Ground Granulated Blast Furnace Slag (GGBS) as a concrete additive
- Current situation and scenarios for its use in Germany -

23.03.2007

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1 Introduction

On the basis of the mandate from the EU Commission there is currently a harmonised European standard for ground granulated blast furnace slag (abbreviated to GGBS) as a concrete additive (DIN05, DIN05-1, prE 05, prE 05-1).

The draft standard was subdivided into two parts according to the standards or draft standards for fly ash and silica dust, which are aligned with the structure of the cement standard.

- Part 1: Composition, requirements and conformity criteria
- Part 2: Conformity evaluation

With the finalisation of the standard taking place during the course of 2006, the standard can be expected to come into force at the beginning of 2007.

The regulations for the use of GGBS that are defined as per DIN 15167 are to be established at National level.

The production and use of cement that contains GBS has a long history in Germany. In 2004, cement that contains GBS accounted for around 25% of the domestic sales of German cement manufacturers. Currently there is use of GGBS in Germany in the sector that is not subject to building inspection at the plants of one concrete roof tile producer and one concrete materials manufacturer. In a few European countries, for example in Great Britain, GGBS is on the other hand also used in building and in civil engineering work as a concrete additive. This current situation report should, in addition to the documented experience with GGBS as a concrete additive, also present the necessary requirements for research as well as meaningful concepts for application regulations. The discussions on the derivation and definition of application regulations should take into account both the level of knowledge in the use of granulated blast furnace slag for cement production in Germany and its use as a concrete additive. On the other hand, consideration should be given to the technical regulation background of other already established concrete additives used in the building trade in Germany.
2 Situation in relation to the use of granulated blast furnace slag (GBS) in Germany

2.1 Cements that contain GBS

In 2004 in Germany there was a production of 7.45 million tons of blast furnace and 6.22 million tons of steel works ash. Some 70% of the blast furnace slag was subjected to granulation to obtain GBS, which was almost exclusively utilized for the production of cement containing blast furnace slag with a GBS content of up to 95%. In 2004, 5.1 million tons of blast furnace slag was used as GBS in cement production [Feh05].

After Emil Langen had discovered the latent hydraulic characteristics of vitreous solidified blast furnace slag in the years 1861/62, GBS rapidly became popular as a component of cement. The production and use of cement that contains blast furnace slag has a long and successful history in Germany. Portland blast furnace cements (earlier called: Iron Portland cements) and blast furnace cements have been in industrial production for more than 100 years and have been subject to standards for almost 100 years [Web98]. The first German standard for Iron Portland cement with a GBS content <30% was introduced in 1909 and the first standard for blast furnace cement with a GBS content of <85% came into force in 1917. There are 9 cements containing GBS mentioned in the new European cement standard, which can contain between 6% and 95% GBS (Table 2.1).

All cements containing granulated blast furnace slag (granulated blast furnace slag) which meet the EN197-1 requirements are permitted for the production of cements that have GBS content.

These requirements are:
Glass content— at least two thirds;
Total CaO, MgO and SiO$_2$ – at least two thirds;
\[(\text{CaO} + \text{MgO})/(\text{SiO}_2)\] – greater than 1.0.
Table 2.1: Cements containing GBS as per DIN EN 197-1, DIN EN 197-4, DIN 1164 and DIN EN 14216.

<table>
<thead>
<tr>
<th>Cement</th>
<th>Composition (percentage by weight) a</th>
<th>Additional components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Portland-cement-clinker</td>
<td>GBS</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>S</td>
</tr>
<tr>
<td>CEM II/A-S</td>
<td>80-94</td>
<td>6-20</td>
</tr>
<tr>
<td>CEM II/B-S</td>
<td>65-79</td>
<td>21-35</td>
</tr>
<tr>
<td>CEM II/A-M c</td>
<td>80-94</td>
<td></td>
</tr>
<tr>
<td>CEM II/B-M c</td>
<td>65-79</td>
<td></td>
</tr>
<tr>
<td>CEM III/A d,e</td>
<td>35-64</td>
<td>66-80</td>
</tr>
<tr>
<td>CEM III/B d,e</td>
<td>25-34</td>
<td>81-95</td>
</tr>
<tr>
<td>CEM V/A, c, e</td>
<td>40-67</td>
<td>18-30</td>
</tr>
<tr>
<td>CEM V/B, c, e</td>
<td>28-38</td>
<td>31-50</td>
</tr>
</tbody>
</table>

a The values in the table relate to the sum of the composition’s main and additional components
b The silica dust content is limited to 10%
c In Portland cement clinker and composite CEM V, the main components except for Portland cement clinker must be specified in the description of the cement.
d Designation as per DIN EN 107-4 CEM III/... L III/C,
e Designation as per DIN EN 14218: VLH III/B, VLH III/A, VLH IV/B, VLH V/A, VLH V/B,
Pzhoublast furnace cement CEM II/S
Portland composite cement CEM II/M

The percentage shares of the cements containing GBS in the domestic sales of members of the German Cement Manufacturers Association are shown in Fig. 2.1.

![Fig. 2.1: Domestic sales in 2004 of the BDZ members by types of cement – proportions in % [BDZ04]](image)

In 2004, cement containing GBS accounted for around 25% of the domestic sales of the Members of the German Cement Manufacturers’ Association. Of these figures some 7% was for CEM II/A-S and CEM II/B-S and around 9% for CEM III/A and around 1.5% for CEM III/B.
The average cement content in ready-mixed concrete in 2004 came to a total of 290 kg/m³ [ERM05] and around 44 Mio. m³ of ready-mixed concrete was produced [BTB06]. Thereby in 2004 some 44 million m³ x 0.290 t/m³ = 13 Million tons of cement have been used in ready-mixed concrete. In 2004, 5 million tons of blast furnace slag was used as GBS in cement production [Feh05]. Assuming that some 80% of the GBS (= cement containing GBS) is used in ready-mixed concrete (cement containing GBS has up till now only been used to a limited degree in precast parts and concrete products) there is an average content of granulated blast furnace slag as a principal component of cement in ready-mixed concrete of (0.8 x 5 Million t) / 44 Million m³ x 1000 or. (0.8 x 5 Million t) / 13 Million t x 290 kg/m³ = 90 kg/m³. In addition, the use of fly ash as a concrete additive has been established (see Section 5). An average content of some 50 kg/m³ is produced in relation to the manufactured volumes of ready-mixed concrete.

2.2 Production of cement that contains blast furnace slag

2.2.1 Chemical – mineralogical optimisation

2.2.1.1 General items

From the construction suitability point of view, the reaction capacity of the GBS is the significant quality characteristic. This depends first and foremost on the conditions of production such as the composition of the ash or the run-off conditions, but is also influenced by different parameters in the cement-making process. Included amongst these are the combination of the GBS with a suitable clinker, the adaptation of the sulphate carrier and - when there is a separate or partially separate grinding process - the grinding fineness of the cement components. These parameters are to be matched to each other in such a way in the production of cement containing GBS that a homogenous product having high quality and highly consistent features is produced. The influence of the chemical-mineralogical parameters on the GBS reaction in the cement is described below.

If GBS is mixed without any further additives with water and a low proportion of the GBS goes into the solution, the reaction is very quickly disrupted. It is assumed that the cause of this is the fact that a coating of hydration products develops on the surface of the GBS granules, which impedes the access of water and prevents the further reaction [Kon69, Reg83]. In order to achieve the strengths that are called for in the construction field within technically usable periods of time, the GBS reaction must be accelerated by the so-called activator. From this, it is assumed that the coating of hydration products in the presence of an activator is more permeable against water and any delay of the reaction is thereby prevented [Ans54, Jon77, Hin87].

There is generally a difference in the activation of the latent hydraulic reaction between alkaline and sulphate activation. Activators are for the most part cement clinker, sulphate or calcium hydroxide, but there are also other alkaline materials such as for example alkali hydroxide, alkali carbonate or sodium silicate. The activator can in this case have the effect of being a catalyst, i.e. the reaction of the GBS is accelerated without the activator being directly a part of the reaction. But the activator can also work as a reaction partner for the GBS.
2.2.1.2 Alkaline activation

First and foremost in alkaline activation the solubility of the GBS is influenced. The solubility of the aluminium silicate becomes greater with the increasing pH value of the invasive solution (Fig. 2.2) [Fra90]. The increase in solubility is particularly strong in the relevant pH value range of more than 10.

The application of alkaline reacting material provokes an increased solubility of the blast furnace slag silicates and improves the reaction capability of the GBS. The alkaline compounds that are suitable as activators can be ranked in three classes:

- Alkaline salts of weak acids (except for silicates) e.g. sodium carbonate, sodium fluoride [Hra92, Mal86, Bry92, Par86, And88, Wan94]
- Alkaline silicate, e.g. sodium silicate, sodium silicate in a compound with sodiumfluorosilicate [Teo72, Par86, And87, Skv86, Wan94]
- Alkali hydroxide [And87, Iso86, Tal85, Mal86]

Ca(OH)$_2$ is also included amongst the alkaline activators. Ca(OH)$_2$ has a different effect from the alkaline salts: it functions not only as a catalyst for the GBS reaction but also as a partner to the reaction. CSH phases, which are similar to those of the Portland cement hydration and calcium-aluminate hydrate such as for example C4AH$_{13}$ are generated in this reaction [Dro80, Voi76, Reg80]. The corresponding procedures for the activation of GBS were already patented in 1908 [Küh08].

2.2.1.3 Sulphate activation

The reaction of the GBS can also be stimulated by the addition of sulphate-containing compounds such as calciumsulphate. The effectiveness of this activator is based upon the reaction of the GBS with the sulphate ions subject to the formation of Etringit, CSH-phases and aluminium hydroxide (Kei58, Küh51, Voi73, Dai80). The reaction speed of the GBS is however comparatively low when exclusively stimulated with sulphates. The effectiveness of the sulphate activation can only be improved to any significant degree with the addition of alkaline reacting materials [Reg80, Cze77]. With simultaneous alkaline activation an increase in the sulphate content has a positive effect on the reaction speed of the GBS [Dai80].
The sulphate activation is used in particular in sulphate slag cements, which contain at least 75 M.-% and mostly between 80 and 85 M.-% GBS. As activators, these cements contain between 10 and 15 M.-% anhydrite and around 5 M.-% of an activator, which is generally speaking Portland cement clinker. In Germany the production of these cements was started in the 1970s, as the quality of the GBS no longer met requirements, in particular with respect to the Al$_2$O$_3$ content.

The DIN 4210 "sulphate slag cement" has placed two demands on the GBS to be used: the aluminium oxide content may not be lower than 13 M.-% and the content of CaO + MgO + Al$_2$O$_3$/SiO$_2$ must be $\geq$ 1.6. According to Yamauchi and Kondp [Yam52] the Al$_2$O$_3$ content should be at least 14 M.-% and to achieve high quality cement should even be at 20 M.-%. Based upon the current state of knowledge, the Al$_2$O$_3$ content in the 1960s was continuously lowered so that there were no longer any adequate GBSs available to meet the correct quality standard.

In recent years, sulphate slag cements have been redeveloped using the present day GBS qualities. The requirements in relation to the GBSs for these sulphate slag cements correspond to those that are to be found in EN 197-1 [CUA04, BSI04, NFP03].

### 2.2.1.4 Combined alkaline and sulphate activation

In hardened cement paste, the GBS is subjected to a combined sulphate and alkaline activation. In this, the sulphate activation is predominant in the initial stage of hydration and after termination of the solidification reactions the reaction of the GBS is for the most part alkaline activated. The pore solution in the hardened cement paste is characterized by the ever-present calcium hydroxide in the surplus due to very high pH values of at least 12.5. In addition it contains in the early hydration stage high contents of sulphate ions, which originate from the calcium sulphate added as a solidification actuator and from the alkaline sulphates of the clinker. Sulphate is bound during the solidification process and forms calcium-aluminate-sulphate-hydrates, so that the sulphate concentrations are lowered. At the same time the sulphate ions are replaced by hydroxide ions and the pH value increases [Lon73]. After the conclusion of the solidification reactions, the pore solution contains for the most part alkali and hydroxide ions and the pH value is between 13 and 14. The solubility of the calcium in the high alkaline pore solution is still only minimal. The predominant part is present in the hardened cement paste in the form of solid Ca(OH)$_2$ [Gun83, Od182].
2.2.1.5 Influence of the sulphate carrier composition on the solidifying and hardening processes

The basic facts regarding the influence of the sulphate carrier composition on the solidification and the strength development have been known since the 1970s from the publications of Locher, Richartz und Sprung [Loc76, Loc80, Loc82, Loc83]. However in every cement plant the optimal sulphate carrier compound must be individually determined in expensive laboratory and operational tests for each cement. There is a content of aluminates phases in Portland cement clinker (C₃A, C₄AF), the reaction of which commences immediately after the addition of water to this cement. If the ground clinker without further additions to the clinker is mixed with water, then the aluminates form leaf-shaped hydrates, which leads to an immediate solidification of the cement (so-called “Löffelbinder” [spoon binder]). In order to prevent this undesirable reaction and to guarantee a satisfactory processibility of the cement, calcium sulphate is added to the cement as a solidification actuator.

The composition of the sulphate carrier is of decisive importance for the solidification behaviour of the cement. As a rule a mixture of natural gypsum and anhydrite is used as a solidification actuator. Calcium sulphates can also be utilized which come as industrial byproducts. In the cement grinding process the gypsum dehydrates depending on the temperature of the product being ground partially or completely into calcium sulphate semi-hydrate. The combination of mineral phases, in which the calcium sulphates are present, determines the content of soluble sulphate which is contained at the beginning of the hydration in the pore solution [Kei71].

In Portland cement the composition of the sulphate carrier is matched to the re-activity of the tri-calcium aluninate. The amount of water-soluble sulphate must be measured at the start of the hydration precisely to a level so that the hydrating C₃A proportion is bound exclusively as ettringite (3 CaO – Al₂O₃ – 3 CaSO₄ – 32 H₂O). In the event of the sulphate amount being too low, monosulphates (3 CaO – Al₂O₃ – CaSO₄ – 12 H₂O) or even – when the amount of sulphate is clearly too low – calcium aluminates are generated. The prismatically extended or tabular crystals that are created form a join that is similar to a house of cards in the space between the cement particles. The bridging-over of the interim spaces leads to so-called “rapid solidification”. When the amount of sulphate is too high, secondary plaster is created. The prismatically stretched and/or tabular gypsum crystals also provoke a bridging-over of the hollow areas and lead to “false solidification”. Amounts of sulphate are accordingly either too high or too low and both lead therefore to an unsatisfactory processibility of the cement. With blast furnace cements, mixtures of anhydrites and semi-hydrates are presented as being the most beneficial [Bru02].

The sulphate optimisation of cement is not only of major importance for the processibility but also for the development of the strength. The maximum strength of cement can only be achieved if the cement particles are already packed together as tightly as possible at the beginning of the hydration. However, in non-sulphate optimised cements, the reaction products of mono sulphate and aluminates hydrate and gypsum already prevent an optimal sealing of joins in the initial stage of hydration.

The optimal sulphate carrier composition for a cement depends on the volume and reactivity of the C₃A in the clinker [Loc76]. Clinkers with a high C₃A content or a higher C₃A reaction capability require as a rule sulphate carrier mixes with a higher amount of easily soluble sulphate, that is to say, a higher proportion of calcium sulphate-semi-hydrate. If the proportion or the reaction capability of the C₃A is lower, the need for easily soluble sulphate is also reduced. In this case as a rule sulphate carriers with a higher proportion of anhydrites are used. Depending on the raw material composition and the type and volume of the combustion material that is used, the reactivity of the C₃A can change, to which the cement production must be responsive. In addition to the volume and reactivity of the C₃A, the sulphate demand also depends on the grinding fineness of the clinker. With an increasing specific surface of the clinker – and with this of the C₃A – the requirement for sulphate also increases. For cements that have differing strength-categories, differing sulphate volumes are therefore possibly also necessary.
Optimal sulphate contents or sulphate carrier compositions can also not be given for cements containing GBS, but they will in each case be determined by the specific characteristics of the cement. The most advantageous sulphate content depends upon the GBS content, the grinding fineness of the GBS and the clinker which is used and the reactivity of the various components. The optimal sulphate carrier composition must therefore be individually adapted for each type of Portland blast furnace cement. On the one hand, in this respect it must be guaranteed that sufficient sulphate is available at an early point in time for the reaction with $C_3A$. On the other hand, a sulphate carrier with a lower dissolving rate is needed for the slower reacting GBS.

There are indications to be found in numerous documents to the fact that in particular a sulphate additive in the form of anhydrite is advantageous for the reaction capability of GBS [Dai83, Nag60, Mo59]. Investigations made by Schwiete and Dölbor [Sch63] with differing sulphate carrier compositions have shown that a mixture of 25 M.-% gypsum und 75 M.-% anhydrite is particularly advantageous for the reaction capability of GBS. In these mixtures a high portion of sulphate of up to 4 M.-% leads to an optimal strength development [Sch63, Nag60]. It consistently emerges from all of the stated literary references, that the effectiveness of the sulphate carrier depends upon further parameters such as the grinding fineness or the $Al_2O_3$ content of the GBS.

If in the production of cements that contain GBS the same sulphate carrier composition is used as in Portland cement, less ettringite is formed according to investigations of [Lud68, Smo65, Ans54]. Instead of this, an increased amount of monosulphate is generated, which leads to incorrect solidification.

The sulphate carrier composition must therefore be individually adapted to the reaction capability of the cement in order to avoid breakdowns in the solidification reactions and adverse effects in strength development. In this, the chemical-mineralogical composition and the grinding fineness of the component parts of the cement are to be taken into account (in particular clinker, GBS, sulphate carriers).

### 2.2.1.6 Influence of the clinker on the GBS reaction

In addition to the sulphate amount, the activation of the GBS is also decisive for the reaction capability of the GBS in the cement. Numerous investigations show that the composition of Portland cement influences the reaction speed of the GBS.

![Figure 2.3: Influence of the alite and aluminate content of Portland cement clinker on the reactivity of GBS [Dai83]](image)

It is consistently reported in literature that a high alite content of the clinker has a positive influence on the
reaction speed of the GBS [Bru04]. According to [Dem80] the influence of the clinker composition increases with the increasing fineness of the cements containing GBS. On the other hand, investigations by [Dai, Got61] show that the strength contribution of the GBS depends to a great degree also on other parameters of the clinker (Figure 2.3). They have investigated the effect of clinkers with different C_3A and alite contents on the reactivity of the GBS. A decisive criterion in the investigations has been the strength development in the cement. With clinkers that have a low C_3A content, the strength contribution of the GBS clearly increases with an increasing alite content of the clinker. The opposite tendency has been found with clinkers that have a high C_3A content. With an average C_3A content, the contribution to the strength made by GBS is more or less independent from the alite content. It should however be noted that low alite contents are not relevant in practice for normal Portland cement clinker. Investigations show that the effect of the GBS depends very much on the characteristics of the clinker that is used in combination with it. A prediction of the development of the strength can however only be made when both components have qualities that remain the same and their reciprocal influence is known.

Systematic investigations by [Bru04] have shown in addition that the pressure strength development of cements that contain GBS depends both on the quality of the blast furnace slag that is used as well as on the composition of the clinker (Figures 2.4 and 2.5). In the investigations that were carried out, five GBS types, which differed significantly in their chemical composition and which were produced from 15 differing clinkers were used in combination with Portland cement (CEM I 42,5 R). 75 M.-% of GBS was used in all of the cements. The pictures show that after two days, first and foremost, the characteristics of the GBS have a relevant influence on strength. After 28 days, the differences between the GBS in combination with the self same clinker are clearly smaller. First and foremost, the pressure strength is determined by the clinker.
The investigations as a result show that significant changes in the cement characteristics can be caused both by the GBS and by the clinker.

The strengths at two days could be altered both through variation of the clinker as well as of the GBS by approximately 2 to 3 N/mm². The strengths at 28 days could be altered by variation of the clinker by up to approx. 12 N/mm², by variation of the GBS by up to approx 6 N/mm². At the conclusion of this test, the influence of the clinker on pressure strengths is therefore more pronounced than that of the GBS.

The influence of the clinker or of the Portland cement used becomes clearer in Figure 2.6.
GGBS as concrete additive

Figure 2.6: Relative mortar pressure strength of CEM III/B cements with differing GBS's and clinkers after 28 days; analysis: [Här05], data from [Bru04]

Here the data from [Bru04] was applied as relative mortar pressure strengths and with similar GGBS the range of the results with variation of the Portland cement and with similar Portland cement the range of results with variation of the GGBS were given. It was clear that with these investigations, the influence of the Portland cement that was used was greater (max. $\Delta AI = 0.25$) than the influence of the GGBS (max. $\Delta AI = 0.17$).

In the normal practice of cement production, only one type of clinker and one type of GBS is frequently used. Due to this, only relatively small fluctuations occur. The spread of the fluctuations can however be minimised in cement production by the introduction of corrective actions. These actions consist for example of a slight alteration of the cements composition, a variation of the grinding fineness of the main components of the cement and an adjustment of the volumes and the composition of the solidification actuator.

An important parameter in the analysis of the performance capability of GBSs (having comparable chemical and glass contents) is the CO$_2$ content of the GBSs. This applies particularly when there are GBSs that have been stored for longer periods and the drying-out of the GBSs that results from this. Furthermore the TiO$_2$ contents, which, due to the actions of the steel producer in protecting the fire-resistant walls in furnaces (addition of limenite), can change to a not insignificant degree, play an important role.

Increased CO$_2$ contents arise due to a surface carbonisation of GBSs that have been stored in the open-air or when they dry out and make appreciably easier the grindability of the GBSs, which results in a higher fineness according to Blaine with similar grinding energy, which stimulates a hydraulic reactivity. Stored GBSs with higher CO$_2$ and H$_2$O content is however only seemingly easier to grind, as due to the rapid abraison of a thin carbonised and hydrated outer shell of the GBS grains, a high Blaine-value is displayed relatively quickly. But if one compares the grain shell of a freshly ground GGBS with an old one, it then becomes clear that despite the same Blaine value the old GBS is clearly coarser. This has an effect on its performance capability. The supposed better grindability is therefore based on the production of a coarse ground GGBS with a relatively high specific surface.
A large number of publications describe the reduction of the hydraulic performance capability of GBSs due to increased TiO$_2$ contents [e.g. Wan02]. Figures 2.7 and 3.2 show this by way of an example. The measurement and analysis of the activity index under the same framework conditions (similar Portland cement clinker and similar grinding fineness of both the Portland cement clinker and of the GBS) is a basically good possibility for evaluating the hydraulic performance capability of the GBS. It is shown that differing Portland cement clinkers react differently with reciprocal effect with GGBS and the grinding fineness of the GBSs can have a great influence on the activity.

![Graph showing the Influence of TiO$_2$ content on mortar hydraulicity with 70 M.-% GBS and 30 M.-% Portland cement [Dyc06]](image)

**Fig. 2.7:** Influence of the TiO$_2$ content on mortar hydraulicity with 70 M.-% GBS and 30 M.-% Portland cement [Dyc06]

### 2.2.2 Granulometric optimisation

In the production of cements with several main components, the reactivities and grain-size distributions of the cement components determine the characteristics of the cements. The composition of the mixture and the reactivities and finenesses on the cement components have an effect on the strength of cements that contain GBS. The water requirement of the cement and with this the processibility of the concrete is influenced both by the measurement of the slope of the grain size distribution of the cement as well as by the sulphate matching. In addition also the clinker content, the reactivity of the clinker proportion and fineness of the clinker proportion play a significant role in the solidification behaviour.

Cements with several main components can on the one hand be manufactured by means of common grinding or on the other hand with separate grinding of the source material (e.g. clinker, GBS, limestone and sulphate carriers) and subsequent mixing of finely ground primary products.
A partially separate grinding is also possible. In these cases, through a common grinding process, manufactured primary products from Portland cement clinker, limestone and sulphate carriers can be mixed with a GGBS. When there is common grinding, the composition, the grinding fineness and the grain size distribution of the cement can be influenced and with this predetermined cement characteristics can be produced. The production of targeted grain size distributions of the individual components is however not possible here, as the components that are more difficult to grind become concentrated in the more coarse fractions and the components that are more easily ground in the finer fractions.

Separately-ground cement components can on the other hand be precisely adjusted in their grain size distributions and finenesses and consequently they exercise an additional influence on the characteristics of the cement. The additional degree of freedom however contains the risk that undesirable fluctuations of the characteristics of the source materials may affect the characteristics of the cement to a significant degree. When producing cement by means of separate grinding and mixing processes in the cement plant, this risk is countered by ongoing production inspections (regular checking of grinding fineness of the intermediate products from the grinding process and of the cement).

The slope of the grain size distribution of the cement components has a considerable effect on the water requirement of the cement and consequently on the processibility of the concrete. The effects of various grain size distributions of the cement components have been investigated in In [Ver04]. For this, various clinker and GGBSs with similar measurement-related surfaces but different slope measurements of the grain size distribution have been produced and from these, by means of mixtures, cements containing GBS have been produced.

When there are similar clinker components, a substitution of the GBS components by an GGBS with a broader grain size distribution can, despite a similar measurement-related surface of the granulated blast furnace components, lead to an increase in the water requirement.

The chemical composition of the source materials and of the manufactured cement is checked with a high level of frequency in the production of cements containing GBS. Apart from that, during the grinding process, the fineness and grain size distribution of the cement that is produced is constantly inspected or controlled. In addition, the cement characteristics are regularly inspected within the framework of in-house monitoring. The cement manufacturer can accordingly in the event of alterations in the reactivity of the source material immediately react and adjust the grinding fineness and/or the content of GBS of the cement that is being produced. By means of this quality and assurance concept, a precisely-targeted adjustment of the cement characteristics and a high degree of uniformity of the manufactured products is ensured.
2.3 Use of cements that contain blast furnace slag

2.3.1 General items

In 2002, new concrete standards DIN EN 206-1: 2001-07 and DIN 1045-2: 2001-07 were introduced into building inspection. In general all of the cements as per DIN EN 197-1, DIN EN 197-4, DIN EN 14216 and DIN 1164 are suitable for the production of concrete in accordance with these standards. With regard to the durability of concrete produced using these types of cement, consideration must be given however to the cement-dependent differences in accordance with the field of application. In this respect differing regulations for use have been established in the concrete standards in line with the exposure class in which a component is to be assigned. For those cements that were already included in the previous DIN 1164-1 standard, the regulations that had been valid up to now have been updated.

The regulations for the use of cements containing GBS are repeated in the Tables A1 to 84 in Appendix A and can be summarised as follows:

- Cements of the strength classes ≥ 32,5 R with up to 50 % GBS as a main component are permitted for use in all exposure classes as per DIN EN 206-1 and DIN 1045-2.
- Cements of the strength classes ≥ 42.5 R with up to 65 % GBS as a main component are permitted for use in all exposure classes as per DIN EN 206-1 and DIN 1045-2.
- Cements with up to 80 % GBS as a main component are permitted for use in all exposure classes as per DIN EN 206-1 and DIN 1045-2 except for XF4.
- The use of cements with up to 80% GBS as a main component in the exposure class XF4 is permitted subject to the following marginal conditions:
  a) Seawater components: w/z ≤ 0.45; minimum strength class C 35/45 and z ≥ 340 kg/m³
  b) Side cleaning tracks w/z ≤ 0.35; minimum strength class C40/50 and z ≥ 360 kg/m³; in compliance with DIN 19569.
  In both cases there is no need for any air spaces.
- Cements with 80-95% of GBS (CEM III/C) may only be used in concrete for the exposure classes X0, XC2, XD/S2 and XA.
- Limitations in the use of cements containing GBS from Table A2 are the result of limitations in the use of cements corresponding to CEM II as per Table A1 with the main component parts of P, V and LL.

