

WHAT IS SLAG CEMENT?

Slag cement, or ground granulated blast-furnace slag (GGBFS), has been used in concrete projects in the United States for over a century. Earlier usage of slag cement in Europe and elsewhere demonstrates that long-term performance is enhanced in many ways. Based on these early experiences, modern designers have found that these improved durability characteristics help further reduce life-cycle costs and lower maintenance costs.

Using slag cement to replace a portion of portland cement in a concrete mixture is a useful method to make concrete better and more consistent. Among the measurable improvements are:

- Better concrete workability
- Easier finishability
- Higher compressive and flexural strengths
- Lower permeability
- Improved resistance to aggressive chemicals
- More consistent plastic and hardened properties
- Lighter color

When iron is manufactured using a blast furnace, the furnace is continuously charged from the top with oxides, fluxing material, and fuel. Two products—slag and iron—collect in the bottom of the hearth. Molten slag floats on top of the molten iron; both are tapped separately.

The molten iron is sent to the steel producing facility, while the molten slag is diverted to a granulator. This process,



known as granulation, is the rapid quenching with water of the molten slag into a raw material called granules. Rapid cooling prohibits the formation of crystals and forms glassy, non-metallic, silicates and aluminosilicates of calcium.



These granules are dried and then ground to a suitable fineness, the result of which is slag cement. The granules can also be incorporated as an ingredient in the manufacture of blended portland cement.



Granulated Slag



Slag Cement

SLAG CEMENT

RELEVANT TERMINOLOGY

Ground granulated blast-furnace slag (GGBFS): A hydraulic cement formed when granulated blast-furnace slag is ground to a suitable fineness. Commonly referred to as slag cement, or GGBFS.

Hydraulic cement: A cement that sets and hardens by chemical interaction with water and is capable of doing so under water.

Blast-furnace slag: The non-metallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace.

Granulated blast-furnace slag: The glassy, granular material formed when molten blast-furnace slag is rapidly chilled by immersion in water. Also referred to as granules.

Portland cement: A hydraulic cement produced by pulverizing portland-cement clinker, usually containing calcium sulfate.

Blended cement: A hydraulic cement produced by intergrinding portland cement clinker with other materials, or by blending portland cement with other materials, or by a combination of intergrinding and blending.

Portland blast-furnace slag cement: A blended cement consisting of an intimately interground mixture of portland cement clinker and granulated blast-furnace slag, or an intimate and uniform blend of portland cement and fine granulated blast-furnace slag in which the amount of the slag constituent is within specified limits.

Air-cooled blast-furnace slag: The material resulting from the solidification of molten blast-furnace slag under atmospheric conditions. Subsequent cooling may be accelerated by application of water to the solidified surface. (This material can be mined and crushed for use as aggregates in concrete or fill material; it is not cementitious).

Expanded blast-furnace slag: The light-weight cellular material obtained by controlled processing of molten blast-furnace slag with water, or water and other agents, such as steam or compressed air, or both. (This is commonly used as lightweight aggregate; it is not cementitious).

References

1. ACI 116R-00, *Cement and Concrete Terminology*, American Concrete Institute, Farmington Hills, Michigan, 2000.
2. ACI 233R-95, *Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete*; American Concrete Institute, Farmington Hills, Michigan, 1995.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920

e-mail:

info@slagcement.org

web:

www.slagcement.org

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The proportion of slag cement used is usually dictated by requirements of the desired properties of the concrete.

Concrete mixtures containing slag cement should be proportioned according to ACI 211.1.

WHAT IS CONCRETE PROPORTIONING?

Concrete proportioning is the selection of proportions of ingredients to make the most economical use of available materials to produce concrete of the required properties.

WHY USE SLAG CEMENT IN CONCRETE?

In concrete, slag cement may be proportioned from 20 to 80 percent depending on the application. It is substituted for portland cement on a one-to-one basis by mass. The proportion of slag cement used is usually dictated by requirements for strength, durability, time of set, heat generation, or the resistance of the concrete mixture to alkali silica reaction (ASR) and sulfate attack. The range of replacement rates for various applications are shown in Table 1, though specific replacement rates will vary with the particular circumstances.

PROPORTIONING CONCRETE WITH SLAG CEMENT

Concrete mixtures containing slag cement should be proportioned according to ACI 211.1. The specific gravity of slag cement ranges from 2.85 to 2.94, depending on the slag source, as compared to 3.15 for portland cement. The difference in specific gravity means a greater volume of slag cement will be used to replace the same mass of portland cement. The larger percentage of fines usually provides mixtures that are easier to place, finish and consolidate. A higher percentage of coarse aggregate can be used to increase strength and reduce water demand without affecting plastic properties.

In general, water demand for any given slump may be reduced up to five percent. Slag cement should always be included when calculating the water-cementitious material ratio.

Slag cement is compatible with chemical admixtures regularly used in concrete. The effects of chemical admixtures in concrete containing slag cement are similar to their effects in ordinary portland cement concrete. Trial batches will determine proper admixture dosages. Slag cement does not contain carbon and therefore should not cause fluctuations in air content. Slag cement is also compatible with pozzolans such as fly ash or silica fume.

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CONCRETE PROPORTIONING

Table 1

Concrete Application	Slag Cement
Concrete paving	25-50%
Exterior flatwork not exposed to deicer salts	25-50%
Exterior flatwork exposed to deicer salts with w/cm \leq 0.45	25-50%
Interior flatwork	25-50%
Basement floors	25-50%
Footings	30-65%
Walls & columns	25-50%
Tilt-up panels	25-50%
Pre-stressed concrete	20-50%
Pre-cast concrete	20-50%
Concrete blocks	20-50%
Concrete pavers	20-50%
High strength	25-50%
ASR mitigation	25-70%
Sulfate resistance	
Type II equivalence	25-50%
Type V equivalence	50-65%
Lower permeability	25-65%
Mass concrete	50-80%

Percentages indicate replacement for portland cement by mass. These replacement rates are suggested for individual applications and are based on historical performance. Variations in material sources and environmental conditions may require alternate substitution rates. Consult your slag cement supplier for additional assistance.

The percentage of slag cement to use for maximum strength development is usually between 40 and 50 percent. This is also normally the optimum percentage to

Reference

1. ACI 211. 1-91, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*; American Concrete Institute, Farmington Hills, Michigan, 1991.

use in concrete to provide the lowest permeability to the ingress of aggressive solutions and greatest resistance to ASR and sulfate attack. Slag cement used at replacement rates greater than 25 percent can cause an increase in time of set.

The lower heat evolution characteristic of slag cement in the summer is beneficial because it allows more time for placing and finishing concrete. In the winter, increased time of set, occurring with higher percentages of slag cement, can be offset by use of chemical admixtures or heated materials.

RE-PROPORTIONING MIXTURES WITH SLAG CEMENT

Most producers have a selection of mixtures already in use. A simple way to incorporate slag cement is to select a conventional mixture that has demonstrated a satisfactory performance level, based on criteria such as compressive strength, flexural strength, or permeability. Trial batches of equivalent mixtures containing slag cement at various levels should be evaluated for the desired performance characteristics (Table 1).

Trial batches should be performed to verify concrete properties.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org

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Concrete sets and hardens as a result of a chemical reaction called hydration.

Set characteristics of concrete are influenced by a wide variety of factors.

WHAT IS TIME OF SET?

Time of set is defined as the point in time at which penetration resistance reaches specified values. ASTM C 403 identifies initial and final time of set as:

Penetration resistance	
Initial Time of Set	500 psi
Final Time of Set	4000 psi

Typically to a concrete contractor, initial time of set refers to the time at which a concrete surface can bear the weight of an individual with minimal indentation.

When water comes into contact with hydraulic cement, a chemical reaction called hydration occurs. This reaction



combines water with cement forming chemical compounds, increasing the strength of the material and changing it from a plastic, moldable material to a solid capable of withstanding substantial loads.

WHY IS TIME OF SET SIGNIFICANT?

Initial and final set times are important because they give an indication of when the concrete can be properly placed, consolidated and finished.

WHAT INFLUENCES TIME OF SET?

Among other things, the initial and final time of set are influenced by:

- Cementitious material chemistry
- Cementitious material fineness
- Cementitious material content
- Water to cementitious materials ratio
- Concrete and ambient temperatures
- Admixture types
- Fly ash and pozzolan properties



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CONCRETE TIME OF SET

HOW DOES SLAG CEMENT AFFECT TIME OF SET?

At temperatures less than 85 degrees Fahrenheit, concrete containing slag cement can have longer times of set, when compared with 100 percent portland cement concrete. The lower the ambient and/or concrete temperatures, the slower the set times will be (Figure 1). The percentage of slag cement used can also affect times of set. However, replacement rates of less than 30 percent generally will not affect times of set significantly. Slower times of set are beneficial in hot weather because the contractor has a longer time to deliver, place, and finish the concrete. If times of set need to be reduced, accelerators, heated materials or reduced slag cement content may be used (Figure 2).

Figure 1: Effect of Temperature on Initial Time of Set

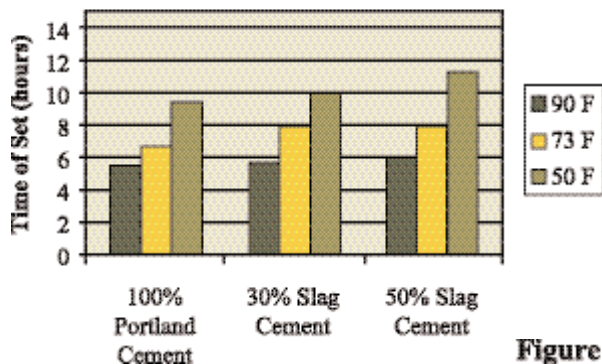
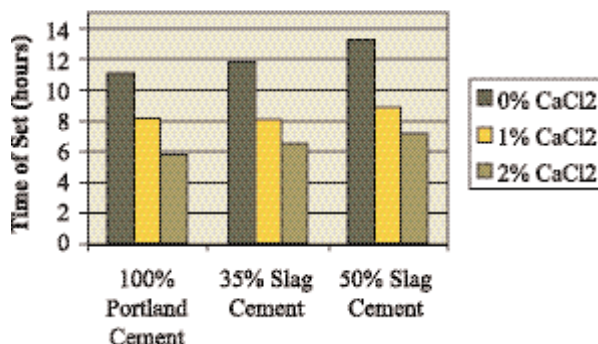


Figure 2: Effect of Accelerators on Initial Time of Set



Reference

1. C403/C403M-99, *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*, American Society for Testing and Materials, West Conshohocken, PA, 2001.

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Slower times of set are often beneficial because the contractor has a longer time to deliver, place and finish the concrete.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org



Saw-cut joints are an effective way to control cracking due to shrinkage.

Joints need to be cut before internal stresses in the concrete become great enough to initiate a crack.

WHAT ARE SAW CUTS?

Saw cuts are a means of creating joints in concrete. Joints are an effective way to control cracking due to shrinkage. Joints are installed at prescribed intervals to determine where cracks occur.

Joints need to be cut after the concrete has achieved enough strength to keep it from raveling, but before internal stresses in the concrete become great enough to initiate a crack. The earlier the concrete can be cut without raveling, the better the chances are that the concrete will not crack before saw cutting.

The difficulty in correctly determining the earliest time for saw cutting is that it changes according to the type of admixtures in the concrete, the ambient temperature and environmental conditions at the site, the cementitious factor in the mix, the types and percentages of mineral admixtures used, and the type of aggregates used. An example of just how difficult it can be to correctly judge the right time for cutting joints is to consider a change in coarse aggregate from gravel to quartzite. A concrete mix with quartzite needs to achieve a compressive strength of nearly 800 psi more than a gravel mix before it can be safely saw cut!



SAW CUTTING JOINTS

HOW DOES SLAG CEMENT AFFECT SAW CUTTING?

When placing concrete manufactured with slag cement, it is important to remember that set times may be increased and early strength development may take longer. The higher the percentage of slag cement used and the lower the ambient temperature, the more pronounced these effects will be. In the summer, when moderate to high temperatures are the norm, mixtures containing up to 50 percent slag cement have been used with success. In colder seasons, the percentage of slag cement may need to be decreased in order to achieve the early strengths necessary to provide an adequate window for saw cutting.



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One method to eliminate the guesswork in the timing of cutting joints in any concrete is using an early entry saw. This method allows a much larger window for saw cutting concrete before the development of uncontrolled shrinkage cracks.

Whatever method is used, it is important for contractors to understand the materials they are using and how these materials will affect the correct time for saw cutting concrete joints. It is also important to understand how these mixes can be adjusted for different environmental conditions.

As a rough guideline, the time to saw cut is delayed approximately 30 minutes for every 10 percent of slag cement replacing portland cement. With colder mixture temperatures the delay may be longer. This delay can be adjusted through the use of accelerating admixtures, heated water or heated aggregates.

Reference

1. *Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements, Volume I: Final Report*; Federal Highway Administration, McLean, VA, 1994.

Early entry saws allow a much larger window for saw cutting concrete before the development of uncontrolled shrinkage cracks.



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Slag cement and portland cement are stored and batched in a similar manner.

Slag cement enhances the consolidation and pumping of concrete.

STORAGE AND HANDLING SLAG CEMENT

Slag cement, like portland cement, must be stored in bins or silos to provide protection from moisture and contamination. Since both slag cement and portland cement are delivered in the same type of container truck, care should be taken to distinguish one material from the other in storage and handling. One quick method of distinguishing between slag cement and portland cement is to compare their color. Slag cement is commonly lighter than portland cement. All handling equipment suitable for use with portland cement is also suitable for use with slag cement.



Figure 1: Concrete with slag cement is produced in a similar manner to concrete without slag cement.

BATCHING

Batching and mixing of concrete containing slag cement is similar to ordinary portland cement concrete. ACI 233 recommends that slag cement be batched following portland cement in the same weighing apparatus. The mixing time and the mixing equipment are the same.

TRANSPORTING

Like all other concrete, slag cement concrete can be transported by a variety of methods and equipment, most commonly, revolving-drum mixers.

PLACING

In some types of construction, concrete is placed in forms and then consolidated. Consolidation densifies fresh concrete within forms, and around embedded items and reinforcement; it also eliminates stone pockets, honeycombs, and entrapped air. Slag cement enhances the consolidation and pumping of concrete by improving its rheology. Although slag cement typically improves the placement characteristics of concrete, proper placing and finishing practices must be followed.

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PRODUCING AND PLACING SLAG CEMENT CONCRETE

FINISHING

Finishing refers to leveling, smoothing, consolidating and otherwise treating surfaces of fresh, plastic concrete to produce a desired surface or appearance. The finishing operation should be carefully planned. Skill, knowledge and experience are needed to properly finish concrete. The finisher must have the proper tools and equipment and adequate manpower. Proper timing of the operations for the existing conditions is critical. In warmer weather, the slower setting characteristics of slag cement concrete can be a benefit to the finisher by allowing sufficient time to complete each step in the finishing process. In cooler weather, finishing operations may need to be delayed due to the slower setting characteristics. Set times can be modified by the addition of chemical admixtures.



Figure 2: Finishing is usually enhanced with slag cement

Most concrete made with slag cement will have less bleed water than concrete made with portland cement alone. Bleeding rates are also usually slower. Virtually all slag cement used in the United States is ground finer than Type I or Type II cements. Coarser slag cements could have equal or greater bleeding.

CURING

As with all concrete, proper curing practices are essential to achieve the desired properties of concrete. All curing practices used with portland cement concrete are generally compatible when slag cement is used, such as wet curing with fog sprays or burlap, or concrete curing compound.



Figure 3: As with all concrete, proper curing practices are essential.

Slag cement can be a benefit to finishers in warm weather.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920

e-mail:

info@slagcement.org

web:

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Low permeability in reinforced concrete is important to maintain structural integrity.

Slag cement reduces concrete permeability.

CONCRETE PERMEABILITY

Permeability is a measure of how easy it is for water, air and other substances such as chloride ions to enter concrete. Concrete contains pores that allow these substances to enter. Larger pores allow easier entry, while smaller pores decrease the rate at which these substances enter the concrete.

A common way to measure permeability of concrete is standard test method ASTM C1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," also known as the rapid chloride permeability test. This method is the most accepted test to determine the relative permeability of concrete. A 60 V electrical potential is established across a sawed four inch diameter concrete cylinder section. The total current passing through the section over time and



Figure 1: Permeable concrete is a principal reason for concrete deterioration due to reinforcing steel corrosion and other deterioration mechanisms.

measured in Coulombs is reported as an indication of permeability. Lower Coulomb values indicate lower permeability. The permeability required is a function of the concrete application.

PERMEABILITY AND CHLORIDE INDUCED CORROSION

Low permeability concrete can help reduce the potential for reinforcing steel to corrode when exposed to chlorides by limiting the permeation of those chlorides into concrete. When reinforcing steel comes into contact with plastic concrete, a chemical reaction occurs between the steel and the concrete that causes a protective layer (a passive layer) to develop around the reinforcing steel. This passive layer protects against corrosion of the reinforcing steel. If the concrete is exposed to de-icing salts, these salts can migrate down to the reinforcing

steel through small pores in the concrete. Over time, the chlorides in these salts can react with the reinforcing steel, breaking down the passive layer and causing the steel to corrode. When reinforcing steel in concrete corrodes, the product of that corrosion (rust) takes up more volume than the original steel, and causes the concrete to crack. After cracks develop, the deterioration accelerates as chlorides are allowed easy ingress to the reinforcing steel. The deterioration of both the concrete and reinforcing steel compromises the integrity of the structure.

