Ground Granulated Blast-Furnace Slag

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Abstract

Since the discovery of the latent hydraulic reactivity of ground granulated blast-furnace slag (ggbfs) by Emil Langen at the end of the 19th century, this material has been used successfully as cement and concrete addition. This chapter includes all relevant information about this valuable material—from production and processing to the effect, which ggbfs additions have on the concrete performance. In this context, light is shed on decisive performance parameters of ggbfs. Of special interest nowadays is certainly also the information given about trace element contents in ggbfs and their leachability. Here and throughout the entire chapter, the latest insights from research and development work are included. Last but not least, the chapter contains very practical information when it comes to the use of ggbfs in concrete, including insights on rheological effects, concrete color and "greening", and adequate curing. Moreover, an overview about relevant norms and standards on ggbfs as concrete addition is given.

AQ1

Keywords

■ ■ ■

AQ2

1.1. Blast-Furnace Slag—An Overview

1.1.1. History of Blast-Furnace Slag

The latent hydraulic reactivity of granulated blast-furnace slag (gbfs) was discovered in 1862 by Emil Langen in Germany (Lea 1971; Smolczyk 1978). The first use of slags in cements dates back to 1865, when in Germany a slag-lime cement was commercially produced. By 1901 the manufacture of "Eisenportlandzement" containing maximum 30% of ground granulated blast-furnace slag (ggbfs) became accepted and in 1907, the first "Hochofenzement" with up to 85% ggbfs content was produced (Moranville-Regourd 1998; Smolczyk 1978). Ever since, ggbfs has been successfully used in cementitious applications.

1.1.2. Production and Use of Blast-Furnace Slag

Blast-furnace slag (bfs) is a by-product in the manufacture of pig iron in the blast furnace. It forms by fusion of the gangue, i.e. non-ferrous material of the iron ore, mainly silica and alumina compounds, with calcium and magnesium oxides of the thermally decomposed carbonatic flux and combustion residues of the coke. These reactions take place at temperatures between 1300 and 1600 ℃. The slag floats on top of the liquid iron and is tapped at regular intervals. When leaving the blast furnace, the molten bfs has a temperature of around 1450 ℃ and is cooled down, either slowly in contact with air in open pits or rapidly through pelletization or granulation. The latter is the state-of-the-art solution. It involves the rapid quenching and mechanical dissemination of the molten slag with water jets. Also dry slag granulation techniques exist, which however never succeeded at large scale. In the context of energy recovery from molten slag, main granulation equipment suppliers have recently revived the development of dry granulation techniques.

Air cooled slag is essentially crystalline and hardly reactive. After crushing and sieving it is typically used as back-fill material in road construction or as aggregate in concrete manufacture.

Gbfs has a maximum particle size around 5 mm and is predominantly vitreous. This high glass content is the prerequisite for the latent hydraulic reactivity of gbfs, which makes it an excellent supplementary cementitious material (SCM) for the production of composite cements as a clinker substitute and for concrete manufacture as a cement substitute.

In order to produce a suitable SCM the gbfs must be ground to a specific fineness, which influences the hydraulic reactivity of the ggbfs.

Per ton of iron produced, between 0.2 and 0.5 t of bfs are obtained. The exact amount depends on the composition of the iron ore and on efficiency and size of the blast furnace. In state-of-the-art blast furnaces, the amount of bfs/ton of iron does not exceed 0.3 t.

The worldwide production of bfs is estimated at ~360 million t/a (Reynolds 2009). About half of it is being granulated and used in cementitious applications as SCM, taking advantage of the latent hydraulic reactivity, which allows for maximum replacement levels of clinker in cement production and of cement in concrete manufacture.

1.1.3. Composition and Reactivity of Gbfs

The main constituents of bfs are lime-silica-alumina and magnesia compounds. Figure 1.1 shows the position of bfs in the ternary diagram CaO-SiO_2-Al_2O_3 including the stability fields of the respective minerals. Gbfs typically contains minor amounts of crystals, normally melilite [solid solutions from Gehlenite $Ca_2Al(AlSi)O_7$ to Akermanite $Ca_2MgSi_2O_7$]. In basic slags with a CaO/SiO_2 ratio >1, also merwinite $Ca_3Mg(SiO_4)_2$ occurs.

Fig. 1.1

Composition of bfs in the ternary diagram CaO-SiO_2-Al_2O_3 with 10% MgO, redrafted after Satarin (1974)
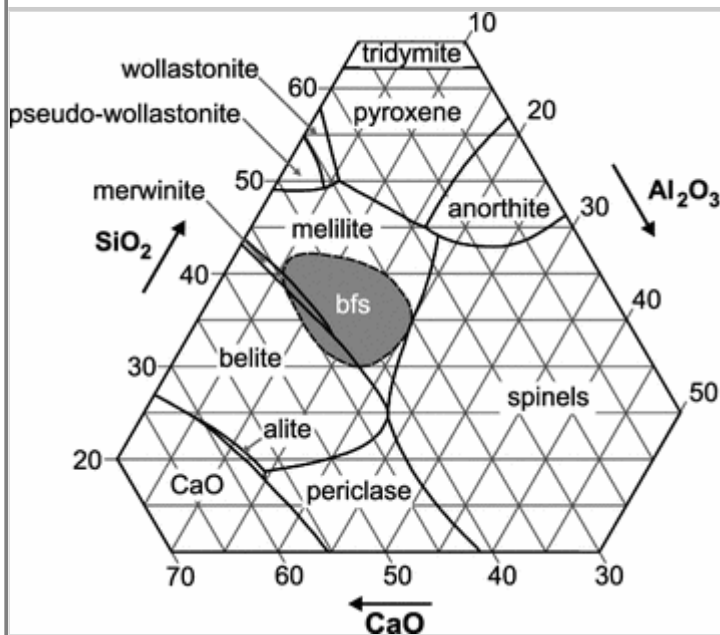
The chemical composition of bfs depends on quality, type and proportioning of the burden, i.e. iron ore, coke and flux, and the fuels used in the blast furnace. Thus, the composition of slags from different regions varies within certain limits (Table 1.1, Matthes 2012). This is especially important to consider when importing gbfs or ggbfs from other parts of the world. However, bfs originating from the same blast furnace exhibits a rather constant composition, because priority for blast furnace operation is a constant quality of the pig iron.

Table 1.1

Typical ranges of selected properties of granulated blast-furnace slags produced worldwide and in specific regions, including chemical composition, glass content, and bulk density (Matthes 2012)

Parameter	Unit	Min	Max	North America	Central and ~~Latin~~South America	Western Europe	Eastern Europe	India, Japan, Australia, RSA

Parameter	Unit	Min	Max	North America	Central and ~~Latin~~South America	Western Europe	Eastern Europe	India, Japan, Australia, RSA
SiO_2	%	32	42	34.6–39.9	33.5–34.8	32.0–39.4	33.5–41.5	32.6–36.9
CaO	%	35	48	35.3–42.8	39.1–43.8	34.9–44.3	36.9–47.5	33.0–43.0
Al_2O_3	%	6	>19	6.6–11.5	10.0–13.0	9.5–12.5	5.5–12.4	10.2–19.3
MgO	%	3	14	7.0–13.1	5.9–9.9	5.0–13.4	2.5–11.2	4.9–13.8
TiO_2	%	0.2	>2	0.3–0.8	0.5–0.6	0.4–1.3	0.2–1.3	0.6–2.1
Na_2O_{eq}	%	0.3	1.2	0.3–0.8	0.4–0.8	0.3–1.2	0.6–1.1	0.4–0.8
SO_3[a]	%	1	4	2.0–3.0	1.1–3.7	2.0–4.5	1.6–3.8	1.7–4.0
CaO/SiO_2	–	0.9	1.3	0.9–1.2	1.1–1.3	1.0–1.3	0.9–1.3	0.9–1.3
Glass content	%	66	100	Not analysed				
Bulk density	kg/l	0.6	1.3	Not analysed				

[a]Although expressed as SO_3 in the chemical analysis, essentially all sulfur in gbfs is present in sulfide form due to the reducing conditions in the blast furnace (% SO_3 = 2.5 x% S^{2-})

The hydration of ggbfs in Portland-composite cements was extensively discussed by Taylor (1997). In presence of water ggbfs hydrates to a limited degree. A protecting film deficient in calcium is quickly formed, which slows down further reaction. If the pH is kept sufficiently high in presence of activators, the ggbfs hydration is accelerated and intensified. The most common activator of ggbfs is Portland cement clinker, but also other alkaline materials, for example water glass, alkali carbonates, alkali hydroxides, etc. can be used. Calcium sulfates accelerate the hydration of medium to high-alumina gbfs glass (Al_2O_3 > 11%) due to the formation of ettringite, which consumes calcium and alumina released from the ggbfs. Calcium sulfates, combined with alkali compounds are effective activators of ggbfs applied in composite cements and also supersulfated cements. In all cases, calcium silicate hydrate (C-S-H) phases form as hydration products, which are responsible for strength development. Depending on the activator, also other phases form which influence hydration progress and strength development (Matthes et al. 2011; Taylor 1997).

In general, the reactivity of a ggbfs increases with increasing contents of CaO, ~~(MgO),~~ Na_2O, and Al_2O_3 and with decreasing contents of SiO_2, FeO, TiO_2, MnO, and MnS (Dron and Brivot 1980; Kollo 1991; Kollo and Geiseler 1987; Schröder 1969; Smolczyk 1978; Sopora 1959; Yang 1969). A high CaO/SiO_2 ratio generally indicates a good reactivity. Elevated alumina contents in ggbfs are favorable for strength development of slag cements in presence of sulfate, especially at early ages due to enhanced ettringite formation (Matthes 2012; Olbrich 1999; Smolczyk 1978).

Numerous indices have been developed to predict and specify the reactivity of ggbfs. Some of them are given in Table 1.2. While such indices may be convenient for quality control of ggbfs from one source, they are not satisfactory for a general prediction of strength of various ggbfs in cement, because there is no linear relationship between strength and oxide contents in ggbfs over a large composition range (Hooton and Emery 1983; Schröder 1961; Smolczyk 1978).

Table 1.2

Summary of the reactivity indices for ggbfs (De Langavant 1949; Ehrenberg et al. 2008a, b; Tetmajer 1886; Tigges 2010; Wang et al. 1994)

Reactivity index	Year	Definition	Criteria
Basicity according to Tetmajer	1886	CaO/ SiO_2	–
German Standard for "Eisenportlandzement" (CEM II-S) AQ3	1909	$\dfrac{CaO+MgO}{SiO_2+Al_2O_3}$	≥ 1
German Standard for "Hochofenzement"	1932	$\dfrac{CaO+MgO+0.33\cdot Al_2O_3}{SiO_2+0.67\cdot Al_2O_3}$ MnO	≥ 1 ≤ 5 wt%
German Standard for special cements	1942	$\dfrac{CaO+MgO+Al_2O_3}{SiO_2}$	≥ 1
F-value according to Keil	1942	$\dfrac{CaO+CaS+0.5\cdot MgO+Al_2O_3}{SiO_2+MnO}$	>1.5
Reactivity according to De Langavant	1949	$20 + CaO + Al_2O_3 + 0.5\cdot MgO - SiO_2$	–
F-value according to Sopora	1959	$\dfrac{CaO+CaS+0.5\cdot MgO+Al_2O_3}{SiO_2+MnO_2}$	>1.5
Basicity according to Schwiete	1963	$\dfrac{CaO+Al_2O_3-10}{SiO_2+10}$	–
Reactivitiy according to Wang	1994	$\dfrac{CaO+MgO+Al_2O_3}{SiO_2+TiO_2}$	–
European Standards for cement and ~~B~~blast-furnace slag	1994 2001 2006	$\dfrac{CaO+MgO}{SiO_2}$ $CaO + MgO + SiO_2$	>1 >67 wt%

Apart from the chemical and mineralogical composition, the degree of pre-hydration of gbfs affects its hydraulic reactivity. Due to its latent hydraulic properties, gbfs starts to hydrate as soon as it gets in contact with water. After granulation the gbfs typically has a moisture content between 8 and 12%, sometimes up to 20%, depending on its pore volume. When gbfs is stockpiled outside, a hard crust of prehydrated gbfs can form on the stockpile over time. When recovering the gbfs, the lumps may require extensive disaggregation before any further pro-cessing can be done. The intensity of the prehydration depends on the reactivity of the gbfs, climatic conditions, particle shape, compaction, and storage time. It can be measured via loss on ignition (LOI), which accounts for chemically bound water, or bound CO_2. While fresh gbfs has an LOI of 0.2–0.5%, stockpiled gbfs can reach an LOI of 2% and beyond (Matthes 2012).

The prehydration of gbfs is relevant for gbfs processing. As the soft hydration products are very easy to grind, a given target fineness is obtained with a lower grinding energy compared to fresh gbfs. Due to the contribution of the soft hydration products to target fineness, the reactive fresh ggbfs grains will be coarser and thus, the compressive strength obtained from prehydrated gbfs will be lower compared to fresh gbfs of same fineness and composition (Ehrenberg 2012; Matthes 2012). When applying the same grinding energy as to fresh gbfs, the prehydrated gbfs will show a higher overall fineness due to the contribution of the soft hydration products, but the reactivity and strength development will be comparable to fresh ggbfs.

Concerning the assessment of gbfs reactivity, strength testing combined with chemical and mineralogical characterization remains a very reliable and simple method. For non-routine analyses, numerous laboratory methods allow assessment of the hydration degree of gbfs. Promising among those are electron microscopy and image analysis (SEM-BSE-IA), isothermal calorimetry and chemical shrinkage (Kocaba et al. 2012).

Apart from the intrinsic reactivity, fineness and particle size distribution of the ground gbfs, in Portland composite systems, the properties of the Portland cement clinker, type and dosage of the calcium sulfate set modifier, the particle size distribution of the cement constituents and the actual concrete mix design determine the ultimate concrete performance (Fig. 1.2, Wolter et al. 2003). In production, the reactivity of ggbfs is mainly controlled by varying fineness and particle size distribution. In the ASTM C 989 there are three strength grades of ggbfs specified, which are largely influenced by gbfs quality, fineness, and also by possible calcium sulfate additions.

Fig. 1.2

Factors affecting the reactivity of ggbfs, redrafted after Wolter et al. (2003)
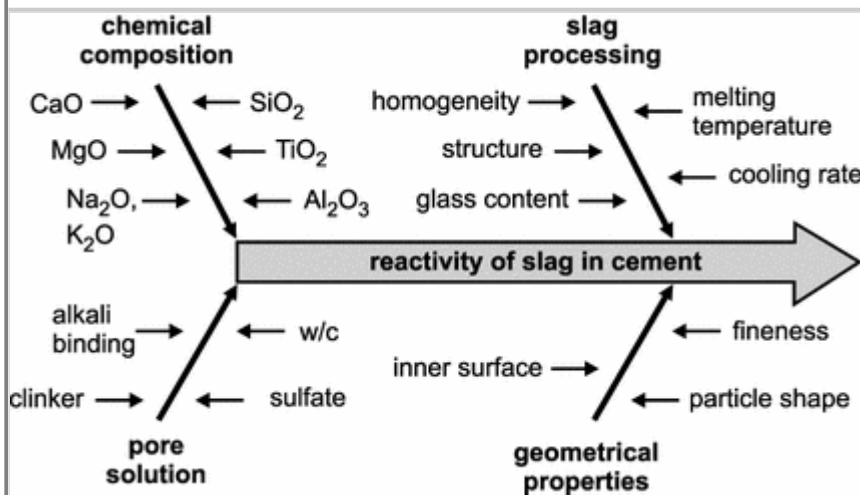
1.1.4. Ggbfs as Cement Constituent and as Concrete Addition

Typical ggbfs contents in concrete range from 20 to ~80% of the total cementitious material. The cement replacement level depends on the requirements on:

– Strength development

– Durability, e.g. resistance to ASR, or attack by sulfates, sea water, or other chemicals or frost and deicing salt

– Heat of hydration

– Setting time.

Ggbfs is either used as a cement constituent replacing Portland clinker and/or as concrete constituent replacing cement. The kind of ggbfs utilization differs locally. North America, the UK and Australia, for example, have a long tradition of using ggbfs as concrete addition, while in Latin America, most of central Europe and India, ggbfs is mainly used as cement constituent.

Both applications have their advantages and disadvantages. The direct use of SCM in concrete gives the concrete producer a maximum flexibility for designing concretes for various applications with a minimum number of silos for cement and SCM. The prerequisite is an adequate knowledge about concrete design and performance. A disadvantage of direct SCM addition to concrete is that the performance of the cementitious part cannot be optimized. In cases, where ggbfs and/or cement were of lower reactivity, higher cement contents can be necessary to achieve the same performance as a concrete made with an optimized Portland composite cement with ggbfs (Fig. 1.3, Addis 1986). Intergrinding calcium sulfate with gbfs can help to improve the reactivity of the cementitious system, especially when the gbfs has a medium alumina content >10%.