Further regulations on cements that contain GBS are given in the following summary:
### Table 2.2: use of cements containing GBS

<table>
<thead>
<tr>
<th>Technical circumstance</th>
<th>Body of regulations</th>
<th>Requirement / permitted cements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement with high sulphate resistance (HS cement)</td>
<td>DIN 1164-10</td>
<td>• CEM III/B and CEM III/C as per DIN EN 197-1</td>
</tr>
</tbody>
</table>
| Cement with an low effective alkali content (NA cement) | DIN 1164-10 | • All cements containing GBS with Na₂O-Equ. ≤ 0,60 %  
               • CEM II/B-S > 21 % GBS and Na₂O-Equ. ≤ 0,70 %  
               • CEM III/A ≤ 49 % GBS and Na₂O-Equ. ≤ 0,95 %  
               • CEM III/A ≤ 50 % GBS and Na₂O-Equ. ≤ 1,10 %  
               • CEM III/B and CEM III/C as per DIN EN 197-1 and Na₂O-Equ. ≤ 2,00 % |
| Special cement with very low hydration heat | DIN EN 14216 | • VLH cements with the composition of a CEM III/B may be used as CEM III/C. |
| k-value approach for fly ash as per DIN EN 450 when using cements containing GBS | DIN 1045-2 | • CEM II/A-S and CEM II/B-S  
               • CEM II/A-M with the main component parts (S, D, P, V, T and LL)  
               • CEM II/B-M (S-D, S-T)  
               • CEM III/A  
               • CEM III/B with up to 70 M-% GBS |
| Concrete with high sulphate resistance with a sulphate content of the aggressive water of SO₄²⁻ ≤ 1500 mg/l | DIN 1045-2 | • CEM II/A-S and CEM II/B-S  
               • CEM II/A-M with the main component parts (S, V, T and LL)  
               • CEM II/B-M (S-T)  
               • CEM III/A |
| k-value approach for silica dust when using cements containing GBS | DIN 1045-2 | • CEM II/A-S and CEM II/B-S  
               • CEM II/A-M with the main component parts (S, P, V, T and LL)  
               • CEM II/B-M (S-D, S-T)  
               • CEM III/A, CEM III/B |
| Increase in the highest permitted water cement value in the exposure class XD/S3 from 0.45 to 0.50 | Rili DAfStB standard „Bulk concrete components“ | • CEM III/A, CEM III/B |

By way of an example, consideration will be given in the following sections to certain characteristics of concrete when using GBS-containing cements.
2.3.2 Carbonisation

The carbonisation of cement related systems is decisively determined by the relative humidity with the exception of the CO₂ content of the atmosphere and the type and volumes of the hydration phases. Figure 2.8 shows the influence of the relative humidity on the carbonization according to Wierig [Wie86]. With this it becomes clear that the strongest carbonisation occurs in the area of the laboratory atmosphere with 65% relative humidity, whilst in the case of unprotected storage in the open air the carbonisation level is only some 20% of that. Cement-related differences in carbonisation behaviour have an extremely strong effect therefore when storage takes place in the laboratory atmosphere whilst in natural surroundings these are significantly reduced and generally immaterial in building practice.

![Figure 2.8: Carbonisation depth in relation to the relative humidity [Wie86]](image)

Accordingly on a 50-year-old concrete road surface, produced with the use of iron Portland cement with 35% GBS (the equivalent today of a CEM II/B-S) only a very small depth of carbonisation of some 0.5 mm was measured [Lan99].

It has been established in several works that the carbonised peripheral shell of concretes with a high amount of GBS cement shows an increased porosity compared to core concrete, see for example [Lan00]. Lower strengths of the carbonised coating were also in part measured with the changed porosity. But Manns und Wesche [Man68] found an increase in strength after an accelerated carbonisation of concrete having a 40% GBS content and for Portland cement. Only when there is a very high GBS content of 82% has the compression strength been slightly below the originally delivered strength after carbonisation.
2.3.3 Resistance against Cl-diffusion

The resistance of concrete against aggressive chlorides clearly increases both with a reducing water cement value as well as with an increasing GBS content – as a result of increasing density (reducing porosity) of the hardened cement paste [Bro82]. See Fig. 2.9.

Figure 2.9: Interrelation of the chloride content in concrete with GBS content and w/c value [Bro82]

In addition to their increased density, cements containing GBS can in addition bind more chloride than Portland cements. According to Gunkel [Gun92] the GBS contents in blast furnace cement increase the binding capacity of cement with chloride. Also in bonding agents that are free of clinker with 85% GBS, 15 % Ca(OH)$_2$ and 6 % gypsum hydratised GBS binds to significant volumes of chloride.

The discovery that the GBS component of the cement significantly increases the chloride binding is closely related to a further characteristic of this type of cement: the extraordinarily low porosity of the hardened cement paste from blast furnace cement against chloride ions which totals something like a one hundredth part of the porosity of a comparable Portland hardened cement paste [Bro82].

2.3.4 Sulphate resistance

Blast furnace cements with GBS contents of at least 65 M.-% are counted according to DIN 1164-10 as cements with a high sulphate resistance, in brief: HS cements. The GBS content of HS cements containing GBS can with building inspection approval be even lower, e.g. at 50 M.-%. Comparable regulations are in force also in many other countries. The high sulphate resistance of concretes and mortars based upon such HS blast furnace cements has been established in numerous laboratory and field trials [Loc66, Loc80b, Bak80, Fre86, Pie93, Hal02, Hig03b]. Also from the building industry no sulphate damage is known when HS blast furnace cements have been used. This applies both for possible sulphate damage on the basis of a driving attack by secondary ettringite or gypsum development as well as for sulphate damage based upon thaumasite formation, which can occur for the most part at temperatures below 15°C [Mul02, Hig03a, Lip03 and Nob03].

The cause of the high sulphate resistance is, in addition to the thinning of the C$_3$A content, due to the GBS proportion and the high diffusion resistance of the hardened cement paste with high proportions of GBS in the cement, which prevents the penetration of sulphate ions. The diffusion resistance is strongly influenced both by the GBS content in the cement and by the w/c ratio. The diffusion resistance at 30 M.-% of GBS is already clearly greater than with Portland cement and at some 40 M.-% of GBS and a w/c ratio of 0.50 can reach levels that are with a GBS content of between 60 and 80.-%. See in this respect also Figure 2
Many comparable investigations into this have resulted in showing that concrete test bodies containing GBS have higher sulphate resistance. In fact GBS from the chemical viewpoint is not inert towards a formation of ettringite, gypsum or thaumasite. However as a result of the hydration of blast furnace cement, a type of dense microstructure of C-S-H phases forms so that no sulphate can penetrate into the hardened cement paste and form any microstructural-damaging reactional products there. This has consequently to do with a physical effect mechanism which is related to the chemical reactions.

2.3.5 Acid resistance

According to Locher - amongst others- [Loc84], the degradation of portland cement concretes that have been embedded in calcium carbonate for 20 years was twice as great as that of blast furnace cement concretes under similar conditions. The influence of the type of cement was more pronounced than that of the water cement ratio. Investigations into high-performance concretes, which have been subject to attack from sulphuric acids, also confirm that concretes with blast furnace cements show a higher resistance to acids. The corrosion depth with the high-performance concretes with CEM III cements was only some 65% of the corrosion depth of a high-performance concrete with CEM-I-HS. A smaller reduction in the strength of the concretes with CEM III cements also resulted from this [Lan05-2].

The higher resistance to acids in sulphate blast furnace cement was even more pronounced. In the long-term test, concrete with sulphate blast furnace cement showed an up to 76% higher resistance against acid attack than a comparable concrete with Portland cement [Wop06].

2.3.6 Alkali-silicic acid reaction

To avoid a damaging alkali-silicic acid reaction (AKR) in accordance with the Alkali Guidelines of the DSfStv under specific pre-requisites such as greater humidity or an alkali ingress from outside, the use of NA cements can be necessary. A succession of national and international publications and practical building experience have shown that the use of NA cements containing GBS (see Table 2.2) contributes to a long-lasting and effective avoidance of a damaging AKR. [e.g. Bij96, Sie01, Sie02, Smo74, Sor73, Tho98]. The decrease of the alkaline proportion dissolved in the pore solution when using cements containing GBS is based first and foremost on the reduced clinker proportion in the cement [Sch06].
2.3.7 Fire resistance

The changeover from Portland cement clinker to GBS leads to an increased stability in the event of fire or quite generally in the effect of the high temperatures. This has differing causes, such as for example the significantly lower content of Portlandite in the hardened cement paste of hydrated cements containing GBS compared to hydrated Portland cements or the differing softening behaviour. The significantly lower reduction in strength of cements containing GBS is of special significance, see Figure 2.10 (contained in [Kol01]).

![Figure 2.10: Influence of temperature on the strength of various cements (from Kol01)](image)

1 Portland cement, 2 Portland blast furnace cement 30 % GBS, 3 blast furnace cement 70 % GBS

2.3.8 Heat development, cracking due to thermal stresses

Breitenbücher [Bre89] has investigated the temperature progression and the development of bondage tensions within the framework of cracks for concretes with differing cements that contain GBS. It has been established that the GBS content of the respective cement with similar clinker was indeed distinctly affected by the heat development in the concrete, but the deformation behaviour, the strength and with that the propensity to cracking changed in different ways. The tensile strength of the concrete develops slowly in many blast furnace cements, so that the concrete shows a higher propensity to cracking than when Portland cement is used. The differing influence of the GBS content on the propensity to cracking of the concrete can according to [Bre89] be traced back to the differing chemical composition of the clinker and the GBS that is used, to differing grinding finenesses and differing sulphate contents.
2.3.9 Colour

The colour measurements in Table 2.3 were established in the production period for a cement formula with 60% white Portland cement clinker and 40% GBS.

Table 2.3:  Colour measurements for a cement formula with 60% white Portland cement clinker and 40% GBS [Dyc06]

<table>
<thead>
<tr>
<th>Cement</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>L</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 42.5 R</td>
<td>78.65</td>
<td>83.33</td>
<td>85.96</td>
<td>93.15</td>
<td>0.70</td>
<td>2.42</td>
</tr>
<tr>
<td>CEM III/A 42.5</td>
<td>72.86</td>
<td>76.90</td>
<td>78.35</td>
<td>90.28</td>
<td>-0.10</td>
<td>3.14</td>
</tr>
</tbody>
</table>

The grinding of 40% GBS in the cement reduced the Y value (luminosity) significantly by approx. 6.5 or the L’ value (brightness) by approx 3 points.

2.3.10 General building inspection-related application approvals

2.3.10.1 General items

In some cases cements which correspond to EN 197-1, are excluded from use in specific exposure classes in the European region, because in the field of the regulations of the respective National appendix to the concrete standard EN 206-1 there is a lack of practical building experience and there are no scientific investigations on the use of these cements. In such cases, in Germany the proof of the suitability for the application in specific exposure classes as per DIN 1045-2, Table F.3.3. Footnote a, can be brought forward within the framework of a general building inspection use permit of the German Institute for Structural Engineering (DIBt). This process corresponds to the procedure of equivalent concrete performance capability described in DIN EN 206-1, Appendix E.

Some Germans Cement Manufacturers have developed new CEM II-M- cements, for which in the years 2004 and 2005 building inspection permits were issued for general use. Amongst these are also cements CEM II/B-M (S-LL) containing GBS. Table B1 in Appendix B shows some examples of permits that have already been issued.
2.3.10.2 Stipulations of the approval

The permit governs the requirements that are different from DIN EN 197-1 in the composition of the cement and its use in concrete as per DIN EN 206-1 together with DIN 1045-2.

The following rules apply in addition to DIN EN 197-1 for the characteristics and the composition of the Portland composite cement CEM II/B-M (S-LL):

- The Portland composite cement CEM II/B-M (S-LL) may only be produced with a specified GBS. The chemical composition of the GBS used must be within the framework of the composition as it has basically been in the tests conducted within the framework of the licensing procedure. The origin of the GBS is to be deposited at the German Institute for Structural Engineering.
- The limestone must correspond in petrographic and mineralogical terms to the rock deposits which have been investigated within the framework of the licensing test. The details are to be deposited at the German Institute for Structural Engineering.
- The chemical composition of the Portland cement clinker must be within the framework of the composition as it has basically been in the tests conducted within the framework of the licensing procedure. The details are to be deposited at the German Institute for Structural Engineering.
- The Portland composite cement CEM II/B-M (S-LL) must be produced from the main component parts according to the process that has been followed with the cement, which has been the basis of the licensing procedure. The manufacturing process is to be deposited at the German Institute for Structural Engineering.
- The composition of the Portland composite cements CEM II.B (S-LL) must be within the ranges as per Table B1.

3 European standard for ground granulated blast furnace slag compared to various national regulations and qualities of granulated blast furnace slag

3.1 General items

The use of GGBS as a concrete additive is the state of the art in various countries and indeed both in relation to body of regulations and also to the practical implementation. Countries such as for example France, Sweden or Austria have rules and regulations for the production and use of GGBS as a concrete additive, but there is currently no or rather only one subordinate use in existence. In Great Britain and Ireland GGBS is used almost exclusively as concrete additive. In the Netherlands and Belgium in earlier times there was an increasing use as a concrete additive. Outside of Europe, GGBS is also used as a concrete additive.

In Germany up until the middle 1960s, GGBS was utilized under the name of Thurament. Thurament was officially approved for use in the production of structures made from concrete and reinforced concrete, but could not be utilized in slender reinforced concrete components such as those used for high buildings and bridges (see 4.3.2.1 and Appendix C).
Currently there is use of GGBS in Germany in the sector that is not subject to building inspection at the plant of one concrete roof tile producer and one concrete materials manufacturer.

3.2 Comparison of different regulations for GGBS with those of the European draft standard prEN 15167-1 (Issue March 2006)

3.2.1 General items

The European draft standard prEN 15167-1, issued in February 2005, forms the basis for the CEN enquiry which was carried out in the year 2005. The Law no 15 of CEN TC 104 authorised with the processing of the draft standard has been reprocessed in September 2005 and the issue of February 2005 is based upon the caveats that resulted from the CEN enquiry. This version (issue of October 2005) is a follow-up basis for the comparison with other European and non-European standards or bodies of regulations with a character that is similar to standards.

Table A5 contains a summary of the requirements of GGBS as a concrete additive, which is contained in the regulations of European countries. Table A6 contains the corresponding regulations for non-European countries.


Of the 17 standards which are listed in Tables A5 and A6, 11 contain the requirements for GGBS and they do not recognize any classification in categories. The other seven sets of rules define various categories which are significantly different due to differing finenesses and strengths or activity indices.

Whilst the Spanish standard UNE 83480 EX only deals with one difference in two classes in relation to filter residue, the Belgian regulation foresees three classes with compression strengths, which correspond to the requirements of EN 197-1 (32.5; 42.5 and 52.5 N/mm\(^2\) after 28 days). Requirements on solidification commencement are aligned to these three strength classes (75 min for the strength class 32.5; 60 min for 42.5 and 45 min for 52.5). The US American Standard includes three classes for the activity index. The Japanese and the Chinese standards also contain three classes for the activity index, but which are linked in addition to three fineness classes. The most extensive classification is undertaken in the French standard, which on the one hand specifies two fineness classes and three classes for the activity index and on the other hand contains three further classes for the product from CaO und Al\(_2\)O\(_3\).

The following sections show the comparison of further requirements, which do not however have to be included in all regulations.
3.2.2 Moisture

Limitations for the moisture content of the GGBS total 1.0 M.- %, with the exception of Spain which permits up to 2.0 M.-%. GBS reacts as latent hydraulic material with moisture to the extent that a limitation of the moisture content in GGBS is sensible in order to prevent premature hydration processes and possible solidifications. The limitation of an ignition loss is not practicable with GGBS, as with the effect of the ignition loss, sulphide oxidises into sulphate and that leads to an increase in weight and with this a precise registration of the moisture content is not possible.

3.2.3 Glass content

The minimum glass content totals two thirds with exception of the regulations in South Africa. Here this is a total of 95 M.-%.

3.2.4 Fineness

There are in some cases minimum requirements with relation to Blaine values and/or to filter residues. With a minimum fineness of 2750 cm³/g according to Blaine the demand of the European draft standard is at the lower level.

3.2.5 Chemical composition (selected parameters)

Most of the regulations limit the ignition losses to 3 M.-% (Belgium, Netherlands 5 M.-%), the sulphide content to 2 M.-% and the chloride content to 0.1%. The SO₃ content is limited to values between a maximum of 2.5 and 4.0.-%. The prEN 15167-1 with 2.5 M.-% is at the lower limit. Blast furnace slag occurs during a reduction process in the blast furnace. The sulphur that has entered into the blast furnace from the raw materials is therefore present in the ash and in the GBS that is produced from this in the form of sulphide. Through the oxidation of sulphide on the surface of GBS grains or due to its partial solution in granulation water and subsequent oxidation and reduction of the granulation waters (circuit water) small quantities of sulphate also get into the GBS. All known standards for GGBS as a concrete additive include limitations of the sulphide and sulphate content. The limits are for sulphide between 1.5 and 2.5 M.-% (prEN 15167 – 1 ≤ 2.0 M.-%). For sulphate the spread is from 2.5 up to 4.0 M.-%. The prEN 15167-1 limits the sulphate content at ≤ 2.5 M.-% and is thereby at the lower limit. The standards, that permit the sulphate content > 2.5 M.-%, in general on the other hand allow a grinding process on sulphate carriers, which has been excluded in the prEN 15167. The great differences in SO₃ content are above all based upon the fact that some standards allow or rather do not exclude the grinding of calcium sulphate.

Very great differences arise also with regard to the limitation of the alkali content. The limits fluctuate between an Na₂O equivalent of a maximum of 0.6 M.-% (Sweden) up to 3.5 M.-% in Austria. Extensive investigations have established that the alkalis of GBS do not lead – or only do so to an insignificant extent- to the increase of the effective alkali content in Portland cement/GBS mixes [Sm84, La03]. In prEN 15167-1 there are therefore also no limitations included for the alkali content. However, upon customer demand, the manufacturer or seller of the GGBS has to declare the Na₂O equivalent content.
Although up until now no periclase has been evident in glass solidified GBSs [CEN05], numerous standards for GGBS as a concrete additive contain limit values for the MgO content. These fluctuate between 10% (Chine Japan & Austria) and 18% in prEN 15167-1. In Austria, the value can be higher, if the volume stability is proven. Various standards contain limitations of the volume stability with a maximum expansion of 10 mm at the test procedure conducted according to Le Chatelier.

The fixings of minimum values for the total of MgO + Al₂O₃ or (CaO + CaO + MgO)/SiO₂ correspond to the requirements which are also placed on GBSs for the production of cement as per EN197. A non-typical value for the classification of GBSs is introduced into the Spanish standard for GGBS with the fixing of a minimum value for the product (CaO x Al₂O₃). In the French standard, GBSs in relation to the content of (CaO x Al₂O₃) are divided into three classes. The higher the content of CaO and Al₂O₃, the higher is also the activity index that is to be achieved.

3.2.6 Compression strength/ activity index

An important parameter in all of the currently known standards for GGBS is the regulations for the proving of a minimum compression strength or of a minimum activity index. Both parameters are to be proven on mixtures with Portland cement. The testing of these binding material mixes is normally carried out in accordance with the testing standards for cement in the respective countries. In Europe according to EN 196-1, the mixture ratios of GGBS to cement fluctuate widely and begin at 25 to 75 and go up to 70 to 30. Based upon these differing pre-requisites, a comparison of the figures is not possible as the test cements can be completely different.

According to prEN 15167-1 the activity index is to be given as the relationship of the compression strength of a mixture composed of GGBS and test cement in mass fractions of in each case 50% to the compression strength of the test cement in question (in percent). Compression strength is to be determined according to EN 196-1, in which the ratio of water to mix and to the water/cement ratio must in each case be 0.50.

3.3 Requirements of the material standard and comparison with the ground granulated blast furnace slag that is available on the market

3.3.1 Data collection

The data that is discussed below is based upon the investigations on European granulated blast furnace slag that have been undertaken in the FehS – Institute for Building Materials Research since 1995. No reference is made to older investigations as the corresponding GBSs are often no longer available because of the concentration processes in the steel industry at increasingly fewer locations. In addition, only investigation results are discussed on those parameters on which as per EN15 167-1 either requirements exist or declarations have to be made upon customer demand.
The chemical compositions, the derived characteristics and the glass content of the GBSs, are summarised in Table 3.1 and Table 3.2. The data has been separately displayed for Germany, for the whole of Europe including Germany and for the four groups of countries of North, West, South and East. The German GBSs are contained in the Western European group of countries. All GBSs originate from industrial wet granulation plants. Whilst random samples were analysed no claim can be made to absolute completeness. The analyses of old types of GBSs or or GBSs have not been included in the evaluation.

Cement and mortar technical investigations were undertaken on a number of European GBSs, amongst other things, for determining the activity index. EN 15167-1 defines the activity index as the relationship of the determined strengths of two mortars as per DIN EN 196-1, which are produced on the one hand with a defined reference Portland cement and on the other hand with a mixture of 50 M.-% of this Portland cement and 50 M.-% of ground granulated blast furnace slag.

### Table 3.1: Chemical Composition of German and European Granulated Blast Furnace Slags

<table>
<thead>
<tr>
<th>Analyses excl. Ignition loss</th>
<th>EN 15167-1</th>
<th>Germany</th>
<th>Europe (incl. Germany)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave.</td>
<td>Max.</td>
<td>Min.</td>
</tr>
<tr>
<td>SiO₂ M.-% Declar.</td>
<td>36,3</td>
<td>39,5</td>
<td>33,5</td>
</tr>
<tr>
<td>Al₂O₃ M.-% Declar.</td>
<td>11,7</td>
<td>15,3</td>
<td>10,1</td>
</tr>
<tr>
<td>TiO₂ M.-% Declar.</td>
<td>0,94</td>
<td>2,45</td>
<td>0,43</td>
</tr>
<tr>
<td>MnO M.-% Declar.</td>
<td>0,31</td>
<td>0,53</td>
<td>0,09</td>
</tr>
<tr>
<td>CaO M.-% Declar.</td>
<td>39,2</td>
<td>42,5</td>
<td>34,6</td>
</tr>
<tr>
<td>MgO M.-% Declar.</td>
<td>9,1</td>
<td>12,4</td>
<td>6,3</td>
</tr>
<tr>
<td>Na₂O M.-% Declar.</td>
<td>0,33</td>
<td>0,67</td>
<td>0,13</td>
</tr>
<tr>
<td>K₂O M.-% Declar.</td>
<td>0,50</td>
<td>0,96</td>
<td>0,13</td>
</tr>
<tr>
<td>Na₂O-eq., Na₂O + 0,658·K₂O M.-% -</td>
<td>0,66</td>
<td>1,31</td>
<td>0,22</td>
</tr>
<tr>
<td>SO₃²⁻ M.-% &lt; 2,5</td>
<td>0,10</td>
<td>0,30</td>
<td>0,00</td>
</tr>
<tr>
<td>S²⁻ M.-% &lt; 2,0</td>
<td>1,16</td>
<td>1,46</td>
<td>0,68</td>
</tr>
<tr>
<td>Cl⁻ M.-% &lt; 0,10 (if need be Declar.)</td>
<td>0,02</td>
<td>0,05</td>
<td>0,01</td>
</tr>
<tr>
<td>Ignition loss M.-% &lt; 3,0</td>
<td>0,38</td>
<td>1,58</td>
<td>0,12</td>
</tr>
<tr>
<td>Glass content Vol.-% &gt; 2/3</td>
<td>98,9</td>
<td>100,0</td>
<td>95,2</td>
</tr>
<tr>
<td>CaO + MgO + SiO₂ M.-% &gt; 2/3</td>
<td>84,6</td>
<td>86,0</td>
<td>80,8</td>
</tr>
<tr>
<td>(CaO + MgO)/SiO₂ M.-% &gt; 1,0</td>
<td>1,34</td>
<td>1,55</td>
<td>1,17</td>
</tr>
</tbody>
</table>
The cement and technical mortar investigation results are summarised separately for German and other European GBSs in Table 3.3. The GBSs have been ground in a laboratory ball-type mill on a specific surface of on average 5350 cm²/g or 5070 cm²/g at a more or less constant grain size distribution.
## Table 3.3: Cement and mortar technical specific values (GGBS/CEM I = 50.50)

<table>
<thead>
<tr>
<th>Sm (HS)</th>
<th>Solidification</th>
<th>Comp. Strength</th>
<th>Activity index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm³/g</td>
<td>Start</td>
<td>Finish</td>
</tr>
<tr>
<td>EN 15167-1</td>
<td>≥ 2750</td>
<td>04:05</td>
<td>03:50</td>
</tr>
<tr>
<td>CEM I 42.5 R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D 1</td>
<td>4210</td>
<td>03:15</td>
<td>03:50</td>
</tr>
<tr>
<td>D 2</td>
<td>4350</td>
<td>03:50</td>
<td>04:25</td>
</tr>
<tr>
<td>D 3</td>
<td>4150</td>
<td>03:40</td>
<td>04:20</td>
</tr>
<tr>
<td>D 4</td>
<td>4140</td>
<td>03:30</td>
<td>04:10</td>
</tr>
<tr>
<td>D 5</td>
<td>4300</td>
<td>03:55</td>
<td>04:30</td>
</tr>
<tr>
<td>D 6</td>
<td>4240</td>
<td>04:10</td>
<td>04:40</td>
</tr>
<tr>
<td>D 7</td>
<td>4150</td>
<td>03:55</td>
<td>04:25</td>
</tr>
<tr>
<td>Average D</td>
<td>4220</td>
<td>03:45</td>
<td>04:20</td>
</tr>
<tr>
<td>Max. D</td>
<td>4350</td>
<td>04:10</td>
<td>04:40</td>
</tr>
<tr>
<td>Min. D</td>
<td>4140</td>
<td>03:15</td>
<td>03:50</td>
</tr>
<tr>
<td>E 1</td>
<td>4200</td>
<td>03:50</td>
<td>04:20</td>
</tr>
<tr>
<td>E 2</td>
<td>4230</td>
<td>03:50</td>
<td>04:30</td>
</tr>
<tr>
<td>E 3</td>
<td>4250</td>
<td>03:50</td>
<td>04:25</td>
</tr>
<tr>
<td>E 4</td>
<td>4350</td>
<td>04:15</td>
<td>04:50</td>
</tr>
<tr>
<td>E 5</td>
<td>4200</td>
<td>04:15</td>
<td>04:55</td>
</tr>
<tr>
<td>E 6</td>
<td>4200</td>
<td>04:05</td>
<td>04:40</td>
</tr>
<tr>
<td>E 7</td>
<td>4200</td>
<td>04:15</td>
<td>04:50</td>
</tr>
<tr>
<td>Average E</td>
<td>4240</td>
<td>04:02</td>
<td>04:38</td>
</tr>
<tr>
<td>Max. E</td>
<td>4350</td>
<td>04:15</td>
<td>04:55</td>
</tr>
<tr>
<td>Min. E</td>
<td>4200</td>
<td>03:50</td>
<td>04:20</td>
</tr>
<tr>
<td>Average (Europe incl. D)</td>
<td>4230</td>
<td>03:33</td>
<td>04:29</td>
</tr>
<tr>
<td>Max. (Europe incl. D)</td>
<td>4350</td>
<td>04:15</td>
<td>04:55</td>
</tr>
<tr>
<td>Min. (Europe incl. D)</td>
<td>4140</td>
<td>03:15</td>
<td>03:50</td>
</tr>
<tr>
<td>D 1</td>
<td>5010</td>
<td>03:50</td>
<td>04:25</td>
</tr>
<tr>
<td>D 2</td>
<td>5010</td>
<td>03:55</td>
<td>04:35</td>
</tr>
<tr>
<td>D 4</td>
<td>5010</td>
<td>03:40</td>
<td>04:20</td>
</tr>
<tr>
<td>D 5</td>
<td>5060</td>
<td>03:45</td>
<td>04:35</td>
</tr>
<tr>
<td>D 7</td>
<td>5010</td>
<td>03:40</td>
<td>04:40</td>
</tr>
<tr>
<td>Average D</td>
<td>5020</td>
<td>03:46</td>
<td>04:31</td>
</tr>
<tr>
<td>Max. D</td>
<td>5060</td>
<td>03:55</td>
<td>04:40</td>
</tr>
<tr>
<td>Min. D</td>
<td>5010</td>
<td>03:40</td>
<td>04:20</td>
</tr>
<tr>
<td>E 1</td>
<td>5070</td>
<td>03:55</td>
<td>04:20</td>
</tr>
<tr>
<td>E 2</td>
<td>5070</td>
<td>04:05</td>
<td>04:45</td>
</tr>
<tr>
<td>E 5</td>
<td>5020</td>
<td>03:45</td>
<td>04:35</td>
</tr>
<tr>
<td>Average E</td>
<td>5050</td>
<td>03:55</td>
<td>04:36</td>
</tr>
<tr>
<td>Max. (Europe incl. D)</td>
<td>5070</td>
<td>04:05</td>
<td>04:55</td>
</tr>
<tr>
<td>Min. (Europe incl. D)</td>
<td>5010</td>
<td>03:40</td>
<td>04:20</td>
</tr>
</tbody>
</table>

D: German GBS, E: European GBS
A German Portland cement with a specific surface and an alkali content in the lower limit area of the range in EN 15167-1 with the CEM 1 42.5 R (see Table 3.4) that was used as the reference cement for determining the activity index was selected in order, for example, to limit the alkaline activation of the investigated GBSs and in this manner to obtain a worst case strength of the blast furnace cement mortar.

