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High-volume ground granulated blast furnace slag (GGBFS) concrete

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Abstract: Ground granulated blast furnace slag (GGBFS) is a by-product of the iron-making process and because of its high calcium silicate content it has excellent cementious content and has been used in the construction industry for years as a replacement for ordinary Portland cement (OPC). GGBFS is also routinely used to limit the temperature rise in large concrete pours and is therefore a desirable material to use in mass concrete placements where control of temperatures is an issue. The more gradual hydration of GGBS cement generates both lower peak and less total overall heat than OPC. GGBFS was approved for use a at a 70% replacement even if it is allowed to use a maximum 25% instead of cement. It has a higher proportion of the strength-enhancing calcium silicate hydrates (CSH) than concrete made with only OPC, and a reduced content of free lime, which does not contribute to concrete strength.

Key words: ground granulated blast furnace slag, high replacement level, workability, strength, durability.

10.1 Introduction

Ground granulated blast furnace slag (GGBFS) has been used in the construction industry for years as a replacement for ordinary Portland cement (OPC). Ground granulated blast furnace slag also has a lower heat of hydration and, hence, generates less heat during concrete production and curing. GGBFS is a desirable material to use in mass concrete placements where control of temperatures is an issue. GGBFS can be used instead of cement with the ratios from 10% to 90%. However, because of its low heat generating characteristics, GGBFS was approved for use at a 70% replacement even if it is allowed to use maximum 25% instead of cement (Richardson, 2006).

The general GGBFS literature indicates that the replacement of OPC by GGBFS typically results in lower early strengths (7 to 28 days), greater long-term strengths, lower chloride ion permeability, less creep, greater sulphate attack resistance, greater alkali silica reactivity (ASR) durability, enhanced workability, less bleeding, lower heat of hydration, and increased steel corrosion resistance. Results for drying shrinkage and freeze–thaw durability are somewhat mixed, although in general, the use of slag appears to be nondetrimental. Besides lower early strength, the downsides to the use

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of GGBFS include extended curing times, increased salt scaling, increased plastic shrinkage cracking, and increased air entrainment dosage required When Grade 120 (highest activity) slag is used, at least a 70% replacement may be needed to meet specification requirements. Most ready-mix concrete producers use 50% replacement with highly reactive slag during warm weather (Richardson, 2006).

10.2 The use of high-volume ground granulated blast furnace slag (GGBFS) concrete

Most cement plants consume great amounts of energy and have a negative affect on the environmental because of the destructive greenhouse gases they emit to the atmosphere during the production process. Therefore, cement producers benefit from various mineral additives so as to reduce the CO_2 emission and increase the production rate by decreasing energy consumption. One of those mineral additives is granulated blast furnace slag, which occurs during the production of pig iron in the iron and steel factories, a major part of which is ready to be used as an alternative binding material. The use of industrial by-products containing a high percentage of silica and alumina as an additive in cement or concrete, an area convenient for the utilization of large volumes of waste materials, will help the environmental problems to some extent. By preventing the rapid consumption of limited natural resources, the production of more qualified and more economic materials instead of traditional ones will also be possible.

The use of GGBFS, which has an amorph structure and shows pozzolan characteristics when finely granulated, as a replacement material within the systems of cement or concrete positively affects the properties of fresh and hardening concrete. The slag use provides an advantage especially in avoiding the thermal cracks in mass concrete and solving the durability problems such as corrosion resistance, sulphate attack and ASR. On the other hand, when the slag is used in the concrete structures which will be exposed to hard conditions, there are some points, especially for cold climates, to be taken into consideration, such as preference of low rate of water/binder (w/b) in the mixture and, because the slag has a low speed of hydration, the need for a longer cure process compared with concrete with OPC.

10.3 Composition and properties of ground granulated blast furnace slag (GGBFS) concrete

When GGBFS is combined with water it shows a low rate of binding. Its speed of hydration is quite slow compared with OPC. It is used together with alkali salts or some amount of OPC so as to increase the speed of hydration.

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As a result of the combination of OPC and GGBFS, firstly calcium-silicate components such as C_3S and C_2S, which are structurally found in the OPC clinker, start the hydration and then $C_3S_2H_3$, gels of C-H-S together with $Ca(OH)_2$ (portlandite), which gives hydraulic binding property to cement, start to produce CH. The reaction between the additional CH and the pozzolan results in C-S-H. The emission of CH after the hydration of OPC gives no noticeable contribution to the resistance and is destructive in the sense of durability. Hence, it is aimed at reducing CH after its reaction with pozzolan. Moreover, owing to the fact that pozzolan provides economic advantages and positive environmental contributions, in *addition* to OPC, pozzolan mineral additives such as fly ash, blast furnace slag, silica fume and natural zeolite have started to be used. The necessary amount of CH for GGBFS to gain hydraulic binding property is provided by CH produced by the hydration of OPC. Similarly to the hydration of OPC, the reactions between GGBFS and CH engender the formation of new gels of C-H-S which has a binding property. The reactions of GGBFS and CH are quite similar to those of pozzolan. Under normal temperatures, the reaction between GGBFS and OPC occurs in two phases. When the hydration starts, the reaction of slag and alkali hydroxides stands in the forefront; then, however, the reactions of slag and CH become dominant (Erdoğan, 1995).

During the early hydration of the slag cement, the Portland cement releases calcium hydroxides (CH) with the ratio of 28% of its weight. In practice, however, this ratio does not exceed 20% of its weight. Hardened cement paste that has a greater density and smaller pore sizes than an equivalent OPC paste, thus permeability and ionic diffusivity are reduced. Smaller pore size relates to lower permeability, although this does not necessarily mean lower total porosity. Slag–OPC and OPC mixes may result in similar total porosities, but the slag–OPC pore structures tend to be finer. Total porosity is important to mechanical properties such as compressive strength, but is less critical to properties that are associated with durability such as permeability. Durability seems to be related to larger pores. However, it has been reported that a 60% slag mortar mix not only had smaller pore sizes but also a somewhat smaller pore volume. Higher CH contents are associated with greater permeability and lower durability (Richardson, 2006).