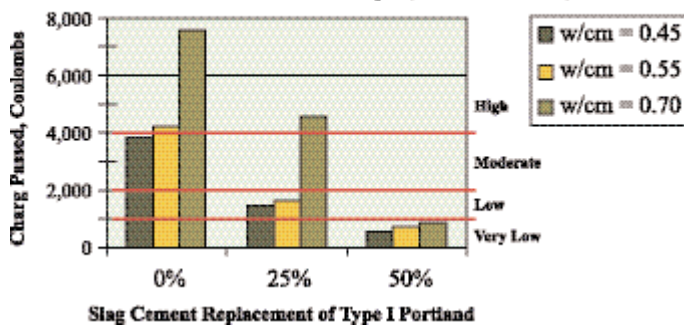
REDUCING PERMEABILITY

REDUCING PERMEABILITY WITH SLAG CEMENT

When portland cement hydrates, it forms calcium-silicate hydrate gel (CSH) and calcium hydroxide ($\text{Ca}(\text{OH})_2$). CSH is the "glue" that provides strength and holds the concrete together. Permeability is related to the proportion of CSH to $\text{Ca}(\text{OH})_2$ in the cement paste. The higher the proportion of CSH to $\text{Ca}(\text{OH})_2$, the lower the permeability of the concrete. When slag cement is used as part of the cementitious material in a concrete mixture, it reacts with $\text{Ca}(\text{OH})_2$ to form

additional CSH, which in turn lowers the permeability of the concrete. Generally, the higher the percentage of slag cement in a concrete mixture, the lower the permeability of the concrete. Concrete with lower permeability can generally be achieved by substituting between 25 to 65 percent slag cement for portland cement. Figure 2 shows the ability of a specific slag cement to reduce the permeability of concrete as measured by the rapid chloride permeability test.

Figure 2: Effect of Slag Cement on Concrete Chloride Ion Penetrability² (ASTM C1202)



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References

1. ASTM C1202-97 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, American Society for Testing and Materials, West Conshohocken, PA 2001.
2. Fernandez, J and Malhotra, V. M., "Mechanical Properties, Abrasion Resistance, and Chloride Permeability of Concrete Incorporating Granulated Blast-Furnace Slag," *Cement, Concrete and Aggregates*, CCAGDP, Vol. 12, No. 2, Winter 1990.

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Farmington Hills, MI 48331

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e-mail:

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web:

www.slagcement.org



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The use of slag cement is an extremely effective way of reducing the potential for sulfate attack.

Slag cement reduces the permeability of the paste and prevents the intrusion of aggressive sulfates.

WHAT IS SULFATE ATTACK?

Sulfate attack is a common form of concrete deterioration. It occurs when concrete comes in contact with water containing sulfates (SO_4). Sulfates can be found in some soils (especially when arid conditions exist), in seawater, and in wastewater treatment plants.

Waterborne sulfates react with hydration products of the tri-calcium aluminate



Figure 1: The Hap Cremeans water treatment plant in Columbus, OH used 30% slag cement with Type II portland cement to achieve sulfate resistance.

(C_3A) phase of portland cement, and with calcium hydroxide ($\text{Ca}(\text{OH})_2$) to form an expansive crystalline product called ettringite. Expansion due to ettringite formation causes tensile stresses to develop in the concrete. When these stresses become greater than the concrete's tensile capacity, the concrete begins to crack. These cracks allow easy ingress for more sulfates into the concrete and the deterioration accelerates. Sulfates also cause chemical disintegration of some of the cement hydration products.

Principal factors that affect the rate and severity of sulfate attack are:

1. Permeability of the concrete.
2. Concentration of sulfates in the waterborne solution.
3. C_3A content.
4. $\text{Ca}(\text{OH})_2$ content.

MITIGATING SULFATE ATTACK

One of the most common ways of protecting against sulfate attack is to reduce the alumina content by limiting the C_3A in portland cement. Historically, Type II portland cement (with C_3A between 5 and 8 percent) and Type V portland cement

(with C_3A less than 5 percent) have been specified for moderate and severe sulfate environments, respectively. The use of slag cement is also an extremely effective way of reducing the potential for sulfate attack¹.

HOW DOES SLAG CEMENT MITIGATE SULFATE ATTACK?

The use of slag cement reduces the likelihood of sulfate attack in three ways:

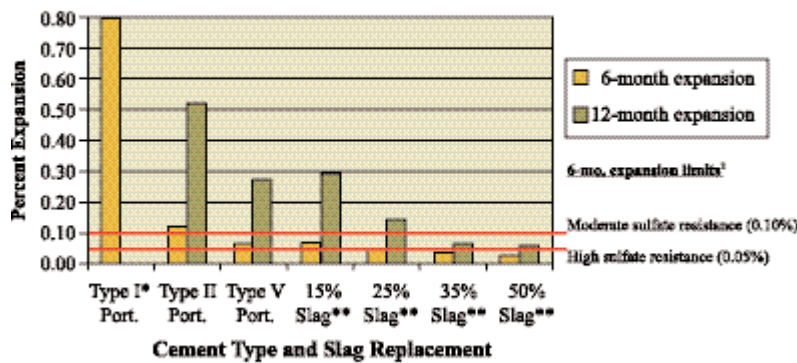
1. Slag cement does not contain C_3A , so its addition in concrete dilutes the total amount of C_3A in the system.
2. Slag cement reduces concrete permeability, making it harder for sulfates to penetrate into concrete.
3. Slag cement reacts with excess $\text{Ca}(\text{OH})_2$ to form additional calcium-silicate hydrate gel (the "glue" that provides strength and holds the concrete together). This decreases the total amount of $\text{Ca}(\text{OH})_2$ in the system.

MITIGATING SULFATE ATTACK

Used in the proper proportions, slag cement can give a Type I cement the sulfate resisting properties of a Type II cement (usually 25 to 50 percent slag cement replacement for portland), and it can give a Type I or a Type II cement the sulfate resisting properties of a Type V cement (usually 50 to 65 percent slag cement replacement for portland).

The sulfate resistance of Type I, II and V portland cements compared with a portland-slag cement combinations, tested in accordance to ASTM C1012, is shown in Figure 2. For this combination of materials, 15 and 25 percent slag cement replacement achieved moderate sulfate resistance, and 35 and 50 percent achieved high sulfate resistance, based on ASTM C989 six month expansion limits.

Figure 2: Effect of Cement Type and Slag Cement Replacement on Sulfate Resistance (ASTM C1012)



*Type I sample failed at 244 days
 **Slag cement combined with Type I portland

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References

1. ACI 201.2R-92, *Guide to Durable Concrete*; American Concrete Institute, Farmington Hills, Michigan, 1992.
2. ASTM C1012-95a, *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*, American Society for Testing and Materials, West Conshohocken, PA, 2001.
3. ASTM C989-99, *Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars*, American Society for Testing and Materials, West Conshohocken, PA, 2001.

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phone: 847.977.6920
 e-mail: info@slagcement.org
 web: www.slagcement.org



The best way to mitigate ASR is to prevent its occurrence through the proper use of materials in the concrete mixture.

Slag cement reduces the amount of alkali in the system that is available for reaction with the aggregate.

WHAT IS ALKALI-SILICA REACTION?

Alkali-silica reaction (ASR) is a chemical reaction between the alkalis in portland cement and certain types of silica minerals present in some aggregates.



Fig. 1: ASR causes expansion and cracking of concrete structures and pavements

MITIGATING ASR

It is very difficult, if not impossible, to halt the ASR reaction once it begins. It may be possible in some instances to limit the ingress of water into the concrete, but this will only slow down rather than stop the progress of deterioration. The best way to mitigate ASR is to prevent its occurrence through the proper use of materials in the concrete mixture. There are several ways to mitigate ASR. One option is to

The reaction product is a hygroscopic gel, which absorbs moisture and swells. Under certain circumstances, the formation of the gel can cause expansion and, eventually, cracking of the concrete. Factors that affect the rate and severity of ASR include:

- The reactivity of the aggregate (amount and type of reactive silica minerals present).
- The availability of alkalis in the concrete.
- The exposure conditions (moisture availability and temperature).
- The type of concrete element (size and reinforcement details).

In some cases, ASR may cause severe concrete deterioration, leading to a loss in serviceability or rendering the concrete more susceptible to damage by other processes, such as freezing-and-thawing or chloride ingress and corrosion.

HOW DOES SLAG CEMENT MITIGATE ASR?

The use of slag cement will reduce the potential of ASR occurring by reducing the amount of alkali in the system that is available for reaction with the aggregate. A greater proportion of the alkalis are bound by the hydration products of slag cement compared with portland cement and this means that the alkali concentration in the concrete pore solution is reduced which, in turn, reduces the risk of reaction with the aggregate. The amount of slag required will depend on the reactivity of the aggregate and the alkali contributed by the portland cement; typically the level needed ranges from 30 to 60% by mass of total cementitious material. Figure 2² shows the impact of slag on the 2-year expansion of concrete prisms (ASTM C1293) containing moderately to highly reactive aggregates and cement with a very high alkali content (1.25% Na₂O equivalent).

The amount of slag required with a particular reactive aggregate can be determined by testing various slag-aggregate combinations in the accelerated mortar-bar test (ASTM C1567)³ or the concrete prism test

limit the alkali content of the concrete by minimizing the amount of alkali contributed by the portland cement. Another solution is to limit or prohibit the use of reactive aggregates. It is often impractical to specify either of these options if suitable materials (low-alkali cements or nonreactive aggregates) are not available. Another alternative is to specify slag cement to prevent ASR when reactive aggregates are used.¹

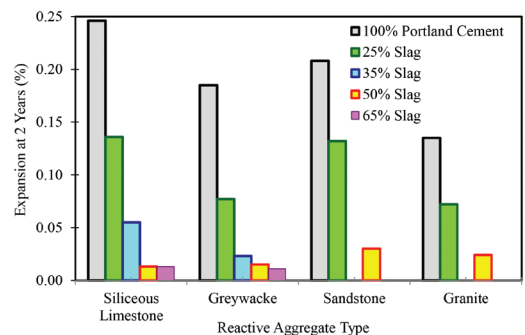


Fig. 2: Effect of slag on the expansion of concrete containing reactive aggregate²

(ASTM C1293).⁴ Alternatively, the prescriptive approach of AASHTO PP65-11⁵ can be used. In this standard practice, the minimum level of slag is determined by consideration of aggregate reactivity, alkali availability, the exposure conditions, and the size and type of the concrete structure.

ALKALIS IN SLAG CEMENT AND ASR

Slag cement contains a small amount of alkalis. Typically, the amount of alkali is similar to that of low-to-moderate-alkali portland cement (for example, 0.5 to 0.7% Na₂O equivalent). Some guide specifications and standard practices, such as AASHTO PP65-11,⁵ allow the option of limiting the alkali content of concrete when reactive aggregates are used. In such cases, it is not necessary to include the alkalis in the slag in the calculation of the concrete alkali content, as they are generally considered to be unavailable for reaction with the aggregate.²

Figure 3 shows the alkali concentration (expressed in terms of hydroxyl ion, OH⁻, concentration) of the pore solution extracted from 2-year-old cement paste samples produced with high-alkali cement and various levels of slag.⁶ The slag reduces the concentration of the hydroxyl ions beyond that expected from mere

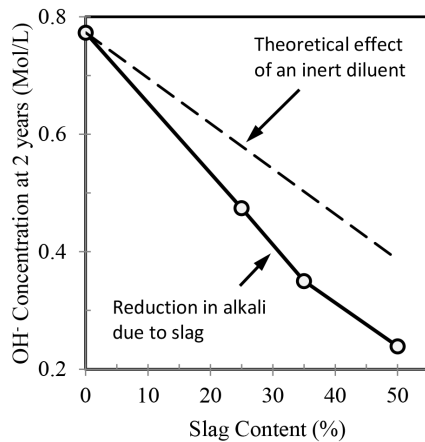


Fig. 3: Effect of slag on pore solution alkalinity

dilution of the portland cement. This means that slag does not contribute its alkalis to the pore solution but actually removes some of the alkalis provided by the portland cement. These alkalis will not be available for reaction with the aggregate.

Figure 4 shows the expansion of concrete prisms at 2 years plotted against the alkali content of the concrete considering only the alkalis provided by the portland cement.⁶ It can be seen that for a given amount of portland cement alkalis the expansion is reduced in the presence of slag, especially at higher levels of replacement. This again indicates that rather than contributing alkali to the ASR slag effectively consumes some of the alkalis provided by the portland cement so that they are not available to react with the aggregate.

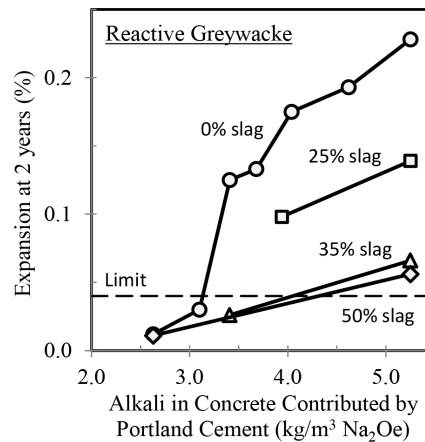


Fig. 4: Effect of alkali contributed by portland cement on expansion of slag cement concrete (1 kg/m³ = 1.686 lb/yd³)

References

1. ACI 201.2R-08, "Guide to Durable Concrete," American Concrete Institute, Farmington Hills, MI, 2008, 49 pp.
2. Thomas, M. D. A., and Innis, F. A., "Effect of Slag on Expansion due to Alkali-Aggregate Reaction in Concrete," *ACI Materials Journal*, V. 95, No. 6, Nov.-Dec. 1998, pp. 716-724.
3. ASTM C1567-13, "Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)," ASTM International, West Conshohocken, PA, 2013.
4. ASTM C1293-8b, "Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction," ASTM International, West Conshohocken, PA, 2008.
5. AASHTO PP65-11, "Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction," American Association of State Highway and Transportation Officials, Washington, DC, 2011, 24 pp.
6. Bleszynski, R. F., "The Performance and Durability of Concrete with Ternary Blends of Silica Fume and Blast-Furnace Slag." PhD thesis, University of Toronto, Toronto, ON, Canada, 2002, 1074 pp.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

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The amount of slag required with a particular reactive aggregate can be determined by testing various slag-aggregate combinations in the accelerated mortar-bar test (ASTM C1567)³ or the concrete prism test (ASTM C1293).⁴ Alternatively, the prescriptive approach of AASHTO PP65-11⁵ can be used.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone:
847-977-6920

e-mail:
info@slagcement.org

Web:
www.slagcement.org

High thermal stresses in mass concrete can result in cracking and loss of structural integrity.

When slag cement is incorporated in a concrete mixture, less heat is generated and thermal stress is reduced.

WHAT IS MASS CONCRETE?

According to ACI 207, “**mass concrete** is any large volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change to minimize cracking.” Cement hydration generates heat. Heat dissipates from concrete slowly; the thicker the section, the longer it will take the interior to cool. This can result in large temperature differentials between the concrete surface and its interior. The concrete is then subject to high thermal stresses, which can result in cracking and loss of structural integrity.

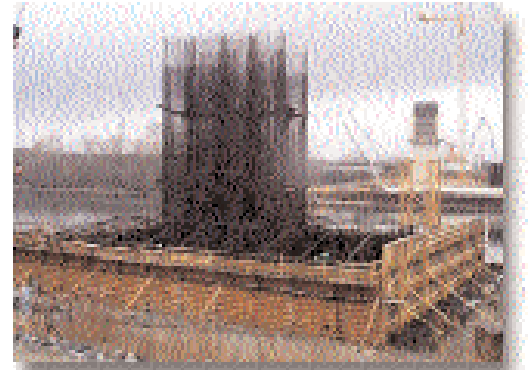


Figure 1: The 16-foot thick footings on the Pocahontas Parkway in Virginia used 75% slag cement with Type II portland cement to reduce concrete peak and differential temperatures.

REDUCING THERMAL STRESS

There are three generally accepted strategies for reducing thermal stress in concrete:

- Reduce the total cementitious content
- Reduce the portland cement content
- Slow down the hydration process through the use of various admixtures or cooling the concrete.

HOW DOES SLAG CEMENT HELP?

When slag cement is incorporated in a concrete mixture, less heat is generated and thermal stress is reduced:

- Due to increased strength with slag cement, the total cementitious content can be reduced
- Portland cement content is reduced by the percentage of slag cement used
- Hydration characteristics of slag cement are such that the early rate of heat generation and peak temperature of the concrete are reduced.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

REDUCING THERMAL STRESS IN MASS CONCRETE

SLAG REPLACEMENT LEVELS

Generally 65 to 80 percent is considered an optimum replacement range for mass concrete applications. These levels typically provide significant heat reduction while achieving desired strengths. Levels from 50 to 65 percent have been used successfully in smaller mass concrete placements. Mixtures should be tested with job materials to ensure required thermal and strength characteristics.

