Concrete constituents and technology, concrete engineering

Portland-composite cements have increasingly been gaining in importance as the cements works have to make a contribution to reducing CO₂ emissions. This can be achieved primarily by using cements in which the clinker portion is reduced and the share of other main constituents, such as blastfurnace slag, fly ash or limestone meal, is increased. The objective pursued by the Research Institute’s work is to optimise these cements in such a way as to enable their application without restrictions in all areas of concrete construction.

Some research projects are still concerned with preventing a harmful alkali-silica reaction (ASR). Damage partly attributable to an alkali-silica reaction occurred at a few concrete pavements after a service life of 6 to 10 years. Based on the investigations it had carried out, VDZ gave recommendations regarding the alkali content of road paving cements.

The interaction of cement and admixtures constitutes a further key topic of the research conducted by the Concrete technology department. The investigations cover the new generation of super-plasticisers, shrinkage reducing admixtures and air entraining agents.

The results of scientific work were published in lectures and reports, and immediately found their way into standardisation work. Employees of the Institute made a major contribution to this work, particularly as far as the compilation and introduction of new standards in the field of concrete was concerned. An A1 amendment to DIN 1045-2 was published in time before the transition period from the old to the new generation of standards expired, rendering DIN EN 206-1 and DIN 1045-2 the only standards that may be applied for new structures. Moreover, mention must be made of the cooperation in the compilation of several guidelines by the German Committee for Reinforced Concrete (DAfStb) and in regulations issued by the Research Association for Roads and Traffic (FGSV).
Portland-composite cements

The use of Portland-composite cements enhances the ecological efficiency of concrete construction as the clinker content of these cements is lower than that of Portland cements. The utilisation of other main constituents allows to reduce the CO₂ emissions during cement manufacture in particular. Projected to the annual domestic dispatch of the German cement works, which totals some 30 million t (average from 1999 to 2003), a 5% decline in the average clinker proportion, for example, would allow to reduce annual CO₂ emissions by more than 1 million t. This presupposes, however, that these cements are largely comparable to Portland cements in terms of their construction properties and their inclusion in the set of regulations.

Preconditions set by standards and areas of application in building practice

To estimate the future potential of new cements, it is useful to have a look at the share of the cements dispatched in Germany subdivided by their area of application in building practice. Tab. V-1 roughly summarises these figures for the year 2000. A distinction is made between the categories of common building construction, civil and underground engineering, traffic areas and other applications. The breakdown highlights that some 50% of the cements manufactured in Germany are used to produce ready-mixed concrete for internal and external components to be employed in common building construction, i.e. in the construction of residential and commercial buildings. 14% of cement dispatch is used to produce precast elements for building construction. The domestically dispatched cements applied in civil and underground engineering account for a share of about 12%, while some 19% of the cements are employed in the manufacture of concrete products for traffic areas and in concrete road construction. The remaining dispatch share of 8% is used in unreinforced concrete.

The cements with several main constituents assigned to strength class 32,5 which have been manufactured in Germany to date comply with all the major requirements for the production of in-situ concrete – irrespective of whether it is ready-mixed or site-mixed – for common building construction. The strength development of these cements is fast enough for common manufacturing processes. The concretes made from these cements are adequately protected against steel corrosion in concrete induced by carbonation and chloride. They further possess freeze-thaw resistance that is adequate in the climate conditions prevailing in central Europe. In-situ concrete for civil engineering structures, such as tunnels or bridges, is usually made from cements of higher strength classes, i.e. mostly from Portland cement CEM I these days. CEM II and CEM III cements can, however, be applied in this area, too, and have conquered growing market shares. The domain of common building construction including residential construction and commercial building construction thus represents an essential market segment. If new cements meet the requirements for these areas of application, large market segments can be opened up for these cements.

In principle, all cements in accordance with DIN EN 197-1 and DIN 1164 lend themselves to the production of concrete according to DIN EN 206-1 and DIN 1045-2. With regard to the durability of the concretes made from these cements, however, differences induced by the cement type used have to be taken into account depending on the area of application. The concrete standards lay down corresponding different application rules depending on the exposure class that a structural element is to be classified in. Furthermore, the application of several CEM II cements not used in Germany before, such as Portland-limestone cements with limestone contents of up to 35 wt.% (CEM II/B-LL) and Portland-composite cements with up to 35 wt.% blastfurnace slag and limestone (CEM II/B-M (S-LL)), is also subject to restrictions. These restrictions relate to application in structural elements exposed to freeze-thaw and chloride attack in particular (exposure classes XS, XD, XF). When such cements are to be applied in areas for which their use is not permissible according to the concrete standard, a national technical approval has to be obtained. This is the case with new CEM II-M cements developed by some German cement manufacturers. The first technical approvals for such CEM II-M cements were granted last year. As these cements increasingly prove themselves in practical application, which is substantiated by the data base compiled as part of research projects, the necessity of such approvals can be dispensed with by modifying the application rules accordingly. Given this scenario, the Research Institute carried out investigations to extend the data base for concretes made from new Portland-composite cements. These chiefly consisted of determining the parameters relevant to durability that Portland-limestone cements with limestone contents of up to 35 wt.% (CEM II/B-LL) and Portland-composite cements with up to 35 wt.% blastfurnace slag and limestone (CEM II/B-M (S-LL)) possess. Further investigations will centre on Portland-fly ash cements with up to 35 wt.% siliceous fly ash and Portland-composite cements CEM.

<table>
<thead>
<tr>
<th>Area of application</th>
<th>Structures</th>
<th>Cement strength class</th>
<th>Cement type</th>
<th>In-situ concrete</th>
<th>Factory-made concrete</th>
</tr>
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<tbody>
<tr>
<td>Various applications</td>
<td>Unreinforced concrete</td>
<td>32,5 N/R</td>
<td>CEM I CEM II CEM III CEM IV CEM V</td>
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<td>-</td>
</tr>
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<td>Common building construction</td>
<td>Internal components</td>
<td>32,5 N/R 42,5 N/R</td>
<td>CEM I CEM II CEM III</td>
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<td>14</td>
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<td>Commercial building construction</td>
<td>External components</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Civil and underground engineering</td>
<td>Bridges, tunnels, hydraulic engineering and marine structures, pipes</td>
<td>52,5 N/R 42,5 N/R 32,5 N/R</td>
<td>CEM I CEM II CEM III</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Traffic areas</td>
<td>Paving blocks, quarries</td>
<td>52,5 N/R 42,5 N/R</td>
<td>CEM I CEM II CEM III</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td>Roads, airfield surfaces, ballastless track</td>
<td>32,5 R</td>
<td>CEM I CEM II CEM III</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

Tab. V-1: Areas of application and share in domestic dispatch of German cements in %
II-M (V-LL) and CEM II-M (S-V) of different compositions.

**Durability of concretes made from Portland-composite cements**

Comparative durability investigations of concrete presuppose that the concretes possess a comparable strength level as a parameter for similar microstructure formation at the time of testing, which is usually after 28 days. For that reason, Portland-composite cements should have a comparable 28-day compressive strength, which ranges between 44 and 48 MPa in the area of practical relevance for German cements of strength class 32.5 R. The fineness of the main cement constituents Portland-cement clinker, blastfurnace slag and limestone therefore had to be varied in such a way as to ensure that the strength level indicated was roughly matched when the composition of the cements varied. The strength development, the porosity and the pore size distribution, the carbonation, the resistance to chloride penetration and the resistance to freeze-thaw with and without de-icing salt of the mortars and concretes made from these cements were investigated. The composition of the mortars and concretes was geared to the limit values for the composition of concrete according to the exposure classes of DIN 1045-2.

**Carbonation**

**Fig. V-1** illustrates the development over time of the carbonation depths of some of the concretes investigated, which had the composition required for exposure class XC3. The range of values to be assumed according to technical literature for the cements CEM I to CEM III/B under the testing conditions prevailing in the present case is given in the Figure as well. These cements may be applied in all exposure classes for carbonation-induced reinforcement corrosion. It becomes apparent from the representation that the carbonation depths determined for concretes made from cements with up to 35 wt.% limestone were within the range mentioned above, although at 40 MPa the 28-day standard compressive strength of the cement with 35 wt.% limestone was fairly low. The same applied to the carbonation depths of concretes made from Portland-composite cements with up to 35 wt.% blastfurnace slag and limestone. The porosity of mortars made from Portland-limestone cements increases slightly as the content of limestone meal gets higher. The increase in the carbonation depth of the concretes made from cements containing limestone correlated with the rise in the proportion of pores > 0.1 µm of the corresponding mortars at the age of 28 days.

**Resistance to chloride penetration**

According to bibliographical reference, the use of up to 25 wt.% limestone does not substantially impair the resistance to chloride penetration. The resistance to chloride penetration of concretes made from Portland-limestone cement and having a limestone content > 25 wt.% was assumed to be slightly lower than that of concretes containing Portland cement. The results achieved here confirmed this assumption. **Fig. V-2** shows the chloride migration coefficients measured for concrete with a water/cement ratio w/c = 0.50 and a cement content c = 320 kg/m³ at an age of 35 days. Different laboratory-made cements were used to produce these concretes. At the same time, however, the chloride migration coefficient values determined for Portland-limestone cements with up to 35 wt.% limestone were found to be within the usual range of values for Portland cements and Portland cements with a high sulfate resistance given in publications (D_{Cl,M} between approx. 10 and 25-10⁻¹² m²/s). In concretes made from cements containing blastfurnace slag, the amount of capillary pores, which is decisive for essential transport processes, is reduced in favour of the gel pore volume, which is largely irrelevant for transport processes. When Portland-composite cements with up to 35 wt.% blastfurnace slag and limestone were used, the chloride migration coefficients therefore fell short of the coefficient of the Portland cement tested and exceeded that of the Portland-slag cement with 35 wt.% blastfurnace slag.
Resistance to freeze-thaw and freeze-thaw with de-icing salt

When damage is caused by freeze-thaw attack, a distinction is made between external and internal damage. External damage is visible as surface scaling. Internal damage to the microstructure can, for example, be ascertained by means of ultrasonic transit time measurement and the dynamic modulus of elasticity thus derived (see also the section on durability). The significance of a drop in the dynamic modulus of elasticity in terms of the concrete properties to be expected after exposure to freeze-thaw has, however, been clarified neither for laboratory-made concretes nor with regard to the durability of concretes in practical application so far. The modulus was determined as part of the investigations of new cements as well as to gather experience and to compare it with figures quoted in publications as well as with acceptance criteria discussed in various bodies.

In the trials conducted, concretes with a water/cement ratio \(w/c = 0.50\) and a cement content \(c = 320\,\text{kg/m}^3\) which were produced from the laboratory-made Portland-limestone cements with up to 35% limestone did not exhibit significantly higher scaling rates than concrete made from Portland cement even when water saturation was high in the CF test. A systematic influence of the limestone content was not discernible. This applied to the scaling of the concretes made from Portland-composite cements with up to 35 wt.% blastfurnace slag and limestone, too (Fig. V-3). The relative dynamic moduli of elasticity of these concretes determined by the CIF method are shown in Fig. V-4. Differentiation in terms of the limestone content is more pronounced here than it is with scaling. The testing of concrete according to the CIF method implies various acceptance criteria that will not be discussed here. The acceptance criterion of 75% after 28 freeze-thaw cycles laid down in the “Freeze-thaw testing of concrete” code of practice by the Federal Waterways Engineering and Research Institute was met by a wide margin by all concretes. On the whole, the relative dynamic elasticity moduli of the concretes made from Portland-composite cements were within the range of values obtained for concretes made from Portland cements. In the cube test method, the same concretes displayed virtually no change in the relative dynamic modulus of elasticity after up to 100 freeze-thaw cycles regardless of the cement used. This means that even after 100 freeze-thaw cycles, critical saturation was not reached in this test.

The influence of different Portland composite cements on the concrete’s resistance to freeze-thaw with de-icing salt is depicted in Fig. V-5. The scaling behaviour of the concretes made from Portland-composite cements did not differ significantly from that of concrete containing Portland cement. The scaling rates of all concretes after 28 freeze-thaw cycles fell considerably short of the value of 1.5 kg/m², which is generally used as acceptance criterion in this test.