Fig. 1.3

Concrete compressive strength of composite cements with 50% ggbfs versus 50% ggbfs site blends, redrafted from Addis (1986)
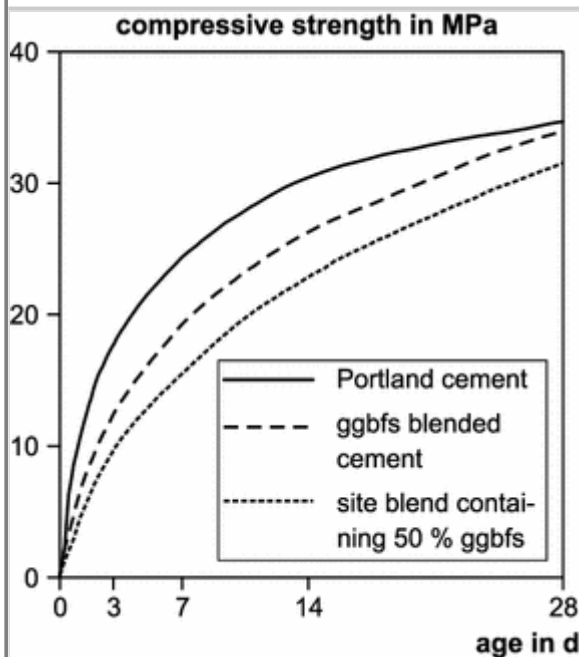
When using ggbfs as concrete addition it is the responsibility of the ready mix concrete producer to handle changes in the quality of cement and SCMs. This is typically done via adjustments to the concrete design. Composite cements are optimized for performance including quality control of the single cement constituents, optimization of type and dosage of the calcium sulfate phase for optimum setting and hardening and optimum fineness and particle size distribution for best fresh concrete properties and strength. Due to permanent quality control of all cement constituents and of the final product by the cement producer, the concrete producer will obtain cements with a consistent quality.

When proportioning concrete with ggbfs, the lower specific gravity of ggbfs of ~2.9 g/cm^3 versus Portland cement of ~3.14 g/cm^3 has to be considered. Replacing cement by ggbfs on a mass basis leads to higher volume of cementitious phase, which usually improves placeability, finishability, and compaction of the concrete. Moreover, coarser aggregate can be used to increase strength and to reduce water demand without affecting plastic properties (SCA 2002).

Ternary composites including Portland cement and ggbfs plus another SCM such as fly ash, silica fume or limestone are beneficial to further improve concrete properties, e.g. in high performance concrete. Combinations with fly ash can further improve workability due to the ball-bearing effect of spherical fly ash particles and further reduce heat of hydration. Combinations with silica fume will further increase strength and reduce permeability of the concrete at early ages (ACI 2011; Matthes 2012).

1.2. Relevant Standards for Ggbfs as Cement and Concrete Addition

The different options of using ggbfs, either as a cement or concrete constituent, are reflected by the existing standards. Examples of standards for ggbfs as a cement addition are the European EN 197-1 or ASTM C 595. They include different cement classes differentiated according to the amount of Portland clinker and to the type and amount of SCMs. EN 197-1 for example differentiates between Portland composite cements with up to 35% SCMs, be it pure or in combinations. Apart from that, three classes of blast-furnace cements exist, CEM III/A, B, C, which have ggbfs contents from 36 to 95%. So far, apart from 5% minor constituents, no combinations with other SCMs are allowed in these blast-furnace cements, but this is expected to change in the revised version. The CEM V/A and CEM V/B cements are low clinker cements

containing a combination of ggbfs and pozzolans or siliceous fly ash, each with minimum contents of 18 and 31%, respectively.

Special cements for exposure to chemical attack are usually covered by national standards. In this respect, slag composite cements are often mentioned. For example, the French NF P 15-317 on sea-water resisting cements allows CEM II/A-S, II/A-M (S-V), CEM III/A with minimum 60% ggbfs and CEM III/B, CEM III/C and CEM V cements, together with specifications on the composition of the cements and clinker, including C_3A and sulfate contents etc. The same cements plus CEM II/B are allowed by NF-P 15-319, which specifies cements for applications in high sulfate environment, again in connection with chemical specifications. The German DIN 1164 defines CEM III/B and CEM III/C cements according to EN 197-1 as high sulfate resistant.

Examples of standards on ggbfs as addition to concrete, mortar and grouts are the American ASTM C 989 and the European EN 15167-1:2006. ASTM C 989 differentiates three grades of ggbfs, based on their strength development when mixed at 50% with a reference, ordinary Portland cement (OPC). The addition of calcium sulfate is allowed. EN 15167-1 does not include strength classes and does not foresee calcium sulfate additions. Apart from standards for single SCMs such as ggbfs as concrete addition, also combinations are specified, for example by the Austrian öNORM B 3399 or by ASTM C 1697.

Recommendations on how to account for ggbfs in the concrete mix design are given by the European concrete standard EN 206. The EN 206 lists ggbfs conforming to EN 15167-1, along with fly ash and silica fume, as type II concrete additions. The prescriptive k-value concept as well as the Equivalent Concrete Performance Concept (ECPC) and Equivalent Performance of Combinations Concept (EPCC) are included.

The *k*-value concept is based on the comparison of the 28-day strength performance of a reference concrete with a specified cement versus a test concrete, in which part of this cement is replaced by a type II addition. The concept permits type II additions to be taken into account by replacing the term "water/cement ratio" with "equivalent water/cement ratio" (w/c_{eq} = water/(cement + k · addition)). The amount of (cement + k · addition) shall not be less than the minimum cement content required for the relevant exposure class. According to EN 206:2013, the k-value for ggbfs and the maximum acknowledgeable amount of ggbfs have to comply with the respective national regulations. In Annex L, the following recommendations are given: The k-value of ggbfs in combination with CEM I or CEM II/A shall be 0.6. The maximum ggbfs useable for calculating the water/binder ratio and the minimum cement content shall comply with the weight ratio ggbfs/cement ≤1.0.

As the k-value concept, also the performance concepts ECPC and EPCC are used on a national basis. The ECPC permits amendments to the requirements for minimum cement content and maximum water/cement ratio when one or more specific additions and one or more specific cements are used, for which the manufacturing source and characteristics are clearly defined and documented. Such amendments are in place for example in Belgium and the Netherlands. The concept includes comparative testing of concrete compositions, which deviate from the generally specified and accepted design criteria for defined applications versus the specified reference composition. If the defined properties such as compressive strength, resistance to carbonation, chloride penetration and freeze-thaw deicing salt attack, are comparable, the suitability of the new concrete design can be certified. In Belgium the methodology for the assessment and the validation of the fitness for use of cements or additions for concrete as slag amongst others is described in NBN B15-100.

The EPCC treats a combination of a cement and additions as technically equivalent to a standardized cement of the same composition. This concept may permit a defined range of combinations to count fully towards the requirements for maximum w/c ratio and minimum cement content specified for the standardized cement (EN 206).

In North America, k-values are not used and ggbfs is treated as equivalent to Portland cement. Due to its latent hydraulic properties, ggbfs is referred to as slag cement. For concrete placements in cool weather, ggbfs replacement levels are often reduced, while they are increased in hot weather to provide similar setting times and early-age strength development. The ACI 233R *Guide to the use of Slag Cement in Concrete and Mortar* (ACI 2011) states, that the proportioning techniques for concrete incorporating ggbfs are similar to

those used in proportioning concrete made with Portland cement or blended cement. Methods for proportioning are given in the ACI 211.1 *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*. Adjustments must be made for changes in solid volume due to the difference in specific gravity of slag and Portland cement.

1.3. ~~Health and Safety Issues~~

Gbfs and ggbfs composition and trace elements

Ggbfs is a vitreous material containing silica, alumina, magnesia and calcium oxides. It also contains a small quantity of iron, sodium, titanium and manganese oxides. The oxides do not actually occur in free form but as silica-based glass. The content of crystalline silica is <1%. Wet gbfs or ggbfs is alkaline. The pH in water is 8–11 (Material Safety Data 2008). As such it is incompatible with acids, ammonium salts, and aluminum metal. Solubility in water is negligible and specific gravity is 2.7–3.1 g/cm^3. Emergency Overview.

Gbfs consists of sand-sized granules, ggbfs is a fine powder. A single short-term exposure to the dry material is not likely to cause serious harm. Exposure to wet material can cause serious, potentially irreversible tissue (skin or eye) destruction in the form of chemical (caustic) burns. The same type of tissue destruction can occur if wet or moist areas of the body are exposed for sufficient duration to these materials by chemical (caustic) burns or an allergic reaction.

Routes of exposure are eye contact, skin contact, inhalation, and ingestion.

For handling and storage, gbfs or ggbfs should be kept dry until use.

Skin Protection is essential to avoid potentially severe skin injury. Actions that cause dust to become airborne should be avoided. It is recommended to wear safety glasses with side shields or safety goggles (Material Safety Data 2008).

1.4. Selected Environmental Aspects on Gbfs and Ggbfs

It is recognized that supplementary cementitious materials or additions used as secondary main constituents in cement or concrete influence the environmental impact during manufacturing and service life of the material. In this chapter, the CO_2 emissions, the heavy metal contents and leaching and radioactivity are discussed.

1.4.1. CO_2 Footprint

Using ggbfs as secondary main constituent, either in cement or in concrete production reduces the carbon footprint of total cementitious materials. Proceeding from 913 kg CO_2/t CEM I and 67 kg CO_2/t ggbfs as quoted in the UK, the CO_2 footprint of the cementitious materials can be reduced to less than 30% of that of CEM I, due to the high replacement levels of ggbfs (Table 1.3).

Table 1.3

CO_2e (carbon dioxide equivalent) of combinations with ggbfs produced at the concrete plant (Technical Datasheet 2014)

Combination (CEM I + ggbfs)	**Content of the addition**	**CO_2e[a] (without transport of constituents to the concrete plant)**
	wt%	**kg CO_2e/t (addition content low–high)**
CIIB-S	21–35 (ggbfs)	735–617
CIIIA	36–65 (ggbfs)	608–363

Combination (CEM I + ggbfs)	Content of the addition	CO e (without transport of constituents to the concrete plant)
	wt%	kg CO e/t (addition content low–high)
CIIIB	66–80 (ggbfs)	354–236

[a]CO_2e can be interpolated for proportions of addition between the minimum and maximum, noting that the minimum CO_2e is associated with the highest proportion of addition

When using supplementary cementitious materials, attention has to be paid to the allocated environmental impact. Bfs is a useful by-product, and part of the environmental load of the steel production can be allocated to it. In this context different allocation principles can be adopted (Van den Heede and De Belie 2012). In some countries the environmental load from steel production is completely attributed to the steel and the only environmental load of the ggbfs results from grinding and transport. In the UK, the carbon footprint of ggbfs is 67 kg/t. This excludes any CO_2e allocation from the primary process, i.e. iron production. According to EN 15804, processes contributing of the order of 1% or less to the overall revenue are allowed to be neglected.

1.4.2. Heavy Metal Contents

Gbfs may contain small quantities of heavy metals. Table 1.4 compares the contents of these elements with that of OPC. The heavy metal contents of gbfs are usually lower than that of OPC.

Table 1.4

Contents of heavy metals and trace elements of CEM I and blast furnace slag

Parameter	CEM I (Brameshuber and Vollpracht 2007)			Gbfs[a]	
	n	Range	Average	n	Median
	–	mg/kg		–	mg/kg
Antimony (Sb)	21	<1–9.4	2.4	53	<5
Arsenic (As)	14	<2–12	6.1	53	<5
Barium (Ba)	8	104–818	346	–	–
Lead (Pb)	21	5–145	27	53	<5
Cadmium (Cd)	18	<0.1–1.7	0.5	53	<0.5
Chromium (Cr)	21	29–129	61	53	21.2
Cobalt (Co)	15	5.6–14	8	–	–
Copper (Cu)	18	14–101	35	53	<5
Molybdenum (Mo)	14	<1–6.9	2.9	53	<5
Nickel (Ni)	18	14–84	31	53	<5
Mercury (Hg)	18	0.003–0.7	0.06	–	–
Selenium (Se)	5	<5–10	5.9	–	–
Thallium (Tl)	15	<0.1–3.9	0.6	–	–

Parameter	CEM I (Brameshuber and Vollpracht 2007)			Gbfs	
	n	Range	Average	n	Median
	–	mg/kg		–	mg/kg
Vanadium (V)	16	22–100	39	53	34
Zinc (Zn)	14	30–514	146	53	7.4
n: Number of tested samples					
[a]Results from the database of the FEhS, Duisburg, personal note from Dr. Bialucha					

1.4.3. Leaching

The Technical Committee 351 of the European Committee for Standardization (CEN/TC351) is developing harmonised leaching tests for building materials. For monolithic materials like concrete, the following technical specification has been published: CEN/TS 16637-2:2014 (Construction products—Assessment of release of dangerous substances—Part 2: Horizontal dynamic surface leaching test—DSLT).

The DSLT is a method to determine the release of substances from a specimen with demineralised water in contact with its surface as a function of time. The specimen is placed in a leaching vessel and completely submerged in the demineralised water, which is changed at defined time steps (0.25, 1, 2.25, 4, 9, 16, 36 and 64 days). The leachates are analysed for the relevant parameters. The cumulative release of these parameters is calculated in relation to its surface (Eq. 1.1)

$$R_n = \sum_{i=1}^{n} r_i = \sum_{i=1}^{n} c_i \cdot \frac{L}{A}$$
1.1

R_n cumulative release of the substance for period n including fraction i = 1 to n in mg/m^2

r_i release of the substance in fraction i in mg/m^2

c_i concentration of the substance in leachate i in mg/l

L/A   volume of the liquid, divided by the surface area of the sample, L/A = (80 ± 10) l/m^2.

Similar tank tests have been carried out in the Netherlands and in Germany for many years. The leaching steps and the L/A-ratio differ, but the principle of the test is the same. The storage conditions before starting the leaching test are relevant. Even a slight carbonation of the surface changes the pH of the leachates and thus the concentration of heavy metals (Rickert and Vollpracht 2014). Thus, for comparative studies it is necessary to use the same storage conditions.

The release of trace elements from mortars and concretes made of commercial Portland cement and blast furnace slag cements was studied by Rickert et al. (2011), Rickert and Vollpracht (2014), Van der Sloot et al. 2001, and Vollpracht, RTWH Aachen (unpublished data). The trace element contents of the cements used (Table 1.5) indicate, that CEM III cements do not show elevated contents versus CEM I, except for V and Ba in some cases.

Table 1.5

Contents of heavy metals and trace elements of the cements used in the mortars/concretes of the tank leaching tests, (2011) [CEM I B1 (2011), CEM III/A (2011)], Rickert and Vollpracht (2014) [CEM I B1 (2014), CEM III/B (2014 (2001) [CEM I N1, N2, D1, D2, H1, H3, H6, H7, H9)]

Heavy metal/trace	CEM I	C

Heavy metal/trace	CEM I 1[a]	N1	N2	D1	D2	H1	H3	H6	H7	H9	B1 (2011)	B1 (2014)	C II 1[a]
	mg/kg	N1	N2	D1	D2	H1	H3	H6	H7	H9	B1 (2011)	B1 (2014)	C hl 1
Sb	2	2.1	<1	1.2	3.6	4.8	<1	<1	<1	3.9	8.6	3.8	5
As element	mg/kg 4	23	4.5	8.6	6.9	7.2	2.3	5.7	10	4.9	16	172	m 2
Ba	331	–	–	–	–	–	–	–	–	201	47	269	42
Pb element	14	20	30	106	15	64	12	19	5.8	57	29	155	14
Cd	0.2	0.21	0.38	0.61	<0.1	0.96	0.15	0.57	0.51	0.94	1.46	4.93	<0
Cr	59	184	70	76	29	89	92	578	129	33	85	41	46
Co	4	12	8.9	7.3	7.5	13	14	22	7.6	5.9	12	11	4
Cu	22	16	14	16	29	54	16	27	16	15	89	158	18
Mo	–	1.9	5	6.9	1.1	3.7	<1.0	<1.0	<1.0	4.3	2.7	39	–
Ni	36	61	22	45	14	47	25	75	42	14	41	25	23
Hg	0.2	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.12	0.05	0.12	<
Se	–	–	–	–	–	–	–	–	–	–	<1	<1	–
Tl	0.2	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.5	< 1	<0.2	3.37	0.
V	–	44	30	31	22	100	73	36	34	27	67	35	–
Zn	281	55	43	104	130	382	33	83	30	223	528	1178	24

[a]Unpublished data Vollpracht, RWTH Aachen; –: Not determined

After demoulding the samples were wrapped airtight in a polyethylene foil and stored at 20 ± 3 ℃ until testing. The leaching tests started at 28 or 56 days. The release of Ba, Cr, Co, Cu, Ni, Pb of CEM III cement concrete is comparable to Portland cement concrete, the release of V can be higher (Figs. 1.4, 1.5, 1.6 and 1.7). The concentrations of Sb, As and Se were below 1 µg/l, the concentrations of Cd below 0.5 µg/l and of Hg below 0.1 µg/l for all tested mixtures. Due to these low concentrations the release was not calculated.