The hydraulic binding property of GGBFS depends on the factors such as chemical characteristic of the slag, the concentration of alkali in the reactive system, the amount of vitreous structure in the slag, the fineness of the slag and the OPC used together with and the temperature during the hydration. Owing to the complexity of the factors which affect the hydraulic binding value of the slag, in previous years, to determine this value, a simple method was satisfactorily used. Provided that the slag is in accordance with the condition of $CaO + MgO + Al_2O_3/SiO_2 > 1$, its hydraulic binding value is accepted suitable. To assign the hydraulic binding value of the slag, the slag-activity

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index according to the ASTM C 989 standards is checked. The standard of ASTM C 989 constituted in 1982 divides GGBFS having hydraulic character and capability to be used as a mineral additive in concrete production into three groups as Grade 80, Grade 100 and Grade 120 regarding the slag-activity index. The standard states that the maximum amount of the slag remaining on the 45 μm sieve should be 20% and the maximum amount of air in the mortar prepared with this slag should be 12%. Furthermore, the amount of S in the slag is constrained to at most 2.5% and SO_3 at most 4% (Erdoğan, 1995). Because GGBFS cement reacts more slowly, especially at lower temperatures, it is typically ground finer than OPC. Lim and Wee (2000) found that more finely ground GGBFS had greater early strengths, but after 28 days the greater fineness caused little difference (Richardson, 2006). When the Blaine fineness increases at GGBFS, concrete shall have more brittle characteristics: this is an important factor at the mechanical properties of the concrete.

10.3.1 Fresh concrete properties

There are various studies on the unit weight and workability of fresh concrete having a high volume of GGBFS.

Fresh unit weight

The unit weight of fresh concrete when it is poured is between 2.35 and 2.55 kg/dm^3 and the theoretically calculated unit weight is between 2.27 and 2.50 kg/dm^3. The results are very close to each other (Bilim, 2006).

Need for water and workability

Concrete with GGBFS needs less water than those with OPC, because of the smooth surface texture of slag particles and the delay in the chemical reaction (Newman and Choo, 2003). Having less surface roughness and a lower density than clinker, GGBFS provides more volume of cement paste and positively affects the workability of slag concrete (Bilim, 2006). When the workability of the concrete with GGBFS is concerned, the amount of cement, the rate of slag, the amount of aggregate, the type of slag and the interaction between them are very important. The reduction in the need for mixing water of GGBFS is related to its vitreous and non-absorbent surface structure (Mehta, 1989; Bilim, 2006). Owing to the fact that GGBFS have less surface roughness and a lower density compared to clinker, GGBFS provides more volume of cement paste and this renders the slag concrete more workable. In their study on workability of mortar with GGBFS, when low water/cement rate (0.20) and high rate of water-reducing admixture are used, Ohama et al. (1995) determine that the fluency of the mortar is improved due

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to the partial replacement of slag with cement and the process is positively affected by the fineness of the slag. According to Güllü (1996), because of the increased volume of cement paste and smooth slip planes inside the paste, additing GGBFS to fresh concrete improves the workability of it and increases the set time 30–60 minutes under the temperature of 23 °C.

Depending to its low density, GGBFS with high rates forms more paste, thus the workability of it develops. By means of good workability, the amount of rough aggregate is increased; hence the amount of the paste can be decreased. Nevertheless, Bush et al. (2000) obtained a mediocre reduction in sedimentation with GGBFS of 25%. Among the mixtures tested by Sanjayan and Sioulas (2000), for a constant w/b, the mixtures with slag showed 20–50% higher sedimentation. However, in the study of Duos and Eggers (1999), the sedimentation decreased by increasing the amount of slag under 23 °C.

10.3.2 Hardening concrete properties

The start and finish of setting time, hydration heat and bleeding issues are examined in a hardening concrete with a high ratio of GGBFS.

Setting time

Because GGBFS reacts with higher range water reducer (HRWR) than OPC, the slag use causes an increase in the setting time of the concrete (Bilim, 2006). This increase in drying time is much more at high-level replacements over 50% and at temperatures under 10 °C. The setting time of the concrete with GGBFS is longer than for OPC and the higher the amount of the slag, the longer the time. This characteristic is important in order to avoid cold joint formation during the pouring of large mass concrete. Hogan and Meusel (1981) found that both the initial and final setting time of the concrete with 40%, 50% and 65% slag is approximately one hour longer than the times of the concrete with OPC. Brooks et al. (2000) reported that the initial and final setting time of concrete with 40% or more GGBFS shows a noticeable delay respectively more than 11 and 17 hours.

Heat of hydration

The use of GGBFS in concrete decreases the maximum concrete temperature and prolongs the time to reach this maximum temperature by diminishing the hydration heat. Moreover, the rate of temperature change is reduced by the increased GGBFS rate. This feature is very beneficial in pouring large mass concrete since it avoids higher temperatures. The decrease in temperature during application depends on several factors such as the size of the section,

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the amount of the cement, the rate of the slag, the fineness of the binding components and their chemical composition (Bilim, 2006). The hydration speed of the slag and the temperature change is lower than those of the OPC. Therefore, because the partial replacement of the slag with OPC creates cement with lower hydration speed, the increase in the temperature of the concrete produced by such cement remains lower (Soroka, 1993). Alshamsi (1997) examined the effects of GGBFS and micro-silica on the hydration temperature of the concrete. In conclusion of this study, he declared that the amount of the cement is significantly effective on the increase of hydration temperature and GGBFS reduces the temperature increase in cement paste more than micro-silica does. Additionally, it is reported that those materials substituted by cement certainly affect the time for reaching the peak temperature, and while GGBFS is delays the time for reaching peak temperature, micro-silica accelerates it. Slag concrete both decreases the maximum temperature of the concrete and prolongs the time to reach this maximum temperature by reducing the hydration heat (Bilim, 2006).

