime | | 8,85 | 0,34 | n. s. |

Tables 3 and 4 show the chemical composition of the starting materials portland cement clinker, portland cement, granulated blastfurnace slag and limestone.

Table 3: Chemical composition of the starting materials Portland cement clinker, Portland cement and Granulated blastfurnace slag for the production of cements

| Parameter | Unit | C1 | PC1 | PC2 | PC3 | S1 |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| $SiO_2$ | mass.-% | 21,2 | 23,6 | 22,5 | 22,5 | 35,3 |
| $Al_2O_3$ | | 5,91 | 3,90 | 3,65 | 3,71 | 12,1 |
| $TiO_2$ | | 0,27 | 0,22 | 0,21 | 0,21 | 0,76 |
| $P_2O_5$ | | 0,10 | 0,13 | 0,12 | 0,13 | 0,02 |
| $Fe_2O_3$ | | 2,61 | 1,31 | 1,23 | 1,26 | 0,38 |
| CaO | | 66,1 | 64,7 | 65,5 | 65,8 | 40,6 |
| MgO | | 1,44 | 0,76 | 0,76 | 0,73 | 8,88 |
| $SO_3$ | | 0,80 | 2,45 | 3,66 | 3,34 | 0,25 |
| $S^{2-}$ | | n. d. | n. d. | n. d. | n. d. | 0,78 |
| $K_2O$ | | 0,95 | 0,73 | 0,73 | 0,64 | 0,44 |
| $Na_2O$ | | 0,18 | 0,16 | 0,16 | 0,16 | 0,31 |
| $Na_2O$-eq. | | 0,81 | 0,64 | 0,64 | 0,58 | 0,60 |
| $CO_2$ | | 0,14 | 1,66 | 0,90 | 0,60 | 0,11 |
| TOC | | n. d. | n. d. | n. d. | n. d. | n. d. |
| Clay content | g/100g | n. d. | n. d. | n. d. | n. d. | n. d. |
| $C_3S$ | mass.-% [1)] | 64,5 | 52,5 | 62,7 | 63,3 | - |
| $C_2S$ | | 12,4 | 29,4 | 18,1 | 17,9 | - |
| $C_3A$ | | 11,3 | 8,28 | 7,69 | 7,82 | - |
| $C_4AF$ | | 7,97 | 4,08 | 3,80 | 3,90 | - |
| C1: Portland cement clinker | | | | | | |
| PC1 – PC3: Portland cement CEM I | | | | | | |
| S1: Granulated blastfurnace slag (GBFS) | | | | | | |
| 1) acc. to Bogue | | | | | | |

Table 4: Properties of investigated limestone meals

| Property | | | Limestone meal | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | LL1 | LL2 | LL3 | LL4 | LL5 | LL6 | LL7 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $SiO_2$ | | M.-% | 0,15 | 3,47 | 0,43 | 3,85 | 6,99 | 6,68 | 7,34 |
| $Al_2O_3$ | | | 0,01 | 0,59 | 0,43 | 1,41 | 2,59 | 2,26 | 2,35 |
| $TiO_2$ | | | 0,03 | 0,05 | 0,17 | 0,08 | 0,11 | 0,12 | 0,12 |
| $P_2O_5$ | | | 0,01 | 0,06 | 0,05 | 0,04 | 0,03 | 0,03 | 0,03 |
| $Fe_2O_3$ | | | 0,01 | 0,16 | 0,03 | 0,50 | 0,92 | 0,87 | 0,81 |
| CaO | | | 55,5 | 53,4 | 56,3 | 50,6 | 48,2 | 50,0 | 46,8 |
| MgO | | | 0,42 | 0,28 | 0,16 | 1,29 | 1,22 | 0,94 | 1,25 |
| $SO_3$ 2) | | | 0,03 | 0,61 | 0,02 | 0,02 | 0,04 | 0,59 | 0,65 |
| $K_2O$ | | | 0,02 | 0,15 | 0,02 | 0,29 | 0,74 | 0,58 | 0,69 |
| $Na_2O$ | | | 0,02 | 0,04 | 0,01 | 0,02 | 0,13 | 0,09 | 0,09 |
| $Na_2O$-Äqu. | | | 0,03 | 0,14 | 0,02 | 0,21 | 0,62 | 0,47 | 0,54 |
| $CO_2$ | | | 43,4 | 40,3 | 42,5 | 41,0 | 37,9 | 36,8 | 38,6 |
| $H_2O$ | | | 0,16 | 0,75 | 0,25 | 0,83 | 0,97 | 1,05 | 1,23 |
| TOC | | | 0,013 | 0,074 | 0,013 | 0,081 | 0,081 | 0,067 | 0,093 |
| $CaCO_3$ | | | 98,6 | 91,6 | 96,6 | 93,2 | 83,1 | 83,6 | 87,7 |
| Clay content Methylenblauwert | | g/100g | 0,03 | 0,40 | 0,13 | 0,27 | 0,33 | 0,23 | 0,33 |
| spec. surface spez. Oberfläche | Blaine | $cm^2/g$ | 7000 | >10000 | 7000 | 5410 | 5430 | 5140 | 4380 |
| | BET | | 11880 | 50590 | 24360 | 65780 | 42410 | 47514 | 73810 |
| | BET/ Blaine | - | 1,7 | 5,1 | 3,5 | 12,2 | 7,8 | 9,3 | 16,9 |
| X' | | µm | 11,0 | 7,0 | 10,4 | 16,5 | 16,1 | 12,9 | 17,5 |
| n | | – | 0,85 | 0,83 | 0,74 | 0,72 | 0,87 | 0,92 | 0,90 |

### 4.2.6 Cements

All cements which have been produced been produced and investigated are presented in tables 5 to 7 have. Partners aggreed, that the planned strength after 28 d for all cements is 45 - 50 MPa acc. to EN 197-1 as a rule. If the strength of the tested cement is significantly lower than 45 - 50 MPa, partners use a reference cement with a reduced strength. It can be derived from tables 5, 6 and 7, that this range of values was achieved by cements CEM 1-2, 3-2, 5b, 6, 7, 8-3, 12-1, 14-17, 18. The strength values of cements RefC, 2-2 are also in the typical range for cements of the strength class 32,5 R in Germany. The values for cement 9-3 and 17 is are slightly above the limit for that strength class. The standard strength of the other cements is significantly below this range.

Table 5: Particle size distribution, specific surface area (Blaine), density, position parameter x', slope n, void content P and strength development of cements

| Parameter | Unit | PC1 | PC2 | PC3 | RefC | CEM 1-0 | CEM 1-1 | CEM 1-2 | CEM 2-1 | CEM 2-2 | CEM 3-1 | CEM 3-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Particle size distribution (% Passing) | | | | | | | | | | | | |
| 0,1 µm | mass.-% | 0,56 | 0,86 | 1,39 | 0,75 | 0,88 | 2,82 | 0,87 | 1,19 | 0,86 | 1,24 | 1,10 |
| 0,3 µm | | 2,33 | 3,81 | 5,88 | 3,00 | 3,12 | 9,70 | 3,86 | 5,46 | 4,06 | 5,49 | 4,63 |
| 0,5 µm | | 3,72 | 6,44 | 9,81 | 4,86 | 5,18 | 13,3 | 6,56 | 9,55 | 7,14 | 9,41 | 7,69 |
| 0,7 µm | | 5,04 | 8,83 | 13,2 | 6,44 | 7,75 | 15,1 | 9,00 | 13,2 | 10,0 | 12,8 | 10,4 |
| 1,0 µm | | 7,05 | 12,1 | 17,5 | 8,52 | 12,7 | 18,4 | 12,3 | 17,9 | 14,1 | 17,2 | 13,9 |
| 1,5 µm | | 10,1 | 17,2 | 24,2 | 12,0 | 19,9 | 24,2 | 17,8 | 25,9 | 20,9 | 24,4 | 19,5 |
| 2,0 µm | | 12,8 | 21,8 | 30,4 | 15,3 | 26,0 | 30,2 | 23,1 | 33,4 | 27,2 | 31,1 | 24,9 |
| 2,5 µm | | 15,1 | 26,0 | 36,0 | 18,4 | 31,0 | 35,9 | 27,9 | 40,2 | 32,9 | 37,2 | 29,8 |
| 3,0 µm | | 17,1 | 29,7 | 40,8 | 21,0 | 35,1 | 41,0 | 32,1 | 45,9 | 37,6 | 42,5 | 34,1 |
| 6,0 µm | | 25,5 | 45,3 | 59,8 | 31,7 | 50,3 | 60,2 | 48,2 | 65,1 | 54,4 | 62,6 | 51,5 |
| 12 µm | | 37,0 | 66,5 | 81,5 | 44,8 | 65,7 | 79,9 | 67,7 | 82,9 | 72,0 | 82,0 | 70,1 |
| 32 µm | | 68,0 | 98,6 | 99,9 | 72,8 | 89,2 | 99,2 | 97,5 | 99,7 | 97,9 | 99,3 | 96,0 |
| 63 µm | | 93,3 | 100 | 100 | 91,3 | 99,8 | 100 | 100 | 100 | 100 | 100 | 100 |
| 90 µm | | 99,4 | 100 | 100 | 97,8 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 125 µm | | 100 | 100 | 100 | 99,9 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 200 µm | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Blaine | g/cm² | 2660 | 5200 | 7050 | 2900 | 5580 | 6680 | 5580 | 8320 | 7100 | 7040 | 5830 |
| x' | µm | 25,2 | 9,7 | 6,3 | 21,3 | 10,6 | 6,6 | 9,5 | 5,9 | 8,2 | 6,3 | 8,9 |
| n | - | 0,83 | 0,92 | 0,90 | 0,79 | 0,84 | 0,81 | 0,91 | 0,90 | 0,90 | 0,90 | 0,87 |
| P | vol.-% | 48,4 | 54,1 | 58,4 | 44,6 | 48,7 | 57,4 | 52,2 | 57,1 | 52,3 | 54,2 | 52,1 |
| Density | g/cm3 | 3,13 | 3,11 | 3,11 | 3,16 | 3,00 | 2,95 | 2,95 | 2,94 | 2,95 | 2,95 | 2,96 |
| Strength development acc. to EN 197-1 | | | | | | | | | | | | |
| 2d | MPa | 21.8 | 51.1 | 58.2 | 23,9 | 22,1 | 36.9 | 32.1 | 40.2 | 35.5 | 35.5 | 33.4 |
| 7d | | 42.6 | 64.1 | 68.0 | 39,4 | 32,2 | 47.2 | 39.5 | 48.2 | 43.6 | 45.1 | 39.8 |
| 28d | | 57.7 | 75.3 | 77.7 | 51,2 | 39,7 | 53.8 | 47.0 | 54.3 | 52.5 | 40.3 | 46.6 |
| 90d | | 67,0 | 78,9 | 79,0 | 59,2 | n. d. | 54,0 | 46,9 | 53,5 | 54,7 | 48,2 | 49,5 |

| | | | |
|---|---|---|---|
| RefC = | Reference Cement – 100 % K (2700 g/cm²) + sulphate | | |
| CEM 1-0 = | 65 % K (3500 g/cm²) + 35 % LL1 + sulphate | | |
| CEM 1-1 = | 65 % PC3+ 35 % LL1 | CEM 1-2= | 65 % PC2+ 35 % LL1 |
| CEM 2-1 = | 65 % PC3+ 35 % LL2 | CEM 2-2= | 65 % PC2+ 35 % LL2 |
| CEM 3-1 = | 65 % PC3+ 35 % LL3 | CEM 3-2= | 65 % PC2+ 35 % LL3 |
| R.f. = | Results following | n. d. = | not determined |

Table 6: Particle size distribution, specific surface area (Blaine), density, position parameter x', slope n, void content P and strength development of cements

| Parameter | Unit | CEM 11-1 | CEM 11-2 | CEM 12-1 | CEM 12-2 | CEM 13-1 | CEM 13-2 | CEM 4-2 | CEM 6 | CEM 7 | CEM 8-3 | CEM 9-3 | CEM 5b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Particle size distribution (% Passing) | | | | | | | | | | | | | |
| 0,1 µm | mass.-% | 0,91 | 0,76 | 0,86 | 0,70 | 1,00 | 0,82 | 1,28 | 1,10 | 0,65 | 0,80 | 0,78 | 1,03 |
| 0,3 µm | | 4,30 | 3,53 | 3,66 | 2,91 | 4,17 | 3,44 | 4,07 | 3,44 | 3,07 | 3,45 | 3,21 | 4,65 |
| 0,5 µm | | 7,54 | 6,00 | 6,10 | 4,68 | 6,88 | 5,73 | 6,61 | 5,75 | 5,38 | 2,80 | 5,18 | 8,01 |
| 0,7 µm | | 10,6 | 8,42 | 8,26 | 6,32 | 9,20 | 7,67 | 9,46 | 8,11 | 7,55 | 7,86 | 6,97 | 11,0 |
| 1,0 µm | | 14,8 | 12,2 | 11,2 | 8,80 | 12,2 | 10,2 | 14,4 | 11,9 | 10,7 | 10,6 | 9,51 | 15,1 |
| 1,5 µm | | 21,8 | 18,2 | 16,0 | 12,8 | 17,3 | 14,4 | 21,7 | 18,0 | 16,0 | 15,1 | 13,5 | 21,8 |
| 2,0 µm | | 28,4 | 23,8 | 20,7 | 16,6 | 22,3 | 18,6 | 27,6 | 23,7 | 21,1 | 19,3 | 17,3 | 28,0 |
| 2,5 µm | | 34,3 | 28,7 | 25,0 | 20,0 | 26,8 | 22,5 | 32,5 | 28,7 | 25,7 | 23,2 | 20,6 | 33,6 |
| 3,0 µm | | 39,3 | 33,0 | 28,8 | 23,0 | 30,8 | 26,0 | 36,5 | 32,8 | 29,8 | 26,6 | 23,5 | 38,2 |
| 6,0 µm | | 57,6 | 49,0 | 35,0 | 34,7 | 37,3 | 40,8 | 51,2 | 47,2 | 44,5 | 39,3 | 35,1 | 53,4 |
| 12 µm | | 77,1 | 67,8 | 62,4 | 48,1 | 63,5 | 57,5 | 66,6 | 62,1 | 59,4 | 53,4 | 48,9 | 66,2 |
| 32 µm | | 98,1 | 96,0 | 91,4 | 76,0 | 87,5 | 85,2 | 90,0 | 89,1 | 86,8 | 80,9 | 77,3 | 89,0 |
| 63 µm | | 100 | 100 | 100 | 96,2 | 99,1 | 98,4 | 99,9 | 99,9 | 99,5 | 98,4 | 97,3 | 99,8 |
| 90 µm | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 125 µm | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 200 µm | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Blaine | $g/cm^2$ | 6700 | 5660 | 4725 | 3475 | 4840 | 4290 | 5450 | 5310 | 4830 | 4220 | 3630 | 7130 |
| x' | µm | 7,5 | 9,5 | 11,4 | 18,5 | 11,7 | 13,9 | 10,1 | 11,4 | 12,6 | 15,3 | 17,8 | 10,1 |
| n | - | 0,91 | 0,91 | 0,88 | 0,81 | 0,81 | 0,84 | 0,81 | 0,84 | 0,84 | 0,80 | 0,81 | 0,77 |
| P | vol.-% | 56,3 | 52,6 | 51,0 | 47,6 | 51,6 | 51,6 | 54,8 | 51,1 | 51,9 | n. d. | n. d. | n. d. |
| Density | g/cm3 | 2,92 | 2,93 | 2,97 | 2,97 | 2,92 | 2,92 | 3,03 | 3,00 | 3,00 | 3,00 | 3,05 | 2,97 |
| Strength development acc. to EN 197-1 | | | | | | | | | | | | | |
| 2d | MPa | 28,2 | 25,7 | 22,1 | 8,8* | 9,2* | 9,6* | 24,1 | 23,3 | 21,7 | 20,9 | 18,6 | 25,0 |
| 7d | | 35,1 | 33,7 | 37,1 | 21,5 | 24,5 | 25,0 | 32,8 | 36,6 | 36,7 | 35,2 | 35,1 | 36,9 |
| 28d | | 40,1 | 38,3 | 50,9 | 34,3 | 43,6 | 37,0 | 42,8 | 46,5 | 47,0 | 47,4 | 53,7 | 44,4 |
| 90d | | 40,7 | 37,4 | 56,7 | 45,3 | 53,6 | 47,3 | n. d. | 51,4 | 56,0 | 49,1 | 62,6 | 47,3 |

| | | | |
|---|---|---|---|
| CEM 11-1 = | 55 % PC3+ 45 % LL1 | CEM 11-2= | 55 % PC2+ 45 % LL1 |
| CEM 12-1 = | 50 % PC2+ 20 % LL1 + 30 % S1 | CEM 12-2 = | 50 % PC1+ 20 % LL1 + 30% S1 |
| CEM 13-1 = | 30 % PC3+ 20 % LL1 + 50 % S1 | CEM 13-2= | 30 % PC2+ 20 % LL1 + 50% S1 |
| CEM 4-2 = | 65 % K + 30 % LL1 + sulphate | CEM 7 = | 65% K + 25% LL1 + 10% S1 + sulph. |
| CEM 5b = | 65 % K + 35 % LL2 + sulphate | CEM 8-3 = | 65% K + 20% LL1 + 15% S1 + sulph. |
| CEM 6 = | 65 % K + 30 % LL1 + 5 % S1 + sulph. | CEM 9-3 = | 65 % K + 35 % S1 + sulph. |
| R.f. = | Results following | * = | to be repeated |

Table 7: Particle size distribution, specific surface area (Blaine), density, position parameter x', slope n, void content P and strength development of cements

| Parameter | Unit | CEM 14 | CEM 15 | CEM 16 | CEM 17 | CEM 18 | CEM 19 |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Particle size distribution (% Passing) | | | | | | | |
| 0,1 µm | mass.-% | 0,88 | 0,68 | 0,67 | 0,63 | 0,64 | 0,77 |
| 0,3 µm | | 3,76 | 3,05 | 3,01 | 2,86 | 2,85 | 3,26 |
| 0,5 µm | | 6,35 | 5,26 | 5,18 | 4,88 | 4,79 | 5,37 |
| 0,7 µm | | 8,56 | 7,21 | 7,16 | 6,76 | 6,60 | 7,28 |
| 1,0 µm | | 11,3 | 9,79 | 9,89 | 9,42 | 9,28 | 10,0 |
| 1,5 µm | | 16,1 | 14,1 | 14,4 | 13,7 | 13,6 | 14,5 |
| 2,0 µm | | 20,8 | 18,3 | 18,7 | 17,8 | 17,6 | 18,8 |
| 2,5 µm | | 25,2 | 22,3 | 22,7 | 21,6 | 21,3 | 22,7 |
| 3,0 µm | | 29,3 | 25,9 | 26,3 | 25,0 | 24,6 | 26,1 |
| 6,0 µm | | 46,0 | 41,3 | 41,7 | 39,7 | 38,6 | 40,5 |
| 12 µm | | 64,3 | 62,1 | 62,7 | 60,4 | 57,5 | 57,9 |
| 32 µm | | 91,6 | 93,0 | 95,3 | 92,6 | 87,2 | 83,2 |
| 63 µm | | 99,5 | 99,9 | 100 | 99,9 | 98,3 | 96,7 |
| 90 µm | | 100 | 100 | 100 | 100 | 100 | 100 |
| 125 µm | | 100 | 100 | 100 | 100 | 100 | 100 |
| 200 µm | | 100 | 100 | 100 | 100 | 100 | 100 |
| Blaine | $g/cm^2$ | 5250 | 5250 | 5150 | 4880 | 4570 | 4640 |
| x' | µm | 11,0 | 11,5 | 11,1 | 12,0 | 13,9 | 14,6 |
| n | - | 0,87 | 0,93 | 0,94 | 0,94 | 0,88 | 0,83 |
| Water demand | mass% | 31,5 | 31,0 | 32,0 | 32,5 | 28,5 | 28,0 |
| Density | $g/cm^3$ | 2,96 | 2,97 | 2,96 | 2,95 | 2,97 | 2,92 |
| Strength development acc. to EN 197-1 | | | | | | | |
| 2d | MPa | 31,8 | 32,0 | 32,8 | 31,7 | 23,2 | 11,0 |
| 7d | | 41,6 | 42,1 | 42,9 | 40,3 | 36,5 | 27,1 |
| 28d | | 46,9 | 46,5 | 48,0 | 46,5 | 51,1 | 43,3 |

Composition

| Cement | PC2 | PC3 | LL4 | LL5 | LL6 | LL7 | S1 |
|---|---|---|---|---|---|---|---|
| | mass % | | | | | | |
| 1 | 2 | | | | | | |
| CEM 14 | 65 | - | 35 | - | - | - | - |
| CEM 15 | 65 | - | - | 35 | - | - | |
| CEM 16 | 65 | - | - | - | 35 | - | - |
| CEM 17 | 65 | - | - | - | - | 35 | - |
| CEM 18 | 50 | - | - | 20 | - | - | 30 |
| CEM 19 | - | 30 | - | 20 | - | - | 50 |

PC2, PC3: Portland cement LL4 – LL7: Limestone meal
S1: Ground granulated blastfurnace slag

Investigations on fly ashes have been reduced due to the quality of calcareus fly ashes in Germany (Sub-task 1.3). A lot more modifications have been made with cements containing limestone (Sub-task 2.2), because of the actual situation in Germany. where the use of higher amount of limetone was a great interest during the project time. The cements given in table 7 have been tested.

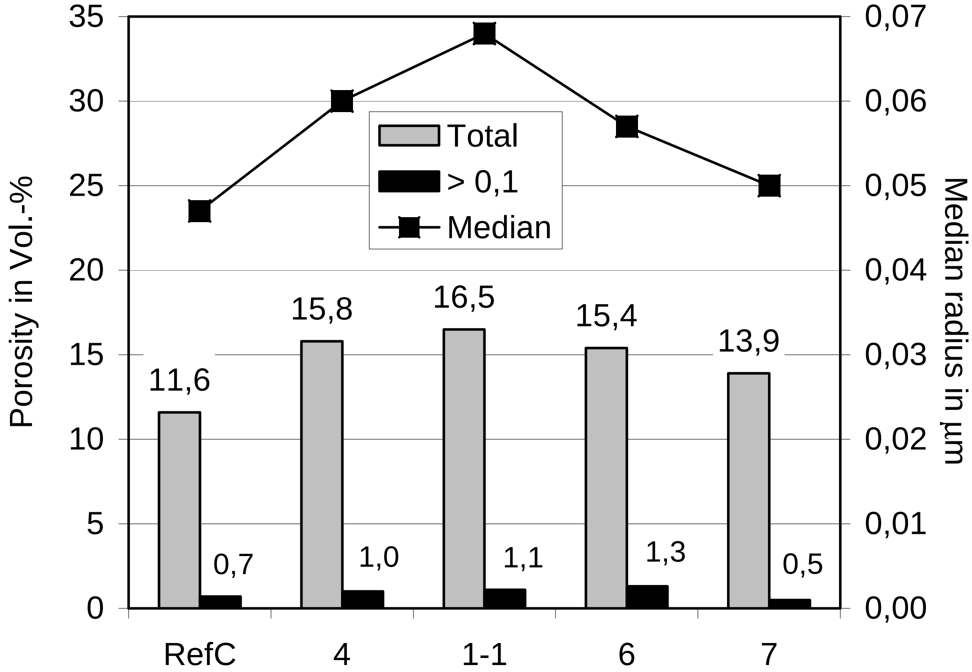
### 4.2.7 Microstructure (Porosity and Pore size distribution)

Results are compiled in table 7.

Table 1: Results of mercury intrusion porosimetry on mortars with w/c = 0.50

| Cement | Age | $\rho_{Hg}$ | $\rho_{g,Hg}$ | Porosity | | | | Median radius | Threshold radius | Internal surface area |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | total | ≤ 0,01 | ≤ 0,1 | > 0,1 | | | |
| | | | | | µm | | | | | |
| | | g/cm³ | | vol.% | | | | µm | | m²/g |
| RefC | 2d | 2,59 | 2,17 | 16,0 | 2,3 | 10,8 | 5,2 | 0,069 | 0,20 | 6,3 |
| | 28d | 2,49 | 2,20 | 11,6 | 2,3 | 11,0 | 0,7 | 0,047 | 0,06 | 6,6 |
| | 90d | 2,47 | 2,18 | 11,7 | 2,3 | 11,1 | 0,6 | 0,044 | 0,06 | 6,6 |
| 4 | 28d | 2,48 | 2,09 | 15,8 | 1,8 | 14,8 | 1,0 | 0,060 | 0,07 | 6,4 |
| 1-1 | 2d | 2,54 | 2,07 | 18,3 | 2,1 | 10,1 | 8,2 | 0,213 | 0,25 | 6,3 |
| | 28d | 2,51 | 2,09 | 16,5 | 1,8 | 15,4 | 1,1 | 0,068 | 0,09 | 6,6 |
| | 91d | 2,48 | 2,09 | 15,8 | 1,8 | 15,0 | 0,8 | 0,058 | 0,07 | 6,7 |
| 6 | 2d | 2,51 | 2,08 | 17,2 | 2,2 | 10,6 | 6,5 | 0,159 | 0,23 | 6,6 |
| | 28d | 2,47 | 2,09 | 15,4 | 2,4 | 14,1 | 1,3 | 0,057 | 0,06 | 7,3 |
| | 91d | 2,48 | 2,12 | 14,6 | 2,1 | 13,8 | 0,8 | 0,052 | 0,06 | 6,9 |
| 7 | 28d | 2,48 | 2,16 | 13,9 | 2,2 | 13,4 | 0,5 | 0,050 | 0,06 | 6,9 |
| each figure is an average value of two measurements | | | | | | | | | | |

It can be concludes from table 7 and figure 1, that the replacement of Portland cement clinker by limestone can lead to a higher total porosity and a higher amount of capillary pores > 0,1 µm and a higher median pore radius. The use of already 10 % of ggbs together with 25 % limestone and 65 % Portland cement clinker leads to a significant reduction of all three parameters. Even the total porosity is still higher then that of the mortar with Portland cement, the amount of capillary pores > 0,1 µm and the median pore radius are in the range of the mortar with the Portland cement.




| | | | | | | |
|---|---|---|---|---|---|---|
| Clinker | 100 K1 | 80 K1 | 65 K1 | 65 K1 | 65 K1 | % |
| GGBS | - | - | - | 5 S1 | 10 S1 | % |
| Limestone | - | 20 LL1 | 35 LL1 | 30 LL1 | 25 LL1 | % |

Figure 1: Total porosity, porosity > 0,1 mm and median radius of mortars with w/c = 0.50

### 4.2.8 Concrete

Table 8 gives an overview about the concrete mixes and the test methods.

Table 8: Overview of concrete mixes under investigation

| Cement | c<br>kg/m³ | w/c | AEA | $f_{cm}$<br>28 d | $d_c$ | $D_{Cl, M}$ | CT | BT | CF/CIF | CDF | ST |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| RefC | 300 | 0,60 | - | x | - | - | x | - | - | - | - |
| | 320 | 0,50 | - | x | - | x | - | - | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | - |
| CEM 1-0 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 1-2 | 300 | 0,60 | - | x | x | - | - | - | - | - | - |
| | 320 | 0,50 | - | x | - | - | - | x | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | x |
| CEM 2-2 | 300 | 0,60 | - | x | x | - | - | - | - | - | - |
| CEM 3-2 | 300 | 0,60 | - | x | x | - | - | - | - | - | - |
| CEM 4 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 5 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 6 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 7 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 8 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 9 | 320 | 0,50 | - | x | - | x | - | - | - | - | - |
| CEM 12-1 | 280 | 0,60 | - | x | x | - | - | - | - | - | - |
| | 300 | 0,60 | - | x | x | - | x | - | - | - | - |
| | 320 | 0,50 | - | x | - | x | - | x | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | x |
| CEM 13-1 | 300 | 0,60 | - | x | x | - | x | - | - | - | - |
| | 320 | 0,50 | - | x | - | x | - | x | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | x |

Table 8: Continuation

| Cement | c kg/m$^3$ | w/c | AEA | $f_{cm}$ 28 d | $d_c$ | $D_{Cl, M}$ | CT | BT | CF/CIF | CDF | ST |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| CEM 14 | 300 | 0,60 | - | x | - | - | x | - | - | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | - |
| CEM 15 | 300 | 0,60 | - | x | x | - | x | - | - | - | - |
| | 320 | 0,50 | - | x | - | x | - | x | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | - |
| CEM 16 | 300 | 0,60 | - | x | - | - | x | - | - | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | - |
| CEM 17 | 300 | 0,60 | - | x | - | - | x | - | - | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | - |
| CEM 18 | 300 | 0,60 | - | x | x | - | x | - | - | - | - |
| | 320 | 0,50 | - | x | - | x | - | x | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | x |
| CEM 19 | 300 | 0,60 | - | x | x | - | x | - | - | - | - |
| | 320 | 0,50 | - | x | - | x | - | x | x | - | - |
| | 320 | 0,50 | x | x | - | - | - | - | - | x | x |

AEA: Air entraining agent

$f_{cm}$: Concrete compressive strength

$d_c$: Depth of carbonation

$D_{Cl, M}$: Rapid chloride migration method

CT: Cube test acc. to prENV 12390-9

BT: Beam test acc. to CEN Report "Testing the Freeze-thaw Resistance of Concrete – Internal Structural Damage" (Feb. 2003)

CF/CIF: CF test acc. to prENV 12390-9 / CIF test acc. to CEN Report "Testing the Freeze-thaw Resistance of Concrete – Internal Structural Damage" (Feb. 2003)

CDF: CDF test acc. to prENV 12390-9

ST: Slab test acc. to prENV 12390-9

#### 4.2.8.1 Fresh concrete properties

Fresh concrete properties of all investigates concrete mixes are compiled in table 9.

Table 9: Content of superplastizicer SP and Air entraining agent AEA; Fresh concrete properties: Density $\rho_f$, Flow diameter a, Degree of compactibiliy v, Air void content AC, Temperature $T_f$

| c | w/c | Concrete | Cement | AEA | $\rho_f$ | $a_{10}$ | $v_{10}$ | $AC_{10}$ | $T_f$ |
|---|---|---|---|---|---|---|---|---|---|
| kg/m³ | | | | mass% of c | kg/dm³ | mm | - | vol% | °C |
| 280 | 0,60 | C1 | RefC | - | 2,360 | 410 | - | 1,8 | 21 |
| | | | 12-1 | - | 2,355 | 440 | - | 1,3 | 24 |
| 300 | 0,60 | C2 | RefC | - | 2,380 | 470 | 1,09 | 1,5 | 21 |
| | | | 1-2 | - | 2,340 | 390 | - | 1,6 | 22 |
| | | | 2-2 | - | 2,330 | 400 | - | 1,7 | 21 |
| | | | 3-2 | - | 2,350 | 410 | - | 1,2 | 21 |
| | | | 12-1 | - | 2,340 | 420 | - | 1,2 | 22 |
| | | | 13-1 | - | 2,340 | 470 | - | 1,0 | 19 |
| | | | 15 | - | 2,340 | 400 | - | 1,1 | n. d. |
| | | | 14 | - | 2,350 | 400 | - | 1,6 | 20 |
| | | | 16 | - | 2,350 | 410 | - | n. d. | 21 |
| | | | 17 | - | 2,350 | 410 | - | 1,0 | 21 |
| | | | 18 | - | 2,350 | 420 | - | 1,1 | 23 |
| | | | 19 | - | 2,340 | 410 | - | 1,1 | 21 |
| 320 | 0,50 | C3 | RefC | - | 2,370 | 410 | - | 2,1 | 19 |
| | | | 1-2 | - | 2,380 | - | 1,31 | 1,4 | 21 |
| | | | 4 | - | 2,360 | 390 | 1,20 | 2,0 | 23 |
| | | | 5 | - | 2,360 | - | 1,47 | 1,8 | 24 |
| | | | 6 | - | 2,380 | - | 1,37 | 1,7 | n. d. |
| | | | 7 | - | 2,360 | - | 1,37 | 1,8 | 24 |
| | | | 8 | - | 2,360 | - | 1,31 | 1,5 | 23 |
| | | | 9 | - | 2,370 | - | 1,31 | 1,6 | 20 |
| | | | 12-1 | - | 2,360 | - | 1,28 | 1,4 | 23 |
| | | | 13-1 | - | 2,350 | - | 1,29 | 1,5 | 21 |
| | | | 15 | - | 2,360 | - | 1,33 | 1,6 | 22 |
| | | | 18 | - | 2,370 | - | 1,32 | 1,3 | 20 |
| | | | 19 | - | 2,355 | - | 1,31 | 1,5 | 21 |
| | | C4 | RefC | 0,036 | 2,300 | 380 | - | 5,0 | 20 |
| | | | 1-2 | 0,15 | 2,285 | - | 1,21 | 4,6 | 21 |
| | | | 13-1 | 0,17 | 2,290 | - | 1,16 | 4,9 | 21 |
| | | | 14 | 0,12 | 2,260 | - | 1,23 | 5,2 | 22 |
| | | | 15 | 0,17 | 2,245 | 330 | - | 5,2 | 20 |
| | | | 16 | 0,15 | 2,250 | 310 | - | 5,1 | 21 |
| | | | 17 | 0,15 | 2,260 | - | 1,38 | 4,8 | 22 |
| | | | 18 | 0,15 | 2,260 | 360 | - | 5,2 | 20 |
| | | | 19 | 0,19 | 2,260 | 370 | 1,26 | 4,9 | 21 |

#### 4.2.8.2 Strength development

All determined compressive strength values are are compiled in tables 10 to 15.