Figure 2 shows the specific heat of hydration of an ordinary portland cement and combinations from 25 to 75 percent slag cement substitution. Note that each increasing level of slag cement reduces peak heat of hydration of the

binder. More importantly, the area under each curve represents total heat generated. This area reduces dramatically when the substitution rate increases from 50 to 75 percent, indicating that significantly less total heat is generated for 75 percent slag cement, even though the peak heat of hydration is not much reduced from 50 percent substitution.

Figure 3 shows the effect of slag cement on temperature rise in mass concrete. Note that peak temperature dropped by 19 degrees F with 65 percent slag cement substitution, and by 42 degrees F for 80% substitution.

Figure 2: Effect of Slag Cement on Heat of Hydration

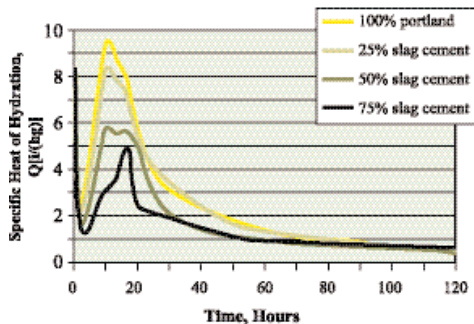
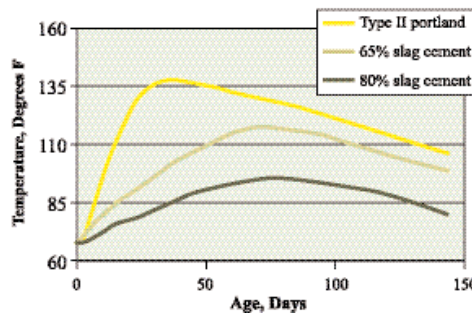


Figure 3: Effect of Slag Cement on Temperature Rise in Mass Concrete



Reference

1. ACI 207.1R-97, *Mass Concrete*; Concrete Institute, Farmington Hills, Michigan, 1992.

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65 to 80 percent is considered an optimum replacement range for mass concrete applications.



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38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org



Greening does not affect concrete performance.

WHAT IS “GREENING?”

Hardened concrete containing slag cement may show mottled green or blue-green areas on the surface in the first few days after placement. This temporary condition is commonly called “greening.”

WHAT CAUSES GREENING?

The blue-green color is attributed to a complex reaction of sulfide sulphur in slag cement with other compounds in portland cement. The degree and extent of the coloration depends on the rate of oxidation, the percentage of slag used, curing conditions and the porosity of the concrete surfaces. Surface greening



Figure 1: Greening occurred in concrete made with slag cement after forms were removed on the Canadian Chancery in Washington, D.C.

occurs in only a small percentage of concrete made with slag cement. However, the interior of the concrete may remain blue-green indefinitely.

GREENING AND CONCRETE PERFORMANCE

Greening does not affect concrete performance. The desired hardened concrete properties, such as strength, lower permeability and durability are not compromised if greening occurs.



Figure 2: Exposure to sunlight and air allowed the concrete surface at the Canadian Chancery to oxidize and lighten.

Greening does not need to be treated.

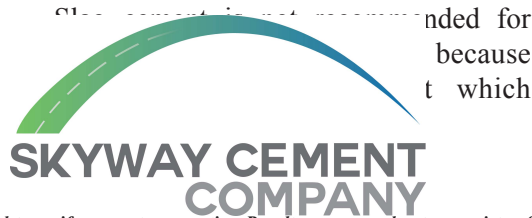
GREENING

HOW LONG DOES GREENING LAST?

In most concrete made with slag cement, the surface becomes light gray or white within hours after the concrete surface has been exposed to direct sunlight and air. If greening does occur, it usually appears within a week of concrete placement and typically disappears within a week, after oxidation starts.

Surface greening diminishes as oxidation progresses and does not need to be treated. Typically, surfaces showing greening will mature to a uniform light gray or white appearance. Some factors

that may cause slower oxidation rates include: extended wet curing, wet weather, cold weather, shade, continuously moist, dark environments, sealed surfaces, and/or a steel-troweled, burnished, or otherwise densified surface. It is uncommon for greening to persist after a week of exposure to dry air and sunlight.



As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture conditions. Nothing contained herein shall be construed as a warranty of fitness for a particular purpose.



Greening typically disappears within a week of initial appearance.

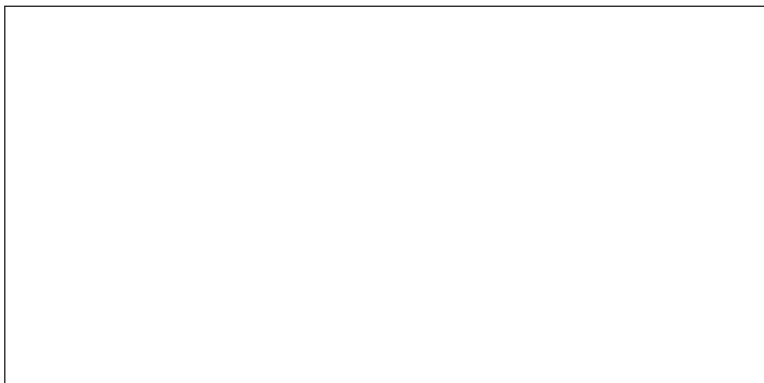


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Slag cement is the co-product of a controlled process, iron production, which results in a very uniform composition from source to source.

Slag cement does not contain carbon and does not cause instability in the entrained air content.

SUPPLEMENTARY CEMENTITIOUS MATERIALS

Modern concrete often includes the use of supplementary cementitious materials (SCM). These materials are often co-products of other processes or natural materials. Some require further processing before they are suitable for concrete. Some of these materials have cementitious properties when used alone; others, called pozzolans, do not.

COMPOSITION AND CONSISTENCY

Slag cement and fly ash are the two most common SCMs used in concrete. Most concrete produced today includes one or both of these materials. For this reason their properties are frequently compared to each other by mix designers seeking to optimize concrete mixtures.

While chemical similarities exist, these materials have different effects on concrete. These differences are based in part on the proportion of oxides in each material (Table 1).

Table 1: Typical Chemical Oxides for Various Cementitious Materials

	Portland Cement	Slag Cement	Fly Ash C	Fly Ash F
CaO	65	45	25	3
SiO ₂	20	33	37	58
Al ₂ O ₃	4	10	16	20
Fe ₂ O ₃	3	1	7	10
MgO	3	6	7	1

The ternary diagram, shown in Figure 1 shows that slag cement is more closely related to portland cement than fly ash. This is one reason why slag cement can be used in much larger amounts. Both are used as a replacement for a portion of the portland cement. Slag cement replaces as much as 50 percent in normal concrete (and up to 80 percent in special applications such as mass concrete). Fly ash is usually limited to 20 or 30 percent.

Slag cement is the co-product of a controlled process, iron production, which results in a very uniform composition from source to source. Fly ash is a byproduct of electric power generation that varies from source to source.

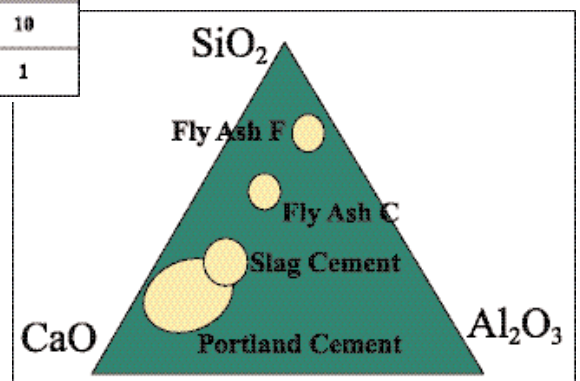


Figure 1: Ternary diagram of cementitious materials

SLAG CEMENT AND FLY ASH

Concrete Properties

Slag cement is a more uniform product than fly ash. As a result, concrete made with slag cement will generally have more uniform properties than concrete made with fly ash.

Plastic Properties

Water Reduction. The use of either material should result in a reduction of the required water content to reach a given consistency. This effect with slag cement is due to its influence on paste characteristics and absorption. With fly ash, this is primarily due to the particle shape and size distribution. This allows for small reductions in water reducing admixtures.

Air Entrainment. Air contents can vary depending on any number of factors. Carbon content variability in fly ash is one of the major causes of fluctuating air contents. Slag cement does not contain carbon and does not cause instability in the entrained air content.

Time of Set. Time of initial set is influenced by the use of slag cement and fly ash. Concrete made with slag cement can have faster set times than concrete made with fly ash (Figure 2).

Pumpability and Finishability. Pumpability with slag cement and fly ash is generally improved largely due to the addition of fines to the matrix. Finishability is also improved.

Hardened Properties

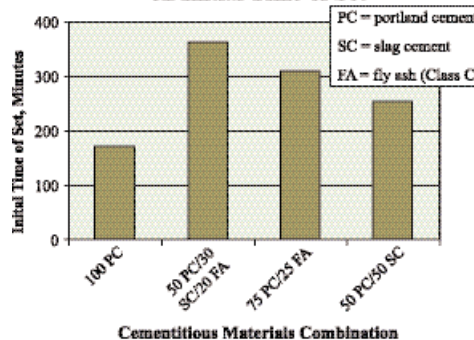
Strength. At 28 days, both slag cement and Class C fly ash will achieve higher strength than Class F fly ash and straight portland cement in concrete mixtures.

Permeability. At normally specified replacement levels, concrete made with slag cement will have lower permeability than concrete made with Class F or C fly ash when tested according to ASTM 1206 (rapid chloride permeability test).

Sulfate Attack and Alkali-Silica Reaction (ASR). Slag cement and Class F fly ash will both provide protection against sulfate attack and ASR. Class C fly ash may not provide this protection.

Color. Slag cement will provide lighter concrete with higher reflectivity than plain portland cement concrete. Class C and Class F fly ash will produce, respectively, a buff or darker gray concrete.

Figure 2: Effect of Slag Cement and Fly Ash on Initial Time of Set



Note: Cured at 50° F with a 2% non-chloride accelerating admixture

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.



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Farmington Hills, MI 48331

phone: 847.977.6920
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TERMINOLOGY

Slag cement (Ground granulated blast-furnace slag): A hydraulic cement formed when granulated blast-furnace slag is ground to a suitable fineness.

Granulated blast-furnace slag: The glassy, granular material formed when molten blast-furnace slag is rapidly chilled as by immersion in water. Also referred to as granules.

Blast-furnace slag: The non-metallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, which is developed in a molten condition simultaneously with iron in a blast-furnace.

Blast-furnace: A furnace used to reduce raw materials into molten iron. Combustion is forced with pressurized air.

Air-cooled blast-furnace slag: The material resulting from the solidification of molten blast-furnace slag under atmospheric conditions. Subsequent cooling may be accelerated by application of water to the solidified surface. (This material can be mined and crushed for use as aggregate in concrete or fill material, but is not cementitious.)

Expanded blast-furnace slag: The lightweight cellular material obtained by controlled processing of molten blast-furnace slag with water, or water and other agents, such as steam or compressed air or both. (This is commonly used as lightweight aggregate and is not cementitious.)

Portland cement: A hydraulic cement produced by pulverizing portland-cement clinker and usually containing calcium sulfate.

Blended cement: A hydraulic cement produced by inter-grinding portland cement clinker with other materials, or by blending portland cement with other materials, or by a combination of inter-grinding and blending.

Portland blast-furnace slag cement: A blended cement consisting of an intimately interground mixture of portland cement clinker and granulated blast-furnace slag or an intimate and uniform blend of portland cement and fine granulated blast-furnace slag in which the amount of the slag constituent is within specified limits.

Hydraulic cement: A cement that sets and hardens by chemical interaction with water and is capable of doing so under water.

Pozzolan: A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Glass: An inorganic product of fusion, which has cooled to a rigid condition without crystallization.

SPECIFICATIONS

Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars - ASTM C 989¹

This specification covers three grades of finely ground granulated blast-furnace slag for use as a cementitious material in concrete and mortar. The material described in this specification can be used 1) for blending with portland cement to produce a cement meeting the requirements of Specification C 595 or 2) as a separate ingredient in concrete and mortar mixtures. The material may also be useful in a variety of grouts and mortars.



Slag granules stockpiled and awaiting grinding.



Slag Cement



Microscopic slag cement illustrating its glassy nature



Air-cooled slag aggregate (non-cementitious)

TERMINOLOGY AND SPECIFICATIONS

SPECIFICATIONS

Standard Specification for Blended Hydraulic Cements - ASTM C 595²

This specification pertains to five classes of blended hydraulic cement for both general and special applications, using slag cement, or a pozzolan or both, with portland cement, or portland cement clinker or slag with lime. This specification prescribes ingredients and proportions. The two most common types of blended cement using slag cement are:

- Type IS - Portland blast-furnace slag cement (in which slag constituent is between 25 percent to 70 percent by mass)
- Type I(SM) - Slag-modified portland cement (in which slag constituent is less than 25 percent)

Standard Performance Specification for Hydraulic Cement - ASTM C 1157³

This specification covers hydraulic cements for both general and special applications. It is a specification that defines performance requirements for cement and does not restrict the composition of the cement or its constituents. The specification classifies cements by type, based on specific requirements for general use, high early strength, and heat of hydration. Optional requirements are provided for alkali-reactive aggregates.

Ground Granulated Blast-Furnace Slag (Reported by ACI Committee 233) Concrete⁴

This report primarily addresses the use of slag cement along with portland cement in the production of concrete. Other slags derived from the smelting of materials other than iron ores are not discussed. The material characteristics described in this report apply to slag cement and not other forms or types of slag.

Specifications for Structural Concrete

This specification is a reference standard for use in any building project by citing it in the project specifications. The user supplements it as needed by designating individual project requirements. The document covers materials and proportioning of concrete; reinforcing and prestressing steels; production, placing, and curing of concrete; and formwork design and construction. Methods of treatment of joints and embedded items, repair of surface defects and finishing of formed surfaces are specified. Separate chapters are devoted to slab construction and finishing, architectural concrete, mass concrete and materials and methods for constructing post-tensioned concrete. Provisions governing testing, evaluation and acceptance of concrete, as well as for acceptance of the structure, are included.

Building Code Requirements for Structural Concrete⁶ (Reported by ACI Committee 318)

The code portion of this document covers the proper design and construction of structural and plain concrete for buildings. The code has been written in such form that it may be adopted by reference in a general building code. Among the subjects covered are: drawings and specifications; inspection; materials; durability requirements; concrete quality, mixing, and placing; formwork; embedded pipes and construction joints; analysis and design; strength and serviceability; flexural and axial loads; shear and torsion; slab systems; walls; footings; precast concrete; composite flexural members; and prestressed concrete.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

References

1. ASTM C989-99, Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars, American Society for Testing and Materials, West Conshohocken, PA, 2003
2. ASTM C595-03, Standard Specification for Blended Hydraulic Cements, American Society for Testing and Materials, West Conshohocken, PA, 2003.
3. ASTM C1157-02, Standard Performance Specification for Hydraulic Cement, American Society for Testing and Materials, West Conshohocken, PA, 2003.
4. ACI 233R-95, Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete, American Concrete Institute, Farmington Hills, Michigan, 1995.
5. ACI 301-99, Specifications for Structural Concrete, American Concrete Institute, Farmington Hills, Michigan, 1999.
6. ACI 318-02, Building Code Requirements for Structural Concrete, American Concrete Institute, Farmington Hills, Michigan, 2002.



ASTM C989 specifies finely ground granulated blast-furnace slag for use as a cementitious material in concrete and mortar.

Blended cements incorporating slag and portland cement are specified in ASTM C595.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org

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Slag cement is a raw material that is used in a wide variety of commercial and architectural concrete construction applications. This information sheet is intended to provide guidance to specifiers in the absence of slag cement specifications, or for the addition of slag cement to an existing specification.

Slag cement should be used as a pound for pound replacement for a portion of the portland cement in a concrete mixture. Depending on the desired properties or application, various replacement levels can be used. Table 1 lists suggested replacement levels for a variety of common applications.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

As with all concrete mixtures, trial batches should be performed to verify concrete properties.

Table 1: Suggested Slag Cement Replacement Levels

Concrete Application	Slag Cement
Concrete paving	25-50%
Exterior flatwork not exposed to deicer salts	25-50%
Exterior flatwork exposed to deicer salts with $w/cm \leq 0.45$	25-50%
Interior flatwork	25-50%
Basement floors	25-50%
Footings	30-65%
Walls & columns	25-50%
Tilt-up panels	25-50%
Pre-stressed concrete	20-50%
Pre-cast concrete	20-50%
Concrete blocks	20-50%
Concrete pavers	20-50%
High strength	25-50%
ASR mitigation	25-70%
Sulfate resistance	
Type II equivalence	25-50%
Type V equivalence	50-65%
Lower permeability	25-65%
Mass concrete	50-80%
<p>Percentages indicate replacement for portland cement by mass. These replacement rates are recommended for individual applications and are based on historical performance. Variations in material sources and environmental conditions may require alternate substitution rates. Consult your slag cement supplier for additional assistance.</p>	

Slag cement should be used as a pound for pound replacement for portland cement in a concrete mixture.