Bleeding

Wainwright and Ait-Aider (1995) pointed out that the bleeding of fresh concrete is controlled by the fine materials in the mixture with respect to the amount and reactivity of the cement. While the replacement of GGBFS with OPC brings about a decrease in the speed of hydration, it causes an increase both in amount and speed of bleeding. The main reason of this increase is the delay in the hydration mechanism caused by the slag poured to cement paste; the decrease in the development speed of hydration products is a result of this. Olorunsogo (1998) examined the bleeding characteristics of the mortar produced by cement with slag and the distribution of the granule size of GGBFS. According to him, independently from the distribution of granule size and the w/b rate, for the mixture of both w/b rates of 0.35 and 0.45, the higher the slag rate, the higher the rate and capacity of bleeding. Whatever the rate of slag replacement and distribution of granule size were, for all mixtures, the increase in the w/b rate from 0.35 to 0.45 caused an increase at a percentage respectively by 86%, 83% and 71% in the bleeding, rate of mortar with 0%, 30% and 70% slag. This increase in bleeding, together with the increased rate of w/b, being a result of the larger average distance between the granules, is caused by weak cohesive attractive forces which occur because of the granule contact (Bilim, 2006).

10.3.3 Hardened concrete properties

Unit weight, compressive strength and strength development, tensile strength, splitting-tensile strength, modulus of elasticity, creep, shrinkage, permeability

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and chemical stability and capillary water absorption are examined in high-volume GGBFS.

Unit weight

The unit weight of hardened concrete with GGBFS is less than that of control concrete. Regarding the concrete age, the unit weight of the concrete with GGBFS increases more than normal concrete. While the unit weight in normal concrete does not change greatly for years, generally, it increases noticeably in concrete with GGBFS. The most significant reason for this is that the slag in the concrete with GGBFS produces new CSH, by combining with CH in the first times of hydration. As is known, even if the concrete gets older, the hydration slowly continues. As a result of this the new C-S-H production goes on until the silicates finish deriving from slag and the unit weight value slightly increases. For further ages, however, since the density of the slag is less than that of the cement, the unit weight of the concrete with high-volume GGBFS is smaller than the control concrete. For instance, the dry unit weight of the 28-days-old concrete with 10%, 20%, 30% GGBFS are 5%, 10% and 14% less than the control concrete. The unit weight of the same concretes after 90 days are 2%, 5% and 6% less than the control concrete as well (Öz, 2006).

Compressive strength and strength development

When the equal amounts of cement and w/b rate are concerned, the slag concrete has less compressive strength at early ages and more compressive strength at late ages than has the concrete with OPC. Because GGBFS hydrates slower than OPC, the rate of strength development is lower at early ages for slag concrete. High-volume slag replacement instead results in a lower rate of strength development. However, when a suitable humidity condition is provided, the long-term strength of the slag concrete will probably be higher. This higher strength in late terms stems from the partial long-term strength of the slag and the micro-structure which is intensively hydrated due to the slower hydration reaction. When the temperature is increased, the rate of strength development of the slag concrete is also more than that of the concrete with OPC (Bilim, 2006). Yeau and Kim (2005) found that on 28th day the performance of the concrete with GGBFS is similar to that of control concrete; however, on 56th day the concrete with GGBFS has a superior performance to the concrete with OPC. According to the researchers, all of the concretes with up to 55% slag showed a lower compressive strength than the control concrete within 7 days. The results of the tests demonstrated that the hidden binding property of GGBFS, together with the increasing rate of slag replacement, slow down the strength development at early

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ages. But at ages such as 28, 56 and 91 days, the strength development of the concrete with GGBFS is similar to greater than or that of the slag-free control concrete with OPC.

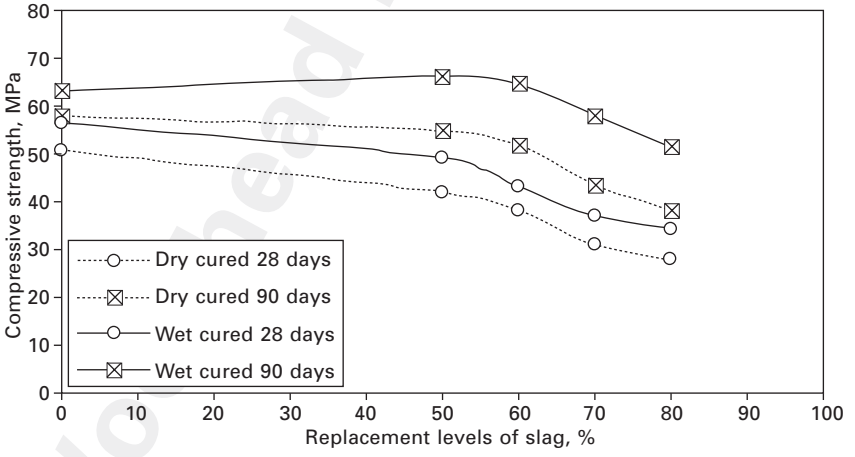
Sakai et al. (1992), who studied on the features of slag concrete which they produced mixing blast furnace slag of four different fineness such as 300, 400, 500 and 600 m^2/kg into 300 m^2/kg cement with a replacement rate from 50% to 80%, found that the finer the slag, the higher the compressive strength according to the results of the experiments.