Table 10: Compressive strength development of concretes with c = 320 kg/m³ and w/c = 0.50

| Age | Specimen | Cement | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | RefC | 1-0 | 4 | 6 | 7 | 8 | 9 | 5 |
| d | | N/mm² | | | | | | | |
| 2 | 1 | 23,1 | 22,7 | 26,2 | 27,9 | 26,6 | 24,1 | 21,1 | 30,0 |
| | 2 | 24,3 | 23,5 | 26,1 | 28,2 | 27,6 | 23,8 | 21,4 | 30,4 |
| | 3 | 24,5 | 23,6 | 26,1 | 27,6 | 26,8 | 24,0 | 21,0 | 31,0 |
| | MV | 24,0 | 23,3 | 26,2 | 27,9 | 27,0 | 24,0 | 21,2 | 30,5 |
| 7 | 1 | 39,2 | 31,4 | 33,7 | 41,2 | 37,0 | 36,6 | 35,9 | 39,4 |
| | 2 | 38,8 | 32,0 | 32,2 | 40,4 | 37,3 | 36,6 | 36,5 | 39,3 |
| | 3 | 40,0 | 31,1 | 33,6 | 41,5 | 37,5 | 36,3 | 35,5 | 38,7 |
| | MV | 39,4 | 31,5 | 33,2 | 41,0 | 37,3 | 36,5 | 36,0 | 39,1 |
| 28 | 1 | 55,9 | 43,1 | 45,4 | 55,4 | 49,7 | 51,0 | 56,5 | 51,7 |
| | 2 | 55,7 | 43,8 | 46,1 | 55,1 | 50,1 | 50,7 | 57,9 | 52,6 |
| | 3 | 55,5 | 44,2 | 46,3 | 56,2 | 49,1 | 50,7 | 56,6 | 52,4 |
| | MV | 55,7 | 43,7 | 46,0 | 55,6 | 49,6 | 50,8 | 57,0 | 52,2 |
| 91 | 1 | 61,5 | 48,9 | 51,7 1) | 59,6 | 56,8 | 57,6 | 65,8 | 58,4 2) |
| | 2 | 60,3 | 49,5 | 52,4 1) | 62,2 | 55,7 | 57,8 | 65,7 | 56,6 2) |
| | 3 | 60,9 | 49,6 | 52,5 1) | 60,2 | 56,3 | 58,7 | 64,1 | 56,8 2) |
| | MV | 60,9 | 49,3 | 52,2 | 60,7 | 56,3 | 58,0 | 65,2 | 57,3 |

MV: Mean value 1) Test age: 88 d 2): Test age: 87 d

Table 11: Compressive strength development of concretes with c = 300 kg/m³ and w/c = 0.60

| Age | Specimen | Cement | | | | |
|---|---|---|---|---|---|---|
| | | 12-1 | 13-1 | 15 | 18 | 19 |
| d | | N/mm² | | | | |
| 2 | 1 | 16,8 | 7,29 | 22,6 | 16,9 | 8,1 |
| | 2 | 17,6 | 7,47 | 22,0 | 16,9 | 8,7 |
| | 3 | 16,8 | 7,32 | 21,6 | 17,5 | 7,9 |
| | MV | 17,1 | 7,36 | 22,1 | 17,1 | 8,2 |
| 7 | 1 | 29,0 | 19,0 | 31,0 | 27,3 | 21,3 |
| | 2 | 28,5 | 19,1 | 30,0 | 27,9 | 21,8 |
| | 3 | 29,5 | 19,3 | 30,9 | 27,8 | 21,6 |
| | MV | 29,0 | 19,1 | 30,6 | 27,7 | 21,5 |
| 28 | 1 | 42,7 | 31,3 | 40,5 | 41,1 | 33,1 |
| | 2 | 41,1 | 30,2 | 41,2 | 40,6 | 33,1 |
| | 3 | 41,2 | 29,1 | 40,5 | 39,1 | 33,8 |
| | MV | 41,7 | 30,2 | 40,7 | 40,3 | 33,3 |
| 91 | 1 | R. f. | R. f. | R. f. | R. f. | R. f. |
| | 2 | R. f. | R. f. | R. f. | R. f. | R. f. |
| | 3 | R. f. | R. f. | R. f. | R. f. | R. f. |
| | MV | - | - | - | - | - |

R. f.: Results follow
MV: Mean value

Table 12: 28d-Compressive strength of concretes with c = 280/300 kg/m$^3$ and w/c = 0.60

| Age | Specimen | Cement | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RefC | 2-1 | 3-1 | 4-2 | 1-0 | 6 | 8-3 | 12-1 1) | 12-1 | 13-1 |
| d | | N/mm$^2$ | | | | | | | | | |
| 28 | 1 | 34,7 | 37,8 | 34,5 | 32,3 | 30,4 | 35,2 | 34,3 | 39,2 | 42,7 | 31,3 |
| | 2 | 37,6 | 38,5 | 33,6 | 34,5 | 30,3 | 34,5 | 34,1 | 39,2 | 41,1 | 30,2 |
| | 3 | 35,2 | 37,6 | 34,3 | 32,7 | 31,3 | 35,8 | 35,5 | 38,3 | 41,2 | 29,1 |
| | MV | 35,8 | 38,0 | 34,1 | 33,2 | 30,7 | 35,2 | 34,6 | 38,9 | 41,7 | 30,2 |
| 1) | c = 280 kg/m$^3$ | | | | | | | | | | |

Table 13: 28d-Compressive strength of concretes with c = 280/300 kg/m$^3$ and w/c = 0.60

| Age | Specimen | Cement | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1-2 | 2-2 | 3-2 | 14 | 15 | 16 | 17 | 18 | 19 |
| d | | N/mm$^2$ | | | | | | | | |
| 28 | 1 | 41,7 | 39,6 | 40,9 | 40,7 | 40,5 | 42,9 | 38,2 | 41,1 | 33,1 |
| | 2 | 41,2 | 39,9 | 40,3 | 41,0 | 41,2 | 41,2 | 39,1 | 40,6 | 33,1 |
| | 3 | 41,5 | 40,1 | 41,1 | 39,6 | 40,5 | 43,7 | 38,9 | 39,1 | 33,8 |
| | MV | 41,5 | 39,9 | 40,7 | 40,4 | 40,7 | 42,6 | 38,8 | 40,3 | 33,3 |

Table 14: 28d-Compressive strength of concretes with c = 320 kg/m$^3$ and w/c = 0.50

| Age | Specimen | Cement | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | RefC | 1-2 | 12-1 | 13-1 | 15 | 18 | 19 |
| d | | N/mm$^2$ | | | | | | |
| 28 | 1 | 55,9 | 55,7 | 53,6 | 45,3 | 53,5 | 57,8 | 45,0 |
| | 2 | 55,7 | 55,0 | 54,0 | 44,7 | 53,1 | 58,0 | 45,4 |
| | 3 | 55,5 | 56,8 | 54,3 | 45,7 | 53,4 | 58,5 | 44,1 |
| | MV | 55,7 | 55,9 | 54,0 | 45,2 | 53,3 | 58,1 | 44,8 |

Table 15: 28d-Compressive strength of concretes with c = 320 kg/m$^3$ and w/c = 0.50 and artifical air-voids

| Age | Specimen | Cement | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RefC | 1-2 | 12-1 | 13-1 | 14 | 15 | 16 | 17 | 18 | 19 |
| d | | N/mm$^2$ | | | | | | | | | |
| 28 | 1 | 43,0 | 43,4 | 43,9 | 36,5 | 37,7 | 35,7 | 37,8 | 39,3 | 43,1 | 37,5 |
| | 2 | 44,0 | 43,3 | 45,5 | 35,0 | 38,0 | 35,5 | 37,2 | 40,2 | 42,8 | 36,9 |
| | 3 | 45,1 | 43,1 | 45,0 | 35,8 | 37,6 | 36,3 | 36,8 | 40,0 | 43,9 | 37,5 |
| | MV | 44,0 | 43,3 | 44,8 | 35,8 | 37,8 | 35,8 | 37,2 | 39,8 | 43,3 | 37,3 |

#### 4.2.8.3 Carbonation

The carbonation depth was tested using beams 100 x 100 x 400 $mm^3$. Curing regime: 1d moulded, 6d water storage, (20±2) °C / (65±5) % r. H. Evaporation in the climate chamber was (45±15) g/($m^2$×h). Carbonation was test on concrete with c = 280/300 $kg/m^3$ and w/c = 0.60. Results are compiled in table 16.

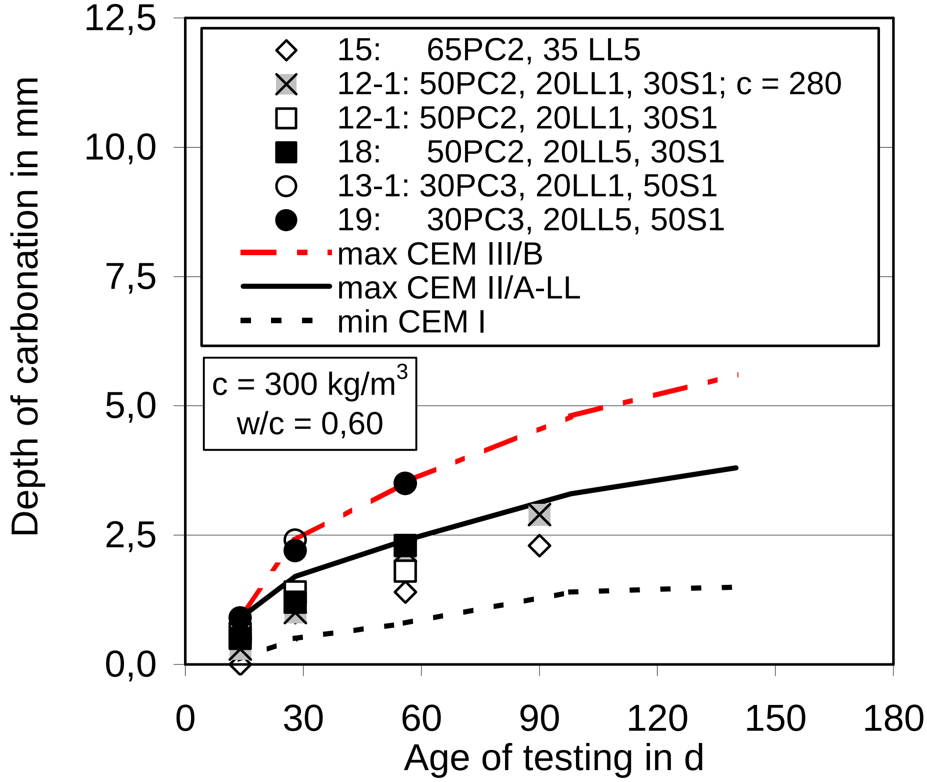
Table 16: Depth of carbonation of concretes with c = 280/300 $kg/m^3$ and w/c = 0.60

| Age | Specimen | Cement | | | | | |
|---|---|---|---|---|---|---|---|
| | | 12-1 1) | 12-1 | 13-1 | 15 | 18 | 19 |
| d | | mm | | | | | |
| 14 | 1 | 0,3 | 0,6 | 0,6 | n. d. | 0,5 | 1,0 |
| | 2 | 0,4 | 0,6 | 0,5 | n. d. | 0,5 | 0,8 |
| | 3 | 0,3 | 0,5 | 0,5 | n. d. | 0,5 | 0,9 |
| | MV | 0,3 | 0,6 | 0,5 | - | 0,5 | 0,9 |
| 28 | 1 | 0,9 | 1,5 | 2,3 | 1,0 | 1,0 | 2,3 |
| | 2 | 1,0 | 1,5 | 2,4 | 1,0 | 1,3 | 2,1 |
| | 3 | 1,3 | 1,3 | 2,5 | 1,0 | 1,3 | 2,1 |
| | MV | 1,0 | 1,4 | 2,4 | 1,0 | 1,2 | 2,2 |
| 56 | 1 | 2,1 | 1,9 | 3,4 | 1,4 | 2,5 | 3,5 |
| | 2 | 2,3 | 1,8 | 3,4 | 1,3 | 2,1 | 3,4 |
| | 3 | 2,3 | 1,6 | 3,6 | 1,6 | 2,1 | 3,5 |
| | MV | 2,2 | 1,8 | 3,5 | 1,4 | 2,3 | 3,5 |
| ~90 | 1 | 2,9 | R. f. | R. f. | 2,1 | R. f. | R. f. |
| | 2 | 2,8 | R. f. | R. f. | 2,4 | R. f. | R. f. |
| | 3 | 3,0 | R. f. | R. f. | 2,3 | R. f. | R. f. |
| | MV | 2,9 | - | - | 2,3 | - | - |
| ~180 | 1 | R. f. | R. f. | R. f. | R. f. | R. f. | R. f. |
| | 2 | R. f. | R. f. | R. f. | R. f. | R. f. | R. f. |
| | 3 | R. f. | R. f. | R. f. | R. f. | R. f. | R. f. |
| | MV | - | - | - | - | - | - |

R. f.: Result following
1) c = 280 $kg/m^3$

In figure 2 these results are plotted in comparison to values for concrete with CEM I, CEM II/A-LL and CEM III/B taken from previous investigations [7, 14]. Up to 90 d the carbonation depth of the concretes with clinker contents of 50 and 65 % were in the range for concrete with Portland limestone cements CEM II/A-LL reported in [7].

Concretes using cements with a clinker content of only 30 % showed carbonation depth comparable to values reported for concrete with CEM III/B in [14]. As a consequence the carbonation depth for all investigated concretes was in the range of concrete with cements which are allowed to use in exposure classes with regard to carbonation induced corrosion.




max CEM III/B acc. to [14]; min CEM I and max CEM II/A-LL acc. to [7]

Figure 2: Depth of carbonation of concretes with c = 280/300 kg/m$^3$ and w/c = 0.60

### 4.2.8.4 Penetration of chlorides

Table 17 and Figure 3 show the influence of limestone and blastfurnace slag on the resistance of concrete against chloride penetration including some of the cements given in tables 5 and 6. In general the migration coefficients shown in figure 3 are comparable to diffusion coefficients but they are somewhat higher because the chloride penetration is accelerated using a potential of about 30 volts. The rapid chloride migration method (RCM) is decribed in the report on the Brite EuRam III project DuraCrete [4].

The exclusive use of limestone meal besides clinker in a range up to 35 % may lead to a resistance against chloride penetration in the range of Portland cement – as it can be seen in this example. On the other hand there is the benefit of slag – in this figure represented by Portland slag cement (CEM 9) with a slag content of 35 %.

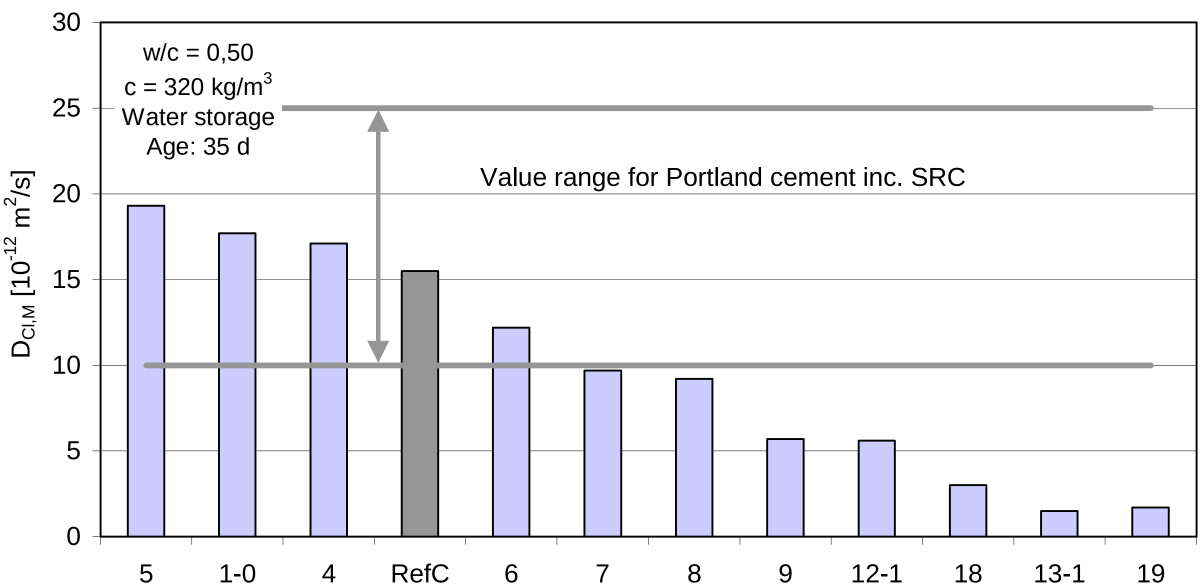
Table 17: Chlorid-Migration-Coeffizient $D_{Cl,\ M}$ of concretes with c = 320 kg/m$^3$ and w/c = 0.50

| Cement | Curing | Age | Temperature | Time | Penetration depth | | $D_{Cl,\ M}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | | | SV | MV | SV | MV |
| | | d | K | s | | | | |
| RefC | W | 35 | 292,95 | 29700 | 13,5<br>11,3<br>11,5 | 12,1 | 17,4<br>14,5<br>14,7 | 15,5 |
| 1-0 | W | 35 | 292,60 | 28800 | 13,60<br>13,20<br>13,30 | 13,4 | 18,0<br>17,4<br>17,5 | 17,7 |
| 4 | W | 35 | 293,78 | 28200 | 11,80<br>13,30<br>12,70 | 12,6 | 16,0<br>18,1<br>17,3 | 17,1 |
| 5 | W | 35 | 293,63 | 30600 | 15,9<br>15,1<br>14,8 | 15,3 | 20,2<br>19,1<br>18,7 | 19,3 |
| 6 | W | 35 | 292,98 | 86400 | 27,40<br>25,20<br>28,80 | 27,1 | 12,4<br>11,3<br>13,0 | 12,2 |
| 7 | W | | 293,54<br>293,54<br>293,54 | 85800 | 20,8<br>21,4<br>21,5 | 21,2 | 9,5<br>9,8<br>9,8 | 9,7 |
| 8 | W | 35 | 293,88 | 86400 | 20,3<br>20,5<br>19,7 | 20,4 | 9,2<br>9,3<br>8,9 | 9,2 |
| 9 | W | 35 | 293,95 | 86400 | 12,6<br>13,8<br>12,6 | 12,9 | 5,6<br>6,1<br>5,6 | 5,7 |
| 12-1 | W | 35 | 292,20 | 106500 | 16,2<br>15,2<br>15,2 | 15,5 | 5,8<br>5,5<br>5,5 | 5,6 |
| | | 98 | 292,09 | 265200 | 16,9<br>15,4<br>16,8 | 16,4 | 2,5<br>2,2<br>2,5 | 2,4 |

Table 17: Continuation

| Cement | Curing | Age | Temperature | Time | Penetration depth | | $D_{Cl,M}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | | | SV | MV | SV | MV |
| | | d | K | s | | | | |
| 13-1 | | 35 | 292,17 | 346200 | 13,0<br>13,9<br>12,0 | 13,0 | 1,5<br>1,6<br>1,3 | 1,5 |
| 18 | | 35 | 292,55 | 174300 | 14,4<br>-<br>12,5 | 13,5 | 3,2<br>-<br>2,7 | 3,0 |
| 19 | | 35 | 292,53 | 269400 | 11,3<br>10,7<br>13,6 | 11,9 | 1,6<br>1,5<br>1,9 | 1,7 |

W: Water storage until testing




SCR = Sulfate resisting cements

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Clinker | 65 K1 | 65 K1 | 70 K1 | 100 K1 | 65 K1 | 65 K1 | 65 K1 | 65 K1 | 50PC2 | 50PC2 | 30PC3 | 30PC3 | % |
| Slag | - | - | - | - | 5 S1 | 10 S1 | 15 S1 | 35 S1 | 30S1 | 30S1 | 50S1 | 50S1 | % |
| Limestone | 35 LL2 | 35 LL1 | 30 LL1 | - | 30 LL1 | 25 LL1 | 20 LL1 | - | 20 LL1 | 20 LL5 | 20 LL1 | 20 LL5 | % |
| $f_{cm}$ in MPa | 52.2 | 43.7 | 46.0 | 56.7 | 53.4 | 49.6 | 50.8 | 57.0 | 54.0 | 58.1 | 45.2 | 44.8 | - |

Figure 3: Chloride migration coefficient $D_{Cl,M}$ of concrete with w/c = 0.50 und c = 320 kg/m$^3$ – Cements acc. to tables 5 to 7 - Water storage

Concretes using cements outside the scope of EN 197-1 with 20 % limstone and 50 % clinker/30 % blast furnace slag or 30 % clinker/50 % blast furnace also show a very good performance with regard to the resistance against chloride penetration.

#### 4.2.8.5 Freeze-thaw resistance

Concrete structures must possess adequate resistance to environmental impacts during their service life. Depending on the types of exposure a structure or component undergoes, this includes adequate resistance to freeze-thaw or freeze-thaw with de-icing salt. The applicable regulations usually specify requirements to be met by constituents and concrete composition in accordance with the respective exposure classes assigned. These concrete technology specifications are based on many years of experience with normal strength concrete gathered in building practice. Many different test methods have been developed. No single test method can completely reproduce the conditions in the field in all individual cases. Nevertheless, any method should at least correlate to the practical situation and give consistent results. Such a test method may not be suitable for deciding whether the resistance is adequate in a specific instance but will provide data of the resistance of the concrete to freeze-thaw-attack and freeze-thaw-attack in the presence of de-icing agents. If the concrete has inadequate resistance then the freeze-thaw attack can lead to two different types of damage, namely to scaling (surface weathering) and to internal structural damage. The European prestandard prENV 12390-9 covers testing for scaling resistance. This European prestandard has one reference method (slab test) and two alternative methods (cube test and CF/CDF-test). A CEN Report describes the testing for internal structural damage. This CEN Report contains three different test methods, which are well proved in different parts of Europe: beam test, slab test and CIF-test. Always they produce consistent results. For that reason no single test method can be established as reference test method.

Cube test

Results of the cube test are compiled in table 18.

Cube specimens, immersed in de-ionised water are subjected to freeze thaw attack. The freeze-thaw resistance is evaluated by the measurement of mass loss of the cubes.

Table 18: Scaling and relative dynamic modulus of elasticity (RDM) of concretes with c = 300 kg/m$^3$ and w/c = 0.60 tested with the cube test

| Cement | No. of FTC | Scaling | | | rel. dyn. E | | |
|---|---|---|---|---|---|---|---|
| | | Specimen | | Mean | Specimen 1) | | Mean |
| | | 1+2 | 3+4 | | 1+2 | 3+4 | |
| | | M.-% | | | % | | |
| RefC | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,10 | 0,11 | 0,10 | 101,0 | 101,0 | 101,0 |
| | 28 | 0,16 | 0,15 | 0,16 | 102,0 | 102,4 | 102,2 |
| | 56 | 0,23 | 0,22 | 0,23 | 102,8 | 103,4 | 103,1 |
| | 74 | 0,28 | 0,25 | 0,27 | 103,3 | 102,9 | 103,1 |
| | 100 | 0,37 | 0,34 | 0,36 | 102,8 | 102,4 | 102,6 |
| 1-2 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,15 | 0,12 | 0,13 | 102,8 | 104,2 | 103,5 |
| | 28 | 0,34 | 0,22 | 0,28 | 101,4 | 104,2 | 102,8 |
| | 56 | 0,95 | 0,72 | 0,83 | 99,6 | 103,7 | 101,6 |
| | 74 | 1,24 | 0,99 | 1,12 | 98,7 | 103,7 | 101,2 |
| | 100 | 2,34 | 1,94 | 2,14 | 94,7 | 99,6 | 97,1 |
| 2-2 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,28 | 0,29 | 0,29 | 103,2 | 104,1 | 103,6 |
| | 28 | 0,57 | 0,77 | 0,67 | 101,3 | 100,4 | 100,9 |
| | 56 | 1,55 | 1,86 | 1,71 | 98,7 | 97,4 | 98,0 |
| | 74 | 2,24 | 2,75 | 2,50 | 97,4 | 95,8 | 96,6 |
| | 100 | 3,61 | 4,52 | 4,06 | 94,0 | 92,6 | 93,3 |
| 3-2 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,14 | 0,15 | 0,15 | 103,8 | 103,2 | 103,5 |
| | 28 | 0,35 | 0,40 | 0,37 | 101,9 | 101,8 | 101,8 |
| | 56 | 1,01 | 1,10 | 1,06 | 98,2 | 97,3 | 97,8 |
| | 80 | 1,91 | 1,82 | 1,87 | 96,8 | 95,2 | 96,0 |
| | 100 | 2,81 | 3,13 | 2,97 | 94,7 | 91,5 | 93,1 |
| 12-1 | 0 | 0,00 | - | 0,00 | 100,0 | - | 100,0 |
| | 14 | 0,14 | - | 0,14 | 98,1 | - | 98,1 |
| | 28 | 0,43 | - | 0,43 | 95,9 | - | 95,9 |
| | 58 | 1,40 | - | 1,40 | 81,8 | - | 81,8 |
| | 72 | 2,01 | - | 2,01 | 74,6 | - | 74,6 |
| | 100 | 3,03 | - | 3,03 | 55,4 | - | 55,4 |
| 13-1 | 0 | 0,00 | - | 0,00 | 100,0 | - | 100,0 |
| | 14 | 1,71 | - | 1,71 | 92,5 | - | 92,5 |
| | 28 | 3,22 | - | 3,22 | 91,3 | - | 91,3 |
| | 56 | 4,90 | - | 4,90 | 78,3 | - | 78,3 |
| | 74 | 5,83 | - | 5,83 | 63,2 | - | 63,2 |
| | 100 | 7,42 | - | 7,42 | 53,5 | - | 53,5 |

Table 18: Continuation

| Cement | No. of FTC | Scaling | | | rel. dyn. E | | |
|---|---|---|---|---|---|---|---|
| | | Specimen | | Mean | Specimen 1) | | Mean |
| | | 1+2 | 3+4 | | 1+2 | 3+4 | |
| | | M.-% | | | % | | |
| 14 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,15 | 0,14 | 0,14 | 102,3 | 100,9 | 101,6 |
| | 28 | 0,36 | 0,57 | 0,47 | 101,4 | 100,9 | 101,2 |
| | 56 | 1,23 | 1,68 | 1,45 | 93,6 | 96,4 | 95,0 |
| | 74 | 2,00 | 2,85 | 2,42 | 85,8 | 87,8 | 86,8 |
| | 100 | 3,45 | 4,91 | 4,18 | 80,9 | 80,6 | 80,8 |
| 15 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,13 | 0,10 | 0,12 | 97,7 | 100,9 | 99,3 |
| | 28 | 0,40 | 0,30 | 0,35 | 95,6 | 98,2 | 96,9 |
| | 56 | 1,28 | 1,19 | 1,24 | 84,0 | 86,0 | 85,0 |
| | 72 | 2,10 | 2,04 | 2,07 | 73,4 | 76,0 | 74,7 |
| | 100 | 3,34 | 4,04 | 3,69 | 65,7 | 62,3 | 64,0 |
| 16 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,15 | 0,13 | 0,14 | 101,4 | 101,9 | 101,6 |
| | 28 | 0,30 | 0,31 | 0,30 | 96,0 | 99,1 | 97,5 |
| | 56 | 1,06 | 0,98 | 1,02 | 91,4 | 95,2 | 93,3 |
| | 72 | 1,46 | 1,36 | 1,41 | 86,3 | 91,9 | 89,1 |
| | 100 | 3,34 | 3,02 | 3,18 | 80,4 | 86,1 | 83,2 |
| 17 | 0 | 0,00 | 0,00 | 0,00 | 100,0 | 100,0 | 100,0 |
| | 14 | 0,25 | 0,21 | 0,23 | 100,5 | 99,5 | 100,0 |
| | 28 | 0,63 | 0,72 | 0,67 | 96,5 | 93,5 | 95,0 |
| | 56 | 2,16 | 2,29 | 2,23 | 87,0 | 78,1 | 82,5 |
| | 72 | 3,13 | 3,30 | 3,22 | 78,0 | 68,2 | 73,1 |
| | 100 | 6,77 | 7,13 | 6,95 | 56,6 | 66,3 | 61,5 |
| 18 | 0 | 0,00 | - | 0,00 | 100,0 | - | 100,0 |
| | 14 | 0,18 | - | 0,18 | 97,7 | - | 97,7 |
| | 28 | 0,51 | - | 0,51 | 93,8 | - | 93,8 |
| | 56 | 1,62 | - | 1,62 | 72,8 | - | 72,8 |
| | 73 | 2,49 | - | 2,49 | 60,9 | - | 60,9 |
| | 98 | 3,28 | - | 3,28 | 49,9 | - | 49,9 |
| 19 | 0 | 0,00 | - | 0,00 | 100,0 | - | 100,0 |
| | 14 | 1,08 | - | 1,08 | 96,8 | - | 96,8 |
| | 28 | 2,05 | - | 2,05 | 93,4 | - | 93,4 |
| | 56 | 3,85 | - | 3,85 | 82,9 | - | 82,9 |
| | 74 | 4,58 | - | 4,58 | 76,0 | - | 76,0 |
| | 100 | 5,83 | - | 5,83 | 70,2 | - | 70,2 |

1) mean value of two cubes in one container

It is well known from previous investigations, that to some extend a correlation exsists between the specific surface acc. to BET and the specific clay mineral content in g/g (Ca + Mg)$CO_3$ (Figure 4) and that the clay content of the limestone to some extent can influence the freeze thaw resistance of concrete.

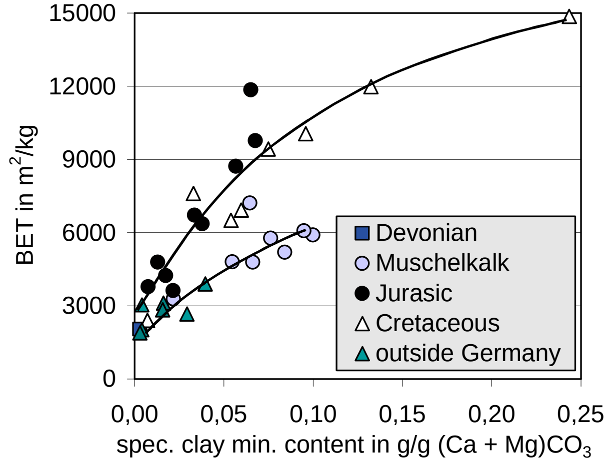



Figure 4: Limestone – Specific surface acc. to BET dependent on the specific clay mineral content acc. to [13]

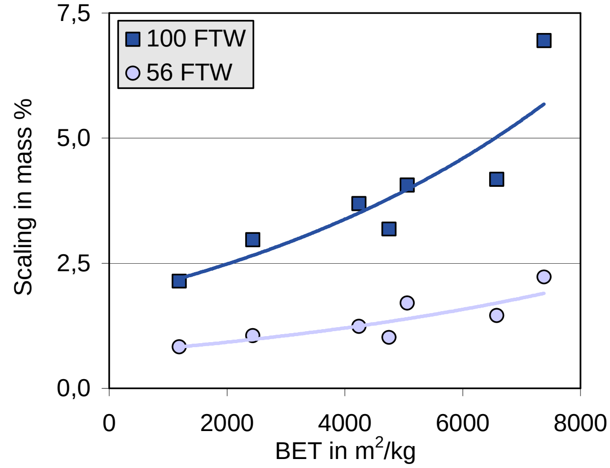



Figure 5: Scaling of concrete (w/c = 0,60; c = 300 kg/m$^3$) using CEM II/B-LL with 35 % limestone dependent of the BET surface of the limestone

For the concretes with w/c = 0,60 and c = 300 kg/m$^3$ using CEM II/B-LL with 35 % limestone a correlation between the scaling determined in the cube test and the BET surface of the limestone was established acc. to figure 5.