**Table 3.4:** Specific values of the reference Portland cement that has been used

<table>
<thead>
<tr>
<th></th>
<th>EN 15167-1</th>
<th>CEM I 42.5 R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength class</td>
<td>≥ 42.5</td>
<td>42,5 R</td>
</tr>
<tr>
<td>Specif. surface</td>
<td>≥ 3000</td>
<td>3520</td>
</tr>
<tr>
<td>C3A</td>
<td>6 - 12</td>
<td>10.3 *</td>
</tr>
<tr>
<td>Na$_2$O-equivalent</td>
<td>0.5 - 1.2</td>
<td>0.52</td>
</tr>
<tr>
<td>Na$_2$O + 0.658 K$_2$O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rc (2 days) N/mm$^2$</td>
<td></td>
<td>29,4</td>
</tr>
<tr>
<td>Rc (7 days) N/mm$^2$</td>
<td></td>
<td>46,8</td>
</tr>
<tr>
<td>Rc (28 days) N/mm$^2$</td>
<td></td>
<td>57,4</td>
</tr>
<tr>
<td>Rc (91 days) N/mm$^2$</td>
<td></td>
<td>65,3</td>
</tr>
</tbody>
</table>

* calculated as per Bogue

### 3.3.2 Discussion

With regard to chemical and physical requirements, it is to be confirmed that despite the current high tests that are being carried out, only very few individual figures for two individual parameters do not meet the requirements of EN 15167-1.

The minimum glass content of 2/3 was exceeded by a total of four granulated blast furnace slags. Two GBSs originating from current East European production have 45.6 Vol.-% and 60.7 Vol.-%. One GBS originates with 60.4 Vol.-% from Western Europe. This analysis was drawn up in 1998. According to details in the literature [Per02], the glass content of the GBSs produced today is at over 80 Vol.-%.

The maximum ignition loss of 3 M.-% was only exceeded in two cases from amongst 76 analyses. A granulated blast furnace slag originating from Eastern Europe had an ignition loss of 4.74 M.-% and there was from Southern Europe a GBS with an ignition loss of 3.94 M.-%. Both figures are well above the average and are normally only determined with old GBS products. Depending on their chemical composition, their glass content and their selected grinding fineness, however, even these GBSs are suitable for cement production.

With regard to the mortar technical characteristics, it is to found that all investigated GBS have maintained the requirements of EN 15167-1 with regard to the solidification commencement and the activity index at the age of 7 and 28 days. Only the E5 GBS at the age of 28 days meets the requirement with 71% (at 4200 cm$^2$/g) or with 75% (at 5020 cm$^2$/g) just marginally.

Currently there exists a very little experience with East European GBSs with respect to the activity indices. On the basis of the existing chemical and physical analysis this should be ok.
FEhS – Institute for Building Material Research has to date assumed that possibly some of today’s East European produced GBSs at normal fineness cannot meet the requirements of EN 15167-1.

But in investigations conducted by the Wilhlem Dyckerhoff Institute for Building Materials Technology into GBS from Czech Republic, Poland and Ukraine, the requirements of EB 15167-1 on the activity index were in fact satisfied (Table 3.5).

### Table 3.5: Activity index of East European granulated blast furnace slags [Dyc06]

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Percent age</th>
<th>Origin</th>
<th>Blaine value</th>
<th>GGBS Percent age</th>
<th>2 d MPa</th>
<th>7 d MPa</th>
<th>28 d MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Absolute</td>
<td>Relative</td>
<td>Absolute</td>
</tr>
<tr>
<td>CEM I 42,5R</td>
<td>100 M.-%</td>
<td>Czech Rep</td>
<td>2960 cm²/g</td>
<td>0 M.-%</td>
<td>37,2</td>
<td>1,0</td>
<td>53,2</td>
</tr>
<tr>
<td></td>
<td>50 M.-%</td>
<td>Poland</td>
<td>3290 cm²/g</td>
<td>50 M.-%</td>
<td>14,2</td>
<td>0,4</td>
<td>30,3</td>
</tr>
<tr>
<td></td>
<td>50 M.-%</td>
<td>Ukraine</td>
<td>3000 cm²/g</td>
<td></td>
<td>13,5</td>
<td>0,4</td>
<td>30,3</td>
</tr>
<tr>
<td></td>
<td>100 M.-%</td>
<td>Czech Rep</td>
<td>2960 cm²/g</td>
<td>0 M.-%</td>
<td>12,6</td>
<td>0,3</td>
<td>27,1</td>
</tr>
<tr>
<td></td>
<td>50 M.-%</td>
<td>Poland</td>
<td>3290 cm²/g</td>
<td>50 M.-%</td>
<td>13,9</td>
<td>0,4</td>
<td>28,7</td>
</tr>
<tr>
<td></td>
<td>50 M.-%</td>
<td>Ukraine</td>
<td>3000 cm²/g</td>
<td></td>
<td>13,5</td>
<td>0,4</td>
<td>27,5</td>
</tr>
<tr>
<td></td>
<td>50 M.-%</td>
<td></td>
<td></td>
<td></td>
<td>13,9</td>
<td>0,4</td>
<td>29,5</td>
</tr>
</tbody>
</table>

With glass contents of ≥ 70 % and aluminium contents up to 6.7% the mixes with two different CEM I 42.5 R achieve an activity index after 28 days at 90%, and > 50% after 7 days. The experiments of the Dyckerhoff Institute for Building Material Technology show that these GBSs have a lower performance capability in cement than German GBSs.

### 3.4 Uniformity

Modern blast furnaces are high-performance units, which are capable of producing daily up to 12,000 tons of pig iron. It is therefore necessary for their effective operation that they are continuously and uniformly supplied with burden (steel girdle and additives such as limestone and dolomite) and coke. This calls for a careful selection of the raw material components and of their uniformity before they are used in the blast furnace. From this there results also inevitably a high uniformity of the blast furnace slag and of the granulated blast furnace slag (GBS) that is produced from it. Figure 3.1 shows by way of an example the fluctuations of the Al₂O₃ content in a GBS during the course of one year.
GGBS as concrete additive

Figure 3.1: Range of variations of the content of $\text{Al}_2\text{O}_3$ during the course of one year of a selected plant [investigations conducted by the FehS Institute for Building Material Research, unpublished]

This applies in a similar way also for the other parameters of the GBS. One exception can be, under certain marginal conditions, the content of $\text{TiO}_2$ in the GBS. The natural content of $\text{TiO}_2$ in the GBS is some 0.5% depending on the composition of the raw materials. Materials containing titanium such as for example limenite in small percentages are added to the burdening in order to extend the operating life of blast furnaces (often towards the end of the working life prior to a refurbishment using fireproof material). This can lead to an increase in the content of $\text{TiO}_2$ in the GBS of up to some 2% but generally to a lower value. If the $\text{TiO}_2$ content in the GBS goes up, this can lead to lower strengths in cements that contain GBS. Whether such a reduction in strength occurs and how high this is, depends on the composition of the GBS and in particular its basicity (C/S) and its $\text{Al}_2\text{O}_3$ content, but also on the performance capability and the composition of the clinker that is used for producing the cement. Alkali-rich Portland cement clinkers generally react somewhat less sensitively to higher $\text{TiO}_2$ contents in the GBS than clinkers that are low in alkali.

Figure 3.2 shows the influence of a GBS with a natural $\text{TiO}_2$ content of 0.6% and with higher $\text{TiO}_2$ contents of 1.0 up to 2.6% on the strength of a CEM III/ 32.5 with 75 M.-% of ground granulated blast furnace slag. The original GBS has an $\text{Al}_2\text{O}_3$ content of 10.9 and a basicity C/S of 1.14. The higher $\text{TiO}_2$ contents have been achieved by means of a repeat sintering of the GBS in the laboratory, dosing with $\text{TiO}_2$ and subsequent granulation. In addition, investigations were carried out with a higher $\text{Al}_2\text{O}_3$ content and with higher and lower basicity [Lan00].
GGBS as concrete additive

Figure 3.2: Influence of higher TiO$_2$- contents on the compression strength of CEM III/B with 75% GBS at differing Al$_2$O$_3$-content or differing basicity [Lan00]

Based upon the very complex interaction of the TiO$_2$, the standard for ground granulated blast furnace slag contains no requirements on these parameters as the influence of the TiO$_2$ is captured with the determining of the activity index.

3.5 Influence of ageing on the characteristics of blast furnace slag and ground granulated blast furnace slag

Dried GBS and dried GGBS are not subject to ageing in dry storage based upon the lack of reaction partners. The storage of wet GBS, particularly in the open air, leads on the other hand to a hardening process as a consequence of the increased chemical combination of water and CO$_2$. The significant influences on the hardening of GBS are illustrated in Figure 3.3 according to Lang [Lan97].

When stored and hardened GBSs are ground and their grinding fineness is assessed based upon the specific surface according to Blaine, then these GBSs can show an appreciably easier ability to be ground in comparison to freshly-produced GBSs. That means that the hardened GBS requires less grinding energy to achieve the same specific surface than freshly-produced GBS of similar origin. But it possesses a coarser grain boundary and with that also seemingly a less latent hydraulicity. Older and fresher GBS also shows with comparable grain boundaries a comparable performance capability. This also demands to some extent the same energy expenditure in the grinding process [Lan97].
Figure 3.3: Influences on the hardening of GBS according to [Lan97]

Verfestigung von Hüttensand : solidification of GBS

### 3.6 Pelletised blast furnace slag

The vitreous solidified blast furnace slag results from the rapid cooling of a fusible phase. Special plants have been developed and built for guaranteeing a high uniformity of the vitreous-solidified product, for its efficient production and for maintaining the relevant work and environmental protection regulations. Granulation plants have become by far the most widespread, in which the wet ash is finely separated with high pressure water jets and intensively cooled as GBS. This granulation process indeed meets the requirements mentioned in the introduction, but demands a dehydration of the GBS to a water content of some 8 to 10 M-% before being shipped and with this an expensive water storage and preparation and an additional drying process before or during the grinding.

There have therefore already been efforts earlier to produce GBS by means of an air granulation system. But in the industrial benchmark, no sufficient rapid cooling of the ash has been achieved so that the glass content in these granulated blast furnace slags are clearly less than those for water granulated GBSs. As an alternative, pelletising plants have been developed in which the basic principle of the air granulation is still preserved but in addition small quantities of water are introduced for the intensive deterrence of the wet ash.

There is a plant like this in operation for example in Fos-sur-Mer in France. As a granulation plant is also operated on the same site, the products produced in two ways can be directly compared with each other. The chemical composition of granulated and pelletised blast furnace slag is to a large extent identical according to [Per02]. However the publication contains no data.
In Fos-sur-Mer there are some 600,000 tons of granulated and some 500,000 tons of pelletised blast furnace slag produced annually [Per02]. Both products are processed independently from their manufacturing process in the cement industry but are also exported to a significant extent to other countries that utilise ground granulated blast furnace slag as a concrete additive.

A diagrammatical representation of the pelletising plant in Fos-sur-Mer is shown in Figure 3.4.

Figure 3.4: Diagram of the pelletising plant in Fos-sur-Mer [Per02]

The pelletising plant operates in a sealed area so that dust or noise emissions cannot arise. This plant design principle was first used in Canada and has been operated since the mid-1970s in Fos-sur-Mer. During the course of this time, several technical and technological alterations in the pelletising process have been carried out, in particular the addition of water was increased. Thanks to the changes, a constant production of pelletised blast furnace slag with a glass content > 80% is guaranteed. Since the upgrading of the plant in 2001, no significant differences in the use of pelletised and granulated blast furnace slag as a main component in cement have been found. The saving of water and energy is viewed as a significant advantage in the operation of a pelletising plant. [Per02]

Investigations made by Ehrenberg [Ehr05] show that the granulation processes can have a significant influence on the characteristics of the GBS. The GBSs shown in Figure 3.5 have been produced from the same blast furnace slag through wet granulation and through pelletising (air cooling).
With a comparable chemical composition, the GBSs showed clear differences in glass content, in their density and in porosity. In comparison to granulated blast furnace slag, the pelletised blast furnace slag has an approximate 19% reduced glass content, an approximate 14% reduced density and an approximate 70% increased porosity. The GBS samples were taken prior to the upgrading of the plant in 2001 and are thereby no longer representative for consideration today.

New and up to now unpublished investigations of the FehS Institute for Building Materials Research into a granulated and a pelletised GBS from France, which have been produced from the ash of a blast furnace, only showed small differences in characteristics. The glass content was 88.9 % / 94.4% and the activity index after 28 days 102 / 103 on the pelletised/granulated GBS. Thereby this pelletised GBS had an output capability like the granulated GBS from the same ironworks and had a higher activity index than some granulated GBSs. Apart from these individual results there are, however, no systematic investigations into the characteristics of pelletised GBS available.
4 Use of ground granulated blast furnace slag (GGBS) as a concrete additive ¹

4.1 Results of research

4.1.1 Fresh concrete

4.1.1.1 Required water content, consistency and processibility

Freshly mixed concrete characteristics are dependent on the substitution rate and the type of introduction of the GBS or GGBS (cement or concrete additive). According to [Hoo00], in the use of GGBS as concrete additive in the USA, the GGBS is always finer than the CEM I that is used, which then leads to a more cohesive concrete mix, which can be more easily compacted through vibrations. Under this prerequisite, greater proportional volumes of coarse rock granulation can be used in order to reduce the water requirement of the concrete [AC195]. It has been established that the use of GGBS in concrete production generally leads to a higher degree of slump (Figure 4.1) or a reduced volume of water for obtaining the similar slump is required [ACI95, Nag89, Ans00]. According to [Meu83, And93], the water requirement of the concrete with GGBS is generally from 3 to 5% lower than the concrete without GGBS for a given slump. The improved processibility of the GGBS concrete can be traced back to the increase in the volume of paste through the mass-related substitution of a CEM I [Hin06, Hoo00 and And93]. According to [Egg02] the improved processibility, pumping capability and retention of the consistency is achieved due to the level and dense surfaces of the GGBS particles. GGBS absorbs only little, if any, water during the mixing process, which also reduces the water requirement of the concrete.

![Figure 4.1: Slump of the concrete with and without GGBS [Meu83] Specific surface (Blaine) of the GGBS 5580 cm²/g](image)

According to [AC195, Egg02], the consistency of the fresh concrete with GGBS changes more slowly than the concrete without GGBS. According to [Meu83, Muk04] concretes with new rule 50 M.-% substitution of the CEM I by GGBS anyway hardly show any change in solidification behaviour.

¹ Concretes and mortar in which GGBS is designated hereinafter as GGBS concretes or GGBS mortar.
As in the use of GGBS as a concrete additive, sulphate is exclusively introduced through the CEM I and its sulphate content is improved on the pure CEM 1, the sulphate requirements coming from the GGBS components remain uncovered. This can accordingly be reflected in poor processing characteristics [Bru02].

### 4.1.1.2 Air content
The natural air pocket content in concretes with GGBS is somewhat lower. GGBS concretes need a somewhat higher addition of air pocket creators in order to achieve the air content of comparable concretes with CEM I [Hoo00, AC195].

### 4.1.1.3 Solidification
As a rule, the solidification times are extended with increasing content of GGBS, in which the temperature has here a higher influence than the substitution of the cement by GGBS [Egg02, Hoo00, AC195, Nag89 and Hin]. No great difference has been observed between GGBS product classes 100 and 120 (according to ASTM C898). According to [Hoo00] at temperatures of < 15°C, the solidification times of the concrete with GGBS can be delayed by up to two hours. According to [Hin06] the increase of the GGBS content in the binding agent from 35 M.-% auf M.-65 % extends the commencement of the consolidation by 60 minutes.

According to [AC195], the delaying effect can be made less severe or eliminated by the application of a conventional accelerator [AC195].

### 4.1.1.4 Bleeding
Generally, bleeding is dependent on the relationship between a specific surface of the solids and the water content in the concrete. If the GGBS is finer than Portland cement CEM 1, its application leads to a reduced bleeding and vice versa [Ac195, Hin, Ans00]. Anyway, this interdependence is not quantified in these publications by the results of investigations. For example Japanese cements with GGBS additives thus show on the basis of finer particles of GGBSa smaller tendency to bleeding [Dai91]. As per [Hoo00, And93, Muk04] bleeding can occur at lower temperatures and high substitution rates of the CEM I due to GGBS. Increased bleeding in concretes with GGBS and CEM I of similar fineness can be caused by a lower absorption capacity of the denser GGBS particles [AC195].

### 4.1.2 Hardened concrete

#### 4.1.2.1 Heat development, cracking due to thermal stresses
The temperature increase in concretes with GGBS elapses more slowly, which amongst other things reduces the thermally caused development of cracks [Hig91, Hoo00, Dai91, Osb02, Nag89]. In this way the maximum temperature reduces in a bulk concrete which has 35 M.-% GGBS in the bonding agent by approx. 9% and with 70 M.-% GGBS by approx. 35% [Hin06]. The hydration heat (hydration time 3 d) of theGGBS-CEM I mixes reduces at 20°C in line with the increasing GGBS content. According to [Kok89] with a slower heat development, the total released hydration heat of the bonding agent mixes is with a 35 to 55 M.-% GGBS higher than that of the CEM I. Generally speaking, the temperature increase and the hydration heat of the concrete is dependent on the reactivity of the GGBS and of the CEM I.
4.1.2.2 Finishing treatment

The hydration speed of the clinker minerals is higher than that of the GGBS. For this reason the concretes with GGBS show a higher sensitivity to inadequate finishing treatment (drying out) when they are young. This applies in particular for low temperatures. Thus, the compression strength of the concrete is achieved with 80 M.-% CEM I substitution by GGBS (Osp = 4000 cm²/kg) after 56 d outside storage at 5 °C and approx. 70 % r. h. only 6.8 N/mm² [Miu00]. Japanese scientists [Nag89] have confirmed this temperature influence on strength (Figure 4.2). For this reason it is recommended in Japan [Nag89] to ensure during finishing treatment that the temperature is not less than 10°C and with bulk concretes not less than 7°C.

![Figure 4.2: Influence of storage temperature on the relative strengths](image)

According to [Hig91], a very slow strength development is only achieved with continuous dry storage. In the early hydration area with concretes that have CEM I and GGBS, the drying-out has only a small influence on the final strengths if the concrete is moistened again after a specified drying-out phase. According to [Hig91], measured higher sensitivity of the concrete with GGBS under laboratory conditions on laboratory test units with respect to drying out is not relevant in practice. Permeability measurements on drill cores from a 200 mm thick concrete block have shown that a concrete with GGBS is not more sensitive than a concrete with CEM I.
This can be traced back to the temperature increase in the early hydration area and with that an acceleration of the reaction of the GGBS. In particular, the concretes with higher GGBS contents and slower strength development need a longer and more careful final treatment [Hoo00m Osb98m Aus92].

The earliest strengths of the GGBS concretes can be increased by means of a heat treatment [Miu00, Dai91]. [Esc04] have investigated the microstructure of CEM I–GGBS mixes (40 M.-% CEM I and 60 M.-% GGBS) after a one-year hydration at 10 and 60 °C and have established that GGBS reacts significantly more quickly at higher temperatures. In this way, after one-year’s storage at 10°C only insignificantly reacted GGBS grains were observed, whereas on the other hand at 60°C some GGBS grains were completely hydrated. Japanese researchers [Kok89] have established that the hydration heat measured after 7 days of Portland cement – GGBS mixes stored at 10% centigrade continuously decreased with increasing GGBS contents. At higher temperatures from 35 to 65°C, the maximum hydration heat was achieved with mixes having approximately 35% GGBS. The authors [Dai91] conclude from this that GGBS at higher temperatures reacts more quickly and the reaction reduces more quickly than with CEM I, so that at higher substitution rates the activation effect due to these cement is too low, in order to accelerate the GGBS reaction. The strength development of heat-treated (1 d, 30°C) samples, which were then stored at 5 or 20°C depends on the fineness of the GGBS. The use of a conventional GGBS fineness (4000 cm²/g) leads to a higher growth in strength after they need treatment compared to the samples with the finest GBS ((8000 cm²/g) [Miu00].

It has been recognized that the later strengths and the density of the concrete with CEM I are negatively influenced by higher temperatures in the early stage of hydration (heat treatment, increase in the temperature in bulky components). According to [Hig91] this effect has not been observed with concretes that have GGBS. Aldea and others [Ald00] have investigated the influence of heat treatments (80 °C and 175 °C) on the characteristics of concretes with differing GGBS contents. It has been established that for optimal durability of the concrete with GGBS, a moisture treatment at room temperature is the most suitable.

4.1.2.3 Strength

The compression and bending strengths of concretes with GGBS can vary widely. They are dependent on the composition and fineness of the GGBS, the proportion of the GGBS in the concrete, the w/(z+h)-figure, the composition and fineness of the CEM 1 that is used and the conditions of the final treatment. The earliest strengths (1 to 3 d) of the concretes with the substitution of cement by GGBS are as a rule less than the comparable concretes [Hoo00, Hwa86, Raj03, Nob02, Nag89, Hin]. When the substitution rate is not very high, GGBS concretes after 14 days achieve comparable or even higher strengths than comparable concretes with CEM I. Typical strength developments of mortars with GGBS in relation to the substitution of the cement and the storage period are presented in Figure 4.3. According to [Dat95], a typical Portland cement concrete achieves after 7 days approx. 70 to 80 % of the 28 d strength and a further increase in strength up to 90 days comes to approximately 5 to 10%. The strength of the concrete with approx. 50 M.-% GGBS normally totals after 7 days approx. 40 to 60% of the 28-day strength and the further increase in strength up to 90 days is of the order of approximately 10 to 20%. The optimal substitution of CEM I by GGBS with regard to the late strengths is to be found according to [Bab00, ACI95, Meu83, Nob02, Hog91] in the range between a 40 and 60 M.-%. [Tou01] and others have produced concretes with 60, 70 und 80 M.-% substitution of cement with an GGBS of Product Class 120 as per ASTM and the highest strengths have been determined on samples with 70 M.-% GGBS. High early strengths are achieved when microsilica is used in addition to the GGBS.
Differing reactions had been established to the environmental or processing temperatures in the development of the strength of the GGBS-concretes in comparison with CEM I – concretes: at low temperatures, the strength development slows down more strongly, whilst at high temperatures it accelerates more strongly [Miu00, Hoo00, ACI95, Nag89]. When using GGBS as a concrete additive in cold regions – as is generally the case - the concrete formula and the duration of the final treatment must be adjusted in line with the strength development.

Figure 4.3: Influence of the GGBS content on the mortar strengths (as per [Hwahe86] from [Bab00])
The strength of the GGBS concretes or mortars depends upon the fineness of the GGBS. The strengths of the concretes increase with an increasing specific surface of the GGBS [Tas98, Ehr05, Pal03m Miu00, Hog81 and Sch69] (Figure 4.4). Apart from the specific surface, the grain size distribution of the GGBS is also of significance [Wan04, Ehr05]. A higher proportion of fine particles (< 3 µm) with the same specific surface leads to higher early strengths and a higher proportion of particles in the range from 3 up to 20 µm to higher final strengths [Wan04]. Higher early strengths can be achieved by using the finest GBS and an optimal adjustment of the grain size distributions of the GBS and the clinker proportions [Ehr05]. The fineness of the GGBS particularly influences also the development of the strengths at low temperatures. In this way, the strength development of mortar test samples with 50 M.-% CEM I substitution by GGBS with a specific surface of 8000 cm²/g at 5°C is comparable with the strength development of reference samples, but on the other hand comparable samples with an GGBS with 4000 cm²/g show a significantly slower strength development [Miu00] (Figure 4.5). Gao and others [Gao05] have determined the micro-hardness of cements with GGBS and established that with an increasing GBS fineness of 4250 cm²/g to 6000 cm²/g, a lower CEM I change (20 M.-% instead of M.-40 %) is sufficient in order to strengthen the weak.
crossover zones between the additional grain and the cement matrix.

**Figure 4.5:** Influence of the temperature and of the fineness of GGBS on the development of the strength of the mortar (diagram according to data from [Miu00])

Water cement figures and physical and chemical-mineralogical characteristics of the cement can also influence the performance capability of the GGBS in concrete. The strengths of the test samples increase with the reducing \( w/(z+h) \)-figure (Figure 4.6), in which an increasing \( w/(z+h) \)-figure can have a positive influence in a determined \( w/(z+h) \)-range (between 0.63 and 0.67) on the contribution of the GGBS to the strengths of concretes [Meu83, ACI95] (Figure 4.7).

The fineness of the GGBS should be higher than that of the cement for a good performance capability of the concrete. According to Pal and others [Pal03] the GGBSs with the following finenesses (specific surface according to Blaine) are marketed for application in concrete in various countries:

- United Kingdom: 3750 – 4250 cm\(^2\)/g,
- The Netherlands approx. 4,500 cm\(^2\)/g,
- USA: 4500 – 5500 cm\(^2\)/g,
- Canada: approx. 4500 cm\(^2\)/g,
- India: 3500 – 4500 cm\(^2\)/g,
- Malaysia: approx. 4500 to 5000 cm\(^2\)/g.

The ageing of the GBS leads to lower strengths of mortars with a high GGBS content in the bonding agent [Fri94, Bru02]. The negative influence of the ageing can partly be offset by having finer grinding processes [Fri94]. According to [Bru02] a solution to this problem can be found if parallel to the use of basic sand - a certain amount of fresh sand is available so that a mix of both qualities is used. [Lan97] stored 5 different GBSS for up to 9 months in the open air and has then ground them to a specific surface of approx. 4200 cm\(^2\)/g. The ground granulated blast furnace slag (GGBS) was homogenised with a ground standard clinker in the ratio of 60/40 and an additional 75/25 sulphate carrier. No effects from the period of outside
storage on the cement strengths were observed.

**Figure 4.6:** Influence of the GGBS proportion in the bonding agent and of the w/(c+h) ratio on the compression strength of concretes [Meu83]

**Figure 4.7:** Relative strengths of concrete test samples with GGBS (average values from the samples with differing HSN content) depending on w/(c+h) ratio [Meu83]
In practice in the UK up to 85 M.-% CEM I has been substituted by GGBS, for example when building the British Library. If higher GGBS contents are used in the concrete, the strength requirements are sometimes specified for a greater age than 28 days. In such cases, the judgement of the conformity is made on test sample units, which have been tested at this specified age. This is a regular procedure in Germany with concretes with slower hardening characteristics. The strength certification at a greater age in Germany is not however the general rule, but is to be agreed as is appropriate. Figure 4.8 shows the strength development of three concretes with in each case 300 kg/m³ of bonding agent (CEM I without GGBS and with substitution of 40 or 70 M.-% of the CEM I by GGBS) [App92].

![Figure 4.8: Compression strength of concretes with CEM I and 40 M.-% or 70 M.-% subsitution by GGBS. Bonding agent content in each case is 300 kg/m³ [App92])](image)

The final strength of a bonding agent mix (blast furnace cement) is however clearly dependent on the respective final strength that the respectively used clinkers develop in pure CEM 1 [Bru02]. According to [Nag89] the activity index of the GGBS depends on the CEM I that is used. According to [Nag81], gypsum additives in GGBS up to 3 M.-% SO₃ have no clearly negative influence on the characteristics of the concrete. Depending on the composition of the GGBS and of the CEM I that is used, these can contribute to small increases or also reductions in strength. Bruckmann [Bru02] has found that the highest early strengths of bonding agent mixes with 32 M.-% GGBS (CEM II B/S) ware achieved with a sulphate proportioning in the range of between 2.0 und 3.0 M.-%. In this, the optimal sulphate proportioning depends also on the clinker that is used. According to [Hin06] smaller strengths of GGBS concretes are caused partially by the gypsum proportioning not being optimal especially at higher substitution rates (> 50 M.-%) . According to [Fri94], the increasing of the sulphate content by 1 to 4 % by additional gypsum in mortars with 70 M.-% CEM I substitution by GGBS leads to the reduction by 30 % of the compression strengths after 28 days storage.
Also in the work carried out by Schwiete, stated by Ludwig [Lu68], it has been found that the strengths of a blast furnace cement that has a high content of GBS reduce if with a separate portroning the gypsum or semihydrate contents exceed 1 M.-% SO₃. On the other hand, the 2-4% addition of artificial anhydrite leads to an improvement of the 7 to 28 day strengths compared with a sulphate-free control mix. Also the alkali proportion in a CEM I influences the strength of GGBS-containing mortar [Fri85, Loc00].