Fig. 1.4

Release of barium and lead from mortars and concretes with different cements (Rickert et al. 2011; Rickert and Vollpracht 2014; Van der Sloot et al. 2001; Vollpracht, unpublished data)
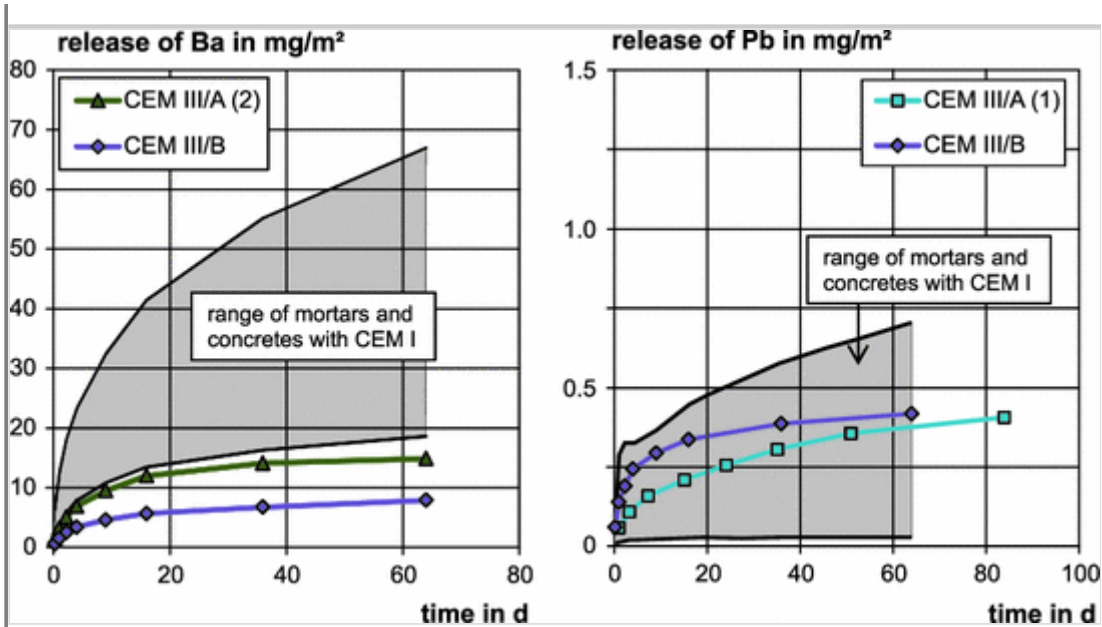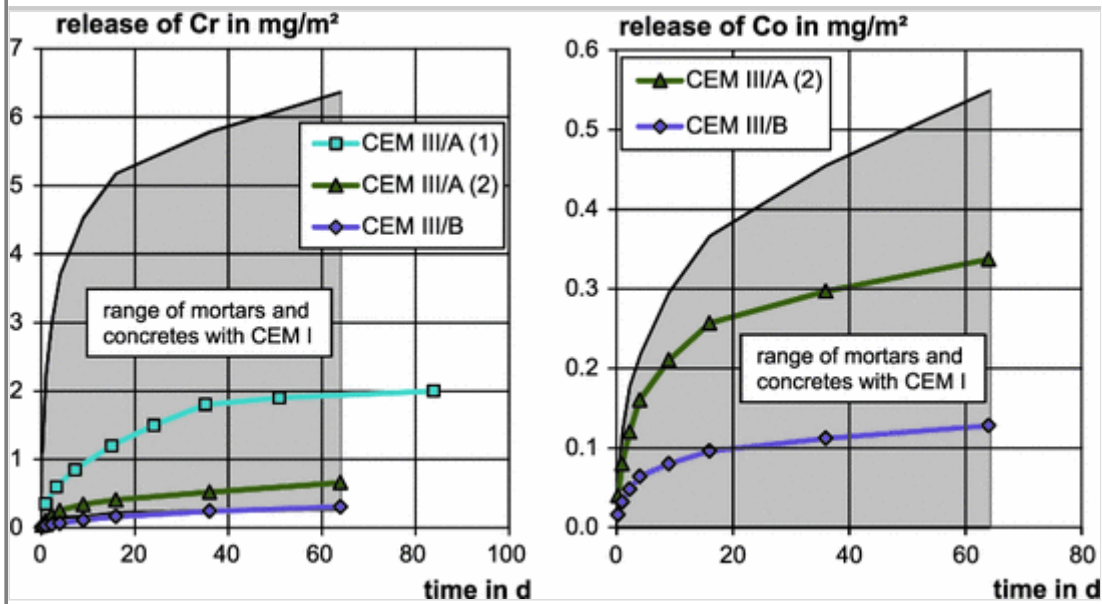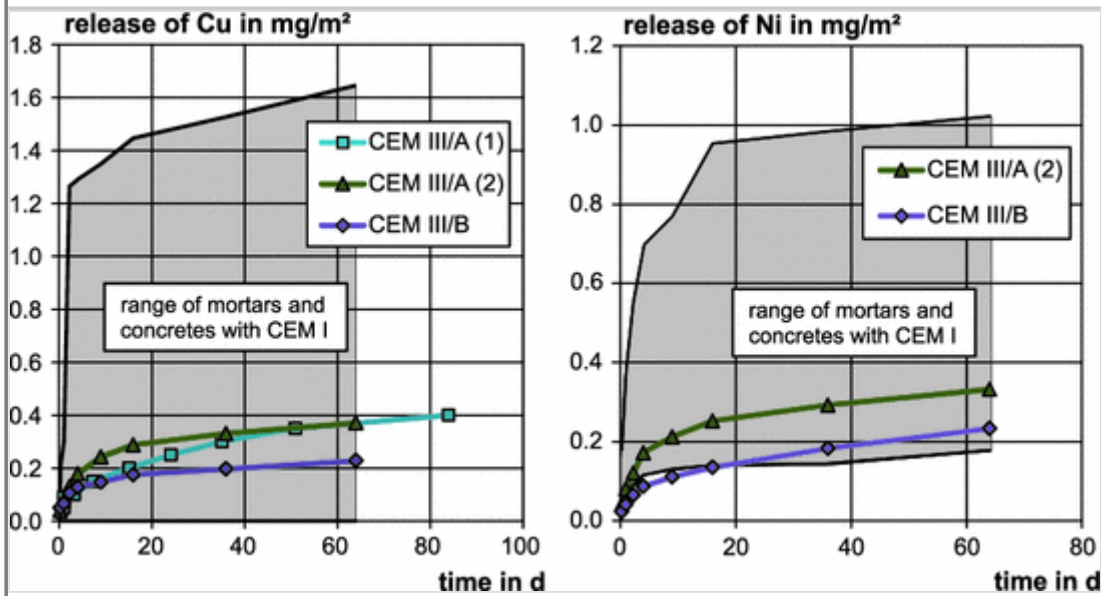
Fig. 1.5

Release of chromium and cobalt from mortars and concretes with different cements (Rickert et al. 2011; Rickert and Vollpracht 2014; Van der Sloot et al. 2001; Vollpracht, unpublished data)

Fig. 1.6

Release of copper and nickel from mortars and concretes with different cements (Rickert et al. 2011; Rickert and Vollpracht 2014; Van der Sloot et al. 2001; Vollpracht, unpublished data)

Fig. 1.7

Release of vanadium from mortars and concretes with different cements (Rickert et al. 2011; Rickert and Vollpracht 2014; Van der Sloot et al. 2001; Vollpracht, unpublished data)
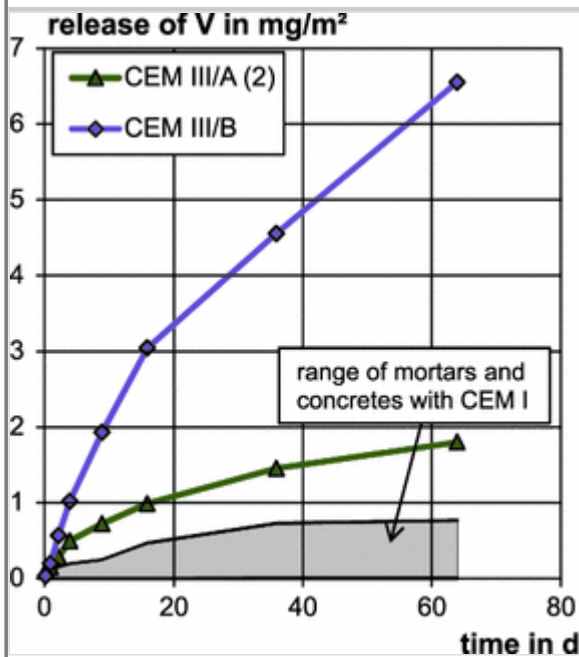
In the EU the evaluation of leaching results is regulated at national level.

1.4.4. Radioactivity

The radioactivity of gbfs or ggbfs generally does not exceed typical concentrations in other commercial products and building materials (Table 1.6).

Table 1.6

Radioactivity of gbfs compared to natural rocks and other building materials

Material	Ra-226	Th-232	K-40	Reference

Material	Ra-226	Range	Th-232	Range	K-40	Range	Reference
	Bq/kg Average	Range	Bq/kg Average	Range	Bq/kg Average	Range	–
Soils (worldwide)	32 Bq/kg	n. i.	45 Bq/kg	n. i.	412 Bq/kg	n. i.	UNSCEAR Report (2010)
Limestone	24	4–41	5	2–20	90	<40–240	–
Sand/gravel	15	1–39	16	1–64	380	3–1200	
Basalt	26	6–36	29	9–37	270	190–380	
Sandstone	20	13–70	25	15–70	500	<40–1100	
Tuff	100	<20–200	100	30–300	1000	500–2000	
Granite	100	30–500	120	17–311	1000	600–4000	
Expanded clay	40	<20–70	70	30–90	600	70–800	Bundes-ministerium für Umwelt, Naturschutz und Reaktorsicherheit (1993)
Brick	50	100–200	52	12–200	700	100–2000	
Gbfs	100	40–200	100	30–300	500	200–1000	
Fly ash	200	26–1110	100	14–300	700	170–1450	
CEM I	30	10–50	20	10–40	200	100–700	
CEM II	60	20–100	80	30–200	100	< 40–200	
Concrete	30	7–92	23	4–71	450	50–1300	
Average for building materials	50	–	50	–	500	–	UNSCEAR Report (2008)

n. i.: No information

According to Bialucha (2000), who tested 30 gbfs, all samples had sums of Ra-226 + Th-232 lower than the German sum index of 500 Bq/kg, above which a material is required to be observed (Table 1.7). For 80% of the slags this sum was below 200 Bq/kg. The content of K-40 was lower than stated in Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (1993).

Table 1.7

Radioactivity of bfs (30 samples), (Bialucha 2000)

Material	Ra-226		Th-232		K-40	
	Average	Range	Average	Range	Average	Range

Material	Rq/R26		Bh/R32		Re4Dg	
Bfs	Average	Range	Average	Range	Average	Range
	130	66–260	63	28–129	167	60–405

1.5. Impact of Ggbfs on Fresh Concrete Properties and Setting Time

1.5.1. Workability and Superplasticizer Demand

Using ggbfs in concrete ~~generally~~ improves workability. Thus, with increasing content of ggbfs, either the water/binder ratio (w/b), the dosage of superplasticizer or the paste content can be reduced, compared to a mix with Portland cement (Figs. 1.8 and 1.9) (Beushausen et al. 2012; Eren et al. 1995; Megat Johari et al. 2011; Osborne 1989; Wimpenny et al. 1989).

Fig. 1.8

Effect of water content on slump of concrete mixtures with and without ggbfs (Meusel and Rose 1983)
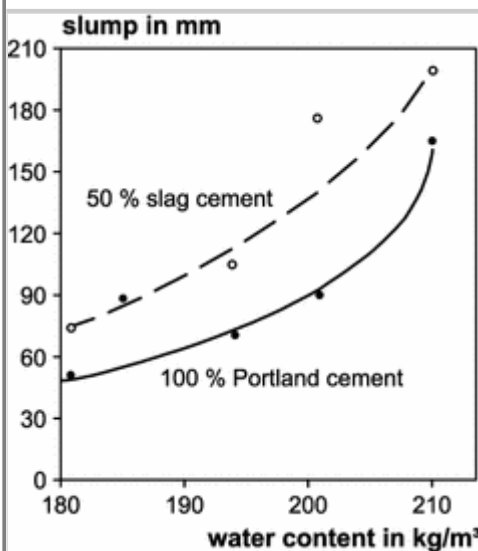
Fig. 1.9

Effect of partial cement replacement by ggbfs on dosage of superpasticizer (naphthalene based) required for concrete with a slump of 150 mm, redrafted after Domone and Soutsos (1995)
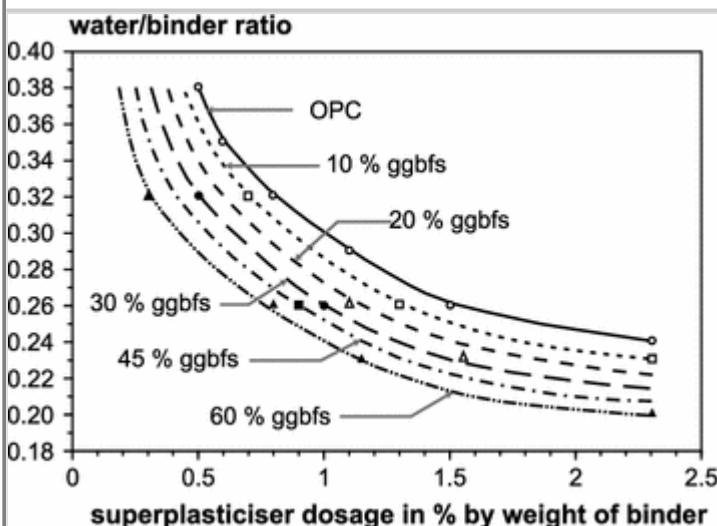
This workability improvement by ggbfs additions is usually perceivable at elevated contents of ggbfs of at least ~50 wt% of total cementitious material. It can be attributed to the smooth, glassy surface of ggbfs, which creates slip planes in the paste (Wood 1981). Moreover, ggbfs has a latent hydraulic reactivity and therefore binds less water than Portland cement during concrete manufacture. At ggbfs contents of 40–65% the mixing water can be reduced by ~5% compared to OPC concrete (Lothia and Joshi 1995; Meusel and Rose 1983). If in presence of major amounts of ggbfs the mixing water volume or superplasticizer dosage would not be adjusted, excessive bleeding may occur, coupled with prolonged setting and strength reduction.

The effectiveness of ggbfs to reduce superplasticizer demand decreases with increasing ggbfs fineness and/or at low water/binder ratios <0.3 (Gesoğlu et al. 2009; Lothia and Joshi 1995; Marushima et al. 1993; Nakamura et al. 1991; Peterson Becknell and Hale 2011). Boukendakdji et al. (2012) confirmed in SCC concrete the effectiveness of ggbfs additions of 15% and higher in reducing superplasticizer demand for a targeted workability.

Regarding the response of cements to polycarboxylate-based superplasticizers (SP), CEM III/B with 72% ggbfs showed a higher sensitivity towards SP dosage than OPC (Alonso et al. 2007; Hamada et al. 2000; Puertas et al. 2005). The relation between ggbfs content and SP demand decreases with increasing w/b (Carette and Malhotra 1987). The influence of 0–75% ggbfs additions on the zeta potential and rheology of cement pastes with and without polycarboxylate-based admixtures was studied by various authors (Palacios et al. 2009a, b).

Fulton (1974) and Swamy (1990) mention the improved cohesiveness of concrete containing major amounts of ggbfs. However, this cohesiveness, also called "stickiness", does not impair the ease of compaction on the construction site. Also high ggbfs concrete is easy to compact by conventional mechanical vibration. When comparing the placeability of concrete using the Vebe apparatus, concrete with 50% ggbfs was easier to place than the mix without ggbfs (Fulton 1974).

Shi et al. (2004) confirmed the workability improvement through ggbfs additions in concrete, which resulted in a decrease in plastic viscosity and yield stress. With decreasing amorphous content of the ggbfs this dispersing effect was reduced. However, also contradictory experiences exist, especially when working at very low w/b ratios as done by Soutsos (1992). Under such conditions the influence of ggbfs on the rheological properties can be rather limited (Fig. 1.10).

Fig. 1.10

Effect of partial cement replacement by ggbfs on the yield (g) and plastic viscosity (h) values for concrete mixes with water/binder ratio of 0.26 and a slump of approx. 150 mm, data from Soutsos (1992)
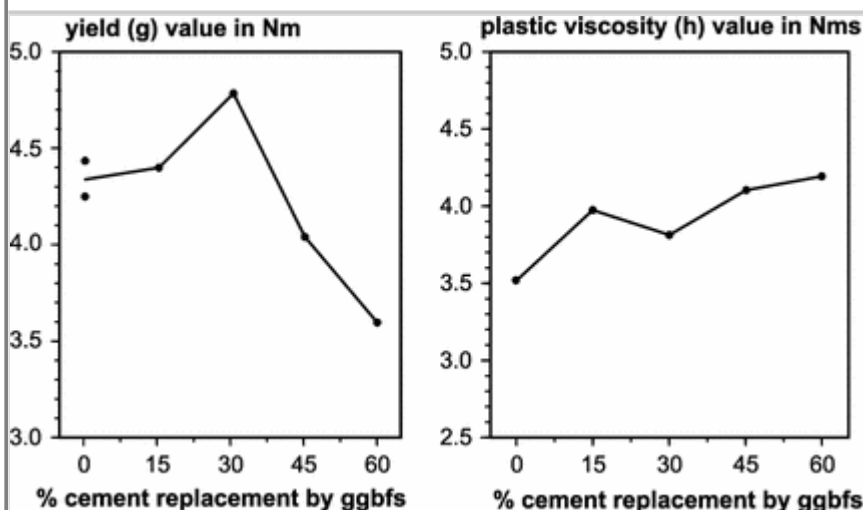
Generally, the effects of chemical admixtures on concrete with ggbfs are similar to those for OPC concrete. Retarding admixtures are typically more effective when ggbfs is present, especially if the cement is low in C_3A or alkalis (ACI 2011). At elevated ggbfs contents, the dosage of air entraining agent usually has to be increased to achieve a target air content, especially at low w/b (ACI 2011; Lothia and Joshi 1995; Matthes 2012).