Beam test

Beams with a dimension of 400 mm x 100 mm x 100 mm are subjected to freeze-thaw attack in presence of de-ionised water. The freeze-thaw resistance is measured as relative dynamic modulus of elasticity by using fundamental transverse frequency respectively after 56 freeze-thaw cycles. Results are complied in table 19.

Table 19: Relative dynamic modulus of elasticity (RDM) of concretes with c = 320 kg/m$^3$ and w/c = 0.50 tested with the beam test

| Cement | No. of FTC | Beam No. | | | Mean |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| | | % | | | |
| 1-2 | 0 | 100,0 | 100,0 | 100,0 | 100,0 |
| | 14 | 98,2 | 98,4 | 98,4 | 98,3 |
| | 28 | 98,4 | 98,4 | 98,6 | 98,5 |
| | 44 | 98,8 | 98,6 | 98,2 | 98,5 |
| | 56 | 98,8 | 98,9 | 98,1 | 98,6 |
| 12-1 | 0 | 100,0 | 100,0 | 100,0 | 100,0 |
| | 14 | 98,5 | 98,1 | 97,9 | 98,2 |
| | 28 | 98,2 | 98,6 | 98,6 | 98,5 |
| | 42 | 99,3 | 99,2 | 99,2 | 99,2 |
| | 56 | 99,9 | 99,7 | 99,7 | 99,8 |
| 13-1 | 0 | 100,0 | 100,0 | 100,0 | 100,0 |
| | 14 | 97,3 | 97,2 | 97,8 | 97,4 |
| | 28 | 97,8 | 97,7 | 98,4 | 98,0 |
| | 42 | 98,0 | 97,7 | 98,6 | 98,1 |
| | 56 | 98,2 | 98,1 | 98,5 | 98,3 |
| 15 | 0 | 100,0 | 100,0 | 100,0 | 100,0 |
| | 14 | 97,5 | 97,9 | 98,0 | 97,8 |
| | 28 | 96,7 | 97,6 | 97,6 | 97,3 |
| | 42 | 96,6 | 97,5 | 97,5 | 97,2 |
| | 56 | 96,0 | 97,6 | 97,5 | 97,0 |
| 18 | 0 | 100,0 | 100,0 | 100,0 | 100,0 |
| | 14 | 98,4 | 97,8 | 98,0 | 98,1 |
| | 30 | 98,9 | 98,5 | 98,5 | 98,6 |
| | 42 | 99,5 | 99,2 | 99,5 | 99,4 |
| | 56 | 99,9 | 99,6 | 99,2 | 99,5 |
| 19 | 0 | 100,0 | 100,0 | 100,0 | 100,0 |
| | 16 | 97,7 | 97,5 | 98,1 | 97,8 |
| | 28 | 98,2 | 97,7 | 98,6 | 98,2 |
| | 42 | 98,5 | 98,0 | 98,6 | 98,4 |
| | | | | | |

The acceptance criterion for the beam test without de-icing salt acc. to [B3303] is a decrease of the relative dynamic modulus of elasticity (RDM) of 5 % after 56 FTC in comparison to a concrete using a CEM II/A cement. In this study, no reference concrete was tested. Taking into acount, that none of the tested concretes had a relative dynamic modulus of elasticity after 56 FTC lower then 97 %, this criterion was kept by all investigated concretes.

## CF/CIF test

CF specimens, obtained by splitting a 150 mm cube mould with a centralised PTFE plate, are subjected to freeze-thaw attack in presence of de-ionised water. The freeze-thaw scaling resistance is evaluated either by the measurement of mass scaled from specimens or measured as relative dynamic modulus of elasticity by using ultrasonic pulse transit time after 28 or 56 freeze-thaw cycles.

Table 20: Scaling of concretes with c = 320 $kg/m^3$ and w/c = 0.50 tested with the CF-test

| Cement | FTC | Specimen | | | | | Mean | s | v |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | | |
| | | $kg/m^2$ | | | | | | | % |
| RefC | 14 | 0,107 | 0,124 | 0,185 | 0,134 | 0,081 | 0,126 | 0,038 | 30,4 |
| | 28 | 0,159 | 0,204 | 0,264 | 0,215 | 0,165 | 0,201 | 0,043 | 21,2 |
| | 42 | 0,218 | 0,302 | 0,363 | 0,291 | 0,233 | 0,281 | 0,058 | 20,7 |
| | 56 | 0,305 | 0,416 | 0,459 | 0,393 | 0,327 | 0,380 | 0,064 | 16,8 |
| 1-2 | 16 | 0,027 | 0,030 | 0,040 | 0,022 | 0,041 | 0,032 | 0,008 | 25,5 |
| | 28 | 0,045 | 0,061 | 0,053 | 0,049 | 0,066 | 0,055 | 0,009 | 16,0 |
| | 42 | 0,081 | 0,106 | 0,088 | 0,099 | 0,137 | 0,102 | 0,022 | 21,2 |
| | 56 | 0,156 | 0,180 | 0,146 | 0,155 | 0,190 | 0,165 | 0,019 | 11,4 |
| 12-1 | 14 | 0,072 | 0,058 | 0,100 | 0,071 | 0,058 | 0,072 | 0,017 | 24,2 |
| | 28 | 0,101 | 0,082 | 0,162 | 0,115 | 0,090 | 0,110 | 0,031 | 28,6 |
| | 42 | 0,136 | 0,120 | 0,215 | 0,153 | 0,120 | 0,149 | 0,040 | 26,7 |
| | 56 | 0,188 | 0,167 | 0,293 | 0,262 | 0,182 | 0,218 | 0,055 | 25,4 |
| 13-1 | 14 | 0,113 | 0,089 | 0,092 | 0,102 | 0,115 | 0,102 | 0,012 | 11,7 |
| | 28 | 0,206 | 0,187 | 0,271 | 0,199 | 0,596 | 0,292 | 0,173 | 59,3 |
| | 42 | 0,411 | 0,340 | 0,475 | 0,906 | 0,875 | 0,601 | 0,268 | 44,6 |
| | 56 | 0,740 | 0,623 | 0,912 | 1,158 | 1,155 | 0,917 | 0,241 | 26,3 |
| 15 | 14 | 0,052 | 0,052 | 0,061 | 0,065 | 0,067 | 0,059 | 0,007 | 11,7 |
| | 28 | 0,073 | 0,088 | 0,094 | 0,104 | 0,111 | 0,094 | 0,015 | 15,8 |
| | 42 | 0,103 | 0,123 | 0,164 | 0,164 | 0,166 | 0,144 | 0,029 | 20,3 |
| | 56 | 0,176 | 0,194 | 0,303 | 0,309 | 0,286 | 0,254 | 0,063 | 25,0 |
| 18 | 16 | 0,063 | 0,048 | 0,049 | 0,074 | 0,091 | 0,065 | 0,018 | 27,8 |
| | 28 | 0,161 | 0,076 | 0,067 | 0,124 | 0,153 | 0,116 | 0,043 | 37,1 |
| | 42 | 0,281 | 0,121 | 0,123 | 0,238 | 0,244 | 0,201 | 0,074 | 37,0 |
| | 56 | 0,469 | 0,201 | 0,186 | 0,427 | 0,394 | 0,335 | 0,132 | 39,5 |
| 19 | 13 | 0,025 | 0,024 | 0,028 | 0,024 | 0,036 | 0,027 | 0,005 | 18,3 |
| | 27 | 0,053 | 0,053 | 0,061 | 0,047 | 0,066 | 0,056 | 0,008 | 13,4 |
| | 41 | 0,146 | 0,125 | 0,182 | 0,105 | 0,149 | 0,142 | 0,029 | 20,4 |
| | 57 | 0,448 | 0,390 | 0,441 | 0,275 | 0,289 | 0,369 | 0,082 | 22,3 |

Table 21: Relative dynamic modulus of elasticity (RDM) of concretes with c = 320 kg/m$^3$ and w/c = 0.50 tested with the CIF-test

| Cement | FTC | Specimen | | | | | Mean | s | v |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | | |
| | | % | | | | | | | % |
| RefC | 14 | 101,8 | 101,3 | 100,8 | 100,0 | 100,3 | 100,9 | 0,8 | 0,7 |
| | 28 | 101,6 | 100,5 | 100,8 | 98,9 | 100,3 | 100,4 | 1,0 | 1,0 |
| | 42 | 101,8 | 101,1 | 100,5 | 98,9 | 99,2 | 100,3 | 1,2 | 1,2 |
| | 56 | 100,8 | 99,2 | 100,5 | 97,6 | 97,6 | 99,1 | 1,5 | 1,5 |
| 1-2 | 16 | 99,7 | 99,6 | 98,8 | 98,9 | 99,3 | 99,3 | 0,4 | 0,4 |
| | 28 | 95,0 | 93,9 | 94,1 | 91,9 | 94,1 | 93,8 | 1,1 | 1,2 |
| | 42 | 79,6 | 78,6 | 77,9 | 73,3 | 78,2 | 77,5 | 2,4 | 3,1 |
| | 56 | 64,3 | 62,9 | 61,9 | 59,2 | 63,4 | 62,3 | 1,9 | 3,1 |
| 12-1 | 14 | 83,3 | 81,3 | 81,8 | 82,3 | 79,4 | 81,6 | 1,4 | 1,8 |
| | 28 | 62,6 | 63,1 | 64,9 | 65,6 | 64,5 | 64,1 | 1,2 | 1,9 |
| | 42 | 49,6 | 50,7 | 54,0 | 55,7 | 54,9 | 53,0 | 2,7 | 5,0 |
| | 56 | 43,5 | 43,4 | 44,7 | 45,6 | 44,9 | 44,4 | 0,9 | 2,1 |
| 13-1 | 14 | 88,6 | 87,9 | 89,0 | 87,9 | 87,5 | 88,2 | 0,599 | 0,7 |
| | 28 | 74,5 | 73,2 | 77,2 | 73,0 | 74,0 | 74,4 | 1,712 | 2,3 |
| | 42 | 64,9 | 62,6 | 66,8 | 59,3 | 59,2 | 62,6 | 3,372 | 5,4 |
| | 56 | 36,0 | 40,0 | 41,3 | 37,0 | 37,4 | 38,3 | 2,213 | 5,8 |
| 15 | 14 | 92,9 | 94,6 | 88,2 | 89,1 | 91,2 | 91,2 | 2,7 | 2,9 |
| | 28 | 59,9 | 58,1 | 51,6 | 52,7 | 56,0 | 55,7 | 3,5 | 6,3 |
| | 42 | 37,5 | 39,5 | 38,1 | 37,2 | 36,4 | 37,7 | 1,2 | 3,1 |
| | 56 | 36,5 | 36,2 | 37,0 | 38,1 | 37,8 | 37,1 | 0,8 | 2,2 |
| 18 | 16 | 67,0 | 68,1 | 69,2 | 66,3 | 63,3 | 66,8 | 2,252 | 3,4 |
| | 28 | 48,5 | 48,1 | 51,3 | 51,0 | 46,0 | 49,0 | 2,180 | 4,4 |
| | 42 | 40,1 | 40,9 | 40,3 | 40,7 | 40,3 | 40,5 | 0,338 | 0,8 |
| | 56 | 34,8 | 37,2 | 36,1 | 35,2 | 35,4 | 35,7 | 0,948 | 2,7 |
| 19 | 13 | 85,8 | 84,2 | 84,2 | 82,9 | 85,0 | 84,4 | 1,105 | 1,3 |
| | 27 | 69,7 | 71,4 | 70,5 | 68,3 | 72,7 | 70,5 | 1,676 | 2,4 |
| | 41 | 54,9 | 57,8 | 58,3 | 52,1 | 57,5 | 56,1 | 2,598 | 4,6 |
| | 57 | 38,8 | 38,4 | 43,2 | 34,8 | 37,0 | 38,4 | 3,081 | 8,0 |

<u>Assessment of the Freeze-thaw resistance</u>

The following table summarizes the assessment of the freeze-thaw resistance by means of the acceptance criteria for the different test methods taken from different sources.

Table 22: Assessment of the Freeze-thaw resistance

<table>
<tr><td rowspan="3">Cement</td><td colspan="4">Cube test</td><td colspan="2">CF/CIF</td><td>Beam test</td></tr>
<tr><td colspan="4">c = 300 kg/m$^3$; w/c = 0,60</td><td colspan="3">c = 320 kg/m$^3$; w/c = 0,50</td></tr>
<tr><td colspan="5">Scaling after</td><td colspan="2">$E_{dyn}$ after</td></tr>
<tr><td rowspan="3"></td><td colspan="2">56 FTC</td><td colspan="2">100 FTC</td><td colspan="2">28 FTC</td><td>56 FTC</td></tr>
<tr><td>≤ 5 1)</td><td>≤ 3 1)</td><td>≤ 10 1)</td><td>≤ 5 1)</td><td>≤ 1,00 2)</td><td>≥ 75 2)</td><td>≥ 95 3)</td></tr>
<tr><td colspan="4">M.-%</td><td>kg/m$^2$</td><td colspan="2">%</td></tr>
<tr><td>RefC</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>n. d</td></tr>
<tr><td>1-2</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td>12-1</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>no</td><td>yes</td></tr>
<tr><td>13-1</td><td>yes</td><td>no</td><td>yes</td><td>no</td><td>yes</td><td>74,4</td><td>yes</td></tr>
<tr><td>15</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>no</td><td>yes</td></tr>
<tr><td>18</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td>no</td><td>yes</td></tr>
<tr><td>19</td><td>yes</td><td>no</td><td>yes</td><td>no</td><td>yes</td><td>no</td><td>yes</td></tr>
<tr><td>2-2</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td><td colspan="3" rowspan="5">n. d.</td></tr>
<tr><td>3-2</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td>14</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td>16</td><td>yes</td><td>yes</td><td>yes</td><td>yes</td></tr>
<tr><td>17</td><td>yes</td><td>yes</td><td>yes</td><td>no</td></tr>
</table>

1) Concrete tested with the cube test has a sufficient freeze thaw resistance (~ XF1), if the scaling is lower than 5 mass% after 56 FTC and 10 mass% after 100 FTC. These values can be lowered for concrete for the exposure class XF3 (3 mass% after 56 FTC and 5 mass% after 100 FTC) [12].

2) Concrete for the exposure class XF3 must not have a relative dynamic modulus of elasticity after 28 FTC lower then 75 % and a scaling > 1,00 kg/m$^2$ [2].

3) The acceptance criterion acc. to ÖNORM B 3303 [8] is a decrease of the relative dynamic modulus of elasticity of 5 % after 56 FTC in comparison to a concrete which is applicable for exposure class XF3 acc. to ÖNORM B 4710-1 [9]. In this study, no reference concrete was tested. Taking into acount, that none of the tested concretes had a relative dynamic modulus of elasticity after 56 FTC lower then 97 %, this criterion was kept by all investigated concretes.

#### 4.2.8.6 Freeze-thaw resistance with de-icing salts

Concretes exposed to chlorides are predominantly also loaded by freeze-thaw cycles.

The European prestandard prENV 12390-9 covers testing for scaling resistance. This European prestandard has one reference method (slab test) and two alternative methods (cube test and CF/CDF-test).

CDF-test

CDF specimens, obtained by splitting a 150 mm cube mould with a centralised PTFE plate, are subjected to freeze-thaw attack in presence of 3 % sodium chloride (NaCl) solution. The freeze-thaw scaling resistance is evaluated by the measurement of mass scaled from specimens after 28 freeze-thaw cycles

The CDF-test indicates the suitability of a concrete mixture for highly water saturated concrete exposed to significant attack by freeze-thaw cycles with de-icing salts, if a limit value for scaling of 1.5 kg/m$^2$ after 28 freeze-thaw cycles is not exceeded. Results of the CDF-test are compiled in table 23.

Table 23: Scaling of concretes with c = 320 kg/m$^3$ and w/c = 0.50 and artifical air-voids tested with the CDF-test

| Cement | FTC | Specimen 1 | 2 | 3 | 4 | 5 | Mean | s | v |
|---|---|---|---|---|---|---|---|---|---|
| | | kg/m$^2$ | | | | | | | % |
| RefC | 14 | 0,743 | 0,366 | 0,188 | 0,190 | 0,163 | 0,330 (0,227) | 0,245 (0,093) | 74,1 (41,1) |
| | 28 | 1,102 | 0,533 | 0,293 | 0,301 | 0,257 | 0,497 (0,346) | 0,355 (0,126) | 71,5 (36,5) |
| | 42 | 1,410 | 0,660 | 0,373 | 0,419 | 0,366 | 0,646 (0,455) | 0,444 (0,139) | 68,8 (30,6) |
| | 56 | 1,769 | 0,853 | 0,499 | 0,563 | 0,493 | 0,835 (0,602) | 0,542 (0,170) | 64,9 (28,3) |
| 1-2 | 8 | 0,249 | 0,304 | 0,208 | 0,214 | 0,234 | 0,242 | 0,039 | 15,9 |
| | 14 | 0,412 | 0,489 | 0,354 | 0,367 | 0,389 | 0,402 | 0,053 | 13,3 |
| | 28 | 0,592 | 0,747 | 0,501 | 0,605 | 0,562 | 0,601 | 0,091 | 15,1 |
| | 42 | 0,943 | 1,037 | 0,724 | 0,826 | 0,758 | 0,858 | 0,131 | 15,2 |
| | 56 | 1,110 | 1,219 | 0,878 | 0,945 | 0,876 | 1,005 | 0,153 | 15,2 |
| 12-1 | 6 | 0,497 | 0,382 | 0,188 | 0,198 | 0,175 | 0,288 | 0,144 | 50,1 |
| | 14 | 0,896 | 0,722 | 0,391 | 0,394 | 0,363 | 0,553 | 0,242 | 43,7 |
| | 28 | 1,386 | 1,281 | 0,706 | 0,777 | 0,663 | 0,963 | 0,343 | 35,6 |
| | 42 | 1,823 | 1,666 | 0,976 | 1,097 | 0,958 | 1,304 | 0,410 | 31,4 |
| | 56 | 2,273 | 2,087 | 1,339 | 1,434 | 1,308 | 1,688 | 0,456 | 27,0 |
| 13-1 | 6 | 1,849 | 1,876 | 1,551 | 1,732 | 1,716 | 1,745 | 0,129 | 7,4 |
| | 14 | 2,730 | 2,720 | 2,393 | 2,430 | 2,478 | 2,550 | 0,162 | 6,4 |
| | 30 | 3,431 | 3,585 | 3,264 | 3,197 | 3,275 | 3,350 | 0,156 | 4,7 |
| | 42 | 3,854 | 3,973 | 3,687 | 3,666 | 3,732 | 3,782 | 0,129 | 3,4 |
| | 56 | 4,391 | 4,414 | 4,123 | 4,148 | 4,206 | 4,257 | 0,137 | 3,2 |
| Values in brackets: without specimen 1 | | | | | | | | | |

Table 23: Continuation

| Cement | FTC | Specimen 1 | 2 | 3 | 4 | 5 | Mean | s | v |
|---|---|---|---|---|---|---|---|---|---|
| | | kg/m² | | | | | | | % |
| 14 | 8 | 0,153 | 0,176 | 0,160 | 0,143 | 0,106 | 0,148 | 0,026 | 17,7 |
| | 14 | 0,238 | 0,262 | 0,232 | 0,210 | 0,147 | 0,218 | 0,044 | 20,1 |
| | 28 | 0,351 | 0,343 | 0,328 | 0,292 | 0,229 | 0,309 | 0,050 | 16,1 |
| | 42 | 0,408 | 0,417 | 0,392 | 0,348 | 0,276 | 0,368 | 0,058 | 15,8 |
| | 56 | 0,646 | 0,574 | 0,574 | 0,466 | 0,438 | 0,540 | 0,085 | 15,8 |
| 15 | 4 | 0,046 | 0,029 | 0,052 | 0,050 | 0,033 | 0,042 | 0,010 | 24,7 |
| | 14 | 0,112 | 0,104 | 0,131 | 0,152 | 0,141 | 0,128 | 0,020 | 15,5 |
| | 28 | 0,187 | 0,178 | 0,251 | 0,286 | 0,239 | 0,228 | 0,045 | 19,9 |
| | 42 | 0,251 | 0,228 | 0,343 | 0,434 | 0,326 | 0,316 | 0,082 | 25,9 |
| | 56 | 0,425 | 0,459 | 0,585 | 0,643 | 0,505 | 0,524 | 0,090 | 17,2 |
| 16 | 4 | 0,037 | 0,047 | 0,030 | 0,027 | 0,035 | 0,035 | 0,008 | 21,4 |
| | 14 | 0,129 | 0,144 | 0,113 | 0,092 | 0,127 | 0,121 | 0,019 | 16,1 |
| | 28 | 0,223 | 0,229 | 0,183 | 0,168 | 0,239 | 0,209 | 0,031 | 14,9 |
| | 42 | 0,298 | 0,307 | 0,266 | 0,228 | 0,309 | 0,282 | 0,035 | 12,3 |
| | 56 | 0,411 | 0,440 | 0,418 | 0,391 | 0,465 | 0,425 | 0,029 | 6,7 |
| 17 | 4 | 0,095 | 0,071 | 0,073 | 0,070 | 0,062 | 0,074 | 0,012 | 16,7 |
| | 14 | 0,210 | 0,205 | 0,206 | 0,171 | 0,170 | 0,192 | 0,020 | 10,3 |
| | 28 | 0,359 | 0,332 | 0,368 | 0,312 | 0,307 | 0,336 | 0,027 | 8,2 |
| | 42 | 0,572 | 0,517 | 0,565 | 0,466 | 0,459 | 0,516 | 0,053 | 10,3 |
| | 56 | 0,648 | 0,603 | 0,635 | 0,534 | 0,527 | 0,589 | 0,056 | 9,5 |
| 18 | 5 | 0,289 | 0,229 | 0,327 | 0,300 | 0,241 | 0,277 | 0,041 | 14,9 |
| | 15 | 1,072 | 0,899 | 1,108 | 1,048 | 1,035 | 1,032 | 0,080 | 7,7 |
| | 29 | 1,485 | 1,253 | 1,577 | 1,493 | 1,530 | 1,468 | 0,125 | 8,5 |
| | 43 | 2,102 | 1,860 | 2,195 | 2,189 | 2,036 | 2,077 | 0,138 | 6,6 |
| | 61 | 2,673 | 2,405 | 2,870 | 2,760 | 2,488 | 2,639 | 0,191 | 7,3 |
| 19 | 10 | 2,118 | 2,274 | 2,296 | 2,203 | 2,231 | 2,224 | 0,070 | 3,1 |
| | 14 | 2,426 | 2,594 | 2,613 | 2,659 | 2,637 | 2,586 | 0,093 | 3,6 |
| | 28 | 3,272 | 3,480 | 3,427 | 3,499 | 3,483 | 3,432 | 0,094 | 2,7 |
| | 40 | 4,130 | 3,934 | 3,976 | 4,004 | 4,000 | 4,009 | 0,073 | 1,8 |
| | 56 | 4,630 | 4,569 | 4,529 | 4,628 | 4,633 | 4,598 | 0,047 | 1,0 |

With the exception of the concretes with cements 13-1 and 19, all concretes kept the acceptance criterion for scaling of 1.5 kg/m² after 28 freeze-thaw. The scaling of the concrete with cement 18 was very near to this criterion (1,468 kg/m²). All concretes except those with cements 13-1, 19 and 18 showed a moderate increase of scaling even up to 56 FTC.

<u>Slab test</u>

Slab specimens, sawn from concrete test specimens, are subjected to freeze-thaw attack in presence of a 3 mm deep layer of de-ionised water or 3% sodium chloride (NaCl) solution. The freeze-thaw resistance is evaluated by the measurement of mass scaled from slab after 56 freeze-thaw cycles.

The Slab test indicates the suitability of a concrete mixture for highly water saturated concrete exposed to significant attack by freeze-thaw cycles with de-icing salts, if a limit value for scaling of 1.0 kg/m$^2$ after 56 freeze-thaw cycles is not exceeded.

Results of the Slab test are complied in table 24.

Table 24: Scaling of concretes with c = 320 kg/m$^3$ and w/c = 0.50 and artifical air-voids tested with the slab test

| Cement | FTC | Specimen | | | | Mean | s | v |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | | | |
| | | kg/m$^2$ | | | | | | % |
| 1-2 | 7 | 0,125 | 0,092 | 0,072 | 0,069 | 0,090 | 0,046 | 51,1 |
| | 14 | 0,240 | 0,196 | 0,195 | 0,163 | 0,198 | 0,093 | 46,8 |
| | 28 | 0,339 | 0,333 | 0,302 | 0,232 | 0,302 | 0,141 | 46,9 |
| | 42 | 0,427 | 0,425 | 0,374 | 0,264 | 0,373 | 0,179 | 48,1 |
| | 56 | 0,460 | 0,450 | 0,409 | 0,299 | 0,405 | 0,192 | 47,4 |
| 12-1 | 7 | 0,146 | 0,154 | 0,127 | 0,117 | 0,136 | 0,062 | 46,0 |
| | 14 | 0,281 | 0,242 | 0,203 | 0,220 | 0,237 | 0,110 | 46,4 |
| | 28 | 0,381 | 0,317 | 0,294 | 0,298 | 0,323 | 0,148 | 46,0 |
| | 42 | 0,413 | 0,367 | 0,327 | 0,327 | 0,359 | 0,164 | 45,8 |
| | 56 | 0,420 | 0,400 | 0,359 | 0,350 | 0,382 | 0,173 | 45,4 |
| 13-1 | 7 | 0,457 | 0,414 | 0,525 | 0,502 | 0,475 | 0,216 | 45,6 |
| | 14 | 0,817 | 0,744 | 0,837 | 0,803 | 0,800 | 0,359 | 44,9 |
| | 28 | 0,966 | 1,017 | 1,173 | 0,844 | 1,000 | 0,463 | 46,2 |
| | 42 | 1,034 | 1,159 | 1,578 | 0,937 | 1,177 | 0,580 | 49,3 |
| | 56 | R. f. | R. f. | R. f. | R. f. | - | - | - |
| 18 | 14 | 0,264 | 0,220 | 0,283 | 0,272 | 0,260 | 0,119 | 45,7 |
| | 28 | 0,330 | 0,256 | 0,352 | 0,355 | 0,323 | 0,150 | 46,4 |
| | 42 | 0,341 | 0,270 | 0,397 | 0,383 | 0,348 | 0,163 | 46,9 |
| | 56 | 0,362 | 0,315 | 0,512 | 0,422 | 0,403 | 0,195 | 48,3 |
| 19 | 7 | 0,491 | 0,560 | 0,521 | 0,586 | 0,540 | 0,244 | 45,2 |
| | 14 | 0,713 | 0,794 | 0,741 | 0,926 | 0,793 | 0,364 | 45,9 |
| | 28 | 0,768 | 1,053 | 0,822 | 1,081 | 0,931 | 0,439 | 47,1 |
| | 42 | 0,849 | 1,127 | 0,883 | 1,282 | 1,035 | 0,496 | 47,9 |
| | 56 | R. f. | R. f. | R. f. | R. f. | - | - | - |

<u>Assessment of the Freeze-thaw resistance with de-icing salts</u>

The following table shows summarizes the sssessment of the Freeze-thaw resistance by means of the acceptance criteria for the different test methods taken from different sources.

Table 25: Assessment of the freeze-thaw resistance with de-icing salts

| Cement | Concrete | CDF test | Slab test |
|---|---|---|---|
| | | Scaling | |
| | w/c | 28 FTC | 56 FTC |
| | | ≤ 1,50 [2] | ≤ 1,00 [5] |
| | | $kg/m^2$ | |
| RefC | 0,50, AEA | yes | n. d. |
| 1-2 | | yes | yes |
| 12-1 | | yes | yes |
| 13-1 | | no | no |
| 15 | | yes | n. d. |
| 18 | | 1,468 | yes |
| 19 | | no | no |
| 2-2 | | yes | n. d. |
| 3-2 | | yes | n. d. |
| 14 | | yes | n. d. |
| 16 | | yes | n. d. |
| n. d.: not determined | | | |

### 4.2.9 Summary and conclusions

With regard to the durability of concrete, the folling can be concluded:

<u>Carbonation</u>

- Concrete using Portland-limestone cement CEM II/B-LL with 35 % limestone and concrete using cements with 30 % ggbs and 20 % limestone besides clinker showed carbonation depth in the range of Portland and Portland-limestone cements CEM II/A-LL.
- Concrete using cements with 50 % ggbs and 20 % limestone besides clinker showed carbonation depth in the range of the maximum values which are reported in the literature for blastfurnace cements CEM III/B with up to 80 % ggbs.

<u>Resistance against chloride penetration</u>

- The resistance of concrete against chloride penetration using Portland-limestone cement CEM II/B-LL with 35 % limestone is comparable to that of concretes with Portland cement.

- The use of cements with 20 to 30 % limestone in combination with 5 to 15 % ggbs reduces the chloride migration coefficient to values in the range between Portland cements and Portland-slag cement CEM II/B-S.
- Chloride migration coefficients of concrete using cements with 30 % ggbs and 20 % limestone are in the range of concretes with Portland-slag cement CEM II/B-S.
- Chloride migration coefficients of concrete using cements with 50 % ggbs and 20 % limestone are in the range of concretes with Blastfurnace cements CEM III/A.

Freeze thaw resistance

The assessment of the Freeze-thaw resistance depends to some extend to the test-method which is used. For the determination of the sacling the cube-test and the CF-test acc. to the European prestandard prENV 12390-9 were used. Internal damage by means of the relative dynamic modulus of elasticity (RDM) was determined using the beam-test and the CIF-test acc. to the CEN report.

- The concrete with the Portland cement and the concrete with Portland limestone cements CEM 1-2 were assessed to be usable for all exposures with freeze thaw attack independend of the test method.
- The most severe accepance criterion was the decrease of the relative dynamic modulus of elasticity of max 25 % after 28 FTC.
- None of the investigated concretes showed a reduction of the relative dynamic modulus of elasticity of more then 3 % in the beam test.
- The scaling after 100 FTC of the concretes with w/c = 0,60 using CEM II/B-LL with 35 % limestone tested with the cube test showed a sigificant correlation to the quality of the limestone expressed as the specific surface (BET).
- Concretes using cements with 50 % ggbs and 20 % limestone: Assessment of the freeze thaw resistance dependent on the kind of test.
- Concretes using cements with 50 % ggbs and 20 % limestone showed high scaling in the cube test and a significant decrease of the RDM in the CIF test. Within the beam test, no sigificant change in the RDM was detectable.

Freeze thaw resistance with de-icing salts

For the assessment of the Freeze-thaw resistance with de-icing salts the slab-test and the CDF-test acc. to the European prestandard prENV 12390-9 were used.

- In all cases the two test methods led to the same assessment of the concretes.
- Only concretes using cements with 50 % ggbs and 20 % limestone were assessed not to be applicable for exposures with freeze thaw attack with de-icing salts and a high water saturation (exposure class XF4 acc. to EN 206-1)

## 4.3 Partner 2: CTG

### 4.3.1 General

The cements that are under assessment by CTG are described in Table 26.

Table 26: Cements under assessment by CTG

| No | Cement | Notation | Constituents | | | | |
|---|---|---|---|---|---|---|---|
| | | | Clinker<br>K | Blast furnace slag<br>S | Limestone<br>LL | Glass<br>G | Brick<br>B |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | Blastfurnace cement | CEM III/A | 50 | 50 | | | |
| 2 | Limestone cement | CEM 45LL | 55 | | 45 | | |
| 3 | Limestone-slag cement | CEM 40S-20LL | 40 | 40 | 20 | | |
| 4 | Recycled pozzolanic cement | CEM 30G-15B | 55 | | | 30 | 15 |
| 5 | Reference cement | CEM Ref | 100 | | | | |

As can be noticed by the analysis of Table 26, one cement is a standard cement according to EN 197-1, three are cements having a composition beyond the EN 197-1 and the remaining one is the reference cement. In particular two constituents of cement No. 4 (glass and brick) are not taken into account by EN 197-1 among the possible main constituents of standard cements.

The reason for the choice of the cements No. 1- 4 is briefly described in the following.