In order to charge the contribution of the GGBS to the strength development an activity index is to be determined for the respective GGBS. ASTM C989 defines the activity index as the ratio between 28 day strengths of mortar samples with 50 M.-% CEM and 50 M.-% GGBS and reference samples with 100% CEM I, expressed as a percentage. Depending on the relative strength that is achieved, the GGBS is classified in three product classes of 80, 100 and 120. According to Hooton and others [Hoo83], the reactivity of the GGBS is dependent on the glass content, the chemical and mineralogical composition, the fineness and the type of activation. The chemical composition of the GBS accordingly plays an important role with regard to its reactivity towards cement. According to DIN EN 197-1 [DIN04] the mass ratio (CaO+MgO)/SiO₂ must be greater than 1,0. The most recent investigations by the BDZ [VDZ05] show that the chemical reactivity of the GBS must not categorically correlate with the strength contribution. Also according to Mantel [Man94], no clear correlation exists between the chemical compositions of the GGBS or of the CEM I and the strength development of their mixes. According to what he says, the activity of the GGBS depends mainly upon the fineness.

The GBS consists generally of more than 90 M.-% of glass. The European cement standard [DIN04] prescribes, for limiting GBS to be used for cement production, that the GBS must be in terms of volume proportions more than two thirds of vitreous material and must consist of at least two thirds of CaO, MgO und SiO₂. Some researches show that GBS with a lower glass content of 30 - 65 M.-% can be suitable for concrete production [Pal03].

The activity of GGBS can therefor not be clearly judged solely through the glass content and chemical composition. Here the fineness of the grinding and the grain size distribution of the GGBS, the activation effect of different cement clinkers, the GGBS proportion in the binding agent and the type and volume of the sulphate carrier are also of significance.

### 4.1.2.4 Elasticity module

The elasticity module of the GGBS cements is similar to that of the CEM 1 concretes [Hoo00, ACI95, Muk04]. According to [And93], the elasticity module of the concretes with GGBS is somewhat higher than that of the concretes containing CEM I with the same strength.

### 4.1.2.5 Drying shrinkage

Concretes with CEM I and GGBS with the same type and the same volume proportion of rock granulation (the same cement paste content) show the same drying shrinkage [Hoo00, San04, And93] although in [ACI95, Hog81, Nag89, Hin] also a higher drying shrinkage is reported for the concrete with GGBS. This effect can be partially traced back to a higher cement paste volume that has arisen due to the mass substitution of the cement by GGBS. According to [Muk04], the shrinkage of the concrete with 50 M.-% substitution is somewhat lower than that of the reference concrete. According to [Nag89, Muk04] the shrinkage of the GGBS concretes depends on the duration of the final treatment. A final treatment that is too short leads to a higher shrinkage.
The gypsum content of the bonding agent influences the shrinkage behaviour of the concretes [Ale79]. In concretes with 35 M.-% GGBS in the bonding agent, in a similar way to GGBS-free concretes, the drying speed decreases with an increasing SO\textsubscript{3} content [Hin06].

4.1.2.6 Creeping
The creeping of GGBS-containing concretes is similar to that of concretes without GGBS. In the earlier ages (three days) the creeping levels of the concretes with GGBS is somewhat higher [Nag89]. According to [Hin06], the creeping reduces with an increasing GGBS content in the bonding agent of the concrete. Also, an increasing sulphate content (1.5 M.-% bis 4.5 M.-% SO\textsubscript{3} in the bonding agent) leads to a reduced creeping level of concretes with 35 M.-% GGBS in the bonding agent.

4.1.2.7 Concrete structure
The pore size distribution and the porosity of the concretes containing GGBS are different from those of the concretes with CEM I. The structure of the cement paste with GGBS is characterised by a lower porosity and reduced pores diameter in the centre. This can lead to reduced permeability and higher durability of the concrete [ACI95, Loc00].

4.1.2.8 Colour
The substitution of CEM I by GGBS leads among other things to a clearly brighter colour of the surface of the concrete [AC195, Nag89, Con05]. This also allows the volume of the pigments in the production of coloured concretes to be reduced [Con05]. When using a white cement up to 30 M.-% can be substituted by GGBS, without the colour quality of the concrete surface being affected [AC196].

The internal part of GGBS concrete during the hardening process turns blue-green due to complex reactions of the sulphide. Upon contact with air, this colouring is reduced due to oxidation.

4.1.2.9 Additives
The influence of additives on the characteristics of concretes containing GGBS is similar to that with concretes that have pure CEM I. The use of GGBS with a higher fineness level than that of the CEM I can call for increased addition of pore forming materials at higher substitution volumes [AC195, Nagand89, Muk04]. In contrast to that, the use of a liquid in the concretes with GGBS is lower [AC95] – an effect which can also be observed when using GBS-containing cements.
The delaying effect increases with the use of a constant volume of a retarder with increasing content of GGBS [ACI95]. According to [Muk04] the volumes of additives should be re-optimised with the differing proportions of GGBS.

4.1.2.10 Carbonisation

The carbonisation of concretes with GGBS is similar to that of concretes with CEM I of comparable strength [Hig91, Hoo00]. Higher substitution rates of the EMI can lead to higher speeds of the carbonisation [Dai91, Hig91, Osb98, Nag89], in which the final treatment duration has a strong influence [Nag89]. According to Osborn [Osb98], concretes with 50 M.-% CEM I substitution of GGBS show a similar carbonisation behaviour to CEM I concretes under most laboratory and field conditions if the concrete formulae are similar. Clear and others have found [Cle91] in a field research in an industrial application in concretes with 50 M.-% GGBS in the bonding agent after three years of storage only a marginally higher carbonisation depth than in the reference concretes without GGBS, which according to the authors' evaluation hardly increases the risk of steel corrosion. In any case, with concretes with a high GGBS content a higher carbonisation rate has in particular been found, if a dry micro climate (internal component) is predominant. In a field research into rain-protected concrete supports with 70 M.-% GGBS (370 kg/m³ bonding agent) after 9.5 years, a depth of up to 26 mm of carbonisation was measured, whereas on unprotected concrete tiles of the same composition the carbonisation depth was only 4.5 mm [Osb98]. Under wet conditions (e.g. storage on wet floors) the carbonisation of the concretes containing a high quantity of GGBS was just as slow as with CEM I concretes.

Higgins [Hig91] states that the influence of the GGBS content in concrete is only of secondary significance for the rate of carbonisation in addition to the strengths and environmental conditions. The use of concretes with high GGBS contents is not worth recommending for the production of slender steel reinforced concrete pillars. If with steel reinforced concrete components have to be exposed to environmental conditions that are favourable for carbonisation, it is recommended that the CEM I substitution by GGBS should be limited to 50 M.-% [Osb98].

According to [Fri94], the sulphate content – 1 up to 4 M.-% SO₃ in relation to the bonding agent – in mortars with 30 M.-% CEM I and 70 M.-% GGBS has no influence on the carbonisation when freshly produced GBS is used. When using an artificially aged GBS, the carbonisation depth increases with increasing sulphate content.

4.1.2.11 Resistance against CI-diffusion

Concretes with GGBS show a high resistance against the penetration of Cl-ions, which has been shown in several laboratory and field researches [Hig91, Hoo00, Dai91, Yea05, Osb98, Raj03, ACI95, Cle91, Nob02, Nag89, Tho97]. The permeability of a concrete for Cl-ions reduces with increasing GGBS proportions and age of the concrete. GGBS-containing concretes with CEM I show lower permeability figures than GGBS containing similar concretes with low C₃A blast furnace cement (type V. as per ASTM) [Yea05]. Aldea and others [Ald00] have established that at 80°C heat-treated concretes with GGBS are up to 50% more permeable for Cl-ions than 28 days concretes stored in damp conditions at room temperature. The lowering of the diffusion possibility of CI ions is to be traced back to the density of the cement paste structure and an increased absorption capability of the hydration products of the GGBS for CI ions [Hig91, Hoo00, Dhi96, Nob02, Gun92].
4.1.2.12 Frost resistance

The frost resistance of concretes with GGBS is comparable with the resistance of CEM I concretes of similar strength and air pores content [Hig91, Hoo00, ACI95, Nag89, And93]. High cement substitution rates (> 60 M.-%) and the disclaiming of LP generators can lead to a reduction of the frost resistance [Hig91].

4.1.2.13 Frost and de-icing salt resistance

With a substitution of a CEM I by ~ 50 M.-% GGBS, the resistance of the resulting concretes against frost-de-icing salt attack – as known – can be significantly reduced [Hoo00, Afr94, Osb98, ACI95, Loc00]. This can be partially offset by the introduction of additional air pores. Also a suitable final treatment leads to a higher resistance of the cement against frost and de-icing salt attack. As a further action against this attack, the coating of concrete surfaces that are under stress is recommended [Osb98]. The higher sensitivity of the GGBS concretes against frost and de-icing salt attack is to be traced back to the carbonisation of the concrete surface and the higher capillary porosity of such concrete surfaces [Loc00, Lan03].

4.1.2.14 Resistance to reaction against alkali-silicic acids

It is recognized worldwide that GGBS in the concrete reduces the risk of an alkali-silicic acid reaction (AKR) [Tho96, Hig91, Tho94, ACI95, Hog81, Nob02]. With increasing proportions of GGBS, the expansions of concretes with alkali sensitive additives are reduced. According to [Tho96] a 50 M.-% substitution is necessary in order to eliminate the AKR sensitive rock granulations (siliceous limestone) and 35 M.-% substitution so as to prevent a less reactive graywacke. According to [AC195] and [Nob02] an GGBS content in the bonding agents of > 40 M.-% is necessary in order to avoid the expansion reactions based on an AKR (Na$_2$O$_{eq}$ des CEM I < 1 M.-%). The mechanism of action is not however conclusively explained. A reduction of the alkali permeability caused by the density of the hardened cement paste is certainly of significance here [Hig91, Dai91]. As per [Hoo00], the presence of GGBS included in the hardened cement paste matrix leads to the lowering of the hydroxyl ions in the pore solution and to the integration of higher contents of alcalis into the CSH phases.
GGBS as concrete additive

4.1.2.15 Resistance to sulphate attack

The partial substitution of the CEM I by GGBS in large volumes leads generally to the improvement of the sulphate resistance [Hig91, Hoo00, ACI95, Hog81, Loc00]. The sulphate resistance of GGBS-containing concretes is dependent on the substitution volumes of the CEM I, on the C₃A content in the CEM I, the aluminium oxide content in the GGBS and the w/(c+h) ratio. With a CEM I substitution by GGBS > 65.-% a similar or higher sulphate resistance is achieved than in concretes with CEM I blast furnace cement. In Germany at least 65 M.-% is specified for blast furnace cement with high sulphate resistance of the GBS. In the UK, the aluminium oxide content (Al₂O₃), 15 M.-% may not be exceeded in GGBS for concretes with a high sulphate resistance [Hig91]. At higher Al₂O₃ contents in the GGBS, limiting the C₃A content in the cement to 10 M.-% is recommended. In accordance with the Canadian and American experiences [AC195], at least 50 M.-% of the CEM I must be substituted by GGBS for a good sulphate resistance of the concrete, in which the C₃A CEM I can be 12 M.-% as long as the Al₂O₃ content in the GGBS does not exceed 11 M.-% According to Locher [Loc66, Loc00], between 20 M.-% und 55 M.-% GBS appears as a pronounced minimum in sulphate resistance, even with mixes with C₃A-free clinker. A significant cause of the high sulphate resistance is the high diffusion resistance of the hardened cement paste with high proportions of a GGBS (> 65 M.-%), which prevents the penetration of sulphate ions.

In contrast to the German experiences with blast furnace cements that contain GBS, various investigations from UK and the USA also establish that mixes from GGBS (proportion > 65 M.-%) and Ordinary Portland Cement (OPC) in no way always provoke a higher sulphate resistance of the concrete than the pure OPC. Examples in this respect:

- In long-term investigations over a period of up to 16 years, sulphate storages were performed by F.C. Stark both under laboratory and field conditions. The concrete bodies were exposed to a high sulphate attack and a moisturising and drying cycle. Figure 4.9 shows in a graphic representation the weathering behaviour of the bodies that were tested on the basis of OPC or of mixes of OPC and GGBS. The GGBS-containing test bodies showed stronger weathering than the test bodies that had an OPC base [Sta02].

- Higgins and Crammond have investigated concrete bodies that have been produced on the basis of OPC, SRPC (HS Portland cement) and mixes (70 M.-% GGBS / 30 M.-% OPC) and different rock granulations. The test bodies have been stored at 5 °C or, at 20 °C in various sulphate-containing solutions. Depending on the rock granulation, the GGBS containing test bodies showed either a better or also a worse sulphate resistance behaviour than the test bodies based on pure OPC [Hig03a].

- Investigations by Higgins have shown that by means of the addition of a small proportion of calcium sulphate or calcium carbonate, the sulphate resistance of GGBS-containing concretes is improved [Hig03b].
4.1.2.16 Resistance to effects of sea water

Investigations over many years in several countries have shown that GGBS in concrete leads to the increasing of the resistance against seawater [Hig91]. A substitution of CEM I by 25 - 35 M.-% GGBS improved the resistance of the concrete. According to [Osb98] concretes with a binding agent of 380 kg/m³, a w/(c+h) of 0.5 und 70 M.-% substitution of the CEM by GGBS show a good resistance against the effects of seawater, if the concrete components remained under water. In the tidal area where also frost and dew changes take place, these concretes show some flaking.

4.1.2.17 Acid resistance

In general, GGBS-containing concretes are more capable of resistance against the effect of diluted acids than CEM I-containing concretes [Bou91, Nob02]. It should be noted here that normally the quality of the concrete - in particular the w/b ratio – can have a higher influence on the resistance to acids than the composition of the bonding agent [Osb99].
4.1.2.18 Resistance to erosion

The erosion resistance of concretes that have 50 M.-% GGBS after 7 days of storage is comparable with the corrosion resistance of concretes with pure CEM I [Hig91]. According to [And93] the substitution volume should not exceed 50 M.-% for concretes with good erosion resistance.

4.1.2.19 Tendency to blooming

Concretes with GGBS have a lower tendency to blooming man CEM I concretes [And93].

4.1.2.20 Fire resistance

Ravindrarajah and others have investigated the fire-resistance of concretes with differing bonding agents [Rav02]. It has been found that the temperature-dependent drop-off of the strength of the concretes with 62 M.-% GGBS and 38 M.-% CEM I is comparable with that of CEM I concrete up to 1000 °C.

4.2 Regulations for use

4.2.1 General items

Basically all rules for use are oriented towards the 125 years of experience in the production and use of cements containing GBS. This has its effect in numerous publications on the use of ground granulated blast furnace slag in concrete, in which the freshness and set concrete characteristics, the longevity and special characteristics such as sulphate resistance, avoidance of damaging alkali-silicic acid reaction and chloride bonding are compared with those of concretes with GBS–containing cements.

Presented below are the basic principles of the rules for use in different countries. In this, it should be taken into account that all of the rules for use for GGBS as a concrete additive are embedded in the on-site applicable higher-ranking rules for the composition of concrete (water-cement ratio, minimum cement content), concrete covering etc. A direct, all-country embracing comparison is therefore not always possible.

4.2.2 Belgium

Belgium has an ATG (Technical Agreement) on a set of regulations for the composition and the characteristics of GGBS for the use in concrete, see Section 3. Up until now however very little GGBS has being directly used with the concrete as the substitution rates are still subject to major limitations. A maximum of 45% of the cement may be replaced by GGBS with a K-value of 0.9. With exposure classes X F, XC3 and XC4 there is normally a maximum of 20%. A reprocessing of the rules for use is in the course of preparation.
4.2.3 Finland

Finland uses one third of its granulated blast furnace slag as concrete additive. The use is made with a $K$-value of 0.8 for all permitted types of cement. The $K$-value totals 1.0 for the exposure class XA.

4.2.4 France

In France the use of GGBS in concrete is currently made as per the $K$-value concept. Accordingly, up to 30% GGBS with a $K$-value of 0.9 may be used.

4.2.5 Great Britain and Ireland

Ireland has taken over both the British requirements on GGBS [BS 1992] as well as the use practices, so that both countries can be considered jointly.

Great Britain has introduced its first standard for Portland slag cement in 1923. Today in Great Britain there is practically no cement produced that contains GBS. The use of GBS is today more or less exclusively as a concrete additive. A multitude of regulations apply for the use of GGBS in concrete and according to the field of application. A summary can be found on the Internet [In 2]. But for general use, in addition to the standard for GGBS the European standard EN 206 and the British addition to this standard of BS 8500 [BS 2002] are of special significance.

BS 8500 extends the exposure classes as per EN 206 and arranges these classes for the use of particular cements or combinations of Portland cement and GGBS, fly ash or ground limestone. These combinations correspond in their respective composition to the compositions of cements as per EN 197. Concrete-mixer produced concretes with Portland cement and GGBS as a bonding agent are compared according to GGBS-content with CEM II/B-S or CEM III/B - produced concretes and can be used on an equal footing for the exposure classes like the corresponding cements as per EN 197.

As the strength development of a mixture from Portland cement and GGBS depends both on its composition, granulometry and sulphate content amongst other things, the manufacturers of GGBS test their product with Portland cement which the user of the GGBS specifies for his particular concrete production. From this, recommendations are made for the optimal volumes of GGBS taking into account the regulations according to BS 8500 and as needs arise any supplementary regulations specifying minimum or maximum contents of granulated blast furnace slag (Figure A7). For special applications or specially exposed structures, use is made in addition of a "consultant".

Table 4.5 Section 4.3.2.3 contains a summary from Ireland with classifications of cement contents (cement = Portland cement + GGBS), substitution volumes, minimum strengths and maximum water cement ratios for the different exposure classes as per EN 206 [ in 3] and examples of uses for three different applications with three different exposure classes.
The rules apply for mixes with CEM I 42.5 N or higher. Representative samples of each monthly average sample of the concrete additive material and of each monthly average sample of the CEM I are taken each month, which are then evaluated for general use. Combinations of this concrete additive material and of the cement samples are tested in specified mix ratios for compression strength in conformity with the testing methods for the determination of cement strength as per BS EN 196-1, with all references to "cement" contained therein being assigned to the "mixture".

Where a certification by a third party is required, the certifying body can selectively exclude specified mix ratios.

The strength results are evaluated as per the requirements for a strength class which is stated in Table 4.1.

The sliding average values of the early and standard strength are calculated as averages of the most recent test values, taken over a period of time of not less than six months and not more than 12 months except with a new combination. In this case, the sliding average values are based upon all available data.

The requirements count as being met if the relevant lower limits in Table 4.1 are maintained with statistical certainty and the relevant upper limits are not exceeded. The statistical certainty is at the lower limit + 5 N/mm² related to the lower limit for the standard strength and +3 N mm² for the limit value of the early strength, statistically calculated from the testing of the individual values. A detailed overview of the provisions in BS 8500 -2 is included in Appendix D.

**Table 4.1:** Requirements on strength classes for combinations as per BS 8500

<table>
<thead>
<tr>
<th>Strength class of the combinations</th>
<th>Early strength</th>
<th>Standard strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 days N/mm²</td>
<td>7 days N/mm²</td>
</tr>
<tr>
<td>22.5L</td>
<td>—</td>
<td>12</td>
</tr>
<tr>
<td>32.5L</td>
<td>—</td>
<td>12</td>
</tr>
<tr>
<td>32.5N</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>32.5R</td>
<td>—</td>
<td>20</td>
</tr>
<tr>
<td>42.5L</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>42.5N</td>
<td>20</td>
<td>—</td>
</tr>
<tr>
<td>52.5L</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>52.5N</td>
<td>20</td>
<td>—</td>
</tr>
</tbody>
</table>

The statistical certainty takes into account the fluctuations of the cement and of the concrete additives. A statistical certainty is not necessary for the upper limit as the possibility that a mix exceeds the upper limit for the specified suitability is improbable. Regardless of the test results that are received, the proportions of GGBS should not exceed 85 M.-%.
Issue of certificates

If a conformity certificate according to this process is issued, this relates to the GGBS of a specific origin combined with a CEM I of a specific origin. The certificate must contain:

- Identification of the origin of the GGBS and of the CEM I.
- The month, which represents the most recent mix samples.
- The period of time for which the evaluation will be used if it is less than 6 months.
- The test results for the mix samples, corresponding to the mix ratios.
- Details of the permitted mix ratios, which conform to the requirements of this Appendix, confirming the strength class of the mix.
- The signature of the person responsible for the test.
- BS 8005-2 contains in addition an informative appendix in which an example for the conformity process is given.

In the national application documents for EN 206 relating to the requirements on the composition of the concretes, no differences are made in this respect as to proportions that are used of GGBS and CEM I in practice on the building installations or if a cement of a similar type is used.

4.2.6 Netherlands

The Netherlands is traditionally the country with probably the highest production of GBS containing cements per capita. Albeit, the parallel production and use of GGBS as a concrete additive commenced in 2001. The use is controlled by means of the BRL 9325 and the BRL 0340 [BR06a, BR06b]. A KOMO product certificate as per BRL 9325 confirms the equivalence with regard to compression strength of an GGBS-Portland cement mix with a cement containing GGBS, which contains similar granulated blast furnace slag. The tests correspond to those on cements (GGBS/CEM I = 50.50 or 70.30). Durability investigations are not carried out with this. A KOMO certification as per BRL 9340 confirms the suitability of the GGBS – Portland cement – mix as per BRL 9325 for the use in concrete for specific locations-(exposure) classes. The certified concrete compositions must correspond to the compositions as per NEN 6720. The concrete technical strength and durability tests are made in comparison to a reference concrete. GGBS - Portland cement-mixes have been determined for the KOMO certifications as per BRL 9325 and 9340 and can be utilized as cements containing granulated blast furnace slag which have a similar granulated blast furnace slag content in the concrete.
4.2.7 Austria

Austria has in fact one standard for GGBS and other concrete additives with the ÖNORM B 3309. Practically no use of GGBS in concrete takes place with the exception of application areas which in Germany would be considered as coming under the building-inspection non-regulated area.

4.2.8 Sweden

Some 20,002 to 30,000 tonnes of GGBS per year together with CEM I all CEM I I with a K-value of 0.6 are used in Sweden. This volume corresponds to 20 to 30% of the granulated blast furnace slag produced in Sweden. The substitution volume is limited to 50%. But there are variations for differing exposure classes. The proportion of GGBS can total up to 230% of the cement content for X0 and XA1. The proportion of GGBS should be between 150 and 400% of the CEM I proportion for CEM I / GGBS mixes as a bonding agent with a higher sulphate resistance. The regulations are contained in the Swedish adaptation of EN 206-1 [SVE2004]. Cements containing GBS are not produced in Sweden.

4.3 Fields of application and practical experience

4.3.1 General items

The use of GGBS as a concrete additive has a long tradition in various countries. The following sections give a country-related summary.

4.3.2 Europe

4.3.2.1 Germany

General items

Germany has operated the use of GGBS directly in concrete production by means of building inspection permits (see Appendix C) probably as one of the first countries in parallel to the production of cements containing GBS from the 1940s up to the 1960s.

Thurament

After many years of preparation, in 1923 the production of Thurament was started by the Saxony Thuringia Portland Cement factory Prüssing Co., A.-G., Division of the Thuringia Unterwellenborn Cement Factory. [Th1038]. In the book "Thurament" [Th1938] coverage is given to characteristics, application examples, including an extensive photographic documentation and the results of suitability investigations of the Federal Materials Testing of Berlin Dahlem, of the Kaiser Wilhelm Institute for Silicate Research and of other testing institutions.

Thurament was moreover also offered by other cement plants. The cement pocketbook [ZE 1968] mentions the Heidelberg AG Portland cement factory and the Sulzbach Rosenberg factory 1968/69 ultimately as a producer of Thurament. The use of this has been made since 1943 on the basis of a permit. Up until now, it could not be clarified whether or when this permit was withdrawn. The core statements of the permit can be found in [ZE 1968 and KE 1963].

In this is stated: "Thurament consists of a finely ground, granulated, basic, latent hydraulic blast furnace slag with small volumes of activators, principally gypsum. On 1.0 part by weight of the Thurament – Portland cement- mix a maximum 0.5 part by weight of Thurament may be allotted. A larger proportion of up to 0.66 part by weight of Thurament requires special permission based upon ongoing suitability tests. Subject to these prerequisites, Thurament may be taken into account on the requisite minimum content of bonding agent."
The strength was tested on a mortar mixture from the same parts of Portland cement and Thurament as with cement according to DIN 1164. The mortar must achieve the values that are given in this standard for Portland cement Z275. The strength must as a rule after 28 days and at the latest after 56 days achieve at least 70% of the strength which resulted at the similar tests for a mortar mixture without the Thurament additive at the same test age. Thurament was used for bulky components which can be kept wet for longer, such as for example foundations, supports, piles, dams and barrages and for fields of application within the meaning of DIN 4030 – concrete in concrete-harming waters and soils – with increased Thurament proportions as needs arise.

But Thurament was not only used in combination with Portland cement. In [Th 1938] it says: “Cement + Thurament mixes differ in accordance with the type of cement that is used (Portland – Iron Portland – or blast furnace cement), in accordance with the stresses in the structure and according to the requisite resistance capability against the effects of chemicals and other things.” On the possible mixing ratios it is stated: “Basically any cement can be processed with Thurament, even blast furnace cement, as this still separates sufficiently lime hydrate. Depending on the strength and resistance capability against chemical effects, the following mixtures can be utilized:

- Portland cement (PZ) and high-quality Portland cement
  0.34 PZ + 0.66 Thurament up to 0.66 PZ + 0.34 Thurament

- Iron Portland cement (EPZ)
  0.50 EPZ + 0.50 Thurament up to 0.80 EPZ + 0.20 Thurament

- Blast furnace cement (HZ)
  0.66 HZ + 0.34 Thurament up to 0.80 HZ + 0.20 Thurament

In addition, Thurament has also been used in combination with lime hydrate. The mix ratios ranged from 0.25 parts of lime hydrate and 0.75 parts of Thurament up to 0.80 parts of lime hydrate and 0.20 parts of Thurament. In the construction of dams in the 1930s the concrete formula was as per that stated in Table 4.2:

**Table 4.2:** Concrete formula for dams in kg/m³.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>89</td>
</tr>
<tr>
<td>Thurament</td>
<td>134</td>
</tr>
<tr>
<td>Slack 0 – 0.5 mm</td>
<td>345</td>
</tr>
<tr>
<td>Slack 0.5 – 2 mm</td>
<td>193</td>
</tr>
<tr>
<td>Slack 2 – 8 mm</td>
<td>254</td>
</tr>
<tr>
<td>Chippings 8 – 15 mm</td>
<td>382</td>
</tr>
<tr>
<td>Chippings 15 – 30 mm</td>
<td>380</td>
</tr>
<tr>
<td>Chippings 30 – 65 mm</td>
<td>760</td>
</tr>
<tr>
<td>Water</td>
<td>175</td>
</tr>
<tr>
<td>Water bonding agent factor</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Some further structures and their concrete composition are specified in Table 4.3. In addition, as part of the building of the country's motorways, numerous bridges were made with mixes of Portland cement and Thurament. In addition to the foundations for the bridge-building work, there was in particular the application for the concreting of the piles and supports. A special item is the dam on the Obere Saale at Hohenwarte, in the building of which in 1938 a mixture of 0.60 parts by volume of trass cement and 0.40 parts by volume of Thurament was used.