Conclusions and outlook

According to the investigations conducted, also the Portland-composite cements with blastfurnace slag and limestone (CEM II/B-M (S-LL)) which have not been applied in Germany to date can be utilised in concretes of all exposure classes with regard to corrosion of the reinforcement induced by carbonation and chloride, and freeze-thaw attack with and without de-icing agent. To substantiate the investigation results on the resistance to freeze-thaw and freeze-thaw with de-icing salt of concretes made from Portland-limestone cements CEM II/B-LL, the Research Institute is carrying out supplementary investigations of limestones with a CaCO₃ content ranging between 75 and 90 wt.%.

Cement and admixtures

The use of concrete admixtures to control the properties of the fresh and hardened concrete is state of the art today. Some 90% of the concrete produced in Germany contains concrete admixtures. Overall, more than 550 concrete admixtures are presently available in Germany, which can be classified in 14 different functional groups. At approx. 70%, concrete plasticisers and super-plasticisers account for the lion’s share.

The influence that concrete admixtures have on the hydration of cement is most often determined empirically and forms the subject of controversial discussions. There is still a substantial lack of scientifically
founded understanding of the precise working mechanisms of some admixtures. This applies to long-term retarding admixtures, shrinkage reducing admixtures on the basis of polycarboxylate ether, and novel air-entering concrete admixtures in particular, the function of which formed the subject of extensive investigations.

**Long-term retarders (LTR)**

LTR are organic retarding admixtures which, due to their composition, can severely inhibit the hydration of cement, in some cases for several days. In addition to their utilisation for fresh concrete recycling, LTR are used to retard the setting of shotcrete in case of long transport routes, and for mass concrete. The LTR approved as recycling aids in Germany primarily contain 2-phosphonobutane-1,2,4-tricarboxylic acid (PBTC).

A research project sponsored by the Federal Association of Industrial Cooperative Research Associations (AiF) and the Dyckerhoff Foundation systematically investigated the effects of LTR on the hydration of pure clinker phases, clinker and Portland cements. Investigations of pure clinker phases revealed that the extended set retardation is based essentially on blocking the hydration of the calcium silicates. LTR prevented the hydration of C₃S almost fully for up to 180 days. The addition of LTR resulted in increased phase conversion with pure C₆A and in reduced phase conversion with pure C₆AF. In the case of mixes consisting of C₆A and sulphate agent, the LTR led to a short-term acceleration in the formation of primary ettringite. The further course of hydration of C₆A and C₆AF, respectively, and the reaction of hemihydrate with water to form gypsum were retarded significantly. When the mixes of C₆A and sulphate agent additionally contained calcium hydroxide, all other hydration reactions except for primary ettringite formation were inhibited.

The investigations of Portland cements confirmed the results obtained from the investigations of pure clinker phases. With Portland cements with optimised sulphate agents, the long-term retardation of the hydration of the calcium aluminates and calcium silicates was always accomplished as planned. When the supply of calcium sulphate was too low, the addition of LTR strongly accelerated the hydration of C₆A, which resulted in particularly fast stiffening and setting. The further strength development was, however, strongly impeded since the lower-reactivity calcium silicates were retarded at the same time. The working mechanisms of the LTR in case of addition to a Portland cement that were derived from the test results are shown in Fig. V-6. It schematically depicts the cross section of a clinker particle and of sulphate agents (C₆H). In the alkaline medium of the pore solution, the PBTC splits off five protons and is present in completely dissociated form ([C₆H₂O₃]P)⁺. Owing to the calcium and sulphate ions supplied by the sulphate agents, a thin layer of primary ettringite is formed on the surface of the calcium aluminates, which retards the further hydration of C₆A. Apart from that, the sulphate agent supplies an adequate quantity of calcium ions for the immediate formation of hardly soluble calcium phosphate (Ca₅₋₁₋₃(C₆H₂O₃)P). The calcium phosphate "seals" both the surfaces of the clinker particle and those of the sulphate agents not yet dissolved. The further penetration of water (H) and the further ion exchange, respectively, are impeded massively, which results in the planned extended retardation of hydration.

When the supply of sulphate agents in Portland cements is missing or too low (Fig. V-7), only small quantities of dissolved calcium are available. As a consequence of the calcium demand of the PBTC, the hydration of reactive clinker phases, such as C₆A, is briefly accelerated in these cases. The hexagonal calcium aluminate hydrates (CAH) which are then increasingly formed mostly lead to marked stiffening or setting. The calcium ions released during this short acceleration phase are fixed by PBTC. The hardly soluble calcium phosphate thus produced coats the surfaces of the individual clinker particles in different ways. The surfaces of relatively slow-reacting clinker phases, such as C₆S and C₆S, which are largely free of hydration products when the hardly soluble compounds are formed, may be covered with a largely closed coating of calcium phosphate. Surfaces partly covered with hydration products already, such as those of the C₆A, possess a fairly large specific surface area. The quantity of calcium phosphate formed is usually not sufficient to fully "seal" these areas. As water penetration and ion exchange cannot be
Based on lignin, melamine and naphthalene sulphonate. This may for example result in a faster decrease of consistency, segregation, intensive bleeding or significant retardation of strength development. More profound understanding of the interaction of super-plasticisers and cement or concrete, respectively, is required to prevent such undesired reactions.

Fundamental investigations carried out as part of a research project sponsored by the AiF are aimed at determining the influence that the chemical structure of the PCE molecules and the chemico-mineralogical composition of ordinary cements have on the dispersion and the strength development of the pastes, mortars and concretes made from them. The essential parameters induced by admixtures and cement that may cause undesired reactions, such as rapid loss of workability or low early strength, are being recorded systematically.

The structure or composition, respectively, that “robust” PCEs must have in order to plasticise the majority of ordinary cements as effectively as possible and as planned is to be identified.

The first main emphasis of the investigations consists of compiling a data base on the exact chemico-mineralogical composition of selected ordinary cements, and on the composition and molecular structure of ordinary PCEs. In addition to various PCEs and cements, also the margin of variation in different cement and super-plasticiser shipments will be analysed. Moreover, the composition of the pore solution of some cement pastes at an early age shall be added to the data base. The second main emphasis consists of systematically investigating the interaction of the ordinary PCEs and individual cements on the basis of cement/PCE mixes that are chosen in consideration of the data base established. In this way, the cement and admixture parameters responsible for optimum efficiency of the PCEs are to be determined. The influence that the molecular structure of the PCE molecules has on the dispersion, the effective period and the strength development of pastes and mortars made from model cements is to be investigated on the basis of purposefully synthesised PCEs having main and side chain lengths of different definition. To that end, rheological parameters, such as the yield value and the dynamic viscosity, as well as the zeta potential and the composition of the pore solution are determined.

In a first step, the chemical composition and the physical parameters of 15 ordinary super-plasticisers on PCE basis were investigated. The molecular structure was identified using NMR (Nuclear Magnetic Resonance) spectroscopy and GPC (Gel Permeation Chromatography), respectively, as well as through the determination of the specific anionic charge volume. Initial results of these investigations suggest that some of the 15 super-plasticisers contain nearly identical PCE molecules. The specific charge describes the actually effective charge of the main chain of the PCE molecule. Fig. V-8 summarises the specific anionic charge volumes determined for the 15 super-plasticisers (FM). The charge of the PCE molecules range between about 80 and 2070 charge equivalents per gramme of polymer. Sorption to positively charged cement surfaces of super-plasticisers with very low charge density is presumably
markedly lower than sorption of super-plasticisers with a high specific anionic charge volume.

**Determination of the zeta potential**

The sorption of super-plasticiser molecules on the cement particle surfaces is investigated by measuring the zeta potential. In conjunction with rheological investigations it is examined whether the zeta potential allows to draw conclusions on the initial plasticising action and the duration of the plasticising effect of super-plasticisers.

The zeta potential is an electro-kinetic potential in the contact surface between the mobile and the rigid part of the double layer formed at the phase boundary between solids and aqueous solutions (Fig. V-9). The potential indicates the charge conditions on the particle surface. Up to now, it has only been possible to determine the zeta potential in highly diluted cement suspensions (w/c ~ 1000) by means of measuring electrophoretic mobility, i.e. via the molecular velocity in an electric field generated. Given the high influence that the solids content and the ion strength, among other factors, have on the zeta potential, a transfer of the results to suspensions with w/c ratios common in practical use is highly incorrect.

Since September 2004 the Research Institute has had the possibility of determining the zeta potential of suspensions with a very high solids content (w/c ≥ 0.40) by means of a new electro-acoustic measuring method. The device consists of a probe that stimulates the molecules in the suspension to perform relative motions via an ultrasonic field (Fig. V-10). As a consequence the charged molecules form dipoles. The electric field generated is measured as a colloidal vibration current and converted to the zeta potential. The input data required are the density and the ultrasonic speed of the solid and the liquid phase, the particle size distribution, and the concentration. The temperature, the pH value and the conductivity of the respective solutions can be determined in parallel to the zeta potential. An automatic burette allows the stepwise addition of admixtures, for example.

By way of example, Fig. V-11 illustrates the influence of super-plasticisers (SP) on melamine sulphonate (MS) and polycarboxylate ether (PCE) basis on the zeta potential of a cement paste. While the anionic super-plasticiser containing melamine sulphonate as an active ingredient causes the zeta potential to shift in a negative direc-
Admixtures have primarily been employed since 1997. In Germany, shrinkage reducing admixtures have been in use also in Europe since about 1980. Shrinkage Reducing Admixtures (SRA) were developed in Japan in the early 1980s. These admixtures have been in use also in Europe since about 1997. In Germany, shrinkage reducing admixtures have primarily been employed in floor screed works and in mortar applications so far. They are, however, presently not used in load-bearing structural elements made from concrete, reinforced concrete and prestressed concrete as general building inspectorate approvals for this type of admixture have not been issued yet.

Shrinkage reducing admixtures

Concrete shrinkage leads to deformations that may cause stress in structural elements in case of constraint. As a consequence, cracks (superficial cracks or separation cracks) that impair durability may occur. Shrinkage lowers the crack-proofness of large-surface structural elements, such as floor slabs, and of high-strength concrete components at an early age. Shrinkage is induced by changes in the moisture content of concrete, which change the interior forces in the microstructure of the hardened cement paste matrix as a consequence of the environmentally induced drying or self-desiccation of the concrete. This results in tensile stress, which causes the matrix to contract. Deformation is impeded by the aggregates to some degree.

Shrinkage Reducing Admixtures (SRA) were developed in Japan in the early 1980s to reduce concrete shrinkage. These have been in use also in Europe since about 1997. In Germany, shrinkage reducing admixtures have primarily been employed in floor screed works and in mortar applications so far. They are, however, presently not used in load-bearing structural elements made from concrete, reinforced concrete and prestressed concrete as general building inspectorate approvals for this type of admixture have not been issued yet.

Research results published to date show that the statements on the working mechanisms and effects of SRA are contradictory. This applies both to investigations of hardened cement paste and of mortar and concrete. There has previously been a lack of conclusive research results that explain the effects these admixtures have on the pore structure, the material parameters and the long-term behaviour of both hardened cement paste and concrete. The Research Institute is conducting investigations on the working mechanisms of shrinkage reducing admixtures as part of a research project sponsored by the AiF. This project is aimed at identifying the fundamental workings of shrinkage reducing admixtures as they interact with cement. On the basis of these results, the potential of shrinkage reducing admixtures can be estimated and taken advantage of to enhance the performance of the building material concrete.

The determination of the microstructure and hydration properties of hardened cement paste and mortar samples containing SRA is an essential part of the investigations carried out by FIZ. Moreover, interest particularly focuses on identifying both the share of the autogeneous shrinkage and of the drying shrinkage of hardened cement paste obtained when different shrinkage reducing admixtures are utilised. A measuring device allowing to determine the hygric deformation behaviour of conserved hardened cement paste samples stored nearly frictionless was developed to measure the autogeneous shrinkage at low w/c ratios (Fig. V-12). Measurement is continuous and starts about 6 hours after water addition. Initial results have shown that the overall shrinkage of hardened cement paste samples (w/c = 0.40) can be reduced by up to 50% by adding SRA at a quantity of about 2 wt.% relative to the cement.