- CEM III/A — Standard cement potentially characterised by excellent performances. As a function of the production process, the focus can be shifted on different aspects such as, for example, high long term strengths or high durability.
- CEM 45LL — The standard limestone cements contain 35% of limestone as a maximum value. Their good performances after several years of use in many different environments suggest to test the described composition.
- CEM 40S-20LL — The ternary composition based on clinker, slag and limestone could allow to define a blending cement characterised by excellent properties both at the fresh and hardened state.
- CEM 30G-15B — The ground brick has been successfully used as pozzolanic material. Nevertheless mortars and concretes in which the cement has been partially substituted by ground brick showed high water demand and low durability. The use of a third recycled pozzolanic material will be investigated in order to reduce the aforesaid problems.

### 4.3.2 Starting materials

The chemical compositions, with the exception of glass which is a common soda-lime glass, are shown in Table 27. For the clinker the potential mineralogical composition is reported too.

Table 27: Chemical composition of the starting materials and potential mineralogical composition of clinker

| Parameter | Unit | Clinker | Slag | Limestone | Brick |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| Source | % by mass | Rezzato (BS) | Taranto | Rezzato (BS) | Impruneta (FI) |
| SiO2 | | 21.54 | 34.27 | 1.28 | 50.89 |
| Al2O3 | | 5.25 | 9.98 | 0.30 | 18.74 |
| Fe2O3 | | 2.36 | 2.80 | 0.15 | 7.68 |
| CaO | | 67.17 | 41.05 | 54.15 | 10.35 |
| MgO | | 1.63 | 7.53 | 0.39 | 3.07 |
| SO3 | | <0.16 | 1.76 | <0.06 | 0.72 |
| Na2O | | 0.29 | 0.34 | <0.08 | 0.62 |
| K2O | | 0.28 | 0.15 | 0.05 | 3.43 |
| SrO | | <0.07 | 0.09 | <0.03 | <0.3 |
| Mn2O3 | | 0.08 | 0.37 | <0.04 | 0.12 |
| P2O5 | | 0.51 | <0.03 | <0.03 | 0.14 |
| TiO2 | | 0.27 | 1.35 | 0.02 | 0.82 |
| l.o.i. | | 0.37 | 2.16 | 43.43 | - - - |
| C3S (Bogue) | | 68.13 | - - - | - - - | - - - |
| C2S (Bogue) | | 10.72 | - - - | - - - | - - - |
| C3A (Bogue) | | 9.92 | - - - | - - - | - - - |
| C4AF (Bogue) | | 7.17 | - - - | - - - | - - - |
| Cl- | | - - - | 0.211 | - - - | - - - |
| Insoluble residue | | - - - | 0.81 | - - - | - - - |

### 4.3.3 Production of cements

The clinker, the slag and the limestone for the preparation of the cements have been ground, in 30 kg batches, by a laboratory mill. The granulometric properties of the ground materials are shown in Table 28. Two clinkers having different fineness have been ground: the coarser to prepare the reference cement (Clinker Re) while the finer to prepare the blending cements (Clinker Bl). Main granulometric properties of glass and brick are reported as well. The granulometric distribution has determined by Laser Diffraction technique in the range 0.9 – 175 mm; Blaine values have been measured according to EN 196-6.

Table 28: Granulometric properties of ground materials

| Parameter | Unit | Clinker Bl | Slag | Limestone | Glass | Brick | Clinker Re |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 0.9 | % by mass | 6.0 | 4.1 | 12.2 | 4.6 | 6.2 | 5.2 |
| 1.1 | | 7.2 | 5.1 | 14.4 | 6.4 | 8.7 | 6.3 |
| 1.3 | | 8.4 | 6.3 | 16.5 | 8.1 | 10.9 | 7.3 |
| 1.5 | | 9.7 | 7.6 | 18.5 | 9.6 | 12.8 | 8.2 |
| 1.8 | | 11.4 | 9.5 | 21.4 | 11.7 | 15.4 | 9.7 |
| 2.2 | | 13.5 | 12.1 | 24.9 | 14.1 | 18.3 | 11.5 |
| 3.7 | | 21.3 | 22.5 | 36.4 | 21.3 | 26.4 | 17.8 |
| 5.0 | | 27.4 | 31.4 | 44.5 | 26.5 | 31.8 | 22.7 |
| 7.5 | | 37.5 | 47.0 | 56.9 | 34.8 | 40.5 | 31.2 |
| 10.5 | | 47.8 | 62.8 | 67.8 | 42.4 | 48.6 | 39.8 |
| 15.0 | | 60.0 | 79.2 | 78.8 | 51.2 | 58.5 | 50.5 |
| 21.0 | | 71.8 | 91.0 | 87.6 | 60.2 | 69.0 | 61.5 |
| 25.0 | | 77.6 | 95.3 | 91.2 | 65.0 | 74.7 | 67.3 |
| 30.0 | | 83.2 | 97.9 | 94.2 | 70.2 | 80.6 | 73.3 |
| 43.0 | | 92.0 | 99.8 | 98.0 | 80.7 | 90.8 | 83.9 |
| 51.0 | | 94.9 | 99.9 | 98.9 | 85.5 | 94.4 | 88.2 |
| 61.0 | | 97.0 | 100.0 | 99.5 | 90.1 | 97.1 | 91.9 |
| 73.0 | | 98.5 | 100.0 | 99.8 | 94.1 | 98.7 | 94.8 |
| 87.0 | | 99.3 | 100.0 | 99.9 | 96.9 | 99.6 | 96.9 |
| 103.0 | | 99.7 | 100.0 | 100.0 | 98.7 | 99.9 | 98.2 |
| 123.0 | | 100.0 | 100.0 | 100.0 | 99.7 | 100.0 | 99.1 |
| 147.0 | | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| x’ | µm | 16.4 | 10.6 | 9.1 | 22.6 | 16.6 | 22.1 |
| n | - | 0.96 | 1.30 | 0.88 | 0.80 | 0.82 | 0.91 |
| Blaine | g/cm² | 3500 | 4200 | 5050 | 3950 | 3950 | 2950 |

The four cements to investigate and the reference cement have been prepared by adding the gypsum[1] and then by mixing the constituents. In Table 29 is shown the gypsum content for each cement and the final value of Blaine specific surface.

Table 29: Gypsum content and final Blaine specific surface.

| No | Cement | Notation | Gypsum content [%] | Blaine specific surface [cm²/g] |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| 1 | Blastfurnace cement | CEM III/A | 5 | 3950 |
| 2 | Limestone cement | CEM 45LL | 2.75 | 4200 |
| 3 | Limestone-slag cement | CEM 40S-20LL | 4 | 4150 |
| 4 | Recycled pozzolanic cement | CEM 30G-15B | 3.9 | 3100 |
| 5 | Reference cement | CEM Ref | 5 | 2950 |

[1] 85% $CaSO_4 \bullet 2H_2O$ ; 15% $CaSO_4$

### 4.3.4 Cement properties

In Table 30 the standard properties of cements 1 to 5 are presented. The tests have been carried out according to EN 196-1 and EN 196-3.

Table 30: Standard properties of cements

| Parameter | Unit | CEM III/A N. 1 | CEM 45LL N. 2 | CEM 40S-20LL N. 3 | CEM 30G-15B N. 4 | CEM Ref N. 5 |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Water demand | % | 30.8 | 30.6 | 30.2 | 34.0 | 32.0 |
| Initial setting time | h:min | 3:37 | 2:50 | 2:49 | 3:36 | 2:07 |
| Final setting time | h:min | 4:17 | 3:48 | 4:06 | 5:06 | 2:41 |
| Soundness | mm | 0 | 0 | 0 | 0 | 0 |
| Strength development | | | | | | |
| 1d | MPa | 7.8 | 5.3 | 5.5 | 6.1 | 18.2 |
| 2d | MPa | 15.5 | 10.6 | 11.8 | 10.3 | 26.7 |
| 7d | MPa | 37.3 | 20.2 | 32.7 | 18.5 | 40.9 |
| 28d | MPa | 57.6 | 27.1 | 44.6 | 31.7 | 50.3 |

### 4.3.5 Cement classification

In Figure 6 the values of mechanical strength reported in Table 30 are plotted. On the same plot the threshold limits for three strength classes according to EN 197-1 (32.5 N – 32.5 R – 42.5 N) have been superimposed.

From the analysis of table 23 and Figure 6 it can be observed that, with respect to the requirements of EN 197-1:

- cement N. 1 (CEM III/A) well satisfies the requirements for strength class 42.5 N;
- cement N. 2 (CEM 45LL) is quite far from the minimum threshold limits for strength class 32.5;
- cement N. 3 (CEM 40S-20LL) can be included in the classes 32.5 N, 32.5 R and 42.5 N, even if the class that better fits its strength development is 32.5 N;
- cement N. 4 (CEM 30G-15B) exhibits a compressive strength at 28 days that is slightly lower than the required value for class 32.5; the two day and the seven days requirements are satisfied;
- cement N. 5 (CEM Ref) well satisfies the requirements for strength class 42.5 R.

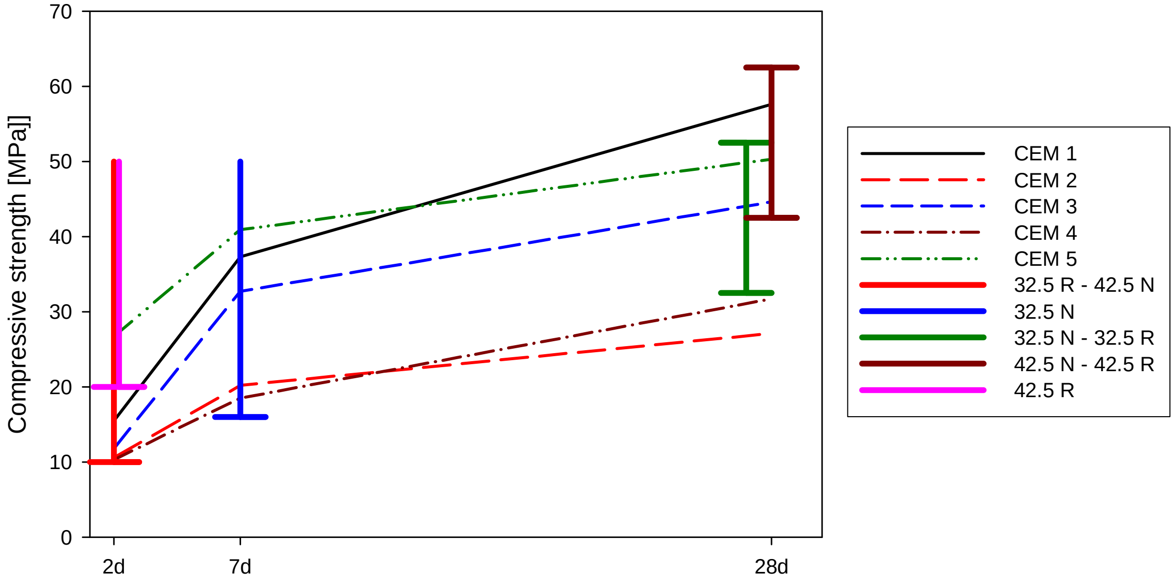



Figure 6: Mechanical strengths of tested cements and strength classes threshold limits

The possible classification of the laboratory cements is summarized in Table 31.

Table 31: Possible classification of cements under assessment by CTG

| No | Cement | Notation | Maximum strength class according to EN 197-1 |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1 | Blastfurnace cement | CEM III/A | 42.5 N |
| 2 | Limestone cement | CEM 45LL | none |
| 3 | Limestone-slag cement | CEM 40S-20LL | 42.5 N |
| 4 | Recycled pozzolanic cement | CEM 30G-15B | none |
| 5 | Reference cement | CEM Ref | 42.5 R |

From the analysis of Table 31 can be observed that two cements cannot be classified according to EN 197-1.

### 4.3.6 Cement composition refinement

In the case of cement 4 (Limestone-slag cement) the distance from the standard requirement is very low (Figure 6), therefore it has been extended the experimental work in order to further optimize the granulometric distribution of the starting constituents. Two additional experimental compositions for this blended cement have been prepared, as shown in Table 32.

Table 32: Compositions for the refinement of CEM 30G-15B.

| No | Cement | Glass fineness [cm²/g ] | Brick fineness [cm²/g ] |
|---|---|---|---|
| 1 | 2 | 3 | 3 |
| 1 | CEM 30G-15B (G6B5) | 6000 | 5000 |
| 2 | CEM 30G-15B (G5B6) | 5000 | 6000 |

The standard properties of the two cements described in Table 32 are shown in Table 33.

Table 33: Standard properties of cements

| Parameter | Unit | CEM 30G-15B (A1) | CEM 30G-15B (A2) |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| Water demand | % | 33.0 | 33.0 |
| Initial setting time | h:min | 3:13 | 2:35 |
| Final setting time | | 4:21 | 3:48 |
| Soundness | mm | 0 | 0 |
| 1d | MPa | 6.5 | 7.4 |
| 2d | | 10.3 | 11.2 |
| 7d | | 19.5 | 20.7 |
| 28d | | 38.1 | 35.5 |

In the following Figure it is shown that both the cements now fulfil the standard requirement for the class 32.5 N.

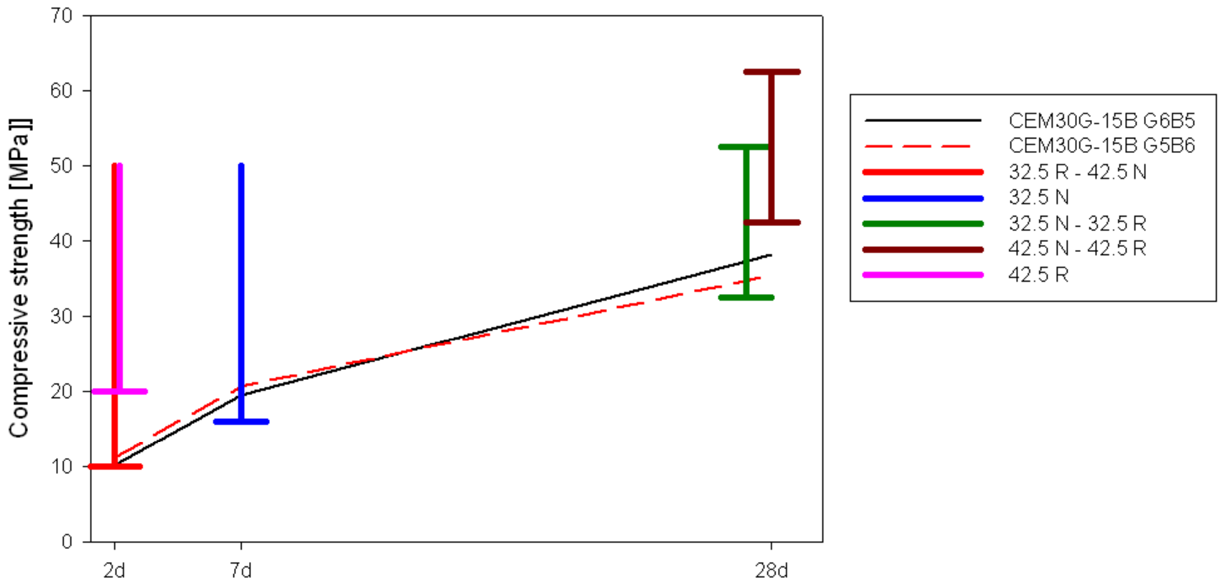



Figure 7: Comparison between standard requirement for compressive strength of cements and the two cements CEM 30G-15B respectively G6B5 and G5B6.

### 4.3.7 Results on concrete

#### 4.3.7.1 General

The behaviour of the experimental cements has been tested in concrete mixes. The concrete compositions are given in Table 34.

Table 34: Concrete compositions

| Mix Type | CLS1 | CLS2 | CLS3 |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| CEM content [kg/m³] | 300 | 280 | 320 |
| Aggregate (fluvial) (Füller grading curve - $\varnothing_{max}$ = 20 mm) [kg/m³] | 1900 | 1935 | 1920 |
| Water reducing admixture (Naphtalene sulphonate) [l/m³] | 0.24÷0.56 | 0.22÷0.36 | 0.22÷0.28 |
| w/c ratio | 0.55 | 0.60 | 0.50 |

Each mix type has been tested with some of the developed experimental cements, according to table 35.

Table 35: Strength development for concrete mixes

| Mix Type | CLS1 | CLS2 | CLS3 |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| CEM III/A | X | | |
| CEM 45LL | X | | |
| CEM 40S-20LL | X | X | X |
| CEM 30G-15B | X | X | X |
| CEM Ref | X | | |

#### 4.3.7.2 Compressive strength

The compressive strength development has been tested on cubic specimens conforming to EN 12390-1 (side 10 cm) and adopting a test procedure conforming to EN 12390-3.

In Figure 8 and 9 are shown the test results respectively for mix type CLS1 and mix type CLS2-CLS3.

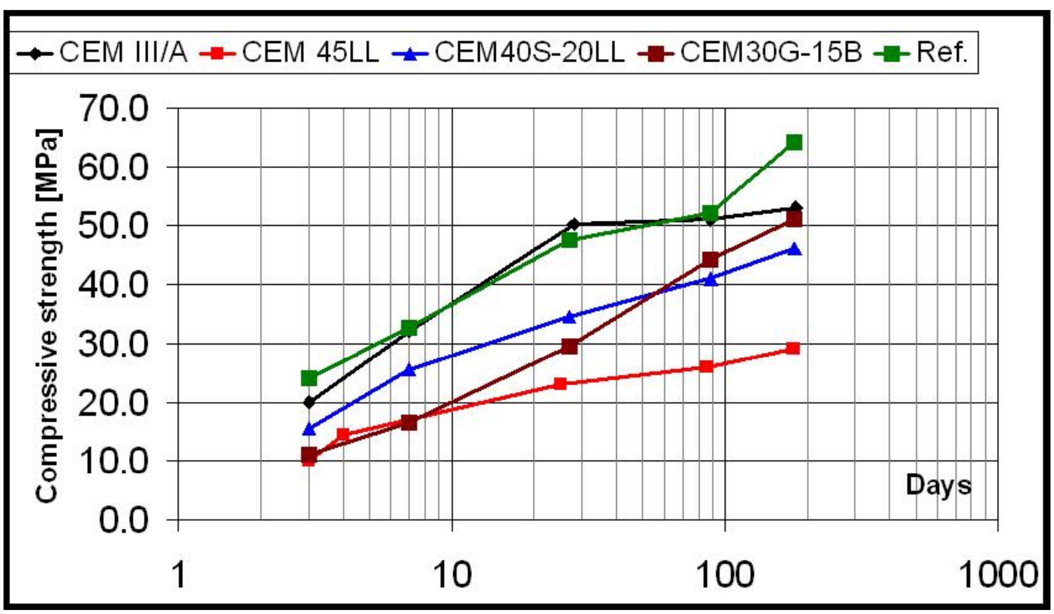



Figure 8: Compressive strength development for mix type CLS1.

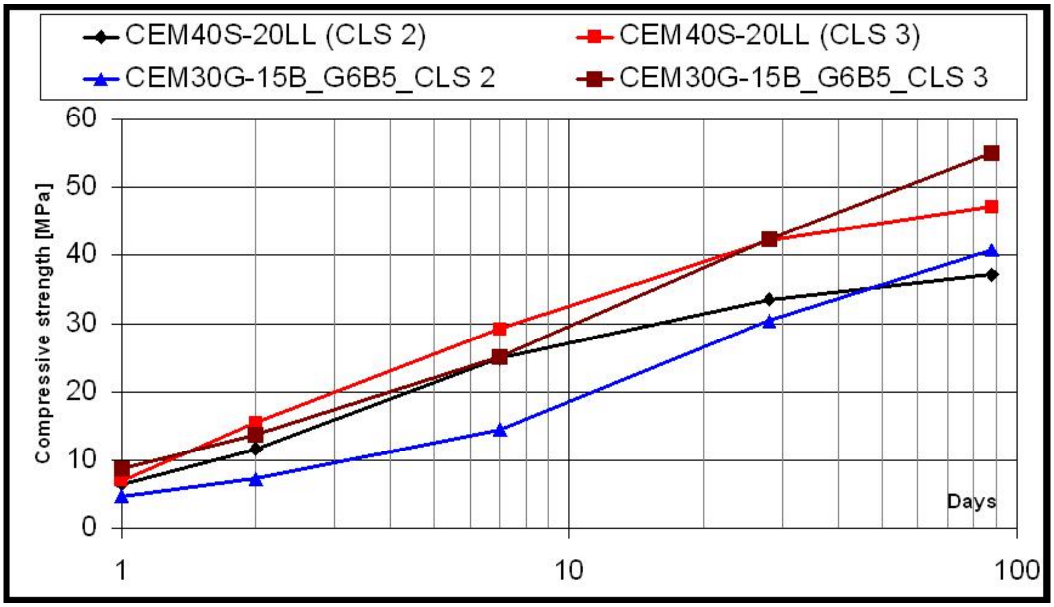



Figure 9: Compressive strength development for mix types CLS2-CLS3.

From the analysis of Figures 8 and 9 it can be noticed a regular development of the compressive strength with time. The only unexpected exception is the mix type CLS1 based on CEMIII/A. This mix shows a stable value of compressive strength in the time period 28d – 90d and a slightly increasing trend in the period 90d – 180d; this trend seems to indicate a more evident increase for curing periods longer than 180d.

### 4.3.7.3 Drying shrinkage

For all the three mix types it has been measured the value of drying shrinkage. The measurement has been performed on beam specimens (10 x 10 x 40 cm) cured for 1 day in the mould and then, after the demoulding, stored in a conditioned environment (20±2 °C; 50±5 % R.H.). The dimensional changes have been measured on three sides of the specimens and the values of drying shrinkage expressed as their average value.

In Figure 10 it is shown the development of drying shrinkage with time for mix type CLS1; in Figure 11 the same quantities are shown for mix types CLS2 and CLS3.

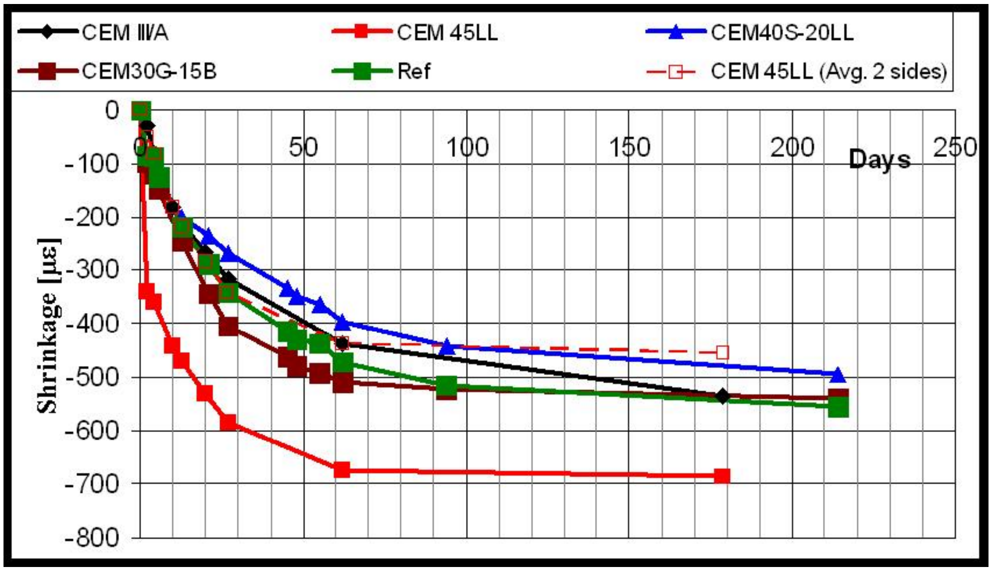



Figure 10: Drying shrinkage development for mix type CLS1.

In Figure 10 it is evident an anomalous early increase of drying shrinkage for cement CEM 45LL. This increase is probably due to experimental problems; in effect by discarding one of the three instrumented sides of the specimen, the behaviour of the mix seem to be closer to the expected one.

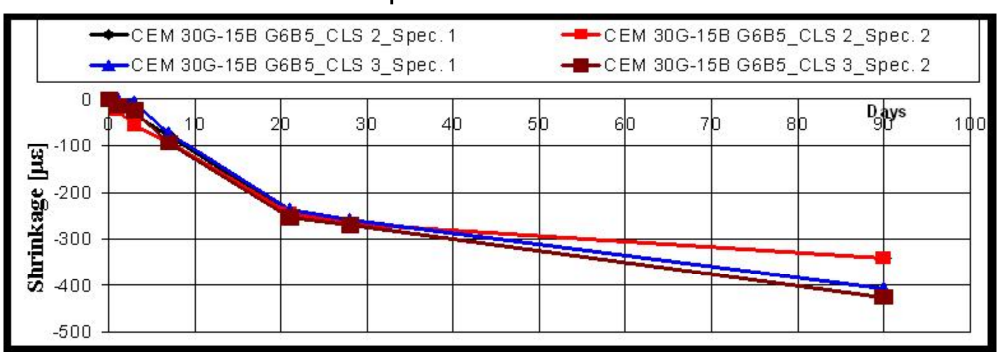



Figure 11: Drying shrinkage development for mix type CLS2 and CLS3 (cement 30G15B G6B5)

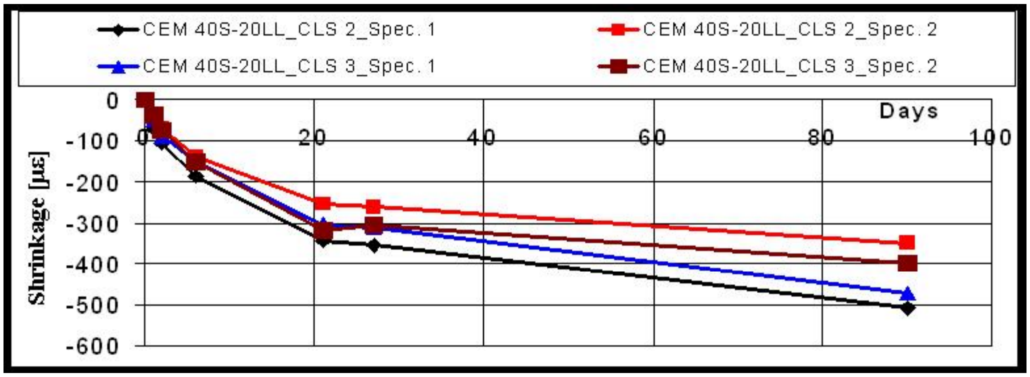



Figure 12: Drying shrinkage development for mix type CLS2 and CLS3 (cement 40S-20LL)

For all the mixes that have been tested the drying shrinkage development generally doesn't exhibit anomalous behaviour; the values of drying shrinkage fall in the expected range.

#### 4.3.7.4 Freeze/thaw testing (beam test)

The freeze/thaw resistance has been assessed only for mix type CLS1. The test has been performed on beam specimens conforming to EN 1290-1 (10 x 10 x 40 cm) and the adopted test procedure is conforming to UNI 7087. According to this procedure the specimens are subjected to freeze/thaw cycle of 12 hours and consisting of the following steps:

- cooling in air up to -20±1°C with a cooling rate of 4.5°C/h
- maintenance of air temperature of -20±1°C for 2 hours
- thawing by water at +5±1°C and maintenance in water at +5±1°C

The test results, expressed by relative young modulus (Degradation Factor) as a function of cycle number,are shown in Figure 13.

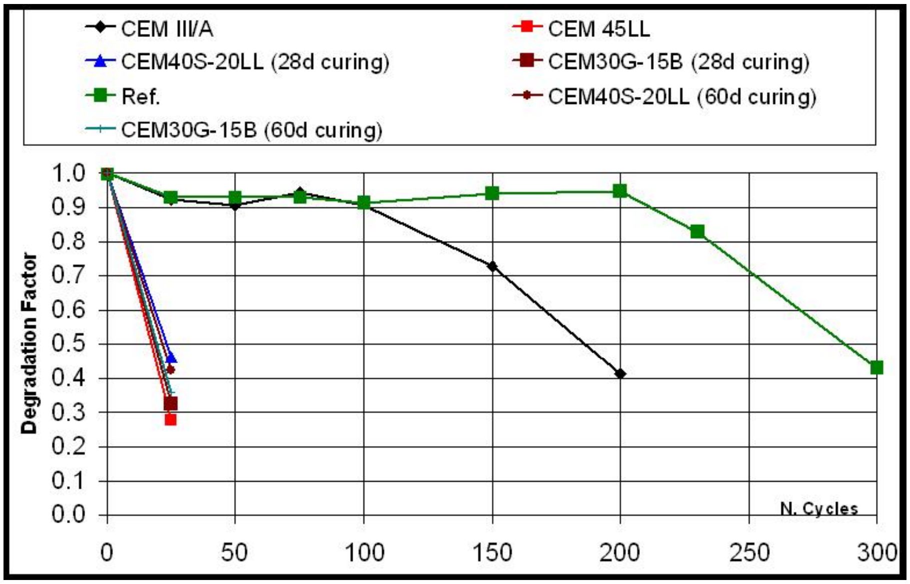



Figure 13: Results of freeze/thaw testing (beam test) for mix type CLS1.

From the analysis of Figure 13 can be observed that all the mixes have shown a bad resistance to freeze/thaw testing. In particular the mixes based on CEM 45LL, CEM 40S-20LL and CEM 30G-15B have shown a poor resistance to freeze/thaw attack even after a curing of 60 days, which is longer than the standard curing of 28 days. The mixes based on CEM III/A and CEM ref have shown a better behaviour, but none of them has reached the maximum cycle number (300) with a value of the Degradation Factor higher than 0.8. According to the Italian Standard the test should have been stopped after about 130 cycles for CEM III/A and about 230 cycles for CEM ref. Taking into account that the test was included in a research activity, it has been continued down to the value of about 0.4.

#### 4.3.7.5 Freeze/thaw testing with de-icing salt (slab test)

The test has been performed according to the European Technical Specification EN 12390-9. The test has been performed for the mix type CLS2 based on cements CEM 40S-20LL and CEM 30G-15B G6B5. Test results are reported in the following table.

Table 36: Test results for freeze/thaw testing with de-icing salt (slab test).

| Cement type | Scaled material after 28 cycles [kg/m³] |
|---|---|
| 1 | 2 |
| CEM 40S-20LL | 2.5 |
| CEM 30G-15B G6B5 | 0.7 |

As can be noticed from data in table 36, for both the mixes the scaled material after 28 cycles is more than 1 kg/m³ in one case and close to this value for the second concrete. On this basis it can be concluded that the tested concretes have a poor resistance against frost attack in presence of de-icing salt.

#### 4.3.7.6 Mercury intrusion porosity and sulphate/chloride penetration

Concrete specimens of the mix type CLS2 based on cements CEM 40S-20LL and CEM 30G-15B G6B5 have been subjected to test for porosity determination and chloride/sulphate penetration.

The porosity has been determined by mercury intrusion technique.

The chloride/sulphate penetration test have been performed by assuring a capillary suction for the specimens. The bottom basis of each test specimen has been submerged in the test solution that reached the height of 30 mm on the lateral surface; the remaining lateral surface has been painted with a waterproofing agent. The test has been carried out in a conditioned environment (20±2 °C; 50±5 % R.H.) for 28 days. At the end of the test the specimens have been splitted and the depth of penetration has been measured. In the following are listed the details of the test procedures.

Sulphate penetration

Test solution: $Na_2SO_4$ 0.5 mol/l

Profile detection: dry the split surface in a oven and then spray the split surface with a solution 3:1 of BaCl2 (2,1 mol/l) and KMnO4 (2,1 mol/l) and then wash with demineralised water.

Chloride penetration

Test solution: $CaCl_2$ 0.27 mol/l

Profile detection: dry the split surface in a oven and then spray the split surface 5 times with a solution of 0,1 g of fluorescein in 100 cm³ of ethylic alcohol (70%); then spry the split surface with a solution of $AgNO_3$ (0,1 mol/l).

The test results for chloride and sulphate penetration are listed in the table below. In the case of CEM 30G-15B G6B5 it has not been possible to detect any penetration profile, probably due to the colour of the concrete (red/brown).