In research performed by Sanjayan and Sioulas (2000), for the compounds at 100 MPa pressure level, with slag of 70% when compared with the compounds with OPC, the strength percentage for the 7th, 28th, 56th and 91st days were respectively found to be 46%, 71%, 85% and 96%. The strength percentage on the 91st day, for the compounds with 50% slag at 40 MPa is 97%.

Güneyisi and Gesoğlu (2008) studied 0, 50, 60, 70 and 80% replacement rates of GGBFS in concretes and showed the changes of compressive strengths in accordance with the concrete's age and curing conditions. The compressive strength values of the control concretes are between 50.6 and 63.1 MPa and compressive strength values of the GGBFS concretes are between 27.9 and 66.2 MPa as shown in Fig. 10.1.

Flexural strength

The slag concrete, under a determined compressive strength, has a higher tensile strength than the concrete with OPC (Newman and Choo, 2003). Sivasundaram and Malhotra (1992) obtained nearly 8 MPa of strength in 14 days.



10.1 Effects of slag replacement and curing conditions on 28 and 90-day compressive strength of concretes (Güneyisi and Gesoğlu, 2008).

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Splitting-tensile strength

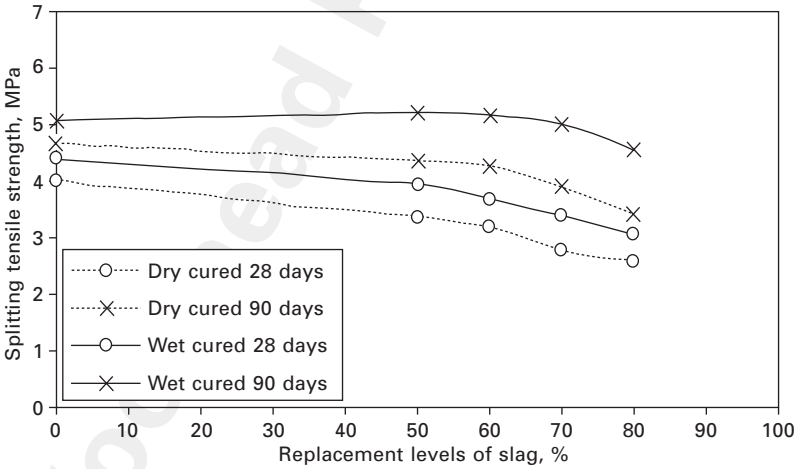
The results of splitting experiments are similar to those for compressive strength. Increasing the slag amount, causes the splitting strength to decrease. Güneyisi and Gesoğlu (2008) stated that it is not valid for the samples containing 50% and 60% slag and cured in water for 90 days. Furthermore, as shown in Fig. 10.2, the decrease in splitting strength is less than the decrease in compressive strength. The results of splitting and compressive strength for the samples with 80% are lower.

Modulus of elasticity

Under a determined compressive strength, GGBFS has an improving impact on the modulus of elasticity of the concrete compared to concrete with OPC (Newman and Choo, 2003). At early ages, although the secant elasticity modulus of the concrete including 30–70% of slag and cured in water is similar to the concrete with OPC, it increases at later ages. Nevertheless, the modulus of elasticity of the concrete cured in air is lower than the concrete with high-volume slag cured in water at late ages (Brooks et al. 1992; Bilim, 2006). For equal strengths for 28 days, the modulus of elasticity of the concrete prepared with slag cement is a little bit higher.

Creep

Chern and Chan (1989) found that the creep behaviour of the concrete with OPC is similar to that with GGBFS. Under the cure conditions without



10.2 Effects of slag replacement and curing conditions on 28 and 90-day splitting tensile strength of concretes (Güneyisi and Gesoğlu, 2008).

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humidity loss, along with the increasing slag replacement rate, the creep of the concrete decreases; on the other hand, under dry cure conditions, the concrete with GGBFS shows greater creep deformation than with OPC (Bilim, 2006). In their study on creep and drying shrinkage of high performance concrete, Jianyong and Yan (2001) substituted OPC with GGBFS and silica fume (SF) as a filling material and found that the highest creep value was obtained in the concrete in which SF and GGBFS were used together. Under the cure conditions without humidity loss, the more the slag ratio, the less the creep of concrete. With high replacement ratios such as 70%, the decrease in the creep of the concrete is about 50% (Newman and Choo, 2003). The decrease in creep is generally related to the higher strength that the concrete with slag gains at further ages. However, since there is less strength in later periods for the concrete under dry cure conditions, the differences observed in creep behaviour are less evident, and for most applications in which the drying shrinkage is not very much, the creep behaviour of the slag concrete is similar to of with OPC (Bilim, 2006).

Shrinkage

The results of research about the shrinkage of the slag concrete differ because of the experiment conditions and the various materials used, but those differences are not very significant. In general, the slag concrete affects shrinkage similarly to the concrete with OPC (Bilim, 2006).

It is known that GGBFS increases autogenous shrinkage. Lim and Wee (2000) obtained the highest shrinkage in 91 days for concrete with 50% GGBFS among other high-performance concretes with 30%, 50%, 65% and 50% GGBFS and 0.30 w/b. They showed that when the fineness of GGBFS is increased, autogenous shrinkage increases as well. A large amount of autogenous shrinkage causes deep cracks in concrete structures. Even though those cracks do not appear on surface, they create crucial tensile activity inside the concrete. Therefore, it is necessary to observe the autogenous shrinkage of the concrete with GGBFS. The autogenous shrinkage of the concrete with 0%, 10%, 30% and 50% GGBFS was examined. It was found that the autogenous shrinkage of the concrete with 10% GGBFS is higher, increasing autogenous shrinkage by a ratio of 6%.