Air entraining agents

Air entraining agents generating a large number of small, evenly distributed air voids with a diameter ≤ 300 µm in the fresh concrete have to be added to the concrete to achieve adequate resistance to freeze-thaw. In the hardened concrete, the air voids serve as an expansion space for reducing the pressure created when the pore solution freezes. Road paving concrete, which is exposed to severe attacks by deicing salt in the winter, has to be made in the form of air-entrained concrete. Bridge caps and scraper tracks of sewage treatment plants constitute further examples of application.
Air entrainers belong to the surface-active agents also known as tensides. A feature all tensides have in common is their hydrophobic/hydrophilic molecular structure. They are made up of a covalent hydrophobic hydrocarbon chain and an hydrophilic polar carboxyl, sulphate or sulphonate group. The basic materials used for air entrainers are primarily soaps made from natural resin (wood resin); for a couple of years, synthetic active ingredients (e.g. alkyl polyglycol ether, alkyl sulphate or alkyl sulphonate) have been utilised increasingly as well. The active ingredients are applied separately or in combination.

The starting point from which the investigations at the Research Institute proceeded was damage that had occurred in the production of road paving concrete. The air void content of the hardened concrete was considerably higher than that of the fresh concrete in some cases. The Research Institute conducted initial investigations of six ordinary air entraining agents – three based on synthetic active agents, three based on natural active agents – to determine the cause of damage. The trial results showed that a substantial increase in air content can occur only if, as a consequence of too short mixing, an excessive quantity of air entrainer was metered during production in order to attain the desired air void content. In that case, the fresh concrete is supplied with air entrainer that is inadequately decomposed and activated. The air void content may increase if mixing energy is subsequently applied. No systematic influence of the type of active ingredient (synthetic or natural) on air void formation was detected.

As knowledge of the exact interactions of the active ingredient forming air voids, the mixing time and the quantity added is inadequate, the effort that has to be expended in initial testing and during construction work in order to avoid deficient applications is tremendous. A research project sponsored by the AiF is therefore determining the basic workings of active ingredients forming air voids upon interaction with cement. Two focal topics that are based on each other are being studied.

First of all, a database including the active ingredients contained in ordinary air entrainers and their concentrations is compiled. To that end, the data on the air entraining agents currently available is gathered on the basis of information provided by manufacturers and literature research. As this information is frequently not accessible, own investigations are carried out additionally to determine the chemical composition of the admixtures by infrared spectroscopy. Moreover, their pH value, density, solids content and refractive index are identified. Using the data base thus established, various ordinary air entrainers are chosen on the basis of their active ingredients to carry out the planned investigations on the second key topic of “cement paste and mortar investigations”. As the air entrainers often consist of a mix of different substances, pure chemical substances are included in the investigations as well.

A total of 10 substances (4 ordinary air entraining agents and 6 active ingredients) were selected. The sorption behaviour (sorption on cement / precipitation of the active ingredients from the pore solution / floatability of cement) of the substances generating air voids is investigated using cement paste, while mortar forms the basis for studying air void formation as a function of the type and quantity of the active ingredient added and of the mixing time. Supplementary trials are to serve to examine the combination of super-plasticisers and air entrainers as well.

The first flotation tests aimed at defining the sorption behaviour of the air entrainers were started. During the mixing process, the air entrainer molecules arrange around air bubbles, or the polar group of the molecule, which usually has a negative charge, is sorbed by positively charged areas of the cement particles (Fig. V-13). The adhesion of the air voids to the cement particles enhances the stability of the air voids in the fresh concrete. In the flotation test water, cement and air entrainer are mixed in a vessel and fine air bubbles are injected into the suspension. When air entrainer molecules are sorbed by cement particles, air bubbles can accumulate and rise to the water surface with the cement particles, where the foam produced is skimmed off over a constant period. When the foam has dried, the quantity of cement floated can be determined. Fig. V-14 shows initial results by way of example. The investigations covered two ordinary air entraining agents on the basis of a natural and a synthetic active ingredient, respectively; the quantity added was varied. With the air entrainer based on synthetic active ingredients, the quantity of floated cement rises continually as the quantity added is increased. With the air entrainer based on wood resin, by contrast, the proportion of floated cement stops increasing once a certain quan-
Concrete road pavings

A few concrete road pavings were damaged by crack formation 6 to 12 years after they had been laid. The Research Institute of the Cement Industry closely examined the concrete used in the pavement. To determine whether an ASR had contributed to the damage, drill cores were taken from damaged and damage-free sections of the road pavings, stored in a fog chamber at 40 °C and subjected to expansion measurement. In addition to that, polished thin sections of the concretes were produced and assessed under the light-optical microscope (Fig. V-15). This revealed that involvement of an ASR in some of the damage cases could not be ruled out. It became evident in particular that with the “road” type loading case (intense external alkali supply and high dynamic stress), aggregates not cited in the alkali guidelines of the German Committee for Reinforced Concrete (DAfStb) so far can lead to disruption of the internal microstructure as a result of an ASR. These include greywackes from different areas of extraction (cf. Fig. V-15), quartz porphyry and recycled aggregates.

Prevention of a harmful ASR

When a harmful ASR cannot be prevented by using non-reactive aggregates, the alkali content of the pore solution must be reduced by utilising low-alkali cements or pozzolanic additions. The mode of action that latent hydraulic and pozzolanic main cement constituents and concrete additions, respectively, have on the alkalinity of the pore solution were thoroughly investigated by the Research Institute (see Chapter III).

The swelling capacity of the alkali silicates produced during an ASR depends on their chemical composition. Sodium and potassium silicates display an inclination to absorb water and swell accordingly. Various observations have led to the assumption that the silicates formed from lithium show no swelling tendency in the concrete under certain preconditions.

Use of lithium

The effect of lithium was investigated in some tentative tests the Research Institute conducted using alkali-reactive aggregates from German deposits. Concretes were made from north German gravel and high-grade gravel chippings from the Upper Rhine region, respectively, using lithium nitrate and lithium hydroxide. Pursuant to publications, the molar ratio of lithium and the total of potassium and sodium in concrete should amount to 0.8 (lithium nitrate) or 1.0 (lithium hydrox-
ide), respectively, when highly reactive aggregates are utilised. The quantity metered thus directly depends on the alkali content of the Portland cement used and on the cement content of the concrete. For investigation purposes, a Portland cement with Na₂O of 1.3 wt.% (test cement) was used, and the concrete was prepared with 500 kg/m³ cement.

The phenomenologic behaviour of the concretes was studied on the basis of the expansion and the dynamic modulus of elasticity of 10 x 10 x 50 cm bars, and on the basis of the crack formation in a 30 cm cube. The use of lithium compounds significantly reduced the expansion of the concrete bars stored in the fog chamber at 40 °C in comparison to the bars made from a concrete without admixtures (Fig. V-16). Moreover, the concrete cubes did not exhibit any cracking when lithium had been used. The favourable effect of lithium compounds for this type of storage was thus confirmed. Long-term investigations of samples stored on the roof of the Düsseldorf Institute building are to reveal whether this result can be transferred to realistic ambient conditions.

Influence of lithium on the pore solution

The mode of action of lithium compounds was investigated by squeezing out pore solutions of concretes containing lithium and by determining their concentration of lithium, potassium and sodium. A comparison with the total alkali quantity input into the concrete via cements and admixtures shows that the binding of lithium to the hydration products or the alkali-silica gel is considerably better than that of sodium or potassium. Further basic research will be necessary, however, to identify the exact mode of action of lithium. Lithium compounds are currently not utilised in Germany due to their high price.

**Effect of an ASR on the alkalinity of the pore solution**

Knowledge of the point of time following concrete manufacture at which an ASR starts and of the quantity of alkalis from the pore solution that is consumed in this reaction has been inadequate so far. For that reason, the alkali content of the pore solution of concretes containing different aggregates (limestone, gravel with opaline sandstone and flint from north Germany, high-grade gravel chippings from the Upper Rhine region) was determined at different points of time. Fig. V-17 illustrates that the potassium ion concentration in the pore solution of a concrete containing opaline sandstone and flint is markedly lower than that of concrete with inert limestone as early as after a few days. As a consequence of the high proportion of alkali-sensitive constituents, a correspondingly high quantity of potassium ions is combined in the ASR reaction products. The potassium ion concentration of concrete with high-grade gravel chippings from the Upper Rhine region decreases only slightly although the expansion of these concretes after storage in a 40 °C fog chamber was fairly large (Fig. V-16). A drop in the alkali ion concentration of the pore solution therefore does not allow to draw any conclusions about correspondingly severe concrete damage. The alkali ion concentration that is required to trigger a harmful ASR with different aggregates forms the subject of further investigations.

**External alkali supply**

Experience gained in road construction (“road” type loading case) indicates that external alkali supply in combination with freeze-thaw attack can trigger or intensify a harmful ASR when the aggregates contain constituents that react with alkalis. The exact correlations have not been clarified yet. A pertinent research project was initiated in cooperation with the Bauhaus university in Weimar. Concretes of different composition are exposed to attacks by freeze-thaw, by de-icing salt, and by a combination of freeze-thaw and de-icing salt. Subsequent damage that may possibly occur as a consequence of an ASR is studied by examining the expansion of the bars and the cracking of the cubes. In some cases, the concretes shall also be pre-damaged mechanically. The impact of different de-icing agents is examined. Furthermore, alkali profiles throughout the specimen cross section are established. In combination with microstructure investigations, this is to serve to evaluate the relationship between an attack by de-icing salt and an ASR.

**Methods of testing**

When an alkali-reactive aggregate has to be used because a non-reactive aggregate is not available for economic reasons, the evaluation of its sensitivity to alkalis constitutes a crucial prerequisite for the choice of appropriate measures aimed at preventing concrete damage. Test methods
for supranational application that allow to perform this evaluation have not yet been available in Europe. This is mainly due to the fact that experiences with a harmful ASR differ from country to country. There is a lack of investigation results that compare the behaviour shown by different aggregates in various test methods to their behaviour in practical use or under realistic conditions, respectively. This gap is to be closed by means of the EU-sponsored PARTNER project, in which 24 institutions – most of them from Western Europe – are involved. The goal of the project is to develop a uniform European testing system for evaluating the sensitivity of aggregates to alkalis.

Data on the west European aggregates known to be alkali-sensitive was gathered. It is to be published in an atlas comprising microscopic pictures of aggregate details as well as exact petrographical descriptions and information on the behaviour of the aggregates in construction practice. Of these aggregates, 22 were picked out for laboratory investigations. Upon determination of their parameters, their sensitivity to alkalis was examined using methods already available. Three petrographical analysis methods, one chemical method, two mortar tests, four concrete tests and field site tests are conducted, the results of which are compared to the experience gained in practice. Finally, interlaboratory tests are conducted to obtain statistical data on the comparability and reproducibility of the test methods.

In addition to petrographical investigations, the Institute has so far primarily carried out concrete tests and organised the field site tests (cf. Fig. V-18) in 8 different locations in Europe. These locations are representative of the cold moderate climate in North Europe with and without external alkali supply, the moderate climate in Central Europe, and the warm climate in South Europe.

Fig. V-19 shows the expansion of concrete prisms (c = 440 kg/m³, w/c = 0.50) that were made using reactive and non-reactive aggregates from European deposits. The specimens were stored at 60 °C over water in accordance with RILEM AAR-4. It can be seen that the expansion of all concrete with reactive aggregates that are shown exceeded the limit value of 0.02% as early as after some 90 days. In order to establish a connection with the experiences previously gained in Germany, concretes containing the same aggregates were tested according to Part 3 of the German alkali guidelines. These investigations have not been completed yet. The current status of the investigations suggests, however, that the 60 °C test method seems to be more “rigid” than testing in the 40 °C fog chamber.