Table 37: Test results for mercury intrusion porosity and chloride/sulphate.

| Cement type | Porosity<br><br>[%] | Sulphate penetration<br>*Mean value*<br>[mm] | Chloride penetration<br>*Mean value*<br>[mm |
|---|---|---|---|
| 1 | | | 2 |
| CEM 40S-20LL | 11.3 | 2.6 | 2.2 |
| CEM 30G-15B G6B5 | 23.1 | n.d. | 1.1 |

No standard exists for the classification of concrete as a function of sulphate and chloride penetration according to this test method. Nevertheless it can be observed that the values are typical of concrete characterised by a medium level of permeability. These values are in apparent contrast with the high values of porosity detected by mercury intrusion technique. This can be explained by taking in two account two aspects:

- capability of binding the ions involved in the tests;
- small pore sizes of the microstructure of these concretes, as typically observed for pozzolanic cements.

#### 4.3.7.7 Depth of carbonation

For the mix type CLS2, based on cements CEM 40S-20LL and CEM 30G-15B G6B5, it has been performed the carbonation test. The measurement has been performed on beam specimens (10 x 10 x 40 cm) cured for 1 day in the mould and then, after the demoulding, stored in a conditioned environment (20±2 °C; 50±5 % R.H.). The carbonation depth has been measured by splitting the specimens and the by spraying the split surface with a phenoftalein solution. In the following Figure are shown the test results up to 150 days.

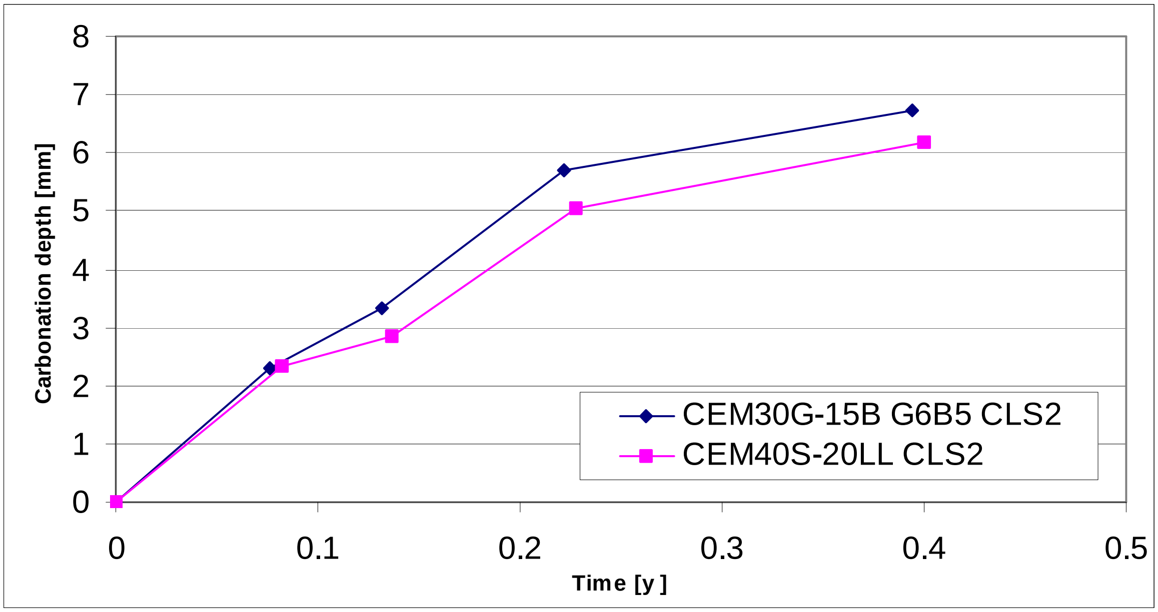



Figure 14: Results of of carbonation tests for mix type CLS2.

The curves in Figure 14 are fitted by the relation:

$$CD = k\sqrt{t}$$

where:

CD : Carbonation Depth [mm]

t: Exposure time [y]

The k value for the curves is about 10 mm x $y^{-0,5}$. That is typical for concretes of medium ÷ high porosity [3, 10].

#### 4.3.7.8 Concluding remarks

For the considered starting compositions it has been successfully verified the possibility of fitting the requirements of EN 197-1, with the only exception of the high volume limestone cement; for this cement a further experimental work should be carried out.

The tests in concrete have pointed out that good performances can be achieved in terms of basic physico-mechanical characteristics; on the contrary the analysed concretes based on experimental cements have exhibited poor durability properties.

## 4.4 Partner 3: NORCEM

### 4.4.1 General

Norcem's work with blended cements in cluster 2 include cements in and beyond the limits of EN 197-1.

Some of the cements according to EN 197-1 would, however, be new in the Norwegian market, containing a new constituent (limestone), or greater quantities of substitutes (more fly ash), or mixes of additional constituents (fly ash and limestone).

These new cement types have so far not been approved in the Norwegian application documents and therefore would need further documentation of durability for certain applications.

### 4.4.2 Workplan

A series of laboratory made blended cements have been subjected to various performance testing in concrete, including chloride penetration as well as frost/freeze-thaw resistance. The programme is a "screening test" for mapping of performance, made with certain boundary conditions, and care must be taken in generalizing the conclusions.

All together, the series comprised 16 different mixes with cements containing different clinker substitutes :

- 8 of the mixes were made with cement and strength grade designed for housing, w/c ratio of these being 0,60 and 0,50. These were tested for frost scaling in pure water only, at the age of 1 month and 3 months.
- 8 of the mixes were with cement and strength grade designed for other construction works, w/c ratio of these being 0,50 and 0,40. They were tested for a) freeze-thaw scaling in 3 % NaCl, at the age of 1 month and 3 months, and b) chloride penetration at two different ages, the results of the first one have been included below.

The properties being investigated comprise:

<u>Basic properties</u>

- Slump initially.
- Densiy and initial total air content.
- Compressive (100 mm cube) strength according to NS-EN 12390

Carbonation

One prism of 10 x 10 x 50 $cm^3$ per mix. Demoulded after one day and stored at 65 % RH. Testing by twistoff after 1, 3, 6 and 12 months + 2 & 4 years.

Chloride penetration of mix 9 – 16:

3 cylinders (10 x 20 cm) per mix, were cut in 5 cm slices at the age of 7-10 days. Prior to and after cutting : stored in water until 28 days of age, then packed in plastic until testing.

Frost (mix nos. 1-8) & Freeze-Thaw testing (9-16):

For each mix, 4 cubes 15 cm are made and de-moulded after 24 hours, then subjected to water storage until the age of 7 days. Stored at prescribed conditions until the age of 10-12, days, then packed in plastic until further preparation:

All samples are cut at the age of 21 days. All samples are pre-conditioned in the controlled climate (20 °C, 65 % RH, 45 ± 15 $g/m^2h$) until pre-saturation prior to testing. Testing start for cubes 1a, 2a, 3a, 4a at 31 days, 1-4b at 3 months age. This means that the samples to be tested at 3 months will have their test surface exposed to laboratory climate (& carbonatization) for appr. two months prior to testing, as they more or less would under field conditions.

Mix nos. 1-8 are to be tested in pure water only, mix nos. 9-16 in 3 % NaCl only.

Norcem Eco-Serve Concrete Mix Overview is given in table 38.

Table 38: Norcem Eco-Serve Concrete Mix Overview

| No. | Cement | Ident. | FA | LL | w/c 0,60 | w/c 0,50 | w/c 0,40 |
|---|---|---|---|---|---|---|---|
| Concrete without air entrainment | | | | | | | |
| 1 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 | Ref. Std. FA | AI2 | 20 | 0 | X | | |
| 2 | CEM II A-V | PP1 | 20 | 0 | X | | |
| 3 | ‘’ | PP1 | 20 | 0 | | X | |
| 4 | CEM II B-“M” | PP2 | 20 | 10 | X | | |
| 5 | ‘’ | PP3 | 30 | 20 | X | | |
| 6 | ‘’ | PP3 | 30 | 20 | | X | |
| 7 | CEM II A-LL | PP4 | 0 | 20 | X | | |
| 8 | CEM I (Ref. 80% Ind, 20%Anl) | PP7 | 0 | 0 | X | | |
| Concrete with air entrainment | | | | | | | |
| 9 | CEM I 42,5 | BP2 | 0 | 0 | | X | |
| 10 | ‘’ | BP2 | 0 | 0 | | | X |
| 11 | CEM II A-V | PP1 | 20 | 0 | | X | |
| 12 | CEM II B-V | PP5 | 35 | 0 | | X | |
| 13 | ‘’ | PP5 | 35 | 0 | | | X |
| 14 | CEM II ”B”-V | PP6 | 50 | 0 | | X | |
| 15 | ‘’ | PP6 | 50 | 0 | | | X |
| 16 | CEM I(Ref. 80% Ind, 20%Anl) | PP7 | 0 | 0 | | | X |

### 4.4.3 Basic properties

The basic properties of all investigated concrete mixes are given in tables 39 and 40.

Table 39: Basic properties of investigated concrete mixes: Composition and fresh concrete properties

| Nr | Cement | [FA] | [LL] | [C] | [SP] | [AE] | [Air] | Slump |
|---|---|---|---|---|---|---|---|---|
| - | - | % | % | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | vol.% | mm |
| Mixes without air entrainment : | | | | | | | | |
| 1 | Ref. Std.FA | 20 | 0 | 325 | - | - | 1,7 | 80 |
| 2 | CEM II A-V | 20 | 0 | 325 | - | - | 1,8 | 110 |
| 3 | ‘’ | 20 | 0 | 365 | - | - | 1,8 | 50 |
| 4 | CEM II B-“M” | 20 | 10 | 325 | - | - | 1,4 | 95 |
| 5 | ‘’ | 30 | 20 | 325 | - | - | 1,4 | 110 |
| 6 | ‘’ | 30 | 20 | 365 | - | - | 2,0 | 55 |
| 7 | CEM II A-LL | 0 | 20 | 325 | - | - | 2,6 | 70 |
| 8 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 325 | - | - | 2,6 | 70 |
| Mixes with air entrainment : | | | | | | | | |
| 9 | CEM I 42,5 | 0 | 0 | 365 | - | 0,219 | 6,5 | 100 |
| 10 | ‘’ | 0 | 0 | 415 | 0,468 | 0,180 | 7,2 | 80 |
| 11 | CEM II A-V | 20 | 0 | 365 | 0,247 | 0,630 | 5,8 | 130 |
| 12 | CEM II B-V | 35 | 0 | 365 | 0,145 | 0,986 | 6,2 | 120 |
| 13 | ‘’ | 35 | 0 | 415 | 0,451 | 0,978 | 5,4 | 85 |
| 14 | CEM II ”B”-V | 50 | 0 | 365 | 0,145 | 1,425 | 5,2 | 130 |
| 15 | ‘’ | 50 | 0 | 415 | 0,458 | 1,349 | 6,7 | 130 |
| 16 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 415 | 0,653 | 0,209 | 7,0 | 80 |

For the mixes without air entrainment, the workability properties range appears to be limited, i.e. no large differences between the cement types. In general, additions appear to be positive. As expected, the AEA dosage requirement increases with the FA content.

Table 40: Basic properties of investigated concrete mixes: compressive strength develoment

| Nr | Cement | [FA] | [LL] | fc 2 | fc 7 | fc 28 | fc 90 |
|---|---|---|---|---|---|---|---|
| - | - | % | % | MPa | MPa | MPa | MPa |
| Mixes without air entrainment : | | | | | | | |
| 1 | Ref. Std.FA | 20 | 0 | 25,7 | 34,8 | 45,1 | 56,3 |
| 2 | CEM II A-V | 20 | 0 | 24,3 | 31,0 | 39,8 | 49,5 |
| 3 | ‘’ | 20 | 0 | 34,2 | 44,3 | 55,0 | 65,9 |
| 4 | CEM II B-“M” | 20 | 10 | 21,4 | 31,2 | 39,9 | 49,8 |
| 5 | ‘’ | 30 | 20 | 11,6 | 17,5 | 26,4 | 35,8 |
| 6 | ‘’ | 30 | 20 | 19,4 | 27,1 | 41,3 | 51,5 |
| 7 | CEM II A-LL | 0 | 20 | 27,0 | 35,9 | 42,4 | 47,4 |
| 8 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 32,1 | 40,3 | 49,2 | 52,3 |
| Mixes with air entrainment : | | | | | | | |
| 9 | CEM I 42,5 | 0 | 0 | 27,3 | 36,4 | 44,1 | 48,7 |
| 10 | ‘’ | 0 | 0 | 42,6 | 48,1 | 58,0 | 65,3 |
| 11 | CEM II A-V | 20 | 0 | 29,4 | 38,3 | 48,1 | 60,5 |
| 12 | CEM II B-V | 35 | 0 | 20,1 | 25,4 | 34,8 | 47,5 |
| 13 | ‘’ | 35 | 0 | 34,3 | 44,2 | 57,6 | 74,3 |
| 14 | CEM II ”B”-V | 50 | 0 | 13,2 | 17,6 | 26,7 | 38,7 |
| 15 | ‘’ | 50 | 0 | 24,0 | 29,1 | 43,2 | 59,1 |
| 16 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 52,7 | 61,0 | 70,1 | 78,4 |

Laboratory made cement CEM II/A-V exhibits lower strength than factory made cement, as expected. For the w/c=0,60 mixes, substituting another 10% of the clinker with LL resulted in no strength reduction, and : 20% LL alone exhibits strength at least in line with that of 20% pfa. The 30% pfa – 20% LL combination changes the performance significantly.

With w/c=0,40 (air entrained), increasing the pfa content from 20% to 35% even appears to increse the long term strength (but lowers the early strength, as expected).

At w/c=0,50 (air entrained), the /B-V exhibits long term strength on the level of the CEM I, while the /A-V is significantly better.

### 4.4.4 Carbonation

The carbonation depths of all investigated concrete mixes are given in table 41.

Table 41: Carbonation depth

| No. | Cement | [FA] | [LL] | 1 Month | 3 M | 6 M | 12 M |
|---|---|---|---|---|---|---|---|
| - | - | % | % | mm | mm | mm | mm |
| Mixes without air entrainment : | | | | | | | |
| 1 | Ref. Std.FA | 20 | 0 | 3,3 | 5,0 | 6,3 | R.f. |
| 2 | CEM II A-V | 20 | 0 | 3,3 | 5,0 | 6,6 | R.f. |
| 3 | ‘’ | 20 | 0 | 2,3 | 4,0 | 4,0 | R.f. |
| 4 | CEM II B-“M” | 20 | 10 | 4,0 | 6,0 | 9,0 | R.f. |
| 5 | ‘’ | 30 | 20 | 7,0 | 10,0 | 13,0 | R.f. |
| 6 | ‘’ | 30 | 20 | 4,0 | 7,0 | 9,0 | R.f. |
| 7 | CEM II A-LL | 0 | 20 | 3,0 | 5,0 | 6,0 | R.f. |
| 8 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 2,0 | 4,0 | 5,0 | R.f. |
| Mixes with air entrainment : | | | | | | | |
| 9 | CEM I 42,5 | 0 | 0 | 3,0 | 4,0 | 6,0 | R.f. |
| 10 | ‘’ | 0 | 0 | 2,0 | 3,0 | 4,0 | R.f. |
| 11 | CEM II A-V | 20 | 0 | 3,0 | 4,0 | 5,0 | R.f. |
| 12 | CEM II B-V | 35 | 0 | 4,0 | 7,0 | 7,5 | R.f. |
| 13 | ‘’ | 35 | 0 | 3,0 | 4,0 | 5,0 | R.f. |
| 14 | CEM II ”B”-V | 50 | 0 | 6,0 | 9,0 | 9,5 | R.f. |
| 15 | ‘’ | 50 | 0 | 4,0 | 8,0 | 7,5 | R.f. |
| 16 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 2,0 | 3,0 | 3,0 | R.f. |

R.f.: Result follows

The most significant results at this very early stage is the negative effect of LL on carbonation. Increasing the pfa content to 50% also provides a negative effect.

### 4.4.5 Chloride penetration

Investigations have been performed by VDZ (comp. 4.2.8.4) All values mean of three samples, stored in water until testing at the age of 84 – 90 days. Results are compiled in table 42.

Table 42: Results of RCM

| No. | Cement | [FA] | [LL] | w/c | Age | Penetr. depth | $D_{Cl}$ |
|---|---|---|---|---|---|---|---|
| - | - | % | % | - | d | mm | |
| 9 | CEM I 42,5 | 0 | 0 | 0,50 | 85 | 17,3 | 7,7 |
| | | | | | 225 | 16,2 | 7,2 |
| 10 | | 0 | 0 | 0,40 | 84 | 11,9 | 4,9 |
| | | | | | 226 | 9,7 | 3,9 |
| 11 | CEM II A-V | 20 | 0 | 0,50 | 84 | 14,4 | 6,3 |
| | | | | | 230 | 18,9 | 2,0 |
| 12 | CEM II B-V | 35 | 0 | 0,50 | 86 | 16,6 | 7,1 |
| | | | | | 241 | 13,3 | 1,5 |
| 13 | | 35 | 0 | 0,40 | 90 | 12,4 | 2,6 |
| | | | | | 227 | 9,3 | 0,7 |
| 14 | CEM II ”B”-V | 50 | 0 | 0,50 | 90 | 23,8 | 10,3 |
| | | | | | 245 | 19,2 | 2,9 |
| 15 | | 50 | 0 | 0,40 | 91 | 20,1 | 7,4 |
| | | | | | 241 | 15,0 | 1,6 |
| 16 | CEM I(Ref. 80% Ind, 20%Anl) | 0 | 0 | 0,40 | 92 | 10,7 | 4,5 |
| | | | | | - | - | - |

Of all w/c=0,40 mixes at the age of ~ 90 d, 35% pfa performed best, thereafter the CEM I references. The 50% pfa may performed better at a later stage (~ 240 d). Of the w/c=0,50 mixes at the age of ~ 240 d, the 20-35% pfa mixes were best, thereafter the 50 % pfa mix. The range in property difference is larger for the w/c=0,40 mixes.

### 4.4.6 Freeze thaw resistance

The test has been performed with the slab test according to the European Technical Specification EN 12390-9 with pure water. Results are compiled in tables 43 and 44.

Table 43: Results of freeze thaw tests at the age of one month after X (c) nos. of frost cycles

| No. | Cement | FA/LL | w/c | 7 c | 14 c | 28 c | 42 c | 56 c |
|---|---|---|---|---|---|---|---|---|
| - | - | - | - | $kg/m^2$ | $kg/m^2$ | $kg/m^2$ | $kg/m^2$ | $kg/m^2$ |
| Mixes without air entrainment : | | | | | | | | |
| 1 | Ref. Std.FA | 20/0 | 0,60 | 4,0 | 8,0 | 7,5 | 4,0 | 8,0 |
| 2 | CEM II A-V | 20/0 | 0,60 | 2,0 | 3,0 | 3,0 | 2,0 | 3,0 |
| 3 | ‘’ | 20/0 | 0,50 | 0,01 | 0,02 | 0,04 | 0,04 | 0,05 |
| 4 | CEM II B-“M” | 20/10 | 0,60 | 0,02 | 0,04 | 0,09 | 0,11 | 0,11 |
| 5 | ‘’ | 30/20 | 0,60 | 0,03 | 0,07 | 0,12 | 0,22 | 0,24 |
| 6 | ‘’ | 30/20 | 0,50 | 0,01 | 0,03 | 0,05 | 0,06 | 0,06 |
| 7 | CEM II A-LL | 0/20 | 0,60 | 0,01 | 0,02 | 0,21 | 0,3 | 0,34 |
| 8 | CEM I(Ref. 80% Ind, 20%Anl) | 0/0 | 0,60 | 0,01 | 0,02 | 0,03 | 0,05 | 0,06 |

For all of these series, except for mix nos 7 & 8, ultra pulse velocity and visual inspection indicated internal damages, which may have caused too low scaling values. The scaling level of mix no 7 is considered to be high, so only the CEM I performed satisfactory.

Table 44: Results of freeze thaw tests at the age of three months after X (c) nos. of frost cycles

| Nr | Cement | FA/LL | w/c | 7 c | 14 c | 28 c | 42 c | 56 c |
|---|---|---|---|---|---|---|---|---|
| - | - | - | - | $kg/m^2$ | $kg/m^2$ | $kg/m^2$ | $kg/m^2$ | $kg/m^2$ |
| Mixes without air entrainment : | | | | | | | | |
| 1 | Ref. Std.FA | 20/0 | 0,60 | 0,07 | 0,11 | 0,24 | 0,28 | 0,31 |
| 2 | CEM II A-V | 20/0 | 0,60 | 0,04 | 0,07 | 0,19 | 0,24 | 0,3 |
| 3 | ‘’ | 20/0 | 0,50 | 0,04 | 0,09 | 0,12 | 0,14 | 0,17 |
| 4 | CEM II B-“M” | 20/10 | 0,60 | 0,06 | 0,16 | 0,31 | 0,38 | 0,4 |
| 5 | ‘’ | 30/20 | 0,60 | 0,35 | 0,97 | 1,55 | - | - |
| 6 | ‘’ | 30/20 | 0,50 | 0,04 | 0,13 | 0,24 | 0,27 | 0,28 |
| 7 | CEM II A-LL | 0/20 | 0,60 | 0,03 | 0,07 | 0,14 | 0,2 | 0,22 |
| 8 | CEM I(Ref. 80% Ind, 20%Anl) | 0/0 | 0,60 | 0,04 | 0,07 | 0,09 | 0,18 | 0,39 |

Also for these series, internal damage was considerable, again except for the CEM I reference. The scaling level, however, is significant. No acceptance level exists for the boundary conditions during this procedure, so a clear conclusion still cannot be drawn.

### 4.4.7 Freeze thaw resistance with de-icing salts

The test has been performed with the slab test according to the European Technical Specification EN 12390-9 with 3 % NaC. Results are compiled in tables 45 and 46.

Table 45: Results of freeze thaw tests with de-icing salts at the age of one month after X (c) nos. of frost cycles

| No. | Cement | FA/LL | w/c | 7 c | 14 c | 28 c | 42 c | 56 c |
|---|---|---|---|---|---|---|---|---|
| - | - | - | - | kg/m$^2$ | kg/m$^2$ | kg/m$^2$ | kg/m$^2$ | kg/m$^2$ |
| Mixes with air entrainment : | | | | | | | | |
| 1 | Ref. Std.FA | 20/0 | 0,60 | 0,07 | 0,11 | 0,24 | 0,28 | 0,31 |
| 2 | CEM II A-V | 20/0 | 0,60 | 0,04 | 0,07 | 0,19 | 0,24 | 0,3 |
| 3 | ‘’ | 20/0 | 0,50 | 0,04 | 0,09 | 0,12 | 0,14 | 0,17 |
| 4 | CEM II B-“M” | 20/10 | 0,60 | 0,06 | 0,16 | 0,31 | 0,38 | 0,4 |
| 5 | ‘’ | 30/20 | 0,60 | 0,35 | 0,97 | 1,55 | - | - |
| 6 | ‘’ | 30/20 | 0,50 | 0,04 | 0,13 | 0,24 | 0,27 | 0,28 |
| 7 | CEM II A-LL | 0/20 | 0,60 | 0,03 | 0,07 | 0,14 | 0,2 | 0,22 |
| 8 | CEM I(Ref. 80% Ind, 20%Anl) | 0/0 | 0,60 | 0,04 | 0,07 | 0,09 | 0,18 | 0,39 |

None of these – air entrained - series exhibited internal damage. Best performance (“Very Good”) was achieved with all the reference cement mixes, all of type CEM I. Good performance was achieved with 35% pfa (w/c=0,40) and 20% pfa (w/c=0,50). Acceptable performance was achieved with 35% pfa (w/c=0,50) and – close to the boarder line – 50% pfa (w/c=0,40). The latter (50%pfa) was not acceptable when increasing the w/c-ratio to 0,50.

Table 46: Results of freeze thaw tests with de-icing salts at the age of three months after X (c) nos. of frost cycles

| Nr | Cement | FA/LL | w/c | 7 c | 14 c | 28 c | 42 c | 56 c |
|---|---|---|---|---|---|---|---|---|
| - | - | - | - | kg/m$^2$ | kg/m$^2$ | kg/m$^2$ | kg/m$^2$ | kg/m$^2$ |
| Mixes with air entrainment : | | | | | | | | |
| 9 | CEM I 42,5 | 0/0 | 0,50 | 0,47 | 0,7 | 0,76 | 0,77 | 0,78 |
| 10 | ‘’ | 0/0 | 0,40 | 0,11 | 0,23 | 0,36 | 0,4 | 0,45 |
| 11 | CEM II A-V | 20/0 | 0,50 | 0,79 | 0,97 | 1,03 | 1,04 | 1,05 |
| 12 | CEM II B-V | 35/0 | 0,50 | 0,92 | 1,12 | 1,2 | 1,21 | 1,22 |
| 13 | ‘’ | 35/0 | 0,40 | 0,33 | 0,5 | 0,68 | 0,7 | 0,71 |
| 14 | CEM II ”B”-V | 50/0 | 0,50 | 1,04 | 1,78 | 2,25 | 2,3 | 2,33 |
| 15 | ‘’ | 50/0 | 0,40 | 0,88 | 1,19 | 1,24 | 1,25 | 1,25 |
| 16 | CEM I(Ref. 80% Ind, 20%Anl) | 0/0 | 0,40 | 0,03 | 0,05 | 0,08 | 0,09 | 0,09 |

Dealying the test start generally increased the scaling level. The ranking from above was kept more or less, but the 35% pfa (w/c=0,40) now performed better than the CEM I reference with w/c-ratio 0,50.

### 4.4.8 Conclusions

- Especially if long term strength is taken into consideration, the CEM II/B-V appear to be promising, based on strength, chloride intrusion.
- Combining 10% LL with 20-35% pfa should be further investigated.
- For the housing concrete sector, frost resistance should be further investigated – with air entrainement and concerning internal damage.

## 4.5 Partner 5: TITAN

### 4.5.1 General

The aim of this investigation is to produce two categories of blended cements, one according to EN 197-1 and the other with even greater levels of additions, explore their properties and expand the investigation to concrete made with a selection of the above cements.

### 4.5.2 Raw materials

The raw materials that have been chosen as additives in this project are two fly ashes (because of the significant differences in chemistry), limestone and natural pozzolana. Prior to their implementation, these materials were chemically and mineralogically characterized. The chemical and mineralogical analyses are summarized in the following tables.

Table 47: Chemical analyses

| | FLY ASHES (FA) | | LIMESTONE (LL) | POZZOLANA (P) |
|---|---|---|---|---|
| | A | B | | |
| $SiO_2$ | 35,24 | 51,26 | 2,77 | 60,96 |
| $Al_2O_3$ | 16,82 | 19,39 | 1,39 | 15,10 |
| $Fe_2O_3$ | 5,91 | 8,44 | 0,64 | 3,36 |
| CaO | 28,83 | 11,82 | 50,60 | 6,10 |
| MgO | 2,83 | 2,27 | 0,71 | 1,28 |
| $K_2O$ | 1,35 | 1,81 | 0,14 | 2,13 |
| $Na_2O$ | 0,72 | 0,53 | - | 0,62 |
| $SO_3$ | 5,30 | 2,91 | - | 1,49 |
| f.CaO | 7,60 | 8,80 | - | - |
| LOI | 3,00 | 1,67 | 40,50 | 8,93 |

Table 48: Mineralogical analyses

| | | FA | | LL | P |
|---|---|---|---|---|---|
| | | A | B | | |
| Quartz | $SiO_2$ | + | + | | + |
| Gehlenite | (Ca,Al,Si.Mg,Fe)$SiO_2$ | | | | |
| Hematite | $Fe_2O_3$ | + | + | | + |
| Lime | CaO | + | + | | |
| Calcite | $CaCO_3$ | + | + | + | + |
| Illite | $KAl_2Si_3AlO_{10}(OH)_2$ | + | | | + |
| Albite | $NaAlSi_3O_8$ | + | + | | + |
| Portlandite | $Ca(OH)_2$ | + | + | | |
| Anhydrite | $CaSO_4$ | + | + | | |
| Dolomite | $Ca(Mg,Fe)(CO_3)_2$ | | | + | + |
| Sanidine | $(K,Na)AlSi_3O_8$ | + | + | | |
| Coesite | $SiO_2$ | + | + | | |
| Montmorillonite | $NaMgAlSiO_2(OH)H_2O$ | | + | | + |
| Akermanite | $MgAlSi1.5O_6$ | + | + | | |

- FA: FA(A) is clearly of the calcareous type, whereas, FA(B)is only marginally calcareous. The higher % $SO_3$ content of FA(A) is due to greater amount of CaSO4. Part of the f.CaO existing in the ashes was hydrated forming $Ca(OH)_2$. The LOI of both ashes was relatively low and below the 5% (max) limit required by the EN 197-1, for use in the cement.
- LL:Calcite is the major constituent of the limestone. Some dolomite and very little quartz are also present.
- P: Natural pozzolana consists of the minerals presented above and of amorphous $SiO_2$ which is the active constituent.

### 4.5.3 Blended cements

Cement production consisted of three phases:

Phase 1: Production of reference cements of various strength classes. Some of those cements were also used as the main constituent of the blended cements.

Phase 2: Preparation of the raw materials. Preparation included grinding of the fly ashes, limestone and pozzzolana to certain fineness. The particle size distributions (PSD) of the fly ashes, the limestone and the pozzolana are shown in tables 49 and 50.

Phase 3: Blending of reference cements with the grinded additives.