**Table 4.3**: Examples of the use of "Thurament"

<table>
<thead>
<tr>
<th>Structure</th>
<th>PZ Parts by vol</th>
<th>Thurament Parts by vol</th>
<th>Rock granulations</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuchsturm at Jena</td>
<td>0,25</td>
<td>0,75</td>
<td>4</td>
<td>Sand</td>
</tr>
<tr>
<td>Sewerage container Jesewitz</td>
<td>0,25</td>
<td>0,75</td>
<td>6</td>
<td>Gravel sand</td>
</tr>
<tr>
<td>Intake structure Wurzen 1926</td>
<td>0,34</td>
<td>1,26</td>
<td>9</td>
<td>Gravel sand</td>
</tr>
<tr>
<td></td>
<td>1,0</td>
<td>0,60</td>
<td>12 bzw. 16</td>
<td>k.A.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Piles</td>
</tr>
<tr>
<td>Paradies Bridge Jena 1927/28</td>
<td>0,75</td>
<td>0,75</td>
<td>4,5</td>
<td>Gravel</td>
</tr>
<tr>
<td></td>
<td>0,75</td>
<td>0,75</td>
<td>8</td>
<td>Gravel</td>
</tr>
<tr>
<td>Pink Dam</td>
<td>0,34</td>
<td>0,66</td>
<td>k.A.</td>
<td>k.A.</td>
</tr>
<tr>
<td>Bleiloch Dam</td>
<td>0,5</td>
<td>1,0</td>
<td>6</td>
<td>Diabas</td>
</tr>
<tr>
<td>Oker-Düker Inland canal 1932</td>
<td>160 kg/m³</td>
<td>160 kg/m³</td>
<td>k.A.</td>
<td>k.A.</td>
</tr>
</tbody>
</table>

The **Figures 4.10 to 4.13** show some examples for the production of structures in Portland cement-Thurament-concretes. All of the photos have been taken from [Th1938].
Figure 4.10: Bleilochtal dam 1930/1931

Figure 4.11: Oker-Düker of the inland canal 1932

Figure 4.12: Bridge for the highway in Bavaria
By way of a summary, Fritz Keil stated in his book in 1949 on "Blast furnace slag": "Thurament is composed of high clay-containing slag sand from Unterwellenborn and contains gypsum at a volume of some 3 to 4 & as an activator. Thurament is used as a hydraulic additive above all in solid structures in weirs, dams and other water structures and for larger foundations... The mixes of Portland cement and Thurament are different from blast furnace cement in that the Thurament is more coarsely ground and contains somewhat hydratised slag, which is mixed only on the site and cannot be analysed in terms of its quality by a simple test. The use of Thurament will therefore remain limited also in the future to large well-established and monitored building sites. Since 1943 Thurament has been officially permitted for use in the production of structures made of concrete and reinforced concrete... It may … not be used with fine slender designed reinforced concrete structures for example in house and bridge building applications."

4.3.2.2 United Kingdom

GGBS was produced for the first time in 1960 and used for structural installations in steel works. In 1972 GGBS was officially recognized as a separate concrete additive (agreement certificate) and was used for numerous building projects [Hig91-1]. By 1996, the sales of GGBS had grown to more than 1 million tons per year and in the year 2000 to over 1.5 million tonnes per year and GGBS was used in some one third of the ready-mixed concrete produced in the United Kingdom. According to [Fer04, Hig05], in Great Britain there are some 2 million tons per annum of GGBS currently used as concrete additive in a total cement sales volume of some 12 million tons per annum.

Generally speaking, 40 up to 50 M.-% of the CEM I is substituted in the production of ready-mixed concrete by the use of GGBS as a concrete additive and in some cases up to 70 M.-%. Approximately 30% of concretes are produced with GGBS. The durability (resistance against AKR, sulphate attacks and chloride penetration) of the concrete can be improved with a higher GGBS content. The strength development is then admittedly slowed down. GGBS is used in the production of other cements such as site-batched concrete and ready-made concrete components. Apart from its use for concrete production, GGBS is used for the local stabilisation of soils. In this case a mix of GGBS and of lime is mixed with the soil which contributes to an improvement in strength and stability. Such stabilised soils can serve as the basis for the building of roads [Hig05].
The concretes with GGBS are especially suited for external structural components under climatically changing stress or attack from aggressive media. Typical examples in Great Britain are piers in the sea, harbour walls, dams or bridges over river estuaries such as for example over the estuary of the River Severn [Bro95, Bou91m Hig96 and Hol96]. Gwyn and others [Gwy91] report on the structure of solid components of a sluice-gate on the harbour at Barrow.

Table 4.4: Composition of bulk concrete of the sluice-gate at Barrow harbour

<table>
<thead>
<tr>
<th>Components</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I</td>
<td>125 kg/m³</td>
</tr>
<tr>
<td>GGBS</td>
<td>295 kg/m³</td>
</tr>
<tr>
<td>Fine rock granulation</td>
<td>746 kg/m³</td>
</tr>
<tr>
<td>Coarse lime granulation</td>
<td>1022 kg/m³</td>
</tr>
<tr>
<td>Water</td>
<td>210 kg/m³</td>
</tr>
<tr>
<td>Liquifier</td>
<td>2.1 l/m³</td>
</tr>
</tbody>
</table>

A temperature increase of maximum 40°C was measured when using GGBS 70 M.-% of the bonding agent and with this a thermally-caused cracking development was prevented. On the other hand, a high GGBS proportion in this concrete should have guaranteed the longevity of the concrete components being subjected to aggressive weather and sea conditions. The concrete composition that was used is to be found in Table 4.4. GGBS was successfully used for the structure of the 812 m long Dartford-Thurrock Bridge [McG91]. A bonding agent mix with 70 M.-% GGBS und 30 M.-% CEM I was used for the substructure of the bridge. In this, a concrete of strength-class C 40 was used for the piles. The use of GGBS enabled hydration heat to be lowered and at the same time the sulphate resistance to be increased. Concretes with 50 M.-% GGBS in the bonding agent were used for the bridge cladding and the bridge guard rails.

GGBS-containing concretes were used on the basis of their acid resistance also in mooring areas where there is slightly acid water. Examples of these applications are to be found in the spillway of the Boy Scout Reservoirs in the Pennines and the construction of the Grassholme Reservoir in County Durham [Bou91].

GGBS was used in order to minimalise the risk of an alkali-silicic acid reaction (AKR) in the construction of the Snow Hill Car Park in Birmingham and on a bridge on the A24 road in the East Midlands [Bou91].

GGBS (40 M.-% - 50 M.-%) is often used for constructions through which water flows such as for example in Thurm Hall Reservoir, Ackworth Moor Water Tower amongst other places. In order to increase the resistance against aggressive groundwater, in the construction of a piling wall on the British Library 85 M.-% of GGBS was mixed into the bonding agent of the concrete. The Meteor Centre in Derby and a factory extension in Long Eaton are examples for the use of GGBS in industrial floors.

Further fields of application of the GGBS are in the production of plaster tiles, concrete roof tiles and the stabilisation of soils (in a mixture with limestone) [Hig00, Hig98].
4.3.2.3 Ireland

The ground granulated blast furnace slag is designated as "GGBS cement" and is used for concretes in different applications. Typical substitution volumes: 40 – 50 M.-% GGBS for ready mixed concrete, 25 M.-% up to 70 M.-% GGBS for concrete manufactured parts, > 55 M.-% GGBS for bulk concretes and 50 up to 95 M.-% GGBS for concretes with a high resistance against aggressive media. Large projects with the use of GGBS in Ireland are: Lee Tunnel, Luas Bridge, Boyne Bridge. In the building of the Luas Bridge in all of the concretes 40 M.-% CEM I was substituted by GGBS [eco, Fer04]. In Table 4.5 the concrete formulae with GGBS is presented by way of an example.

Table 4.5: Typical examples of concrete formulae using GGBS in Ireland [eco06]
4.3.2.4 Netherlands

In the Netherlands, the use of GGBS as a concrete additive is controlled by the National Evaluation Directive BRL 9340. According to information from Langelaan [Lan05] GGBS is used amongst other things for road building, foundations of wind energy installations and underwater concrete. Actual examples of this are:

- **Eersel roadbuilding project using slip form products** *(Figure 4.14).* Concrete formula:

  - CEM I 42,5 175 kg/m³
  - GGBS 175 kg/m³
  - w/(z+h) 0.38 – 0.46

  **Additional material** Air pore creator, liquifier and retarder

  According to [Lan05], this concrete formula is used for the construction of the 30 cm thick coating of road concrete. This concrete composition has been used repeatedly for road construction concrete in the Netherlands.

- **Foundations of a wind energy installation with a special formula for low heat development.** The highest temperature in the cement was at 46°C. Concrete formula:

  - CEM I 42,5 70 kg/m³
  - GGBS 270 kg/m³
  - w/(z+h) 0,46

  **Additional material** Liquifier

*Figure 4.14:* Road construction (covering layer) with GGBS Eersel Project, Netherlands [Lan05]
4.3.3 World-wide

4.3.3.1 Australia

GGBS for concrete production has been continuously produced in Western Australia since 1974 and in Eastern Australia since 1982 [Hin06]. The normal substitution rates on CEM I by GGBS in concrete production in Australia are between 20 and 70 M.-%. In normal concretes, 20 to 40 M.-% GGBS is used in the bonding agent and for those concretes that have to withstand aggressive media, this is up to 65 M.-% and for the avoidance of AKR 50 - 65 M.-% [And93, Tho97].

GGBS has been successfully used for example in the construction of the Maribymong River bridges [And93].

4.3.3.2 Japan

According to Japanese standards, in line with the application, GGBS can be used as a concrete additive in any mix proportions [Neb02]. According to [Nag89], it is recommended in the JSCE recommendations to maintain the CEM I substitution I by GGBS in the range of between 30 and 70 M.-%. GGBS with a specific surface of 4000 cm²/g is used for the production of conventional concretes. The finer up to 6000 cm²/g ground GGBS (Esment Super 60) is used for concretes with early strengths and good durabilities under aggressive application conditions. Between 1998 and 2002, "Esment Super 60" has been successfully used in 22 cases. GGBS is furthermore used for the production of self-levelling screeds (Eslevel) and for building components with high acid resistance [Neb02].

In Japan [Nag89] the following recommendations are given for concretes with GGBS according to the application:

- The cement substitution by GGBS should total 50-70 M.-% in bulk concretes.
- Special actions must be undertaken with concretes at low average daily temperatures (<4°C) : The GGBS should show a high activity index and the concrete temperature when it is being applied should be in the range from 7 to 20°C and the final treatment period should be extended.
- The cement substitution by GGBS should be higher than 40 M.-% for concretes in sea water.
- GGBS is used for road concretes amongst other things in order to reduce the AKR risk. Special attention should be given to the final treatment of the concrete. It is recommended to keep the concrete damp up until the point when the bending tensile strength has reached 70 M.-% of the specified final strength.
- 50 - 70 M.-% substitution is recommended for concretes for the dam building and for other parts a substitution of< 60 M.-%. In this, the minimum concrete temperature may go down to 5°C if the average daily temperature is not below 5°C.

Further application examples have been given for stressed structures, which have been erected with the use of GGBS in Japan and amongst others there is the Akashi-KaikyoOohashi Bridge which is almost 4 km long. Three different concrete formulae were used for this structure:
GGBS as concrete additive

- 15% CEM I, 85% GGBS with fineness of 6000 cm²/g (Blaine)
- 30% CEM I, 40% GGBS with fineness of 4000 cm²/g (Blaine) and 30% fly ash
- 45% CEM I, 55% GGBS with fineness of 4000 cm²/g (Blaine)

A mixture of CEM I, 45% GGBS with fineness of 4000 cm²/g (Blaine) and 20% fly ash was used as the bonding agent for the foundation of the 296 m high Landmark Tower in Yokohama. A high-performance concrete with 70% CEM I, 20% GGBS and a fineness of 8000 cm²/g (Blaine) and silica dust was produced for the Liver City skyscraper complex (of some 45 stories) [NIP2003]. In 2004, some 2 million tons of granulated blast furnace slag was used as concrete additive in Japan. In the same year, Japan has exported just to Taiwan alone [NIP 2005] almost 2 million tons of granulated blast furnace slag of the almost 20 million tons produced, which was used for the production of Portland blast furnace cement and as a concrete additive. There are no more precise details available.

4.3.3.3 Canada

GGBS was for the first time used in 1976 as a concrete additive in Canada in the province of Ontario. [Bou05, Hoo00]. The substitution rates were then relatively small: 20 - 25 M.-% in the summer and 15 – 20 M.-% in the winter. After 20 years of experience and a wide recognition the substitution rate is between 20 and 50 M.-%. The substitution rate of cement for special concretes such as for example bulk concretes is at 60 to 70 M.-%. A comparable resistance against the effects of sulphate is achieved at a 50 M.-% substitution of the CEM I by GGBS as it is in the application of a blast furnace cement. A moderate resistance to the sulphate of the concrete is achieved with a 35 M.-% substitution. To avoid AKR, in the building dams in Ontario 50 M.-% CEM I has been substituted by GGBS [Hoo00]. In several cases, 50 M.-% of the CEM I has been substituted by GGBS in order to avoid thermally caused crack development in bulk concretes. In one case even cement with a 70 M.-% substitution has been successfully used for the production of a solid foundation.

In Ontario, GGBS is the most frequently used concrete additive [Hoo00]. In accordance with the recommendation of the Ministry of Transport of Ontario, only up to 25 M.-% of the cement may be substituted by GGBS in concretes that could be at risk from frost-de-icing salt attack. The partially contradictory results of the laboratory and field investigations into concretes containing GGBS has led to this limitation [Afr94].

Concretes with 50 M.-% CEM I substitution by GGBS and with alkali sensitive graywacke or microcrystalline quartz were used in 1989 for the construction of dams and water-power stations on the Magpie River. When the structure was inspected in 1996, there were no traces of any AKR damage discovered [Hoo00].

One of the largest projects in Canada in which GGBS1 was the construction of the Scotia Plaza Office Tower in Toronto. Some 36,000 tonnes of GGBS with a CEM I substitution in concretes of 20 M.-% up to 30 M.-% were used [Bou05, Muk04]. A further project in which 50 M.-% CEM I was substituted was the building of the foundation slab (3 x 37 x 1.5 m³) for the Belmont Development Project in York Mills Place Toronto. The bonding agent content in the concrete totalled 330 kg/m³, the w/(c+h) ratio was at 0.48 and the highest concrete temperature with an outside temperature of 21°C was measured at 41°C. After 7 days and 90 days the concrete strengths reached 26.3 N/mm² and 47.3 N/mm² respectively [Muk04].
The use of GGBS in Canada for the production of various concretes in 2002 is presented in Table 4.6.

Table 4.6: The production of concretes with GGBS in Canada in the year 2002 [Bou05]

<table>
<thead>
<tr>
<th>Concrete application</th>
<th>Volume t/a</th>
<th>Substitution volume M.-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>House building (Ready mix concrete for foundations, ground, roadways, pathways; concrete components such wall blocks, tiles, etc.)</td>
<td>36,000</td>
<td>15 - 40</td>
</tr>
<tr>
<td>Office and industrial structures (tall buildings, car parks, foundations for industrial buildings, floors for warehouses, etc.)</td>
<td>144,000</td>
<td>15 - 40</td>
</tr>
<tr>
<td>Infrastructure (Bridges, roads, bus stops, to lesser extent manholes, wall blocks etc.)</td>
<td>36,000</td>
<td>15 - 40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>216,000</strong></td>
<td><strong>15 - 40</strong></td>
</tr>
</tbody>
</table>

According to [Bou05] the slow hardening process and the strength development of GGBS concretes are a technical drawback for the more widespread use of GGBS as a concrete additive in Canada.

4.3.3.4 Malaysia

Malaysia imports granulated blast furnace slag which is crushed in a rolling mill and used both for the production of GBS cements and directly for concrete production. In line with the field of application, cements are produced with three differing GBS contents of 30, 50 and 70% through separate grinding processes and mixtures. No additional sulphate setting is made in the production of cement.

The contents of GGBS in the concrete are oriented to the contents in the cements with comparable exposures of the concrete, but are freely configured in line with suitability tests. In this, it is a pre-requisite that at the same contents of GBS and at the same strength there is to be a comparable durability. The cement manufacturer is also at the same time producer and shipper of the GGBS. Therefore, GGBS with a similar composition grinding fineness, etc is used both in the cement and in the concrete. In 1999, there was some two thirds of the overall produced GGBS used in cement and about one third used in concrete [Lan99].

4.3.3.5 China

With more than 30 million tons per year, China is worldwide the most significant producer and user of granulated blast furnace slag. Its use in concrete has climbed to more than 7 million tons in 2004, with the introduction of the GB/T 18046 standard for GGBS. Currently there are numerous new milling installations being built for granulated blast furnace slag. The whole cement production in 2004 came to a total of around 900 million tons per annum.
4.3.3.6 South Africa

The blast furnace slag in South Africa contains for the most part > 98 M.-% glass. The ground GGBS up to at least 3500 cm²/g has been in the last 30 years sold as a concrete additive under the name of "Slagment"[sla06]. According to [sla06], nowadays up to 50,400 tonnes of Slagment is produced each month. For the most part, CEM I it is substituted in concretes with GGBS 50 M.-% by Slagment. The substitution is often at 70% for the use of concrete in aggressive media and for concretes with a low hydration heat. Slagment can be used for: building concrete, foundations, pre-stressed concrete, bulk concrete, ready-made concrete parts, ready-mixed concrete, concrete with increased sulphate resistance, soil stabilisation, roadbuilding (concrete roads) and concretes with alkali sensitive additives, etc.

Slagment has been used definitely in South Africa for the following applications:

- In 1995 for the building on 684 houses in Johannesburg. Here Slagment was mainly used in the production of foundations but also as a component part of the mortar or plaster. A premixed CEM I- Slagment mixture (PBFC) was used.
- 50 M.-% CEM I- substitution by Slagment (30,000 t) was used in the construction of a 21 km long highway cover between Pretoria and Johannesburg.
- Slagment was used in 1964 for the making of the runways at the airport of Pretoria. The concrete, which was specified for the strength of 20 N/mm² after 28 days, achieved compression strength of 89 N/mm² after 30 years. Nothing has been reported on the concrete formula and the Slagment proportion in the bonding agent.

Depending on the field of application, up to 85% of the Portland cement is substituted by GGBS.

4.3.3.7 USA

In the USA 3.46 million tons of GGBS (slag cement) was sold in 2004 for concrete manufacture. The growth compared with 2003 was 15.5% [Sla-1]. The development of the GGBS market is presented in Figure 4.15. Overall in the USA in 2004, 95 million tonnes of cement were produced [BDZ2004].

Most of the ready-mixed concrete producers use GGBS as a substitute with the use of GGBS 50 M.-% of the CEM I by GGBS of higher activity when the weather is warm. When the weather is cold or with the use of GGBS of lower activity, concretes with 20 up to 30 M.-% of GGBS are produced. With heat-treated concrete finished parts, most bonding agent mixes are used with 40 up to 60 M.-% of GGBS. The application fields and the normal substitution rates of the CEM I with GGBS are presented in Table 4.7. Tables 4.8 and 4.9 show the particularities of the use of GGBS in the United States in 1995.
Figure 4.15: Development of the GGBS market in the USA [Sla-1]

Table 4.7: Normal application fields and substitution rates of GGBS in concrete in the USA according to information from the Slag Cement Association [Sla-1]

<table>
<thead>
<tr>
<th>Use of the concrete</th>
<th>Substitution rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road concrete, concrete surfaces without loads with de-icing salt, concrete surfaces with frost de-icing salt loading and w/(z+s) &lt; 0.45, inside components, basement floors, walls and pillars, wall elements (tilt-up panels), pre-stressed concrete, ready-made concrete parts, precast tiles, plaster tiles, high strength concrete</td>
<td>25 – 50 M.-%</td>
</tr>
<tr>
<td>Foundations (footings)</td>
<td>30 – 65 M.-%</td>
</tr>
<tr>
<td>Concrete pipes, precast concrete blocks</td>
<td>20 – 50 M.-%</td>
</tr>
<tr>
<td>Concrete with AKR resistance</td>
<td>25 – 70 M.-%</td>
</tr>
<tr>
<td>Concrete with sulphate effects resistance</td>
<td>25 – 50 M.-%</td>
</tr>
<tr>
<td>Equivalent ASTM cement Type II</td>
<td>50 – 65 M.-%</td>
</tr>
<tr>
<td>Equivalent ASTM cement Type V</td>
<td></td>
</tr>
<tr>
<td>Water permeable concrete</td>
<td>25 – 65 M.-%</td>
</tr>
<tr>
<td>Bulk concrete</td>
<td>50 – 80 M.-%</td>
</tr>
</tbody>
</table>
Further instructions, in which proportions of Portland cement should be substituted by GGBS are to be found in the data sheet for “GranCem Cement” [HOL2002]. Here below are some selected examples: For concretes that should have a sulphate resistance as per a cement type II as per ASTM (Portland cement with moderate sulphate resistance) at least 35% of the cement should be substituted by GGBS. If the concrete should have a high sulphate resistance (as per the use of a Portland cement of type V as per ASTM) at least 50% of the normal Portland cement should be substituted by GGBS. These values are clearly subject to the regulations in Germany for cements that contain granulated blast furnace slag. A substitution of 35 to 50% of the Portland cement is recommended for high-strength concretes.

**Table 4.8:** Comparison of the use of GGBS in certain US states (information from 1995) [Duo99]

<table>
<thead>
<tr>
<th>US State</th>
<th>Use</th>
<th>Application</th>
<th>Substitution %</th>
<th>How long [Years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florida</td>
<td>Yes</td>
<td>Structural concrete</td>
<td>50 to 70 M.-%</td>
<td>12</td>
</tr>
<tr>
<td>Indiana</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N. Carolina</td>
<td>Yes</td>
<td>Road concrete</td>
<td>Up to 50 M.-%</td>
<td>N.D</td>
</tr>
<tr>
<td>Michigan</td>
<td>Permitted</td>
<td></td>
<td>Up to 40 M.-%</td>
<td>N.D</td>
</tr>
<tr>
<td>New York</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virginia</td>
<td>Yes</td>
<td>Mainly road concrete</td>
<td>35 to 50 M.-%</td>
<td>10</td>
</tr>
<tr>
<td>Maryland</td>
<td>Yes</td>
<td>Road concrete and structural concrete</td>
<td>25 to 50 M.-%</td>
<td>13</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Yes</td>
<td>Structural concrete</td>
<td>25 to 50 M.-%</td>
<td>N.D</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>Yes</td>
<td>Structural and road concrete</td>
<td>up to 40 M.-%</td>
<td>N.D</td>
</tr>
<tr>
<td>S. Carolina</td>
<td>Yes</td>
<td>Mainly structural concrete</td>
<td>up to 50 M.-%</td>
<td>8</td>
</tr>
<tr>
<td>Illinois</td>
<td>Permitted</td>
<td></td>
<td>up to 25 M.-%</td>
<td>N.D</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>Yes</td>
<td>Mainly structural concrete</td>
<td>up to 50 M.-%</td>
<td>N.D</td>
</tr>
<tr>
<td>Alabama</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kentucky</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missouri</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Jersey</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N.D = No details
### Table 4.9: Particularities of the use of GGBS in certain US states (information from 1995) [Duo99]

<table>
<thead>
<tr>
<th>US State</th>
<th>How were rules developed?</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florida</td>
<td>Processed by the Jacksonville Harbour Authority</td>
<td>…GGBS it is preferably used in order to increase corrosion resistance. In Road concretes GGBS is not used. GGBS is used in combination with micro-silica at a substitution rate of the CEM I at 50 to 55 M.-% of concrete additives.</td>
</tr>
<tr>
<td>Indiana</td>
<td></td>
<td>…still no work experience, apparent durability problems</td>
</tr>
<tr>
<td>North Carolina</td>
<td>N.D.</td>
<td>…GGBS not used for high early strengths or in combination with 1P and 1S cements. However in a demonstration project higher strength and high temperatures observed.</td>
</tr>
<tr>
<td>Georgia</td>
<td>N.D.</td>
<td>… should correspond to GGBS of product class 120. GGBS is not used in combination with fly ash or with 1P cement. The substitution volume depends on the environmental temperature: when ( T = 40°F ) (15.5 °C) – 50 M.-%, when 40°F (15.5 °C) &lt; ( T &lt; 60°F ) (4.4 °C) – tos 30 M.-%, when temperatures &lt; 4.4 °C use of GGBS not permitted.</td>
</tr>
<tr>
<td>Michigan</td>
<td>N.D.</td>
<td>… is not permitted to use GGBS in the months of October thru. April. GGBS not used for economic reasons.</td>
</tr>
<tr>
<td>Ohio</td>
<td>Based on test laboratory results</td>
<td>…GGBS is only used in product classes 100 and 120 as per ASM 989, the maximum substitution rates between 15th October and 1st April – 25 M.-%, or 40 M.-%. GGBS is used, in order to achieve low permeability and shrinkage.</td>
</tr>
<tr>
<td>New York</td>
<td>N.D.</td>
<td>…research work will be carried out for possible use of GGBS.</td>
</tr>
<tr>
<td>Virginia</td>
<td>Regional guidelines</td>
<td>…if GGBS is not included in 1P-cement. Cement type W can be used, if the alkali content is &gt; 0.4 M.-%. GGBS should only be used in product classes 100 and 120.</td>
</tr>
<tr>
<td>Maryland</td>
<td>Experience of other states</td>
<td>… GGBS is used for low permeability and to prevent AKR. Only GGBS product class 120.</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>N.D.</td>
<td>… GGBS is used according to specified rules to prevent AKR.</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>N.D.</td>
<td>… GGBS is mainly used for economic reasons in concrete manufacturer parts und partly in ready-mixed concrete production.</td>
</tr>
<tr>
<td>Delaware</td>
<td>Experience of other states</td>
<td>… GGBS should meet the requirements of ASTM C989. GGBS was originally used for economic reasons at that time to prevent AKR. No great problems with the solidification of road concretes and sawing after 18 hours is not seen as a problem. Consumption 22,000 tons in 1993</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>N.D.</td>
<td>…Used for the production of bridge cladding with the aim of reducing the permeability of the concrete and preventing corrosion of the reinforcing steel.</td>
</tr>
<tr>
<td>New Hampshire</td>
<td></td>
<td>… GGBS is only used between April and October, only GGBS of product class 100 and 120.</td>
</tr>
</tbody>
</table>

It can be seen from Table 4.8 that in 1995 GGBS was used as a concrete additive in numerous US states.
In the majority of the states, the substitution volume was limited to 50 M.-%. GGBS was mainly used for the production of structural concretes and road concretes. It has been for the most part recommended only to use a higher product class (100 and 120 hours per ASTM 989). The highest recommended substitution volume is almost always dependent on the environmental temperature (Georgia) or on the time of year (Michigan, Ohio, Illinois) (Table 4.9).

Based on the investigations of the “Louisiana Department of Transportation and Development” (LA DOTD), the following recommendations in the use of GGBS of product classes 100 and 120 given [Egg02, Duo00] are given:

- The substitution of CEM I by GGBS may for dosage and mix-related technical reasons not exceed 45 M.-% in a ready-mixed concrete plant.
- In on-site produced CEMI-GGBS-mixes the GGBS content may total 50 M.-%.
- It is not permitted to mix GGBS jointly with fly ash or fly ash containing cement.
- Prior tests are necessary in order to demonstrate the compatibility of the mix components. The mix design may only be subsequently accepted.
- The producer must show by suitability tests that each required concrete strength characteristic is achieved in mixes with GGBS.
- The performance of the GGBS product class 100 or 120 depends on the origin of the GGBS. For this reason the LA DOTD requires information on every change of the GGBS origin.
In recent years GGBS has been successfully used in several projects:

- **Milwaukee’s Kilbourn Tower, Milwaukee, Wisconsin**: Several different concrete formulae were used here in the construction of a 34-story skyscraper in order to achieve the necessary strengths in the range of 17 N/mm² und 83 N/mm². In this CEM I was substituted with 20 M.-% GGBS und 10 M.-% SFA.

- **Slag Cement Pavements Beat ASR in Delaware**: Since 1989 and a 51-mile long road has been built using GGBS (slag concrete). In total approximately 760,000 m³ have been used for the construction. The CEM I substitution in the concrete totaled between 35 and 50 M.-%. The strength of the concrete exceeded the required value of 24 N/mm² and was for the most part at 28 N/mm². Delaware was one of the first states in the USA, in which a 50 M.-% CEM I substitution by GGBS has been carried out. The object of the use of GGBS was here amongst other things also for preventing AKR.

- **75 – Four-Mile Test Section in Michigan**: A road concrete was tested in Michigan using GGBS. The tests are frost - dew cycles, aggressive deferrisation and loading from intensive traffic. The surface layer was processed with a 25 M.-% substitution limit in deeper layers with 40 M.-%.

- **The Helena, 601 w. 57th, Manhattan, New York**: An apartment block with 597 apartments was constructed in Manhattan. In the course of this, 45 M.-% GGBS was used in the bonding agent of the concrete. The construction was carried out also during winter. In order to achieve the necessary performance, instead of altering the concrete formula, the concrete and the area beneath the concrete was heated.

- **$1.9-billion AirTrain JFK project**: Some 153,000 m³ of concrete was used for 483 pillars for the construction of the airport railway. In this 20 to 30 M.-% CEM I was substituted by GGBS. Precast concrete segments with 40 M.-% GGBS were also used in the bonding agent.

