SUPPLEMENTARY CEMENTING MATERIALS (SCMs) IN BLENDED CEMENT

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Abstract

Sustainability and environmental concerns have been key considerations for the cement industry in recent years. To make a contribution to climate protection by reducing CO2 emissions, a particular significance constituents attaches to cements. Cements containing several main constituents appear very promising with regard to the strength development and durability of concrete. Supplementary Cementing Materials (SCMs) are a material that, when used in conjunction with Portland cement, contributes to the properties of concrete, sometimes in the fresh state, but more often in the hardened state through hydraulic or pozzolanic activity, or both. Therefore, the supplementary materials are no longer considered as merely ‘cement replacement materials’ or ‘extenders’. Supplementary Cementing Materials represent a broad class of predominately glassy materials that have been found to provide beneficial properties to Portland cement concrete, the optimum amount to use should be established by testing to determine (1) whether the material is indeed improving the property, and (2) the correct dosage rate, as an overdose or underdose can be harmful or not achieve the desired effect. The materials may be interground with cement clinker to create a blended cement. By blending the cement and SCMs at the cement manufacturing plant, the chemical composition of the final product can be carefully and deliberately balanced, thereby reducing the risk of incompatibility problems. There is also less variability in the properties of a manufactured blended cement compared to SCMs added at the concrete plant.

Keywords:
Supplementary Cementing Materials (SCMs), Blended Cement, Pozzolans, Filler, Pozzolanic and Hydraulic Reaction

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I. Introduction

A. Environmental issues

Cement industry is characterized by intensive energy consumption; traditionally, the primary fuel used is coal. A wide range of other fuels are also used, including petroleum coke, natural gas and oil. In addition to these fuel types, the cement industry has been using various types of waste as fuels for more than 10 years.

The high energy requirements and the release of significant amounts of carbon dioxide, by the burning of fossil fuels together with the calcinations of its raw materials, makes cement production a concern for global warming. In theoretically, the increased volumes of carbon dioxide and other greenhouse gases released mainly by the burning of fossil fuels, land clearing, agriculture and they are the primary sources of warming.

To make a contribution to climate protection by reducing CO2 emissions, a particular significance constituents attaches to cements. Cements containing several main constituents appear very promising with regard to the strength development and durability of concrete.

B. Cement Applications

Cement is a basic material for building and civil engineering construction. The manufacturing of and use of cement products make cement one of the most valuable and useful mineral products in the world. The vast majority of cement is used to make concrete and concrete products.

Originally, for concrete making, only three materials are used:

- Cement
- Aggregate (coarse and fine)
- Water

And to improve the quality of concrete is done by additions to the concrete mix. There are two types of additions to the concrete mix,

- Chemical products termed chemical admixtures, or simply ‘admixtures’
  Admixtures were introduced to the concrete mix to improve various desirable properties of concrete, both in fresh and hardened state.
- Inorganic materials called ‘supplementary cementing materials’

Originally, employed purely for economic reasons, supplementary cementing materials were simply cheaper than the Portland cement they were partially replacing. Either they could be
obtained from natural deposits with little, or no, processing, or they were a byproduct or waste from an industry.

Later on, growing concern for the environment increased the use of supplementary cementing materials. Mass scale quarrying for raw materials for the production of Portland cement raised ecological concerns. Moreover, the use of industrial wastes such as blast furnace slag, fly ash and silica fume as supplementary cementing materials provided means for their disposal.

As a further step, supplementary cementing materials were employed to enhance various desirable properties of concrete – sometimes in the fresh state, but more often in the hardened state. Therefore, the supplementary cementing materials are no longer considered as merely ‘cement replacement materials’ or ‘extenders’.

Until the end of the eighties, Portland cements were in general expected to be ‘pure’; that is, with no minor additions other than gypsum or grinding aids. Then, appropriate inorganic materials, termed “Supplementary Cementing Materials (SCMs)”, were introduced to Portland cement mainly in order to develop various desirable properties of concrete in which the cement was a constituent. The resulting product is termed “Blended Portland Cement” or “Portland Composite Cement”, and this method has already become popular.