One additive: FA – table 63 at the end of chapter 4.5

- The water demand of the mixtures with F.A. is higher than the reference cement and it is higher with the higher (45%) addition level. The effect of FA(A) (which is calcareous) on water demand increase is less profound than the one from FA(B) (which is marginally calcareous).
- The setting time is getting longer as the F.A. addition is getting higher and as the PSD of F.A. is getting coarser. The impact of the marginally calcareous FA(B) is stronger.
- The strength (28d) of the admixtures are lower than the reference cement but it is approaching the later by finer grinding. The higher addition level has a stronger impact on strength when the FA is coarser.
- Grinding the calcareous FA(A) of the same nominal fineness (1- μ
μ

Table 49: Grain size distribution of Fly Ashes (% passing)

| µm | FA(A) | FA(A) | FA(A) | FA(A) | FA(A) | FA(B) | FA(B) | FA(B) | FA(B) | FA(B) |
|---|---|---|---|---|---|---|---|---|---|---|
| Laser +45 | As received | *2,0* | *6,5* | *16,0* | *19,8* | As received | *1,0* | *6,8* | *14,8* | *22,4* |
| 1 | 2,3 | 13,6 | 9,7 | 5,0 | 4,1 | 1,0 | 7,2 | 5,2 | 3,9 | 3,1 |
| 1,5 | 2,7 | 17,8 | 13,0 | 6,3 | 5,2 | 1,2 | 10,0 | 7,1 | 5,2 | 4,1 |
| 2 | 4,1 | 26,8 | 20,0 | 10,0 | 8,2 | 2,0 | 16,9 | 12,1 | 8,8 | 6,9 |
| 3 | 6,2 | 38,3 | 28,7 | 14,6 | 11,7 | 2,8 | 26,5 | 18,2 | 13,4 | 10,4 |
| 4 | 8,6 | 46,8 | 34,4 | 19,2 | 15,3 | 3,8 | 33,1 | 23,4 | 17,5 | 14,0 |
| 6 | 11,4 | 56,2 | 41,9 | 24,3 | 19,1 | 4,9 | 42,7 | 30,0 | 22,7 | 18,1 |
| 8 | 16,0 | 66,1 | 50,0 | 31,8 | 25,6 | 6,9 | 52,4 | 38,5 | 29,8 | 24,4 |
| 12 | 22,5 | 75,6 | 60,8 | 40,2 | 33,7 | 9,5 | 65,6 | 49,9 | 39,3 | 32,5 |
| 16 | 31,4 | 83,0 | 69,2 | 49,6 | 43,5 | 13,3 | 75,6 | 61,3 | 48,8 | 42,0 |
| 24 | 42,8 | 90,5 | 81,4 | 60,9 | 55,3 | 18,5 | 89,2 | 76,4 | 62,2 | 53,4 |
| 32 | 56,3 | 96,5 | 89,5 | 73,8 | 69,0 | 27,1 | 95,1 | 88,5 | 75,4 | 67,3 |
| 48 | 76,0 | 100,0 | 100,0 | 89,7 | 86,1 | 45,9 | 100,0 | 100,0 | 93,5 | 86,9 |
| 64 | 82,0 | 100,0 | 100,0 | 93,2 | 91,4 | 56,5 | 100,0 | 100,0 | 94,3 | 91,4 |
| 96 | 94,9 | 100,0 | 100,0 | 100,0 | 100,0 | 81,4 | 100,0 | 100,0 | 100,0 | 100,0 |
| 128 | 98,7 | 100,0 | 100,0 | 100,0 | 100,0 | 95,3 | 100,0 | 100,0 | 100,0 | 100,0 |
| 192 | 100 | 100,0 | 100,0 | 100,0 | 100,0 | 100 | 100,0 | 100,0 | 100,0 | 100,0 |

Table 50: Grain size distribution of limestone and pozzolana (% passing)

| µ | LL | | | | P | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Laser +45 | 5 | 13,5 | 20 | 35 | 5,8 | 13,6 | 24,4 | 8 | 5 |
| 1 | 8,8 | 9,2 | 8,2 | 8,1 | 3,1 | 2,5 | 1,9 | 3,2 | 3,3 |
| 1,5 | 11,7 | 11,9 | 11,1 | 10,7 | 5,5 | 4,4 | 3,3 | 5,6 | 5,9 |
| 2 | 18,6 | 18,3 | 17,8 | 17,6 | 13,3 | 10,6 | 8,3 | 13,3 | 13,9 |
| 3 | 25,5 | 24,3 | 24,6 | 23,7 | 22,7 | 18,2 | 14,4 | 22,6 | 23,8 |
| 4 | 31,0 | 29,7 | 29,7 | 29,0 | 29,0 | 24,1 | 19,4 | 29,1 | 30,4 |
| 6 | 37,0 | 33,5 | 35,4 | 33,6 | 37,4 | 31,1 | 25,3 | 37,1 | 38,4 |
| 8 | 45,3 | 41,3 | 43,2 | 41,3 | 46,4 | 40,0 | 33,2 | 46,3 | 47,2 |
| 12 | 53,8 | 46,9 | 51,1 | 47,5 | 57,1 | 49,6 | 41,6 | 56,9 | 58,1 |
| 16 | 61,6 | 54,6 | 58,4 | 55,3 | 66,1 | 59,3 | 50,8 | 67,2 | 67,2 |
| 24 | 68,8 | 59,3 | 65,2 | 61,1 | 79,4 | 70,9 | 61,3 | 79,8 | 80,6 |
| 32 | 77,7 | 68,5 | 73,6 | 69,7 | 89,0 | 82,3 | 72,4 | 90,1 | 90,1 |
| 48 | 91,0 | 78,7 | 86,3 | 79,9 | 99,3 | 94,9 | 87,4 | 99,9 | 100,0 |
| 64 | 93,9 | 82,9 | 89,0 | 84,8 | 99,3 | 96,3 | 91,6 | 99,9 | 100,0 |
| 96 | 100,0 | 95,1 | 100,0 | 96,1 | 100,0 | 100,0 | 99,9 | 100,0 | 100,0 |
| 128 | 100,0 | 98,7 | 100,0 | 99,0 | 100,0 | 100,0 | 99,9 | 100,0 | 100,0 |
| 192 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 |

Table 51: Reference cements (particle size distribution, physicochemical properties)

| µ | I-52.5 | | | I-42.5 | | I-32.5 |
|---|---|---|---|---|---|---|
| 1 | 8,5 | 8,0 | 6,9 | 6,3 | 5,9 | 3,8 |
| 1,5 | 10,7 | 9,9 | 9,1 | 7,8 | 7,2 | 4,6 |
| 2 | 15,7 | 14,8 | 14,5 | 11,8 | 10,9 | 6,9 |
| 3 | 21,3 | 19,6 | 19,9 | 15,9 | 14,9 | 9,7 |
| 4 | 26,4 | 24,6 | 24,9 | 20,4 | 19,3 | 12,8 |
| 6 | 32,0 | 29,3 | 30,3 | 24,6 | 23,5 | 16,2 |
| 8 | 40,3 | 37,8 | 39,0 | 32,1 | 30,9 | 22,8 |
| 12 | 50,3 | 47,0 | 49,0 | 40,4 | 40,2 | 31,9 |
| 16 | 61,1 | 59,4 | 61,3 | 50,8 | 52,0 | 43,0 |
| 24 | 75,7 | 75,4 | 77,8 | 60,9 | 64,6 | 54,5 |
| 32 | 88,3 | 90,1 | 91,3 | 73,7 | 78,0 | 67,5 |
| 48 | 100,0 | 100,0 | 100,0 | 88,8 | 92,7 | 83,3 |
| 64 | 100,0 | 100,0 | 100,0 | 95,3 | 97,4 | 91,2 |
| 96 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 |
| 128 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 |
| 192 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 | 100,0 |
| < 3 | 21,3 | 19,6 | 19,9 | 15,9 | 14,9 | 9,7 |
| >32 | 11,7 | 9,9 | 8,7 | 26,3 | 22,0 | 32,5 |
| 3 - 32 | 67,0 | 70,5 | 71,4 | 57,8 | 63,1 | 57,8 |
| n= | 0,9 | 1,0 | 15,56 | 22,16 | 20,41 | 28,83 |
| d= | 15,8 | 16,4 | 0,97 | 0,90 | 0,97 | 1,01 |
| | | | | | | |
| Blaine | | | 3820 | 3030 | 3220 | 2500 |
| %H2O | 25,4 | 27,6 | 27,40 | 23,8 | 23,8 | 23,8 |
| I.Set | 95 | 150 | 110 | 120 | 80 | 110 |
| F.Set | 145 | 200 | 150 | 160 | 120 | 160 |
| Le Chat. | 0,1 | | | | | |
| | | | | | | |
| 1day | 18,5 | 18,4 | 18,2 | 12,5 | 11,7 | 8,0 |
| 2days | 29,8 | 29,6 | 29,1 | 20,5 | 20,5 | 12,5 |
| 7days | 44,0 | 47,3 | 42,2 | 36,8 | 36,1 | 23,3 |
| 28days | 66,0 | 64,6 | 61,5 | 51,0 | 50,6 | 41,4 |

<u>One additive: LL</u>

- Water demand and setting times are not significantly influenced neither by the addition level nor by the fineness of limestone.
- Strength values are substantially decreased by the addition of limestone and the increase of the addition level from 35% to 45% is reflected by a decrease of strength in the order of 10MPa.

- The strength results indicate that there is an optimum PSD of the limestone in order to soften the negative impact on strength. The optimum PSD is different according to the addition level but in both cases it is sifted to coarser limestone. Nevertheless it has to be noticed that the various limestone fineness were not solely the result of more intense grinding but for the finest one it was the result of sieving.

Table 52: Mixtures with LL (particle size distribution, physicochemical properties)

| µm | I-52.5 | 35% LL | I-52.5 | 35% LL | | | 45% LL | | |
|---|---|---|---|---|---|---|---|---|---|
| Laser +45 | | 13,5 | | 5 | 20 | 35 | 5 | 20 | 35 |
| 1 | 8,5 | 9,1 | 6,9 | 7,6 | 7,0 | 6,6 | 7,4 | 7,0 | 6,4 |
| 1,5 | 10,7 | 11,9 | 9,1 | 10,4 | 9,5 | 9 | 9,8 | 9,7 | 8,7 |
| 2 | 15,7 | 18,2 | 14,5 | 16,8 | 15,8 | 15,2 | 15,8 | 16,4 | 14,8 |
| 3 | 21,3 | 25,1 | 19,9 | 23,5 | 22,1 | 21,6 | 22,4 | 23 | 20,8 |
| 4 | 26,4 | 30,3 | 24,9 | 28,5 | 27,1 | 26,5 | 27,7 | 27,9 | 25,6 |
| 6 | 32,0 | 36,1 | 30,3 | 34,8 | 32,8 | 32,1 | 34,2 | 33,7 | 30,6 |
| 8 | 40,3 | 43,7 | 39,0 | 43,0 | 41,1 | 40,1 | 42,5 | 42 | 38,4 |
| 12 | 50,3 | 52,8 | 49,0 | 52,8 | 50,9 | 49,0 | 52,3 | 51,3 | 46,5 |
| 16 | 61,1 | 61,6 | 61,3 | 61,9 | 61,1 | 59,0 | 62,2 | 60,5 | 55,8 |
| 24 | 75,7 | 73,9 | 77,8 | 74,6 | 75,2 | 72,1 | 75,7 | 73,2 | 67,3 |
| 32 | 88,3 | 83,7 | 91,3 | 84,4 | 86,5 | 83,1 | 86,5 | 83,6 | 77,5 |
| 48 | 100 | 95,3 | 100 | 96,3 | 96,7 | 93,2 | 97,7 | 94,2 | 87,1 |
| 64 | 100 | 95,8 | 100 | 96,3 | 96,7 | 94,0 | 97,7 | 94,7 | 89,3 |
| 96 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 95,0 |
| 128 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 98,7 |
| 192 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| < 3 | 21,3 | 25,1 | 19,9 | 23,5 | 22,1 | 21,6 | 22,4 | 23,0 | 20,8 |
| >32 | 11,7 | 16,3 | 8,7 | 15,6 | 13,5 | 16,9 | 13,5 | 16,4 | 22,5 |
| 3 - 32 | 67,0 | 58,6 | 71,4 | 60,9 | 64,4 | 61,5 | 64,1 | 60,6 | 56,7 |
| n= | 0,9 | 0,8 | 15,56 | 15,40 | 15,57 | 17,45 | 14,83 | 16,51 | 21,23 |
| d= | 15,8 | 15,8 | 0,97 | 0,89 | 0,93 | 0,89 | 0,94 | 0,88 | 0,82 |
| | | | | | | | | | |
| BLAINE | | | 3820 | 4270 | 3990 | 4150 | 4510 | 4320 | 4260 |
| %$H_2O$ | 25,4 | 25,2 | 27,4 | 26,8 | 27,1 | 26,6 | 26,8 | 26,8 | 25,4 |
| I.Set | 95 | 80 | 110 | 100 | 110 | 120 | 100 | 90 | 100 |
| F.Set | 145 | 120 | 150 | 150 | 150 | 180 | 160 | 140 | 140 |
| Le Chat. | 0,1 | 0,1 | | | | | | | |
| | | | 18,2 | | | | | | |
| 1day | 18,5 | 10,4 | 29,1 | 10,5 | 12,1 | 10,2 | 7,8 | 7,5 | 8,3 |
| 2days | 29,8 | 17,5 | 42,2 | 16,2 | 19,6 | 17,0 | 12,1 | 12,5 | 14,0 |
| 7days | 44,0 | 27,9 | 61,5 | 26,0 | 29,5 | 27,1 | 19,7 | 19,2 | 21,5 |
| 28days | 66,0 | 37,5 | | 35,8 | 40,4 | 37,0 | 26,0 | 26,8 | 29,2 |

One additive: P

- Water demand of mixtures with pozzolana is higher than the one of the reference cement.
- Setting times of mixtures with pozzolana are longer than the one of the reference cement.
- The effect of pozzolana fineness on water demand and setting time is negligible,

while on strength is only minor with the optimum lying at the finer PSDs.

- The increase of pozzolana addition from 35% to 45% is reducing strength by 5MPa on average.

Table 53: Mixtures with P (particle size distribution, physicochemical properties)

| μ | I-52.5 | 35% P | | | 45% P | | | I-52.5 | 35% P | | 45% P | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Laser +45 | | 5,8 | 13,6 | 24,4 | 5,8 | 13,6 | 24,4 | | 5 | 8 | 5 | 8 |
| 1 | 8,5 | 5,4 | 5,2 | 4,9 | 4,9 | 4,8 | 4,4 | 6,9 | 4,2 | 3,6 | 4,3 | 3,8 |
| 1,5 | 10,7 | 7,3 | 6,8 | 6,3 | 6,7 | 6,4 | 5,9 | 9,1 | 5,7 | 5,6 | 5,9 | 5,7 |
| 2 | 15,7 | 12,5 | 11,1 | 10,3 | 11,5 | 11,4 | 10,0 | 14,5 | 9,8 | 11,1 | 10,9 | 11,7 |
| 3 | 21,3 | 19,1 | 16,8 | 15,7 | 18,2 | 17,5 | 15,2 | 19,9 | 14,7 | 19,2 | 17,0 | 19,3 |
| 4 | 26,4 | 24,5 | 22,0 | 20,8 | 23,4 | 22,8 | 20,0 | 24,9 | 18,8 | 24,3 | 22,5 | 25,4 |
| 6 | 32,0 | 31,0 | 29,0 | 26,8 | 30,5 | 28,9 | 25,6 | 30,3 | 25,0 | 32,5 | 29,4 | 32,7 |
| 8 | 40,3 | 39,5 | 37,7 | 34,8 | 38,3 | 37,2 | 33,4 | 39,0 | 34,2 | 39,8 | 39,5 | 41,6 |
| 12 | 50,3 | 50,2 | 48,8 | 44,6 | 49,3 | 47,0 | 42,4 | 49,0 | 47,9 | 51,9 | 52,0 | 52,2 |
| 16 | 61,1 | 60,3 | 59,3 | 55,0 | 58,9 | 58,1 | 53,0 | 61,3 | 61,4 | 60,1 | 65,2 | 63,0 |
| 24 | 75,7 | 74,6 | 73,4 | 67,4 | 73,8 | 71,3 | 65,3 | 77,8 | 77,8 | 76,8 | 79,6 | 77,6 |
| 32 | 88,3 | 86,5 | 85,5 | 80,2 | 84,3 | 84,5 | 77,8 | 91,3 | 89,9 | 85,5 | 92,0 | 89,8 |
| 48 | 100 | 98,7 | 99,4 | 94,4 | 97,7 | 98,2 | 92,3 | 100 | 100 | 98,2 | 100 | 100 |
| 64 | 100 | 98,7 | 99,4 | 95,6 | 97,7 | 99,2 | 94,6 | 100 | 100 | 98,2 | 100 | 100 |
| 96 | 100 | 98,7 | 99,9 | 98,3 | 97,7 | 100 | 99,1 | 100 | 100 | 100 | 100 | 100 |
| 128 | 100 | 99,6 | 99,9 | 99,5 | 99,4 | 100 | 99,7 | 100 | 100 | 100 | 100 | 100 |
| 192 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| < 3 | 21,3 | 19,1 | 16,8 | 15,7 | 18,2 | 17,5 | 15,2 | 19,9 | 14,7 | 19,2 | 17,0 | 19,3 |
| >32 | 11,7 | 13,5 | 14,5 | 19,8 | 15,7 | 15,5 | 22,2 | 8,7 | 10,1 | 14,5 | 8,0 | 10,2 |
| 3 - 32 | 67,0 | 67,4 | 68,7 | 64,5 | 66,1 | 67,0 | 62,6 | 71,4 | 75,2 | 66,3 | 75,0 | 70,5 |
| n= | 0,9 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 15,56 | 16,58 | 15,76 | 14,86 | 14,87 |
| d= | 15,8 | 16,5 | 17,1 | 19,8 | 17,2 | 17,7 | 21,1 | 0,97 | 1,13 | 1,10 | 1,14 | 1,12 |
| | | | | | | | | | | | | |
| BLAINE | | | | | | | | 3820 | 5080 | 4880 | 5160 | 4550 |
| %$H_2O$ | 25,4 | 34,0 | 34,2 | 34,2 | 36,0 | 36,0 | 36,6 | 27,4 | 33,2 | 29,6 | 36,0 | 30,3 |
| I.Set | 95 | 120 | 120 | 130 | 120 | 120 | 140 | 110 | 155 | 180 | 140 | 180 |
| F.Set | 145 | 180 | 170 | 180 | 180 | 180 | 180 | 150 | 195 | 210 | 180 | 220 |
| Le Chat. | 0,1 | | | | | | | | | | | |
| | | | | | | | | | | | | |
| 1day | 18,5 | 12,8 | 13,1 | 12,5 | 10,7 | 9,9 | 10,0 | 18,2 | 11,1 | 9,6 | 8,4 | 9,8 |
| 2days | 29,8 | 19,3 | 20,7 | 18,6 | 15,8 | 15,7 | 15,3 | 29,1 | 16,2 | 14,5 | 12,0 | 14,7 |
| 7days | 44,0 | 31,1 | 30,4 | 28,9 | 26,4 | 24,6 | 24,5 | 42,2 | 26,3 | 21,5 | 20,1 | 22,2 |
| 28days | 66,0 | 43,0 | 42,8 | 41,2 | 39,2 | 37,2 | 35,3 | 61,5 | 42,0 | 36,1 | 35,0 | 36,6 |

- Comparing mixtures with limestone and mixtures with pozzolana at the same addition level and of the same fineness it is concluded that the superiority of pozzolana is obvious only at the high addition. At the level of 35% addition, the higher strength of admixtures with pozzolana are almost canceled by their higher water demand. On the other it should be emphasized that at later ages, the strength increase of pozzolana mixtures is more sizeable:

| | 28d | 90d | 180d |
|---|---|---|---|
| μ | 43,0 | 51,1 | 54,6 |
| μ | 35,8 | 39,4 | 41,3 |

<u>One additive: Comparison</u>

In order to summarize the effect in cement of each material as a main constituent (each one alone) the following can be concluded:

| Paramter | 35% Addition | | | 45% Addition | | |
|---|---|---|---|---|---|---|
| | FA | LL | P | FA | LL | P |
| Water Demand | + | 0 | + | ++ | 0 | ++ |
| Setting | + | 0 | + | ++ | 0 | + |
| Strength | - | -- | -- | - | --- | -- |

<u>Three additives: FA + P + LL</u>

From the results in table 54 it is apparent that blended cements with I-52.5, FA, LL and P were within the I-32.5 class with the low (58%) and the high (69%) cement type I content. At the same strength level, blended cements had similar setting times and higher water demand than the I-32.5 cement which is justified by the higher Blaine values. The production of blended ternary cements consisting of fly ash, pozzolana and limestone is able to come up with a balance between strength – water demand – cost. The question of optimum durability regarding to concrete strength is validated by the concrete mix designs that follows.

From all the blended cements presented in this section, strength was the base criterion in order to select those that were used in concrete tests.

Table 54: Admixtures with FA, P and LL (particle size distribution, physicochemical properties)

| µm | I-52.5 | 6% FA(A) 17% P 8% LL | 6% FA(A) 17% P 8% LL | 15% FA(A) 12% P 15% LL | 15% FA(A) 12% P 15% LL | 6% FA(A) 17% P 8% LL | 15% FA(A) 12% P 15% LL |
|---|---|---|---|---|---|---|---|
| 1 | 6,9 | 5,9 | 5,7 | n. m. | 6,4 | 5,8 | 6,7 |
| 1,5 | 9,1 | 7,6 | 7,5 | | 8,4 | 7,9 | 9,2 |
| 2 | 14,5 | 12,3 | 12,0 | | 13,7 | 13,2 | 15,5 |
| 3 | 19,9 | 17,7 | 17,6 | | 19,5 | 19,8 | 22,6 |
| 4 | 24,9 | 22,6 | 22,3 | | 24,4 | 25,0 | 28,2 |
| 6 | 30,3 | 28,7 | 28,2 | | 30,4 | 32,0 | 34,8 |
| 8 | 39,0 | 38,0 | 37,0 | | 39,3 | 40,5 | 43,7 |
| 12 | 49,0 | 50,5 | 49,6 | | 51,1 | 51,6 | 54,1 |
| 16 | 61,3 | 63,6 | 62,3 | | 63,7 | 62,2 | 64,8 |
| 24 | 77,8 | 79,3 | 78,7 | | 78,7 | 77,7 | 78,7 |
| 32 | 91,3 | 91,2 | 90,2 | | 90,1 | 88,5 | 89,6 |
| 48 | 100 | 100 | 100 | | 99,8 | 99,0 | 99,1 |
| 64 | 100 | 100 | 100 | | 100 | 99,0 | 99,1 |
| 96 | 100 | 100 | 100 | | 100 | 99,9 | 100 |
| 128 | 100 | 100 | 100 | | 100 | 100 | 100 |
| 192 | 100 | 100 | 100 | | 100 | 100 | 100 |
| < 3 | 19,9 | 17,7 | 17,6 | | 19,5 | 19,8 | 22,6 |
| >32 | 8,7 | 8,8 | 9,8 | | 9,9 | 11,5 | 10,4 |
| 3 - 32 | 71,4 | 73,5 | 72,6 | | 70,6 | 68,7 | 67,0 |
| n= | 15,56 | 15,43 | 15,87 | | 13,72 | 14,54 | 13,53 |
| d= | 0,97 | 1,04 | 1,04 | | 1,07 | 1,05 | 1,01 |
| | | | | | | | |
| BLAINE | 3820 | 4660 | 4860 | 5060 | 5240 | 4860 | 5370 |
| $\%H_2O$ | 27,4 | 29,4 | 30,2 | 30,4 | 31,4 | 29,6 | 30,0 |
| I.Set | 110 | 130 | 110 | 120 | 120 | 130 | 130 |
| F.Set | 150 | 190 | 160 | 160 | 140 | 170 | 170 |
| | | | | | | | |
| 1day | 18,2 | 12,5 | 13,0 | 10,2 | 10,0 | 12,2 | 11,1 |
| 2days | 29,1 | 19,4 | 19,9 | 16,6 | 16,3 | 20,1 | 17,6 |
| 7days | 42,2 | 30,3 | 31,3 | 26,3 | 27,1 | 32,0 | 27,6 |
| 28days | 61,5 | 41,4 | 43,2 | 39,1 | 40,1 | 44,7 | 41,5 |

n. m.: not measured

### 4.5.4 Concrete

#### 4.5.4.1 General

Two concrete categories (with cement contents equal to 280 and 320 kg/m$^3$) were evaluated according to rheological, mechanical and durability properties. The results of the various tests are presented below. Two OPC cements were used as reference cements, the first equal to strength class 32.5 and the second to 42.5.

#### 4.5.4.2 Rheological and mechanical properties

Basic concrete properties were measured during the period under review, for both concrete categories, according to following European standards: EN 12350-Part 2 (Slump), EN 12350-Part 7 (Air content) and EN 12390-Part 3 (Compressive Strength). The water/cement ratios (w/c) were calculated according to EN 206-1 and as it was agreed by the Partners, it was fixed to 0.50 (for the category with c=320 kg/m$^3$) and 0.60 (for the category with c=280kg/m$^3$). A water reducing admixture was used in order to obtain a slump within the range 10-12 cm and therefore the cement's impact on the concrete's workability could be evaluated indirectly. The compressive strength was measured at the age of 2, 7, 28 and 90 days, the results are presented in the tables below.

Results are summarized in tables 55 to 58.

<u>Concrete mixtures with cement strength class 42.5</u>

Table 55: Rheological and mechanical properties - c=280 kg/m$^3$, w/c= 0.60

| C=280 kg/m$^3$ w/c= 0.60 | I-42.5 | 35% FA(A) | 35% FA(A) | 35% FA(A) | 45% FA(A) | 45% FA(A) | 45% FA(A) | 35% FA(A) | 45% FA(A) |
|---|---|---|---|---|---|---|---|---|---|
| Addition Laser +45µm | | 6,5 | 16 | 19,8 | 6,5 | 16 | 19,8 | 2 | 2 |
| | Rheological Properties | | | | | | | | |
| Admixture (% w/w cem) | 1,0 | 1,0 | 2,3 | 2,3 | 2,0 | 2,4 | 2,4 | 2,3 | 2,3 |
| Slump (cm) | 12 | 12 | 12 | 12 | 12 | 10 | 10 | 11 | 10 |
| Air Content (%) | 2,0 | 1,9 | 2,3 | 2,2 | 2,1 | 2,1 | 2,0 | 2,0 | 2,3 |
| | Mechanical Properties | | | | | | | | |
| $f_{2\ days}$ (MPa) | 22,1 | 16,2 | 13,2 | 13,2 | 11,0 | 14 | 13,0 | 13,5 | 11,9 |
| $f_{7\ days}$ (MPa) | 36,0 | 33,9 | 28,7 | 26,5 | 26,2 | 27 | 27,2 | 29,4 | 27,4 |
| $f_{28\ days}$ (MPa) | 46,9 | 50,2 | 42,0 | 40,0 | 42,4 | 42,9 | 40,3 | 47,2 | 44,9 |
| $f_{90\ days}$ (MPa) | 53,9 | 56,1 | 49,2 | 46,0 | 49,8 | 49,3 | 43,1 | 51,4 | 52,3 |

Table 56: Rheological and mechanical properties - c=320 kg/m$^3$, w/c= 0.50

| C=320 kg/m$^3$ w/c= 0.50 | I-42.5 | 35% FA(A) | 35% FA(A) | 35% FA(A) | 45% FA(A) | 45% FA(A) | 45% FA(A) | 35% FA(A) | 45% FA(A) |
|---|---|---|---|---|---|---|---|---|---|
| Addition Laser +45μm | | 6,5 | 16 | 19,8 | 6,5 | 16 | 19,8 | 2 | 2 |
| | Rheological Properties | | | | | | | | |
| Air Content (%) | 2,3 | 1,6 | 1,7 | 1,7 | 1,8 | 2,2 | 2,2 | 1,6 | 1,8 |
| Slump (cm) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 |
| | Mechanical Properties | | | | | | | | |
| $f_{2\ days}$ (MPa) | 24,3 | 28,3 | 27,6 | 27,9 | 25,8 | 24,9 | 24,0 | 28,8 | 25,6 |
| $f_{7\ days}$ (MPa) | 37,8 | 41,8 | 40,7 | 38,6 | 39,6 | 36,8 | 33,7 | 43,0 | 42,2 |
| $f_{28\ days}$ (MPa) | 52,2 | 57,1 | 53,4 | 54,9 | 57,1 | 53,6 | 49,4 | 60,1 | 57,2 |
| $f_{90\ days}$ (MPa) | 59,1 | 65,0 | 62,2 | 60,3 | 65,4 | 61,6 | 55,7 | 65,7 | 65,6 |

<u>Concrete mixtures with cement strength class 32.5</u>

Table 57: Rheological and mechanical properties – c = 280 kg/m$^3$, w/c= 0.60

| C=280 kg/m$^3$ w/c= 0.60 | I-32.5 | 35% LL | 35% P | 6% FA(A) 17% P 8% LL | 15% FA(A) 12% P 15% LL | 35% F.A.(B) | 45% F.A.(B) |
|---|---|---|---|---|---|---|---|
| | Rheological Properties | | | | | | |
| Admixture (% w/w cem) | 0,9 | 1,5 | 1,7 | 1,9 | 1,9 | 1,4 | 2,2 |
| Air Content (%) | 1,9 | 3,6 | 2,5 | 1,3 | 1,4 | 1,3 | 1,0 |
| Slump (cm) | 12 | 12 | 12 | 11 | 12 | 12 | 11 |
| | Mechanical Properties | | | | | | |
| $f_{2\ days}$ (MPa) | 12,1 | 10,9 | 11,5 | 14,4 | 12,0 | 12,1 | 10,1 |
| $f_{7\ days}$ (MPa) | 24,5 | 22,2 | 25,4 | 25,1 | 21,7 | 23,4 | 21,1 |
| $f_{28\ days}$ (MPa) | 35,0 | 28,1 | 38,1 | 35,7 | 33,6 | 38,2 | 36,4 |
| $f_{90\ days}$ (MPa) | 40,0 | 29,6 | 45,4 | 43,8 | 39,1 | nm | nm |

Table 58: Rheological and mechanical properties – c = 320 kg/m$^3$, w/c= 0.50

| C=320 kg/m$^3$ w/c= 0.50 | I-32.5 | 35% LL | 35% P | 6% FA(A) 17% P 8% LL | 15% FA(A) 12% P 15% LL | 35% F.A.(B) | 45% F.A.(B) |
|---|---|---|---|---|---|---|---|
| | Rheological Properties | | | | | | |
| Admixture (% w/w cem) | 1,2 | 1,7 | 2,0 | 2,5 | 2,5 | 1,8 | 2,7 |
| Air Content (%) | 2,0 | 2,2 | 1,6 | 1,9 | 1,9 | 1,3 | 0,8 |
| Slump (cm) | 11 | 11 | 12 | 11 | 11 | 11 | 11 |
| | Mechanical Properties | | | | | | |
| $f_{2\ days}$ (MPa) | 18,9 | 17,3 | 18,9 | 21,4 | 16,9 | 16,7 | 14,0 |
| $f_{7\ days}$ (MPa) | 32,5 | 29,0 | 33,0 | 36,0 | 29,9 | 29,5 | 28,6 |
| $f_{28\ days}$ (MPa) | 48,1 | 36,5 | 47,3 | 50,0 | 45,6 | 47,6 | 46,6 |
| $f_{90\ days}$ (MPa) | 54,0 | 38,5 | 56,0 | 57,9 | 51,7 | nm | nm |

#### 4.5.4.3 Carbonation

The method that was used in this test in order to measure the carbonation depth was agreed by the Partners. Test specimens of 100 x 100 x 400 mm$^3$ were stored in water for six days before their placement in a climate chamber with T=20ºC and RH=65%. The carbonation chamber settings were adjusted to 800 ppm concentration of $CO_2$ (typical concentration for Greek urban area) and the depth was measured after 28, 56, 90 and 180 days with the use of phenolphthalein index on 30-50 mm thick concrete slices. The results are presented below.

Table 59: Carbonation depth of concrete with class 42.5 cements

| C=280 kg/m$^3$ w/c=0.60 / Carbonation at the age of | I-42.5 | 35% FA(A) | 35% FA(A) | 35% FA(A) | 45% FA(A) | 45% FA(A) | 45% FA(A) | 35% FA(A) | 45% FA(A) |
|---|---|---|---|---|---|---|---|---|---|
| Addition μ | | 6,5 | 16 | 19,8 | 6,5 | 16 | 19,8 | 2 | 2 |
| 28days (mm) | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| 56 days (mm) | 2 | 5 | 6 | 6 | 8 | 7 | 7 | 7 | 8 |
| 90 days (mm) | 3 | 6 | 6 | 7 | 8 | 8 | 8 | 8 | 8 |
| 180 days (mm) | nm | 9 | 10 | 11 | 12 | 12 | 13 | 12 | 12 |

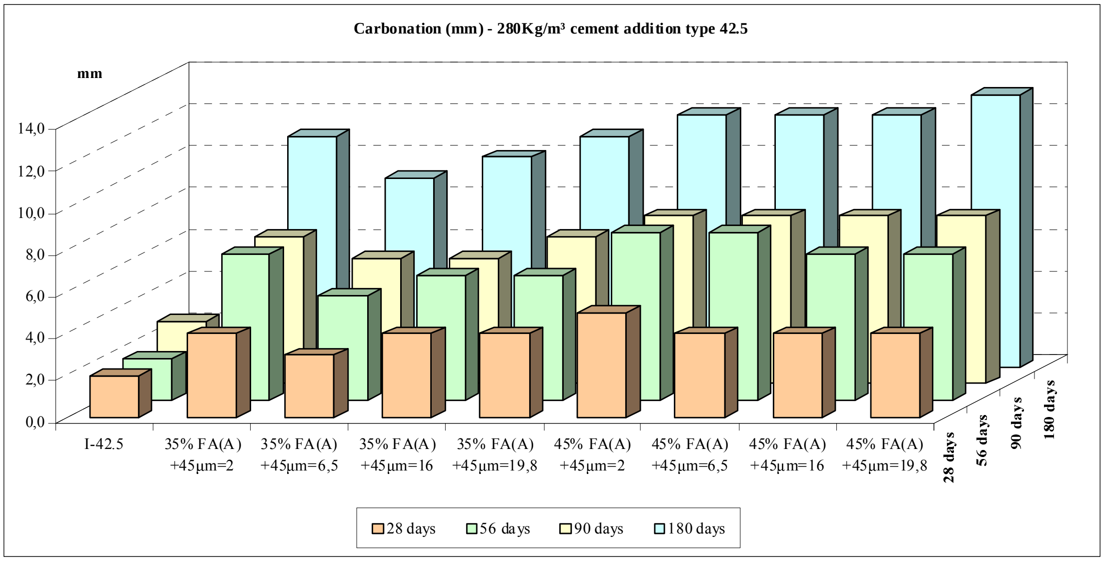



Figure 15: Carbonation depth of concrete with 42.5 cements

Table 60: Carbonation depth of concrete with class 32.5 cements

| C=280 kg/m$^3$ w/c=0.60 Carbonation at the age of | I-32.5 | 35% LL | 35% P | 6% FA(A) 17% P 8% LL | 15% FA(A) 12% P 15% LL | 35% FA(B) | 45% FA(B) |
|---|---|---|---|---|---|---|---|
| 28 days (mm) | 5 | 6 | 5 | 4 | 4 | 5 | 6 |
| 56 days (mm) | 5 | 6 | 5 | 4 | 5 | n. d. | n. d. |
| 90 days (mm) | 5 | 6 | 6 | 5 | 6 | n. d. | n. d. |

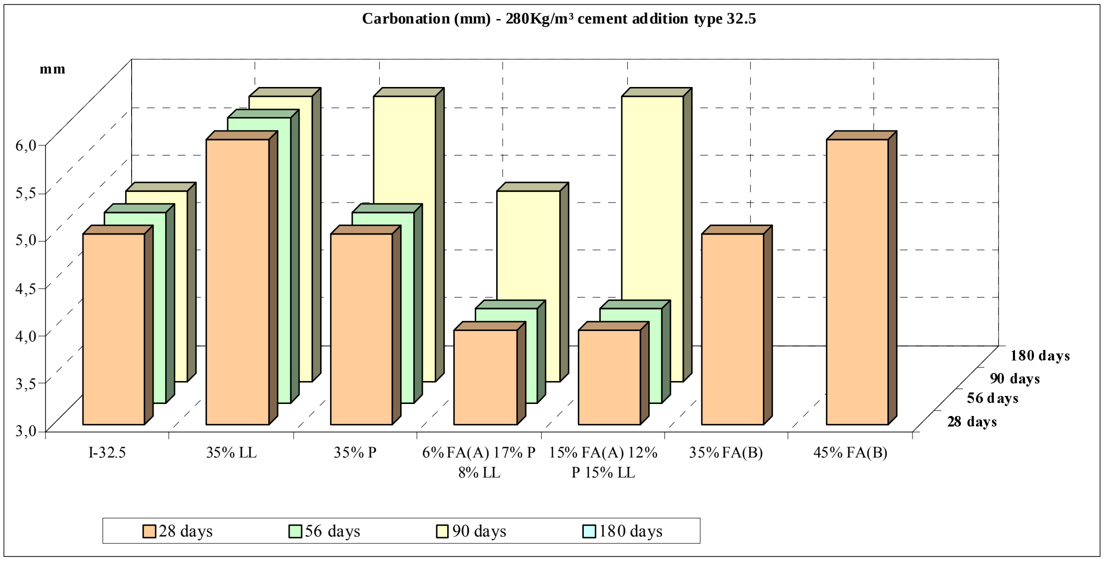



Figure 16: Carbonation depth of concrete with 32.5 cements

#### 4.5.4.4 Chloride Permeability

The Rapid Chloride Permeability Test was performed according to ASTM C 102-97 on cylindrical specimen. The estimation of the chloride ion penetrability was based on the charge (coulombs) passing through each specimen, see table below.