FOR GENERAL USE

Cementitious Materials

1. Portland cement shall conform to the requirements in ASTM C-150¹ or ASTM C-1157².
2. Slag cement shall conform to the requirements in ASTM C-989³.
3. Blended cement shall conform to the requirements in ASTM C-595⁴.
4. Pozzolans shall conform to the requirements in ASTM C-618⁵.
5. Silica fume shall conform to the requirements in ASTM C-1240⁶.
6. The water-cementitious materials ratio (W/CM) shall be calculated by dividing the weight of water by the weight of portland cement, plus slag cement plus pozzolans.

SUGGESTED SPECIFICATIONS

FOR SPECIAL EXPOSURES AND APPLICATIONS

Exposure to Sulfates

1. For moderate exposure where ASTM C150, Type II cement is required, a Type I with 25 to 50 percent slag cement (by mass of cementitious material) can be used.
2. For severe exposure where ASTM C150, Type V cement is required, a Type I or a Type II cement with 50 to 65 percent slag cement (by mass of cementitious material) can be used.
3. For very severe exposure an ASTM C150 Type V cement with a minimum of 50 percent slag cement (by mass of cementitious material) can be used.
4. The sulfate resistance of the concrete shall be confirmed by testing in accordance to ASTM C-1012⁷.

Mass Concrete

1. For mass concrete placements, the percentage of portland cement to be replaced shall be 50 to 80 percent (by mass of cementitious material).
2. Thermal properties of the concrete shall be verified prior to construction to ensure conformity to project requirements.

Alkali-Silica Reactivity

1. When using reactive aggregate, slag cement shall be used at replacement levels between 25 and 70 percent (by mass of cementitious material).
2. Mitigation of ASR shall be verified by testing in accordance to ASTM C-1260⁸.
3. If the specific slag/portland cement mixture is shown to mitigate ASR in accordance with ASTM C-1260, low alkali cement is not necessary.

Exposure to Deicing Salts

1. Concrete exposed to deicing salts shall have a W/CM ratio of 0.45.
2. Concrete shall have an adequate air - void system as defined in ACI 201.2R⁹.
3. Proper finishing and curing practices, in accordance with ACI 302¹⁰ and ACI 308¹¹ shall be followed.
4. Slag cement replacement can be 25 to 50 percent (by mass of cementitious material).

Freeze - Thaw Durability

1. Concrete shall have a W/CM of 0.45.
2. Concrete shall have an adequate air - void system as defined in ACI 201.
3. Slag cement replacement can be 25 to 80 percent (by mass of cementitious material).

References

1. ASTM C150-02a, Standard Specification for Portland Cement, American Society for Testing and Materials, West Conshohocken, PA, 2003.
2. ASTM C1157-02, Standard Performance Specification for Hydraulic Cement, American Society for Testing and Materials, West Conshohocken, PA, 2003.
3. ASTM C989-99, Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars, American Society for Testing and Materials, West Conshohocken, PA, 2003.
4. ASTM C595-03, Standard Specification for Blended Hydraulic Cements, American Society for Testing and Materials, West Conshohocken, PA, 2003.
5. ASTM C618-03, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete, American Society for Testing and Materials, West Conshohocken, PA, 2003.
6. ASTM C1240-03, Standard Specification for Use of Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout, American Society for Testing and Materials, West Conshohocken, PA, 2003.
7. ASTM C1012-02, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution, American Society for Testing and Materials, West Conshohocken, PA, 2003.
8. ASTM C1260-01, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), American Society for Testing and Materials, West Conshohocken, PA, 2003.
9. ACI 201.2R-01, Guide to Durable Concrete, American Concrete Institute, Farmington Hills, Michigan, 2001.
10. ACI 302.1R-96, Guide to Concrete Floor and Slab Construction, American Concrete Institute, Farmington Hills, Michigan, 1996.
11. ACI 308.1R-98, Standard Specification for Curing Concrete, American Concrete Institute, Farmington Hills, Michigan, 1998.



As with all concrete, proper finishing and curing is essential to ensure resistance to deicer scaling.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org

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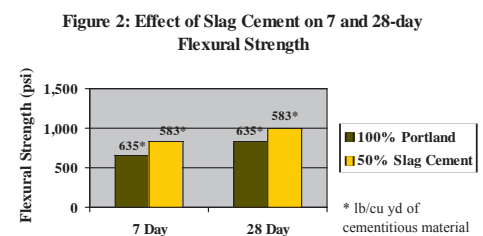
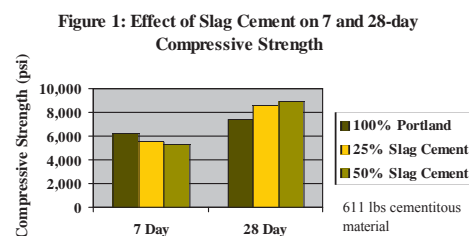
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WHY ARE IMPROVED STRENGTHS IMPORTANT?

Concrete made with slag cement provides higher compressive and flexural strengths compared with straight portland cement concrete. Improved strengths make it easier to achieve specified safety factors of the concrete mixture and can provide engineers with a tool to optimize concrete element designs. It provides enhanced material properties allowing producers to optimize concrete mix designs. Owners may realize decreased life cycle costs.

HOW DOES SLAG CEMENT IMPROVE STRENGTH?

Slag cement increases the compressive and flexural strength of conventional concrete (Figures 1 and 2) and is often a vital component in producing high strength concrete. 28-day strengths generally increase as the percentage of slag cement increases, up to about 50 percent slag cement as a percent of cementitious material. When portland cement reacts with water, it forms calcium silicate hydrate (CSH) and calcium hydroxide ($\text{Ca}(\text{OH})_2$). CSH is the glue that provides strength and holds concrete together, $\text{Ca}(\text{OH})_2$ is a byproduct of portland cement hydration that does not contribute to strength. When slag cement is used as part of the cementitious material in a concrete mix, it reacts with water and $\text{Ca}(\text{OH})_2$ to form more CSH. The additional CSH densifies the concrete matrix, enhancing strength.



HOW DOES SLAG CEMENT AFFECT STRENGTH DEVELOPMENT?

When slag cement is used in concrete mixes, early strength development may be slower while ultimate strengths will be higher than straight portland cement mixtures. If more rapid strength development is required, the concrete mixture can be modified with conventional technology, for example, the use of accelerating admixtures, or use of heated materials or curing conditions. Concrete made with slag cement will have higher strength growth over the lifetime of the concrete element compared with straight portland cement concrete mixtures. Several factors influence the strength development of the mixture. They include:

- Chemical composition of the slag.
- Proportions of the slag component.
- Temperature of the curing environment.
- Chemical composition of the cement component.
- Temperature of the concrete.
- Fineness of the slag component.
- Availability of soluble alkali.

Concrete made with slag cement provides higher compressive and flexural strengths compared with straight portland cement concrete.

The additional calcium-silicate hydrate made with slag cement densifies the concrete matrix, enhancing strength.

COMPRESSIVE AND FLEXURAL STRENGTH

Slag cement has a particularly significant effect on the flexural strength of concrete. Flexural strength (or modulus of rupture) is one of the principal factors in concrete pavement design. Increased flexural strength is evident in Figure 2, where 50 percent slag cement achieved a 20 percent strength improvement, even though total cementitious content was decreased by 52 lb/cu yd. Improved flexural strengths are attributed to the increased denseness of the paste and improved paste-aggregate bond.

WHAT ARE THE BENEFITS OF IMPROVED STRENGTH?

Feature	Benefit Compressive Strength	Benefit Flexural Strength
Improved Safety Factor	Greater reliability	Greater reliability
Optimized element design	Thinner members Lighter members Fewer members Less dead load More usable floor space	Thinner section
Optimized mix designs	Lower cementitious factors Less shrinkage Lower heat	Lower cementitious factors Less shrinkage Less curling
Life cycle cost	Increased service life	Increased service life Lower maintenance costs Greater ability to handle unexpected increases in traffic volumes

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

Slag cement increases the ratio of flexural to compressive strength in concrete.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920

e-mail:

info@slagcement.org

web:

www.slagcement.org

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High performance concrete describes concrete with enhanced properties not found in conventional concrete.

Slag cement has been used effectively in high performance concrete for over twenty years.

WHAT IS HIGH PERFORMANCE CONCRETE?

There are several definitions for high performance concrete. Most of these definitions describe concrete with enhanced properties not found in conventional concrete. Some of these properties include higher compressive and flexural strength, lower permeability, lower heat generation, greater resistance to alkali silica reaction and greater resistance to sulfate attack. Slag cement has been used effectively in high performance concrete in North America for over 20 years and is specified by many highway departments in their high performance concrete mixtures.

HIGH COMPRESSIVE STRENGTH

Slag cement increases the strength of conventional concrete and is often a vital component in producing high strength concrete. The higher the percentage of slag cement used (up to 50 percent) in portland cement concrete, the higher the twenty-eight day strengths will be. Many projects have achieved consistent field concrete strengths in excess of 8,000 psi. Additionally, engineers have specified ternary or even quaternary mixtures containing slag cement, portland cement and pozzolans in projects requiring strengths greater than 12,000 psi, such as Reliant Stadium in Houston and Key Tower in Cleveland.



The four "super columns" supporting the retractable roof at Houston's Reliant Stadium consistently achieved field strengths of over 15,000 psi, yet maintained a strict temperature differential and peak temperature, using a portland-slag cement-fly ash mixture.

HIGH FLEXURAL STRENGTH

Concrete flexural strengths in excess of 1,000 psi are common with mixes containing slag cement. Flexural concrete strength is increased due to a stronger bond between the cement paste and aggregate particles. This improved bond results from enhanced paste characteristics that also increase compressive strengths. Lambert Field in St. Louis is an example of a project that benefits from the high flexural strengths achievable with slag cement.



The Charenton Canal Bridge, Louisiana's first HPC bridge deck, achieved a chloride permeability of less than 2,000 coulombs, using a 50/50 percent portland-slag cement mixture.

LOW PERMEABILITY

When slag cement is used as part of the cementitious material in a concrete mixture, it reacts with water and calcium hydroxide ($\text{Ca}(\text{OH})_2$) to form additional calcium silicate hydrate (CSH). CSH is the glue that provides strength and holds concrete together. The additional CSH produced modifies the pore structure of the paste resulting in lower permeability. The level of improvement is proportional to the percentage of slag cement in the mixture, normally between 25 and 65 percent. Lower permeability reduces chloride ion ingress and thus reduces the corrosion potential of the structure. Projects such as Wacker Drive in Chicago and Charenton Canal Bridge in Louisiana used slag cement to help reduce chloride ion penetrability to less than 2,000 coulombs (classified as "low"), by the Rapid Chloride Permeability Test (ASTM C1202).

SLAG CEMENT IN HIGH PERFORMANCE CONCRETE

LOW HEAT FOR MASS CONCRETE

One of the most difficult challenges in designing mass concrete structures is limiting the concrete temperature differential between the center and the surface of the concrete. If this differential becomes too large, thermal cracks can develop in the concrete. Slag cement has been used successfully to substantially reduce the temperature of mass concrete. When used at high replacement rates, slag cement will provide lower heat in mass concrete than concrete produced with low heat cement. Examples include 75 percent slag cement replacement in the I-895 Pocahontas Parkway footings in Richmond, VA and 70 percent slag cement replacement in the Creve Coeur Lake Memorial Bridge in St. Louis.



The I-895 Pocahontas Parkway crossing, with massive footings and columns exceeding 16 ft thick, maintained thermal mass concrete specifications and exceeded 5,000 psi 28-day design strengths using a 75 percent slag cement mixture.

ASR MITIGATION

Alkali silica reaction (ASR) occurs when the alkalis in portland cement react with certain reactive aggregates and water to form an expansive gel that causes concrete to prematurely deteriorate. Slag cement mitigates ASR by combining with the alkalis in portland cement and making them unavailable for the ASR reaction. It also lowers the permeability of the concrete, limiting the amount of water that is available to support the reaction. In some cases, it will lower the total alkali content of the cement paste. Examples of mitigation for reactive aggregates using slag cement include concrete pavements in El Paso, Texas and the Selfridge Air Force Base airfield pavement near Detroit, Michigan.

MITIGATION OF SULFATE ATTACK

Sulfate attack occurs in hardened concrete when sulfates, found in seawater, in some soils and in wastewater, react with the tricalcium aluminate (C_3A) in portland cement paste. The reaction causes a material called ettringite to form. Ettringite formation can result in concrete expansion and premature deterioration. The higher the C_3A of the cement, the greater the potential for sulfate attack. Slag cement does not contain C_3A so the higher the percentage of slag cement used, the lower the C_3A of the mixture and the lower the potential for deleterious expansion. Additionally, slag cement reduces the permeability of the concrete and limits the ability of sulfates to penetrate into the concrete. Examples of mitigating sulfate attack with slag cement include William Preston Memorial Bridge in Maryland and the Hap Cremeans water treatment plant in Columbus, Ohio.

PROPORTIONING HIGH PERFORMANCE CONCRETE WITH SLAG CEMENT

Engineers and concrete producers who have successfully incorporated slag cement in their HPC mixtures have used slag cement in ranges from 20 to 80 percent of cementitious material, depending on the application and desired results.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.



Many projects have achieved field concrete strengths in excess of 14,000 psi with the use of slag cement.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
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PRECAST CONCRETE

Precast concrete is a concrete product manufactured and cured in a casting facility and then shipped to a jobsite for installation.

PRESTRESSED CONCRETE

As with precast concrete, prestressed concrete is a concrete product manufactured and cured in a casting facility and then shipped to a jobsite for installation. Unlike precast concrete prestressed concrete members undergo additional manufacturing processes—i.e. pre-tensioning of the steel strands—to increase the load capacity of the element.

WHAT CONCRETE PROPERTIES ARE IMPORTANT IN PRECAST / PRESTRESSED CONCRETE?

Some of the properties that are important in precast concrete are:

- Strength
- Durability
- Workability
- Color
- Consistency

Slag cement can improve each of these properties.

HOW DOES SLAG CEMENT AFFECT STRENGTH?

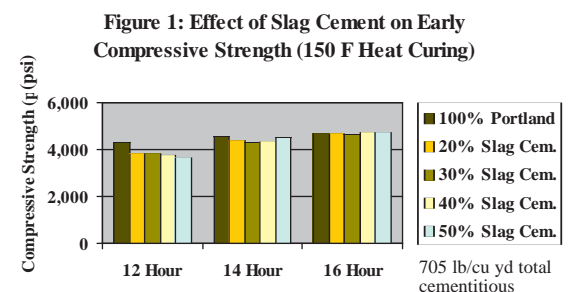
Early strengths are important to precast and to prestressed manufacturing. Heat curing is frequently used in both operations. Slag cement responds well to heat curing and produces early strengths comparable to, or better than, plain portland cement mixes. Without heat curing, early strength may be less than plain portland cement concrete members. Ultimate compressive strengths will be higher using slag cement. Engineering requirements and plant processes will influence mix proportions.

WHERE ARE PRECAST AND PRESTRESSED CONCRETE PRODUCTS USED?

- Building, housing, landscape, and specialty products
- Sanitary and storm water products
- Water and wastewater products
- Transportation products
- Utility, industrial and farm products



Precast/prestressed elements at the Philadelphia Airport parking garage incorporating slag cement.



Slag cement can improve both the plastic and hardened properties of precast and prestressed concrete.

Slag cement reduces concrete permeability, which in turn increases resistance to chloride intrusion.

PRODUCING PRECAST AND PRESTRESSED CONCRETE

HOW DOES SLAG CEMENT AFFECT DURABILITY?

Properly proportioned slag cement mixtures produce more durable precast/prestressed concrete. Slag cement improves durability in the following ways:

- Reduces permeability
- Increases resistance to chloride intrusion, thus improving corrosion resistance
- Reduces susceptibility to sulfate attack
- Mitigates alkali-silica reactivity

By improving the durability of the concrete, the service life of the concrete element may be increased.

HOW DOES SLAG CEMENT AFFECT WORKABILITY?

Slag cement improves the workability of concrete due to its fine grind and glassy structure. Enhanced workability benefits placing, compaction, and finishing of the concrete. The resulting concrete elements may have fewer surface voids and improved consolidation. Slag cement has also been used effectively in the design of self-consolidating concrete mixtures.

PROPORTIONING PRECAST/PRESTRESSED CONCRETE MIXTURES WITH SLAG CEMENT

Precast/prestressed manufacturers who have successfully incorporated slag cement in their products have used slag cement in ranges from 20 to 50 percent of cementitious material.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.



HOW DOES SLAG CEMENT AFFECT CONSISTENCY?

Slag cement is one of the most consistent materials used in concrete. Since it is made in a manufacturing process, chemical composition and particle size are controlled during its production, ensuring not only conformance with specifications, but also low variability from shipment to shipment, and even from source to source. Slag cement does not contain carbon and maintains a consistent particle size, thus ensuring a stable air void system. Precast manufacturers can depend on slag cement to help reduce the variability of their concrete materials.

HOW DOES SLAG CEMENT AFFECT COLOR?

Slag cement is lighter in color than portland cement. Elements made with slag cement will therefore have a lighter finished color. The higher the percentage of slag cement used, the lighter the color will be. This provides greater visibility of the elements and potentially improved safety.



Precast tilt-up elements incorporating slag cement are made on the jobsite.