There are advantages to using a manufactured blended cement in a concrete mix instead of adding Portland cement and one or more SCMs separately to the mix at the concrete plant: By blending the cement and SCMs at the cement manufacturing plant, the chemical composition of the final product can be carefully and deliberately balanced, thereby reducing the risk of incompatibility problems. There is also less variability in the properties of a manufactured blended cement compared to SCMs added at the concrete plant.

II. Blended Cement

Blended cements are produced by intimately and uniformly intergrinding or blending Ordinary Portland Cement (OPC) with one or more Supplementary Cementing Materials (SCMs). Most of SCMs are generally not used as cements by themselves, but when blended with OPC, they make a significant cementing contribution to the properties of hardened concrete through hydraulic or pozzolanic activity.
Blended cements are used in all aspects of concrete construction in the same manner as Portland cements and can be the only cementitious material in concrete or they can be used in combination with other SCMs added at the concrete plant.

A. Classification

Since classification of cements is difficult, it is broad and approximate, for example, cements of the same type may exhibit wide differences in properties while certain types can be classified as more than one type, therefore cement is broadly classified as:

- **Ordinary Portland Cement**
  A general purpose cement still widely used.
- **Portland clinker-based special cements**
  Produced by changing the quality of Portland cement clinker.
- **Blended / composite cements**
  Produced by adding Supplementary Cementing Materials mainly to Portland cement clinker.
- **Other special cements**
- **Natural cements**

There are different standards for classification of cement. The two major standards are the American ASTM C-150 : Specification for Portland Cement, C-595 : Specification for Blended Hydraulic Cements and C-1157 : Performance Specification for Hydraulic Cement - and European EN-197 standard. EN 197 cement types CEM I, II, III, IV, and V do not correspond to the cement types in ASTM, nor can ASTM cements be substituted for EN specified cement, or vice a versa, without the designer’s approval.

The American Society of Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) have published prescriptive standards (ASTM C595 and AASHTO M240) to define five classes of blended cements and prescribe limiting percentages of materials in each. The five classes of blended cement are Type IS-Portland blast furnace slag cement, Type IP and Type P-Portland Pozzolan cement, Type I(PM)-Pozzolan-modified portland cement, Type S-Slag cement and Type I(SM)-Slag-modified portland cement. In ASTM C 595, the cements are described as Type IS, 1P, P, S, I(PM) and I(SM), where S stands for slag, P is for pozzolan and M is for modified and the different types specify the amounts of pozzolan or slag that can be mixed with Portland cement.

ASTM has also published a Standard Performance Specification for Hydraulic Cement (ASTM C 1157) which contains performance requirements with no restrictions on the composition of
the cement or its constituents. This allows the cement manufacturer to optimize strength and durability properties through use of a variety of supplementary cementing materials. The specification classifies cement by type based on specific requirements for general use, high early strength, resistance to sulfate attack, and heat of hydration.

In European standard, EN 197-1 : 2000, the quality of cement is describe and defined by two criteria : the component, consisting of five categories, the five categories of cement are CEM I - Portland cement, CEM II -Portland-composite cement, CEM III –Blast furnace cement, CEM IV Pozzolanic cement and CEM V -Composite cement, and the strength level, consisting of three categories (32.5, 42.5 and 52.5 Mpa).

Traditionally, supplementary cementing materials were used in blended cement individually, the term binary cement is used to refer to blended cements containing OPC and one supplementary cementing materials. Today, due to improved access to these materials, cement producers can combine two or more of these materials to optimize concrete properties. Mixtures using three supplementary cementing materials, called ternary mixtures, are becoming more common.

B. Type of Supplementary Cementing Materials (SCMs)

Supplementary Cementing Materials are materials when used in conjunction with Portland cement, and must never be used on their own, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both. These materials make a considerable contribution to the reduction of the CO₂ emissions from cement works and enhance the quality as well. In general, the benefits derived from the use of SCMs in the cement and concrete industries can be divided into three categories:

- **Engineering benefits**: SCMs can be used to improve a particular concrete property. However, mixtures containing SCMs should be tested to determine whether the SCMs is indeed improving the property, the dosage is correct (an overdose or underdose can be harmful or may not achieve the desired effect), and there are any unintended effects (for example, a significant delay in early strength gain). It is also important to remember that SCMs may react differently with different cements

- **Economic benefits**: Typically, Portland cement represents the most expensive component of a concrete mixture, as it is a highly energy-intensive material. Supplementary Cementing Materials are generally cheaper than Portland cement.