1.5.2. Segregation and Bleeding

Coupled with the effect of workability improvement by ggbfs is an increased tendency to bleeding and segregation. To adjust the concrete design the superplasticizer dosages and/or the water added should be reduced to achieve the target workability. Following the national standards and working practices, further adjustments ensure the required concrete performance in terms of strength development and, potentially, durability (Ait-Aider 1988; Cesareni and Frigione 1969; Matthes 2012; Rickett 1990; Swamy 1990; Wainwright and Ait-Aider 1995; Wainwright and Rey 2000).

Generally, the bleeding capacity and bleeding rate of concrete are influenced by the ratio of the surface area of the solid constituents to the volume of water and thus are sensitive to changes in the surface area of the cementitious constituents (ACI 2011). Thus, if a fine ggbfs would replace a coarser cement, bleeding can be reduced and vice versa. Especially effective for reducing bleeding would be very fine ggbfs (Blaine > 10,000 cm^2/g, Nakamura et al. 1991).

1.5.3. Slump Loss

The data on slump loss of ggbfs concrete are varying. Frigione (1986) reported a reduced rate of slump loss, while Meusel and Rose (1983) reported a similar slump loss of concrete containing 50% ggbfs versus OPC concrete. Lea (1971) described reduced slump loss, especially when OPC with rapid slump loss is replaced by ggbfs. Boukendakdji et al. (2009) reported an increase of open time of self-compacting concrete (SCC) from 30 to 60 min when 15% of Portland cement was replaced by ggbfs.

1.5.4. Setting Time

When OPC is replaced by ggbfs, usually the time of setting is increased. The degree of this increase depends on various factors, for example on the amount of cement substituted, the initial concrete temperature, the w/b ratio, and the properties of the cement and additives used (Fulton 1974; Swamy 1990). In fact, concrete temperature is a key parameter for the setting time of ggbfs composites. The delay of time of set is especially pronounced at low concrete temperatures and/or at major ggbfs contents >50% (Robeyst et al. 2008; SCA 2002; Yoshida et al. 1986). At 20 ℃ and above, the reported results are manifold, reaching from no or little impact (Alshamsi 2001; Hooton 2000; Juenger et al. 2008) to even reduced times of set (Eren et al. 1995). Hogan and Meusel (1981) for example reported that at 23 ℃ initial setting can be prolonged by 30–60 min, while at 29 ℃ hardly any change is detected. Similar trends are described by SCA (Fig. 1.11, SCA 2002) and numerous other authors. Prolonged setting can be compensated either by using accelerators, by reducing the cement substitution by ggbfs in the concrete mix (ACI 2011), or by adjusting the concrete design, including w/b and superplasticizer dosage.

Fig. 1.11

Influence of ggbfs and temperature on time of set, redrafted after SCA (2002)
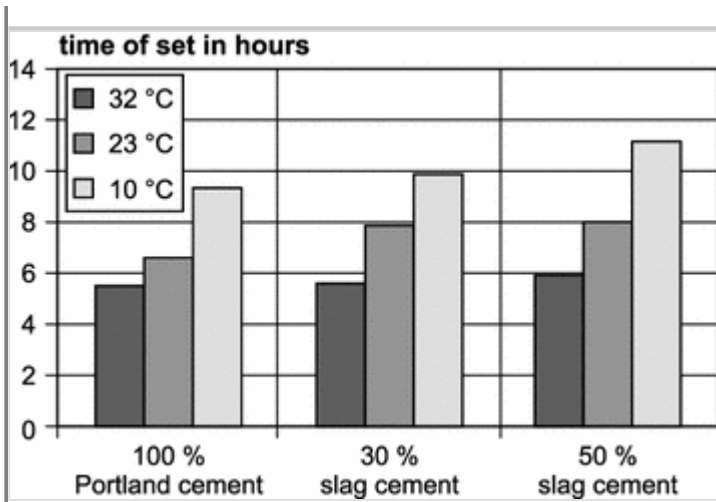
By continuous monitoring of the evolution of the ultrasonic wave velocity through concrete containing high amounts of ggbfs, valuable information can be extracted about the setting behaviour (Robeyst et al. 2008). In Fig. 1.12, three important stages can be distinguished. During the dormant period, the P-wave velocity is nearly constant. However at that time, the signal attenuation is large and the determination of the signal onset time and thus P-wave velocity is less accurate. After the dormant period, the P-wave velocity increases rapidly as the stiffness of the concrete develops. The P-wave velocity is lower for mixes containing high amounts of ggbfs (>50%), because the stiffness develops slower. For these mixes, the initial increase in P-wave velocity is mainly due to the hydration of OPC. Moreover, at early ages, the presence of ggbfs decelerates the temperature rise and increases the distance between the cement particles (Robeyst 2009). When comparing different CEM III cements, the increase of P-wave velocity depends not only on the ggbfs content, but also on their fineness, clinker reactivity, and content of set modifiers and accelerators (Robeyst et al. 2008; Robeyst 2009). For concrete with high ggbfs contents in the binder [S85 and S (CEM III/C 32.5)], a second increase of P-wave velocity can be noticed, which can be attributed to the hydration of slag particles.

Fig. 1.12

Evolution of the P-wave velocity in function of concrete age (left: slag added as a separate component to the concrete mix at OPC replacement levels ranging from 0 to 85%, right: blended cements) (left: slag added as a separate component to the concrete mix, right: blended cements) (Robeyst et al. 2008)
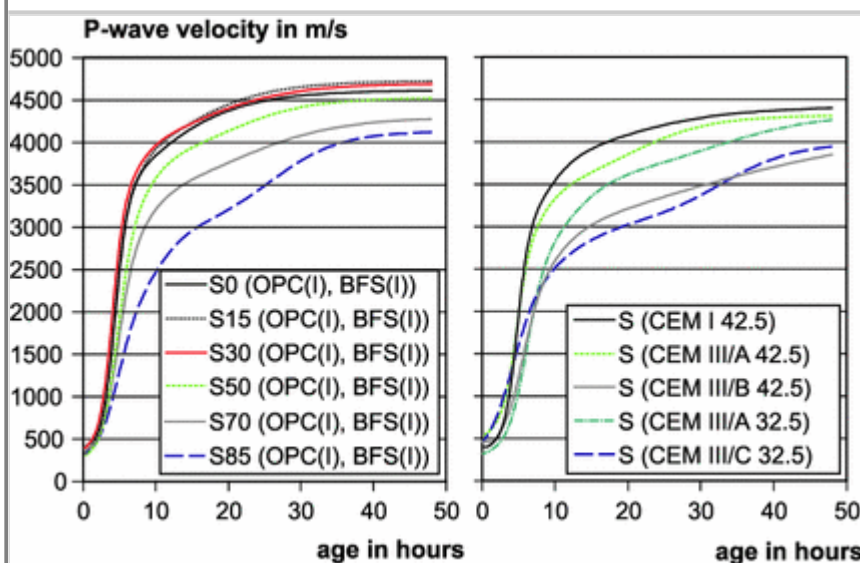
In comparison to the more traditional tests to determine the initial and final setting times (e.g. penetration resistance test), the ultrasonic transmission method is non-destructive. The change of ultrasonic velocity in

time is sensitive to the differences in setting behaviour of the tested mixtures. The initial setting seems to correspond with the inflection point of the velocity versus time curve and the final setting with the point at which the velocity increase levels off (Robeyst 2009).

1.6. Impact of Ggbfs on Heat of Hydration

The hydration of cement is an exothermal chemical process. Based on the mineralogical composition of the Portland clinker and the total heat produced during complete hydration of these minerals, the total theoretical hydration heat of OPC can be determined (Q_{tot}). For cement composites with ggbfs, the maximum heat released at the end of the reaction can be experimentally determined. Literature results range from 355 to 461 J/g ggbfs (Bensted 1981; De Schutter 1999; Kishi and Maekawa 1995; Schindler and Folliard 2003).

By replacing part of the hydraulic, rapidly hydrating OPC by the latent hydraulic, slower reacting ggbfs, the heat production rate and total heat of hydration is reduced. This is especially beneficial for mass concrete to avoid thermal shrinkage cracking.

The heat production rate of ggbfs containing concrete is also sensitive to curing temperature (Fig. 1.13) and so is its strength development.

Fig. 1.13

Heat output per kilogram binder of mortar grade C45 cured at 20, 30, 40 and 50 ℃ at ~~different~~ cement replacement rates of 20, 35, 50 and 70% with ggbfs. ~~r~~Redrafted after Turu'allo (2013)
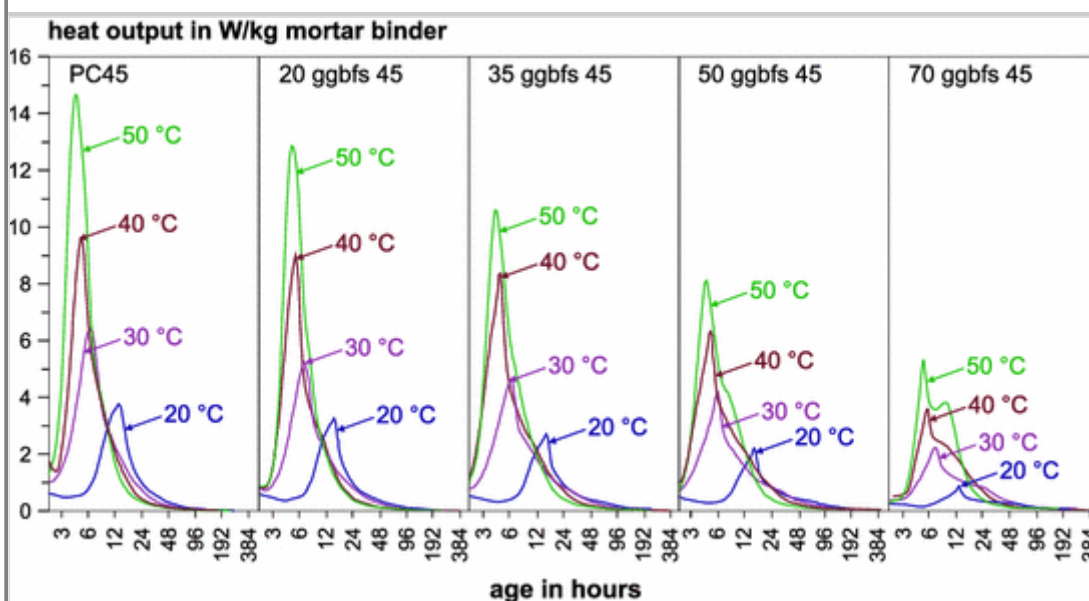
Some researchers reported, that the tensile strain capacity of concrete with 70% ggbfs at early age was lower than that of equivalent OPC concrete and it was estimated, that with sections over 2.5 m deep the reduced tensile strain capacity of ggbfs concrete may cancel out the benefit of the reduced temperature rise (Bamforth 1980). Also others indicated, that the use of ggbfs should not be based on its ability to reduce heat of hydration alone (Springenschmid et al. 1994; Thomas and Mukherjee 1994).

Apart from reducing the total cementitious content, the partial replacement of OPC by ggbfs or other SCMs is an effective and common means to reduce peak temperatures in mass concrete (Fig. 1.14). Generally, OPC replacement rates between 65 and 80% are considered effective, whereas for smaller mass pours 50–65% ggbfs were successfully used (SCA 2002).
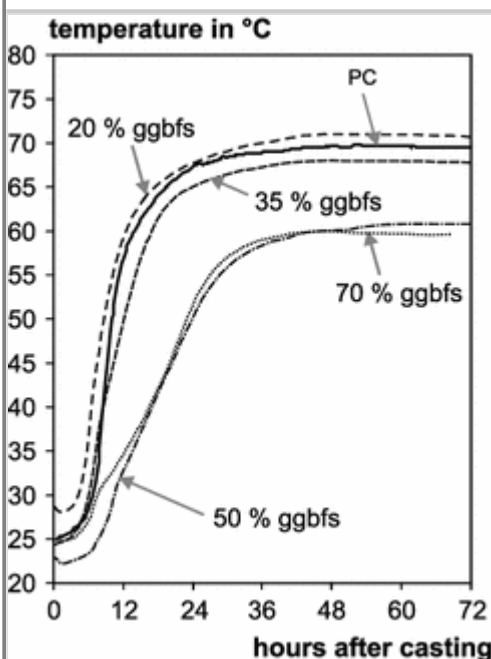
Fig. 1.14

Effect of ggbfs additions on temperature increase versus time in mass concrete, adopted from SCA (2002)
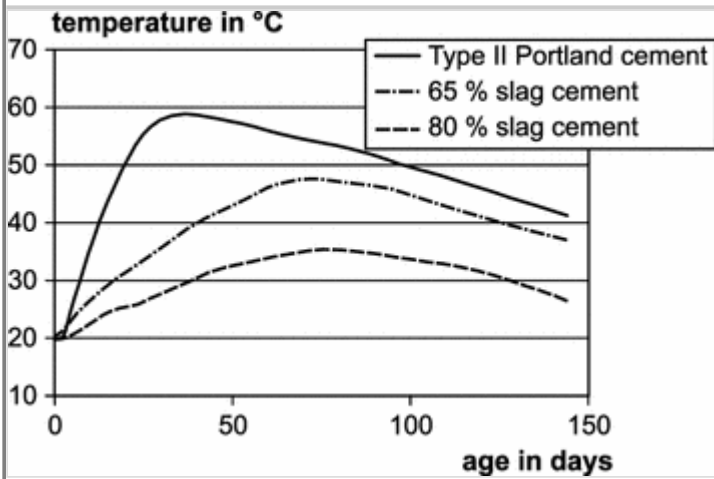
For mass concrete projects the performance of the concrete designs should be tested using the local materials to ensure their performance regarding temperature and strength development. Adiabatic tests may be used for this purpose. The adiabatic temperature histories of concretes with different ggbfs contents are shown in Fig. 1.15 (Soutsos et al. 2005). The Portland cement concrete had a temperature rise of 45 ℃ from the casting temperature of 25 ℃. Low levels of cement replacement with ggbfs, i.e. 20 and 35%, do not appear to be effective in reducing the peak temperature. Higher levels of 50 and 70% are required to reduce the peak temperature by 10 ℃. It must be noted that the high levels of cement replacement also, in addition to reducing the peak temperature, reduce the rate of temperature rise at early ages.

Fig. 1.15

Adiabatic temperature histories for concretes with target mean strengths 94–105 MPa, redrafted after Soutsos et al. (2005)

Bamforth 1980 showed that, although the temperature development in mass concrete decreases with increasing replacement of OPC by ggbfs, this effect becomes less pronounced with increasing volume poured, i.e. higher lift heights (Fig. 1.16, Bamforth 1980). Nevertheless, temperature data from the center of

three 4.5 m deep foundations containing 144–212 m^3 of concrete respectively, revealed the following temperature increases:

Fig. 1.16

Effect of ggbfs and lift height on temperature increase of massive concrete foundations redrafted after Bamforth (1980)
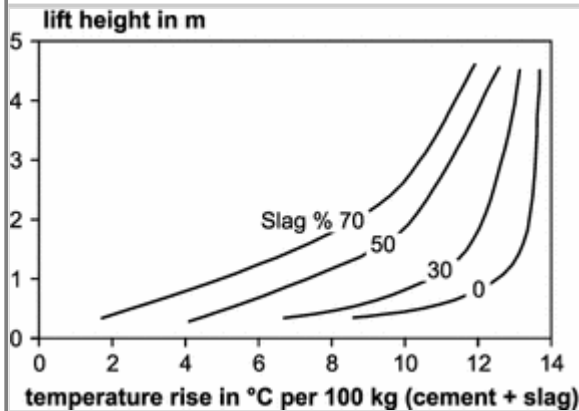

- Plus 54.5 ℃ from placing temperature of 20.5 ℃ for OPC concrete

- Plus 47.5 ℃ from placing temperature of 21.5 ℃ for concrete with 30% low calcium FA

- Plus 46.0 ℃ from placing temperature of 18.0 ℃ for concrete with 75% ggbfs (Bamforth 1980).

The temperature development in concrete blocks is not only affected by their size but also by the ambient temperature at the time of casting. Strength grade and level of replacement by ggbfs both affect the temperature increase in the concrete. Figure 1.17 shows concrete blocks that were cast to determine the ratio of in situ strength, determined from cores, to companion cubes cast and cured alongside the blocks. The different temperature histories of the same mix during winter and summer make such ratios impossible to determine. Winter temperatures allow more heat dissipation from the concrete blocks and the lower reaction of ggbfs assists in obtaining lower peak temperatures. The differences in peak temperatures between the OPC and ggbfs mixes increased with winter conditions.