Enhanced workability with slag cement concrete results in fewer surface voids and improved consolidation around reinforcing steel and prestressing tendons.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org

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Slag cement is an ideal material for concrete pipe because it can improve the factors most important in concrete pipe manufacturing.

Early age strength is usually equivalent to or greater than portland cement concrete when heat curing is used.

WHAT FACTORS ARE IMPORTANT IN CONCRETE PIPE MANUFACTURING?

There are several methods of manufacturing concrete pipe. Depending on the process, slag cement proportioning may vary. Certain factors, however, are important to the manufacturers of all concrete pipe:

- Strength at early ages
- Surface texture and density
- Permeability
- Sulfate resistance
- Consistency

Slag cement is an ideal material for concrete pipe because it can positively affect all of these factors.

HOW DOES SLAG CEMENT AFFECT STRENGTH?

Heat is a great activator for slag cement. Since most concrete pipe manufacturers use heat to cure their products, early age strength is usually equivalent or superior to straight portland cement concrete. At 28 days, strengths are superior when concrete pipe is manufactured with slag cement.

HOW DOES SLAG CEMENT AFFECT PERMEABILITY?

When slag cement is used as part of the cementitious material in a concrete mixture, it reacts with calcium hydroxide (Ca(OH)_2) to form additional calcium silicate hydrate (CSH). CSH is the glue that provides strength and holds concrete together. The additional CSH produced modifies the pore structure of the paste resulting in lower permeability. The level of improvement is proportional to the percentage of slag cement in the mixture.



Stockpiled concrete pipe, manufactured with slag cement.

HOW DOES SLAG CEMENT AFFECT SURFACE TEXTURE AND DENSITY?

Slag cement improves surface texture and density. The fine grind and glassy structure of slag cement provides a surface that is tighter and smoother. This results in concrete pipe that has fewer surface voids and fits into place with more precision.

PRODUCING CONCRETE PIPE WITH SLAG CEMENT

HOW DOES SLAG CEMENT AFFECT SULFATE RESISTANCE?

Concrete pipe is often exposed to harsh local environments. Sulfate attack occurs in hardened concrete when sulfates, found in seawater, in some soils and in wastewater, reacts with the tricalcium aluminate (C_3A) in portland cement paste. The reaction causes a material called ettringite to form. Ettringite can cause concrete to expand and prematurely deteriorate. The higher the C_3A of the cement, the greater the potential for sulfate attack. Slag cement does not contain C_3A so the higher the percentage of slag cement used, the lower the C_3A of the mixture and the lower the potential for deleterious expansion. Additionally, slag cement reduces the permeability of the concrete and limits the ability of sulfates to penetrate into the concrete.

HOW DOES SLAG CEMENT AFFECT CONSISTENCY?

Slag cement is one of the most consistent materials used in concrete. Since it is made in a manufacturing process, chemical composition and particle size are controlled during its production, ensuring not only conformance with specifications, but also low variability from shipment to shipment, and even from source to source. Slag cement does not contain carbon and maintains a consistent particle size, thus ensuring a stable air void system. Concrete pipe manufacturers can depend on slag cement to help reduce the variability of their concrete materials.



Concrete pipe manufactured with slag cement.

PROPORTIONING CONCRETE PIPE MIXTURES WITH SLAG CEMENT

Concrete pipe manufacturers who have successfully incorporated slag cement in their products have used slag cement in ranges from 20 to 50 percent of cementitious material.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

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The use of slag cement reduces concrete permeability and susceptibility to sulfate attack.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org



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CONCRETE BLOCK

While only a few basic methods are used in the initial forming of concrete block, there are many methods of curing. Depending on the temperature and length of curing, slag cement proportioning may change. Some of the properties that slag cement can impart are:

- An architecturally appealing lighter color
- A finer, tighter surface texture or more swipe
- Reduced efflorescence
- Decreased permeability
- Increased compressive strengths

Block manufactured with slag cement will have a lighter finished color.

HOW DOES SLAG AFFECT COLOR?

Slag cement is lighter in color than portland cement. Block manufactured with slag cement will therefore have a lighter finished color. The higher the percentage of slag cement used, the lighter the color will be. If the block remains unpainted or unsurfaced, the lighter color is often viewed as a positive enhancement.

Slag cement helps reduce efflorescence.



A cube of concrete block, made with slag cement, awaiting shipping.



Concrete block machine producing block with slag cement.

HOW DOES SLAG CEMENT AFFECT SURFACE TEXTURE?

Due to the fine grind and glassy structure of slag cement, the surface texture of concrete block is tighter and may increase swipe. Some manufacturers have reported reduced cycle times when slag cement is used.

HOW DOES SLAG CEMENT AFFECT EFFLORESCENCE?

Slag cement combines with calcium hydroxide and soluble salts in portland cement, locking them in the paste and reducing their migration to the surface of the unit during curing and in service, thus helping to reduce efflorescence.

PRODUCING CONCRETE BLOCK WITH SLAG CEMENT

HOW DOES SLAG CEMENT AFFECT PERMEABILITY?

When slag cement is used as part of the cementitious material in a concrete block mixture, it reacts with calcium hydroxide ($\text{Ca}(\text{OH})_2$) to form additional calcium silicate hydrate (CSH). CSH is the glue that provides strength and holds concrete together. The additional CSH produced modifies the pore structure of the paste resulting in lower permeability. The level of improvement is proportional to the percentage of slag cement in the mixture.



Color comparison of a block made without (left) and with (right) slag cement.

HOW DOES SLAG CEMENT AFFECT COMPRESSIVE STRENGTH?

The curing temperature affects the compressive strength of concrete block in mixtures containing slag cement: the higher the curing temperature of the block, the higher the percentage of slag cement that can be used. Typical slag cement replacement levels for optimum strength in concrete block are between 20 percent and 50 percent.

PROPORTIONING BLOCK MIXTURES WITH SLAG CEMENT

Concrete block manufacturers who have successfully incorporated slag cement in their products have used slag cement in ranges from 20 to 50 percent of cementitious material.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

The additional cementitious material produced by slag cement modifies the pore structure of the paste resulting in lower permeability.



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The durability, versatility and beauty of concrete are vital to residential homes, and slag cement is playing an increasingly larger role in this segment..

Slag cement can be used in almost any residential concrete application: Footings, slabs, driveways and even insulating concrete form construction.

Engineers, architects and specifiers have long used slag cement in major projects to achieve improved concrete performance. These performance enhancements are becoming more important to builders of residential homes, and their owners. The durability, versatility and beauty of concrete are vital to residential homes, and slag cement is playing an increasingly larger role in this segment.

WHERE CAN SLAG CEMENT BE USED IN RESIDENTIAL CONSTRUCTION?

Slag cement can be used in almost any residential concrete application. It has been used in footings, basement walls, basement floor slabs, sidewalks, driveways, and garages. Slag cement has been used in mixes for above-grade insulating concrete form (ICF) concrete walls for safe, energy-efficient homes as well. In addition to these concrete applications, slag cement is also used in masonry construction.



Completed exterior of a home with insulating concrete forms, in Wisconsin.

WHAT ARE THE BENEFITS OF SLAG CEMENT IN RESIDENTIAL CONSTRUCTION?

- Improved workability
 - Easier placement
 - Improved consolidation
 - Decreased "honeycombing"
 - Improved finishing characteristics
- Lighter Color
 - Aesthetically pleasing
- Smoother surfaces
 - Fewer blemishes
 - More uniform finish
- Long service life
 - Improved strength
 - Resistant to sulfate attack
 - Mitigates alkali silica reaction
 - Reduced permeability



Insulating concrete form construction using concrete with 60 percent slag cement, 30 percent portland cement and 10 percent fly ash.

Slag cement is preferred in decorative concrete. Because of its lighter base color, colors may appear more vibrant in integrally colored and stamped concrete. Concrete containing slag cement can be acid etched and stained as well.

SLAG CEMENT IN RESIDENTIAL CONCRETE

DOES SLAG CEMENT AFFECT THE CONSTRUCTION PROCESS?

Slag cement has been used extensively in residential construction with little or no impact on construction processes. Wall forms can usually be removed on the same schedule as other mixes. When backfilling a foundation, care must be taken by the excavator to make sure walls are not subjected to excessive pressures from machinery and backfill material. The same is true in walls containing slag cement.



Self-consolidating concrete for residential floor slab using 50 percent slag cement, 50 percent portland cement.

Finishing of flatwork requires proper timing by finishers before the operations are begun. In cooler temperatures, the timing of the operations may be delayed. Flatwork crews should avoid premature finishing. Lower water content, accelerators or adjusted mixture proportions can help address any delays in time of set if they are anticipated.



Decorative residential concrete with 25 percent slag cement: Interior acid stained concrete (top) and exterior stamped and colored concrete (bottom)

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WILL SLAG CEMENT BE DURABLE IN EXTERIOR APPLICATIONS?

Exterior concrete containing slag cement has shown good durability in severe conditions. Various mixture proportions have performed well in a wide range of environments. To assure good performance, concrete—whether or not it contains slag cement—should have:

- Adequate air void systems
- Water-cementitious materials ratio (W/CM) below 0.45
- Correct finishing practices
- Proper curing

Exterior concrete containing slag cement has shown good durability in severe conditions.



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38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
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Ternary mixtures include three different cementitious materials.

The Empire State Building was constructed using combinations of slag cement, portland, and lime in the masonry.

WHAT ARE TERNARY CONCRETE MIXTURES?

Ternary concrete mixtures include three different cementitious materials. This report addresses those combinations of portland cement, slag cement, and a third cementitious material. The third component is often fly ash, but silica fume is not uncommon. ASTM C595 blended cement used in combination with a third cementitious material also is considered a ternary mixture. Other materials in combination with portland and slag cement, such as metakaolin or rice husk ash, are not currently in common usage and will not be discussed here.

Slag cement has been used in ternary mixtures for decades. For example, the Empire State Building was constructed using combinations of slag cement, portland and lime in the masonry. Ternary mixtures using slag cement, fly ash and portland have stabilized soils and hazardous wastes.

WHAT ARE THE BENEFITS OF A TERNARY MIXTURE?

Ternary mixtures can be designed for:

- High strength
- Low permeability
- Corrosion resistance
- Sulfate resistance
- ASR resistance
- Elimination of thermal cracking

Compressive strengths exceeding 10,000 psi were achieved in 1989 in the construction of Scotia Plaza in Toronto. More recently, compressive strengths over 13,000 psi were attained in Reliant Stadium.



Reliant Stadium (NFL) in Houston, which opened in 2002, used a portland-slag cement-fly ash mixture to achieve both high strength and low heat in its four massive "super columns," supporting the retractable roof.

Cementitious Component	Scotia Plaza		Reliant Stadium	
	Lb / cu yd	% of Total Cementitious	Lb / cu yd	% of Total Cementitious
Portland	530	65%	450	50%
Slag Cement	228	28%	270	30%
Silica Fume	60	7%	0	0%
Fly Ash	0	0%	180	20%

WHERE CAN TERNARY BLENDS BE USED?

Ternary mixtures can be used—and have been used—in virtually any concrete application.

- General construction (residential, commercial, industrial)
- Paving
- High performance concrete
- Precast concrete
- Masonry and masonry units
- Mass concrete
- Shotcrete

TERNARY CONCRETE MIXTURES WITH SLAG CEMENT

CAN TERNARY BLENDS BE USED IN EXTERIOR CONCRETE EXPOSED TO FREEZING AND THAWING?

Ternary blends have been used in concrete exposed to freezing and thawing and de-icing chemicals. Proper air entrainment, adequate curing, and good concrete practices will maximize the ability of any concrete to resist freezing and thawing and de-icing chemicals. A number of mixture proportions have been used with good results. Some paving projects have performed for over five years in severe conditions with no apparent loss of durability.



In 1998, airfield pavements were constructed at the Minneapolis Airport using a portland blast-furnace slag blended cement consisting of 35% slag cement, with an addition of 10% Class C fly ash. Performance of the concrete has been excellent.



Structural concrete in the Key Tower (formerly Society Tower) in Cleveland achieved over 13,000 psi using a portland-slag cement-silica fume ternary mixture.

WHAT MIXTURE PROPORTION SHOULD BE USED?

The optimum mixture proportions for ternary blends, as with other concrete, will be dependent on the final use of the concrete, construction requirements and seasonal considerations. As with other concrete, cold weather will affect the early strength gain and mixture proportions may need to be adjusted to assure job-site performance.

In low W/CM applications such as paving, mixtures with 15 percent fly ash and 30 percent slag cement component have been used successfully. Key Tower in Cleveland, completed in 1990, used 65 percent portland, 27 percent slag cement and 7 percent silica fume to achieve strengths exceeding 14,000 psi.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

Ternary blends have been used in general construction, high performance concrete, paving, precast, mass concrete, masonry and masonry units, and shotcrete.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920

e-mail:

info@slagcement.org

web:

www.slagcement.org

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WHAT ARE BLENDED CEMENTS?

ACI 116, Cement and Concrete Terminology¹, defines blended cements as hydraulic cements "consisting essentially of an intimate and uniform blend" of a number of different constituent materials. They are produced by "intergrinding portland cement clinker with the other materials or by blending portland cement with the other materials or a combination of intergrinding and blending."



IS blended cement (33 percent slag content) was used to produce a noticeably lighter concrete masonry unit on the right.

Blended cement containing slag cement is most commonly specified under ASTM C595, Type IS or Type I (SM).

HOW IS SLAG CEMENT USED IN BLENDED CEMENTS?

Slag cement can be used to produce blended cement that complies with ASTM C595, Standard Specification for Blended Hydraulic Cements². Type I (SM), or slag-modified portland cement, contains less than 25 percent slag by mass of the finished cement. Type IS, portland blast-furnace slag cement, contains between 25 and 70 percent slag by mass of the finished cement. These cements are often produced by blending the pre-ground constituents at the cement plant, or in terminals equipped with blending equipment.

Blended cements produced by intergrinding of the constituent materials use granulated blast-furnace slag, the glassy granular material that results in slag cement when ground to a fine powder. Slag granules are added to the grinding mill along with portland cement clinker and the materials are ground simultaneously.

Slag cement can also be used as a constituent in hydraulic cements produced under ASTM C1157, Standard Performance Specification for Hydraulic Cement³.

Blended cement may allow a concrete producer to take advantage of benefits of slag cement despite storage constraints.

WHAT ARE THE BENEFITS OF BLENDED CEMENTS?

Blended cements can be produced to provide the benefits in performance that are also available when slag cement is used as a separate component of the concrete mix. By varying the proportions of the blend, attributes such as sulfate resistance and resistance to alkali silica reaction can be attained with blended cement. A blend designed for a specific project requirement can also be produced. For concrete producers, blended cement may allow them to take advantage of the benefits of slag cement despite storage constraints.

BLENDED CEMENTS

CAN OTHER MATERIALS BE USED WITH BLENDED CEMENTS?

Concrete can be produced with blended cement containing slag plus other cementitious materials (most commonly fly ash or silica fume) added at the batch plant. These are considered ternary systems. Ternary systems can be designed to attain performance characteristics that may be difficult to achieve in a binary system.



Airport paving at Spirit of St. Louis Airport in Chesterfield, MO, placed with blended cement (Type 1 (SM)) and Class C Fly Ash added separately.

HOW ARE THE CEMENTS BLENDED?

There are a number of systems that are used to make blended cements. Some systems are capable of "on-demand" blending, while others may blend the materials in a fixed percentage into a storage silo. All of the systems meter the constituent products in the desired proportions, and then blend them to a uniform mixture. In most cases proportions can be adjusted to produce blends that optimize the desired properties in concrete.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

References

1. ACI 116R-00, Cement and Concrete Terminology, American Concrete Institute, Farmington Hills, Michigan, 2000.
2. ASTM C595-03, Standard Specification for Blended Hydraulic Cements, American Society for Testing and Materials, West Conshohocken, PA, 2003.
3. ASTM C1157-02, Standard Performance Specification for Hydraulic Cement, American Society for Testing and Materials, West Conshohocken, PA, 2003.

Some blending systems are capable of "on-demand" blending, while others may blend the materials in a fixed percentage into a storage silo.



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38800 Country Club
Farmington Hills, MI 48331

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Utilization of slag cement in concrete lessens the burden on landfills, reduces emissions and conserves energy.

One of the great benefits of slag cement is that portland cement can be replaced in relatively large percentages using mainstream technology.

RECOVERING A VALUABLE PRODUCT

Blast-furnace slag is produced in a blast furnace during the reduction of iron ore to iron. It consists of non-metallic minerals, which are tapped off from the blast furnace while molten. By processing blast furnace slag into slag cement or slag aggregate, the material is diverted from landfills. Utilization of slag cement in concrete not only lessens the burden on landfills, it also conserves a virgin manufactured product (portland cement), reduces air emissions at the blast furnace and through the avoided manufacture of portland cement, and decreases the embodied energy required to produce the cementitious materials in concrete.



Figure 1: Slag cement not only reduces energy, emissions and virgin material requirements in concrete, it also lightens the concrete, so exposed concrete surfaces reflect more light and help reduce the urban heat island effect.

HOW DOES SLAG CEMENT MAKE CONCRETE GREENER?