- **Keystone Concrete Products – New Holland, Pennsylvania**: Concrete manufactured parts such as floor tiles, wall elements, etc. have been manufactured here for agricultural construction. The GGBS content in the bonding agent in the production of the manufactured products totaled 25 M.-%.

- **Charenton Canal Bridge in Louisiana**: In the construction of the Charenton Canal Bridge 50 M.-% GGBS was used instead of the originally specified concrete additives such as micro silica and fly ash. In this way, the work could be carried out with a lower bonding-agent content whilst meeting the requirements on the strength development and density of the concrete.
4.3.4 Summary

Granulated blast furnace slag is used in Germany practically almost exclusively as a main component in the production of Portland composite cements CEM II/A and CEM II/B and for the blast furnace cements CEM III/A, CEM III/B and CEM III/C. In some countries—United Kingdom, Ireland, the Netherlands, France, Belgium, USA, Canada, Japan, Australia and South Africa granulated blast furnace slag is separately ground and the GGBS is used as concrete additive material. Numerous investigations have been carried out on mortars and concretes with substitution of CEM I by GGBS. In summary the following can be stated:

- In general GGBS has a rather positive influence on fresh concrete characteristics. The processibility is improved in most cases. In this base substitution rates, the fineness of the GGBS and the type and volume of the sulphate carrier of the cement is significant. Bleeding is reduced with the use of higher fineness GGBS.

- The solidification process of the concretes is delayed with an increasing GGBS content. Temperature has a high influence on the solidification of concrete containing GGBS.

- The temperature development proceeds more slowly with an increasing GGBS content, which reduces a thermally-caused cracking development in bulk concretes.

- Due to a slower strength development the correct final treatment of concretes with GGBS is of major importance.

- The strength development of concretes with GGBS is as a rule slower than that of CEM I similar concretes. This is dependent on the chemical composition, the grain size distribution and the fineness of the GGBS and of the CEM I, the type and volume of the sulphate carrier, the substitution rate, the environmental temperature and the duration of the final treatment.

- Partly contradictory results arise with regard to the drying speed of concretes with GGBS. For the most part only minor variations of the shrinkage behaviour in comparison with CEM I concretes have been observed.

- The creeping behaviour of the concretes with GGBS depends on age and the substitution rates. In the later ages, the creeping of the concrete with GGBS is comparable or somewhat higher than that of similar concretes.

- The effect of the additive material on the characteristics of the concretes containing GGBS is similar to that of concretes with CEM I. Under certain circumstances it can however be necessary to maintain the same characteristics to increase the amount of input of air pore generators in the mix. Additions of retarding agents or flux material should amongst other things be reduced.

- The speed of the carbonisation of the concretes that have a high GGBS content is as a rule higher than the reference concretes with Portland cement. The final treatment and the environmental conditions play a decisive role in this.
Concretes with GGBS show a high resistance against the penetration of CI ions and an increased chloride binding capability.

The frost resistance of concretes with artificial air pores with and without GGBS as a concrete additive is similar according to what is stated in literature.

With the substitution of CEM I by ~ 50 M.-% GGBS, the resistance of the concrete against frost/de-icing salt attack can be clearly reduced.

By means of the substitution of CEM I by greater volumes of (> 50 M.-%) GGBS, the sulphate resistance of the concrete can be clearly improved.

GGBS-containing concretes are more capable of resisting the attack of diluted acids than are CEM I concretes.

With a substitution rate of up to 50 M.-% and an adequate final treatment, concretes with GGBS have a similar wear resistance to that of CEM I concretes.

Concretes with GGBS have a lower tendency to blooming than CEM I concretes.

**Principle fields of application of concretes with GGBS:**

- **Bulk concretes:** There have been reports in several countries on the successful use of GGBS in the manufacture of bulk concrete components. Up to 80% of the CEM I is substituted by GGBS when GGBS is used. The lowering of the hydration heat enables thermally-caused cracks to be avoided.

- **Road concretes:** GGBS is used here for the avoidance of alkali-silicic acid reaction. The use of higher contents of GGBS in roadbuilding can be limited due to a lower frost-de-icing salt resistance (Canada). The substitution volumes of the CEM I by GGBS in the use of GGBS in various countries are principally in the range of 15-50%.

- **Concrete manufactured parts and elements (wall blocks, covered tiles, concrete paving, concrete pipes):** when GGBS is used here the substitution rate is between 15 and 50% GGBS

- **Ready mix concrete for foundations, ceilings etc.:** the substitution rates with the use of GGBS in the range of between 15 and 50% vary slightly according to the country.

- **Concrete with increased sulphate resistance:** in this application GGBS concretes with more than 50% GGBS are used.

The use of GGBS as a concrete additive material has increased in recent years particularly in the USA and in European countries. There is a series of publications on the successful use of GGBS in various building projects, many of which are in the USA and United Kingdom.
5 Use of concrete additives Type II in Germany

5.1 Emergence of application regulations

5.1.1 General items

Ground granulated blast furnace slag has been used as a concrete additive material in Germany up until now only to a relatively small extent. In Germany up until the middle 1960s, GGBS was utilized under the name of Thurament. Thurament was officially approved for use in the production of structures made from concrete and reinforced concrete, but could not be utilized in slender reinforced concrete components such as those used for high buildings and bridges. Discussions on the introduction and definition of possible application regulations should take into account on the one hand the level of knowledge, which exists through the use of granulated blast furnace slag in cements or from international experience (see sections 2 and 4). On the other hand, consideration should be given to the technical regulation background of other already-established concrete additives. In this respect, the non-organic, reactive concrete additive materials (Type II) that is to say for the most part fly ash and silica dust subjected also to tempered crushed rock should be investigated. In addition to the lists of the historical development of the sets of regulations, what evidence there has been available of technical characteristics at the respective point in time of the regulations or has been targeted, is of particular interest. The statements concentrate on the general concrete standards and these specific material standards together with the associated guidelines and decrees. Divergent findings in separate sets of rules for example from the fields of road construction such as the ZTV-K or ZTV-ING are not taken into account in detail.

5.1.2 Fly ash

5.1.2. History of the body of rules and regulations

Fly ash as the residue from the combustion of carbon for energy production was first of all mentioned in the 1930s as a concrete additive material. Experiences with the new materials were collected in their first application in large engineering constructions (for example the "Hungry Horse Dam in 1948) and the first standardisation was made in the sphere of ASTM/MAN87b/ in 1954. Due to the increasing use in the following years there were also a series of standardised descriptions of fly ash produced in other countries (Japan 1958, USS1963, United Kingdom 1965, India 1966, Australia 1971 when/MAN 87b/)

In Germany the use of the so-called "Concrete additive materials" has been possible since the introduction of the DIN 1045: 1959 /DIN59/. Insofar as these materials were not described by the supplementary standard (DIN 4226) or Trass Standard (DIN 51043), their usability had to be proven by an approval mark or a general building inspection permit. Later on, the Institute for Building Technology Berlin (IfBt) which had been founded in the meantime established for fly ash that its use as a supplement as per DIN 4226 was no longer allowed and in any case had to be made via an approval mark /IFB73/. At that time in Germany a large number of individual ruling projects had successfully used fly ash already. In /KEL69/ alone there was a reference list of some 120 construction plants in which fly ash was used in "aggressive resistant concrete, waterproof concrete, facing concrete, pump concrete, shotcretes and compressed mortar" /KEL 69/. It should be noted that in all of these building activities, the concrete additive may not be taken into account in the minimum cement content or the water cement value and the fly ash was therefore used as a supplement to the specified cement content according to the concrete standard. The motivations for the use were to be found therefore first and foremost in the processing technological advantages. It was however naturally known that fly ash concretes possess a high subsequent hardening potential and if need be a higher density than for example pure Portland cement concretes.
The application experiences and a succession of building material technological investigations at various independent testing institutes led to the application by a producer for the establishment of a cement equivalent effectiveness with the approval mark of its fly ash. The apportioning concept specified for example for external components that the cement content up to a value of 240 kg/m\(^3\) can be substituted by fly ash. A direct calculation value for the apportioning was not defined. As a compensation for the efficiency not being similar to cement, the water content of the concrete was reduced by the volume which could be saved with regard to a similar slump thanks to consistence improving effect of fly ash. Strictly speaking this was, within the meaning of the present day standard, a first concept of "similar performance capability". The application was granted by the responsible state authorities for North Rhine Westphalia in 1970.

The IfBt did not want to follow the type of ruling that had been made and first of all determined that there should be no further approval marks, which contained the apportioning regulations for concrete additive materials. In addition, the special regulation in the approval mark of the EFA-Füller RM was not extended over the original approval time (1975). Similar applications (1974 and 1981) were refused.

In 1980 in the IfBt, a new "Guidelines for the issuing of approval marks for anthracite fly ash as concrete additive in accordance with DIN 1045 (approval mark guidelines)" /IFB80/ was adopted which still specified no apportioning of fly ash. In the following years a series of building inspection permission procedures were operated by the cement industry for fly ash-containing pozzolanic cement /IFB83/. In 1983 compared to DIN 1045: 1972 / DIN72/ a sharpening-up took place as for the requirements on the minimum cement content for external components within the framework of the "Guidelines for the Improvement of the Durability of External Components made from Reinforced Concrete" of the German Committee for Reinforced Concrete /DAF83/. At the same time the fly ash industry started a new initiative based upon further results of investigations. Referring to the k-value concept of Smith’ /SM167/, a generally applicable effectiveness factor for fly ash is to be established which is provided with an approval mark of the IfBt. As initiated by the Technical Committee of the IfBt, at the Institute of Building Research in Aachen in a project, the current state of proceedings on the "Influence of Fly Ash on the Compression Strengths and Durability of Mortars and Concretes" was summarised and the available test figures were inspected in terms of significance /F219/. Following some discussions in the technical bodies, the K-value that was proposed in an experts' report was to a large extent accepted by the Technical Committee of the IfBt, so that from 1984 fly ash with an approval mark in the following manner could be apportioned on the minimum cement content and the water cement ratio of the concrete:
Reduction of the minimum cement content for external components from 300 to 270 kg/m³, with appropriate suitability testing, ongoing monitoring and addition of double cement saving volumes on fly ash.

- Apportioning of a fly ash volume of a maximum f/z = 0.25 with the K-value 0.3 on the water cement value with all normal concretes and concretes with special characteristics but not with underwater concretes and concrete with a high resistance against frost – de-icing salt attack.

- For underwater concrete: Reduction of the cement content by up to M.-% at at least the same high overall bonding agent content, together with a permitted increase on the water cement ratio at w/z = 0.7 (without apportioning).

- All regulations apply only when using Portland cement, iron Portland cement and blast furnace cement with less than 70 M.-% granulated blast furnace slag.

Subsequent to this, upon application the approval marks of all anthracite fly ash products on the market were made subject to the new application rule. Furthermore there were from the IIfBt detailed questions answered as to how related test expenditures that were dependent on the manufacturing procedures /IIFB86, transfer of the apportioning rules on internal components /IIFB88/ or first approval marks for fly ash from the combustion of varying carbon sources (on a Wartesilo regulation, /IIFB89/). Furthermore the apportioning of fly ash also in combination with the Portland limestone cement that had been on the market since around 1986 was permitted. The new edition of the DIN 1045: 1988 /DIN88/ made reference actually to the set of regulations of the DafStb Guidelines “External Building Components” /DAF83/, but no consideration was given in the application regulations to fly ash as a concrete additive.

The continuing work on fly ash research brought more extensive proof of the performance capability of cement/fly ash combinations, in particular also in the sphere of durability. Based on these acknowledgements and a series of applications for the extension of the apportioning regulations a renewed discussion of the regulations for the effectiveness of fly ashes in concrete was made in the technical committees of the German Institute for Structural Engineering of Berlin which had in the meantime stemmed from the IIfBt. Last but not least in the light of the European standard for concrete or fly ash which was starting to emerge in July 1992 the K-value for fly ashes with approval mark was raised to k=0.4. As a supplement to the already formulated exception of “underwater concrete” in 1993 an extended apportioning with K = 0.7 was given also for the use in drilling pile concrete. Based upon the results of research from 1992, an application was made for the cancellation of the limitation of use in prestressed concrete with immediate adhesion, and this was also achieved in 1995.

The adoption was made in 1994 and in 1995 the introduction under the building supervision of a European fly ash standard DIN EN 450 /EN 95/, which had been processed since 1988 was achieved. The DIN EN 450: 1995 in fact as a material standard provided the parameters for the origin of the fly ash and its chemical physical and mineralogical characteristics. Application rules for the use in concrete and the procedures for the continuous checking of conformity were however not included. In 1996 the DafStb Guidelines for "Use of Fly Ash according to DIN EN 450 in Concrete Structures" /DAF95/ were adopted, which went ahead with the K-value concept from the approval mark regulations. There was a supplement to the regulation to the effect that mixes of non-sulphate containing cements with at least 20 M.-% fly ash were considered as being sulphate resistant against loadings of up to 1.500 mg/l. Fly ashes with approval marks or (from 1995) general building inspection approved fly ash that met the specifications of the
standard could from then on be sold as standardized building material. Individual fly ashes that deviated from the DIN EN 450: 1995 standard, in particular because of varying combustion compositions or subsequently switched preparation stages (e.g. storage/drying) were transferred to being subject to general building inspection permits in the same way as the existing approval marks for fly ashes from the combustion of hard brown coals. Furthermore the first permit for fly ash from brown coal combustion was applied for and issued in 1998. The DIBt introduced the "Approval Guidelines" /DIB93a/ and the "Monitoring Guidelines" /DIN93n/ to establish the procedures for approvals of concrete additive materials and for their monitoring.

The non-harmonized European concrete standard DIN EN 206 /EN 06/ and the related National Application Document DIN 1045, Parts 1 to 4, were introduced into building inspection in 2001. In DIN 1045-2:2001 /DIN01/ the regulations of /DAF96/ were taken up and revised with regard to the recognizable flies ash proportion and the joint use with silica dust. The DadStb Guidelines could thereupon be withdrawn. In anticipation of the revising of the European fly ash standard, the DIN 19880 / DIN02/ was installed as a supplement which governed the product monitoring for fly ashes as per DIN EN 450. In addition to the checking of material characteristics for the first time the preparation and introduction of a plant quality manual has been specified. The approval and monitoring guidelines of the DIBt additive materials were updated also in this respect /DIB02/.

The new version of the DIN EN 450, Parts 1 and 2, was implemented in 2006 /EN 05/. Further to the 1995 version, there are basically in this rulings questions on the product monitoring (category 1+) on the preparation of fly ashes and on the joint combustion of secondary combustion materials. The basis for the last aspect is a CEN report /CEN01/, in which Europewide results from investigations into fly ashes that are produced from the joint combustion of various secondary combustion materials are summarized. As no European standardized analysis procedures and evaluation criteria exist for the environmental compatibility of materials, the testing of these material characteristics is delegated to the national level. In Germany proof is to be shown via general building inspection permits.

Nowadays SFA is established as a concrete additive material in Germany. An average content of some 50 kg/m³ is produced in relation to the manufactured volumes of ready-mixed concrete.

Currently there are ongoing discussions in committees on a possible apportioning of fly ash also in the exposure classes XF2 and XF4 that have been hitherto excluded.

Regardless of the material standard DIN EN 450 and of the concrete standards, more extensive regulations in relation to the use of fly ash have been made in the building inspection-related field.
Alkali guidelines

With the DAFStb guidelines on "Precautionary measures against harmful alkali reaction in concrete (alkali guidelines)" introduced in 1986, /DAF86/ allowance was made for the use of fly ash in combination with alkali reactive additives under the moisture classes WF and WA, so that their use has to be explicitly regulated within the respective approval marks. As an alternative a targeted suitability certification could be introduced. The formulations of the versions of the guidelines since 1997 /DAF97/ then referred to internationally published recognition (e.g. /KOL89/) according to which the effective alkali content of fly ashes is simply to be set at 1/6th of the provable total alkali content to be proved in the concrete additive.

Bulk concrete

Fly ash has been used in the production of pile concrete in Germany already since the 1960s. In particular, in very bulky foundation slabs of, for example, power stations since the 1980s there has been by means of approvals, the use of individual concrete formulae, the cement content of which has been greatly reduced and replaced by large volumes of fly ash for the reduction of temperature stress from outflowing hydration heat /BÜC96/. In order to be able to use such concretes also in smaller-dimensioned but nevertheless bulky building components in a practical fashion, at DIBt special concretes - after extensive material tests - have received general building inspection approval as "bulk concrete".

The "Concrete for Bulk Building Components" DafStb Guidelines that have in the meantime been introduced deal with concretes with modestly reduced cement content in comparison to DIN 1045-2. These guidelines were introduced into building inspections with the list of building regulations 2006/1.

5.1.2.2 Experimental technological proof

There has also been increasingly much research carried out into materials with the use of anthracite fly ash as concrete additive commencing around the middle of the 20th century. Up until the beginning of the 1970s, these operations took place principally in the USA, Japan, United Kingdom and France. The presentation of this work has up until now been abstained from because overseas experiences with materials only have an indirect effect on the German building inspection regulations. The following description of experimental activities is limited therefore to the German-speaking area. It makes reference to research reports to the extent that they relate to the work of the Institute for Building Research at Aachen (ibac) as a significant research centre for the application of fly ash in concrete. References are made to a selection of the resulting publications instead of for the most part non-accessible research reports of other research points in Germany.
Phase I: up to 1970

The use of fly ash in building concrete was actually possible up until 1970 in Germany but there was no apportioning of the bonding agent content or the ratio of water cement. However the concrete additive was increasingly used towards the middle of the 1960s in order to make use of, in particular, its favourable effects on the processability of the concrete. The recognized subsequent hardening potential was considered as an additional mechanical safety reserve. Systematic researches had been documented only to a small extent in the German-speaking area, in contrast for example to Japan, United Kingdom, France and the USA, /WOG60, MEI62, WIE70/.

Based upon the experiences from numerous building projects with concretes containing fly ash an application was made to the State Building Authority of NRW for the extension of a fly ash approval mark in order to achieve the apportioning of the minimum cement content and also indirectly the water cement ratio. Positive practical experience existed above all for the fresh concrete characteristics, slump, compression capacity, cohesion, reduction of bleeding and pumping capability as well as naturally also for strength development. In the preparation for the application, a number of independent test institutes were charged with making extensive investigations into the effectiveness of fly ash in concrete. The characteristics to be tested included, in addition to the material characteristics, the characteristic values of fresh concrete (rheology, water requirement, solidification), the strength development, the shrinkage, the volume stability, the hydration heat, the water penetration resistance and the corrosion resistance against carbonisation, sulphate, seawater and frost. The investigations came out favourably so that a change of the approval mark of the relative fly ash was made with regard to the minimum cement content.

Phase II: 1970 to 1984

Whilst up until the middle of the 1970s, only a limited systematic fly ash research had taken place in the German-speaking area, an increasingly intensive research activity was then commenced. A series of research results were processed as far as the basic regulation, to be able to apportion fly ash with approval marks on the minimum cement content and the water cement ratio (1984).

The principal effect of fly ash on the strength development was still only secondarily the aim of the series of tests /BLÜ77/. Basic fly ash specification-related and process-technical influences on the reactivity and strength were compiled /F43, R73/ and analysis criteria for fly ashes were deduced /F85/. The lowering of hydration heat in fly ash concretes was investigated as a further characteristic /LUK79/.

The work with regard to the durability of fly ash-containing mortars and concretes concentrated first and foremost on carbonisation /e.g. F158, SCH82, WIE84/. Further investigations were in relation to special chemical loads such as sulphate attack/WAS83, F72/ or limestone-dissolving carbonic acids F/143/. Frost and frost de-icing salt resistances were not often selected as a central subject /LEW80, LEW83/. A comprehensive summary of the available data was evaluated in /F219/ /WES84/ in preparation for the consultations at IfBt on the introduction of apportioning regulations for fly ash. In this, the questions of the durability were dealt with separately for carbonisation and for all other influences indirectly via analyses of the concrete density. Through the undoubtedly extensively increasing signs that the durability of concrete increases with greater density, with this, the strength that is proportional also to the porosity was able to serve as a comprehensive parameter for mechanical and durability characteristics.

Phase III: 1984 to 1992

The concrete additive material research in no way succumbs with the introduction of recognized rules for fly ash with an approval mark. The more so in the years that followed, broad and basic principle-oriented investigations on the effect mechanisms and their influence by fly ash characteristics have been initiated.
GGBS as concrete additive

/KAU85, F230, F235, F280/, the results of which have been finally summarized in /SYB93/. In addition, there have been a series of investigations with different source materials for verifying the K-value approach / e.g. LAC86/. Furthermore concrete-technological and process-technical levels of influence (mix compositions, final treatment) have been analyzed / WIE88, MAN97a, SCH87/. First results on the prestressing steel compatibility have been elaborated /REH86/.

With respect to durability, a series of tests have been already carried out and analyzed on the conclusions /F226, LEH87, VGB89/. Subsequently, very extensive investigations have been carried out into the resistance of fly ash mortars and concretes to corrosion caused by sulphate in conjunction with the investigations on the pore structure /F262, HÄR94/. At the beginning of the 1990s, there had been up till that time in Germany very few of these subjects to which any major consideration had been given. On the one hand, investigations had been started on the chloride penetration resistance of differing bonding agents for the most part containing fly ash /F399/. On the other hand, the environmental compatibility of materials in general and industrial byproducts such as fly ash was treated as a special subject /F366/.

In 1992 an extension of the apportioning regulations for fly ash with approval markings was applied for at the IIBt. The basis were the results of two extensive research projects on this subject (summarized in/VGB 92/). The broadly-based investigations of these projects were agreed from the beginning with the technical committee of the IIBt in view of a possible change of regulations and the results were discussed in the various bodies there.
Phase IV: 1992 until present day

The research into fly ash conducted between 1992 and the present day is broadly specialised in terms of subject. Motivations for investigations that are still basic /F334, HÜT00/ are individualised, but on the basis of published doubt on the principle reaction capability of the concrete additive material, this is countered with evidence coming from new investigative methods. Basic investigations have been financed by the DFG and the DIBt in order to obtain statements concerning what proportion of cement may be substituted by fly ash, without the alkaline deposit in the cement rock that is necessary for protection against corrosion of the reinforcement being wasted. /F397, F405, F505/.

In the last 10 years, a further focal point of the subject has been the use of fly ash in different high-performance concretes. Commencing with the high-strength concrete /F552, F521/ through to high-density concretes /F584, F556/ up to bulk concretes and self-compressing concretes (differing general building inspection approvals), the modern concrete technology for the use of fly ash has been opened up /WAG03, FRI04/. Investigations into granulometry /F302, HUG97/ and into the common apportioning of fly ash with silica dust as a further reactive concrete additive have been carried out /F758/ and with the results the recognized regulations of DIN 1045-2 : 2001 have been verified.

Ongoing research work is oriented around the repeated questions in relation to durability. In this, reference is partly made to investigations that have already been concluded on material that is still on hand in order to be able to carry out long-term observations. A first focal point was in investigations into the effect of fly ash on the chloride transport in concrete /F430 and on the pre-stressing steel compatibility/F436/. A comprehensive presentation and analysis of the early tests and the international research on this subject can be found in /WIE04/.

The resistance against the effects of sulphate is a subject that has not been finally concluded and it is one to which long-term investigations /F1 262, F729, H EI02/ have been devoted. Furthermore there have been appropriate test proceedings for the analysis of sulphate resistance of bonding agents and concretes as a subject for research work. Currently upcoming discussions on damage mechanisms such as later ettringit formation (due to heat treatment) or thauma formation had been handled by separate research projects and still disputedly being discussed /BOLL97, MUL02, KÖH03, LIP03/. Currently a three-part technical report has been produced /BRE04, HEI04, under the auspices of the DafStb.

A further durability subject is the questioning of the fly ash effect already dealt with earlier internationally /CON99/ on the avoidance of alkali-silicic acid reactions /SCH01, F902, HE105a/. Also in the last few years, several research projects on the subject of frost and de-icing salt resistance of fly ash concretes have been dealt with and partially concluded.

Increasingly in the last few years with respect to general building inspection permits, fly ash from the combustion of alternative types of coal (brown coal, anthracite coal /DIE96, LUD97/) or the joint combustion of secondary combustion materials (petroleum coke, carcass meal, clear and industrial sludge, wood, etc.) have come into use. In this respect and as a basis for the argument for renewing the DIN EN 450 standard which now opens the possibility for the joint combustion of a limited list of substitute combustion materials, investigations have been carried out on the environmental compatibility and the technical effect of the joint combustion ash and the results have been summarised throughout Europe /CEN01/.
5.1.3 Silica dust

Silica dust, which can be used as concrete additive material, originates as a rule from the production of silica metal or ferro silicon alloys. The most extensive experience with the concrete additive material is to be found in Norway and Canada which worldwide are among the largest producers of silicon products. Since the beginning of the 1970s, silica dust has being researched and used as a concrete additive to a large extent in these countries. If one considers the lists of literature on the scientific publications in international progress reports on silica dust (e.g./FIP88/) this should be recognized as a significant focal point in North America and Scandinavian publications.

The research stations in Germany up until the 1980s have only concerned themselves sporadically with very fine concrete additive material. Systematic technical publications are not available. But Wesche has already given in 1982 at the "ibausil" conference an article on the evaluation of a strength-related K-value of silica dust with \( K = 3 \) to \( 5 \) /WES82/. Unsuccessful attempts up until this time have finally been documented for the approval of combinations of silica dust and powder forms of concrete liquifier /FB82/.

In 1985 silica dusts from two producers succeeded in obtaining an approval mark. But the use in prestressed concrete with direct bonding or grouted mortars has been excluded in this. A joint use with other concrete additives is also not specified as apportioning of the minimum cement content or the maximum water cement ratio; the maximum content is limited to 10 M.-% of the cement weight. At this time, acceptance procedures of some silica dust containing pozzolanic cements were also processed. In 1988 the first approval mark for a silica dust suspension was issued after questions on the stability, uniformity and processing in the concrete production had been discussed At the beginning of the 1990s, an approval was granted for an approval mark through produced precipitation reactions, which was in particular used in newly-patented wet spray processes for shotcrete production.

The conversion of the approval mark of silica dust for general building inspection permits was made from 1995 on the basis of the approval guidelines /DIB93a/. At this time, the application regulations for silica dust were also extended so that the concrete additive may be recognized within the dosage limits of 10 <.-% of the cement weight with a K-value of 1.0 as for the minimum cement content and the equivalent water cement ratio.

With the introduction of DIN EN 206:2001, in conjunction with DIN 1945-2:2001 the rules for the apportioning of silica dust in the concrete's conceptual design have been included in the standard. Building inspection permitted silica dusts can be included in the contents at the maximum of 11 M.-% of the cement, at full apportioning of the minimum cement content and a K-value of 1.0 for the calculation of the equivalent water cement ratio. Further limitations are to be taken into account in simultaneous application with fly ash.
GGBS as concrete additive

Under the auspices of Norway, an harmonized European material standard for silica dust was commenced at the beginning of 1993. Based on very widely differing concepts of the member countries with regard to the definition of uniform material characteristics and of the product monitoring, this lasted finally until 2005 before the work could be successfully concluded. The building inspection related change of DIN EN 13263:2005 /EN05/ was made in the building regulation lists of 2006/1.

The systematic publication of the results of researches which had been obtained in the German-speaking area but above all from practical knowledge was used first at the end of the 1980s and added-to in particular in relation to the subjects of "Shotcrete" /e.g. DRS87, HIL89, BRE021/ and " High-strength Concrete " /ALT89, ALF89/. In addition a few publications were produced on the questions of material specifications /e.g. NÄG88/ or the effects of silica dust on corrosion of the reinforcements /SCH89/. The effects of the use of a silica dust as an additional grinding material in the production of cement was investigated by Locher /LOC99/. In 1990 again there were reports in German technical newspapers about "new" silica dust material /MAN90/. After the issuing of a technical report, /F334a/ further research work was performed in the 1990s first and foremost on the high-strength concrete /e.g. WIE96, Meng97, GUS98/. Extra fine silica particles originating from the precipitation processes were tested as " Nano-silica" in the sphere of additive material /HAU94/. With regard to possible application regulations in connection with the draft of EN 206, possible limits of the proportion of different pozzolanic cement additives were worked out /F405/ and later also under joint use and apportioning /F758/. Also currently there are still investigations being carried out on special questions such as for example the frost and de-icing salt resistance /FEL04, SET04/.