Pore structure

The pozzolan mineral additives generally decrease the porosity of the concrete. As mentioned before, the slag in the concrete with GGBFS produces new C-S-H, by combining with CH in the first times of hydration. As is known, even if the concrete gets older, the hydration slowly continues.

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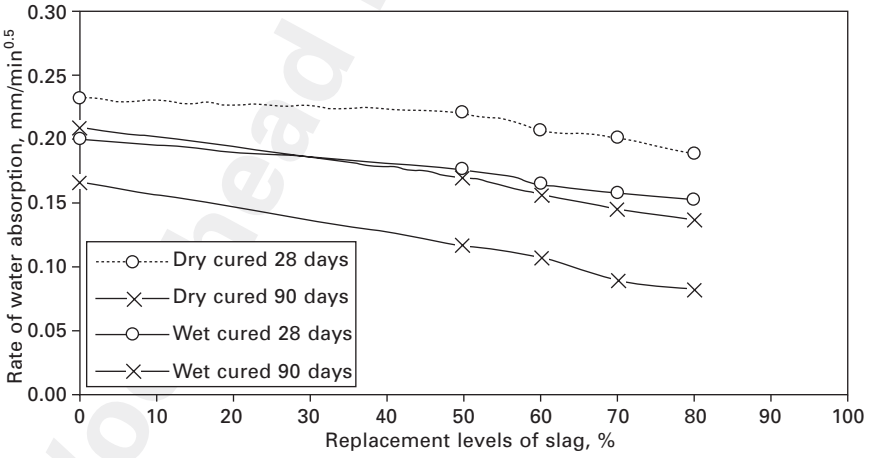
Permeability

Slag is functional for long-term permeability in well-cured concretes, especially at high temperatures. The reasons for this are the continuation of hydration in slag concrete after 28 days, the total porosity does not change even if the increase of the slag amount, smaller gaps by increasing of the cure temperature, while the gaps in the concrete with OPC is augmented the slag concrete is not affected by that (Bilim, 2006).

Sorptivity

The capillary water absorption values of the concrete formed by partial replacement of OPC with GGBFS decreases to an important extent, which is especially crucial for concretes which are exposed to moist and dry conditions. Taşdemir (2003), who found that the capillary water absorption value decreases by increasing compressive strength, also reports that the capillary water absorption value is vulnerable to the cure conditions, and the lowest coefficient of capillary water absorption is obtained from the samples which are kept under 20 °C in lime-saturated water cures during 28 days (Bilim, 2006).

Figure 10.3 shows the variation in water absorption rates with concrete age and curing condition for the control and slag concretes. It is clear that rate of water absorption decreases systematically with an increase in curing period (from 28 to 90 days), and the gradients of the water absorption tend to decrease with increase in the replacement level of slag. Generally, slag concrete performed better than the control concrete and marked improvements



10.3 Effects of slag replacement and curing conditions on 28 and 90-day water absorption rate of concretes (Güneyisi and Gesoğlu, 2008).

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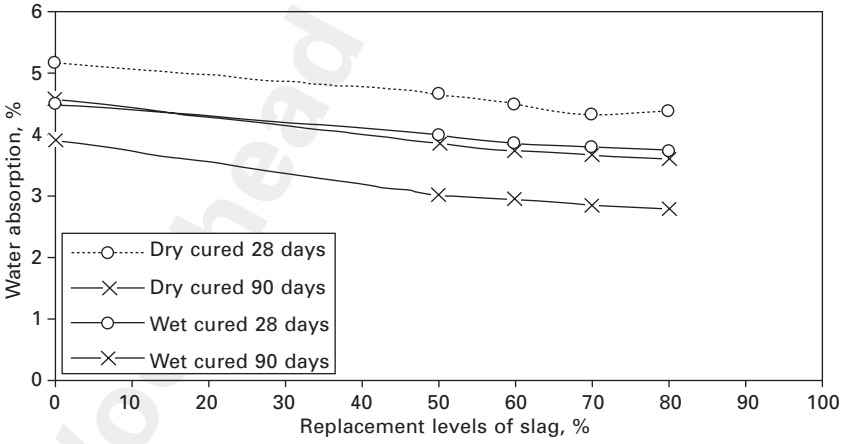
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in terms of lower rate of water penetration through capillary suction were apparent, particularly under wet curing condition.

Furthermore, the reduction in the water absorption with increasing test age was about 12% and 15% for air and wet-cured conventional concretes, respectively, while it was about 18–22% and 30–35% for air and wet-cured slag concretes, respectively. This reduction in the water absorption with age indicates better performance of slag blended cement concretes over conventional concrete. The improvement in the performance of the air-cured samples might be explained by the surface carbonation of the air-cured concrete resulted in enhanced reduction in sorptivity.

Güneyisi and Gesoğlu (2008) showed the correlation between water absorption with the curing conditions and the age of the concrete in Fig. 10.4. Similar to the rate of water absorption test results, water absorption characteristics of the concrete specimens decreased with increasing slag content, irrespective of curing condition and testing age. However, the differences in water absorption are more characteristic after 28 days of curing; water absorption of the GGBFS concretes are less than control concretes. At the age of 90 days, water absorption decreases with the ratio of between 12 and 15% at wet and dry cured control concretes. Decreasing ratio of water absorption at dry cured GGBFS concretes are between 18–22% and at wet cured GGBFS concretes are between 30 and 35%. This reduction in the water absorption with age indicates better performance of slag blended cement concretes over conventional concrete. The improvement in the performance of the air-cured samples might be explained by the surface carbonation of the air-cured concrete resulting in enhanced reduction in sorptivity.



10.4 Effects of slag replacement and curing conditions on 28 and 90-day water absorption of concretes (Güneyisi and Gesoğlu, 2008).