- **Environmental benefits (greenhouse gas emission)**: The production of every tone of Portland cement results in the release of a nearly equivalent amount of carbon dioxide to the
atmosphere thus whenever a quantity of Portland cement is replaced by SCMs, CO2 emissions are reduced by a similar quantity.

Supplementary Cementing Materials represent a broad class of predominately glassy materials that have been found to provide beneficial properties to Portland cement concrete, figure 1. The materials may be interground with cement clinker to create a blended cement or they may be added directly to the concrete mixer during the batching process.

In general, the classification of supplementary cementing material are divided into 2 main groups:

1. **Pozzolanas**

A pozzolan is defined in ASTM C 618 as “a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which 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.” These characteristics make pozzolans ideal additions to Portland cement concrete mixtures.

![Chemical composition ranges for some common supplementary Cementing Materials](source: ECRA, 2007)

Figure 1. Chemical composition ranges for some common supplementary Cementing Materials

ASTM C 618 outlines the physical and chemical requirements of pozzolanic materials. Pozzolanic materials include natural pozzolans (Class N) and by-product materials. Natural pozzolans are notably volcanic ashes, diatomaceous earth, calcined clay, metakaolin clay, and
rice hull ash. By-product material is most typically fly ash, classified as either Class F or Class C, reflecting a difference in chemical composition and origin. The chemical composition of Pozzolanas is not significant for showing their behavior. More important is their mineralogy, and its proportion between the crystalline and glassy phase. The crystalline phase are chemically inactive and the glassy structure are chemically active. Both of these structure will influence the characteristic of Pozzolanic activities. In general, pozzolanic activities can be affected by different mineralogical components, such as amorphous material present in a glassy form, amorphous material containing considerable quantities of strongly bound water, eg monmorillonite, poorly crystalline clay minerals, eg fire clay etc.

a. Natural pozzolans

Natural pozzolans, produced from natural mineral deposits (e.g., volcanic ash or pumicite, diatomaceous earth, opaline cherts and shales), have been used for centuries. The term “pozzolan” comes from a volcanic ash mined at Pozzuoli, a village near Naples, Italy. However, the use of volcanic ash and calcined clay dates back to 2,000 BC and earlier in other cultures. Many of the Roman, Greek, Indian, and Egyptian pozzolan concrete structures can still be seen today, attesting to the durability of these materials.

The most common Class N pozzolans used today are processed materials, having been heat-treated in a kiln and then ground to a fine powder; they include calcined clay, calcined shale, and metakaolin.

- Calcined clays are used in general purpose concrete construction in much the same way as other pozzolans. They can be used as a partial replacement for cement, typically in the range of 15 to 35 percent, and can enhance strength development and resistance to sulfate attack, control alkali-silica reactivity, and reduce permeability. Calcined clays have a relative density between 2.40 and 2.61, with Blaine fineness ranging from 650 to 1,350 m²/kg.

- Calcined shale may contain on the order of 5 to 10 percent calcium, which results in its having some cementing or hydraulic properties. Burnt shale, specifically burnt oil shale, is produced in a special kiln at temperatures of approximately 800 °C. Owing to the composition of the natural material and the production process, burnt shale contains clinker phases, mainly dicalcium silicate and monocalcium aluminate. It also contains, besides small amounts of free calcium oxide and calcium sulfate, larger proportions of pozzolanically reacting oxides, especially silicon dioxide. Consequently, in a finely ground state burnt shale shows pronounced hydraulic properties like portland cement and in addition pozzolanic properties.

- Metakaolin is produced by low-temperature calcination of high-purity kaolin clay. The product is ground to an average particle size of about 1 to 2 µm; this is about 10 times finer than cement, but still 10 times coarser than silica fume. Metakaolin is used in special applications
where very low permeability or very high strength is required. In these applications, metakaolin is used more as an additive to the concrete rather than a replacement of cement; typical additions are around 10 percent of the cement mass.

b. Processed / Manufactured pozzolans

Silica fume

The material is used as a pozzolan and is specified in ASTM C 1240. Silica fume, also called condensed silica fume and microsilica, is a byproduct of the silicon or ferrosilicon industries, figure 2. The product is the vapor that rises from electric arc furnaces used to reduce high-purity quartz with coal. When it cools, it condenses and is collected in cloth bags, then processed to remove impurities. The particles are extremely small, some 100 times smaller than cement grains, and are mainly glassy spheres of silicon oxide.