5.1.4 Tempered pulverized silicate rock

A tempered pulverized silicate rock (volcanic igneous rock) has been marketed in the South West area for more than 25 years as a concrete additive. For many years this product enjoyed the status of an inert material and did not have to be calculated in the minimum cement content or their water cement ratio in the concrete. In a different way from for example crushed limestone, the tempered crushed rock was sold using the approval mark of the Fob and later a general building-inspection approval of the Debt. An apportion ability was established in 2003 of k = 0.6 at a maximum ratio of silicate rock / cement of 0.33. This regulation is limited to concrete with CEM me or CEM II-A-LL. A European technical approval was granted for the concrete additive by Debt in 2005. The regulations for use were given by means of a general building inspection permit.

A further crushed silicate rock received approval as reactive concrete additive in the mid-1990s. The K-value was at K= 0.3 when combined with Portland cement. This product is no longer on the market nowadays.
5.1.5 Expanded clay dust

In 2001 a general building inspection approval has already been issued for a dust-like accumulating byproduct as a concrete additive of Type II. Based upon tests, the following regulations for use in relation to its apportionability were able to be granted to the concrete additive:

- Reduction of the minimum cement content by a maximum of 20 kg/m$^3$ at the minimum of double the cement substitution volume.
- Apportioning on the equivalent water cement ratio with $K = 0.2$. 
6 Summary

6.1 General Items

A harmonised European "Ground granulated blast furnace slag for use in concrete, mortar and grouting mortar" has been compiled by CEN TC104/WG15 on the basis of the mandate M128 of the EU Commission.

This standard DIN EN 15167 was subdivided into two parts according to the standards or draft standards for concrete additives of the Type II for fly ash and silica dust - which are aligned with the structure of the cement standard.

- Part 1 Composition, requirements and conformity criteria
- Part 2 Conformity evaluation

Rules for use for Germany have to be compiled with the introduction of the material standard.

The production and use of cement that contains ground granulated blast furnace slag has a long history in Germany. In the year 2004 cement that contains ground granulated blast furnace slag accounted for around 25% of the domestic sales of German cement manufacturers. Currently there is use of GGBS as concrete additive in Germany in the sector that is not subject to building inspection at the plant of one concrete roof tile producer and one concrete materials manufacturer. In a few European countries, for example in Great Britain, ground granulated blast furnace slag is on the other hand also used in building and in civil engineering work as a concrete additive. This current situation report shows in addition to the documented experience with GGBS as a concrete additive, also the necessary requirements for research and concepts for application regulations. In this the knowledge level is taken into account, which exists through the use of granulated blast furnace slag (GBS) in cements in Germany or international experience with GGBS as a concrete additive. In addition consideration is given to the technical regulation background of other already established concrete additives used in the building trade in Germany.

6.2 Cements that contain blast furnace slag

DIN EN 197-1 and DIN 1164 permit the use of GBS from 6 to 95% for the production of CEM II- and CEM III cements containing GBS. DIN EN 197-4 and DIN EN 14216 contain only requirements for CEM III cements and accordingly allow 36 up to 95% of GBS. Portland blast furnace cements and other blast furnace cements are world-wide for the most part produced using common grinding to an increasing degree but also by separate or two-stage grinding processes.

Systematic investigations have shown that for example the compression strength development of cements containing GBS depends both on the quality of the GBS that is used and on the consistency of the clinker. The higher the GBS proportions are in the cement the more noticeable also become the characteristic fluctuations of the GBS on the performance capability and uniform quality of the cement that is produced from it. This applies the other way round also for the clinker that is used. By cooperation between cement producer and GBS supplier and by means of the in-house monitoring of the GBSs by the cement producer, quality fluctuations in the chemical and physical characteristics of the source material can be recognized and be counterbalanced by suitable measures in the cement production. In this, for example, as a significant influence on the GBS there is the TiO2 content.
The following actions can be taken for this above all by the cement producer:

- Equalisation of the GBS that is used,
- Altering the fineness of clinker or GBS (with a separate grinding process) or changing the overall fineness of the cement (with a common grinding process),
- Changing the formula (increasing or reducing the proportion of GBS),
- Changing the volume and composition of the sulphate carrier.

The ensuring of a high uniformity by means of the above-mentioned actions may not in this only relate to the compression strength, but must also include the processing characteristics (e.g. water requirement and solidification).

The consistency and volume of the sulphate carrier are of decisive importance for the solidification behaviour of the cement. As a rule a mixture of natural gypsum and anhydrite is used as a solidification actuator. Calcium sulphates can also be utilized which come as industrial byproducts.

Optimal sulphate contents or sulphate carrier compositions can also not be given for cements containing granulated blast furnace slag, but they will be influenced by the specific characteristics of the cement. The most favourable sulphate content depends upon the GBS content, the grinding fineness of the GBS and the clinker which is used and the reactivity of the various components. The optimal sulphate carrier composition must therefore be individually adapted for each type of Portland blast furnace or other blast furnace cement types.

Generally all cements in accordance with DIN EN 197-1, DIN EN 197-4 and DIN 1164 are suitable for the 2001-07 and DIN 1045-2: production of concrete according to the concrete standards DIN EN 206-1: 2001-7. With regard to the durability of concrete produced using these types of cement, consideration must be given however to the cement-dependent differences in accordance with the field of application. With the use of cements containing GBS there is also in Germany more than a hundred years of experience with regard to the durability of the concretes produced with these cements. The first standard for blast furnace cement from 1917 already contained the notice: "Blast furnace cement that corresponds to the following German standards is similarly approved with Portland and Iron Portland cement for all State works". No application limitations arise for Portland blast furnace cements in accordance with DIN 1045-2. Cements with up to 80% granulated blast furnace slag as a main component are permitted for use in all exposure classes as per DIN EN 206-1 and DIN 1045-2 except for XF4. Cements of the strength classes ≥ 32.5 R with up to 50% granulated blast furnace slag as a main component and the strength classes ≥ 42.5 up to 65% granulated blast furnace slag as a main component are permitted for use in all exposure classes as per DIN EN 206-1 and DIN 1045-2.
Some types of cements containing granulated blast furnace slag for which there is up to now no experience in Germany such as for example Portland composite cements CEM II/B-M (S-LL) require an approval for use by the German Institute for Structural Engineering (DIBt).

6.3 European blast furnace slag characteristics compared with the requirements of the European standard for ground granulated blast furnace slag

Investigations into European granulated blast furnace slags that have been carried out since 1995 for this current situation report have been prepared in the FehS – Institute for Building Material Research. The data has been separately presented for Germany and the whole of Europe (including Germany and for the four country groupings of North, West, South and East Europe. The German granulated blast furnace slag is contained in the Western European group of countries. All of the blast furnace slag originates from industrial wet granulation plants. With respect to the chemical and physical requirements. Only a few individual figures for two individual parameters did not meet the requirements of EN 15167-1. The minimum glass content of 2/3 was not achieved by four of the 128 granulated blast furnace slags that were investigated. Two of the granulated blast furnace slags with 45.6 Vol. % and 60.7 Vol.-% originated from current east European production. One granulated blast furnace slag with 60.4 volume % originated from Western Europe. With regard to mortar technical characteristics it can be said that with the exception of one GBS, all of the GBSs that were investigated have met the requirements of EN 15167-1 on the commencing of solidification and on the activity index at the age of 7 and 28 days (n = 22). The maximum ignition loss of 3 M.-% was exceeded in two cases out of 76 analyses. There was one GBS from Eastern Europe with a ignition loss of 4.74 M.-%, and one GBS from southern Europe with a ignition loss of 3.94 M.-%.

The maximum sulphate content (SO3) of 66 GBSs investigated was at < 0.41 M.-%.

In investigations conducted by the Wilhlem Dyckerhoff Institute for Building Materials Technology into GBS from Czech Republic, Poland and Ukraine. the requirements of EB 15167-1 on the activity index were in fact satisfied. The tests of the Willhelm Dyckerhoff Institute for Building Material Technology show that these GBSs have a lower performance capability in cement than German GBSs.

New and up to now unpublished investigations of the FehS Institute for Building Materials Research into one granulated and one pelletised GBS from France, which have been produced from the ash of a blast furnace, only showed small differences in characteristics. The glass content was 88.9 % / 94.4% and the activity index after 28 days 102 / 103 on the granulated GBS. Thereby, this pelletised GBS had a performance capability similar to the granulated GBS from the same steelworks and had a higher activity index than some granulated GBSs from other producers. Apart from these individual results, there are, however, no systematic investigations into the characteristics of pelletised GBS available.

6.4 Use of ground granulated blast furnace slag as a concrete additive

Numerous International investigations have been carried out on the use of GGBS in combination with CEM I for mortars and cements especially with regard to the durability characteristics. In summary, the following can be accordingly stated:
GGBS generally influences the fresh concrete characteristics. The processibility is improved in most cases. In this, the base substitution rates, the fineness of the GGBS and the type and volume of the sulphate carrier of the cement are significant. The solidification process of the concretes is delayed with an increasing GGBS content.

The solidification of the concrete is delayed with increasing GGBS content and the temperature development progresses more slowly. The strength development of the concrete with GGBS is as a rule slower and therefore the extended final treatment of concretes with GGBS is of significance.

The influence of the additive material on the characteristics of the concretes containing GGBS is similar to concretes with CEM I. The type and volumes of the additional materials are to be adapted for the conservation of the characteristics with concretes containing GBS.

The speed of carbonisation of the concretes that have a high GGBS content is as a rule higher than the reference concretes with Portland cement.

Concretes with GGBS show a high resistance against the penetration of CI ions.

With the substitution of Portland cement by ~ 50 M.-% GGBS, the resistance of the concrete against frost and-de-icing attack can be clearly reduced and the sulphate resistance of the concrete clearly improved.

Concretes with GGBS have a lower tendency to blooming than CEM I concretes. The results confirm the practical experience which has been obtained both with the use of GBS as a main component in cement production as well as in the use of GGBS as an additive in concrete production.

The use of GGBS as a concrete additive material has increased in recent years in some countries and particularly in the USA. Other countries have only in more recent times commenced with this such as for example China which uses in a total production of 30 million tons of GBS and some 7 million tons of GGBS as a concrete additive. In the United Kingdom, the sale of GGBS had grown by 1996 to more than 1 million tons per annum and in the year 2000 to more than 1.5 million tons per annum, and GGBS was used in some one third of the ready-mixed concrete produced in the United Kingdom. Currently in the United Kingdom there are now some 2 million tons of GGBS used as concrete additive in a cement-use related volume of some 12 million tonnes per annum. The production of ready-mixed concrete produced with the use of GGBS normally has a substitution of 50 to 50 M.-% of the CEM I by GGBS. Depending on the application, substitution rates of 70% and more are utilized.

Incorporated amongst other things in the British experiences in dealing with CEM I/GGBS combinations based on the national rules of use for the EN 206-1, the British application standard BS 8500-2 uses in addition the exposure classes as per EN 206-1 and allocates to these classes the use of specified cements or combinations of CEM I and GGBS. These combinations are allocated in their respective compositions to the compositions of cements according to EN 197-1. The British and Irish regulations assume that cements according to EN197-1 with respect to durability behave in a way that is similar to CEM I/GGBS combinations with similar GBS contents. GGBS is used with CEM I and may not be used in combination with other additives in concrete.
Some further examples can be mentioned:

Some 20,000 to 30,000 tons of GGBS per year together with CEM I or CEM II with a K-value of 0.6 are used in Sweden. This volume corresponds to 20 to 30 M.-% of the granulated blast furnace slag produced in Sweden. The substitution volume is limited to 50 M.-%.

In Ireland the ground granulated blast sand is designated as “GGBS cement” (blast furnace slag cement) and is used for concretes in different applications. Typical substitution volumes: 40 – 50 M.-% GGBS for ready mixed concrete, 25 M.-% up to 70 M.-% GGBS for concrete manufactured parts, > 55 M.-% GGBS for bulk concretes and 50 up to 95 M.-% GGBS for concretes with a high resistance against aggressive media.

GGBS can be used in the Netherlands as a concrete additive when a corresponding so-called attestation or certificate is presented. The use itself is made via an attestation of concrete that is established in the evaluation guidelines. The specifications of the GGBS, of the Portland cement and of the concrete that is produced from these are given in the certificate for one or several compositions according to the exposure classes. The concrete composition that is stated in the certificate must be of a similar value to the Dutch standard NEN 6720. This is obtained by means of a comparison of the strength and of the durability of the concrete composition that is to be certified with the strength and the durability of a reference concrete composition with the minimum cement content and the maximum or lower water cement ratio of the corresponding exposure class. The concrete compositions that are to be certified are to be of a similar value to the concrete compositions according to NEN 6720 if their characteristic strength and durability are greater than or similar to the characteristic strengths and durability of the reference concrete composition.

Austria has in fact one standard for GGBS and other concrete additives with the ÖNORM B 3309. Practically no use of GGBS in concrete takes place with the exception of application areas which in Germany would be considered as coming under the building inspection unregulated area.

There is a series of publications on the successful use of GGBS in various building projects, many of which are in the USA and United Kingdom.

Basically all rules for use are oriented towards the 125 years of experience in the production and use of cements containing GBS. This has its effect also in numerous publications on the use of ground granulated blast furnace slag in concrete, in which the freshness and set concrete characteristics, the longevity and special characteristics such as sulphate resistance, avoidance of harmful alkali-silicic acid reaction and chloride bonding are compared with those of GBS-containing cements. There are numerous reports in these publications on the fact of the positive effects of GGBS as a concrete additive – for example on the resistance against the penetration of chlorides – are comparable to those of cements containing CBS. In contrast to the German experiences with blast furnace cements that contain GBS, various investigations from UK and the USA also establish that mixes from GGBS (proportion > 65 M.-%) and Ordinary Portland Cement (OPC) in no way always provoke a higher sulphate resistance of the concrete than the pure OPC.
6.5 Application of concrete additives Type II in Germany

In Germany the use of the so-called "Concrete additive materials" has been possible since the introduction of the DIN 1045: in 1959. If these materials have not been described by the supplementary standard (DIN 4226) or Trass Standard (DIN 51043), their usability has to be proven by an approval marking or a general building inspection permit.

Today two types of non-organic concrete additives are included in the concrete standards DIN EN 206-1/ DIN 1045-2:

- More or less inactive concrete additives (Type I) and
- pozzolanic or latent water concrete additives (Type II).

The suitability as a concrete additive of the Type I has been proven for crushed rock material as per DIN EN 12620, for pigments as per DIN EN 12878 and for concrete additives with general building inspection approval or European Technical Approval.

The suitability as a concrete additive of Type II is proven for fly ash as per DIN EN 450 and for Trass as per DIN 51043 and concrete additives with general building inspection and approval or European Technical Approval for example silica dust.

Concrete additives of the Type II may, to the extent that the suitability is proven, in the concrete composition be apportioned in the cement content and the water cement ratio.

The K-value approach allows concrete additives of the Type II to be taken into account replacing the "water cement ratio" by "equivalent water cement ratio".

The suitability of the K-value concept applies for fly ash and silica dust as being proven.

The establishment of this set of application regulations is based upon numerous practical experiences in the case of fly ash since the middle of the 20th century and extensive research work in Great Britain, France, Germany, USA and Japan since the beginning of the 1970s. Nowadays SFA is established as a concrete additive material in Germany. An average content of some 50 kg/m³ is produced in relation to the manufactured volumes of ready-mixed concrete.
7 Final conclusions and research requirements

7.1 Application regulation

There are basically two concepts to be considered as application rules for GGBS as a concrete additive

- K-value concept;
- The principle of concrete performance capability of similar value

The K-value concept has to be in this oriented to a "lower quality limit" for the GGBS that is to be inserted. This has the advantage of a generally valid usability with all available cements that are on the market and the maintaining of the existing set of rules for concrete construction methods currently to be found in Germany. On the other hand, however, such a concept is not correct for the actual characteristics of each individual GGBS. With certain GGBSs account has to be taken of the need arises of excess strengths. The possible development of a K-value concept can be oriented to the procedures that are known from concrete additives of fly ash or silica dust. A relatively rapid transfer into the set of standard specifications appears to be achievable. The experiences from the use of cements with granulated blast furnace slag as a further main component can be included whilst taking into account the production process of the cement. The K-value concept is used for GGBS as concrete additive for example in Sweden, France and Finland. The volumes of GGBS that are inserted in practice in these countries are small in comparison to the production of granulated blast furnace slag.

The principle of the equivalent concrete performance capability takes into account the material-specific characteristics of the combination of one or several special cements and an GGBS, i.e. this is made in relation to the kind and the origin (production plant) of the material that is being integrated. An appropriate background and experience is to be created for the development of the principle of equivalent concrete performance capability.

According to present day knowledge, all of the countries that use ground granulated blast furnace slag exclusively or preferably as concrete additives such as United Kingdom, USA, Canada or South Africa are turning towards the principle of equivalent concrete performance capability. This includes giving consideration to the durability of the cements that contain GBS or concretes that are produced with a cement/GGBS mix.

The principle of equivalent concrete performance capability can be used in Germany as per DIN 1045-2, Appendix E only within the framework of the general building inspection approvals. Up until now, these types of approval procedures have not been carried out. Approvals of concretes that deviate from DIN 1045-2 have been issued on many occasions (e.g. for bulk concretes); there are also approvals given for use of Portland composite cements. An extensive research programme is to be carried out with tests on carbonisation behaviour, tests on resistance to the penetration of chlorides, tests on the frost resistance and tests on the resistance to frost-de-icing salt for the approval of these standardised cements for use in particular exposure classes. The results of the acceptance tests are evaluated by the responsible technical committee (SVA) of the DIBt. Requirements that are out of line with the standard are to be established as needs arise in the approval. A comparable procedure is awaited for general building inspection approvals as per Appendix E of DIN 1045-2.
The formulation of a set of rules for use exclusively on the establishment of the strength-level of the concrete is not possible in Germany without a corresponding assurance of the durability characteristics of cements taking into account the lower limit of the performance capability of the GGBSs as per DIN EN 15167. This data principle was determined in the case of fly ash in extensive investigations in relation to the establishment of the K-value concept. This correlation must have to be proven for each individual material combination (e.g. stated combinations of Portland cement and granulated blast furnace slag) when using the principle of equivalent concrete performance capability as per DIN 1045-2, Appendix E, within the framework of general building inspection approvals.

7.2 Blast furnace slag as a principle constituent of cement and ground granulated blast furnace slag as a concrete additive.

By cooperation between cement producer and GBS supplier and by means of the in-house monitoring of the GBSs by the cement producer, quality fluctuations in the chemical and physical characteristics of the GBS can be recognized and be counterbalanced by suitable measures in the cement production.

The cement producer makes adjustments using the chemical and physical characteristic values that are provided by the granulated blast furnace slag supplier and his own results obtained from goods inward inspections in the grinding process of the cement and any quality variances in the GBS. He can first and foremost take the following actions as required:

- Altering the fineness of clinker and GBS (in joint or separate grinding processes)
- Changing the formula (increasing or reducing the proportion of GBS),
- Changing the composition of the sulphate carrier

In all of these actions he must take into account the fact that the performance capability and uniformity of his cement should remain constant for its practical use in the concrete or mortar (e.g. water requirement at increased fineness).

Basically the above stated control values are also available when using GGBS as a concrete additive. The producer of the GGBS can vary its fineness. If it is logistically possible, the strength class of the cement can be adjusted. It is a known fact in the United Kingdom that in the event of fluctuations in characteristics, suppliers of GGBS give recommendations to their customers for increasing or reducing the GGBS proportion in the concrete. Theoretically a change to the sulphate carrier could also be undertaken. The producer or user of GGBS must also react with this to characteristic fluctuations of the GGBS, e.g. following the fluctuation of the TiO₂ content and to the fact that stored GBSs with an increased CO₂ and H₂O content can be ground appreciably more easily, which produces for a similar grinding energy-use a greater fineness according to Blaine, which may misleadingly appear to indicate a higher hydraulicity.
The German cement producers have compiled their know-how of the targeted controlling of the characteristics of cements containing GBS over many years of practical experience. Whether and which one of the levels of control may have been operable under the predominating basic conditions in the use of GGBS as a concrete additive in practice and whether a comparable measure of flexibility and safety can be achieved in the use of cements containing GBS is up until now not known due to a lack of experience.

7.3 Research needs

There are in Germany many years of experience available with regard to the durability of the concretes produced with these cements with the application of cements that contain GBS as per DIN EN 197-1 or DIN 1164. This range of experience would have been presumably abandoned under the basic conditions of the European standard for GGBS if no further demands for GGBS had been made. The GGBS standard defines a minimum performance level for GGBS, which according to current knowledge is below that which can be assumed up until now in the production of GBS-containing cements in Germany. There is little or no experience, for example, with pelletised blast furnace slags. All investigations for a generally applicable set of regulations for use must be presented in accordance with the European materials standard DIN EM 15167 with regard to a future lower limit of the performance capability of GGBS. The performance parameters of the GGBS that is to be approved are to be set as a basis for the compiling of a set of regulations for use for defined GGBSs.

In this respect, investigations must show under which basic conditions GGBSs with a specified minimum performance level as per the European material standard DIN EN 15167 lead in their use as a concrete additive to an adequate durability of the concrete. The rules of the German Institute for Structural Engineering (DIBt) which are to be utilized for the granting of general building inspection approvals apply for the investigations into the use of GGBS. Durability investigations are to be carried out subject to the basic establishment of the limitation formulae as per DIN 1045-2. The formulation of a set of rules for use exclusively through the establishment of the strength level of the concrete is not possible in Germany without a corresponding assurance of the durability characteristics of cements, taking into account GGBSs that generally meet the requirements as per prEN 15167 or are regulated on additional requirements. In this it can be borne in mind if need be that the positive effects of GGBS as a concrete additive – for example on the resistance against the penetration of chlorides – are comparable to those of GBS-containing cements.

A fundamental parameter is, in addition to the equivalent water cement ratio, the content of the GGBS. In addition a check should be made as to with which types of cement a use of GGBS as a concrete additive could be approved. The use of other additives should be included with this in the investigations.
Within the framework of further research or practice-related investigations, the basic possible concepts of the K-value basic approach and the basic approach of the equivalent concrete performance capability (e.g. the British or the Dutch concept) must be systematically carried out and analysed both in the laboratory investigations and also in the practical application in the concrete plant.

When further work is being carried out, the following basic principles should be taken into account:

- The safety level of the DIN 206-1/DIN 1045-2 is to be observed.
- The durability level may not be worse than that given in DIN EN 206-1/DIN 1045-2.

An equivalent concrete quality is to be aimed at in both fresh and set concrete characteristics.

Account is to be taken in these investigations of combinations of GBSs used in Germany (differing quality parameters) with conventional cements or types of cement. The fineness and glass content are significant variation parameters in addition to the GGBS content.

In addition to tests in accordance with EN 196-1, in which the strength contribution of the GGBS with respect to the mortar compression strength is judged, durability investigations must be carried out on the basis of the testing schedules of the DIBt for all exposure classes.

The object is the derivation from the framework conditions and from what is feasible of a set of general application regulations (K-value concept or a concept of similar concrete performance capability). The question of the transferability from laboratory results into practice could be followed up in the form for example of a pilot project.
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8.2 Literature on Section 2

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/SET04/

/SMI67/

/SYB93/

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Table A1: Range of applications of cements containing granulated blast furnace slag as per DIN EN 197-1, DIN EN 197-1/A1, DIN EN 197-4, DIN 1164-10, DIN 1164-12 and FE cements and CEM II-SE as per DIN 1164-11 for the production of concrete as per DIN 1045-2

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<thead>
<tr>
<th>Exposure classes</th>
<th>No corrosion/attack risk</th>
<th>Reinforcement corrosion</th>
<th>Concrete attack</th>
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<td>Carbonisation induced corrosion</td>
<td>Chloride induced corrosion</td>
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<td>X = applicable range of applications</td>
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<td>O = not to be used for production as per this standard</td>
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<td>B</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>CEM II S*</td>
<td>A</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>X</td>
<td>O</td>
</tr>
</tbody>
</table>

* up to see footnotes in Table A3
Table A2: Application range for CEM-II-M-cements containing GBS with three main components as per DIN EN 197-1/A1, DIN 1164-10, DIN 1164-12 and FE cements and CEM II-SE as per DIN 1164-11 for concrete production as per DIN 1045-2.