Table 61: Chloride ion permeability-cements 42.5

| C=320 kg/m$^3$ w/c=0.50<br>Chloride Permeability | I-42.5 | 35% FA(A) | 45% FA(A) | 45% FA(A) |
|---|---|---|---|---|
| Addition Laser μ | | 19,8 | 16 | 19,8 |
| Coulombs | 5160 | 1840 | 1691 | 1740 |
| Chloride Ion Permeability | High | Low | Low | Low |

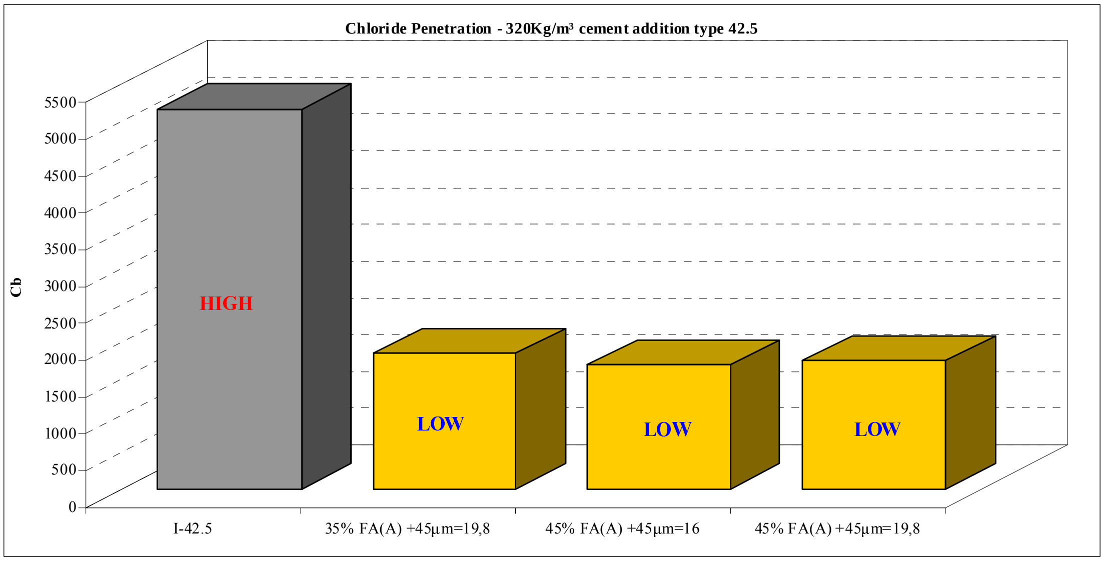



Figure 17: Chloride ion permeability-cements 42.5

Table 62: Chloride ion permeability-cements 32.5

| C=320 kg/m$^3$ w/c=0.50<br>Chloride Permeability | I-32.5 | 35% LL | 35% P | 6% FA(A)<br>17% P<br>8% LL | 15% FA(A)<br>12% P<br>15% LL | 35% FA(B) | 45% FA(B) |
|---|---|---|---|---|---|---|---|
| Coulombs | 5907 | 6457 | 2771 | 3265 | 2368 | 1444 | 1073 |
| Chloride Ion Permeability | High | High | Moderate | Moderate | Moderate | Low | Low |

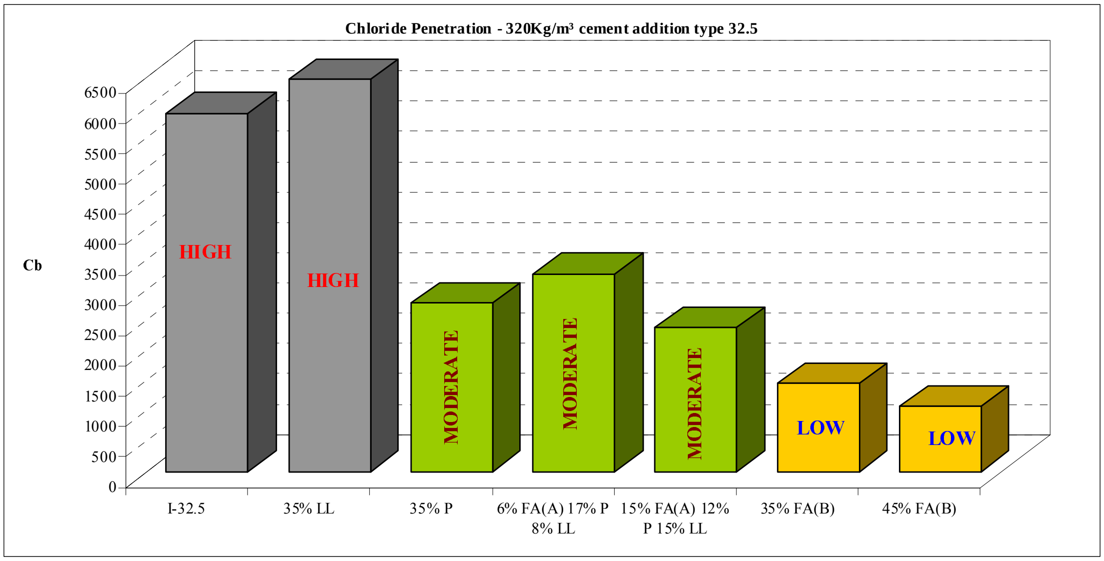



Figure 18: Chloride ion permeability-cements 32.5

#### 4.5.4.5 Sulphate Resistance

Six specimen 4*4*16 $m^3$ were produced (for every examined cement) with mortar according to EN 196-1. The prisms in their moulds were stored in a climate chamber (20 ºC and RH 95%) for two days and then placed in saturated $Ca(OH)_2$ solution for 12 days. Following that, three specimen were in saturated $Ca(OH)_2$ solution for 12 days. Following that, three specimen were placed in 4.4% $Na_2SO_4$ solution (while the rest remained in the $Ca(OH)_2$ solution). The length change was measured at the age of 7, 14, 28, 56, 91 and 140 days and the expansion difference between the results of specimen placed in $Na_2SO_4$ and $Ca(OH)_2$ solution was calculated, see figures below.

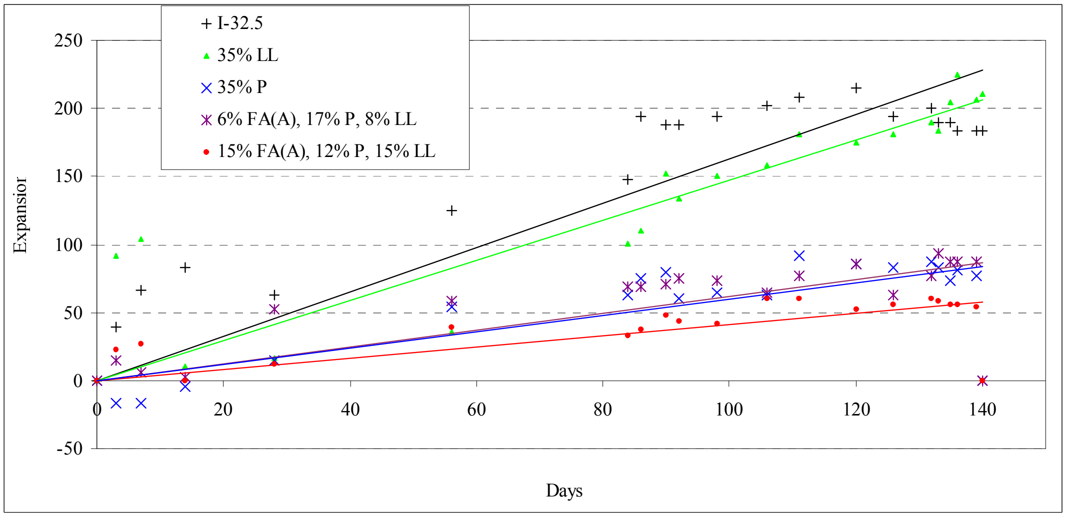



Figure 19: Expansion difference of 32.5 cements in $Na_2SO_4$

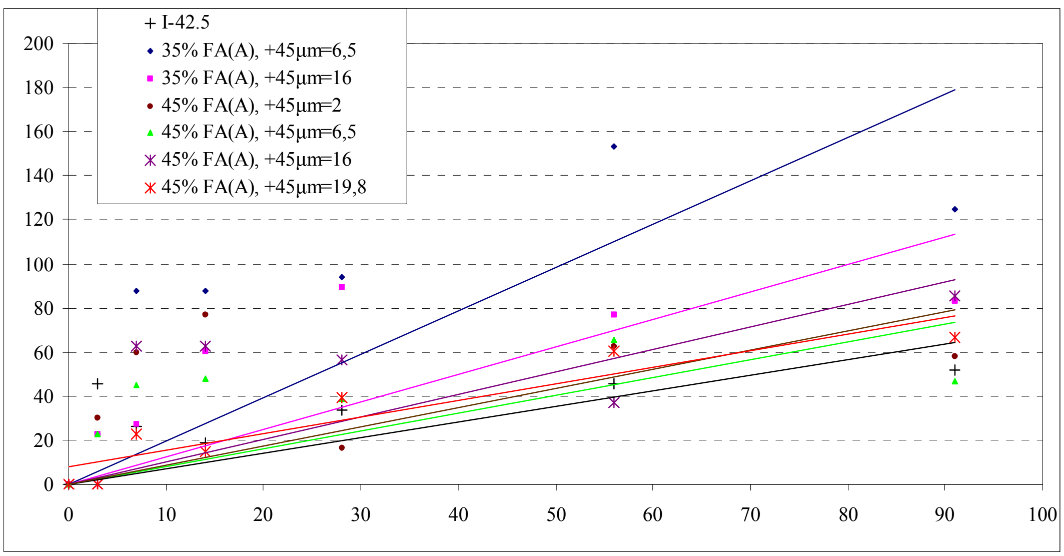



Figure 20: Expansion difference of 42.5 cements in $Na_2SO_4$

#### 4.5.4.6 Conclusions-Discussion

Workability

μ

admixture demand in concrete (2.0 - 2.4 % w/w cement) compared to the reference concrete with reference cement 32.5 (0.9 % w/w cement ) which comes in agreement with measured water demand of the cement. The use of FA(B) 45% and the blended ternary cements demanded the highest admixture percentage (in category of 32.5

cements) followed by the pozzolanic cement (P 35%).

Compressive Strength

In the category with cements 42.5 the majority of the FA(A) concretes showed higher compressive strength than reference cement($f_{90days}$=43.1-56.1 MPa in the group of c=280kg/$m^3$ and $f_{90days}$= 60.3-65.6 MPa in the group of c=320 kg/$m^3$) due to the higher cement strength. The lowest compressive strength was provided by the limestone cement in the category with cements 32.5 and the highest by the pozzolanic cement (P 35%) and the blended ternary cement containing 6% FA(A) 17% P and 8% LL.

Carbonation

The concrete mixings with cements FA(A) 45% indicated higher carbonation depth (8 mm at 90 days and 12-13 mm at 180 days) than with cements FA(A) 35% (6-7 mm at 90 days and 9-11 mm at 180 days) probably because of the lower quantity of $Ca(OH)_2$
T
was varying between 5 and 6 mm at 90 days. It is important that the carbonation front is lower than the concrete cover of the reinforcement (usually 30-60 mm for structural elements).

Chloride Permeability

As expected the chloride permeability was low for concretes with cement FA(A) regardless of the percentage of fly ash and high for the concrete with the reference cement 42.5. Concrete with cement FA(B) performed similar in the 32.5 cement category followed by the concretes with 15%FA(A), 12%P and 15%LL and the pozzolanic cement that was classified as moderate chloride ion penetrability. On the other hand the concrete with the limestone cement did not perform adequately since the penetrability of the chloride was evaluated as “high”.

Sulphate Resistance

It seems that durability against sulphate attack was improved for concrete with pozzolanic cement and the blended ternary cements (6% FA(A), 17% P, 8% LL and 15% FA(A), 12% POZ, 15% LL) compared to reference cement 32.5. On the contrary the concrete with limestone cement (35% LL) was less durable since it exhibited low resistance to expansion. Surprisingly in the category of 42.5 cements the FA(A) showed poor durability compared to reference 42.5. A possible explanation was the low C3A content in reference cement 42.5 (Bogue calculated 5%). The reason that the reference cement 32.5 didn’t perform satisfactorily even though the low C3A content was its low Blaine value.

Table 63: Admixtures with FA (particle size distribution, physicochemical properties)

| µm | I-52.5 | 35% FA(B) | | | | 45% FA(B) | | | | I-52.5 | 35% FA(A) | | | | 45% FA(A) | | | | I-52.5 | 35% FA(A) | 45% FA(A) | 35% FA(B) | 45% FA(B) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Laser +45 | | 1 | 6,8 | 14,8 | 22,4 | 1 | 6,8 | 14,8 | 22,4 | | 2 | 6,5 | 16 | 19,8 | 2 | 6,5 | 16 | 19,8 | | 5 | 5 | 5 | 5 |
| 1 | 8,5 | 6,8 | 7,1 | 6,6 | 6,5 | 7,0 | 6,7 | 6,3 | 6,0 | 8,0 | 10,6 | 8,9 | 7,1 | 6,7 | 10,9 | 8,3 | 6,7 | 6,4 | 6,9 | 6,2 | 5,8 | 5,1 | 5,7 |
| 1,5 | 10,7 | 8,7 | 9,2 | 8,6 | 8,2 | 9,1 | 8,8 | 8,1 | 7,6 | 9,9 | 13,4 | 11,3 | 8,9 | 8,4 | 13,8 | 10,4 | 8,5 | 7,9 | 9,1 | 7,8 | 7,3 | 6,5 | 7,2 |
| 2 | 15,7 | 14,1 | 14,0 | 13,2 | 12,6 | 15,3 | 13,6 | 12,4 | 11,6 | 14,8 | 20,1 | 17,0 | 13,2 | 12,5 | 20,6 | 15,4 | 12,6 | 11,8 | 14,5 | 11,7 | 11 | 9,9 | 11,2 |
| 3 | 21,3 | 21,1 | 20,3 | 19,0 | 17,5 | 22,6 | 19,8 | 17,8 | 16,5 | 19,6 | 26,9 | 23,0 | 18,1 | 17,0 | 28,2 | 21,5 | 17,5 | 16,2 | 19,9 | 15,9 | 15,2 | 13,5 | 15,6 |
| 4 | 26,4 | 27,8 | 25,1 | 23,6 | 22,3 | 29,5 | 24,8 | 22,4 | 20,8 | 24,6 | 33,2 | 28,5 | 22,7 | 21,5 | 35,1 | 27,4 | 22,0 | 20,6 | 24,9 | 20,0 | 19,7 | 17,3 | 19,8 |
| 6 | 32,0 | 34,5 | 31,6 | 29,4 | 27,1 | 35,7 | 31,3 | 28,2 | 25,9 | 29,3 | 38,8 | 34,0 | 27,7 | 26,1 | 41,7 | 34,4 | 27,1 | 25,2 | 30,3 | 26,0 | 26,8 | 22,3 | 24,7 |
| 8 | 40,3 | 44,2 | 39,6 | 36,9 | 34,8 | 46,0 | 39,2 | 35,7 | 33,0 | 37,8 | 48,0 | 42,5 | 35,2 | 33,6 | 51,1 | 44,0 | 34,6 | 32,5 | 39,0 | 35,6 | 37,4 | 31,6 | 33,3 |
| 12 | 50,3 | 54,4 | 50,3 | 47,0 | 43,3 | 56,3 | 50,0 | 45,5 | 42,1 | 47,0 | 57,0 | 52,0 | 44,4 | 42,3 | 60,1 | 54,0 | 44,0 | 41,3 | 49,0 | 48,9 | 51,8 | 44,4 | 44,1 |
| 16 | 61,1 | 67,0 | 60,3 | 56,6 | 53,8 | 68,9 | 60,1 | 55,2 | 51,9 | 59,4 | 68,1 | 63,2 | 55,1 | 53,1 | 70,5 | 64,9 | 54,6 | 52,0 | 61,3 | 63,4 | 64,8 | 57,4 | 56,0 |
| 24 | 75,7 | 80,0 | 75,8 | 71,7 | 66,9 | 80,7 | 75,6 | 69,3 | 65,1 | 75,4 | 80,4 | 77,5 | 70,0 | 67,5 | 82,2 | 78,2 | 69,2 | 65,9 | 77,8 | 79,4 | 79,8 | 70,7 | 68,7 |
| 32 | 88,3 | 92,4 | 87,3 | 83,8 | 80,7 | 93,8 | 87,0 | 81,7 | 77,9 | 90,1 | 92,2 | 89,8 | 83,2 | 81,1 | 92,9 | 90,2 | 82,2 | 79,4 | 91,3 | 92,0 | 90,8 | 83,4 | 81,3 |
| 48 | 100 | 100 | 100 | 100 | 95,2 | 99,5 | 100 | 97,6 | 94,4 | 100 | 100 | 100 | 97,2 | 95,0 | 100 | 100 | 96,5 | 93,7 | 100 | 100 | 100 | 95,6 | 94,3 |
| 64 | 100 | 100 | 100 | 100 | 96,3 | 100 | 100 | 98,6 | 96,4 | 100 | 100 | 100 | 100 | 96,0 | 100 | 100 | 96,5 | 95,4 | 100 | 100 | 100 | 98,9 | 97,7 |
| 96 | 100 | 100 | 100 | 100 | 98,2 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 128 | 100 | 100 | 100 | 100 | 99,5 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 192 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| $< 3$ | 21,3 | 21,1 | 20,3 | 19,0 | 17,5 | 22,6 | 19,8 | 17,8 | 16,5 | 19,6 | 26,9 | 23,0 | 18,1 | 17,0 | 28,2 | 21,5 | 17,5 | 16,2 | 19,9 | 15,9 | 15,2 | 13,5 | 15,6 |
| $>32$ | 11,7 | 7,6 | 12,7 | 16,2 | 19,3 | 6,2 | 13,0 | 18,3 | 22,1 | 9,9 | 7,8 | 10,2 | 16,8 | 18,9 | 7,1 | 9,8 | 17,8 | 20,6 | 8,7 | 8,0 | 9,2 | 16,6 | 18,7 |
| 3 - 32 | 67,0 | 71,3 | 67,0 | 64,8 | 63,2 | 71,2 | 67,2 | 63,9 | 61,4 | 70,5 | 65,3 | 66,8 | 65,1 | 64,1 | 64,7 | 68,7 | 64,7 | 63,2 | 71,4 | 76,1 | 75,6 | 69,9 | 65,7 |
| n= | 0,9 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 0,9 | 0,9 | 1,0 | 1,0 | 0,9 | 1,0 | 1,0 | 1,0 | 15,56 | 15,96 | 15,68 | 18,25 | 18,77 |
| d= | 15,8 | 14,1 | 16,1 | 17,6 | 19,8 | 13,4 | 16,2 | 18,7 | 20,9 | 16,4 | 13,0 | 14,9 | 18,6 | 20,0 | 12,0 | 14,5 | 19,2 | 20,9 | 0,97 | 1,05 | 1,07 | 1,07 | 1,00 |
| | | | | | | | | | | | | | | | | | | | | | | | |
| BLAINE | | | | | | | | | | | | | | | | | | | 3820 | 5470 | 5880 | 4590 | 4900 |
| $\%H_2O$ | 25,4 | 32 | 33,4 | 34 | 34,4 | 33,4 | 35,6 | 36,2 | 36,8 | 27,6 | 29,6 | 30,4 | 36 | 34,6 | 31 | 31,6 | 35,6 | 37,2 | 27,4 | 33,2 | 34,8 | 29,8 | 31,6 |
| I.Set | 95 | 175 | 220 | 230 | 240 | 195 | 240 | 260 | 280 | 150 | 140 | 160 | 180 | 190 | 150 | 190 | 200 | 210 | 110 | 110 | 90 | 220 | 260 |
| F.Set | 145 | 265 | 290 | 300 | 310 | 285 | 320 | 340 | 350 | 200 | 180 | 210 | 230 | 240 | 200 | 250 | 250 | 260 | 150 | 140 | 140 | 270 | 310 |
| Le Chat. | 0,1 | 0 | 0,1 | 0,1 | 0,1 | 0 | 0 | 0,1 | 0,1 | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | |
| 1day | 18,5 | 12,3 | 11,8 | 10,5 | 10,0 | 10,0 | 9,2 | 8,5 | 7,6 | 18,4 | 16,9 | 16,3 | 14,4 | 11,8 | 15,6 | 15,1 | 12,3 | 10,5 | 18,2 | 14,7 | 11,7 | 6,50 | 4,80 |
| 2days | 29,8 | 21,7 | 21,0 | 18,5 | 18,2 | 19,0 | 18,0 | 16,2 | 15,0 | 29,6 | 27,4 | 29,0 | 24,2 | 22,2 | 25,5 | 26,0 | 22,1 | 19,8 | 29,1 | 23,4 | 21,4 | 13,00 | 10,40 |
| 7days | 44,0 | 37,8 | 34,1 | 30,4 | 29,0 | 35,4 | 31,0 | 28,6 | 26,2 | 47,3 | 41,0 | 42,2 | 37,8 | 35,3 | 40,2 | 40,6 | 35,0 | 30,8 | 42,2 | 36,0 | 32,5 | 25,70 | 22,90 |
| 28days | 66,0 | 63,5 | 58,1 | 52,5 | 52,2 | 62,0 | 56,0 | 51,2 | 48,0 | 64,6 | 60,8 | 58,2 | 52,8 | 50,1 | 59,6 | 59,0 | 52,0 | 47,6 | 61,5 | 56,5 | 54,1 | 45,5 | 43,2 |

## 5 List of deliverables

According to the workplan (Annex 1 „Description of work“ to Contract No. G1RD-CT-2002-00782) the deliverables and milestones specified in tables 64 and 65 where to be delivered and maintained.

Table 64: Overview of deliverables in research activities of cluster 2

| Deliverable No. | Output from Task/ sub task No. | Nature of Deliverable and brief description | | Status |
|---|---|---|---|---|
| 1 | 3 | 4 | 5 | 6 |
| D3-D6 | R1.1-R1.5 | Data/Re /Mat | Process data from the production of blended cements and blended cements | 1. and 2. Progress report (Documents ECO-Serve-C2-R-0009 and ECO-Serve-C2-R-0010) |
| D7-D11 | R3.1-R3.5 | Data/Re | • Basic concrete properties<br>• Carbonation<br>• Penetration of chlorides<br>• Freeze-thaw-durability<br>• Chemical resistance | Few changes acc. to chapter 6<br>2. Management report and Final Technical Report (Document ECO-Serve-C2-R-0013) |
| D12 | … | Data/Re | Evaluation of D3-D6 | 1. and 2. Progress report (Documents ECO-Serve-C2-R-0009 and ECO-Serve-C2-R-0010) |
| D13 | … | Data/Re | Evaluation of D7-D11 | 2. Management report and Final Technical Report (Document ECO-Serve-C2-R-0013) |

Table 65: Overview of Milestones in research activities of cluster 2

| Milestone No. | Brief description of milestone / objectives | Status |
|---|---|---|
| 1 | 3 | 4 |
| M3 | Fixing of final work plan (cement compositions, concrete mixtures, etc.) | 1. Management report (Document ECO-Serve-C2-R-0008) |
| M4 | Evaluation of D3-D6 | 1. and 2. Progress report (Documents ECO-Serve-C2-R-0009 and ECO-Serve-C2-R-0010) |
| M6 | Evaluation of D7-D11 | 2. Management report and Final Technical Report (Document ECO-Serve-C2-R-0013) |

Legend to tables 64 and 65:

Milestone/deliverable achieved without changes (green)

Milestone/deliverable achieved with changes (orange)

## 6 Comparison of initially planned activities and work actually accomplished

The following ammendments / modifications of the workplan have to be taken into account:

| | |
|---|---|
| **Partner 1: (VDZ)** | Investigations on fly ashes have been reduced due to the quality of calcareus fly ashes in Germany (Sub-task 1.3). A lot more modifications have been made with cements containing limestone (Sub-task 2.2). This led also to the switching of the expenditure for sub-task 3.5 to sub-task 3.4, where a lot more trials have been performed. VDZ also made investigations on chloride penetration for NORCEM (Sub-task 3.3). |
| **Partner 2: (CTG)** | No relevant deviation from the planned work schedule has to be pointed out. |
| **Partner 3: (NORCEM)** | VDZ makes investigations on chloride penetration for NORCEM (Sub-task 3.3). |
| **Partner 5:** | No relevant deviation from the planned work schedule has to be pointed out. |

In general, the ammendments / modifications led not to any change of the overall budget or limitations of the perceptions and the expected outcome of the project.

## 7 Management and co-ordination aspects

During the project period four meetings took place at the Research Institute of the Cement Industry, Düsseldorf, Germany. The minutes of the meetings are given in annex A.

# 8 Results and Conclusions

## 8.1 Summary of the investigations

The following cements have been investigated within this project:

Cements with maximum amounts of main constituents besides clinker acc. to EN 197-1:

- Portland-limestone cements with up to 20 % of limestone (Norway).
- Portland-limestone cements with up to 35 % of limestone (Germany, Greece).
- Portland-pozzolana cements with up to 35 % of pozzolana (Greece).
- Portland-fly ash cements CEM II-V with 20 (Norway) and 35 % fly ash (Greece, Norway).
- Portland-composite cements CEM II-M with 20 % V / 10 % LL (Norway)
- Portland-composite cements CEM II-M with 5 % S / 30 % LL (Germany)
- Portland-composite cements CEM II-M with 10 % S / 25 % LL (Germany)
- Portland-composite cements CEM II-M with 15 % S / 20 % LL (Germany)

Cements with a composition beyond the limits of EN 197-1:

- Portland-limestone cements with up to 45 % of limestone (Germany, Greece, Italy).
- Portland-fly ash cements 45 % (Greece) and 50 % fly ash (Norway).
- Ternary composition based on clinker, slag and limestone with
  - 40 % ggbs / 20 % LL (Italy);
  - 30 % ggbs / 20 % LL (Germany) and
  - 50 % ggbs / 20 % LL (Germany).
- Ternary composition based on clinker, ground glass and ground brick as pozzolanic material with 30% ground glass / 15% ground brick (Italy).
- Ternary composition based on clinker, fly ash and limestone with 30 % V / 20 % LL (Norway).
- Composition with 6 % V / 17 % P / 15 % LL (Greece)
- Composition with 15 % V / 12 % P / 15 % LL (Greece)

For the considered starting compositions it has been successfully verified the possibility of fitting the requirements of EN 197-1 in line with the agreed range of the standard strength between 45 and 50 Mpa for most of the investigated cements with the exception of cements mentioned in chapter 8.2.2.

The influence of these cements on concrete properties – especially the durability of concrete, can be summarized as follows (ordered by countries).

Germany

| | |
|---|---|
| CEM II/B-LL with 35 % limestone | • Carbonation depth in the range of Portland and Portland-limestone cements CEM II/A-LL.<br>• Resistance against chloride penetartion in the range of Portland cements.<br>• Freeze thaw resistance: The scaling tested with the cube test showed a sigificant correlation to the quality of the limestone expressed as the specific surface (BET).<br>• Freeze thaw resistance with de-icing salts (air-entrained concrete) comparable to concrete with Portland cement. |
| Cement with 30 % ggbs and 20 % limestone | • Carbonation depth in the range of Portland and Portland-limestone cements CEM II/A-LL.<br>• Chloride migration coefficients of concrete using cements with 30 % ggbs and 20 % limestone in the range of concretes with Portland-slag cement CEM II/B-S.<br>• Assessment of the freeze thaw resistance dependent on the kind of test.<br>• Freeze thaw resistance with de-icing salts (air-entrained concrete) comparable to concrete with Portland cement. |
| Cement with 50 % ggbs and 20 % limestone | • Carbonation depth in the range of the maximum values reported in the literature for blastfurnace cements CEM III/B with up to 80 % ggbs.<br>• Chloride migration coefficients in the range of concretes with Blastfurnace cements CEM III/A.<br>• Freeze thaw resistance: High scaling in the cube test and a significant decrease of the RDM in the CIF test. No sigificant change in the RDM in the beam test after 56 FTC.<br>• Not applicable for exposures with freeze thaw attack with de-icing salts and a high water saturation (exposure class XF4 acc. to EN 206-1). |

Greece

In order to summarize the effect in cement of each material as a main constituent (each one alone) the following can be concluded:

| Paramter | 35% Addition | | | 45% Addition | | |
|---|---|---|---|---|---|---|
| | FA | LL | P | FA | LL | P |
| Water Demand | + | 0 | + | ++ | 0 | ++ |
| Setting | + | 0 | + | ++ | 0 | + |
| Strength | - | -- | -- | - | --- | -- |

The influence of the blended cements on the durability of concrete can be summarized as follows:

Carbonation: The concrete mixings with cements FA(A) 45% indicated higher carbonation depth than with cements FA(A) 35% probably because of the lower quantity of $Ca(OH)_2$ produced.

Chloride penetration: Chloride permeability was low for concretes with fly ash cements fly ash and high for the concrete with the reference cement 42.5. Concretes with blended cements with 15%FA, 12%P and 15%LL and the pozzolanic cement were classified to have moderate chloride ion penetrability. Concrete with the limestone cement was evaluated as “high” with regard to chloride permeability.

Sulphate resistance: Durability against sulphate attack was improved for concrete with pozzolanic cement and the blended ternary cements (6% FA(A), 17% P, 8% LL and 15% FA(A), 12% POZ, 15% LL) compared to reference cement 32.5. The concrete with limestone cement (35% LL) was less durable since it exhibited low resistance to expansion.

Italy

The tests in concrete have pointed out that good performances can be achieved in terms of basic physico-mechanical characteristics for the concretes with the cements

- Portland-limestone cements with up to 45 % of limestone;
- Ternary composition based on clinker, slag and limestone with 40 % ggbs / 20 % LL;
- Ternary composition based on clinker, ground glass and ground brick as pozzolanic material with 30% ground glass / 15% ground brick.

On the contrary the analysed concretes based on experimental cements have exhibited poor durability properties.