The loose bulk density is very low and the material is difficult to handle. In order to make it easier to handle, silica fume is usually densified by tumbling in an air stream that causes the particles to agglomerate into larger grains held together by electrostatic forces. Silica fume behaves as a pozzolan when mixed with calcium hydroxide or Portland cement. Hence, the chemical reactions that take place when silica fume is mixed with cement (or lime) are reasonably well understood. The main issues of interest to concrete technology are its tremendous surface area (which requires the use of high range water reducers in many instances) and the presence of carbon particles in the material. Both of these properties may cause air-entrainment issues in concrete.

Source: Kurtis, Kimberly, 2002

*Figure 2. By product of silicon and ferrosilicon alloy production*
Fly ash

Fly ash is the most commonly used SCMs. Fly ash is the residue collected from the flue gases exiting the boiler of a pulverized coal generating station. The fly ash particles are collected in electrostatic precipitators or bag houses and then transferred to a storage silo or sluice pond, Figure 3.

![Fly Ash Diagram](image)

Source: Kurtis, Kimberly, 2002

*Figure 3. By product of fly ash from coal generating station*

Fly ash has a spherical morphology and exhibits a rather wide range of bulk chemical compositions. This wide range of chemical composition has resulted in the creation of two classes of fly ash in ASTM specifications. Class F is fly ash made from burning anthracite and bituminous coal. It generally contains 45 to 65 percent silica and 0.7 to 7.5 percent calcium oxide. The ASTM standard for fly ash (ASTM C 618) does not clearly specify the amount of silica. Class C is fly ash normally produced from lignite or subbituminous coal, which usually contains lime. It generally has 25 to 50 percent silica and 12 to 30 percent calcium oxide.

Class F fly ashes possess largely pozzolanic properties rather than class C fly ashes. ASTM C 618 differentiates Class C and Class F fly ashes based on the sums of the silicon dioxide (SiO2) + aluminum oxide (Al2O3) + iron oxide (Fe2O3). For Class C ash, the sum of SiO2 + Al2O3 + Fe2O3 must be greater than or equal to 50%. For Class F fly ash, the sum of SiO2 + Al2O3 +
Fe₂O₃ must be greater than or equal to 70%. The Class C fly ashes essentially contain 15 to 25% calcium, which makes their performance characteristics different from a low-calcium Class F fly ash.

The pozzolanic reactivity of fly ash depends on particle size distribution, glassy content (greater than 75 percent), composition, and of course available calcium ions. One of the most troublesome materials found in fly ash is carbon. Carbon absorbs air-entraining agents, making it difficult to entrain air in concrete. It also increases the water demand and darkens the concrete. The best fly ash will contain less than 5 percent carbon.

Slag

Ground granulated blast-furnace slag is a predominately glassy material from the iron metal industry, figure 4, this material will be referred to as “slag”. The material is granulated by rapidly quenching the molten slag as it is drawn off the metal. Like fly ash, slag is a glassy material that basically consists of silicates and aluminosilicates of calcium and other bases and to be effective, it must be used with Portland cement or an alkali salt.

The ASTM specification for slag is C 989 and the specification breaks the material into three different grades (80, 100, and 120) based on compressive strength of mortar cubes (slag activity index test). The higher the grade, the more rapid the strength gain in the slag activity index test.

Source: Kurtis, Kimberly, 2002

Figure 4. By product of slag from iron metal industry
Other Pozzolans
Other industrial byproducts like rice husk ash, waste glass, waste fiberglass, etc are potentially useful as concrete constituents. A specification, for rice husk ash, has been recently developed by AASHTO 321 to serve as a specification for these materials, which may not fall under categories covered by other specifications.