<table>
<thead>
<tr>
<th>Exposure classes</th>
<th>X = Applicable range of applications</th>
<th>O = Not to be used for production as per this standard</th>
<th>No corrosion/risk of attack</th>
<th>Reinforcement corrosion</th>
<th>Concrete attack</th>
<th>Prestressing steel compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Carbonisation induced</td>
<td>Frost attack</td>
<td>Aggressive chemical environment</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>corrosion</td>
<td></td>
<td>Wear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chloride induced</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>corrosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other chloride</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>than seawater</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chloride from</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>seawater</td>
<td></td>
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</tr>
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<td>CEM II</td>
<td></td>
<td></td>
<td>X0</td>
<td>X1</td>
<td></td>
<td></td>
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<td>M</td>
<td>A</td>
<td>S-D; S-T; S-LL</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-P; S-V</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-D; S-T; D-T;</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>S-P</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-V</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-LL</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

* a, d, f, and g see footnotes in Table A3
### Table A3: Application range for CEM V cements with three main components as per DIN EN 197-1/A1, DIN 1164-10, DIN 1164-12 and FE cements as per DIN 1164-11 for concrete production as per DIN 1045-2

<table>
<thead>
<tr>
<th>Exposure classes</th>
<th>Reinforcement corrosion</th>
<th>Concrete attack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbonisation induced corrosion</td>
<td>Chloride induced corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X = Applicable range of applications</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>O = Not to be used for production as per this standard</td>
<td>X0</td>
<td>XC1</td>
</tr>
</tbody>
</table>

---

**CEM V**

- **A**
- **B**
- **S-P**

---

**Exposure classes**
- **X**: Applicable range of applications
- **O**: Not to be used for production as per this standard

**CEM V**

- **A**: S-P

---

**Reinforcement corrosion**
- **No corrosion/risk of attack**
- **Carbonisation induced corrosion**
- **Chloride induced corrosion**
  - Other chloride than seawater
  - Chloride from seawater
- **Concrete attack**
  - Frost attack
  - Aggressive chemical environment
  - Wear
  - Prestressing steel compatibility

---

**Notes**
- **a** Some cements that cannot be used according to this table can be used with a general building inspection approval.
- **b** Strength class ≥ 42.5 or strength class ≥ 32.5 R with a GBS–bulk content of < 50 %
- **c** CEM III/B may only be used for the following individual applications:
  - a) Seawater components: w/c ≤ 0.45; minimum strength class C 35/45 and z ≥ 340 kg/m³
  - b) Cleaner lanes w/c ≤ 0.35; minimum strength class C40/50 and z ≥ 360 kg/m³; observing DIN 19569
    - Can be remounted on air pores in both cases.
  - d) In the event of chemical attack by sulphate (except for sea water) cement above exposure class XA1 with high sulphate resistance must be used (HS cement). For the production of concrete with high sulphate resistance a mix of cement and fly-ash may be used with a sulphate content of the aggressive water of SO₄₂⁻ ≤ 1500 mg/l instead of HS cement.
  - e) Special combinations can be more effective. For CEM-II-M cements with three main components see Table A2. For CEM-IV and CEM-V cements with two or three main components see Table A 3.
  - f) The silica dust that is used must meet the requirements of the approval guidelines of the German Institute for Structural Engineering (DIBt) for non-organic concrete additives ("Information" DIBt 24 (1993), No. 4, P 122-132) re. Content of basic Silicium Si.
  - g) Cements that contain P, are excluded as they have not yet been tested for this application.
  - h) Applies only for Trass as per DIN 51043 as main component.
### Table A4: Application range for cements containing GBS as per DIN 14216 for the production of concrete as per DIN 1045-2

<table>
<thead>
<tr>
<th>Exposure classes</th>
<th>Reinforcement corrosion</th>
<th>Concrete attack</th>
<th>Prestressing steel compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbonation induced corrosion</td>
<td>Chloride induced corrosion</td>
<td>Frost attack</td>
</tr>
<tr>
<td></td>
<td>Chloride except sea water</td>
<td>Chloride from sea water</td>
<td></td>
</tr>
<tr>
<td>X = Applicable range of applications</td>
<td>X = Not to be used for production as per this standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>X0</td>
<td>X1</td>
<td>X2</td>
</tr>
</tbody>
</table>

**Notes:**

- If cements that are not to be used as per this table should be used they need a general building inspection approval.
- In the event of chemical attack by sulphate (except for sea water) cement above exposure class XA1 with high sulphate resistance must be used (HS cement). For the production of concrete with high sulphate resistance a mix of cement and fly-ash may be used with a sulphate content of the aggressive water of SO42− ≤ 1500 mg/l instead of HS cement.
Table A5: Standards and sets of regulations for ground granulated blast furnace slag as concrete additive in Europe

<table>
<thead>
<tr>
<th>Requirements</th>
<th>EU</th>
<th>Belgium</th>
<th>Italy</th>
<th>Finland</th>
<th>France</th>
<th>UK</th>
<th>The Netherlands</th>
<th>Austria</th>
<th>Sweden</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>%</td>
<td>≤ 1,0</td>
<td>≤ 1,0</td>
<td>-</td>
<td>-</td>
<td>≤ 1,0</td>
<td>≤ 1,0</td>
<td>-</td>
<td>≤ 2</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2,7 - 3,0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Glass content</td>
<td>%</td>
<td>≥ 67</td>
<td>&gt; 67</td>
<td>-</td>
<td>-</td>
<td>≤ 67</td>
<td>≤ 67</td>
<td>≥ 67</td>
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<td>-</td>
</tr>
<tr>
<td>Grinding fineness</td>
<td>g/cm³</td>
<td>2750</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2250-3250</td>
<td>Class A</td>
<td>Class B</td>
<td>&gt; 750</td>
<td>Class F1</td>
</tr>
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<td>Specific surface</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Filter residue</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>30</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>at 45 μm</td>
<td>%</td>
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<td>-</td>
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</tr>
<tr>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>at 90 μm</td>
<td>%</td>
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<td>-</td>
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<td>-</td>
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<td>Chem composition</td>
<td>%</td>
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<td>≤ 5</td>
<td>≤ 5</td>
<td>≤ 5</td>
<td>≤ 5</td>
<td>≤ 5</td>
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<td></td>
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<tr>
<td>Ignition loss</td>
<td>%</td>
<td>≤ 3,0</td>
<td>≤ 3,0</td>
<td>≤ 3,0</td>
<td>≤ 3</td>
<td>≤ 3</td>
<td>≤ 3</td>
<td>≤ 3</td>
<td>≤ 3</td>
<td>≤ 3</td>
</tr>
<tr>
<td>CaO</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Al₂O₃</td>
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<td>-</td>
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</tr>
<tr>
<td>Mn₂O₃</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>-</td>
<td>≤ 2</td>
<td>≤ 2</td>
<td>≤ 2</td>
<td>≤ 2</td>
<td>≤ 2</td>
<td>≤ 2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SO₃</td>
<td>-</td>
<td>≤ 18</td>
<td>≤ 14</td>
<td>≤ 16</td>
<td>≤ 14</td>
<td>≤ 14</td>
<td>≤ 14</td>
<td>≤ 10,0</td>
<td>≤ 14</td>
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</tr>
<tr>
<td>Cl⁻</td>
<td>-</td>
<td>≤ 2,0</td>
<td>≤ 2</td>
<td>≤ 2,0</td>
<td>≤ 2,0</td>
<td>≤ 2,0</td>
<td>≤ 2,0</td>
<td>≤ 4 (MnO)</td>
<td></td>
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<tr>
<td>Na₂O-Equ.</td>
<td>%</td>
<td>0,01</td>
<td>0,10</td>
<td>0,01</td>
<td>0,05</td>
<td>0,1</td>
<td>0,1</td>
<td>0,1</td>
<td>0,1</td>
<td>0,1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≤ 1,2</td>
<td>≤ 3,0</td>
<td>≤ 0,05</td>
<td>≤ 0,1</td>
<td>≤ 0,1</td>
<td>≤ 0,1</td>
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</tr>
<tr>
<td>CaO + MgO + SiO₂</td>
<td>%</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td>≥ 67</td>
<td></td>
</tr>
<tr>
<td>(CaO+MgO+Al₂O₃)/SiO₂</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(CaO+MgO)/SiO₂</td>
<td>%</td>
<td>≥ 1</td>
<td>&gt; 1,0</td>
<td>&gt; 1,0</td>
<td>&gt; 1,0</td>
<td>&gt; 1,0</td>
<td>&gt; 1,0</td>
<td>&gt; 1</td>
<td>&gt; 1</td>
<td></td>
</tr>
<tr>
<td>CaO/SiO₂</td>
<td>%</td>
<td>-</td>
<td>-</td>
<td>≤ 425</td>
<td>425-550</td>
<td>&gt; 550</td>
<td></td>
<td>-</td>
<td>-</td>
<td>&gt; 325</td>
</tr>
<tr>
<td>CaO x Al₂O₃</td>
<td>%</td>
<td>-</td>
<td>-</td>
<td>425</td>
<td>425-550</td>
<td>&gt; 550</td>
<td></td>
<td>-</td>
<td>-</td>
<td>&gt; 325</td>
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</table>
Table A5: Continued

<table>
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<th>EU</th>
<th>Belgium</th>
<th>Italy</th>
<th>Finland</th>
<th>France</th>
<th>UK</th>
<th>The Netherlands</th>
<th>Austria</th>
<th>Sweden</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidification begin/end</td>
<td>h : min/ h : min</td>
<td>52.5 42.5 32.5</td>
<td>0:45 1:00 1:15</td>
<td>≥ 0 : 45</td>
<td>≥ 8 : 00</td>
<td>-</td>
<td>3) As cement as per EN 197</td>
<td>-</td>
<td>-</td>
<td>1 : 00 12 : 00</td>
</tr>
<tr>
<td>Volume stability</td>
<td>mm</td>
<td>-</td>
<td>≤10</td>
<td>-</td>
<td>-</td>
<td>≤ 10,0</td>
<td>≤ 10</td>
<td>-</td>
<td>-</td>
<td>≤ 10</td>
</tr>
<tr>
<td>Compression strength</td>
<td>N/mm²</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>≥ 12.0</td>
<td>as cement As per EN 197 in mixes with 70 % HS</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 d 7 d 14 d 28 d 91 d</td>
<td>%</td>
<td>≥ 45</td>
<td>≥ 70</td>
<td>-</td>
<td>-</td>
<td>≥ 50</td>
<td>≥ 75</td>
<td>≥ 60</td>
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</tr>
<tr>
<td>Activity index</td>
<td>%</td>
<td>≤ 1,0 (%)</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Permitted additions, gen. SO₃ (%)</td>
<td>≤ 1,0 (%)</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
</tr>
</tbody>
</table>

1) Only applies if gypsum is added by the producer
2) Specified as per EN 196-4 in a mix of 70% ggbs and 30% portland cement 42.5 with a Na₂O-Equiv. ≥ 0.5% and < 0.9%
3) The solidification times of the mixes as per 2) may not be shorter than those of the Portland cement without ggbs
4) Specified in the mix as per 2)
5) Total of the activity index in a mix of 75% uniform cement 375 and 25% GBS 3500 cm²/g as per 28 days less than 90%, but at least 88% is to apply at 91 days
6) Inspection only if the HS contains more than 1.0% CaO free Specified on a mixture of 50% GBS and 50% cement
7) Up to 15% permitted if there is autoclave tests on prisms
8) Comparison mortar from 500 g cement and 1375 g sand: 250 g ggbbs + 250 g gggbs + 1375 g sand in %, water content as per slump. The figures in the table are minimum average values of the last 5 samples, individual elements may be up to 5% under this.
9) Information on demand
10) Testing of mortar with 50% test cement (mixture from CBM I of three producers) with 50% GGBS w/c 0.50
11) The commencement of solidification of a mixture of 50 % GGBS and 50% test cement may at the maximum be twice as long as the time up to the commencement of the solidification of the test cement
12) The Chinese standard GB/T – 18046: 2000 is in terms of content identical to requirements of the Japanese standard
13) Only grinding subsidiaries, the addition of organic grinding subsidiaries is limited to 0.5%


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td></td>
<td></td>
<td>≤ 1,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass content</td>
<td></td>
<td></td>
<td></td>
<td>≥ 95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grinding fineness</td>
<td></td>
<td></td>
<td></td>
<td>≥ 3500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Class 4000 3000-5000</td>
<td>Class 6000: 5000-7000</td>
<td>Class 8000: 7000-10000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter residue</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 45 µm</td>
<td>≤ 20,0</td>
<td></td>
<td>≥ 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 80 µm</td>
<td>≤ 20</td>
<td></td>
<td></td>
<td>≥ 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 90 µm</td>
<td>≤ 20</td>
<td></td>
<td></td>
<td></td>
<td>≥ 20</td>
<td></td>
</tr>
<tr>
<td>Chemical composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>undissolved residue</td>
<td>≤ 2,0</td>
<td></td>
<td>≥ 2,0</td>
<td>≤ 2,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition loss</td>
<td>≤ 3,0</td>
<td></td>
<td>≥ 3,0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>≤ 15,0</td>
<td></td>
<td>≥ 10,0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>≤ 10,0</td>
<td></td>
<td></td>
<td>≥ 10,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>≤ 10,0</td>
<td></td>
<td></td>
<td></td>
<td>≥ 10,0</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>≤ 8,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>≥ 8,0</td>
</tr>
<tr>
<td>MnO₂</td>
<td>≤ 2,0</td>
<td>MnO</td>
<td></td>
<td></td>
<td></td>
<td>≥ 2,0</td>
</tr>
<tr>
<td>SO₂</td>
<td>≤ 1,5</td>
<td></td>
<td></td>
<td></td>
<td>SO₂ ≤ 2,5</td>
<td></td>
</tr>
<tr>
<td>Cl₂</td>
<td>0,02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cl₂ ≤ 0,02</td>
</tr>
<tr>
<td>Na₂O-Equ.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Na₂O-Equ.</td>
</tr>
<tr>
<td>CaO + MgO + SiO₂</td>
<td></td>
<td></td>
<td></td>
<td>≥ 67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CaO+MgO+Al₂O₃)/SiO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO/MgO + SiO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO/SiO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO x Al₂O₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solidification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Begin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume stability</td>
<td></td>
<td></td>
<td></td>
<td>≤ 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 d</td>
<td>≥ 3,5</td>
<td></td>
<td>≥ 12,5</td>
<td>≥ 12,5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 d</td>
<td>≥ 12,5</td>
<td></td>
<td></td>
<td></td>
<td>≥ 12,5</td>
<td></td>
</tr>
<tr>
<td>14 d</td>
<td>≥ 20</td>
<td></td>
<td></td>
<td></td>
<td>≥ 20</td>
<td></td>
</tr>
<tr>
<td>28 d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>≥ 20</td>
<td></td>
</tr>
<tr>
<td>Activity index</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 4000</td>
<td>≥ 55</td>
<td></td>
<td>≥ 75</td>
<td>≥ 95</td>
<td>≥ 75</td>
<td>≥ 95</td>
</tr>
<tr>
<td>Class 6000</td>
<td>≥ 75</td>
<td>≥ 95</td>
<td>≥ 105</td>
<td>≥ 95</td>
<td>≥ 105</td>
<td>≥ 115</td>
</tr>
<tr>
<td>Class 8000</td>
<td>≥ 105</td>
<td>≥ 105</td>
<td></td>
<td>≥ 95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permitted additions, gen. SO₃</td>
<td>≤ 1</td>
<td></td>
<td>≤ 4 %</td>
<td>2,5</td>
<td>Up to max. SO₃-content</td>
<td></td>
</tr>
</tbody>
</table>

GGBS as a concrete additive

Table A6: Standards and sets of regulations for ground granulated blast furnace slag as concrete additive outside of Europe
### Tabelle A7: Recommended GGBS replacement levels in concrete containing GGBS and OPC Based on current engineering practice in the UK and Europe [BS02]

<table>
<thead>
<tr>
<th></th>
<th>No risk of corrosion or attack</th>
<th>Carbonation induced corrosion</th>
<th>Chloride induced corrosion</th>
<th>Freeze/thaw attack</th>
<th>Aggressive chemicals environments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sea water</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum w/c ratio</td>
<td>X0</td>
<td>X1</td>
<td>X2</td>
<td>X3</td>
<td>X4</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>0.60</td>
<td>0.55</td>
<td>0.55</td>
<td>0.60</td>
</tr>
<tr>
<td>Minimum strength class C--</td>
<td>C12/15</td>
<td>20/25</td>
<td>28/35</td>
<td>30/37</td>
<td>30/37</td>
</tr>
<tr>
<td>Minimum cement+ GGBS content kg/m²</td>
<td>280</td>
<td>300</td>
<td>320</td>
<td>320</td>
<td>360</td>
</tr>
<tr>
<td>GGBS Replacement Levels</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>Minimum air content %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: The replacement level of GGBS is the percentage by weight of GGBS to the weight of the total cementitious material in the mix, i.e. GGBS + OPC.

Note 2: Replacement levels for Exposure Classes XO and XC can be up to 80%. In most instances replacement levels used in the UK and Europe are between 40% and 50%.

Note 3: The optimum level of GGBS for resistance to chloride attack is around 50%. BS 8500-1:2002 (Tables A.1 2.1.13) allows for replacement levels between 36% and 80%.

Other considerations including heat of hydration may require higher replacement levels.
Appendix B (CEM II/B-M (S-LL): General building inspection application approvals)

Table B1: Summary of the general building inspection application approvals for Portland composite cements CEM II/B-M (S-LL) – Examples

<table>
<thead>
<tr>
<th>Approval No.</th>
<th>Composition to be maintained in M.-%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clinker</td>
</tr>
<tr>
<td>Z-3.17-1828</td>
<td>70 - 79</td>
</tr>
<tr>
<td>Z-3.17-1829</td>
<td>70 - 79</td>
</tr>
<tr>
<td>Z-3.17-1856</td>
<td>70 - 79</td>
</tr>
<tr>
<td>Z-3.17-1857</td>
<td>70 – 79</td>
</tr>
<tr>
<td>Z-3.17-1858</td>
<td>65 – 79</td>
</tr>
<tr>
<td>Z-3.17-1859</td>
<td>65 – 79</td>
</tr>
<tr>
<td>Z-3.17-1864</td>
<td>65 - 79</td>
</tr>
<tr>
<td>Z-3.17-1876</td>
<td>65 - 79</td>
</tr>
<tr>
<td>Z-3.17-1877</td>
<td>65 - 79</td>
</tr>
<tr>
<td>Z-3.17-1882</td>
<td>65 - 79</td>
</tr>
<tr>
<td>Z-3.17-1880</td>
<td>65 - 79</td>
</tr>
<tr>
<td>Z-3.17-1891</td>
<td>65 - 79</td>
</tr>
</tbody>
</table>

The range of acceptance tests presented below is based upon a test schedule for the acceptance testing of Portland composite cements CEM II/B-M (S-LL) - November 2004 edition. The test schedule is based on the following pre-requisites:

- As per the table F.3.2 of DIN1045-2: 2001:07, Portland composite cement CEM II/B-M (S-LL) may be used in the following exposure classes: X0, XC1, XC2.
- The following further exposure classes will apply for Portland composite cement CEM II/B-M (S-LL): XC3, XC4, XD1 up to XD3, XS1 up to XS3, XF1 up to XF4,XA1 up to XA3, XM1 up to XM3.
- The test schedule contains no certificate for exposure classes XA and XM.
- The tests are to be conducted on samples from a sample grinding with the applied "limit composition" with the lowest clinker content and the highest limestone content.
- The acceptance testing is to be carried out for strength class 32.5 R. When applying for strength classes 32.5 R, 42.5 N and 42.5 R the applicant receives the acceptance for the strength class that has been applied for.
The test schedule for acceptance testing of Portland composite cement CEM II/B-M (S-LL) – November 2004 edition includes the following tests:

<table>
<thead>
<tr>
<th>Test Schedule Section</th>
<th>Range of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Tests on the source materials, Portland cement clinker, granulated blast furnace slag, limestone and sulphate carrier: The chemical composition of all source materials is to be checked. The tests are to be carried out in accordance with DIN EN 196-1 or DIN EN 196-21. When GBS is used, the ratios ((\text{CaO + MgO})/(\text{SiO}_2)) and the glass content are to be determined.</td>
</tr>
<tr>
<td>4</td>
<td>Tests on the cement as per DIN EN 196: a complete cement testing is to be carried out on the Portland composite cement (chemical composition, proportions of main components, grinding fineness, solidification, volume stability, compression strength at ages from 2, 7, 28 and 90 days).</td>
</tr>
<tr>
<td>5</td>
<td>Tests on carbonisation characteristics: the carbonisation tests will be performed on fine concrete prisms. There are two kinds preliminary storage specified. During the main storage the compression strengths is to be determined at in each case two specified times and the carbonisation depth over a period of five years is to be determined at in each case 8 specified times.</td>
</tr>
<tr>
<td>6</td>
<td>Tests on the resistance against chloride penetration: the resistance against chloride penetration is to be determined using a shortcut (migration test). The test is to be carried out at two specified times.</td>
</tr>
<tr>
<td>7</td>
<td>Testing of frost resistance: a cube strength test is used for estimating the frost resistance as per Booklet 422 of the DafStb on a concrete with water to cement ratio w/c = 0.60. The test is performed on cubes with an edge length of 100 mm. The compression strength at the age of 28 days is determined as per DIN 1048-5 on respectively three cubes with an edge length of 150 mm which have been taken from the same production as the sample units for the frost test.</td>
</tr>
<tr>
<td>8</td>
<td>Tests on the frost and de-icing salt resistance: the test of the frost and the de-icing salt resistance is made using the CDF procedure on cement with artificially induced air pores. In addition to the frost and de-icing salt test, decompression strengths at the age of 28 and 56 days and the air pore properties on the set concrete are to be determined. In addition the water penetration depth is to be determined at the age of 28 days. The investigations are to be carried out with the Portland composite cement CEM II/B-M (S-LL) and with a comparable cement CEM II/B-S 32,5 R.</td>
</tr>
</tbody>
</table>
11 Appendix C (Thurament: General building inspection approval)

General building inspection approval

For the company O. M. Z. Vereinigte Ost- und Mitteldeutsche Zement-AG, Göschwitz Plant in Göschwitz (Saale); now for the Maximilian Furnace Steel Works, State-owned Operation

Subj: Thurament

(In accordance with the terms of the General Approval of New Building Materials and Building Methods dated 31.12.1937 (State Official Working Document no. 2/38 Part 1 [page 11), the Thurament from Messrs O.M.Z. Ost und Mitteldeutsche Zement AG, Göschwitz Plant in Göschwitz (Saale) on the basis of the prescribed test certificate subject to the following conditions is recognized as being adequate for use and effective in its use for the production of components from concrete and reinforced concrete.

The approval shall apply for the whole of the State territory and up until 31.3 1948.

Conditions

1. Terminology

a) Thurament is manufactured by „Vereinigten Ost- und Mitteldeutschen Zement AG.“ (O. M. Z.) from granulated, basic, latent hydraulic blast furnace slag of the composition:

$$\frac{CaO + MgO + Al_2O_3}{SiO_2} \geq 1$$

Thurament may only be used in conjunction with Portland cements as per DIN 1164 and produces together with this the bonding agent for mortar and concrete.

b) The highest proportion in Thurament totals 0.5 parts by weight. Thurament at 0.5 parts by weight. Portland cement (Z 225; Z 325 or 425). A larger addition of Thurament is up to 0.66 parts by weight Thurament at 0.34 parts by weight with Portland cement is permitted with special approval of the building inspectorate only after the carrying out of special ongoing suitability tests.

2. Monitoring and identification

The production of Thurament is to be continuously monitored by the test and material inspection office at the Technical University of Dresden in accordance with the guidelines attached hereto.

The packaging shall bear the identification “Thurament”, the details of the gross the weight, the name of the producing plant and the words “Officially Monitored”. Blue sacks are to be utilized in its packaging in paper sacks.
3. Characteristics

a) Strength

α) On-site testing

Portland cement used for this purpose is to be as per DIN 1164 dated July 1942.

The mortar mix:

- 0.5 parts by weight. Thurament
- 0.5 parts by weight. Portland cement as per DIN 1164
- 2.0 parts by weight. Standard sand as per DIN 1164 grain II (coarse)
- 1.0 parts by weight. Standard sand as per DIN 1164 grain II (fine)

The following strengths must be as per DIN 1164 in the test:

<table>
<thead>
<tr>
<th>According to:</th>
<th>7 days</th>
<th>28 days in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending tensile strength</td>
<td>25 kg/cm²</td>
<td>50 kg/cm²</td>
</tr>
<tr>
<td>Pressure</td>
<td>110 kg/cm²</td>
<td>225 kg/cm²</td>
</tr>
</tbody>
</table>

If other Portland cements should be used, then the test must be repeated with these.

β) Testing during the plant inspection

This is to be carried out in the same way and with the same requirements as under .3 α but always with the same fixed Portland cement type from a specified plant prior to the monitoring taking place.

A test using standard lime can be carried out in addition to the test with Portland cement in the plant inspection. In this case there should be in a test

As per DIN DVM 1043 Trass and Sheets 2 and 3 the mortar mix of

- 1.9 parts by weight. Thurament
- 0.4 parts by weight. Standard crushed limestone
- 1.5 parts by weight. Standard sand (DIN 1043 BI. 3)

The following minimum strengths should be found

<table>
<thead>
<tr>
<th>After being deposited in:</th>
<th>7 days</th>
<th>28 days in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>15 kg/cm²</td>
<td>30 kg/cm²</td>
</tr>
<tr>
<td>Pressure</td>
<td>150 kg/cm²</td>
<td>300 kg/cm²</td>
</tr>
</tbody>
</table>

The test with Portland cement always remains the decisive one.

b) Grinding fineness

Thurament must be ground to a fineness so that there is a maximum 20% residue on the screen filter 0.09 DIN 1171 (4900 mesh per 1 cm²).
c) Density

If exceptionally Thurament is added into room parts, then its density is to be agreed to in the conversion of weight to room parts as with cement at 1.20, if it is not determined by tests on site.

4. Range of applications of Thurament

The stipulations of the German Committee for Reinforced Concrete are to apply for the production of components made of concrete and reinforced concrete, unless hereinafter something different is specified.

A prerequisite for the use of Thurament is the performance of the concrete and reinforced concrete work by those specialised companies, which comply with the preliminary remarks of the regulations of the DafStb.

Thurament may only be used in bulk, reinforced or non-reinforced concrete components that are specially for civil engineering work which can be kept in a wet condition for protection against any premature drying out such as for example foundations, abutments, piles, dams and weirs. Thurament may not be used with fine, slender-designed, reinforced concrete structures as for example in house and bridge building.”

In a deviation from § 8 item to the reinforced concrete regulations Thurament component may be apportioned on the necessary minimum content of cement.

Prior to the use of Thurament, suitability and rigidity tests as per Part D of the Reinforced Concrete Regulations are to be carried out using the building materials specified for the building project. During the building work done it must be certified by product inspections that the necessarily cubic strength W 28 is actually maintained. (Product Inspection Part D.)
13 Appendix E (Extract from the certification procedures as per BRL 9340)

The (potential) holder of the certificate shall apply to the certifying centre for the certifying investigation to be performed on a combination of GGBS and of a Portland cement. The certifying centre shall appoint a laboratory that is recognized for this purpose for the carrying-out of the investigations into the required samples.

For the first combination of a GGBS and a Portland cement at the prescribed intervals 9 samples of the GGBS and 9 samples of the reference cement will be taken and investigated as per the established certification procedure approval guidelines. In this certification investigation, the determination of the durability will be carried out on the first three samples of GGBS and Portland cement (one test piece from each sample) and the compression strength in comparison to the reference concrete is to be determined on all samples.

In accordance with the selection of the combination (the volume of GGBS and Portland cement), the applicant must indicate for which environmental class the certificate should apply. A maximum water/bonding agent factor applies for each environmental class, for which an investigation of the durability of the slag/cement concrete is performed and which must be judged by means of the durability aspects of the individual environmental classes.

For any further combination of this GGBS and any other cement, a shortened investigation with three instead of nine samples will be performed. This investigation is limited to the determining of the compression strength of the GGBS/cement concrete and of the reference concrete.

The determining of the compression strength is carried out with two water/bonding agent ratios, respectively 0.45 and 0.65 one and at the option of the applicant one or several GGBS contents in the combination. The overall proportion of GGBS in the GGBS/cement concrete is counted in this as bonding agent.

A certificate will be issued if on the basis of the investigations it is determined that the requirements of this BRL have been fulfilled. Prior to the issue of the first certificate a contract will be agreed between the certifying centre and the certificate holder in which the rights and obligations of each individual and third-party (user of the certificate) are established.

If the results of the investigations of the first sample from a series of 9 (both compression strength as well as durability) show that the combination of the corresponding samples of GGBS and Portland cement meet the requirements, a certificate with a limited validity period can be issued. After the receipt of further results it will be judged as to whether the certificate can be extended.

Once per year an abbreviated investigation will make a check as to whether the criterion of strength development is being met. A certification investigation will be repeated every four years (both for compression strength and durability) on a certified combination.
The requirements and tests according to the judgement guidelines BRL 9340 relate to the use of GGBS from one or several plants (blast furnace slag grinding plants) in concrete in the combination with one or several Portland cements from one or several cement works in one or several compositions in one or several environmental classes. Typical for these compositions is the fact that the requirements of NEN 6720 on the minimal cement content and the maximum water/bonding agent ratio are met solely through the complete apportioning of the GGBS as a binding agent.

The definition for reference concrete is: concrete which being made from normal cement (Portland furnace cement CEM II/A-S, CEM II/B-S or blast furnace cement CEM III/A or CEM III/B) meets the EN 197-1 requirements and has a more or less similar GBS content to the combination that is to be certified and consists of aggregate, additive and water. The total portion of GGBS is counted in this as bonding agent.

In addition to the compression strength in accordance with whatever exposure classes (environmental classes) for which the applicant is applying for certification, the carbonisation and the frost and de-icing salt resistance, the chloride penetration and to the extent that is necessary also the resistance against seawater and sulphates are investigated. The instructions on how these criteria are to be tested are contained in the CUR Notice 48 [Cur]. Tables E1 and E2 contain the compositions of the concrete that is that to be tested.

**Table E1:** Composition of ground granulated blast furnace slag/cement concrete and reference concrete for the determination of the compression strength

<table>
<thead>
<tr>
<th>Composition</th>
<th>Concrete with high w/b</th>
<th>Concrete with low w/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/bonding agent ratio</td>
<td>0.65</td>
<td>0.45</td>
</tr>
<tr>
<td>Content cement + concrete additive material</td>
<td>280 kg/m³</td>
<td>340 kg/m³</td>
</tr>
<tr>
<td>GGBS content</td>
<td>Representative for the reference cement and is within the range of the GBS proportion in the reference cement</td>
<td></td>
</tr>
</tbody>
</table>

**Table E2:** Composition of ground granulated blast furnace slag/cement concrete and reference concrete for the determination of the durability

<table>
<thead>
<tr>
<th>Composition</th>
<th>Environmental class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>w/c / w/b</td>
<td>0.65</td>
</tr>
<tr>
<td>with LBV</td>
<td>without LBV</td>
</tr>
<tr>
<td>Cement / bonding agent[kg]</td>
<td>280</td>
</tr>
<tr>
<td>Water *) [kg]</td>
<td>182</td>
</tr>
</tbody>
</table>

*) Effective water content, i.e. exclusive absorption water of the aggregate

Once per year an abbreviated investigation will make a check as to whether the criterion of strength development is being met. A certification investigation will be repeated every four years (both for compression strength and durability) on a certified combination. The following flowchart (figure E1) shows the complete investigation.

Flowchart of the certification investigation
Application for the first combination of GGBS and Portland cement, Applicants’s input:
- Environmental class(es)
- GGBS and Portland cement
- Reference cement

Sampling: 9 GGBS, cement, and reference cement samples (within 3-6 months; at least one week between samplings)

Characterisation of the GGBS on 9 samples:
- Fineness (Blaine)
- Standard compression strength (2, 7 and 28 days)

Durability investigations with the first three samples of GGBS and Portland cement (one test body for each sample) at maximum w/bf for the associated environmental class(es)
For environmental classes 4, 5c and 5d in addition supplementary characterisation on the first three samples: aluminium oxyde content

Concrete strength is determined on all samples of GGBS and Portland cement and reference cement (7, 28 und 91 d with w/b 0.45 und 0.65)

The GGBS proportion of the combination must match the GGBS content of the reference cement

If the results meet the requirements: issuing of the certificate for the environmental classes, for which durability tests have been performed.

**Figure E1:** Flow chart of the certification investigation as per BRL 9340