Concrete is an inherently green material that is highly durable. It can be used to construct energy-efficient building systems, and reduces the "heat island" effect because of its lighter color. Slag cement can make concrete an even greener material. One of the great benefits of slag cement, from an environmental perspective, is that the replacement of large proportions of portland cement with slag cement in concrete is a commonly used mainstream technology. Typical mixture designs for structural or paving concrete normally use substitution rates between 25 and 50 percent; high-performance and mass concrete applications can use substitution rates up to 80 percent. These high proportions for slag cement dramatically reduce the embodied material, energy and emissions in a cubic yard of concrete.

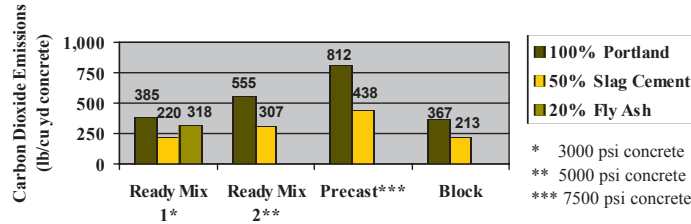
WHAT IS A LIFE CYCLE INVENTORY?

A life cycle inventory (LCI) documents the material inputs, energy inputs and emission outputs associated with manufacturing a product. An LCI has been performed on concrete made with portland cement concrete mixtures for ready mixed concrete, precast concrete and block applications¹. Another LCI study has documented the same mixtures for concrete substituting slag cement for a portion of the portland cement². Also, a limited analysis of a typical mixture incorporating fly ash was performed¹. The results of these studies clearly show the environmental advantage of incorporating slag cement into a concrete mixture.

A life cycle inventory of concrete made with slag cement shows that for each cubic yard of concrete, greenhouse gas emissions can be reduced by almost one-half, energy reduced by up to one-half, and material extraction reduced by up to one-seventh.

CARBON DIOXIDE REDUCTION

Figure 2: Effect of Slag Cement on Embodied Greenhouse Gas Reduction in Concrete



CO₂ emissions significantly since the early 1980's and continues to develop methods that minimize the release of greenhouse gasses. One approach is by offering alternative cementitious materials, like slag cement, to partially replace portland cement in concrete mixtures. Figure 2 illustrates the benefits of substituting 50 percent slag cement in various concrete mixtures. Between 165 and 374 pounds of CO₂ are saved per cubic yard of concrete by using a 50 percent slag cement substitution, a 42 to 46 percent reduction in greenhouse gas emissions.

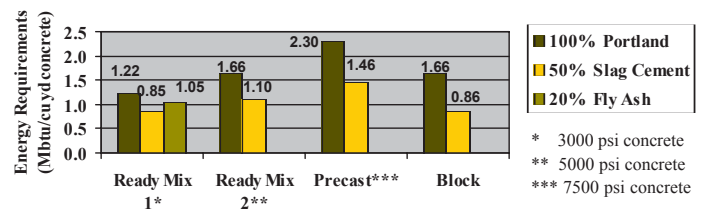
Carbon dioxide (CO₂) is classified as a greenhouse gas. In portland cement manufacturing, almost one ton of CO₂ is released for every ton of portland cement produced. The cement industry has reduced



ENERGY SAVINGS

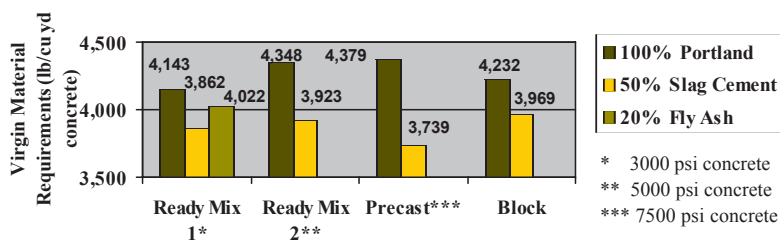
Slag cement requires nearly 90 percent less energy to produce than an equivalent amount of portland cement. Reducing the use of portland cement in concrete by substituting a portion of it with slag cement significantly reduces the embodied energy in a cubic yard of concrete, since portland cement constitutes 70 percent or more of this energy in concrete. Figure 3 shows that embodied energy can be reduced by 370,000 to 840,000 btus with 50 percent slag cement substitution. This is a 30 to 48 percent reduction in embodied energy per cubic yard of concrete.

Figure 3: Effect of Slag Cement on Embodied Energy Reduction in Concrete



REDUCED MATERIAL EXTRACTION

Figure 4: Effect of Slag Cement on Embodied Virgin Material Extraction in Concrete



Raw materials for portland cement are gathered through mining operations. A ton of portland cement actually requires about 1.6 tons of raw material, because of mass lost due to emissions and other factors. Substituting 50 percent slag cement can save between 281 and 640 pounds of virgin material per cubic yard of concrete, a reduction of between 6 and 15 percent (Figure 4).

Raw materials for portland cement are gathered through mining operations. A ton of portland cement actually requires about 1.6 tons of raw material, because of mass lost due to emissions and other factors.

SLAG CEMENT AND THE ENVIRONMENT

COMPARISON WITH FLY ASH CONCRETE

Substituting fly ash for portland cement is another way to make concrete greener. Fly ash is a pozzolan and a by-product of coal combustion for electric power facilities. However, fly ash is normally used in quantities between 15 and 25 percent, as compared with substantially higher substitution levels for slag cement (which is a hydraulic cement). One life cycle inventory study investigated fly ash substitution of 20 percent for a 3,000 psi ready mixed concrete mixture. Table 1 shows the percent savings comparing 35 and 50 percent slag cement with 20 percent fly ash substitutions (typical values for each material). In this example, slag cement provided one and a half to more than twice the savings in emissions, energy and extracted material when compared with fly ash.

Table 1: Environmental Benefits Comparison of Slag Cement and Fly Ash in 3,000 psi Concrete

Environmental Benefit (Substitution Rate for Portland Cement)	Slag Cement (35%)	Slag Cement (50%)	Fly Ash (20%)
Carbon Dioxide Emissions Savings*	30%	43%	17%
Energy Savings*	21%	30%	14%
Reduction in Extracted Material*	5%	7%	3%

*Percentages listed for savings in carbon dioxide, energy and material are based on 100 percent portland cement systems compared with systems containing slag cement or fly ash substitution.

LIGHTER COLOR ENHANCES THE ENVIRONMENT

Slag cement is whiter in color than portland cement or other cementitious materials, such as fly ash or silica fume (Figure 5). This results in lighter-colored concrete products with higher reflectivity. Lighter-colored concrete has multiple environmental benefits:

- Lighter colored pavements, like parking areas and streets, produce brighter environments with higher visibility and improved safety.
- The lighter color of slag cement concrete also helps reduce the heat island effect in large metropolitan areas. Since urban areas have a higher concentration of structures and surfaces that absorb heat, they tend to experience higher temperatures than their rural neighbors do. Buildings and pavements that are lighter in color reflect more light (high albedo surfaces). This helps minimize the heat island effect, which reduces the energy needed for cooling, and lowers ozone levels.



Figure 5: Comparison of various finely divided cementitious materials (Clockwise, from top: slag cement, silica fume, fly ash and portland cement).

Figure 6 : Effect of Slag Cement on Concrete Reflectance

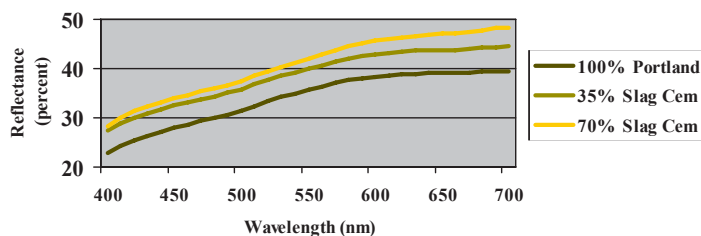


Figure 6 shows how slag cement reflectivity is improved at various levels of the visible spectrum. Figure 1 shows the light color of concrete elements produced from slag cement concrete.

Slag cement results in lighter colored pavements and exposed concrete; this improves visibility and safety, and also helps reduce the urban heat island effect.



SLAG CEMENT AND THE ENVIRONMENT

LEED CREDITS

Leadership in Energy and Environmental Design (LEED) is a system developed by the United States Green Building Council to rate a building's environmental performance³. This system has become the principal method by which buildings can achieve green building certification. The system is based on credits earned in five major categories. Slag cement can positively impact several credit categories including:

- Site credit for reduction of heat islands: Use of high-albedo materials like concrete produced with slag cement.
- Materials credit for building reuse: Slag cement makes concrete structures more durable.
- Materials credit for recycled content: Slag cement is a recycled material used in concrete.
- Materials credit for use of local/regional materials: Slag cement can be considered a local material in many areas.

For more information on the LEED system, visit www.usgbc.org or contact a LEED-accredited professional.

FEDERALLY-AIDED PROJECTS

In 1996 the Environmental Protection Agency recognized slag cement as a "recovered" product under the Federal Resource Conservation Recovery Act. This classification requires that slag cement be specified in concrete on Federally funded projects. For more information on the EPA's Comprehensive Procurement Guidelines—a key component of the federal government's "Buy Recycled" program—visit the website www.epa.gov/epaoswer/non-hw/procure/index.htm.

References

1. Nisbet, Marceau and VanGeem, Environmental Life Cycle Inventory of Portland Cement Concrete (SR 2137a), Portland Cement Association, Skokie, Illinois, 2002.
2. Marceau, M. and VanGeem, M., Life Cycle Inventory of Slag Cement Concrete, letter report from Construction Technology Laboratories to the Slag Cement Association, Sugar Land, Texas, 2003.
3. ECCO EV 27, LEED Green Building Rating System and Concrete, Environmental Council of Concrete Organizations, Skokie, Illinois, 2002.

The EPA's Comprehensive Procurement Guidelines require that slag cement be specified for any concrete used on Federally-funded projects.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org

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Life cycle prediction models are engineering tools used to predict the life and establish the cost of a structure including maintenance and repair.

The use of slag cement to produce concrete can significantly improve the durability of concrete in several ways and consequently extends the life of concrete structures.

WHAT ARE LIFE CYCLE PREDICTION MODELS?

Life cycle prediction models are engineering tools developed from an understanding of concrete performance, gained from basic material research and engineering practice and used to predict the life and establish the cost of a structure, including maintenance and repair. This cost is a balance between the initial fixed cost of construction labor and materials and the variable cost of extended maintenance and repair (subject to the time value of money). Poor initial choices in material selection or construction practices can lead to long-term maintenance and repair expenses that exceed the cost of construction.

LIFE CYCLE COST OF CONCRETE CONSTRUCTION

Some of the properties that may increase the useful life of a concrete structure and decrease life cycle cost are:

- Low permeability
- Increased corrosion resistance
- High compressive and flexure strength
- Improved resistance to sulfate attack
- Better resistance to alkali silica reactivity (ASR)
- Reduced thermal stress

Other important factors that can impact a concrete structure's life cycle include a structure's relationship to the physical environment; structural design and detailing; mixture proportioning and admixtures; reinforcement; concrete production, placement and curing; and construction methods.

SLAG CEMENT, LIFE CYCLE PREDICTION AND COST

The use of slag cement to produce concrete can significantly improve the durability of concrete in several ways and consequently extends the life of concrete structures.

Chemically, slag cement improves resistance to aggressive sulfate solutions and mitigates deleterious reactions between cement alkalis and reactive silica in aggregates.

Physically, slag cement reduces the heat of hydration, thus lessening thermal cracking and improves ultimate compressive and flexural strength. During the life of the structure, these strengths normally increase well beyond the 28-day specified strength, significantly more than plain portland cement concrete.

Possibly the most important effect provided by the use of slag cement is decreased concrete permeability. Lowered permeability inhibits the ingress of chloride ions that can contribute to corrosion of reinforcing steel. Additionally, keeping water out of the concrete matrix significantly decreases susceptibility to many durability problems, such as sulfate attack and ASR.

SLAG CEMENT AND LIFE CYCLE PREDICTION MODELS

A life cycle cost computer model (ACI Life 365)¹, developed in cooperation with the American Concrete Institute's Strategic Development Council, can be used to evaluate the beneficial effect slag cement has on structural durability. It predicts the time to corrosion onset, time for corrosion to reach an unacceptable level, determines a repair schedule after first repair and finally estimates a life-cycle cost based on the initial concrete cost and future repair costs. An example output from this program is shown in Figure 1.

In a real-world example, the Maryland State Highway Administration constructed a bridge deck for Route 64 in Smithburg, MD (Figure 2) and compared



Figure 2: Route 64 bridge deck in Smithburg, MD used high performance concrete with 40 percent slag cement as part of a corrosion-resistant system that extended the predicted life of the structure by 37 years. (Contractor-Joseph Faye Co.; Concrete Supplier-Thomas Bennett Hunter)

While all methods of providing durability should be considered when designing a structure, slag cement can be an efficient and cost effective alternative to more expensive solutions, and can easily be incorporated in an overall strategy to provide a concrete structure that minimizes life cycle costs.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

References

1. Bentz, E., and Thomas, M., Life 365 Service Life Prediction Model (Version 1.1.0), Silica Fume Association, Cleveland, Ohio, 2001.
2. Violetta, B., "Life 365 Service Life Prediction Model," pp 53-57, Concrete International, Farmington Hills, Michigan, December 2000.
3. ACI 365.1R-00 Service-Life Prediction-State-of-the-Art Report, American Concrete Institute, Farmington Hills, Michigan, 2000.

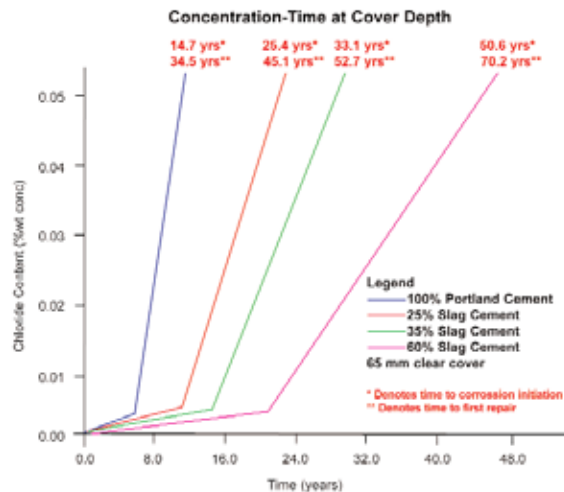


Figure 1: Typical output from ACI Life 365 Service Life Prediction Model demonstrates the significant improvements possible in time to initial corrosion and first repair when slag cement is used.

Assumptions include: Urban bridge deck in Minneapolis, 65 mm clear cover and use of epoxy coated reinforcing steel. (Red text denotes annotations to Life 365 output).

standard concrete with high performance concrete (HPC).³ Corrosion on the deck would initiate at 13 years. Adding epoxy-coated reinforcing steel inhibits corrosion for an additional 25 years. Use of HPC that incorporated 40 percent slag cement, a corrosion-inhibiting admixture and fibers (to limit cracking), increased time to first corrosion to 50 years, and time to significant repair to 75 years. The HPC bridge deck added only \$15,000 to the cost of the structure but increased bridge life by an estimated 37 years. The ACI Maryland Chapter recognized this project with an award for excellence in concrete construction.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
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WHAT IS CONTROLLED LOW STRENGTH MATERIAL?

Controlled Low Strength Material (CLSM) is a self-compacting material, consisting principally of cementitious materials and aggregates, and is used as a backfill material in lieu of compacted fill. The material is known by several other terms such as flowable fill, controlled density fill, flowable mortar or lean-mix backfill. CLSM mixtures have compressive strengths of less than 1200 psi. In most cases, much lower compressive strengths of much less are desired to facilitate future excavation (300 psi is a typical 28 day strength value).

CLSM is a safe, economical alternative to granular fill. The highly flowable mixture is self-compacting and can be placed easily without vibration or tamping. The need to enter confined spaces or excavation areas to manually compact fill is eliminated.

The material can be used as structural fill for buildings and other structures as well as for backfill in utility and road construction. Among other applications, CLSM can fill abandoned tunnel shafts and sewers, plug voids under pavements, and facilitate erosion control.

CAN SLAG CEMENT BE USED IN CLSM?

Slag cement can be used in CLSM by itself, or in combination with other cementitious materials such as portland cement or fly ash. Depending on the job requirements, the need for portland cement may be eliminated.

Table 1 shows two CLSM designs using different combinations of cementitious materials. CLSM A demonstrates that a flowable fill based on 100% slag cement can achieve a moderate level of excavatable (> 300 psi) strength at a relatively low level of cementitious material (195 lb/cy slag cement). CLSM B shows two portland-slag mixtures that achieve moderate CLSM strength at almost half the cementitious material level as a portland-fly ash (Class C) material.

Table 1
Example CLSM Mixtures Using Various Combinations of Cementitious Materials

Description	Units	CLSM A			CLSM B		
		Portland-Slag	Slag-Only	Portland-Fly Ash (C)	Portland-Slag	Portland-Slag	Portland-Fly Ash (C)
Portland Cement	lb/cy	110	0	90	104	114	152
Slag Cement	lb/cy	290	195	0	156	171	0
Fly Ash	lb/cy	0	0	245	0	0	337
Total Cementitious	lb/cy	400	195	335	260	285	489
Fine Aggregate	lb/cy	2897	2803	2846	3407	3382	2803
Water	lb/cy	558	550	500	400	419	422
w/cm	-	1.39	2.82	1.49	1.54	1.47	0.86
7 day comp str	psi	334	101	50	200	240	421
28 day comp str	psi	771	218	72	460	660	696

CLSM is a highly flowable, self-compacting fill material that can be placed easily without vibration or tamping.