2. Filler
Fillers can be natural materials or processed inorganic mineral materials. Due to their physical properties, they have beneficial effects on desirable properties on concrete. By acting as nucleation sites, fillers can significantly enhance the hydration of Portland cement. Although they are usually chemically inert, their possession of some hydraulic properties or their participation in harmless reactions with the products of hydration will cause no problem. Limestone, as a plasticizing material, is a notable example. By the addition of a plasticizing material, the workability of the concrete will be improved.

Durability of concrete is one of the most important parameter limiting the useable limestone qualities. To ensure a high durability, the following requirements should be fulfilled:

- Calcium carbonate (CaCO3)
Limestone is a general term embracing carbonate rocks or fossils, it is composed primarily of calcium carbonates or combinations of calcium and magnesium carbonate with varying amounts of impurities. In nature, limestone usually contains admixture of clay substance and the purities of limestone base on CaCO3 content as shown in table 1. Investigation show that the calcium carbonate content of limestone as a supplementary materials should not be bellow 75 % by mass, although there is no direct correlation between CaCO3 content and durability. 75 % calcium carbonate is always on the safe side.

<table>
<thead>
<tr>
<th>Natural Rocks</th>
<th>CaCO3 content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High grade limestone</td>
<td>96 – 100</td>
</tr>
<tr>
<td>Marlaceous limestone</td>
<td>90 – 96</td>
</tr>
<tr>
<td>Marlstone or calcareous marl</td>
<td>75 – 90</td>
</tr>
<tr>
<td>Marl</td>
<td>40 – 75</td>
</tr>
<tr>
<td>Clayey marl</td>
<td>10 – 40</td>
</tr>
<tr>
<td>Marlaceous clay</td>
<td>4 – 10</td>
</tr>
<tr>
<td>Clay</td>
<td>0 – 4</td>
</tr>
</tbody>
</table>
Content of clay minerals

Interlayer water within the structure of clay minerals can initiate damages of the concrete structure. As an indirect indicator of the content of clay minerals a limit of 1.20 g / 100 g in the methylene blue test according to EN 933-9 was fixed.

Total Organic Carbon (TOC)

The content of total organic carbon of limestone seems to influence the durability of concrete. Therefore a limit of 0.20 % (LL) by mass determined according to EN 13639 was defined. This quality of limestone is characterized by “LL” in EN 197-1. For cement with a lower performance related to durability a second category is defined for the content of total organic carbon with a limit of 0.5 % (L) by mass.

These requirements are laid down in the European cement standard EN 197-1 for limestone as a component of supplementary cementing materials.

III. Reaction of Supplementary Cementing Materials

Base on the reaction, the cementing materials divided into three types:

- Hydraulic materials
  Hydrate on their own and contribute to the strength of concrete.

- Latent hydraulic materials and Pozzolanic
  May exhibit hydraulic activity only upon reacting with another compound in the mixture such as the products of hydration of Portland cement.

- Largely chemically inert materials
  May have a catalytic effect on the hydration of other materials or may have a physical effect on the properties of fresh concrete.

In general, the correlation of hydraulic activity and kind of cementing materials show in figure 5.
Hydraulic cement is a material that sets and hardens when it comes in contact with water through a chemical reaction called hydration. After being mixed with water, Portland cement in the blended cement starts to hydrate immediately and then follow by the supplementary cementing materials:

- The reaction of Pozzolans materials (natural, fly ash and silica fume) with calcium hydroxide, Ca(OH)$_2$, released by the hydration of Portland cement. These materials are known as pozzolanic property.
- The hydration of slag is greatly activated by alkalis or sulfates, and later by the calcium hydroxide, Ca(OH)$_2$, released by the hydration of Portland cement. The slag is known for its latent-hydraulic property, i.e. it is reactive with water, but only at such a slow rate that it is normally mixed with other substances called activators. Some of the activators can be taken simply as catalyst of the slag reaction, because they are highly soluble and can hardly react with the oxides in slag to form solid products. A typical example is NaOH solution. Other activators might take part in the slag reaction in addition to its activation effect. For example, if sulfates are used, it can react with the aluminum and calcium in slag to form a solid hydration product—ettringite.