Fig. 1.17

Temperature rise in concrete blocks made of OPC and a mix of 50% OPC and 50% ggbfs, both with 30 and 50 MPa compressive strength. Left: summer, right: winter (Soutsos et al. 2016)
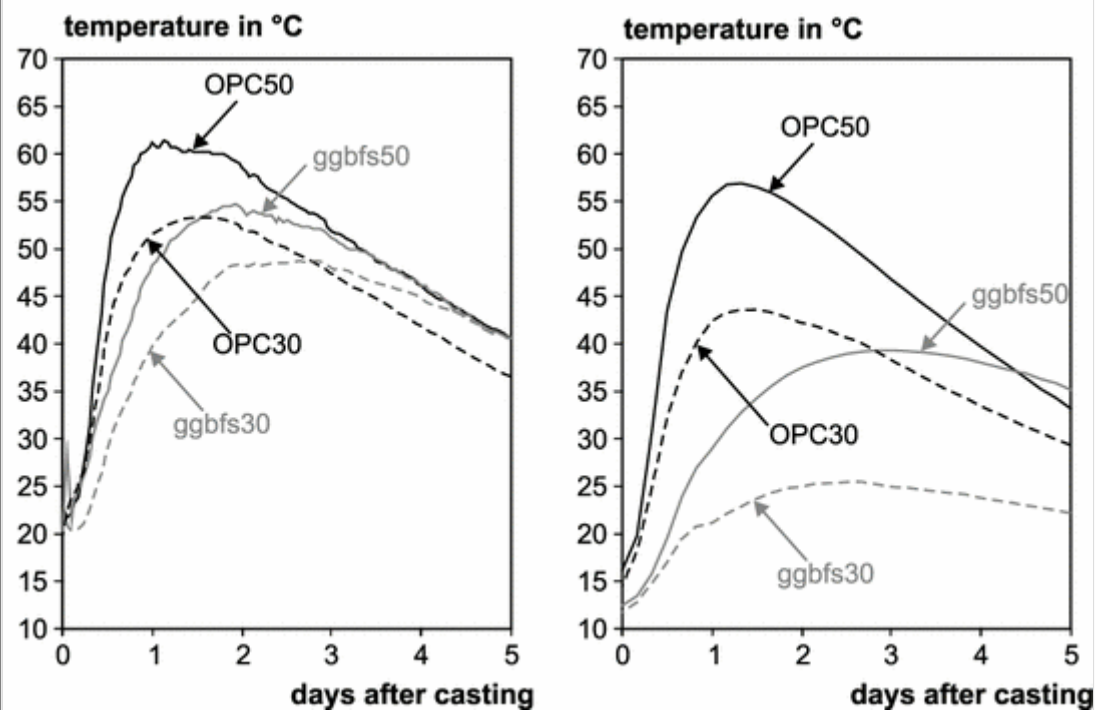
In the laboratory, the core temperature of insulated, very massive concrete blocks can be estimated based on adiabatic calorimetric measurements (De Schutter 1999; De Schutter and Taerwe 1995; Soutsos et al. 2005). As shown in Fig. 1.18, the temperature in OPC concrete can reach over 65 ℃, while these values are significantly decreased as soon as the ggbfs content of the cementitious phase is 50% and higher.

Fig. 1.18

Heat production rate and temperature evolution in function of concrete age under adiabatic conditions, for concrete mixes containing different amounts of ggbfs (ggbfs/(ggbfs + OPC) ranging from 0 to 85%), redrafted after Gruyaert (2011).
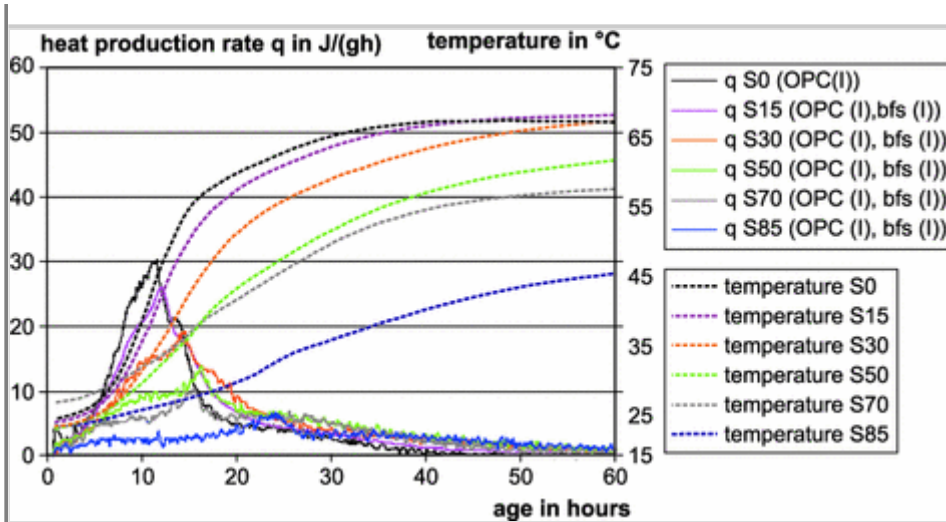
1.7. Impact of Ggbfs on Strength Development

1.7.1. Compressive Strength

1.7.1.1. Hardening at Standard Conditions

Due to its latent hydraulic properties, ggbfs starts to hydrate when in contact with water. However, this reaction diminishes with time. Only in presence of an activator the ggbfs hydration continues. The nature and dosage of activators play an important role for strength development of ggbfs concrete. The most common activator of ggbfs in concrete is Portland cement. Here the ggbfs activation is alkaline due to the liberation of calcium hydroxide and alkalis during Portland clinker hydration and sulfatic due to the presence of calcium sulfate in the cement. Apart from that, ggbfs can also be activated by other compounds such as alkali and alkali earth hydroxides, sulfates, chlorides, nitrates, carbonates, and silicates (Andersson and Gram 1988; Daugherty et al. 1983; Douglas and Brandstetr 1990; Hooton 1987; Malolepszy 1986; Roy and Idorn 1982; Shi and Day 1996; Song and Jennings 1999; Teoreanu and Georgescu 1974). The activation potential depends significantly on the properties of the ggbfs.

Compared to OPC the hydration rate of ggbfs is slower. This is reflected by a later initial setting time and lower early strength with increasing ggbfs content (Fig. 1.19). However, late strength development of concrete with ggbfs composites mostly exceeds that of OPC concrete. Depending on the reactivity and fineness of the ggbfs and its content in the mix, the strength of slag concrete typically reaches the strength of OPC concrete between ~10 and 35 days for a given concrete design (Demirboga 2003; Hewlett 1998; Hogan and Meusel 1981; Neville 1995; Oner and Akyuz 2007; Wang et al. 2007).

Fig. 1.19

Effect of ggbfs on compressive strength, adopted from Hogan and Meusel (1981)
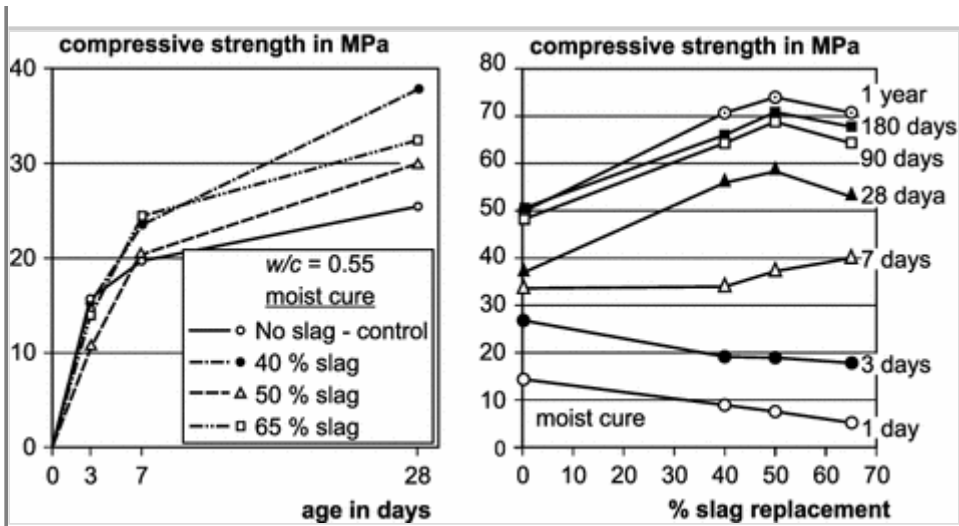
At very high replacement levels, a persistent strength reduction compared to a reference OPC concrete was noticed by several researchers (Duran Atis and Bilim 2007; Khatib and Hibbert 2005). An optimum cement replacement level regarding fresh concrete properties and late strength development is about 50% (Dubovoy 1986; Hogan and Meusel 1981; Hwang and Lin 1986; Meusel and Rose 1983; Roy and Idorn 1982).

The reactivity of ggbfs itself is significantly influencing the strength development at a given ggbfs content and constant fineness (Fig. 1.20). It is mainly governed by its basicity index, expressed as CaO/SiO_2, or also $(CaO + MgO)/SiO_2$ ratio (Matthes 2014). The example given in Fig. 1.20 shows the strength development of 50:50 composites of ggbfs and OPC. Both ggbfs materials were ground to the same fineness. The more reactive ggbfs had a CaO/SiO_2 ratio of ~1.2 and created a far higher strength gain than the ggbfs of low reactivity, which had a CaO/SiO_2 of ~0.9 (Matthes 2014). Furthermore, an elevated alumina content in ggbfs tends to increase early strength development, often on cost of late strength (Matthes 2014; Taylor 1997). Also the presence of minor components can have a significant influence. Especially critical is TiO_2, which significantly reduces ggbfs reactivity and thus strength development at all ages (Matthes 2014).

Fig. 1.20

Influence of ggbfs reactivity on development of compressive strength in standard ASTM mortars (50% OPC, 50% ggbfs), Fineness of ggbfs 4500 cm^2/g Blaine (Matthes 2014)
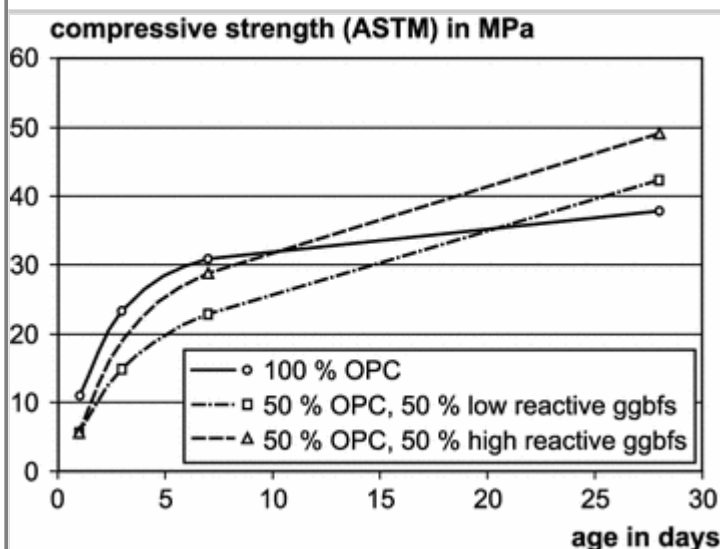

As far as the content of crystalline materials is concerned, gbfs from state-of -the art granulation facilities usually have a glass or amorphous content of >95%. Typical crystalline phases are merwinite or melilite.

Significantly lower amorphous contents will affect strength development, as the latent hydraulic behaviour origines from the glassy phase (Matthes 2014).

Also the fineness of the ggbfs has a major impact on its hydration degree and its strength development, but also on transport properties of the concrete (Chen 2006; Feldrappe et al. 2016; Matthes 2012). Finer grinding mainly improves medium and late strength. The influence on early strength is limited due to the lower hydration rate of ggbfs (Fig. 1.21, Matthes 2014). This is valid for minor and major additions of ggbfs of a fineness ranging from ~3500 to ~6000 cm^2/g Blaine.

Fig. 1.21

Influence of ggbfs fineness on development of compressive strength in standard ASTM mortars (50% OPC, 50% ggbfs), redrafted after Matthes (2014)
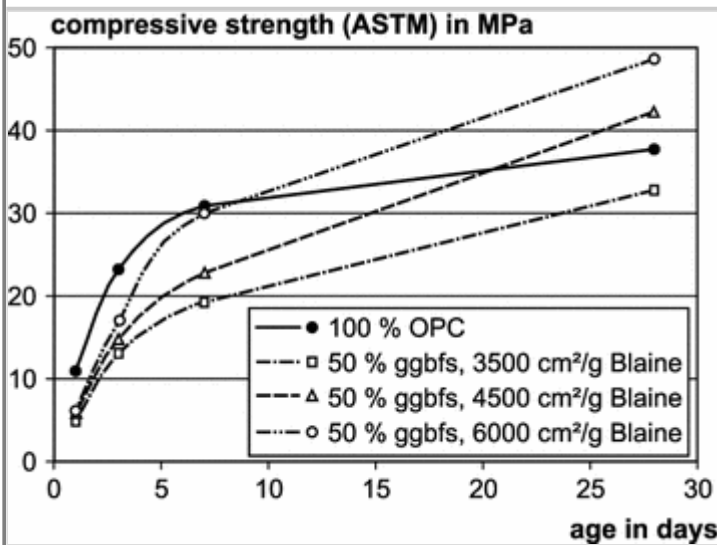
Also concrete design parameters such as w/b, temperature and curing conditions strongly influence the strength gain achievable through ggbfs additions. With increasing w/b, the compressive strength decreases at all ages. The late strength increase due to ggbfs additions tends to be greater for concretes with higher w/b than for concrete with lower w/b (Fulton 1974; Malhotra 1980; Meusel and Rose 1983; Soutsos 1992).

1.7.1.2. Importance of Curing and Curing Temperature

At early ages, all concrete has to be kept in proper moisture and temperature conditions in order to fully develop the required strength and durability properties. As ggbfs has a lower hydration rate than OPC, less hydration products are formed at early stage and less water is bound. Therefore, concrete with ggbfs is more sensitive to poor curing than OPC concrete, especially if the ggbfs content exceeds 30% of cementitious materials (Fulton 1974). Therefore prolonged curing times have to be applied when using ggbfs in concrete as described in procedures such as ACI 308R (2001).

When proportioning concrete mixtures and matching them with construction schedules, which also depend on early strength development, it needs to be taken into account, that the rate of hydration of ggbfs is more sensitive to concrete temperature than that of OPC. This results at low temperatures, i.e. 10 ℃ and below, in a lower early strength development of ggbfs concrete compared to OPC concrete, which however, is compensated by a higher late strength development (Fig. 1.22). According to Hewlett (1998) this is especially true for concrete with w/b ratios above 0.5 and s/b ratios above 0.7. Generally, it is not recommended to use ggbfs at temperatures below 10 ℃ (Neville 1995).

Fig. 1.22

Effect of curing temperature in the range of 10–50 ℃ on strength development of concrete containing varying amounts of ggbfs, redrafted after Soutsos and Turu'allo (2016)
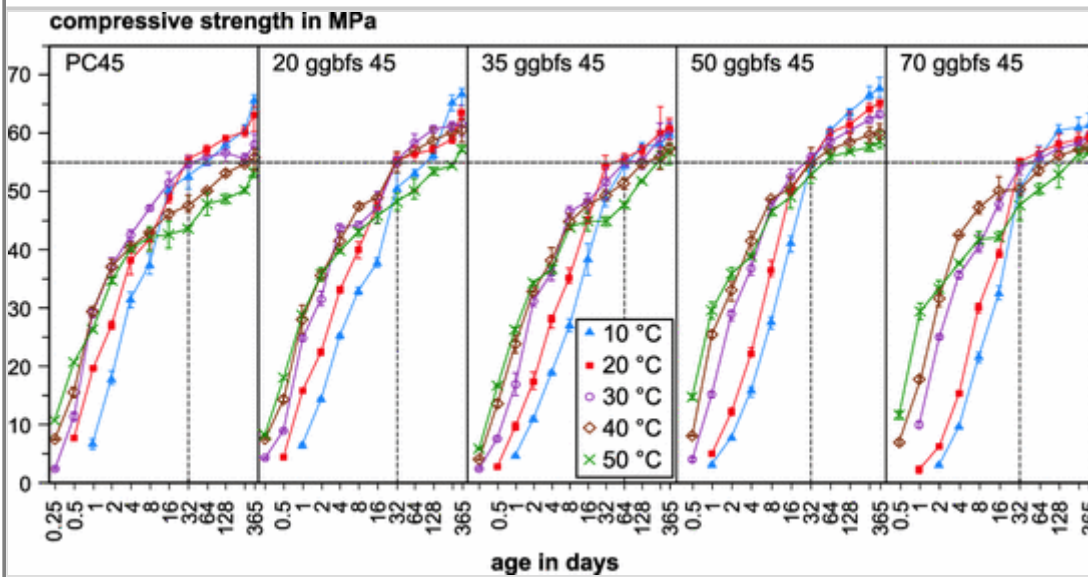
At high temperatures of 30 ℃ and above, as found in hot climates or during steam curing, for example, a higher early strength is achieved in concrete with ggbfs, however often at theon cost of late strength development (Fig. 1.23). The magnitude of this effect depends on the cement and ggbfs fineness and reactivity and on the proportion of ggbfs in the concrete mix (Barnett et al. 2006; Neville 1995; Sato and Masuda 2005). In this context Barnett et al. (2006) recorded, that at elevated curing temperatures the ultimate strength is lower compared to OPC concrete and concluded, that further hydration was prevented due to the formation of dense hydration products around the unhydrated particles. Since the hydration products were not uniformly distributed, a coarser pore structure was obtained. While Barnett et al. (2006) did not observe a clear trend with the cement replacement level, Neville (1995) mentioned, that the harmful effects of high curing temperatures on the long-term strength are not that pronounced in ggbfs concrete, in comparison to OPC concrete.