Performance testing

It is necessary for economic reasons to be able to use alkali-reactive aggregates together with the regionally available cements and additions in the production of concretes that can be relied on not to suffer a harmful ASR. To that end, a performance test method is being developed that allows to quickly test regular concrete compositions for a potential harmful ASR. The 60 °C method mentioned above is already being applied for this purpose in France. The Research Institute has been testing different concrete compositions containing the aggregates known to be alkali-reactive in Germany as part of a project sponsored by the AiF. The results will be compared to the observations made over many years on different structural elements and on samples stored on the roof of the FIZ building under practical conditions. Initial results suggest that this method can at least be applied for dense aggregates.

Durability

Concrete structures must possess adequate durability, i.e. high resistance to environmental impacts, throughout their service life. In addition to the resistance to attack by freeze-thaw and freeze-thaw with de-icing salt, this also implies the resistance to media attacking concrete, such as sulphatic water. The regulations currently in effect specify requirements for constituents (e.g. cement type, type of aggregate) and concrete composition (e.g. water/cement ratio and air content of the fresh concrete) for concretes exposed to aggressive environmental conditions with an impact on durability. These concrete technology specifications are based on many years of experience on normal-strength concretes.
gathered in concrete construction. They ensure that the concretes are highly durable, provided that they have been processed and cured expertly.

**Resistance to freeze-thaw and freeze-thaw with de-icing salt**

When damage is caused by freeze-thaw attack, a distinction is made between external and internal damage. External damage is visible as surface scaling, which consists of small particles or thin layers being detached or flaked off from the concrete surface. De-icing agents usually intensify the damage. Internal damage to the microstructure is defined as progressive destruction of the concrete microstructure deeper inside. The 9% increase in the volume of water when ice is formed generates stresses if the expansion space (in the form of pores) in the microstructure is insufficient. When the stresses generated exceed the tensile strength of the concrete, the microstructure is damaged. This damage is not visible from outside at first, but can, for example, be ascertained by means of ultrasonic transmission time measurement.

Laboratory investigations of concretes without artificially entrained air voids that had been exposed to pure freeze-thaw attacks revealed that a decline in the dynamic modulus of elasticity (= internal damage) can be measured in the case of some concretes although the samples appear to be undamaged from the outside and exhibit only slight surface scaling. The significance that the decline in the dynamic modulus of elasticity of laboratory samples has with regard to the concrete properties to be expected following a freeze-thaw attack has not yet been determined in terms of the durability of the concretes in practical use.

**Freeze-thaw resistance of high-strength concretes**

The research project on the “Freeze-thaw resistance of dense, high-strength concretes” was completed at the Research Institute. The concretes investigated contained 500 kg/m³ cement or cement and silica fume, respectively. The content of silica fume totalled 8 wt.% relative to the cement content. The equivalent water/cement ratio (w/c)eq varied between 0.25 and 0.45. Even after 100 freeze-thaw cycles, the relative dynamic elasticity modulus of all the concretes without silica fume as well as the concretes with silica fume and a (w/c)eq < 0.35 did not decline. These concretes have a high freeze-thaw resistance. By contrast, the concretes containing silica fume and having a (w/c)eq ≥ 0.35 exhibited a significant drop in the relative dynamic modulus of elasticity, which in some cases occurred after only a few freeze-thaw cycles (Fig. V-20).

As described above, damage to the internal microstructure is caused by stresses generated when pore solution freezes as a result of a freeze-thaw attack. The ratio of the pore solution present and the expansion space is defined as the degree of pore filling. According to theory, a concrete will be damaged during one single or at least during few freeze-thaw cycles, if the degree of pore filling reaches a value of about 91%, i.e. the “critical saturation” defined by Fagerlund. Work therefore concentrated on the microstructure and the moisture content of the high-strength concretes. The investigations regarding the significance of the relative dynamic modulus of elasticity as a characteristic variable of damage to the internal microstructure were continued additionally.

**Pore size distribution of the concretes**

The Hg porosity of the mortar matrix of the high-strength concretes as a function of the pore radii was determined by means of mercury intrusion porosimetry. In the investigation, at the age of 28 days the porosity declined in line with a decrease in (w/c)eq as a consequence of the denser microstructure (Fig. V-21). The total Hg porosity and the capillary pore fraction included were lower with the mortars of the concretes containing silica fume than with the comparable mortars of the concretes made without silica fume.

The threshold radius was a further characteristic variable of the concrete microstructure that was derived from the results of pore size distribution (Fig. V-21). The threshold radius describes the pore size starting from which larger quantities of mercury begin to penetrate the micro-
structure. At this point the continuity of the pore structure is disturbed. The transport of liquids through certain pore portions is impaired at that point (“pore blocking effect”). When applied to high-strength concretes, this may mean that the pore solution cannot reach the reserve space required to discharge stresses caused by freeze-thaw attack, or can reach them only in part. As the (w/c) decreases, the limiting radii are generally shifted towards finer pore radii.

The evaluation of the Hg porosity, the gel and capillary pore proportions, respectively, and the limiting radii did not yield any significant discrepancies between the concretes with and without silica fume which would have adequately explained the different behaviour observed when high-strength concretes containing silica fume were exposed to freeze-thaw attack.

**Microstructure properties and freeze-thaw resistance**

The overall porosity of the concretes was determined as water absorption at 15 MPa at the age of 28 days. As expected, it decreased as the equivalent water/cement ratio was lowered. When the (w/c) was identical, the overall porosity of concretes containing silica fume was about 7 to 9% higher than that of concretes without silica fume. At the same time, the natural moisture content of the concretes was determined by drying at 105 °C until constancy of mass was reached. It was generally higher with the concretes containing silica fume than with the concretes without silica fume. For the concretes with (w/c) > 0.35 the difference totalled about 30%, whereas it amounted to about 20% for the concretes with (w/c) < 0.30. The higher natural moisture content of the concretes containing silica fume is presumably attributable to a change in the morphology of the CSH phases caused by the pozzolanic silica fume reaction, which results in more water being combined physically.

In the wake of freeze-thaw testing based on the CIF method, the relative degree of pore filling (RDPF) was calculated as the quotient of the respective total moisture content – i.e. the moisture content after 28 days plus the water absorption during freeze-thaw testing – and total porosity at each testing time. In Fig. V-22 the RDPF is put in relation to the change in the dynamic modulus of elasticity determined at the same time. When the RDPF reached a value of about 90%, a marked decrease in the dynamic modulus of elasticity was observed regardless of the concrete composition. Thus, the damage to the microstructure observed was caused by the “critical saturation” according to Fagerlund being exceeded locally at least.

**Resistance to freeze-thaw with de-icing salt of road paving concrete with CEM II/B-S**

A new research project on the “Resistance to freeze-thaw with de-icing salt of road paving concrete with CEM II/B-S” was commenced at the Research Institute. This project was prompted by damage that had occurred in concrete road paving made from CEM II/B-S 32.5 R as a result of freeze-thaw attack. With the exception of a short section in which different sand had been used, the road pavement was found to have suffered large-surface scaling of the surface mortar and occasional pop-outs after a service life of about one year (one winter period). To determine the cause of the damage, the Research Institute investigated the concrete microstructure of drill cores that had been extracted from the damaged sections of federal highway A4. The results obtained did not explain the scaling observed. For that reason, a research programme aimed at establishing the potential impact that the constituents (cement, aggregate, curing agents) have on the freeze-thaw resistance of road paving concretes is being carried out.

**Laboratory investigations**

The investigations covered concrete compositions typical of road pavings, i.e. with a cement content of 350 kg/m³, a water/cement ratio of 0.43 ± 0.02, and an air void content in the fresh concrete of about 4.5 vol.%. Concrete consistency was adjusted to be nearly identical in all concretes by varying the water content. In addition to ordinary Portland and Portland-slag cement from one manufacturer, two Portland-slag cements with fine and coarse ground granulated blastfurnace slag (GGBS), respectively, were utilised. The aggregates used were Rhénish gravel, high-grade diabase and orthophyre chippings as well as two sands with low (sand A) and high (sand B) water absorption, respectively. The concretes that had suffered damage in practical application had been made using sand B (high water absorption).

The freeze-thaw resistance was examined as scaling using the CDF method according to E DIN EN 12390-9. In addition to the surface concrete onto which a teflon disk in
accordance with the standard, a realistic concrete surface textured by a broom stroke was investigated as well. In conformity with the standard, the specimens were cured in the mould for 1 day, under water for 6 days and in a climatic chamber at 20 °C and 65% r.h. for 21 days. In addition to that, shortened curing (mould for 1 day, at 20 °C and 100% r.h. for 1 day, and in the climatic chamber at 20 °C and 65% r.h. for 26 days) and a curing agent that was sprayed onto the concrete surface textured by a broom stroke in accordance with the manufacturer’s instructions were employed.

Resistance to freeze-thaw with de-icing salt
It was possible to clearly differentiate the sands in terms of their water suction capacity. The water quantities absorbed within 24 hours totalled about 1.5 wt.% for sand A and about 3.5 wt.% for sand B. In compliance with requirements, all the concretes possessed an air void system with a microvoid content > 1.8 vol.% and a spacing factor that ranged significantly below 0.20 mm. The scaling observed in all the concretes cured in accordance with the standard was very slight, irrespective of whether the test surface had been concreted onto a teflon surface or textured by a broom stroke. (Fig. V-23, left-hand side). The cement type or the sand quality were not found to have any impact on the resistance to freeze-thaw with de-icing salt. Scaling of the concretes was slight (Fig. V-23, right-hand side) even when curing had been insufficient (shortened curing).

Road paving concretes have to comply with requirements beyond those specified in DIN EN 197-1. As a consequence, Portland-slag cements with coarser ground granulated blastfurnace slag (GGBS) are frequently applied. Similar to coarsely ground Portland cements, these cements may, under certain circumstances, show a tendency towards higher water secretion and possibly towards heightened curing sensitivity. In practical use, high water secretion is counteracted by higher fineness of certain main cement constituents. Investigations on the resistance to freeze-thaw with de-icing salt of road paving concrete manufactured from laboratory-made Portland-slag cements containing GGBS of different fineness are to reveal to what extent the fineness of GGBS influences the curing sensitivity of such concretes, and thus their resistance to freeze-thaw with de-icing salt. To that purpose, concretes of the above-mentioned composition containing sand B (high water absorption) are produced and tested following the CDF method according to E DIN EN 12390-9. Moreover, the Research Institute is currently preparing a project on the influence and the optimisation of the curing of road paving concrete containing different cements. The project will be executed in cooperation with the Bauhaus university in Weimar.

Sulphate resistance
The question of whether damage to concrete structures caused by thaumasite, which was detected in about 50 concrete structures in England over the past 10 years, might occur in Germany as well was increasingly discussed by the interested parties over the past three years. This damage affected concretes that had been placed in soil containing pyrite. They did not possess adequate sulphate resistance as no sulphate attack had been expected to occur. The soil was aerated intensively when the structures were erected. As a consequence, sulphidic rock oxidised to form sulphate (pyrite oxidation). This resulted in an extraordinary sulphate attack, which in various cases even lowered the pH value of the ground water. The damage observed is thus attributable to a sulphate attack or a combined sulphate-acid attack, respectively, that had not been perceived at the time.

The Research Institute of the Cement Industry gathered the experiences and findings on the topic of “Damage potential due to thaumasite formation”, most of which derive from other countries, and incorporated them into the status report on “Sulphate attack on concrete”, which was issued by the German Committee for Reinforced Concrete (DAfStb) in 2004. To review whether the findings made in England can be transferred to the conditions prevailing in Germany, the DAfStb further compared the soil containing pyrite in Germany and in England. The results are described in the status report as well. Soil containing pyrite that is comparable to that in England does actually exist in Germany (e.g. Poseidon slate). For that reason, the possibility of a sulphate attack caused by pyrite oxidation has to be taken into account in the regions concerned. Since, however, no damage has been reported to date, the concretes in Germany can be assumed to possess adequate resistance in accordance with the specifications of the concrete standard DIN 1045-2. Basically, DIN 4030-1 already deals with hazards to concrete structural elements posed by pyrite in the soil, stipulating separate assessment by an expert, if the sulphide content exceeds 0.01 wt.%. Since almost any soil contains pyrite in this order of magnitude, a working group set up by the DAfStb has called for more precise specifications in DIN 4030-1. The competent standards committee will make the necessary amendments shortly.