In very broad terms, the primary reaction in hydrating cement is the following:

Cement + water = calcium silicate hydrate (C-S-H) + calcium hydroxide, Ca(OH)$_2$. Calcium silicate hydrate (C-S-H) is the primary compound that contributes to the strength and impermeability of hydrated cement paste. Calcium hydroxide, Ca(OH)$_2$, is not as strong and is more soluble, so it is somewhat less desirable. Adding a pozzolans, in the presence of water,
results in conversion of the calcium hydroxide, Ca(OH)$_2$, to more calcium silicate hydrate (C-S-H). Figure 6 and 7 show the general description of reaction.

![Figure 6. Main reaction in blended cement](image)

![Figure 7. Hydration mechanism of cement with pozzolana](image)

Supplementary cementing materials have the different characteristic from each other but are all less reactive than Portland cement. Because do not dissolve rapidly, extremely fine supplementary cementing materials particles act as nuclei for the formation of calcium silicate hydrate which would otherwise form only on the cement grains. This “fine-SCMs” effect brings about a denser and more homogeneous microstructure of the hardened cement paste and the aggregate-paste interfacial zones, resulting in improved workability, strength and impermeability, figure 8 and 9. The extent of the “fine-SCMs” effect depends on the content of extremely fine particles in the cementing materials. This property affects the rate of early-age strength gain and affects the rate of heat development due to cementing reactions. The slower the rate of heat development, the lower the temperature rise and therefore the smaller the likelihood of thermal cracking.
IV. Effects of SCMs in concrete applications

SCMs in concrete affect a wide range of fresh and hardened concrete properties. Some of the effects may be considered desirable and are the reason why the materials are used. Other side effects may be less desirable and have to be accommodated. An understanding of all the potential effects is essential to prevent surprises.
Fresh concrete: In general, SCMs improve the consistency and workability of fresh concrete because an additional volume of fines is added to the mixture. Concrete with silica fumes is typically used at low water content with high range water reducing admixtures and these mixtures tend to be cohesive and stickier than plain concrete. Fly ash and slag generally reduce the water demand for required concrete slump. Concrete setting time may be retarded with some SCMs used at higher percentages. This can be beneficial in hot weather. The retardation is offset in winter by reducing the percentage of SCMs material in the concrete. Because of the additional fines, the amount and rate of bleeding of these concretes is often reduce. This is especially significant when silica fume is used. Reduced bleeding in conjunction with retarded setting, can cause plastic shrinkage cracking and may warrant special precautions during placing and finishing.
**Strength:** Concrete mixtures can be proportioned to produce the required strength and rate of strength gain as required for the application. With SCMs other than silica fume, the rate of strength gain might be lower initially, but strength gain continues for a longer period compared to mixtures with only Portland cement, frequently resulting in higher ultimate strengths. Silica fume is often used to produce concrete compressive strength in excess of 10,000 psi (70 MPa). Concrete containing SCMs generally need additional consideration for curing of both the test specimens and the structure to ensure that the potential properties are attained.

**Durability:** SCMs can be used to reduce the heat generation associated with cement hydration and reduce the potential for thermal cracking in massive structural elements. These materials modify the microstructure of concrete and reduce its permeability thereby reducing the penetration of water and water-borne salt into concrete. Watertight concrete will reduce various forms of concrete deterioration, such as corrosion of reinforcement steel and chemical attack. Most SCMs can reduce internal expansion of concrete due to chemical reactions such as alkali aggregate reaction and sulfate attack. Resistance of freezing and thawing cycles requires the use of air entrained concrete. Concrete with a proper air void system and strength will perform well in this condition.

- **Permeability**, SCMs generally improve potential concrete durability by reducing permeability. Almost all durability-related failure mechanisms involve the movement of fluids through the concrete. Tests show that the permeability of concrete decreases as the quantity of hydrated cementitious materials increases and the water-cementitious materials ratio decreases. With adequate curing, fly ash, GGBF slag, and natural pozzolans generally reduce the permeability and absorption of concrete. GGBF slag and fly ash can result in very low chloride penetration test results at later ages. Silica fume and metakaolin are especially effective and can provide concrete with very low chloride penetration (Barger et al. 1997).