<u>Norway</u>

| | |
|---|---|
| Carbonation: | The most significant result at this very early stage is the negative effect of LL. Increasing the pfa content to 50% also provides a negative effect. |
| Chloride penetration: | Of all mixes and ages 35% pfa performed best. The 50% pfa performed better at a later stage (~ 240 d). |
| Freeze thaw resistance: | For all series with blended cements, internal damage was considerable, except for the CEM I reference. The scaling level is significant. |
| Freeze thaw resistance with de-icing salts (air-entrained concrete) | Best performance (“Very Good”) was achieved with all the reference cement mixes, all of type CEM I. Good performance was achieved with 35% pfa (w/c=0,40) and 20% pfa (w/c=0,50). Acceptable performance was achieved with 35% pfa (w/c=0,50) and – close to the boarder line – 50% pfa (w/c=0,40). The latter (50%pfa) was not acceptable when increasing the w/c-ratio to 0,50. |

Especially if long term strength is taken into consideration, CEM II/B-V appear to be promising, based on strength and chloride intrusion.

## 8.2 Areas for furter research

### 8.2.1 General

- For all CEM II besides CEMII/M and for CEM III, the particle size distribution (fineness) of each component of blended cements should be further investigated aiming to improve cement properties (strength, water demand expansion etc.) and to increase their participation (even beyond EN 197-1).
- For all Composite Cements with more than two main constituents the effect of combination of components should be further investigated focusing on synergy and optimization. The ultimate goal should be to retain the advantages and restrict or cancel weaknesses of each component in terms of process, properties and durability.
- Blended cements should be linked with as many as possible concrete durability properties besides the issues already covered by ECOSERVE. Durability models should be developed and probably virtual testing should be implemented.
- Define (in terms of Standards where appropriate) realistic measurements and/or characterization techniques for properties valuable to assess durability (e. g. aggressive sulfur salts environment).
- Research in utilization of various industrial byproducts not included in EN 197-1. Attention should be focused on locally produced byproducts in order to minimize transportation and to insure that their addition offers equivalent properties to the main constituents of EN 197-1.
- Production of Low-Energy Cements (high $C_2S$ content) in order to reduce fuel consumption and $CO_2$-emissions.
- Considering all possible parameters like environmental conditions, application practices etc, specific component-related issues should be thoroughly investigated (e.g. possible barriers to limestone utilization concerning thaumasite formation and functioning of ettringite in blended cements with high sulphate content).

### 8.2.2 Special items

- For the following cements further experimental work should be carried out:
  - High volume limestone cement with up to 45 % limestone (Germany/Italy);
  - Combining 10% LL with 20-35% pfa (Norway).
  - High volume pozzolanic and limestone cement with 45% additive in strength class 42.5 (Greece).

  For the German situation more test with different limestone qualities have to be carried out. With regard to the freeze thaw resistance more correlations between fiffent test methods are needed (comp. next bullet point).
- For some tests (e. g. beam test) different acceptance criteria are used in Europe. This should be aligned as far as possible.
- Fundamental studies of internal frost damage and testing procedures with regard to the to avoidance of deviations between test results and perception about field performance.

## 9 Acknowledgements

Partners thank the EU for the funding of the investigations.

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# 11 Annex B: Minutes of the meetings

## 11.1 1. Meeting

Date: 05 September 2003 at 11 a.m.
Place: Research Institute of the Cement Industry, Düsseldorf, Germany

Present were:

| | | | |
|---|---|---|---|
| 1 | Manolis Haniotakis | (MH) | Titan Cement Company S.A. |
| 2 | Christoph Müller | (CM) | Verein Deutscher Zementwerke e.V. |
| 3 | Eberhard Siebel | (ES) | Verein Deutscher Zementwerke e.V. |
| 4 | Erik Stoltenberg-Hansson | (ESH) | NORCEM |
| 5 | Paolo Ursella | (PU) | CTG SpA |

Minutes taken by CM.

**Agenda**

1 Opening of the meeting
2 Formalities (Contract etc.)
3 Essential arrangements on the performance of tasks R1-R3 of the work plan:
- Composition of the cements produced in task R1
- Investigations (R2/R3)
- Deliverables
- Milestones
- Schedule
4 Any other business

**Opening of the meeting**

ES welcomed all participants to the 1. meeting of research activities in cluster 2 of the ECO-Serve Network. He then asked for comments to the proposed agenda.

The proposed agenda was adopted.

**Formalities**

All signed contracts will be send to VDZ latest within one week after this meeting. VDZ will then send the contracts to the commission (completed 11.09.2003).

Due to the fact, that the contract shall enter into force following its signature by all the contracting parties (principal contractors and the Community) and because the duration of the project shall be 24 months from the first day of the month after the last signature of the contracting parties, the starting date will be estimated 01.10.2003.

This starting date is 7 month before the date scheduled in Annex I („Description of work") of the contract no. G1RD-CT-2002-00782. The accelerated start was enforced by the commission.

The revised and adjusted timetable for start in October 2003 was given to all partners with the documents ECO-Serve-C2-R-0002 and ECO-Serve-C2-R-0003. All partners agreed on the new timetable and the consequences for milestones and deliverables. Objections can be send to VDZ within two weeks after this meeting.

**Essential arrangements on the performance of tasks R1-R3 of the work plan**

CM presented, which cements VDZ is going to investigate. After his presentation, ES asked the other partners to present their proposals for cements to be investigated. Table A1 gives an overview of the cements, that will be investigated by the partners.

Table A1: Overview of the cements, that will be investigated by the partners in cluster 2

| Partner | Cements |
|---|---|
| Cements with maximum amounts of main constituents besides clinker acc. to EN 197-1 | |
| Verein Deutscher Zementwerke e.V. | - CEM II-W and CEM II-M (S-W)<br>2 Fly ashes (W):<br>1 x Lausitz Area (Jänschwalde)<br>1 x Mitteldeutsches Revier = Halle/Leipzig Area (Schkopau)<br>1 Clinker, 1 GBFS and 10, 20 or 30 % Fly ash<br>- CEM II-LL<br>3 Limestone: Devon, Cretaceous, Jura<br>65 % clinker, 35 % limestone |
| NORCEM | - CEM II-M (V-LL) |
| | 2 cements with up to 30 % Limestone |
| | - selective use of GBFS |
| Titan Cement Company S.A. | - CEM II/B-V with 35 V |
| | - CEM II/B-W with 35 W |
| | - CEM II/B-LL with 35 LL |
| | - CEM IV A/B with LL |
| CTG SpA | - CEM III with 50 % GBFS |

Table A1: Continuation

| Cements with a composition beyond the limits of EN 197-1 | | |
|---|---|---|
| Verein Deutscher Zementwerke e.V. | - | CEM with LL |
| | | Limestone: Devon |
| | | 55 % clinker, 45 % limestone |
| | - | CEM V |
| | | Limestone / GBFS |
| | | - 30 % GBFS, 20 % limestone |
| | | - 50 % GBFS, 20 % limestone |
| NORCEM | - | 2 cements with 35-40 % Fly ash (V) |
| Titan Cement Company S.A. | - | CEM with 45 % V |
| | - | CEM with 45 % W |
| | - | CEM with 45 LL |
| CTG SpA | - | CEM with 35-45 LL |
| | - | CEM V with 40 % GBFS and 20 % LL |
| | - | CEM with pozzolana (mixture of glass/brick with natural pozzolana acc. to EN 197-1) |

The Partners decided not to use silica-fume because no benefit is expected within the ECO-Serve scope. The planned strength for all cements is 45 - 50 MPa acc. to EN 197-1. Every partner uses a typically used cement of his region for comparative tests.

CM will develop a sheet, in which every partner can enlist the cement composition in detail (ECO-Serve-C2-R-0006).

For the comparability and the reproducibility of the investigations and their results, it is essential, that the partners agree on some mortar- and concrete compositions as well as the test methods. As a basis for further discussions document ECO-Serve-C2-R-0004 “Test methods” was delivered to the partners. The results of the discussion are summarised in Table A2.

Table A2: Overview of test methods

| Task | Subject | Test method / Concrete composition |
|---|---|---|
| 2.1 | Physical and chemical properties of components and cements | Particle size distribution, Blaine,<br>EN 196 |
| 2.2 | Interaction between the main constituents | No Test method required |
| 2.3 | Microstructure | Standard: Water uptake under atmospheric pressure and 15 MPa.<br>REMARK: Pore size distribution with Hg-Intrusion is optional. |

Table A2: Continuation

| | | | |
|---|---|---|---|
| 3.1 | Basic concrete properties | Fresh concrete: EN 12350<br>Hardened concrete: EN 12390<br>Compressive strength 2d, 7d, 28d, 90d | c = 280 kg/m³<br>w/c = 0,60<br>c = 320 kg/m³<br>w/c = 0,50 |
| 3.2 | Carbonation | Beams 100 x 100 x 400 mm³<br>*1d moulded, 6d water storage, (20±2) °C / (65±5) % r. H.*<br>Evaporation in the climate chamber:<br>(45±15) g/(m²·h) | c = 280 kg/m³<br>w/c = 0,60 |
| 3.3 | Penetration of chlorides | Rapid chloride migration method (RCM) - comp. Brite EuRam III project DuraCrete | c = 320 kg/m³<br>w/c = 0,50 |
| 3.4 | Freeze-thaw resistance | Beam test | c = 320 kg/m³<br>w/c = 0,50 |
| | Freeze-thaw resistance with de-icing salt | Slab test | c = 320 kg/m³<br>w/c = 0,50, AE |
| 3.5 | Sulphate resistance | There is no Europeanwide accepted test method for the determination of the sulphate resistance of mortar or concrete. Partners will use the test methods, which are commonly used in their countries. | |

**Any other business**

CM reminded all partners to send their bank accounts by email and to proceed with their mapping activities (ECO-Serve-C2-N-0009) as well as the data collection (ECO-Serve-C2-N-0010) and the compilation of application rules (ECO-Serve-C2-N-0011).

Because of the temporal closeness to the planned meeting of the network activities in cluster 2 on 15.10.2003, research partners assigned VDZ to ask the other network partners of cluster 2 to postpone the meeting to one of the following dates: 18., 19., 21. or 24.11.2003.

The meeting closed at 16:00 p.m.

signed
Dr.-Ing. E. Siebel

signed
i. V. Dr.-Ing. C. Müller

## 11.2 2. Meeting

Date: 18 November 2003 at 11 a.m.
Place: Research Institute of the Cement Industry, Düsseldorf, Germany

Present were:

| | | | |
|---|---|---|---|
| 1 | Manolis Haniotakis | (MH) | Titan Cement Company S.A. |
| 2 | Hendrik Möller | (HM) | SCHWENK |
| 3 | Christoph Müller | (CM) | Verein Deutscher Zementwerke e.V. |
| 4 | Terje Rønning | (TR) | NORCEM |
| 5 | Rico van Selst | (RS) | INTRON |
| 6 | Eberhard Siebel | (ES) | Verein Deutscher Zementwerke e.V. |
| 7 | Paolo Ursella | (PU) | CTG SpA |

Absent were:

| | | |
|---|---|---|
| Thorsten Reschke | (TR) | BAW |

Minutes taken by CM.

### Agenda

***Network***

N1 Opening of the meeting
N2 Minutes of the 1. meeting
N3 Formalities (Cost statements etc.)
N4 Discussion of the draft of the 2. periodic report and adoption
N5 Continuation of mapping and data collection - further procedure
N6 Any other business

***Research***

R1 Minutes of the 1. meeting
R2 Fixing the final workplan
R3 Any other business

**Network**

### N1 Opening of the meeting

ES welcomed all participants to the 2. meeting of cluster 2 in the ECO-Serve Network. He then asked for comments to the proposed agenda. The proposed agenda was adopted without changes.

ES especially welcomed RS as a member of the management group. ES asked RS to give an overview of the management activities, the status quo of the network activities and the Warsaw meeting under agenda item N3.

### N2 Minutes of the 1. meeting

The minutes of the first meeting were adopted without comments or changes.

### N3 Formalities (Cost statements etc.)

Report of RS about management activities, status quo of the network activities and the Warsaw meeting.: In the following some essential aspects are summarised.

- ECO-Serve is one of the biggest networks in Europe at the moment.
- The course of the network was not optimal in all cases up to now.
- Cluster 2 is in good progress.
- The ECO-Serve web-site has to become more attractive.
- Web-site: The Management will send a format to report about the progress of the clusters for the presentation on the web-site until 2003-11-20.
- The development of a power-point-presentation for ECO-Serve is in progress. It will present the network in an interactive way. It will lead the user to the clusters with detailed information.
- A first yearly workshop is planned for May/June 2004.
- Indicators for the environmental assessment: Task 2 will development an excel-sheet.

***Cost statements:***

- Principal contractors send the statements directly to Dansk Beton Teknik (DBT) and a copy to VDZ.
- Members are sending cost statements to the contract holders who sign them and forward these to DBT.
- DBT will check that the costs comply with the contract and forward the cost statements to the Commission.
- DBT should receive the statements until ***5$^{th}$ December*** so they can be submitted before ***15$^{th}$ December***. 15th December was fixed because this date is one month after the end of the first year.
- RS: Costs can be claimed. It is possible for example to change man hour into travel to some extend.
- Cost statements have to consider the principles laid down in the network manual compiled by the coordinator

## N4 Discussion of the draft of the 2. periodic report and adoption

| Chapter | Remarks |
|---|---|
| 1 | Adopted without changes. |
| 2 | Adopted without changes. |
| 3 | Figures 1-7 have to be significantly signed as a first draft. Adopted with this complement. |
| 4 | Figure 10 will be added with Cement types in the CEMBUREAU countries 2001; Source: CEMBUREAU statistics with values referring to all strength classes. Adopted with this complement. |
| 5 | Adopted without changes. |
| 6 | Adopted without changes. |

## N5 Continuation of mapping and data collection - further procedure

- TR: Data for Finland will be available presumably in December.
- Besides the enquiry using the questionnaires, all partners will intensify their search using other sources (e. g. data-bases, internet → web-sites of cement producers, official statistics (e. g. Federal Statistical Office Germany) etc.)
- VDZ and RS will contact CEMBUREAU to request to what extent CEMBUREAU statistics can be used for the evaluation in the project.
- Use of questionnaires: Partners will compile a list, to whom they have send the questionnaires and who did not answer.
- While sending the questionnaire, partners will ask for a short comment when the respondent is not able to answer to give a short explanation: „Why not".
- Application rules: For the next meeting all partners will contribute to this chapter.
- To encourage the co-operation with cluster 3, sometime during the duration of the network a common workshop of cluster 2 and cluster 3 might be helpful. As a first step, all partners are invited to join the first workshop of cluster 3 (ECO-Serve-C2-N-0018).
- Second end user: TR will have a meeting with the National road work administration. Possibly he can win them over to join the network.
- ES: The network in no way is a platform for political discussions. All partners agreed.

- Data collection must consider the market situation respectively „historical" evolutions: e. g. „How was Sweden able to have a significant change on cement types within a few years ?"; e. g. England: No blended cements but use of granulated blast furnace slag as a concrete addition.

**N6 Any other business**

none

**Research**

**R1 Minutes of the 1. meeting**

TOP 3: "The planned strength for all cements is 45 - 50 MPa acc. to EN 197-1. Every partner uses a typically used cement of his region for comparative tests."
Remark of MH: Strength 45 - 50 MPa will maybe not be reached with 40 % of fly ash.

> ***Decision: If the strength of the tested cement is significantly lower than 45 - 50 MPa, partners use a reference cement with a reduced strength.***

The minutes of the first meeting were adopted with this complement.

**R2 Fixing the final workplan**

Partners agreed on the concrete compositions and test methods compiled in the minutes of the first meeting. The cement compositions were fixed acc. to ECO-Serve-C2-R-0006.

**R3 Any other business**

none

No date was fixed for the next meeting. The next meeting should take place later on in 2004. VDZ will arrange a date during the summer 2004.

The meeting closed at 15:30 p.m.

## 11.3 3. meeting

Date: 01 February 2005 at 10 a.m.
Place: Research Institute of the Cement Industry, Düsseldorf, Germany

Present were:

| | | | |
|---|---|---|---|
| 1 | Adrian Francu | (AF) | Lafarge Romcim |
| 2 | Bram Doms | (BD) | BBRI |
| 3 | Manolis Chaniotakis | (MH) | Titan Cement Company S.A. |
| 4 | Christoph Müller | (CM) | Verein Deutscher Zementwerke e.V. |
| 5 | Eberhard Siebel | (ES) | Verein Deutscher Zementwerke e.V. |
| 6 | Terje Ronning | (TR) | NORCEM |
| 7 | Roberto Cucitore | (RC) | CTG SpA |

Minutes taken by CM.

### Agenda

| TOP | Content | Report by |
|---|---|---|
| Network – All cluster members (10:00 – 15:00) | | |
| N1 | Opening of the meeting and introduction of new members | |
| N2 | Minutes of the 2. meeting | |
| N3 | ECOServe management: Website – Project center – Power point presentation | B. Dooms |
| N4 | Cluster 2 – network: Status quo | C. Müller |
| N5 | Cluster 2 - network: Demand and reality – statements to work plan and achievements | all members |
| N6 | Any other business | |

| | | |
|---|---|---|
| Research – Only principal contractors (15:00 – 17:00) | | |
| R1 | Status quo of investigations, Adjustment nominal/actual work | CTG, Norcem, Titan, VDZ |

### N1 Opening of the meeting

ES welcomed all participants to the 3. meeting of cluster 2 of the ECO-Serve Network, especially FA and BD, both joining the cluster for the first time. AF is Technical Commercial Manager of Lafarge Romcim SA and a new member of the cluster. BD is member of the management group of the network. ES then asked for comments to the proposed agenda.

The proposed agenda was adopted.

### N2 Minutes of the 2. meeting

The minutes of the second meeting were adopted without comments or changes.

### N3 ECOServe management: Website – Project center – Power point presentation

A presentation about the ECOServe website and the project center was given by BD. Information about the website and the project center are available on the project center:

**ECO-Serve Website Manual.pdf**
**GettingStartedWithViadesk_v2.pdf**

### N4/N5 Cluster 2 – network: Status quo / Demand and reality – statements to work plan and achievements

A presentation about the Status quo of the work of cluster 2 was given by CM and in summarized in Figure A1.

## Overview of deliverables

| Task / Deliverable | | Availablity | |
|---|---|---|---|
| Mapping of activities and stakeholders - ***Questionnaire*** | D0 | 1st periodic report | Project office |
| | | Online | ECOServe website |
| Mapping of activities and stakeholders – ***Results*** | D1 | 2nd periodic report | Project office |
| | | Online | ECOServe website |
| Reference list on blended cements | | 4th periodic report | Project office |
| | | Online | ECOServe website |
| Production of blended cements in Europe | M1,2 | 2nd periodic report | Project office |
| | | Power point presentation | ECOServe website |
| Application of blended cements: Application rules | | 4th periodic report | Project office / |
| | | | ECOServe website |
| Further documents (examples) | | 3rd periodic report | Project office |
| | | Comments of cluster 2 with regard to environmental indicators | Project office |
| | | Minutes of the meetings | Project office |
| Power point presentation about blended cements / work of cluster 2 | | - | Project office |
| | | Online | ECOServe website |

Christoph Müller and Eberhard Siebel, Düsseldorf 35

**Figure A1:** Cluster 2 – Network: Overview of deliverables

The following discussion about the progress of work and the next work steps is summarized in figue A2.

## Action plan for the next period

| Item / Action | Responsible / Schedule |
|---|---|
| Continuation compilation and evaluation of NAR | All members (according to responsibility assignement) |
| Co-operation with cluster 3<br>☞ All members of cluster 2 comment on “State of the art” of cluster 3<br>☞ VDZ prepares statement and send it to cluster 3<br>☞ Proposal: Joint meeting cluster 3 in 2005 | All members send comments to VDZ until 30.04.2005<br>Next meeting cluster 2:<br>13./14.09.2005 or 20./21.09.2005<br>2nd day: Joint meeting with cluster 3 |
| Collect data on the clinker content in practise: Comparison of the use of concrete additions and blended cements<br>Examples: Bridge / house | ☞ VDZ prepares a questionnaire |
| Every member makes a proposals for a good article on the benefits of blended cements for the website. | ☞ 5-10 articles on the benefits of blended cements on the website |
| Updating and improvement of the power point presentation | All members |
| Argumentation paper for the use of blended cements | ☞ first proposal to be prepared by VDZ |
| Proposal for further RTD activities | |

Christoph Müller and Eberhard Siebel, Düsseldorf 36

**Figure A2:** Cluster 2 – Network: Action plan for the next period

## N6 Any other business

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## R1 Status quo of investigations, Adjustment nominal/actual work

The following ammendments / modifications of the workplan have to be taken into account:

| | |
|---|---|
| **All partners:** | Sub-task 1.4 “Silica-Fume” was canceled and sub-task 1.5 “Limestone” was expanded |
| **Partner 1: (VDZ)** | Investigations on fly ashes have been reduced due to the quality of calcareus fly ashes in Germany (Sub-task 1.3). A lot more modifications have been made with cements containing slag and limestone (Sub-task 2.2). VDZ will make investigations on chloride penetration for NORCEM (Sub-task 3.3). |
| **Partner 2: (CTG)** | The selection and analysis of the starting materials has consumed more time than expected. The planned activities are now acc. to schedule. |
| **Partner 3: (NORCEM)** | The production of trial mixes was originally planned for May/June 2004. Due to capacity problems and internal restructuring of work tasks, as well as other strategic issues, led to a re-scheduling of the laboratory programme. The concrete mixes were produced in november/december 2004. VDZ makes investigations on chloride penetration for NORCEM (Sub-task 3.3). |
| **Partner 5:** | No remarks. |

In general, the ammendments / modifications will not lead to any change of the overall budget or limitations of the perceptions and the expected outcome of the project.

The meeting closed at 16:30 p.m.

signed
Dr.-Ing. E. Siebel

signed
i. V. Dr.-Ing. C. Müller

## 11.4 4. Meeting

Date: 20 September 2005 at 10 a.m.
Place: Research Institute of the Cement Industry, Düsseldorf, Germany

Present were:

| | | | |
|---|---|---|---|
| 1 | Manolis Chaniotakis | (MH) | Titan Cement Company S.A. |
| 2 | Michal Glinicki | (MG) | Institute of Fundamental Technological Research, Polish Academy of Sciences |
| 3 | Christoph Müller | (CM) | Verein Deutscher Zementwerke e.V. |
| 4 | Eberhard Siebel | (ES) | Verein Deutscher Zementwerke e.V. |
| 5 | Terje Ronning | (TR) | NORCEM |
| 6 | Antonio Princigallo | (RC) | CTG SpA |

Minutes taken by CM.

**Agenda**

| TOP | Content | Report by |
|---|---|---|
| Network | | |
| N1 | Opening of the meeting and introduction of new members | |
| N2 | Minutes of the 3. meeting | |
| N3 | Discussion of “Argumentation paper "blended cements"” and further procedure | all members |
| N4 | National application rules for blended cements | C. Müller / all members |
| N5 | Comments of cluster 2 on cluster 3 documents: "Baseline report" and draft "BAT-Report" | all members |
| N6 | Any other business | |

| | | |
|---|---|---|
| Research | | |
| R1 | Overview of results (approx. 20 minutes per partner) | CTG, Norcem, Titan, VDZ |
| R2 | Any other business | |

## N1 Opening of the meeting

ES welcomed all participants to the 4. meeting of cluster 2 of the ECO-Serve Network, especially MG both joining the cluster for the first time. ES then asked for comments to the proposed agenda.

The proposed agenda was adopted.

## N2 Minutes of the 3. meeting

The minutes of the third meeting were adopted without comments or changes.

## N3 Discussion of “Argumentation paper "blended cements"” and further procedure

During the 3rd meeting of cluster 2 dated 04.02.2005 in Düsseldorf it was decided, that cluster 2 will prepare an argumentation paper for blended cements. A first draft was prepared by VDZ and provided to members of cluster 2 prior to the meeting.

The aim of this paper is:

(1) to show properties and benefits of blended cements with regard to the environment, cements properties and concrete properties
(2) to compare blended cements and the use of cements and concrete additions (“blending cements”).

Item (2) is of special importance for cements producers with regard to the tendancy to use e. g. fly ash or granuletd blast furnace slags as concrete additions.

As a first stage, the paper will be prepared as an internal document for members of cluster 2. During that stage all information on blended cements – independent wether positive or negative aspects are concerned – should be collected. This aspect especially affects the comparison of blended cements and blending cements.

A first draft was distributed to the participants prior to the meeting (Document ECO-Serve-C2-N-0029).

The general concept of the paper was adopted by members of cluster 2. Remarks, changes and further procedure is mentioned in the annex 1 to these minutes.

## N4 National application rules for blended cements

The latest status of the collection of “National application rules for blended cements” was distributed by CM to the participants (Document ECO-Serve-C2-N-00233).

## N5 Comments of cluster 2 on cluster 3 documents: "Baseline report"and draft "BAT-Report"

The discussion focused on chapter 3 “Concrete production” of cluster 3 document “Best available technology report for the aggregate and concrete industries in Europe (June 2005 (ver. 3).

The discussion can be summarized by means of the following remarks / statements.

These statement will be discussed during the joint meeting of cluster 2 and cluster 3 dated 21.09.2005. From the point of view of cluster 2 there is a strong need to consider these remarks and arguments.

| Reference to chapter / table / figure | Remark | Modification proposal |
| --- | --- | --- |
| Figures 3.2 / 3.5 | Figures are not taken from cluster 2 presentations.<br>Data is taken from cluster 2 reports but it is used in a way, that might lead to misunderstanding and is not appropriate. | Delete these kind of figures or modify them in an adequate way |
| | Someone, who is not familiar with the NADs and their background, might conclude, that these "correlations" can be used independent from the application (exposure class). This is not correct. | |
| | The figures in cluster 2 where prepared to show, that in general the cement content in concrete is not the right measure to evaluate $CO_2$-emissions caused by concrete production, but it is the $CO_2$-emission during the cement production – mainly influenced by the clinker content – combined with the cement content. | |
| | CEM III/B is not a realistic scenario for a reduction potential and even a clinker content of 100 – 150 kg/m$^3$ is too low when we look to these issues on an European level. E. g. with limestone or other fillers and even with fly ash the potential of the CEM III/B cannot be reached due to technical (Durability) reasons. CEM III/B - even if it is applicable in nearly every exposure class, cannot be used for all applications because for its strength development and corresponding curing times. Besides the applicability of cements according to various national annexes to EN 206-1 the availablity of cements per country and the regional availability of blended cements is different. Due to the availability of main constituents besides clinker, not every cement plant is able to produce any kind of blended cement in a cost-effective and ecologically way (transport etc.). | |
| | 150 kg/m$^3$ might be a potential e. g. in Germany, because the German cement industry is going to establish the CEM III/A as a standard cement for the ready mixed concrete industry. | |

| Reference to chapter / table / figure | Remark | Modification proposal |
|---|---|---|
| Figures 3.2 / 3.5 | This concept is not transferrable to other regions, e.g. Italy or Greece.<br>From the technical point of view, the use of blended cements containing<br>20 – 30 % limestone or<br>35 % fly ash or<br>50 % slag might be a potential for different regions in Europe.<br>Cluster 2 will check, what might be a pan-European approach (e. g. CEM II/A or CEM II/B) | Delete these kind of figures or modify them in an adequate way |
| page 22, last paragraph | “wish for relatively high cement contents”<br>Cement contents in the standards are not a “wish” but they are technically and economically feasable and necessary to produce a good workable concrete with a dense and durable microstructure. | Avoid these kinds of assessments. |
| General | BAT for concrete production has to be defined first all in a technical approach manner, not only with the focus on $CO_2$. Durability is very important with regard to the life cycle. It makes no sence to save 20 kg/t clinker or 20 kg/$m^3$ cement in the production phase, when an insufficient durability of the concrete will counterbalance the $CO_2$-emissions that have been avoided. | Use the “durablity approach” |

## N6 Any other business

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## R1 Overview of results

TR, MH, RC and CM gave an overview of the latest delelopments of the research parts of NORCEM, TITAN, CTG and VDZ.

In general it could be noticed, that all investgation have been carried out in line with the workplan and the modifications which have been agreed upon during the project duration. The ammendments / modifications will not lead to any change of the overall budget or limitations of the perceptions and the expected outcome of the project.

Some of the ascertained results can be summarized as follows:

<u>Germany</u>

| | |
|---|---|
| CEM II/B-LL with 35 % limestone | • Carbonation depth in the range of Portland and Portland-limestone cements CEM II/A-LL.<br>• Resistance against chloride penetartion in the range of Portland cements.<br>• Freeze thaw resistance: The scaling tested with the cube test showed a sigificant correlation to the quality of the limestone expressed as the specific surface (BET).<br>• Freeze thaw resistance with de-icing salts (air-entrained concrete) comparable to concrete with Portland cement. |
| Cement with 30 % ggbs and 20 % limestone | • Carbonation depth in the range of Portland and Portland-limestone cements CEM II/A-LL.<br>• Chloride migration coefficients of concrete using cements with 30 % ggbs and 20 % limestone in the range of concretes with Portland-slag cement CEM II/B-S.<br>• Assessment of the freeze thaw resistance dependent on the kind of test.<br>• Freeze thaw resistance with de-icing salts (air-entrained concrete) comparable to concrete with Portland cement. |

| | |
|---|---|
| Cement with 50 % ggbs and 20 % limestone | • Carbonation depth in the range of the maximum values reported in the literature for blastfurnace cements CEM III/B with up to 80 % ggbs.<br>• Chloride migration coefficients in the range of concretes with Blastfurnace cements CEM III/A.<br>• Freeze thaw resistance: High scaling in the cube test and a significant decrease of the RDM in the CIF test. No sigificant change in the RDM in the beam test after 56 FTC.<br>• Not applicable for exposures with freeze thaw attack with de-icing salts and a high water saturation (exposure class XF4 acc. to EN 206-1). |

Greece

| | |
|---|---|
| Carbonation: | The concrete mixings with cements FA(A) 45% indicated higher carbonation depth than with cements FA(A) 35% probably because of the lower quantity of $Ca(OH)_2$ produced. |
| Chloride penetration: | Chloride permeability was low for concretes with fly ash cements and high for the concrete with the reference cement 42.5. Concretes with blended cements with 15%FA, 12%P and 15%LL and the pozzolanic cement were classified to have moderate chloride ion penetrability. Concrete with the limestone cement was evaluated as “high” with regard to chloride permeability. |
| Sulphate resistance: | Durability against sulphate attack was improved for concrete with pozzolanic cement and the blended ternary cements (6% FA(A), 17% P, 8% LL and 15% FA(A), 12% POZ, 15% LL) compared to reference cement 32.5. The concrete with limestone cement (35% LL) was less durable since it exhibited low resistance to expansion. |

Italy

The tests in concrete have pointed out that good performances can be achieved in terms of basic physico-mechanical characteristics for the concretes with the cements

- Portland-limestone cements with up to 45 % of limestone;
- Ternary composition based on clinker, slag and limestone with 40 % ggbs / 20 % LL;
- Ternary composition based on clinker, ground glass and ground brick as pozzolanic material with 30% ground glass / 15% ground brick.

On the contrary the analysed concretes based on experimental cements have exhibited poor durability properties.

<u>Norway</u>

| | |
|---|---|
| Carbonation: | The most significant result at this very early stage is the negative effect of LL. Increasing the pfa content to 50% also provides a negative effect. |
| Chloride penetration: | Of all mixes and ages 35% pfa performed best. The 50% pfa performed better at a later stage (~ 240 d). |
| Freeze thaw resistance: | For all series with blended cements, internal damage was considerable, except for the CEM I reference. The scaling level is significant. |
| Freeze thaw resistance with de-icing salts (air-entrained concrete) | Best performance ("Very Good") was achieved with all the reference cement mixes, all of type CEM I. Good performance was achieved with 35% pfa (w/c=0,40) and 20% pfa (w/c=0,50). Acceptable performance was achieved with 35% pfa (w/c=0,50) and – close to the boarder line – 50% pfa (w/c=0,40). The latter (50%pfa) was not acceptable when increasing the w/c-ratio to 0,50. |

Especially if long term strength is taken into consideration, CEM II/B-V appear to be promising, based on strength and chloride intrusion.

**R2 Any other business**

It was agreed that partners will send their contribution to the final report as word-files not later then 04.11.2005. The report has to cover the whole period from 01.10.2003 until 30.09.2005. Partners will also send also all neccessary administrative / financial information for the cost statement using the corresponding forms (forms used for the first cost statement). The relevant period for the cost statement is 01.10.2004 - 30.09.2005.

The meeting closed at 18:30 p.m.

signed
Dr.-Ing. E. Siebel

signed
i. V. Dr.-Ing. C. Müller