Following the occurrences of damage caused by thaumasite, the regulations governing concrete construction in the case of sulphate attack were modified in England three years ago. For example, the utilisation of carbonaceous aggregates and cements was restricted. Against this backdrop, the use of carbonaceous constituents in concrete was discussed in Germany as well. However, there have been only few systematic investigations on the use of carbonaceous aggregates (limestone, dolomite) and carbonaceous cements and cement/fly ash mixes in the case of sulphate attack to date. The laboratory investigations conducted at the Research Institute revealed that thaumasite formation macerating the microstructure may occur at low temperatures, when the concrete contains carbonaceous constituents and was not manufactured in conformity with the standard.
This is illustrated in Figs. V-24 and V-25. Specimens based on Portland cement only displayed marked thaumasite-induced damage when limestone was used to replace quartz as an aggregate. With the specimens based on highly sulphate resisting cements in conformity with the standard, by contrast, no sulphate-induced damage at all – neither in the form of expansive phases, nor in the form of thaumasite formation – was used even when limestone had been used (Fig. V-26).

The sulphate resistance behaviour of Portland-limestone cement/fly ash mixes was investigated at the Research Institute as well (see also Chapter III). The results confirm the DAfStb assumption that the thaumasite formation occasionally observed in laboratory trials ensues from inadequate compaction of the microstructure, i.e. from insufficient physical sulphate resistance. This is due to the high initial porosity, which is caused by a water/cement ratio of 0.60, and the reactivity of fly ash, which is diminished at low ambient temperatures (< 10 °C).

To allow better alignment of the laboratory investigations and the experience gained in practical application, concrete specimens are to undergo tests under practical conditions and laboratory trials more closely geared to practice over the next three years. The Research Institute will perform this work in cooperation with the university of Weimar and the technical university of Munich on behalf of the DAfStb.

**Fair-faced concrete**

Fair-faced concrete has been enjoying newfound popularity in the architectural design of structures. The artificial “rock” concrete, which can be shaped in the mould at will, is extraordinarily suited to simultaneously perform constructive and creative functions. Renowned architects, such as Ieoh Ming Pei, Tadao Ando and Zaha Hadid have taken advantage of the virtually inexhaustible creative potential inherent in the construction material concrete to make their architectural visions come true (Fig. V-27). In this context, the implementation in building practice of the optical appearance of the concrete surface visualised is of paramount importance for the creative objectives of the designing architect or engineer being achieved. In their view, it is no longer the heavily textured concrete surface, but the shape of the structure that is to characterise its appearance. There has been increasing demand for slim, heavily reinforced structural elements of complicated
shapes that display totally even, poreless surfaces of uniform colour and sharp edges without any discernible construction joints. Given the current state of knowledge in the domains of concrete technology, moulding technique and execution technique, it is, however, not always possible to unerringly meet these demands.

**Need for research**

During the concreting process, it is not possible to either check or control whether the concrete surface quality specified has been obtained. The quality of the exposed concrete achieved cannot be evaluated until the concrete has been demoulded and the concrete surface has dried. Discrepancies in coloration, which cannot be safely avoided in spite of expert planning and execution, have repeatedly given cause for complaint. These include local discolouration and pore formation, but also large-surface “cloud formation” and “marbling” caused by the action of release agents, excessive compaction, discolouration of the mould and concrete bleeding at leakages of the mould, which cannot be prevented completely. The personal empirical experience of the people in charge of building execution and the experts assigned the task of concrete design or supervision, respectively, presently plays a larger role in accomplishing a fair-faced concrete surface that meets expectations than corroborated findings. Some fundamental rules for avoiding deficiencies in exposed concrete have been derived from experience so far. They have been included in the new code of practice on fair-faced concrete issued by the German Concrete and Construction Engineering Association (DBV) and the German Concrete Association of the Cement Industry (BDZ), which does, however, not comprise a scientifically founded description of the causes and relationships underlying the phenomena resulting in complaints.

**Joint research on fair-faced concrete**

An investigation programme called “Joint research on fair-faced concrete”, which is sponsored by the Federation of Industrial Cooperative Research Associations (AiF), is conducted under the joint overall responsibility of the German Cement Works Association (VDZ) and the German Concrete and Construction Engineering Association (DBV). This programme comprises a total of 4 research proposals processed by 6 research centres. Tab. V-2 gives an overview of the research centres involved in the “Joint research on fair-faced concrete” and their key research subjects.

### Tab. V-2: Overview of the research centres involved in the “Joint research on fair-faced concrete” and their key research subjects

<table>
<thead>
<tr>
<th>Research centre(s)</th>
<th>Subject</th>
</tr>
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<tbody>
<tr>
<td>1.1 Research Institute of the Cement Industry, Düsseldorf</td>
<td>Influences on the rheological properties and the sedimentation behaviour of fines paste and concrete, with special consideration of compaction by vibration in comparison to self-compaction</td>
</tr>
<tr>
<td>1.2 Institute for building material science and material testing at the technical university of Munich</td>
<td>Transport mechanisms in hardening concrete – transport and crystallisation processes in view of coloration phenomena</td>
</tr>
<tr>
<td>2 Faculty for building material science and material testing at the technical university of Munich</td>
<td>Fair-faced concrete: investigation of the chemico-mineralogical interaction of fresh concrete, formwork shell and separating agent as a basis for new methods of testing in construction practice</td>
</tr>
<tr>
<td>3 Institute for building materials at the university of Hanover</td>
<td>Robust fair-faced concrete compositions and their testing</td>
</tr>
<tr>
<td>4.1 Institute for building and construction at the technical university of Darmstadt</td>
<td>Interaction of formwork shell, release agent and concrete surface</td>
</tr>
<tr>
<td>4.2 Laboratory for building materials and materials testing at the technical college of Cologne</td>
<td></td>
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The three super-plasticisers applied were based on one active ingredient each (melamine sulphonate, naphthalene sulphonate, polycarboxylate ether). The diagramme illustrates the well-known fact that the super-plasticiser based on polycarboxylate ether (PCE) is most effective. An active substance quantity of about 0.2 wt.% relative to the cement suffices to reach the saturation point. With the super-plasticisers based on naphthalene and melamine sulphonate, the maximum plasticising effect was not reached until 0.6 and 0.7 wt.% active substance, respectively, had been added. This is due to the different working mechanisms of the super-plasticisers. In the case of the naphthalene and melamine sulphonate, respectively, which act electrostatically, large quantities of active ingredient are required for the complete charge reversal of the partici-
cle surface. Given the sterical effect, i.e. the sterical repulsion of the side chains, of the polycarboxylate, by contrast, a fairly small quantity of active ingredient suffices for the saturation point to be reached. Utmost diligence must be exercised in metering to obtain adequate sedimentation stability of the mortar, especially when super-plasticisers based on PCE are used.

Proceeding from these findings, sedimentation trials on mortars will be conducted. “Stable” mortars will be employed to investigate the influence of the compaction energy on the sedimentation behaviour. Concrete trials will be performed to check whether the results obtained from the mortars are transferable.

**Self-compacting concrete**

Self-compacting concrete (SCC) is a high-performance concrete the distinctive performance feature of which consists of the fresh-concrete property of “self-compaction”. It possesses vast potential for streamlining both the production of precast concrete elements and the course of construction at building sites. To benefit from these advantages, utmost diligence in the manufacture and quality assurance is indispensable.

The “window solution” for SCC laid down in the DAfStb guidelines allows manufacturers of self-compacting concrete to determine the workability properties of their SCC in fresh and hardened concrete investigations, and to verify them in initial testing. The manufacturer guarantees the “self-compaction” feature and specifies the target values and permissible deviations for the slump flow measure and the V-funnel flow time. The limits of the range must be continually checked by factory production control in regular production since they may change as a result of fluctuations in constituents. If at least one value is not within the range, e.g. when the concrete is handed over before being poured, the concrete is rejected, or appropriate corrective measures have to be initiated (e.g. subsequent metering of super-plasticiser) in order to bring the SCC back into the workability range, i.e. into the limits of the SCC range for which conformity has been verified. To reduce the cost and effort involved in testing when the self-compacting concrete is handed over in the form of ready-mixed concrete at the building site, the flow time may be applied as an alternative to the V-funnel flow time according to Section 5.4.1 of the SCC guidelines, when a definite correlation with the V-funnel flow time was verified in initial testing.

In addition to determining the influences on the properties of fresh and hardened self-compacting concrete, the possibility of modifying a slump cone in such a way as to allow reproducible and adequately accurate flow times to be measured with it was investigated under the terms of a joint research project of the Research Association for Ready-Mixed Concrete (FTB) in Kamp-Lintfort and the Research Institute of the Cement Industry (FIZ). The flow times were varied by extending the length of the slump cone to different outlet cross sections while maintaining the slope of the cone and the concrete volume to be tested. To that effect, an ordinary slump cone was mounted on a supporting stand. A slide provided in the supporting stand allowed the cone to be closed at the bottom end. Different outlet nozzles having diameters of 50, 60, 70 and 80 mm can be arranged at the bottom end of the supporting stand. The stand was adjusted so as to arrange the slump cone 300 mm above the base plate. Fig. V-29 shows the slump cone, the supporting stand for the slump cone, 4 different flow sections and the slide. The mounted flow cone is depicted in Fig. V-30.

Fig. V-29: Constituents of the flow cone: slump funnel cone, supporting stand for the slump cone, discharge nozzles, and slide

Fig. V-30: Determination of the flow time and the slump flow measure with the flow cone
Six self-compacting concretes of different composition were tested to determine the flow times using the flow cone. The combination of constituents and their mutual ratios allowed to cover almost the entire rheological range, from low-viscosity up to high-viscosity self-compacting concrete. After the slump cone had been filled and the slide had been pulled, the time the SCC needs to flow from the cone was measured in analogy to the funnel method according to the DAfStb guidelines. Only the concretes that did not display any relevant decrease in workability during the test cycle were used in evaluation. Thus, the differences in flow times between the various flow cones and the flow time from the funnel are exclusively attributable to the different cross sections.

In Fig. V-31, the flow times from the cones having flow diameters of 80, 70 and 60 mm are plotted against the V-funnel flow time of the concretes investigated. A linear relation between the respective cone flow times and the V-funnel flow time was obtained in all cases, the correlation coefficient exceeding 90%. While the flow times from the flow cones having a diameter of 80 and 70 mm were underproportional to the V-funnel flow time, the flow cone with a 60 mm diameter exhibited a slightly overproportional flow performance. Although the flow cone having a 50 mm diameter also showed a linear relation to the V-funnel flow time of the concretes investigated, it produced very high flow times, which can be regarded as unfavourable in building practice. For that reason, the 50 mm flow diameter was excluded from the further examinations. In addition to that, it has to be taken into account that, with a diameter of 50 mm, the grading curve and the obstruction tendency of the SCC may have an impact on the flow time from the cone.

On the basis of the research results a cone flow section having a diameter of 63.5 mm was calculated, which resulted in a nearly direct correlation with the V-funnel flow time. The flow cone thus constitutes an alternative method for determining the viscosity of self-compacting concretes the application of which is advantageous in acceptance testing at the building site in particular.

Earth-dry concrete

Earth-dry concrete is applied in road construction products, such as paving blocks, slabs, curbstones or concrete pipes. In stationary production facilities of the concrete plants the dry concrete mixes are compacted so thoroughly by intensive vibratory/compressive compaction in rigid steel moulds that the products can be demoulded immediately, retaining their shape due to what is known as green stability (Fig. V-32). If the concrete composition is appropriate, the concretes compacted in this way achieve the working properties required, such as high strength and density as well as adequate durability, for example with regard to stressing caused by freeze-thaw with de-icing salt or chemical attack.