Slag cement can be used in CLSM by itself or in combination with other cementitious materials such as portland cement or fly ash.

SLAG CEMENT AND CONTROLLED LOW-STRENGTH MATERIAL

HOW IS CLSM DESIGNED AND ORDERED?

Strength, density in place, flow characteristics, subsidence, permeability, and durability are all characteristics that can be designed into slag cement CLSM. Trial mixtures are the best way to determine how well a given set of ingredients will achieve specific performance requirements. Some state highway departments have a recipe of components that will produce the acceptable qualities.

CLSM made with slag cement should be ordered for its intended use. Ready mixed concrete producers typically have developed mixture proportions that make the best use of local aggregates and other materials. Non-standard aggregates that do not meet the requirements for concrete can be utilized in slag cement CLSM.

HOW IS SLAG CEMENT CLSM PLACED?

Slag cement CLSM is placed using the same methods as traditional CLSM. It is normally delivered in a ready mixed truck, and chutes, conveyors, and buckets are used. Mixtures can also be designed for delivery in non-agitating equipment, such as dump trucks, depending on the flow characteristics required. Finally, volumetric mixing trucks, where CLSM components are transported in separate bins on the truck, then mixed immediately prior to placement, can be used to deliver, mix and place the material.

HOW IS SLAG CEMENT CLSM TESTED?

Slag cement CLSM is a high quality manufactured material. Established quality control tests for strength, density, and flow, are appropriate for use with slag cement CLSM. The test methods listed in ACI 229, *Controlled Low-Strength Materials*, provide guidance for establishing slag cement CLSM mixture proportions to meet job requirements.

As with all CLSM mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

Reference

1. ACI 229R, *Controlled Low Strength Materials*; American Concrete Institute, Farmington Hills, Michigan, 1999

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Trial Mixtures are the best way to determine how well a given set of ingredients will achieve specific performance requirements.



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38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920

e-mail:

info@slagcement.org

web:

www.slagcement.org



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Slag cement can be used alone or in conjunction with portland cement or other cementitious materials to improve soil properties and performance.

Soil cement provides a cost-effective alternative to removing and replacing poor soils, building thicker pavement sections, or using geotextile fabrics or grids.

WHAT IS SOIL CEMENT?

Soils vary widely in engineering properties, and often local soils are not adequate to meet the support requirements for a construction project. Soils can be improved by adding portland cement to the soil, mixing thoroughly with a measured amount of water, and densely compacting the mixture. The resulting blend is called “**soil cement.**”

WHERE IS SOIL CEMENT USED?

Soil cement is most often used as a pavement base material for flexible (asphalt or bituminous) pavements or as a subbase for rigid (concrete) pavements. Marginal quality aggregates can also be improved with cement to produce “cement-treated base.” A related application is recycling of failed bituminous pavements by pulverizing the surface/base and stabilizing this material with cement to produce a new pavement base. Subgrade soils (the material below the base) can be modified with cement, though normally with lower strength/performance requirements. This produces a weather-resistant work platform. Additional applications of soil cement include slope and bank protection, low-permeability liners, and stabilized fill material.

Slag cement can be used alone or in conjunction with portland cement or other cementitious materials (such as fly ash or lime) to improve soil properties and performance.

HOW DOES SOIL CEMENT IMPROVE SOIL?

Hydraulic cement, such as portland or slag cement, binds soil particles together, improves compaction, and decreases void spacing. Usually cementitious material is combined in quantities from 2 to 20 percent by weight of the soil or aggregate material. Benefits include:

- Improved unconfined compressive and shear strengths
- Improved soil properties under saturated conditions
- Greater durability in wet/dry and freeze/thaw conditions
- Higher resilient modulus, reducing fatigue cracking and rutting in asphalt pavements
- Reduced plasticity and moisture retention in fine-grained clay soils

HOW CAN SLAG-CEMENT HELP?

Soil cement provides a cost-effective alternative to removing and replacing poor soils, building thicker pavement sections, or using geotextile fabrics or grids.

Slag cement generally produces soil cement with lower early age strength and higher strength at later ages. Slower strength development can decrease the cracking potential of the soil cement base which reduces reflective cracking in flexible pavements. Higher later age strength ensures long term durability and fatigue resistance. Additionally, slag cement can improve performance under high moisture conditions.

USE OF SLAG CEMENT IN SOIL CEMENT

Figure 1: Compressive Strength of a Stabilized Soil

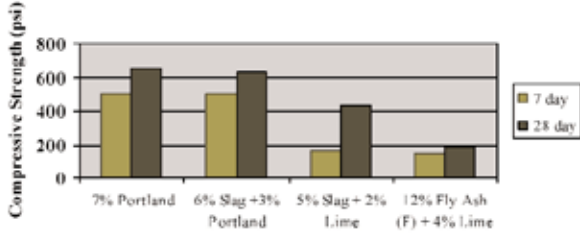
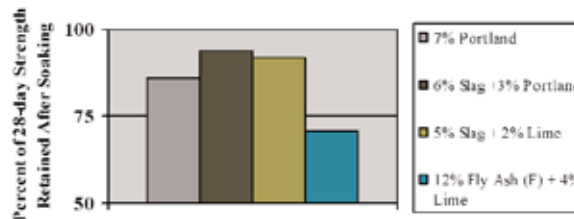


Figure 1 compares, for a specific soil, several mixtures with different types of cementitious materials. The portland-only and the slag-portland mixtures produced similar 7-day and 28-day strengths. The slag-lime mixture produced twice the 28-day strength of the lime-fly ash mixture, using less than half the amount of cementitious material.¹

Figure 2 indicates, for a specific soil, the moisture susceptibility of several mixtures by showing the percentage of 28-day strength retained

Figure 2: Strength Retention under Soaked Conditions for a Stabilized Soil



after soaking in water. The slag cement mixtures (portland-slag and slag-lime) retained higher percentages of strength than the portland-only mixture. When compared with the lime-fly ash mixture, the slag-lime combination provided almost 25% higher strength retention when soaked (with less cementitious material).¹

Slag cement can also help decrease cracking in soil-cement. A slag-portland test section constructed in Mississippi resulted in 33 percent fewer cracks per 100 ft of road than the portland-only soil cement.²⁻³ Finally, for soils that contain sulfates, slag cement can help mitigate sulfate-induced heave often found with lime stabilization.⁴⁻⁶

PROPORTIONING WITH SLAG CEMENT

Slag cement is normally proportioned in quantities from 25 to 100 percent of the cementitious material. Job mixes are developed by proportioning trial batches with actual field materials combined with proposed percentages of cementitious binders. Final binder composition and percentage is made based on meeting specification requirements.

Soil cement produced with a combination of slag and portland cement (or other cementitious materials) is mixed and compacted in a similar manner to portland-only soil cement. The cementitious materials are incorporated in the soil by using either mixed-in-place or central plant (pug mill) methods. Slag can be incorporated separately, or as a component of blended cement. American Concrete Institute's State of the Art Report on Soil Cement, 230.1R,³ provides guidance in design, proportioning, testing, and construction of soil cement for a variety of applications.

Stabilization of sulfate-bearing soils is an emerging technology, so standard expansion test methods do not exist; however reference 6 provides guidelines used by the Louisiana Department of Transportation and Development in its research.

As with all soil cement mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

References

1. Cost, T. and Ahlrich, R. "Use of Slag Cement (GGBFS) in Soil Stabilization," 2003 (draft report)
2. George, K.P., "Soil Stabilization Field Trial - Interim Report III", University of Mississippi/Mississippi DOT, Jackson, MS, 2003.
3. "Reflective Cracking in Cement Stabilized Pavements", IS537, Portland Cement Association, Skokie, IL, 2003
4. Higgins, Kimuthia, and Wild, "Soil Stabilization using Lime-Activated Ground Granulated Blast Furnace Slag", proceedings of the Sixth CANMET/ACI International Conference, Bangkok, Thailand, 1998.
5. Higgins and Kennedy, "Lime + Ground Granulated Blast Furnace Slag Stabilisation of Boulder Clay on the 'A421' Tingevick Bypass", 3rd European Symposium on the Performance and Durability of Bituminous Materials and Hydraulic Stabilised Composites, 1999.
6. Roy, A., Wang, L., Seals, R.K. and Metcalf, J.B., "Stabilization Techniques for Reactive Aggregate in Soil-Cement Base Course," Louisiana State University and Louisiana DOTD, Baton Rouge, 2003
7. ACT 230.1R-90 (Reapproved 1997) State of the Art Report on Soil Cement, American Concrete Institute, Farmington Hills, Michigan, 1997



Slower strength development with slag cement can decrease the cracking potential of the soil cement base which reduces reflective cracking in flexible pavements.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
www.slagcement.org

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Slag cement has been specified and used on several successful waste stabilization projects.

Slag/portland cement combinations raise the pH of waste material, which can lower the solubility of toxic metals, making them less likely to leach out.

WASTE SOLIDIFICATION AND STABILIZATION USING SLAG CEMENT

Portland cement has been used since the 1950's to stabilize potentially hazardous materials in sludges and sediments. Portland cement works by solidification, stabilization, and encapsulation of the waste material.

Research has been conducted on the use of slag cement alone and in combination with portland cement to stabilize waste materials.¹ Based on this research, slag cement has been specified and used on several successful waste stabilization projects.

SOLIDIFICATION

Solidification is the process of reducing the excess water in a waste sludge. Waste management laws generally prohibit waste sludge containing free water to be deposited in landfills. Slag/portland cement mixtures react and chemically bind excess water in a process called hydration.

STABILIZATION

Stabilization is the process of chemically changing a hazardous waste material into a less soluble or less toxic form. Slag/portland cement combinations accomplish this by raising the pH of the waste material. Many toxic metals found in waste sludge have their lowest solubility at higher pH levels and are therefore less likely to leach out. The presence of ferrous iron and sulfur compounds make slag cement an excellent reducing agent that can change toxic metals into less toxic forms.

ENCAPSULATION

Encapsulation is the process of surrounding waste particles with a layer of material that is very low in permeability. This layer of material inhibits the leaching of the hazardous material. Slag/portland cement combinations lower permeability, providing significant reductions in the mobility of toxic material.

RADIOACTIVE WASTE

Technetium is an isotope that is a fission product of uranium. It is a major concern in the disposal of radioactive sludge due to its long half life (213,000 years) and its mobility as soluble pertechnetate. The reduction potential of slag cement has been found to change technetium to a less soluble valence state. When slag cement is used, the leachability of technetium can be decreased by several orders of magnitude.²

WASTE SOLIDIFICATION/Stabilization USING SLAG CEMENT

BROWNFIELD REMEDIATION

Slag has been successfully used for brownfield remediation. Brownfields are sites where their development is complicated by the presence of hazardous contaminants. The Environmental Protection Agency (EPA) places a high priority on brownfield redevelopment as “cleaning up and reinvesting in these properties takes development pressures off of undeveloped, open land, and both improves and protects the environment.”³



Figure 1 - Brownfield Remediation at WE Energies site in Appleton, WI

In Appleton, Wisconsin, a combination of 70 percent slag and 30 percent portland cement was used to remediate coal tar contaminated soil at a WE Energies' former manufactured gas plant which operated from 1867 to 1954. The remediated site (Figure 1) has been converted into a public park and is targeted for potential future development.³

OPTIMUM SLAG / PORTLAND CEMENT MIXTURES

Slag cement has been used in the stabilization and solidification of a variety of waste materials. However, due to the many complex waste forms and compositions, mixtures for waste stabilization must be developed using actual job materials, with test methods and performance criteria specified by an engineer experienced in stabilization/solidification technologies. Any use of slag cement in waste stabilization/solidification must be tested and monitored by a qualified professional and laboratory. Guidance in stabilization/solidification technologies for some wastes can be found in the EPA's guidebook, “Stabilization/Solidification of CERCLA and RCRA Wastes.”⁴

As with all stabilization/solidification mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

References

1. Blue Circle Research
2. Blue Circle Research
3. “Brownfields Cleanup and Redevelopment,” <http://www.epa.gov/swerosps/bf/index.html>, U. S. Environmental Protection Agency, 2005
4. Waste Treatment, (e-newsletter) February 16, 2005, Portland Cement Association, Skokie, IL
5. “Stabilization/Solidification of CERCLA and RCRA Wastes,” EPA/624/6-89/022, Center for Environmental Research Information and Risk Reduction Engineering Laboratory, U. S. Environmental Protection Agency, Cincinnati, 1989

Due to the many complex waste forms and compositions, mixtures for waste stabilization must be developed using actual job materials. Performance criteria, test methods, mixture design, testing and quality control must be performed by qualified professionals and laboratories.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 4833

phone: 847.977.6920

e-mail:

info@slagcement.org

web:

www.slagcement.org

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Shrinkage results from physical and chemical changes that occur in the paste fraction of concrete.

Concrete cracks when its shrinkage is restrained, and the tensile stress induced by the restraint exceeds the tensile capacity of the concrete.

WHAT IS SHRINKAGE IN CONCRETE?

Shrinkage is the time-dependant decrease in concrete volume compared with the original placement volume of concrete. Shrinkage results from physical and chemical changes that occur in the paste fraction of concrete. The two principal types of shrinkage are plastic and drying shrinkage. Plastic shrinkage occurs while concrete is in the plastic state. Drying shrinkage occurs after concrete has reached initial set. Technically, drying shrinkage will continue for the life of the concrete, but most shrinkage will occur within the first 90 days after placement.

WHAT CAUSES SHRINKAGE IN CONCRETE?

Plastic shrinkage results from surface evaporation due to environmental conditions, such as humidity, wind speed or ambient temperature. ACI 305R, *Hot Weather Concreteing*,¹ provides guidance for placement of concrete to minimize plastic shrinkage cracking.

Drying shrinkage in concrete is caused by the loss of moisture in the paste. It is influenced by a variety of factors, including:

- Environmental conditions (temperature and relative humidity)
- Size of the member (surface area to volume ratio)
- Concrete material factors:
 - Volume of Aggregate
 - Elastic modulus of the aggregate
 - Water/cementitious ratio (w/cm) of the paste

EFFECT OF SHRINKAGE ON CONCRETE

Virtually all concrete is subject to some form of restraint, such as steel reinforcement, forms, subgrade, or adjacent members. As concrete begins to lose volume, the restraint inhibits movement, which then induces tensile stress in the concrete. Once the tensile capacity of the concrete has been exceeded, it will crack. In most cases cracking is not a major concern and is normally controlled with various measures, such as contraction and control joint placement, load transfer devices, and proper reinforcement detailing.

Shrinkage is important in applications such as large slabs on grade, containment structures, and reinforced concrete exposed to deicing chemicals. ACI 224, *Control of Cracking in Concrete Structures*,² provides information and guidance on minimizing shrinkage and subsequent cracking.

INFLUENCE OF SLAG CEMENT ON SHRINKAGE

In order to assess the influence of slag cement on drying shrinkage, the SCA commissioned a critical review of available published shrinkage research.³ This study examined 32 relevant references, and utilized data from 62 concrete mixtures where comparable information on concrete with and without slag was available. In the referenced studies, slag cement was incorporated both as a component of blended cement and as a separately batched material.

EFFECT OF SLAG CEMENT ON SHRINKAGE IN CONCRETE

The review concluded that in unrestrained conditions, the drying shrinkage of concrete containing slag cement was slightly higher than concrete without slag cement; this difference is considered insignificant. Quantatively, the average increase in shrinkage was only 2.9 percent, and when corrected for paste volume, this difference was reduced to about 1.5 percent.

Additionally, the effect of the amount of slag in a concrete mixture (in the range from 20 to 80 percent of cementitious material) was found to have no perceptible influence on the relative drying shrinkage of concrete (Figure 1).

Finally, data from one reference⁴ indicated that the restrained shrinkage cracking of concrete containing slag cement appeared to be slightly less than that of concrete without slag cement. Cracking with slag cement was delayed to later ages and resulted in smaller crack widths. The SCA is conducting further research to corroborate these restrained cracking results.

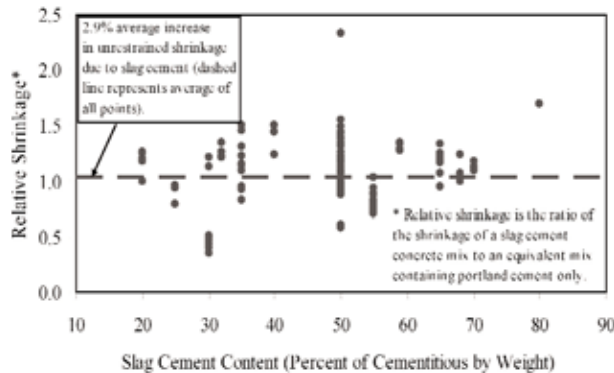
In conclusion, the literature available today indicates there is little increase in drying shrinkage when slag cement is used in concrete, regardless of the percentage used. As for all concrete, when shrinkage is a concern, ACI 224 should be consulted for guidance.