Fig. 1.23

Influence of temperature on strength development of concretes with OPC (CEM I) and ggbfs composite cement (CEM III/A, 36–65% ggbfs), redrafted after Brand et al. (1982)
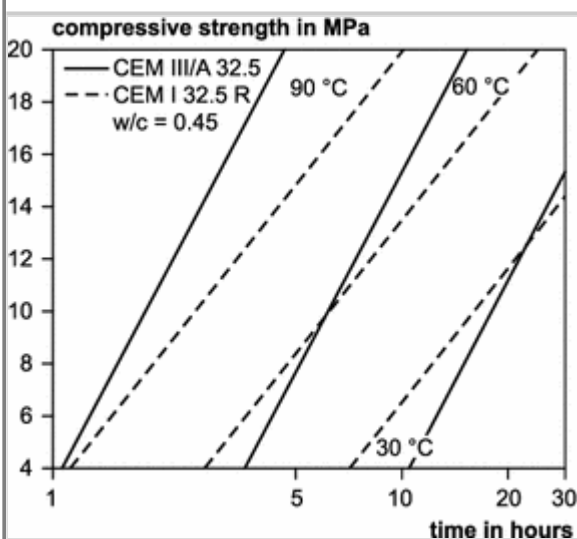
Also the relative humidity has an influence on the strength development of ggbfs concrete. In Neville (1995), the importance of moist curing in case of ggbfs concrete is emphasized. Poor curing in combination with the initial slow hydration process of ggbfs can lead to evaporation of the capillary pore water which prevents further hydration. This was confirmed by Duran Atis and Bilim (2007), who cured ggbfs and OPC concrete at 22 ℃ and a relative humidity RH of 65 and 100%. Concrete with ggbfs, especially at elevated amounts, showed a reduction of compressive strength at 65% RH versus 100% RH of 15%. The compressive strength of OPC concrete was reduced by only 6%.

1.7.1.3. Adiabatic Curing Experiments for Simulation of Field Conditions

In order to get an insight how strength data of ggbfs concrete obtained under laboratory conditions at 20–22 ℃ and close to 100% RH compare to concrete hydrated under field conditions with the influence of the climate and of the dimensions of the concrete elements as described above, Soutsos et al. (2005) compared the strength development of laboratory cured concrete samples with different amounts of ggbfs (Figs. 1.24 and 1.25, left sides) with samples of the same concrete mixes cured under adiabatic conditions (Figs. 1.24 and 1.25, right), which should reflect possible conditions in the field. The authors confirm for the laboratory cured samples the adverse effect of increasing ggbfs contents on early strength, which is set off at later age. Curing under adiabatic conditions revealed and confirmed the higher sensitivity of ggbfs versus OPC to curing temperature. Laboratory cured concrete with 20 and 35% ggbfs achieved at 1 day 90 and 70% of the OPC concrete strength, respectively. Adiabatic curing resulted in 100% OPC strength at 1 day. Concrete with 50 and 70% ggbfs which had developed under laboratory curing 45 and 25% of OPC strength at 2 days achieved essentially 100% of OPC strength during adiabatic curing (Fig. 1.25).

Fig. 1.24

Strength development of concretes with varying ggbfs content at standard 20 ℃ curing (left) and at adiabatic curing (right), redrafted after Soutsos et al. (2005)
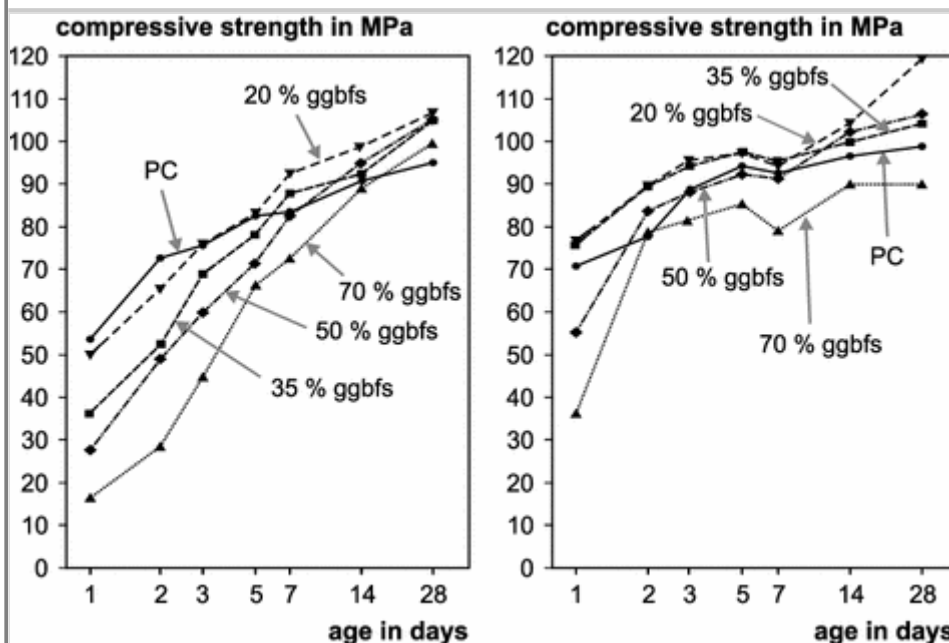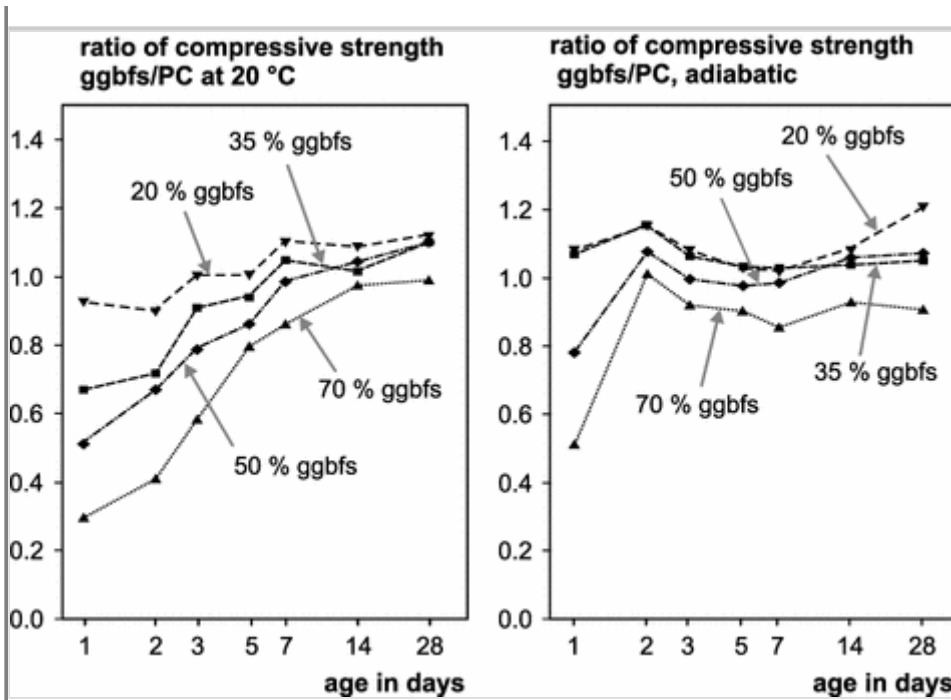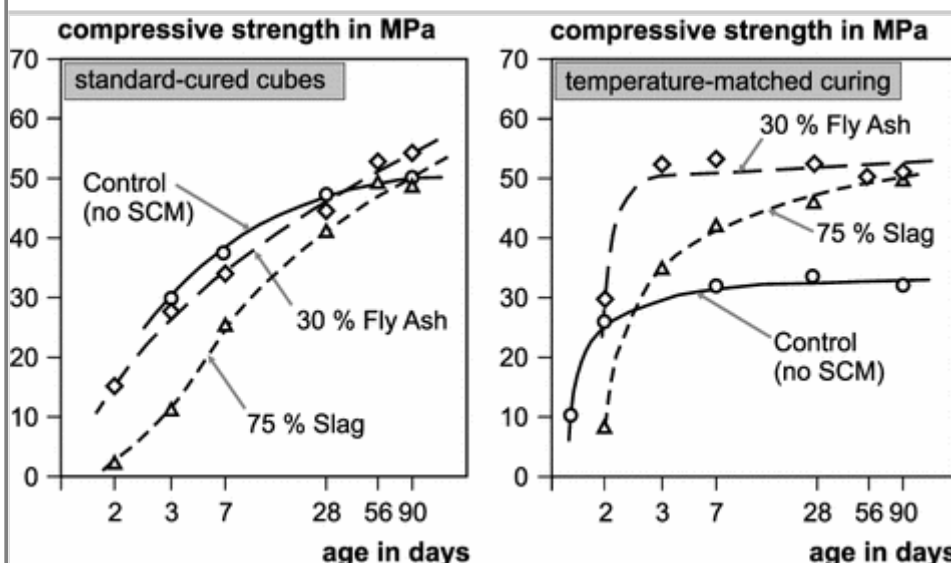

Fig. 1.25

Ratio of compressive strengths of ggbfs concretes to Portland cement concretes under standard (left) and adiabatic (right) curing regimes, redrafted after Soutsos et al. (2005)

While in mass concrete high temperatures can be achieved, which accelerate hardening, under cold conditions and within thin concrete structural elements the concrete temperatures can be lower than during laboratory curing, which can delay strength development. Similar to Soutsos et al. (2005), Bamforth (1980) compared the strength development of laboratory concrete with OPC, 30% FA or 75% ggbfs cement with concrete cured according to temperature profiles measured in mass concrete foundations (Fig. 1.26). During temperature matched curing, all concretes showed a more rapid early strength development, but reduced late strength development, compared to the laboratory cured samples. Interestingly and in contrast to the results by Soutsos et al. (2005), the 90d strength of the OPC concrete was significantly reduced during temperature matched curing. As found by Soutsos et al. (2005), the late strength of the concretes with SCM was essentially comparable under both curing regimes.

Fig. 1.26

Effect of partial OPC replacement by fly ash or ggbfs on the strength development of 100 mm concrete cubes exposed to standard laboratory curing and temperature matched curing reflecting conditions in mass concrete, redrafted after Bamforth (1980)

1.7.2. Flexural and Tensile Strength

Ggbfs in concrete does not only improve compressive strength over the service life, but improves also flexural strength, which is a key parameter for concrete pavements (Fig. 1.27, Hogan and Meusel 1981). This has to be attributed to the denser microstructure achieved through pore refinement, which also results in an improved bonding between paste and aggregates.
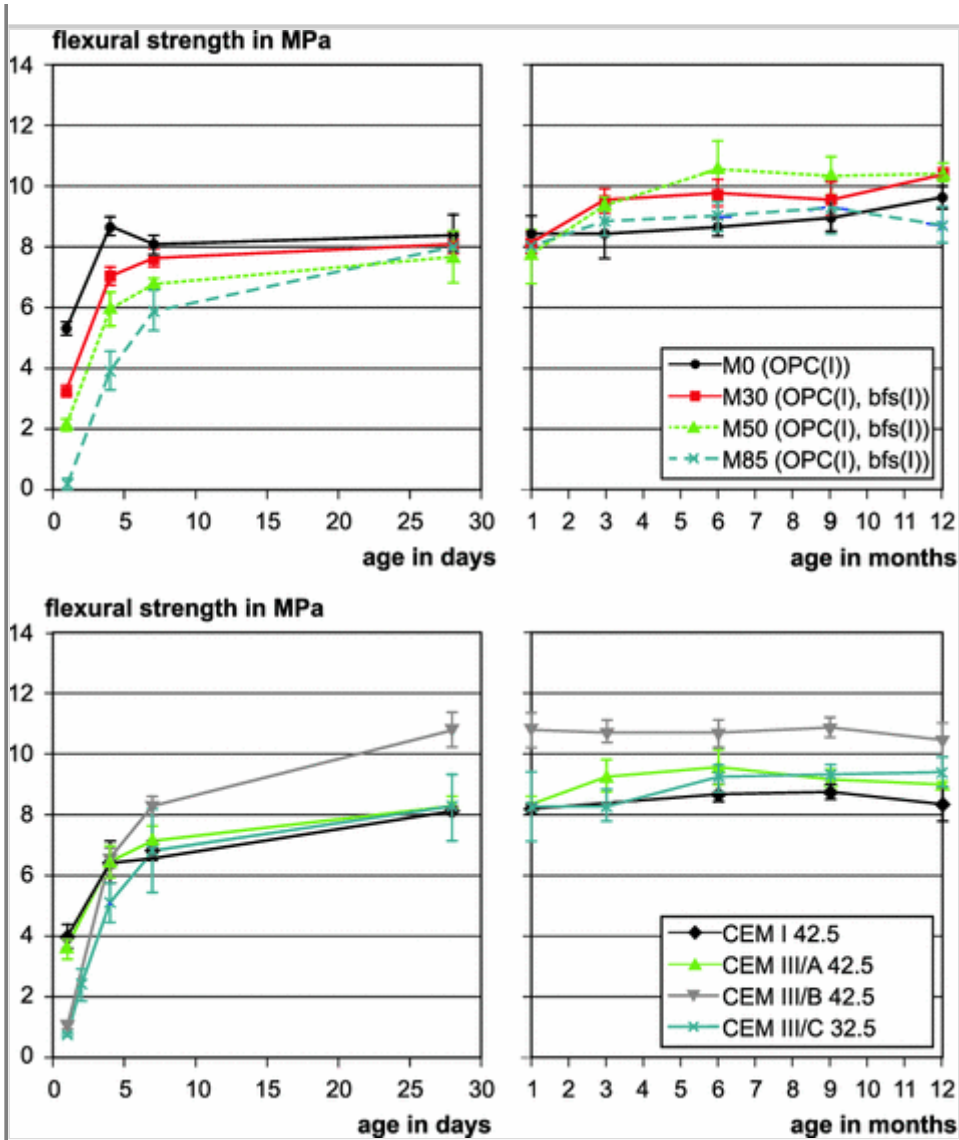
Fig. 1.27

Effect of ggbfs on flexural strength, adopted from Hogan and Meusel (1981)
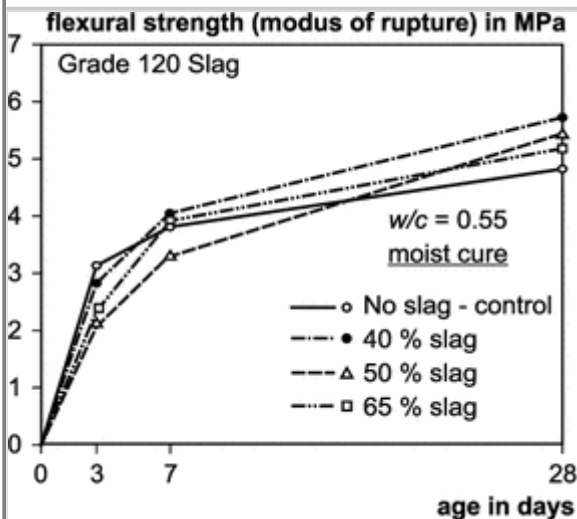
Results obtained from three-point bending tests of water cured mortar prisms, showed at ages below 28 days a decreasing flexural strength with increasing ggbfs content. However at later ages, the concretes with 30–85% ggbfs reached or exceeded the flexural strength of OPC concrete. This was confirmed with mortars containing commercial CEM III/A 42.5 and CEM III/C (Fig. 1.28, Gruyaert 2011).

Fig. 1.28

Evolution of the flexural strength of mortar prisms containing different amounts of ggbfs in function of age (top: ggbfs added as a separate component to the mix at OPC replacement levels ranging from 0 to 85%, bottom: blended cements). Redrafted after Gruyaert (2011).

The relation between the flexural strength and compressive strength for mortar prisms containing different amounts of ggbfs from 1 day to 1 year is essentially constant (Fig. 1.29, Gruyaert 2011). The replacement of cement by ggbfs has no significant effect on this relation. In Neville (1995) different empirical formulae, based on a power law function (Eq. 1.2), are quoted to connect the compressive strength (f_c) with the flexural strength (f_{fl}). The values of the parameters for the best fitted curves are given with 1.106 for k and 0.512 for n.