Concrete technology advancement

Experience has shown that fluctuations in the water content and in the properties of the concrete constituents can have the effect that earth-dry concretes cannot be optimally compacted during processing and are therefore not stable in shape or green stable, respectively. In that case, they do not attain the working properties intended. The material composition concretes should have in order to attain the properties required in spite of major mix fluctuations was investigated in a research project sponsored by the Federation of Industrial Cooperative Research Associations “Otto von Guericke” e.V. (AiF) and carried out by the department for materials in the building trade at Kassel university in cooperation with the Research Institute of the Cement Industry.

The investigations show that the density and strength of earth-dry concretes can be improved by choosing particle compositions with a lower sand portion and by adding fines of medium and high fineness. The inter-particulate attraction, which increases continually as a consequence of fineness, requires the use of high-performance superplasticisers or plasticisers, respectively. In this way it becomes possible to achieve
and even enhance optimum packing density and adequate green stability at a low water content (Fig. V-33). In practical use, mixes have to be optimised for each single works since machine-induced processing conditions have to be taken into account. It is indispensable to include durability criteria into the evaluation of optimisation measures, e.g. the substitution of inert fines for cement portions. Too high w/c or (w/c)_r ratios, respectively, and certain fines may impair durability characteristics even though high degrees of strength are attained.

In the wake of the investigations, a testing instrument with dynamic compaction allowing the realistic production of earth-dry concrete specimens was developed, which can be applied in production control as it enables to test green strength in parallel to production.

Brown discoloration

Through the cooperation of representatives from the cement industry and from precast concrete product manufacturers, further progress was made in solving the problem of brown discoloration, which chiefly occurred in road construction products made from earth-dry concrete, in the period under review. The findings made on the complex chemico-mineralogical and physical influences helped to analyse and frequently eliminate the occurrence of discoloration. Solving the problem presupposes an extensive and objective case analysis. The “Brown discoloration” panel in which bilateral industrial talks were held developed a questionnaire and a checklist, respectively, to compile the relevant material and production-induced parameters for each individual case and jointly initiate measures to reduce or eliminate risks, respectively. Awareness of the problem and the willingness to engage in dialogue to find solutions obviously led to the result that brown discoloration was reported only occasionally any more in 2004. Cooperation in the discussion circle will be continued.

Water-permeable block paving surfaces

Demands to pave fairly large surfaces, such as parking lots, in such a way as to allow rain water to seep away have become more and more frequent for environmental reasons. At the same time, pollutants are to be retained to prevent them from entering the subsoil and the groundwater, respectively, together with the rain water seeping away. An expert committee of the German Institute for Building Technology (DIBt) prepared the approval of corresponding water-permeable and pollutant-retaining concrete paving blocks in cooperation with the Research Institute. In this context, the topic of the environmental compatibility of cement-bound products in terms of soil and ground water protection was broached as well. A corresponding connection was established with the DIBt code of practice on evaluating the effects of construction products on soil and groundwater.

Traffic route engineering

Given its central position in Europe and the progressing enlargement of the European Union to the east, the traffic volume, and the volume in goods traffic in particular, will increase heavily in Germany over the next few years. Although the railway network has been expanded, the main share of the goods traffic will have to be absorbed by the road network. In view of the high traffic load and the introduction of Public-Private Partnership Agreements, which transfer responsibility for the construction and maintenance of a road to a contracting company, the question regarding the service life and the maintenance costs of a road design has taken centre-stage. Durable, low-maintenance and thus economically efficient construction methods accompanied by high environmental compatibility are advantageous.

Road construction

The high durability in spite of exposure to most heavy lorry traffic and the low maintenance costs during service life constitute important arguments in favour of building concrete road pavements. The service life of concrete paving usually tops 30 years. A few occurrences of damage have given rise to uncertainty among the interested parties. The investigations carried out by Research Institute showed that a harmful alkali-silica reaction (ASR) could not be ruled out in some cases (see section on alkali-silica reaction). To ensure a high degree of security against a harmful ASR in concrete road pavements prophylactically, VDZ recommended the following measures:

1. Reduction of the effective alkali content of cements for road paving (Tab. V-3),
2. No use of reactive aggregates included in the alkali guidelines,
3. Use of quartz porphyry, greywacke, chippings from the Upper Rhine valley and all imported aggregates only if an expertise is available.

The associations of the aggregate industry and the Quality Community for Traffic Pavements have adopted these recommendations. The Federal Minister issued these regulations in a circular in early 2005. The list of aggregates that may only be used upon presentation of an expertise was extended to include recycled aggregates.

The Research Association for Roads and Traffic (FGSV) set up a new working group to investigate and discuss the occurrences of damage mentioned as well as further durability aspects of concrete paving. Durability does not only imply the prevention of a harmful ASR, but also the diligent production and curing of concrete. The working group also discussed the use of CEM II cements in road construction. These cements are approved for road construction, but have been applied only very rarely so far. An ad-hoc group of VDZ’s Transport engineering working group is currently compiling a summary of the experience.
gained with CEM II and CEM III cements in road construction which will also incorporate the Research Institute’s investigations on the resistance to freeze-thaw with de-icing salt of road paving concretes made from different Portland-slag cements (see section on durability). According to the recommendations, cements containing blastfurnace slag should be characterised by higher grinding fineness than the CEM II/B-S 32.5 R cements applied previously, and should be utilised as CEM II/B-S cements of strength class 42.5 N in the future. The higher grinding fineness and the faster strength development diminish the water segregation tendency and reduce any potential curing sensitivity.

Regulations
The introduction of the European standards in particular has made it necessary to adapt the regulations applicable in road engineering. The laying of sub-base courses using hydraulic binders, which was previously regulated by the supplementary technical terms of contract and guidelines for sub-bases in road construction (ZTVT-StB), and the construction of road pavements, which was previously regulated by the supplementary technical terms of contract and guidelines for concrete in road construction (ZTV Beton StB), will now be subject to several European standards that have been published. These will have to be transposed into corresponding national regulations and introduced in building practice. In conjunction with the revision of the existing regulations, the regulations for all courses containing hydraulic binders are to be combined in a set of provisions that will cover hydraulically bound sub-base courses in addition to concrete pavements in the future. The future regulations, in the elaboration of which FIZ is involved, will be subdivided into three parts:

- Technical terms of delivery for concrete in road construction (TL Beton StB) to regulate the delivery of building materials and building material mixes
- Supplementary technical terms of contract and guidelines for concrete in road construction (ZTV Beton-StB) to regulate production and
- Technical terms of testing for concrete in road construction (TP Beton-StB) containing technical testing provisions for all tests conducted on building materials, building material mixes and on the finished work.

New construction methods
The “Silent traffic” research programme (sponsored by the Federal Ministry for Education and Research, coordinated by the Federal Highway Research Institute BASfT), in which the Research Institute was involved, consisted of optimising novel, open-pore draining concretes in laboratory trials and testing them in a practical trial. A test section with a length of about 300 m was laid out on a national road in September 2002. The draining concrete layer, which was about 8 cm thick, was placed both on an asphalt and a concrete sub-base. The pavement has been exposed to traffic for three winters. Noise measurements carried out by BASfT have demonstrated that it is acoustically equivalent to open-pore drainage asphalt. The “Silent traffic” programme was completed in 2004. Consultations on its continuation are currently being held.

The standard construction method previously applied in Germany has been an unreinforced concrete pavement with dowelled transversal dummy joints arranged at a 5-metre distance. In neighbouring countries, by contrast, the construction of continuously reinforced concrete pavements with unrestrained crack formation has gained increasing acceptance. The reinforcement results in the formation of numerous, finely distributed cracks in the concrete; as a consequence, the customary cutting of transversal joints can be dispensed with. The costs for the production and dowelling of the joints and the expenses for joint maintenance during service life no longer accrue. As damage chiefly occurred as a consequence of poorly maintained, permeable joints in some cases, experts expect the new construction method to entail improved durability. To gather experiences with the continuously reinforced concrete paving in Germany as well, a test section was laid out on Federal Highway A5 in late 2004 (Fig. V-34). VDZ’s „Transport engineering“ working group attends the developments and experiences.

Permanent way – ballastless track
The high demands made by Deutsche Bahn AG (German rail) on the positional stability of the rails requires the installation of a ballastless track. Various systems were applied in the new railway track from Cologne to Frankfurt taken into operation in 2002. The Rheda system consists of accurately levelling the sleepers into a prefabricated concrete trough and binding them monolithically in the trough with a joint filling concrete. With the “Züblin”

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Tab. V-3: VDZ recommendations for the alkali content given as Na₂O equivalent (characteristic value) of cements used in the construction of concrete road pavements in the road engineering sector

<table>
<thead>
<tr>
<th>Cement</th>
<th>Blastfurnace slag content</th>
<th>Alkali content of the cement Na₂O equivalent</th>
<th>Alkali content of the cement without blastfurnace slag or oilshale Na₂O equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I</td>
<td></td>
<td>≤ 0.80</td>
<td>-</td>
</tr>
<tr>
<td>CEM II/A</td>
<td></td>
<td>-</td>
<td>≤ 0.90</td>
</tr>
<tr>
<td>CEM II/B-T</td>
<td>21 to 29</td>
<td>-</td>
<td>≤ 0.90</td>
</tr>
<tr>
<td>CEM II/B-S</td>
<td>30 to 35</td>
<td>-</td>
<td>≤ 1.00</td>
</tr>
<tr>
<td>CEM III/A</td>
<td>36 to 50</td>
<td>-</td>
<td>≤ 1.05</td>
</tr>
</tbody>
</table>

Fig. V-34: Test section for continuously reinforced concrete paving on Federal Highway A5
design, the concrete sleepers are vibrated into the fresh concrete. In the new section from Nuremberg to Ingolstadt, the Bögl design was executed on larger track sections (about 35 km) for the first time. The system consists of concrete slabs manufactured in precasting works, which are placed onto a hydraulically bound sub-base at the installation site (Fig. V-35). Each slab is provided with a total of 10 pairs of supporting points (sleepers) for rail fixation. After accurately levelling the slabs by means of screwable devices, the gap between the sub-base course and the slab is grouted with a mortar modified by bitumen. After underpouring, the precast slabs are connected to each other lengthwise by means of turnbuckles, and the transversal joints are grouted with concrete, thus generating a continuous pavement. The advantages inherent in this construction method are its high positional accuracy due to prefabrication and tight fitting of the slabs as well as the possibility of replacing individual slabs in case of damage. The varied development work is attended by VDZ’s “Transport engineering” working group.

**Fire protection**

Residential buildings and buildings in which humans linger have to be constructed in such a way as to protect humans and their possessions as well as the buildings from the effects of fire. Concrete makes a major contribution to implementing the necessary protective functions. Concrete does not burn. As a consequence, no smoke is generated and no poisonous gases are released. Moreover, concrete structural elements withstand fire for a fairly long time.

These fire protection properties can be taken advantage of effectively to impede the spreading of the flames in case of fire and to maintain the load-bearing capacity of the design and thus preserve the building. This benefit serves the protection of people as it allows them to save themselves or be safely rescued by the fire brigade in the case of fire. It further serves property protection since the fire brigade gets the possibility of effectively fighting the fire inside the building, which experience has shown to reduce the impact of the fire. In the case of concrete components possessing high fire resistance, the individual elements get through the fire largely unscathed. Thus, the building can still be used afterwards.

**Fire protection activities in the industrial sector**

The “Fire resistance” joint working group under the direction of VDZ, which pools the activities of the concrete and precast concrete element industry, the German Concrete and Construction Engineering Association, the aerated concrete industry and the cement industry, listed the protective functions performed by concrete buildings in the case of fire that ensure

- the protection of people,
- the protection of property for the individual building and adjacent buildings, and
- environmental protection in the case of fire.

This catalogue is available to consultants, building owners and users for information.

The working group members further contributed to concrete being graded as a class A1 construction material, i.e. a material that is absolutely non-combustible without requiring verification, in the classification of construction materials in terms of their fire protection properties, which will be applicable throughout Europe in the future (Fig. V-36, left-hand side). The status applicable in Germany was thus laid down at European level as well.