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10.4 Durability of ground granulated blast furnace slag (GGBFS) concrete

10.4.1 Sulphate resistance

In a study in which Hooton and Emery (1990) used solutions of $MgSO_4$, $CaSO_4$ and Na_2SO_4, 130 different cements were used. Proportionally with the amount of GGBFS, even though the concrete obtained by respectively 45% and 72% GGBFS replacement by sulphate OPC, did not show a deterioration inside 3000 mg/l SO_4 solution for 10.5 years, the concrete with C_3A of a ratio from 3.5% to 12.3% with OPC was badly affected. Frearson (1986) observed that the sulphate resistance of the concrete is affected by GGBFS content rather than water/cement content. The reason for this is related to the decrease in permeability caused by GGBFS. Furthermore, it is known that the increase in sulphate resistance, caused by GGBFS, is due to the decrease in C_3A content. Additionally, slag decreases $Ca(OH)_2$, increases the gels of C-S-H, so improving the strength, and weakens the permeability of the concrete (Abd El Aziz et al., 2005).

10.4.2 Resistance to chloride ion penetration and reinforcement corrosion

Resistance to the effects of chloride

Aldea et al. (2000), made a study on the effects of different cure conditions such as autoclave (175 °C, 0.5 MPa), steam cure (80 °C) and normal cure (20 °C, 100% RH) on the properties of concrete produced by four different slag replacements (0, 25, 50 and 75%). They reported that the cure at room conditions is the best way to improve durability, that it is best to choose steam cure instead of autoclave cure when early strength development is desired, and finally, since a reduction in chloride permeability occurs by increasing slag replacement rate, depending also on application, the use of different slag rates is possible to increase the strength and to decrease the chloride permeability (Bilim, 2006).

Chloride permeability

The slag cement or slag concrete is more resistant to penetration of chloride ions into the concrete than OPC. This positive effect stems from the chemical combination of chloride ions and slag hydration products which reduce the chloride stream in concrete and at the same time decreasing permeability of slag cement. Moreover, this increased strength has a potential to decrease the corrosion risk of steel in concrete structures. The important point in chloride permeability is the chloride binding capacity of the cement. Through studies,

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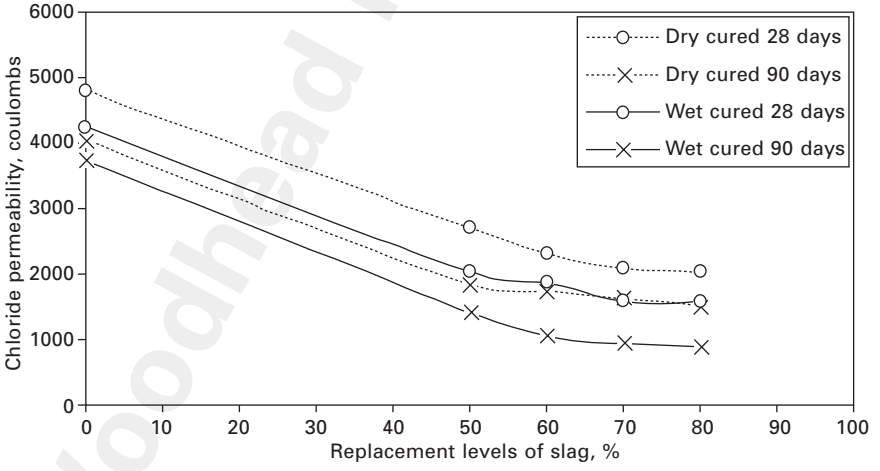
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it is known that C_3A binds chloride. Even though OPC is supposed to bind more chloride ions and to decrease chloride penetration due to having C_3A more than slag cement, the studies prove the contrary. In the analysis done by cement with GGBFS, it is observed that the penetration of chloride ions in OPC is reduced, because the gels of C-S-H bind more chloride. Owing to the fact that the C-S-H occurring after the hydration of slag cement is more than OPC, due to binding chloride ions, the chloride permeability of slag concrete mainly decreases. Sato et al. (1998) examined the effects of different cure conditions (natural environment cure and wet cure) on chloride permeability of concrete with 70% GGBFS. At the end of their study, they observed that the use of GGBFS at a rate of 70% decreases the chloride ion permeability.

Güneyisi and Gesoğlu (2008) mentioned that the chloride permeability decreases considerably in concretes that include more than 50% of GGBFS, as shown in Fig. 10.5. For example, permeability value of 70 and 80% of GGBFS concretes at the age of 90 day is 1000 coulombs and this value is qualified as wonderful in accordance with ASTM 1202.

Corrosion resistance

Song et al. (2003) observed the free chloride permeability of the concrete with GGBFS and found that the higher the amount of GGBFS, the lower the values of free chloride permeability. Additionally, they found that the free chloride permeability of the concrete with 70% GGBFS is 43.8% less than of the control concrete. Yeau and Kim (2005) examined the corrosion



10.5 Effects of slag replacement and curing conditions on 28 and 90-day chloride permeability of concretes (Güneyisi and Gesoğlu, 2008).

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resistance of the concrete with GGBFS and discovered that the steel corrosion potential of the concrete with GGBFS is less than 250 mV. This corrosion value is a very small value. In addition to that, they studied the surface of the steel exposed to corrosion according to the percentage of GGBFS and found that the surface under corrosion decreases, while the amount of GGBFS increases.

10.4.3 Durability to seawater

In his experimental study in which he worked with mortar samples completely sunk in seawater, Regourd (1986) examined the effect of the slag amount against seawater attack and pointed out that by increasing GGBFS amount in cement the expansion decreases. Osborne (1992), who a researched the performance of the concrete with slag and OPC of different C_3A content and seawater, reported that the strength development of the concrete with 70% slag that is completely sunk in seawater improves and it is exposed to fewer chemical attacks with a mediocre chloride permeability.