Fig. 1.29

Relation between the flexural strength (three-point bending test) and compressive strength (mean values) of mortar prisms containing different amounts of ggbfs, indicated by the numbering in the legend. Redrafted after Gruyaert (2011).
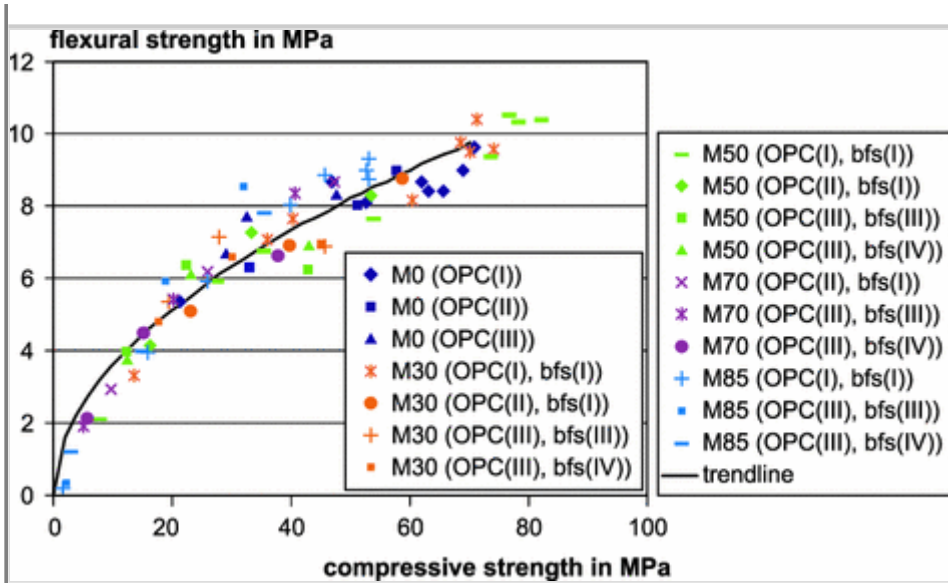
$$f_{fl} = k \cdot (f_c)^n \qquad\qquad 1.2$$

For all concretes, an increase of compressive strength results in an increase of flexural strength, but at a decreasing rate. Consequently, the ratio of the compressive strength to the flexural strength increases as time proceeds.

Regarding tensile strength development, Darquennes (2009) shows a more important increase of tensile strength with time for cements with slag compared to Portland cement. At late ages, tensile strength of concrete with ggbfs cements exceeds the one of OPC concrete (Fig. 1.30).

Fig. 1.30

Evolution of tensile strength with time for Portland and ggbfs composite cements CEM III/A and CEM III/B, redrafted after Darquennes (2009)
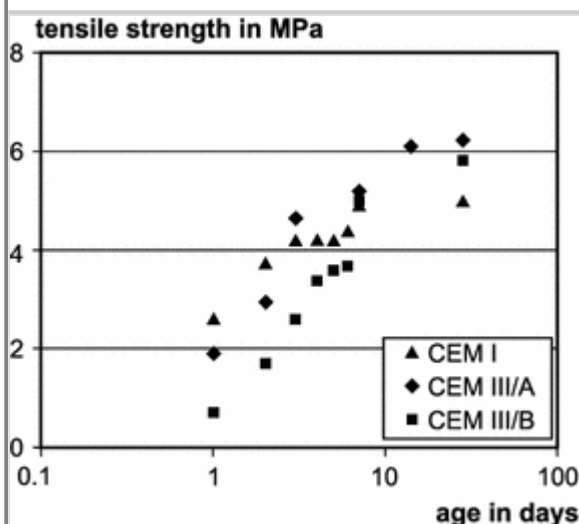

1.8. Impact of Ggbfs on Modulus of Elasticity

The relationship between modulus of elasticity and compressive strength of concrete is essentially unaffected by the presence of SCMs. Existing predictive equations can be used for concrete with and without SCM

(Thomas 2013). Thus, the modulus of elasticity of concrete with moderate amounts of ggbfs can be expected to be lower at early age and higher at late ages (Fig. 1.31, Thomas 2013).

Fig. 1.31

Effect of ggbfs on modulus of elasticity, redrafted from Thomas (2013); data from Wainwright and Tolloczko (1986)
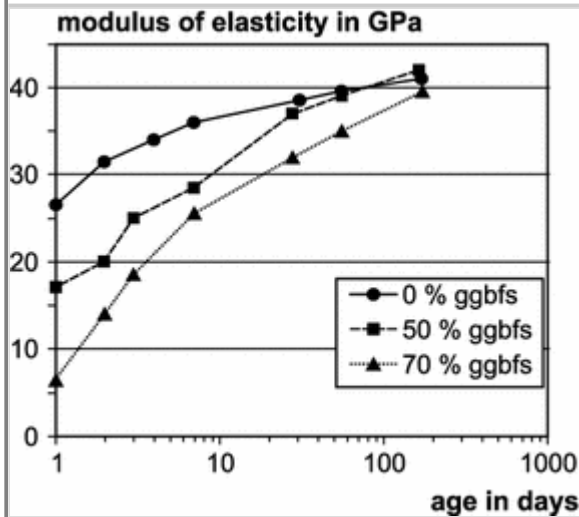
Darquennes (2009) illustrated similarities in the evolution of elastic modulus versus tensile strength for Portland and ggbfs composite cements with high and moderate ggbfs contents (Fig. 1.32, Darquennes 2009).

Fig. 1.32

Elastic modulus E versus tensile strength of Portland cement, CEM III/A and CEM III/B, redrafted after Darquennes (2009)
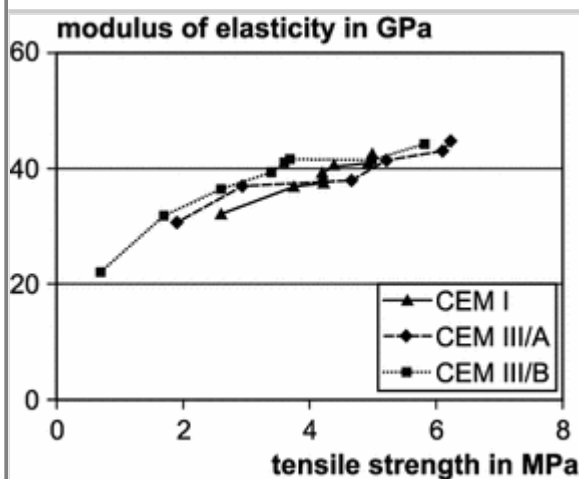
1.9. Impact of Ggbfs on Concrete Color

Usually concrete containing ggbfs has a lighter color than Portland cement concrete. At elevated ggbfs contents >60% the color could be described as off-white.

After demoulding, concrete with ggbfs can exhibit greening at the surface—these are stains of dark bluish-green to black color. Also inside, the concrete displays an intense dark coloration.

These dark stains are caused by sulfide minerals, which form during the hydration of the cement. When finely dispersed in the concrete, these compounds cause shades from green/blue to black, according to their composition. The phases are sulfides of mainly iron and manganese in low oxidation states, which are supplied by the ggbfs. The higher the content of ggbfs in the concrete, the higher the fineness of the binder constituents and the lower the water/cement ratio, the higher is the probability of greening.

Generally, greening at the surface of the concrete is a passing effect. In contact with air, the blue/green color vanishes after a few days due to oxidation of the sulfides to sulfates. Exposure to sunshine accelerates this process.

After the greening has vanished, the concrete containing ggbfs usually is lighter than concrete made from OPC.

If the oxygen in the atmosphere cannot reach the concrete, greening will persist. This can be the case if the concrete surface is sealed, e.g. by traces of oil/fat from the formwork or by a glaze applied on bricks, etc. In the case of excess form oil, the surface greening may persist for several weeks until form oil/fat wears off. In applications where concrete would be permanently sealed and greening would be aesthetically disturbing, e.g. glazed concrete bricks, swimming pools etc., the use of ggbfs should be avoided 💬(References to be inserted in Ref list:

Le Cornec D, Wang Q, Galoisy L, Renaudin G, Izoret L, Calas G (2017) Greening effect in slag cement materials, Cement and Concrete Composites, 84, 93-98.

Problem Clinic (2011) Greening of slag cement concrete. http://www.concreteconstruction.net/how-to/greening-of-slag-cement-concrete_o, August 31, 2011.

Slag Cement Association (2002) Greening, Slag Cement Association P.O. Box 2615 Sugar Land, TX 77487-2615. Slag Cement Association 2002, Matthes 2012, Le Cornec et al 2017).

In rare cases where surface greening does not vanish after several days of exposure to the atmosphere and the stains are optically disturbing, they can be removed by chemical treatment of the surface of the hardened concrete, e.g. with diluted solutions of ~~acetic acid or~~ hydrogen peroxide , sodium hypochlorite, or diammonium citrate (Problem Clinic 2011).. ~~However, such treatments may lead to sealing of the concrete and therefore should be avoided.~~

Inside the concrete, greening will persist as long as oxygen is not entering the system. The denser the structure of the concrete, the longer greening will persist. Thus, greening within the concrete can be regarded as an indicator of the low permeability and thus, high quality of a concrete. ~~The faster the transition zone of blue to grey penetrates into the concrete, the lower is the concrete quality.~~ The core of concrete of good quality can maintain its dark color during the whole service life. ~~When the reinforcement is surrounded by blue/green concrete, no corrosion has occurred, because oxygen could not reach the reinforcement.~~

1.10. Impact of Ggbfs on Shrinkage and Creep

Regarding the influence of ggbfs on shrinkage, conflicting observations exist. Apparently, drying shrinkage of concrete with ggbfs is similar to OPC concrete (ACI 2011). A review by Hooton et al (2009) found that with low-alumina ggbfs, drying shrinkage of concretes over a range of replacement levels was similar to that of OPC concrete. When ggbfs with alumina content in excess of 12% was used, shrinkage was increased due to alumina reacting with some of the calcium sulfate from the OPC, but this could be corrected by intergrinding calcium sulfate with the gbfs. There did not appear to be a difference in relative drying shrinkage between concretes made with blended cement and those made with ggbfs added separately at the time of mixing.

Autogenous shrinkage generally increases with decreasing w/b. For concrete with ggbfs it was shown, that with increasing ggbfs content autogenous shrinkage increased (Fig. 1.33, Fulton 1974; Lee et al. 2006). Other authors reported small differences in shrinkage or even reduced shrinkage when ggbfs was used in

concrete. Obviously, the amount of ggbfs has an influence on the results as well as the amount of calcium sulfate added (ACI 2011).

Fig. 1.33

Effect of ggbfs on autogenous shrinkage of concrete redrafted after Lee et al. (2006)
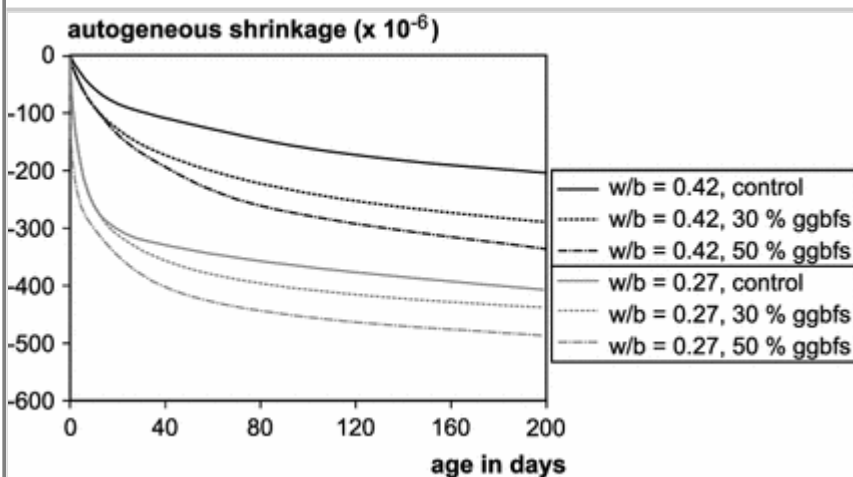
The amount of creep of a concrete mainly depends on the concrete design and nature of loading. The most important parameters to reduce creep are a high aggregate content, a low water content, a low w/b, and sufficient maturity prior to loading, because creep depends on the loading stress/concrete strength ratio (Thomas 2013). The conflicting results in literature on the influence of ggbfs on creep are probably due to different concrete designs and testing regimes. Generally, concrete with major amounts of ggbfs, if loaded at early age, will probably creep more than OPC concrete because of its lower early strength. At late age, this relation is inverse (Fig. 1.34, Brooks et al. 1992).

Fig. 1.34

Effect of ggbfs on basic creep of sealed concrete specimens (Brooks et al. 1992)
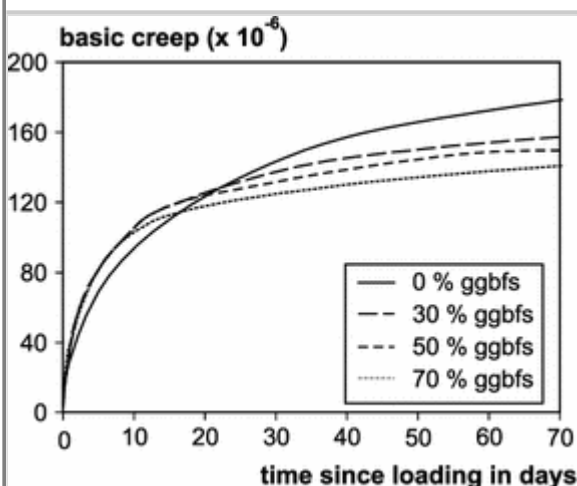
1.11. Impact of Ggbfs on Transport Properties

1.11.1. Pore Refinement and Permeability

The movement of fluids through the concrete can occur by flow, diffusion, and sorption. Strictly speaking, permeability refers to the flow, and penetrability is a more general term including all processes. However, for

concrete research, 'permeability' is commonly used instead of 'penetrability' (Neville 1995).

The permeability of concrete is not simply related to the total volume of pores, but depends on the size, distribution, shape, tortuosity and continuity of mainly the capillary pores. Since the formation of gel gradually fills the pore space, the pore structure continuously changes and the permeability of pastes decreases with progressing hydration (Neville 1995). The partial replacement of cement by ggbfs lowers the permeability, provided that enough time has elapsed for sufficient slag hydration (Taylor 1997). Pores in concrete are partly and progressively filled with C-S-H resulting from the hydration of ggbfs. Compared to an OPC paste of same w/b and comparable maturity, the total pore volume of a slag cement paste would be comparable, even slightly higher. However, the pore structure is strongly refined (Figs. 1.35 and 1.36, Romberg 1978; Roy and Parker 1983). The volume of fine capillary and gel pores is increased at the cost of the volume of large capillary pores. The capillary pores include macropores and mesopores (Fig. 1.35, Roy and Parker 1983). Macropores, 10,000–50 nm in size, and large mesopores of 50–10 nm enable mass transport processes. The mesopores, 50–2.5 nm, are also responsible for shrinkage at 50–80% RH. Thus, a lower volume of capillary pores reduces pore connectivity and thus reduces mass transport processes.

Fig. 1.35

Effect of ggbfs on the pore size distribution of hardened cement pastes, redrafted after Roy and Parker (1983)
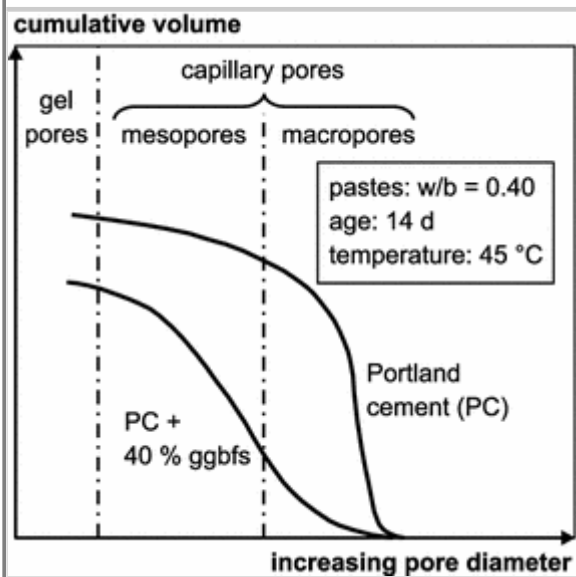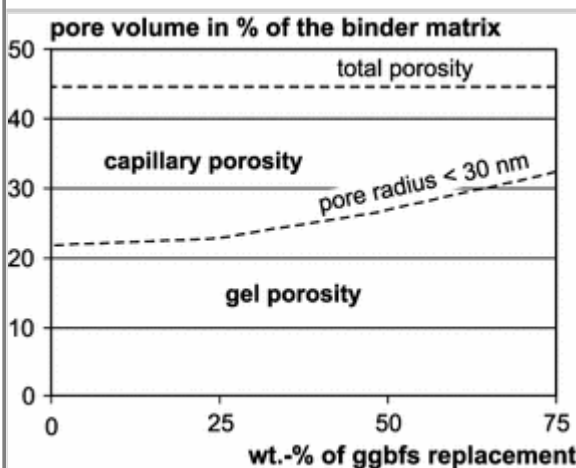

Fig. 1.36

Pore refinement by replacing cement clinker by ggbfs, redrafted after Romberg (1978)

The gel pores, including micropores 2.5–0.5 nm and the interlayer spaces of C-S-H ≤0.5 nm influence both, shrinkage and creep.

Due to this pore refinement the strength of the ggbfs concrete is increased. The reduced permeability on the other hand increases the durability of the concrete against chemical attack, such as chloride, sea water or sulfate ingress. A prerequisite, however, is an adequate curing of the concrete.