To classify structural elements in terms of their fire protection properties, the existing design standard DIN 4102 Part 4 was adapted to the future European provisions of Eurocode 1992-1-2 (Fig. V-36, right-hand side). The concrete and cement industries were involved in this work. On the basis of the adapted regulations, dimensioning of structural elements with regard to fire resistance can be carried out according to the proven principle of DIN 4102-4. Design rules of general applicability have been added for structural elements made from high-strength concrete and for the domains of concrete masonry, porous lightweight concrete, and reinforced aerated concrete.

If the load-bearing capacity of concrete structures is to be measured on the basis of partial safety factors in application of the future European concept according to Eurocode 2, fire protection design can still be performed in accordance with DIN 4102-4 since a national application standard was established which ensures that the design for the normal state (cold-state design) applicable in Europe in the future and the familiar design for the case of fire (hot-state design) according to DIN 4102-4 can be
combined in a manner geared to practical requirements in concrete construction.

Given this development in the field of fire protection standards, practical users will be able to refer to proven tabular provisions, for example regarding minimum density, minimum width and the arrangement of reinforcements in concrete structural elements, in the fire protection of concrete buildings for the next 8 to 10 years.

European activities

Under the direction of CEMBUREAU, task force 2.2 “Fire safety with concrete” has been working on fire protection issues of overriding importance for the European countries. The task force is a panel set up by the European associations of the precast concrete element (IBBM), ready-mixed concrete (ERMC) and cement (CEMBUREAU) industries. It became apparent during the project, which has been underway for 4 years, that the topics of constructional fire protection relating to concrete engineering are nearly the same in the different European countries. On the one hand, technical marketing has to be applied to draw attention to the high importance concrete components have for comprehensive constructional fire protection, and on the other hand the position of concrete construction in the composition and implementation of the European fire protection provisions has to be argued appropriately and expertly.

As a result of cooperation and agreement within the task force, it was possible to downgrade the heat penetration coefficients for concrete exposed to fire, which had been set too high without justification. Fire resistance time is determined by the heating of concrete cross sections as a function of time. The faster heating takes place, the lower fire resistance is. Road tunnels are of major importance in several European countries. An argumentation paper that highlights the advantages of concrete road paving in the case of fires erupting in tunnels was compiled.

The work of the CEMBUREAU task force is to be finished in 2005 with the compilation of a leaflet on fire protection with concrete, which is to furnish fundamental information for practical use.

Modelling

The prediction of the properties of cement and of concrete in particular enables users to make a quick, target-oriented selection of raw materials, and especially of the cement to be used in the respective concretes. To that effect, a growing number of mathematical models that allow to assess the performance of cements on the basis of their chemical composition has been developed. The extension of these models to include the evaluation of concrete properties presupposes that the properties of the other constituents can be described with adequate precision as well.

Simulation of cement hydration

The prerequisite for simulating cement hydration by calculation is an adequately accurate hydration model. Assumptions and simplifications must be made to allow such a model to be converted to a mathematical simulation model. This implies examinations regarding the development with time and the spatial change of the microstructure. Preconditions for this are the correct choice of initial material parameters and an adequately discretised mathematical simulation of the chemico-mineralogical interactions. This includes the experimental determination of material parameters, such as reactivity and density.

Simple models for simulating cement hydration are not up to representing the complex chemico-mineralogical processes. Only due to advances in the field of software and hardware has it been possible for a couple of years to master correspondingly complex mathematical models for the construction material cement by means of calculation. Computer-aided models are used to simulate cement hydration and microstructure development, which in turn serve as the basis for predicting mortar and concrete properties.

Fundamental modelling work in the field of cement properties was performed at the National Institute of Standards and Technology (NIST) in the U.S. The German Cement Works Association is presently the only German partner involved in the current work performed by an international consortium, which consists of developing a so called Virtual Cement and Concrete Testing Laboratory (VCCTL).

Modelling of cement hydration

NIST has performed basic work on modelling cement hydration with the help of “cellular automata” since the early 90ies. The latter consist of a three-dimensional model to describe the development of the hydrate phases and the hardened cement paste microstructure in a cuboid having an edge length of 100 μm. To that end, the cuboid is subdivided into elemental cells having an edge length of 1 μm, which are referred to as “voxels”. This cuboid is first filled with cement particles, the particle size distribution and phase distribution of which are taken into consideration, and with water. In addition to hydration reactions, the chemical reactions taking place in the model comprise the processes involved in the dissolution and nucleation of the solids. They result in a gradual change in the material composition of the solids and the pore solution as well as the microstructure, during which storage conditions can be taken into account as well. In each iterative step, cement particles (voxels) that are in contact with the water of the capillary pore space disengage and move through the pore space. If they meet suitable reaction partners, they can react to form new phases. The partially hydrated hardened cement paste thus essentially consists of 4 phases: cement that is not converted, capillary pore water, CSH gel and calcium hydroxide. The volume percent of the individual phases is analysed to allow the pore structure to be calculated. Evaluations of the progress of hydration relate to the physical properties of the microstructure (strength development, porosity, transport properties, cross-linking density of the reaction products), the spatial chemical composition, chemical shrinkage and temperature development.

This cellular model further allows to examine blastfurnace slag, limestone, fly ash and silica fume, for which reactivity parameters determined by their mineralogical and chemical composition are introduced. According to Powers, the compressive strength of the respective cements is derived from the degree of hydration calculated. Finite-element methods, which refer to the modulus of elasticity of the individual phases, will be employed to that purpose in the future.

Calculations using the NIST model are based on a network of hydration reactions of different scope and varying complexity. The model first requires a complete characterisation of the cement as an input parameter to perform the calculation. To calibrate and validate the model, mathematical simulation is accompanied by experimental investigations of the cements selected. They substantially relate to investigations of hydration and strength development. Fig. V-37 shows schematically how a simulation calculation is carried out.

The modelling of cement hydration based on the NIST model offers the possibility to use calculation to contribute to solving questions of practical relevance about the
The performance of cement and concrete. The effects that changes in clinker composition caused by deviations, e.g. in the control of the rotary cement kiln or in the particle size distributions of the main cement constituents, have on the strength development of the cements can be predicted immediately.

The Research Institute of the Cement Industry is currently concerned with the modelling of cement hydration, pursuing the overarching target to predict the 28-day standard compressive strength of cements already after a short time. In the long run, mathematical modelling is to allow the cost-effective and real-time determination by calculation of the properties of cements as well as the mortars and concretes to be made from them.

It is perfectly conceivable that high-performance models of cement hydration will become firmly established in the standard testing of cements in the future, enabling fully automated online production of cement with integrated quality assurance. The results could be applied directly in production control and concrete manufacture. Moreover, virtual testing opens up the possibility of investigating a large number of parameters in order to develop new materials and optimise existing ones without expending too much effort.

Fig. V-38 shows the steps by which the initial structure of the mathematical element is modelled. The further mathematical simulation of cement hydration proceeds from the basis of this element. The statistical evaluation of clinker phases and gypsum as well as the additional main constituents permits experimental data and numerical evaluation to be compared and controlled, respectively, before simulation calculation is begun.
Simulation results

By way of example, Fig. V-39 shows the microstructure development of a hardened cement paste made from a Portland cement CEM I with a water/cement ratio of 0.50 at selected points of time. The particle size distribution of the cement is taken into account in the original situation (t = 0). The individual clinker phases were determined in terms of quantity and assigned to the individual grain size fractions upon evaluation of the clinker by image analysis. The hydration process clearly shows the dissolution of the cement particles and the increasing formation of a microstructure.

The results yielded by simulation calculation include the degree of hydration and the development of the volume percent of the hydrate products and the decomposition of the individual cement clinker phases, respectively. By way of example, Fig. V-40 shows the development with time of the degree of hydration and the porosity as well as the volume percent of CSH, CH, gypsum and ettringite as a function of the number of calculation cycles. Empirical relationships which include the alkali content allow hydration in relation to time to be represented as a function of the calculation cycles. In addition to that, the mathematical simulation of cement hydration furnishes results on how the pH value of the pore solution and the heat of hydration develop with time.
Determination of compressive strength by calculation

The parameter that is of vital importance for the compressive strength of the hardened cement paste is chiefly the capillary porosity, which substantially depends on the degree of hydration and can be determined empirically by applying various models. To calculate strength, the equation according to Powers, which puts capillary porosity in relation to the volume of the hydration products, can be input in the NIST model first. It proceeds from the assumption of a basic strength, which is diminished by porosity and corresponds to the strength of a microstructure devoid of pores. It is thus irrelevant to the strength of the hardened cement paste whether capillary porosity is based on a higher portion of unhydrated cement, i.e. a decreased degree of hydration, or on a lower capillary porosity of the hydrated cement. It is thus not possible to transfer hardened cement paste strength to standard compressive strength without some restrictions. Influences of aggregates and reactivity as a function of the water/cement ratio, the particle shape and distribution of additives and fines have to be taken into account additionally. The NIST model permits to consider the reaction potential for the formation of compact grained reaction products, surface reactions and the porosity of the matrix. The model allows to incorporate grading influences of the inert and reactive substances into the calculation. The influence of sand has not yet been implemented at present. Porosity changes in the contact zone as a function of the hydrate products generated can be implemented mathematically. The deformation properties of the hardened cement paste in relation to the stiffness of the hydrated and unhydrated portions are determined by means of finite element calculations. In this way it becomes possible to determine the modulus of elasticity of the hardened cement paste and to predict its dependence on other cement properties. A research project aims at finding out to what extent these results can be transferred to standard compressive strength. By way of example, Fig. V-41 shows the mathematically determined compressive strength of a hardened cement paste as a function of age. The compressive strength for cement mortar determined experimentally is bound to deviate due to the proportions of aggregates. It is, however, possible to calibrate the curves, and thus also to make predictions about the standard compressive strength of cements.

Standardisation

The new concrete standards DIN EN 206-1 and DIN 1045 were adopted by the building supervisory authorities in August 2002. An A1 amendment to DIN 1045-2 was elaborated in order to bring the set of standards up to date in technical and formal respect by the time the transition period expired on December 31, 2004. This amendment of the standard became necessary to allow the following items to be taken into account:

- Inclusion of the allowance concept for fly ash in combination with CEM II-M cements
- Changes resulting from the new national or European product standards for cement, concrete admixtures and aggregates
- Incorporation of the corrigenda to DIN 1045-2

In addition to that, the new concrete standards were found not to cover the particular features of massive concrete components. These items are dealt with in guidelines by the German Committee for Reinforced Concrete (DAfStb), which were established in parallel with the A1 amendment in the course of 2004. Employees of the Research Institute were intensely involved in elaborating the amendment to the standard and the guidelines.

Application rules for cement

The A1 amendment regulates the application of the following cements:

- Low heat common cement according to DIN EN 197-1/A1 (LH cement)
- Low early strength blastfurnace cement according to DIN EN 197-4 (CEM III/L)
- Very low heat special cement according to DIN EN 14216 (VLH)
- Special common cement according to DIN 1164-10 (highly sulphate resisting (HS) and low-alkali (NA) cement)
- Cement with short setting time according to DIN 1164-11 (early-setting (FE) and fast-setting (SE) cement)
- Cement with a higher quantity of organic constituents according to DIN 1164-12 (HO)

The A1 amendment introduced the following regulations governing the application of cements according to these standards: VLH cements of CEM III/B composition may be applied like CEM III/C cements. CEM I and CEM II cements can be employed as SE cements (shotcrete cements). All the other cements of the above-mentioned standards are subject to the application rules laid down in DIN 1045-2.