10.4.4 Resistance to carbonation

Carbonation occurs when CO_2 penetrates into the concrete. Both the porosity and the permeability of the concrete have an important role in the mechanism of carbonation. The carbonation of the concrete depends on the cure conditions, water/binding rate, the temperature at which the concrete exposed to carbonation and relative humidity, and the properties of the mineral additives used. The decreased permeability delays the CO_2 penetration deeply through the concrete (Bilim, 2006). Pal et al. (2002) examined the carbonation depth of the concrete with 0%, 30%, 50% and 70% of GGBFS and they observed that the greater the slag rate, the less the carbonation depth.

Sulapha et al. (2003) found that for low Blaine fineness slag (4500 cm^2/g), although the slag concretes were denser, the carbonation rate increased with increasing amounts of slag. This was thought to be attributable to less CH being available due to the pozzolanic reaction, so the carbonation must progress deeper to get at the available CH. Less material is available that is prone to carbonation per unit area to react with CO_2. Initially the pozzolanic reaction is slow, thus porosity is higher and CO_2 diffusion is rapid. However, for higher fineness slags (6000–8000 cm^2/g), carbonation rates were lower than that for OPC, thus pore modification was more dominant than the change in CH content. So, slag mixes tend to have greater depths of carbonation and are more permeable (although not necessarily more porous) and therefore would tend to scale more, especially under severe environmental conditions (Richardson, 2006).

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10.4.5 Freeze–thaw durability

Lane and Ozyildirim (1999) obtained perfect results in their study with the samples of 60% GGBFS and OPC. However, for all experiments, better results are gained for the mixtures with GGBFS rather than for with OPC. The highest resistance factor was obtained in the sample with 50% GGBFS. Pigeon and Regourd (1983) compared the mixtures with OPC and 66% slag. For both groups of samples, the same values are obtained for length changes, massive loss and changes in dynamic modulus of elasticity and compressive strength, air-gap systems and air-gap conditions.

10.4.6 Acid resistance

In their studied where they studied the long and short-term performance of concrete with GGBS and FA, Li and Zhao (2003) prepared concretes with 40% FA and OPC. After 3 days of wet cure, among the samples left in 2% H_2SO_4 solution, under room temperature for times of 4, 8, 16 and 50 weeks, it was observed that concretes with 15% GGBFS and 25% FA are have superior protection against acid attack than concretes with OPC and 40% FA. The change in weight at the end of 50th week is approximately 8%. The weak resistance of concrete with OPC against H_2SO_4 attack is due to the presence of large pores and free $Ca(OH)_2$ in the concrete. The concrete with 40% FA is also poorly resistant to H_2SO_4 attack at an early age. The reason is that there are numerous un-hydrated FA particles in the concrete, and the matrix is significantly porous at an early age. Furthermore, the amount of C-S-H gel in the concrete with 40% FA formed by cement hydration is less than the amount of C-S-H in concretes with OPC or with FA and slag (Bilim, 2006).

10.4.7 Alkali–silica reaction

The replacement of GGBFS with some cement can reduce the amount of alkali. There are several alternative solutions to reduce the destruction deriving from the ASR risk such as constraining the alkali content of the concrete, use of GGBFS or FA, use of low-alkali cement and use of non-reactive aggregate. Kwon (2005), in his study with high-strength concrete (HSC) of 500 kg/m^3 cement, found that for ASR, the overdose alkali content in HSC is a disadvantage and that harmful volume expansions are not observed in concrete if aggregate is used which is non-reactive due to chemical methods and mortars. On the other hand, it is reported that the use of low-alkali cement or 30% GGBFS instead of OPC will avoid the expansions caused by ASR: an increase of approximately between 1.0 and 1.7 kg/m^3 is observed in the alkali content of the concrete with a replacement rate of

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30%. Finally, increased slag fineness is effective in avoiding ASR (Bilim, 2006).

10.4.8 De-icing salt scaling resistance

Richardson (2006) has studied carbonation effects with regard to carbonation depth and rate on porosity, permeability, available calcium hydroxide and carbonation final products. It has been reported in many cases that slag concrete can have high frost resistance, if properly air entrained. However, the resistance to salt scaling of concrete with high (greater than 60%) slag contents cannot be improved by proper air entrainment alone.

10.4.9 Durability of high- and low-temperature effect

By use of GGBFS in concrete, the resistance of the concrete under high temperatures increases as a result of pozzolanic activity of the slag. Poon et al. (2001) exposed high-strength concretes including SF, FA and GGBFS to different temperature conditions maximally to 800 °C. According to experimental results, the concrete with FA and GGBFS, especially under 600 °C showed the best performance compared to control concrete. In previous studies, it was found that the resistance of the concrete with 40% GGBFS and exposed to 200 °C high temperature increased at a rate of 15% in comparison to those tested under room conditions. While the remaining resistance of the concrete with 40% under 400, 600 and 800 °C is 100%, 61 and 29%, the resistance of the controlled concrete is 89, 58 and 24%.

An earlier work on the performance of slag cement at elevated temperatures was done by Grainger (1980). He tested four cement pastes containing 0%, 50%, 70% and 90% replacement of slag by weight with OPC. The maximum tested temperature was 500 °C with an interval of 100 °C. All slag-cement paste specimens experienced an increase in strength between 100 and 250 °C. The 70% slag replacement showed the best results with a residual compressive strength of 190% of the original strength at 110 °C. Moreover, the residual strength of this paste was higher at all temperatures than the original strength. The other two slag-cement paste specimens also showed better residual strengths than the pure cement paste specimen. Sarshar and Khoury (1993) prepared cement paste and concrete specimens incorporating 65% slag by weight of cement and firebrick aggregates. The results were compared with pure OPC cement paste/concrete and 30% pulverized fuel ash (PFA) cement paste. The maximum temperature was 700 °C, while the residual properties were measured at every 100 °C interval. They found that the slag-cement paste and concrete gave the best results among all the specimens tested. The residual compressive strengths of slag concrete were 102% and 80% of the initial cold strength at 450 and 600 °C.