The pore refinement by ggbfs additions was reported by numerous other researchers (Gruyaert et al. 2013; Hadj-Sadok et al. 2011; Megat Johari et al. 2011; Panesar and Chidiac 2009). In Megat Johari et al. (2011), for example, results of mercury intrusion porosimetry of mortars show that with increasing ggbfs contents between 20 and 60% the relative volume of pores in the size range <30 nm is progressively increased at the expense of the relative volume of pores between 30 and 50 nm. Bouikni et al. (2009) showed on the basis of pore refinement, that a high OPC replacement of 50 and 65% by ggbfs with a Blaine of only 350 m^2/kg showed an enhanced performance regarding transport properties, even though total porosity of concrete increased with increasing ggbfs replacement.

De Belie et al. (2010) compared pore size distributions of OPC paste and 50 and 85% ggbfs pastes obtained from data of water vapor sorption isotherms. They found similar pore size distributions in the size range 2–10 nm, but a high reduction of pores in the size range of 1–2 nm when ggbfs was included.

Besides porosity measurements, results of permeability tests can also be found in the literature. The capability of ggbfs to reduce concrete permeability is widely accepted however the extent of its impact varies in literature.

Berndt (2009) performed permeability tests according to ASTM D 5084 on concrete specimens with s/b ratios of 0, 50 and 70%, which were wet cured for 84 days and found similar permeability coefficients for all mixes, ranging from 1.0 to 1.4 $\times 10^{-12}$ m/s. Contrarily, Cheng et al. (2005) obtained permeability coefficients at 91 days, which decreased with increasing ggbfs content. For concrete containing 0, 40 and 60% ggbfs the permeability coefficients obtained by their permeability test setup amounted to 2.56, 1.52 and 1.32 $\times 10^{-13}$ m/s respectively.

Shi et al. (2009) investigated the influence of ggbfs on nitrogen gas permeability of high strength concrete. They found that replacement percentages between 15 and 60% of cement by ggbfs produce no significant further improvement in gas permeability measured as recommended by RILEM TC116-PCD (RILEM 1999). Niknezhad and Kamali-Bernard (2015) measured the intrinsic permeability of different SCCs based on different cements containing various mineral admixtures. Figure 1.37 shows the significant effect of a CEM III with 62% of ggbfs and CEM V with 25% of ggbfs on the decrease of this intrinsic property.

Fig. 1.37

Intrinsic permeability of different SCCs based on different binders (Niknezhad and Kamali-Bernard 2015)
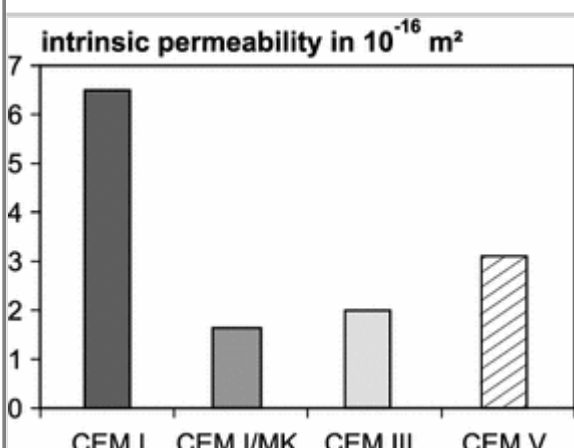
Nokken and Hooton (2004) found that 35% ggbfs replacement of cement in concrete with w/b = 0.40 resulted in reduced water permeability by a factor of 7, and reduced chloride bulk diffusion by a factor of 3 at an age of 28 d.

1.11.2. Sorptivity

Ggbfs influences the transport properties and sorptivity (Güneyisi and Gesoğlu 2008; Hadj-Sadok et al. 2011; Villagrán Zaccardi et al. 2012), even without significant reduction in the volume of accessible pores. This is connected with an increase in tortuosity and pore refinement.

An informative study on the on-site performance of ggbfs concrete is presented in (Lane 2012), where comparisons are made between the properties of ggbfs concretes and OPC concretes used in the construction of bridge decks, all of them with a w/b of 0.45, which were 12–16 years old at the time of testing. Concrete properties were evaluated on extracted cores from the structure. Ggbfs cement concretes generally showed lower transport properties than OPC concrete. Two thirds of samples of ggbfs concrete showed lower capillary suction rates, which were lower than the targeted maximum sorptivity values, whereas only one third of OPC concrete met this limit. The absorption rates of ggbfs concretes were about half of those of OPC concrete. Similar results were found for concrete conductivity, where the values for OPC concrete were double those of ggbfs concrete.

Gruyaert (2011) determined the sorptivity coefficients for specimens containing different amounts of ggbfs at different ages from 1 to 12 months, which were oven-dried at 105 ℃ until constant mass. These sorptivity coefficients decreased with increasing ggbfs contents and decreased as a function of time.

1.11.3. Carbonation

The carbonation resistance of concrete depends mainly on the concrete design parameters, the cement type, especially Portland clinker content, w/c and total water added, and on the applied curing. These parameters determine the long term porosity and permeability of the concrete. Of high importance are furthermore the humidity conditions of the concrete. High carbonation rates are obtained, when the concrete faces conditions between 50 and 70% relative humidity (Hunkeler and Lammar 2012).

Especially the Portland clinker content is decisive for the carbonation rate, because it determines the amount of calcium hydroxide, which is available for carbonation (Fig. 1.38). Consequently, when tested at constant w/b, the carbonation coefficient of concrete increases with the ggbfs content (Brameshuber et al. 2008, 2009; Scholz and Wierig 1988).

Fig. 1.38

Influence of the Portland cement content on the carbonation rate, results from Brameshuber et al. (2008, 2009), Feldrappe et al. (2016)
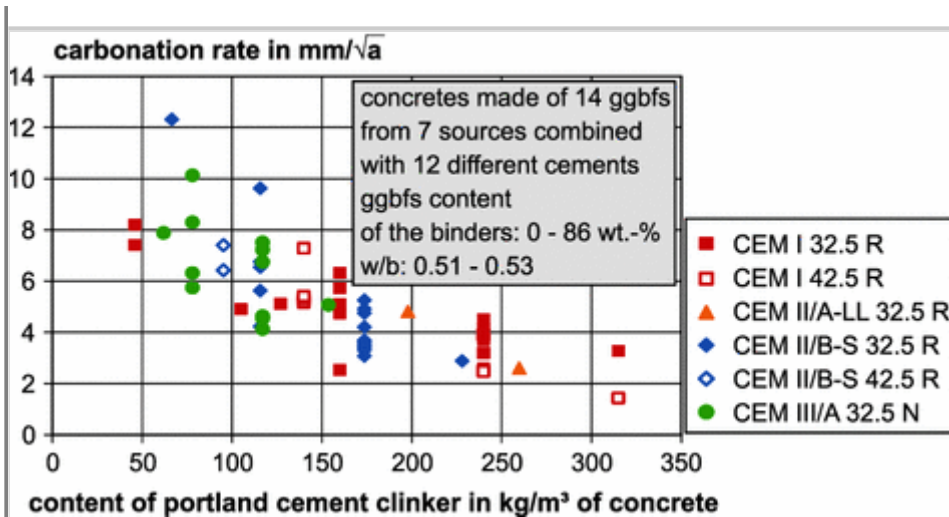
Moreover, it is likely that CO_2 also affects the other phases in ggbfs concrete, especially CSH phases, which also can react with CO_2. The reaction mechanism is that CSH decomposes and a porous silica gel is formed. Since the formation of silica gel results from a condensation of Si-OH groups to Si-O-Si linkages and thus polymerisation of the silicate chains in CSH, this reaction is accompanied by carbonation shrinkage. For ggbfs concrete, the resulting effect of carbonation is thus a coarsening of the pore structure (Sisomphon et al. 2010; Valenza and Scherer 2007a, b). Borges et al. (2010) mention a reduced overall porosity due to pore filling by carbonates, but an increased permeability due to carbonation shrinkage and cracking for ggbfs pastes after carbonation. In contrast, the carbonation of OPC concrete yields a denser microstructure because of the formation of voluminous calcite, which overcompensates the shrinkage induced by CSH decomposition (Sisomphon et al. 2010).

Decisive is also the w/c or w/b ratio. The data of Osborne (1989) show, that concrete with 40% ggbfs and a w/b of 0.45 would have a comparable carbonation coefficient as concrete with OPC with a w/b of 0.55 (Fig. 1.39, Hunkeler and Lammar 2012).

Fig. 1.39

Influence of ggbfs content and w/b on carbonation coefficient (Hunkeler and Lammar 2012), *data* Osborne (1989)
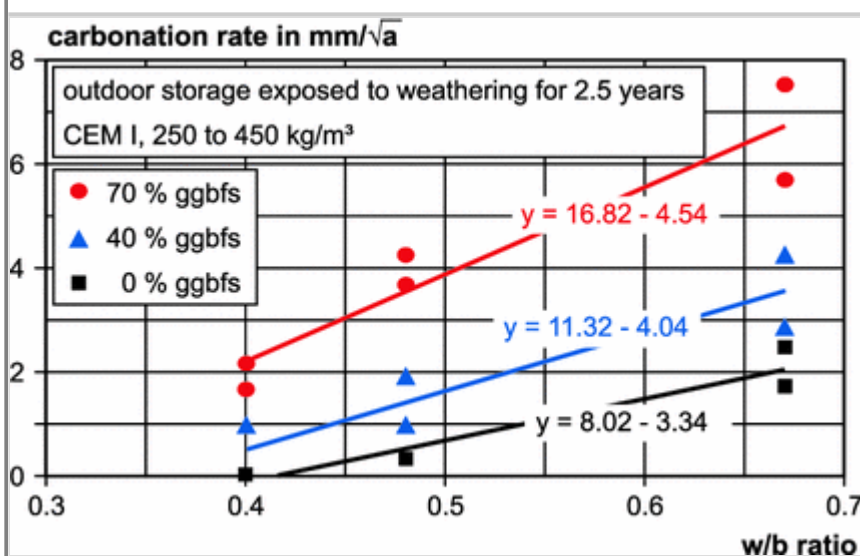
In practice, the concrete is designed to achieve a certain strength at 28 days and a target workability. In presence of major amounts of ggbfs, the water addition can often be reduced, which would lead to a lower concrete permeability and thus to a lower carbonation depth—provided, that the concrete is properly cured.

Most importantly, increasing additions of ggbfs slow down hardening and strength development at early age, so that concrete with major amounts of ggbfs requires adequate curing, more than OPC concrete.

1.11.4. Chloride Ingress

Chloride ingress into concrete can be notably diminished by the addition of ggbfs, with a very significant improvement at replacement levels >50% (Bijen 1996; Tuutti 1982; Bleszynski et al. 2002). This is due to the reduced capillary porosity and the increased chloride binding capacity of ggbfs concrete. Figure 1.40 presents results of free, bound and total chloride content of SCC samples subjected to an electrical steady-state migration test. SCC based on CEM III containing 62% ggbfs or CEM V with 25% ggbfs exhibit a significantly higher bound chloride content than SCC based on OPC (Niknezhad and Kamali-Bernard 2015).

Fig. 1.40

Total, free and bound chloride contents of different SCC samples (Niknezhad and Kamali-Bernard 2015)
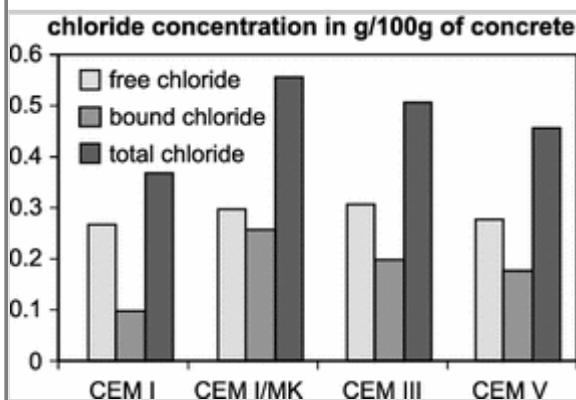
Other authors confirm, that the replacement of cement by ggbfs, fly ash or silica fume has a positive influence on the binding capacity (Angst et al. 2009; Izquierdo et al. 2004; Tang 1996; Thomas et al. 2012). The use of ggbfs increases the chemical (Dhir et al. 1996; Luo et al. 2003) as well as the physical binding of chlorides (Arya et al. 1990). The calcium aluminate hydrates, which are formed during the hydration of ggbfs, can transform to Friedel's salt (Dhir et al. 1996; Luo et al. 2003) and the large amount of CSH gel provides a high surface area for adsorption of chloride ions. According to Xu (1997), the higher binding capacity of cement with ggbfs can be attributed to the dilution effect of sulfate ions. He found that the higher binding capacity disappears when the sulfate level in slag cement paste is increased up to that of OPC paste. Luo et al. (2003) also mention that sulfates greatly reduce the binding capability of ggbfs. They concluded that the lower content of sulfate of ggbfs is one of the reasons for the better performance of ggbfs concrete towards chloride-induced corrosion. Contrarily to these findings, the experiments of Yuan (2008) did not show a higher binding capacity for ggbfs concrete in comparison to OPC concrete.

Over time, the chloride diffusion coefficient of ggbfs concrete decreases significantly - more than in conventional concrete. At early ages the chloride diffusion may be higher for ggbfs concrete in comparison with conventional concrete, but at later ages this relationship is inverted (Thomas and Bamforth 1999). Using ultrafine ggbfs (Blaine = 870 m^2/kg, BET = 4968 m^2/kg), Teng et al. (2013) achieved a 25 and 88% reduction of the chloride migration coefficient according to NT Build 492 (1999) after 28 d of curing with only 30% of cement replacement by ggbfs in concrete with w/b = 0.35 and 0.28 respectively. The ultrafine ggbfs refined the particle size distribution of the cement. Gruyaert (2011) also showed the better performance of ggbfs concrete with regard to chloride ingress with non-steady state migration and diffusion tests. The level of replacement of cement by ggbfs, being 50, 70 or 85%, did not significantly alter the chloride resistance of the concrete. However, the on-going hydration in ggbfs mixes caused still a significant decrease of the migration coefficients with time, while this was not the case for OPC concrete. Chloride bulk diffusion measurements of cores taken from 14 year old concrete slabs showed that 25 and 50% ggbfs replacement of cement reduced values by factors of 2 and 4 respectively, compared to a reference OPC concrete (Hooton et al. 2013).

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Studies on samples exposed in marine environment for 25 years have confirmed significant reduction in the chloride ingress rate of concrete when 45–65% replacement levels of cement by ggbfs are employed (Thomas et al. 2008). The obtained penetration depth of the control concrete with w/c of 0.40 and 0.60 was higher than 100 mm, more than twice of the penetration depth of the 45 and 65% ggbfs concretes. On the basis of these results, a modified model for chloride ingress considering the effect of ggbfs has been established and validated (Riding et al. 2013).

1.11.5. Resistivity

Resistivity is affected by the addition of SCMs and the degree of hydration, as they affect the concrete microstructure and the chemistry of pore solution (Osterminsky et al. 2006). The refinement of pores increases resistivity as it reduces the volume of conductive phase (Basheer et al. 2002). Moreover, resistivity is very sensitive towards changes of the chemical composition and pH of the pore solution. Teng et al. (2013) obtained increases of 81 and 462% of concrete resistivity when replacing 30% of OPC with ultrafine ggbfs in w/c = 0.35 and 0.28 concrete, respectively. This variation was much higher than that of other transport properties. The variation of resistivity with time was more pronounced in ggbfs concrete than in OPC concrete. Ggbfs was observed, among the SCMs, as the one, which increaseds concrete resistivity the most (Basheer et al. 2002; Polder and Peelen 2002). A similar trend was found for reduction of conductivity, the inverse of resistivity, of ggbfs concretes with time (Nokken and Hooton 2006). Concrete with 35% ggbfs was found to increase resistivity by 230% while 50% ggbfs increased resistivity by 400–500%, depending on the Portland cement and the water/binder ratio of the concrete mixtures (Hooton and Charmchi 2015).

Olsson et al. (2013) studied the relationship between desorption isotherms and conductivities of mortars with different binders. Plotting conductivity versus moisture content of mixes prepared with the same w/c ratio, they found different correlations, depending on the ggbfs content (Fig. 1.41, Olsson et al. 2013). Ggbfs has a strong impact on the conductivity of the pore solution. This is confirmed by Lübeck et al. (2012), who obtained a decreased electrical conductivity of pore liquid due to ggbfs replacement of both, OPC and white cement.

Fig. 1.41

Results of conductivity measurements on mortars with w/b = 0.38, as a function of moisture ratio (Olsson et al. 2013)
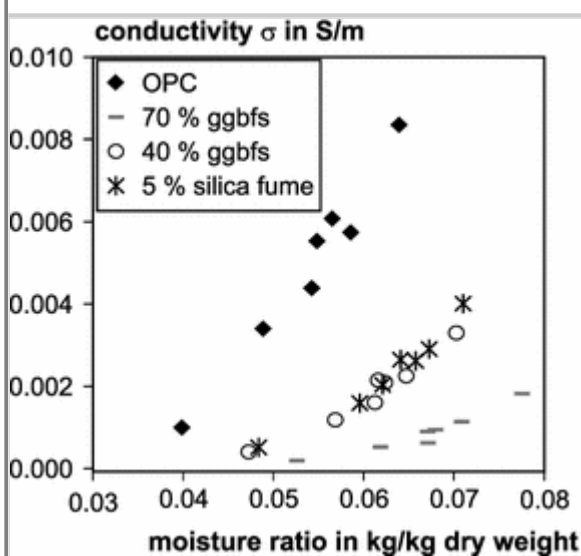
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