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things. You should consult your slag cement professional for assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

Reference

1. ACI 305R-99, Hot Weather Concreting; American Concrete Institute, Farmington Hills, Michigan, 1999
2. ACI 224R-01, Control of Cracking in Concrete Structures; American Concrete Institute, Farmington Hills, Michigan, 2001
3. Hooton, R.D., Stanish, K., and Prusinski, J., "The Effect of Ground, Granulated Blast Furnace Slag (Slag Cement) on the Drying Shrinkage of Concrete - A Critical Review of the Literature," Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Supplementary Papers Volume, American Concrete Institute, 2004.
4. Li, Z., Qi, M., Li, Z., and Ma, B., "Crack Width of High-Performance Concrete due to Restraint Shrinkage," Journal of Materials in Civil Engineering, Vol. 11, No. 3, 1999, pp. 214-23.

Figure 1: Effect of Slag Cement Content on Relative Shrinkage



The literature today indicates there is little increase in drying shrinkage when slag cement is used in concrete, regardless of the percentage used.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847.977.6920
e-mail:
info@slagcement.org
web:
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HIGH VOLUME SUBSTITUTION OF PORTLAND CEMENT

A principal advantage of using slag cement for improved sustainability is the fact that normal substitution rates of slag for portland cement are quite high (Table 1). Generally, within these guidelines, no unusual mixture designs, extensive trial batching, high levels of chemical admixtures, or increases in total cementitious materials are necessary. Substitution at these high percentages can, in fact, reduce cementitious requirements, as slag cement concrete may require *less* cementitious material to achieve a specified ultimate strength. More importantly, high volume substitution with slag cement dramatically reduces embodied energy and greenhouse gas emissions in concrete (i.e. the resource inputs and emissions outputs resulting from the manufacture of concrete and its constituent materials). For instance, a 50 percent substitution of slag for portland cement in a typical ready mixed concrete batch can save 34% of embodied energy (560,000 btu) and 46% of embodied CO₂ emissions (248 lb) per cubic yard.⁵

Table 1 - Suggested Slag Cement Replacement Levels

Concrete Application	Slag* Cement
Concrete paving	25-50%
Exterior flatwork not exposed to deicer salts	25-50%
Exterior flatwork exposed to deicer salts with w/cm ≤ 0.45	25-50%
Interior flatwork	25-50%
Basement floors	25-50%
Footings	30-65%
Walls & columns	25-50%
Tilt-up panels	25-50%
Pre-stressed concrete	20-50%
Pre-cast concrete	20-50%
Concrete blocks	20-50%
Concrete pavers	20-50%
High strength	25-50%
ASR mitigation	25-70%
Sulfate resistance	
Type II equivalence	25-50%
Type V equivalence	50-65%
Lower permeability	25-65%
Mass concrete	50-80%

**Percentages indicate replacement for portland cement by mass. These replacement rates are suggested for individual applications and are based on historical performance. Variations in material sources and environmental conditions may require alternate substitution rates. Consult your slag cement supplier for additional assistance.*

SLAG CEMENT HELPS ACHIEVE LEED POINTS

The attributes described above can help achieve all or part of ten points in the LEED-NC system. The specific credits are listed in Table 2, and are further detailed in SCA's LEED-NC guide.⁶

High volume substitution with Slag Cement dramatically reduces embodied energy and greenhouse gas emissions in concrete.



Table 2: Potential LEED-NC Points with Slag Cement

Category	Credit	LEED Ver.	Description	Possible Points	Potential Slag Cement Contribution
Sustainable Sites	SS 3	2.1 and 2.2	Brownfield Redevelopment	1	Slag cement can be used to stabilize and solidify contaminated soils at brownfield sites.
Sustainable Sites	SS 7.1	2.1 and 2.2	Heat Island Effect: Non-Roof	1	Slag cement is a light-colored material, making concrete more reflective compared with other cementitious materials.
Materials and Resources	MR 1.1 and MR 1.2	2.1	Maintain 75 and 100 Percent of Existing Walls, Floors and Roof	2	Slag cement can extend a structure's useful service life (if it was used in the original concrete) because it improves concrete durability in areas such as corrosion resistance, sulfate attack and alkali-silica reaction.
		2.2	Maintain 75 and 95 Percent of Existing Walls, Floors and Roof	2	
Materials and Resources	MR 4.1 and MR 4.2	2.1	Recycled Content: 5 and 10 Percent of (Post Consumer and ½ Post-Industrial)	2	Slag cement is a recovered post-industrial/pre-consumer material; therefore its use contributes to the total recycled content of a structure.
		2.2	10 and 20 Percent of (Post-Consumer and ½ of Pre-Consumer)	2	
Materials and Resources	MR 5.1	2.1	Regional Materials: 20 Percent Manufactured Regionally	1	Most slag cement in the U.S. is recovered at iron blast furnaces located within the U.S. or nearby in Canada. The slag cement supplier can provide point of origin so the 500-mile radius requirement can be calculated for a specific project. SCA also has facility maps available.
Materials and Resources	MR 5.2	2.1	Regional Materials: 50 Percent Extracted Regionally	1	
Materials and Resources	MR 5.1 and MR 5.2	2.2	Regional Materials: 10 and 20 Percent Extracted, Processed & Manufactured Regionally	2	
Innovation in Design	ID 1.1	2.1 and 2.2	Credit Interpretation Ruling IDc11, Reduction of Total Portland Cement Content for Cast-in-Place Concrete	1	This credit is meant to reduce embodied greenhouse gas emissions in concrete. Slag cement can replace significant amounts of portland cement (Table 1), and also may reduce total cementitious material needed.
Innovation in Design	ID 1.2	2.2	Exemplary Performance	2	Additional points can be obtained by exceeding the requirements of MR Credits 4 and 5. If a project demonstrates 30 percent or greater total recycled value an additional point can be earned. Another point can be earned if a project demonstrates 40 percent or greater for regionally extracted, harvested and manufactured materials.

Slag cement can help achieve all or part of ten points in the LEED-NC system.



LEED BUILDINGS WITH SLAG CEMENT

Slag cement has been used in numerous structures to help achieve LEED points. At Clearview Elementary School in Hanover, PA (Figure 1), 60% slag cement in the insulated concrete form walls and in other concrete elements helped boost the structure's recycled content to achieve MR 4.1 and 4.2 credits. Clearview Elementary is a LEED™ Gold Certified building, and also was the recipient of SCA's first annual award for "Best Use of Slag Cement in Sustainable Construction."



Figure 1: Clearview elementary School, Hanover

SLAG CEMENT AND LEED™



Rendering by Fox & Fowle Architects, NY

Figure 2: The Helena, Manhattan

For the 45-story Helena residential high rise in Manhattan (Figure 2), use of 45% slag cement concrete in the structural beams and columns, and other cast-in-place concrete resulted in achieving both MR 4.1 and 4.2 credits, as well as an Innovation in Design point for reducing portland cement and commensurate embodied greenhouse gas emissions. The Helena is a LEED™ Gold Certified building and also achieved a New York State tax credit for sustainable structures.



Figure 3: 7 World Trade Center - Manhattan

The 741 foot tall 7 World Trade Center (Figure 3) is the first major building constructed in the lower Manhattan Financial District since 9/11. Slag cement replaced 40% of the portland cement in the concrete core, and achieved strengths of over 10,000 psi. This LEED™ Gold Certified structure also received SCA's 2006 award for "Best Use of Slag Cement for Strength."

MORE RESOURCES FOR THE DESIGNER

Visit www.slagcement.org or contact the SCA to receive SCA's LEED™ guide, and related environmental information. Also available on the web are numerous Slag Cement in Concrete information sheets to help the designer and specifier properly select the appropriate slag cement concrete mixture for a specific application. Information on LEED™ can be found at www.usgbc.org/leed.

References

1. U. S. Green Building Council, Green Building Rating System for New Construction & Major Renovations (LEED-NCTM), Version 2.1, Washington, D.C., November 2002 (Revised 3/14/03)
2. U. S. Green Building Council, LEED-NC Green Building Rating System for New Construction & Major Renovations, Version 2.2, Washington, D.C., October 2005
3. Environmental Council of Concrete Organizations, LEED Green Building Rating System and Concrete, EV27, Skokie, IL, 2003
4. RMC Research Foundation, The Ready Mixed Concrete Industry LEED Reference Guide, Silver Springs, MD, 2005
5. Construction Technology Laboratories, "Life Cycle Inventory of Slag Cement Concrete," CTL Project No. 312012, Letter Report to Slag Cement Association May 2, 2003, Skokie, IL
6. Slag Cement Association, LEED-NC™ Guide: Using Slag Cement in Sustainable Construction, Version 1.1, Sugar Land, TX, 2006

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Slag Cement Association
6478 Putnam Ford Drive
Suite 219
Woodstock, GA 30189

phone: 678.494.8248
fax: 678.494.8249
e-mail:
info@slagcement.org
web:
www.slagcement.org

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SLAG CEMENT AND LEED™

Slag Cement in Concrete

No. 28

WHAT IS LEED™?

Leadership in Energy and Environmental Design (LEED) is a national standard developed by the U.S. to certify high performance, sustainable buildings. Currently there are five LEED standards available for use or under development; however LEED-NC, for new construction and major renovation is the most widely used standard.

LEED-NC utilizes a system where points are awarded for achieving specific levels of sustainable performance in six categories: sustainable sites, water efficiency, energy efficiency, materials and resources, and indoor environmental quality, and innovation in design.

Two versions of LEED-NC are currently available for use: 2.1¹ and 2.2², with version 2.2 superseding 2.1 for buildings registered after January 1, 2006.

ACHIEVING LEED POINTS WITH CONCRETE

Concrete is a superior material for building sustainable structures. It is durable, uses abundant, local materials in its manufacture, can use recovered industrial materials in its manufacture, has high reflectivity for reduced urban heat island effect, and utilizes thermal mass to contribute to energy efficiency. Industry publications^{3,4} can guide the designer on how to achieve LEED-NC points with concrete.

MAKING CONCRETE GREENER WITH SLAG CEMENT

Slag cement is a by-product of iron production in a blast furnace. It is a hydraulic cement that can replace between 20 to 80 percent of portland cement in concrete (Table 1) and adds to concrete's sustainable attributes. Slag cement can:

- Reduce virgin material used in the manufacture of concrete
- Reduce disposal and increase use of a recovered industrial material
- Reduce cementitious material needed to achieve a specified strength
- Improve service life through greater concrete durability
- Reduce embodied energy and greenhouse gas emissions
- Increase concrete reflectivity

Slag Cement can
replace between 20 and
80 percent of Portland
Cement in concrete.

Scaling is a surface defect that results from exposure to freezing and thawing conditions.

The number of freeze thaw cycles is a critical factor in determining the existence, severity and extent of deterioration.

WHAT IS SCALING

Scaling is a surface defect (flaking or peeling of a hardened top surface of concrete) that results from exposure to freezing and thawing conditions. The fundamental mechanism that creates the forces that are responsible for the flaking or peeling of the concrete are from the expansion of water upon freezing.

Scaling generally occurs when the concrete has an inadequate air void system which does not provide an outlet for the hydraulic pressure that is created when water freezes.



Figure 1: Typical scaling seen on concrete pavement

The number of freeze thaw cycles is a critical factor in determining the existence, severity and extent of deterioration. Scaling can be identified as *light*; where partial peeling of the surface has occurred and no coarse aggregate is seen, *moderate*; where exposure of aggregate up to 3/8 inch in depth is visible and *severe*; the coarse aggregate stands out or is being dislodged from the concrete paste.

Deicing chemicals¹ such as calcium chloride, magnesium chloride, etc. cause a significant increase in internal pressure and aggravate the concrete system and should be avoided as much as possible.

Additionally deicing chemicals can increase the number of occurrences of freeze thaw events experienced, by suppressing the freezing temperature of a brine (salt/water) solution.

Deicing chemicals are almost always applied to city streets and highways in climates that experience freeze thaw cycles; even though homeowners might not put them directly on their own driveways, salt laden icy slush mixtures can drip from parked cars onto driveways or garage floors.

HOW DO YOU INCREASE A CONCRETE'S RESISTANCE TO SCALING

To increase a concrete's resistance to scaling, the following practices should be followed:

To increase a concrete's resistance to scaling, concrete mixtures should be properly proportioned and contain proper graded and clean aggregate.

1. The water to cementitious (w/c) ratio of the concrete mixture should be below 0.45.
2. The cementitious factor of the concrete should be at least 564 lbs/yd³.
3. Concrete mixtures should be properly proportioned (ACI 211) and contain proper graded and clean aggregate (ASTM C33).
4. The amount of entrained air should conform to the specified amounts in ACI 318, Table 4.4.1 and the average spacing factor of the air void system (determined in accordance to ASTM Standard C 457) should not exceed 0.20 mm (ACI 212.3R).
5. The concrete should be finished properly.
 - a. Do not finish while bleed water is still present on the concrete surface (causes an increase in the w/c at the surface of the concrete)
 - b. Do not sprinkle water on the surface of the concrete as a finishing aid (causes an increase in the w/c at the surface of the concrete)
 - c. Do not finish air entrained concrete with a steel trowel (decreases or eliminates the air from the surface of the concrete). Magnesium **or wood** floats should be used.
 - d. Be careful when finishing with a vibrating screed (can cause a loss of air and a weaker layer of mortar at the surface of the concrete).
 - e. Be careful when placing concrete on a dry, windy day (can cause incomplete hydration and a weakened surface).
 - f. Do not over finishing concrete (can cause a loss of air at the surface of the concrete).
6. The concrete should be cured properly³.
 - a. Concrete should be cured with wet burlap or pigmented curing compound. Curing should begin as soon as it can be applied without marring the surface of the concrete and should be continued for 7 days or until the concrete has reached 70% of its design strength.
 - b. Concrete should be allowed to air dry for a period of one month before experiencing a freeze thaw cycle and/or application of deicer chemicals (NRMCA recommends 1 year before the application of de-icing salts)
 - c. Apply concrete sealer when concrete will be exposed to de-icing chemicals before the proper curing period has been completely achieved (concrete sealers, such as silanes, siloxanes, or linseed oil, are not proof against scaling but some studies indicate that their use can provide added resistance to scaling, especially in the first year).



7. Cementitious Material
 - a. Fly Ash – Can contain carbon which will affect air content. Fly ash is limited by ACI 318, Table 4.2.3, and ACI 301, Table 4.2.2.8, to a maximum of 25% for concrete exposed to freeze / thaw and de-icer salts.
 - b. Slag Cement - Slag cement is limited by ACI 318, Table 4.2.3, and ACI 301, Table 4.2.2.8, to a maximum of 50%.
 - c. Silica Fume – Silica Fume is limited to a maximum of 10% by ACI 318, Table 4.2.3 and ACI 318, Table 4.2.2.8.
 - d. Ternary blends – ACI 318, Table 4.2.3, and ACI 301, Table 4.2.2.8, limit fly ash to 25%, silica fume to 10%, and the total of slag and fly ash or slag and silica fume to 50%.

Deicer Salt Scaling Resistance ACI 318 – Building Code Requirements



Cementitious Materials	Maximum % of Total Cementitious Materials Deicing Chem. Exposure
Slag cement, ASTM C989	50
Fly ash/other pozzolans, ASTM C618	25
Silica fume, ASTM C1240	10
Slag + Pozzolan + Silica Fume	50
Pozzolan + Silica Fume	35

SLAG CEMENT AND SCALING

When designed, finished, and cured properly, concrete mixtures containing slag cement have the same resistance to scaling as concrete mixtures containing straight portland cement. Some consideration that need to be taken into effect when using slag cement in freeze thaw environments, in addition to those previously listed, are:

1. Follow ACI 318 recommendations in freeze and thaw environments.
2. Slag Cement when incorporated into a Mix Design will extend the set time, the increase in set time is inversely proportional to the concrete temperature and proportional to amount of Slag Cement in a mix design. Adjustments in the mix design can and should be made to account for any undesired increase in set time. Properly designed mixtures should not have excessive retardation as very slow setting concrete can be more susceptible to premature finishing.
3. Always inform finishers with any mix design changes i.e. longer setting times or slower bleed rates can affect the concrete finishing properties.

When designed, finished, and cured properly, concrete mixtures containing slag cement have the same resistance to scaling as concrete mixtures containing straight portland cement.



4. Make sure finishers do not finish bleed water into the concrete

Slag cement has been manufactured widely in the United States for over 30 years, and there are thousands of bridge decks, concrete pavements, and sidewalks in freeze thaw environments containing slag cement that have shown excellent scaling resistance.



Figure 1: Typical scaling seen on concrete pavement

References

1. IS001 effective subsistence on concrete.
2. South Dakota Research SD2002-01-G - TPF-5(042)-G.
3. ACI 308.

Slag cement has been manufactured widely in the United States for over 30 years.



Slag Cement Association
38800 Country Club
Farmington Hills, MI 48331

phone: 847-977-6920

e-mail:

info@slagcement.org

web:

www.slagcement.org

About the Slag Cement Association...

The Slag Cement Association is the leading source of knowledge on blast-furnace slag-based cementitious products. We promote the increased use and acceptance of these products by coordinating the resources of member companies. We educate customers, specifiers and other end-users on the varied attributes, benefits and uses of these products.