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10.4.10 Abrasion durability

The abrasion durability of concrete with GGBFS increases by applying the suitable and sufficient cure. While the insufficient cure conditions decrease the abrasion durability to a large extent, slag concrete is affected from that more than concrete with OPC. In their study on abrasion durability and its mechanical features, Fernandez and Malhotra (1990) reported that the strength development of slag concrete indicates the partial usage of GGBFS instead of cement in concrete; however the abrasion durability of slag concrete is lower than that of control concrete without slag. Provided that suitable and sufficient cure is applied, the use of GGBFS in concrete provides some advantage in abrasion durability (Newman and Choo, 2003).

For 28 days and above, to add 50–60% GGBFS to concrete results in higher resistance, whereas to add GGBFS over 80% results in lower resistance. It is understood that to obtain the maximum resistance, the optimum GGBFS rate is 40–60%. The more vitreous content, fineness and alkali content of GGBFS and greater fineness and alkali content of OPC used together will improve the strength development. Using GGBFS up to 80% can increase the resistance to 28 MPa. Therefore, it will be useful to prepare specifications for mixture design and regulations concentrated on the factory operating requirements for high-volume GGBFS and real expectations from the concrete. Hence, more qualified concrete will be obtained regarding workability, resistance and strength, as well as more economic concrete by waste reduction. At the same time air pollution could be reduced.

10.5 Future trends

The following are the types of concrete that are expected to be used in the concrete production applications of today and in the future, as the results of the studies described above:

- *Self-compacting concrete*: Self-compacting concrete (SCC), which is developed especially to be used in structures with dense reinforcement at the end of the 1980s in Japan, has a perfect workability and high resistance to segregation. SCC can easily furnish itself to the dense reinforced areas without using any vibration. The fresh SSC can be defined as a concrete which has the ability to fill the mulding and hold the reinforcement by means of its own weight, while maintaining homogeneity. There are positive effects of GGBFS used instead of cement on cost, and hydration will improve the strength feature of the concrete (Yalçınkaya and Yazıcı, 2010).
- *Roller compacted concrete*: Roller compacted concrete (RCC) is a low-viscosity concrete which is laid in plates before hardening. It is able to carry at least 5 tonnes of roller in order to be compacted. RCC is economic

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because of its very low cement content. This small amount of cement in RCC brings about a decrease in hydration heat. Hence, RCC is not used for mass concrete constructions such as barrages. Karimpour (2010) examined the effects of the interval between mixing and compacting in RCC including high-volume GGBFS. For mixture with 0, 25, 50 and 75% of GGBFS, he observed that the interval between mixing and compacting mainly influences the compressive strength with increasing amounts of GGBFS. According to Karimpour, the increased distance between cement granules because of increased amount of GGBFS is the reason of this. For RCC, concrete without sedimentation is produced.

- *Non-slump concrete*: Togawka and Nakamoto (1992) noted that up to 30% GGBFS used instead of fine aggregate is useful for the compacting and compressive strength of RCC; the surface area of the GGBFS affects the development of strength. They added that larger surface area at early ages and smaller surface area at late ages show higher strength. They also mentioned that the GGBFS with small surface area is more effective at reducing the temperature of concrete.
- *Reactive powder concrete*: Yazıcı et al. (2008) mentioned that for reactive powder concretes with 20, 40 and 60% GGBFS even at 40 and 60%, they obtained compressive strength over 200 MPa. Yazıcı et al. (2010) used concrete with 20, 40 and 60% GGBFS and applied standard, steam and autoclave cure. They obtained compressive strength over 250 MPa in concrete that had autoclave cure with 20% GGBFS addition. In the presence of external pressure, they observed that the compressive strength up to 400 MPa. With the addition of 40 and 60% GGBFS they reached strengths of 210 and 254 MPa by standard cure in 90 days, obtaining 33.2 MPa of flexural strength, 6161 N/m of fractural energy and 17 210 N mm of toughness value and approximately the same results with autoclave cure.
- *Lightweight concrete*: Arreshvhina et al. (2006) observed that compressive strength in aerated concrete with GGBFS addition increases at a rate of 8–63% depending on the cure conditions. Adding a high volume of GGBFS improves compressive strength in aerated concretes and contributes to a better microstructure formation.
- *Ungrounded BFS*: Yüksel and Genç (2007) mentioned that, for concretes in which they use 10, 20, 30, 40, 50% of GBFS and BA (bottom ash) as aggregate, by increasing replacement rates, the resistance of the concrete decreases. BA gives rise to a greater reduction in resistance than GGBFS does and replacement over 40% is more effective. Yüksel et al. (2007) explored the resistance of concrete prepared by industrial waste such as polypropylene fibre, GBFS and BA as fine aggregate towards 800 °C high temperatures. They showed how it is possible to use these wastes with a ratio of 50% of aggregate which covers 30% volume of the concrete.

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Topçu and Bilir (2010), in their studies on shrinkage done by GBFS as fine aggregate, determined that by increasing the GBFS rate, there is a decrease in shrinkage cracks. The reason of this is the gap form related to GBFS structure and, linked with the same reason, flexural strength, compressive strength and modulus of elasticity decrease.

- *Alkali-activated slags*: By means of the activation of GGBFS with alkalis such as NaOH, $NaCO_3$ and $NaSiO_3$ super-qualified concrete can be produced. Topçu and Canbaz (2008) found that alkali-activated mortar with GGBFS does not exceed the danger limit in ASR.

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