Application rules for fly ash

The previous regulations governing the application of fly ash and silica fume as concrete additions laid down in the fly ash guidelines and the national technical approvals for silica fume were adopted in the new concrete standard DIN 1045-2. They are restricted to some of the cements already included in the former DIN 1164. These regulations had to be revised now in order to ensure equal treatment of the “new” cements according to DIN EN 197-1 which some cement works produce (see also section on “Portland-composite cements”). Fly ash can be set off against the water/cement ratio as a concrete addition with an assumed cement-equivalent effect of 40% (k = 0.40). The quantity to be set off must not exceed 33% of the cement content (f/c = 0.33). The above-mentioned regu-
lation was adopted for some CEM II-M cements not containing pozzolana. With CEM II-M cements containing up to 20 wt.% pozzolana, the maximum quantity of an additional fly ash input must not exceed 25% of the cement content (f/c = 0.25). The use of the k-value concept is excluded for CEM II/A-V and CEM II/ A-M (P-V) cements used in concrete of exposure class XF 3 (freeze-thaw attack with high water saturation). The previous regulation, according to which the k-value concept must not be used in case of freeze-thaw attack with de-icing salt (exposure classes XF2, XF4) continues to apply. Tab. V-5 gives an overview of the new regulations and shows the cements for which the possibility of fly ash allowance was newly introduced. Corresponding provisions were adopted to ensure the alkalinity reserve of the pore solution when fly ash and silica fume are utilised. This is why addition of fly ash is limited to f/c < 0.15 for cements containing silica fume (e.g. CEM II/A-M (D-LL), CEM II/B-M (S-D)). With CEM II/A-M (S-T, S-LL, T-LL) cements, the maximum quantity of fly ash permissible is limited to f/c < (0.15 – s/c) · 3 when a combination of fly ash and silica fume is used. For all the other cements listed in Tab. V-5, the combined use of fly ash and silica fume is not permitted.

CEM II-M cements for concretes with high sulphate resistance

Just like the application rules for fly ash, the “fly ash regulation” for concretes with high sulphate resistance had to be supplemented by “new” cements. In case of sulphate contents of $SO_2 > 1500$ mg/l of the attacking water, it is possible now to use mixes of cement and 20% fly ash with fly ash cement CEM II/A-V, Portland-composite cement CEM II/A-M with the main constituents S, V, T, LL or CEM II/B-M (S-T) in the production of highly sulphate resisting concrete.

Aggregates

Since June 1, 2004, the properties of aggregates for normal weight concrete have been regulated by DIN EN 12620 (aggregates for concrete) in combination with the national application standard DIN V 20000-103. The properties of lightweight aggregates are laid down in DIN EN 13055-1. The associated application standard is DIN V 20000-104. For that reason, the corresponding standard references, which had previously been geared to the set of standards of DIN 4226, had to be adapted. Apart from that, no fundamental technical modifications were necessary. The requirement for the resistance of aggregates to wear was cancelled from DIN 1045-2 as compliance cannot be verified, and as it is primarily the hardened cement paste that is exposed to abrasive stress.

Concrete admixtures

In analogy to aggregates, a harmonised European product standard was completed also for concrete admixtures – DIN EN 934-2. To be applied in the domains of building inspectorate relevance, concrete admixtures previously required national technical approvals issued by the German Institute for Building Technology (DIBt). Since May 1, 2003 all admixtures within the scope of the harmonised European standard EN 934 have had to be labelled with the CE marking and had to comply with the requirement this implies. The specifications regarding certain applications which had previously been laid down in the guiding principles for approval and conformity evaluation issued by the DIBt, and the verification of harmlessness in terms of a corrosion-inducing effect on the embedded steel and the tendons, respectively, were included in the standards DIN V 18998 “Assessment of the corrosion behaviour of admixtures” and DIN V 20000-100. Admixtures for grouting mortar used with tendons are covered by DIN EN 934-4 in combination with DIN V 20000-101.

DAfStb guidelines

DAfStb guidelines are compiled in cases when, for example, the European standardisation process does not materialise, or when rapid implementation of research results in practical use is desired. Employees of the Research Institute were again intensely involved in the work on a large variety of DAfStb guidelines during this period under review.

Work on the following guidelines was completed in the period under review:

- Massive structural concrete elements
- Self-compacting concrete
- Concrete with recycled aggregates
- Water-impermeable concrete structures
- Concrete construction in the domain of water-polluting substances

**Massive structural concrete elements**

The guidelines apply to massive structural elements made of concrete, reinforced concrete and prestressed concrete in which the heat-up caused by hydration is higher due to their large dimensions. The regulations apply to structural elements the shortest component dimension of which totals at least 0.80 m and in which restraint and internal stress have to be taken into account to a particular extent. In footnote b to Table F. 2.1, DIN 1045-2 already comprised the possibility of lowering the minimum cement content by 20 kg/m², i.e. from 320

<table>
<thead>
<tr>
<th>Portland-composite cement</th>
<th>Allowance</th>
<th>Max. fly ash quantity that can be set off f/c</th>
<th>Max. silica fume content s/c</th>
<th>No allowance for exposure classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM II/A-M (S-T, S-LL, T-LL)</td>
<td>x</td>
<td>x</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>CEM II/B-M (S-T)</td>
<td>-</td>
<td>-</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>CEM II/A-M (S-D, D-T, D-P, D-V, D-LL)</td>
<td>x</td>
<td>x</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>CEM II/A-M (S-D, D-T)</td>
<td>-</td>
<td>-</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>CEM II/A-M (S-P, P-T, P-LL)</td>
<td>x</td>
<td>x</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>CEM II/A-M (S-V, V-T, V-LL)</td>
<td>x</td>
<td>x</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>CEM II/A-P</td>
<td>x</td>
<td>x</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>CEM II/A-V, CEM II/A-M (P-V)</td>
<td>x</td>
<td>x</td>
<td>0.25</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Tab. V-5: Extension of the application rules for fly ash and silica fume according to DIN 1045-2/A1
to 300 kg/m³, for massive structural elements with minimum dimensions of 80 cm in exposure classes XD/S 2 and XD/S 3. A reduction in the cement content is aimed at lowering the heat of hydration and the associated restraint and internal stresses. The guidelines now permit the reduction of the minimum cement content from 320 to 300 kg/m³ also for exposure classes XF2, XF3, XF4 and XA2. The reduction of the cement content in the different exposure classes in order to minimise heat of hydration was regarded as uncritical with massive structural elements under durability aspects, but it contributes sizeably to reducing a rise in temperature.

The same scenario prompted the reduction of the minimum cement content from 270 to 240 kg/m³ in exposure class XA1 when additions are allowed for. Finally, an increase in the maximum permissible w/c ratio from 0.45 to 0.50 for XS3 and XD3 and the associated change in the minimum compressive strength class was considered necessary in order to ensure adequate workability of mass concrete without having to add disproportionate quantities of concrete admixtures. The increase in the capillary pore portion in the hardened cement paste and the lower chloride penetration resistance resulting from it, which ensued from the change in the maximum permissible w/c ratio, had to be compensated for, however. This is to be achieved by restricting this regulation to concretes made from CEM II/B-V, CEM III/A, CEM III/B or combinations of cement and fly ash as a concrete addition. Provided that curing is adequate, these cements and cement/addition combinations are assumed to contribute to enhancing the resistance to chloride penetration.

Self-compacting concrete

The DAfStb guidelines on “Self-compacting concrete (SCC)” published in the spring of 2002 was adapted to the new standards. The revised version of the guidelines on “Self-compacting concrete” consists of three parts and was issued in November 2003. The guidelines comprise amendments and supplements to the new standards that relate to dimensioning and design, concrete and building execution.

The previous experiences gained in the approval procedures left their mark on the revision of the guidelines. Furthermore, additional detailed quality assurance measures were incorporated. These include the “window solution” for SCC developed by the Research Institute in particular. It allows manufacturers of self-compacting concrete to determine the workability characteristics of their SCC by investigating the fresh and hardened concrete, and to verify them in initial testing. The manufacturers guarantee the “self-compaction” feature and specify target values and permissible deviations for the slump flow measure and the funnel flow time. The limits of the range must be continually checked in regular production by factory production control as an additional quality assurance measure.

By inclusion into the Building Regulations List, the guidelines published in the spring of 2004 were adopted by the building supervisory authorities.

Concrete with recycled aggregates

The DAfStb guidelines “Concrete containing recycled aggregates” are now available with comments included in the version issued in December 2004.

The present Part 1 of the guidelines limits the share of recycled aggregates in the overall aggregate volume of the concrete. This share depends on the composition of the recycled aggregates, i.e. the type delivered. Part 1 of the guidelines regulates the use of aggregate types 1 and 2 according to DIN 4226-100. Type 1 covers gravel and sand from pure crushed concrete. The recycled aggregates of Type 2 may contain up to 30 wt.% non-porous bricks and sand lime bricks in addition to crushed concrete and natural aggregates. Depending on the area of application, the proportions > 2 mm permissible in the concrete are limited to a maximum of 45 vol.% for Type 1 and 35 vol.% for Type 2. Recycled aggregates < 2 mm must not be used. Dimensioning is carried out analogous to the design of normal weight concrete according to DIN 1045-1.

The further work of the DAfStb subcommittee “Concrete with recycled aggregates” is now focused on the second part of the guidelines, in which the share of recycled aggregates > 2 mm may total up to 100%. The use of recycled aggregates < 2 mm is to be excluded in this case as well. A new design concept will be elaborated for the changed concrete properties.

Water-impermeable concrete structures

The use of water-impermeable concrete was regulated by new DAfStb guidelines, which closed a gap in the regulations on the water-proofing of buildings according to DIN 18195 that often turned out to be a competitive disadvantage for concrete construction. The “Water-impermeable concrete structures” guidelines regulate requirements for the fitness for purpose of those structures for which no provisions existed before. They are applicable to structural concrete elements that are fully or partly embedded in the soil and for which concrete assumes both load-bearing and sealing functions. As expensive and time-consuming external sealing measures can be dispensed with, building with water-impermeable concrete is a very cost-effective mode of construction when the groundwater table is high.

Consultants have the task to determine the corresponding exposure and utilisation classes. The exposure classes distinguish between the various ways in which a structure or structural element is exposed to moisture or water. Exposure class 1 applies to structural elements in contact with pressing and non-pressing water. Capillary
water and non-accumulating seepage water are subject to exposure class 2. The properties of the subsoil and the design water level must be taken into consideration for specification.

The term of “utilisation class” was newly introduced. Classes need to be specified in relation to the function of a structure and the service requirements to be met by a structure. Transport of moisture in liquid form is not permissible for structures or structural elements of utilisation class A, i.e. moist spots on the surface of structural elements caused by water passage must be ruled out. Limited water passage is allowed in utilisation class B. Consultants have the task to correctly implement the building owner’s specifications for the planned use of the rooms and to point out to the building owner any measures regarding the atmospheric environment that may possibly be necessary. Explanatory notes supplementing the WU guidelines will presumably be published in early 2005.

Concrete structures in contact with water-polluting substances
The DAfStb guidelines “Concrete structures in contact with water-polluting substances” have been effective for building structures since 1996 in order to protect the soil and the groundwater from water-polluting substances. The experience gathered during the erection and operation of plants corroborates the assumptions made in the guidelines. The guidelines have proven their worth since they first appeared in September 1996.

The guidelines, which comprise six parts, were adapted to the new generation of standards in the period under review. The practical experience gathered over the years found its way into the revision of the guidelines. Parts 1, 3 and 6 of the 1996 issue of the guidelines were revised and integrated in Part 1 of the new guidelines. In addition to the impermeability verification it comprised previously, Part 1 now also includes a simplified selection procedure specified as construction method 6 in the TRwS 132 (Technical Rules on Water-Polluting Substances). The safety parameters for this method, which is on the safe side, can be chosen depending on the inspection interval.

Parts 2 and 4 of the 1996 issue of the guidelines were revised under the direction of the Research Institute. Part 2 of the guidelines in particular, which deals with construction materials and exposure to water-polluting substances, was not only adapted to the new generation of standards, but also revised in terms of concept. For instance, the rules relating to the use of liquid-proof concrete after penetration test (FDE concrete) were simplified. The concretes with water/cement ratios w/c < 0.45 and strength classes > C50/60 previously classified as FDE concretes were assigned to the range of liquid-proof concrete (FD concrete) without penetration test. By reducing testing liquids from 4 to 2, the effort involved in testing was diminished. The regulation on the expansion of design penetration depths in case of low moisture contents was simplified and adapted to the concept of the exposure classes according to DIN EN 206-1. For exposure class XC1, “dry”, a 50% increase in the design values of the penetration depths has to be taken into account. The old Part 4 of the guidelines, which covers the test methods, was incorporated in an Annex A.