- **Alkali-Silica Reactivity Resistance**, alkali-silica reactivity (ASR) of most reactive aggregates can be controlled with the use of certain SCM-s. Low-calcium Class F fly ashes have reduced reactivity expansion up to 70 percent or more in some cases. At optimum dosage, some Class C fly ashes can also reduce reactivity, but at a low dosage a high-calcium Class C fly ash can exacerbate ASR. SCMs reduce ASR (Bhatt 1985, Bhatt and Greening 1978) by (1) providing additional calcium silicate hydrates (C-S-H) that chemically tie up the alkalies in the concrete, (2) diluting the alkali content of the system, and (3) reducing permeability, thus slowing the ingress of water. SCMs that reduce alkali-silica reactions will not reduce alkali-carbonate reactions, a type of reaction involving cement alkalies and certain dolomitic limestones.
Sulfate Resistance, with proper proportioning and materials selection, silica fume, fly ash, natural pozzolans, and GGBF slag can improve the resistance of concrete to external sulfate attack. This is done primarily by reducing permeability and by reducing the amount of reactive elements (such as tricalcium aluminate, C3A) that contribute to expansive sulfate reactions. One study showed that for a particular Class F ash, an adequate amount was approximately 20 percent of the cementitious system (Stark 1989). It is effective to control permeability through mixtures with low water-cementitious materials ratios. Concretes with Class F ashes are generally more sulfate resistant than those with Class C ashes. GGBF slag is generally considered beneficial in sulfate environments. However, one long-term study in a very severe environment showed only a slight improvement in sulfate resistance in concrete containing GGBF slag compared to concrete containing only Portland cement as the cementing material (Stark 1989, 1996). Calcined clay has been demonstrated to provide sulfate resistance greater than high-sulfate resistant Type V cement (Barger et al. 1997).

Resistance to Freeze-Thaw Damage and Deicer,

Scaling, There is a perception that concrete containing SCM-s is more prone to frost-related damage than plain concrete. This is partially due to the severity of the test methods used (ASTM C 666, ASTM C 672), but may also be related to the changing bleed rates and finishing requirements for concretes with SCM-s (Taylor 2004). With or without SCM-s, concrete that is exposed to freezing cycles must have sound aggregates, adequate strength, a proper air-void system, and proper curing methods. For concrete subject to deicers, the ACI 318 (2002) building code states that the maximum dosage of fly ash, GGBF slag, and silica fume should be 25 percent, 50 percent, and 10 percent by mass of cementitious materials, respectively. Total SCMs content should not exceed 50 percent of the cementitious material. Concretes, including pavement mixtures, with SCMs at dosages higher than these limits may still be durable, however. Selection of materials and dosages should be based on local experience. Durability should be demonstrated by field or laboratory performance when new materials and dosages are introduced.

Drying Shrinkage, when used in low to moderate amounts, the effect of fly ash, GGBF slag, calcined clay, calcined shale, and silica fume on the drying shrinkage of concrete of similar strength is generally small and of little practical significance.

The effects of SCM-s on properties of fresh and hardened concrete are summarized in tables 2 and 3.
V. Summary

Use of SCMs in concrete mixtures has been growing in the world since the 1970s. There are similarities among many of these materials:

- SCMs basic chemical components are similar to those of Portland cement.
- Most SCMs are byproducts of other industrial processes.
- The judicious use of SCMs is desirable not only for the environment and energy conservation, but also for the technical benefits they provide to concrete (SCMs contribute to the fresh and hardened properties of concrete)

**Table 2. Effects of Supplementary Cementing Materials on Fresh Concrete properties**

<table>
<thead>
<tr>
<th></th>
<th>Fly ash</th>
<th>Class C</th>
<th>GGBF slag</th>
<th>Silica fume</th>
<th>Calcined shale</th>
<th>Calcined clay</th>
<th>Metakaolin</th>
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<td>Water requirements</td>
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<td>Setting time</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
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</tr>
<tr>
<td>Finisability</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
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<tr>
<td>Pumpability</td>
<td>↑</td>
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<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Plastic shrinkage cracking</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
<td>↔</td>
</tr>
</tbody>
</table>

Sources: Thomas and Wilson (2002b); Kosmatka, Kerkhoff, and Panarese (2003)

* Effect depends on properties of fly ash, including carbon content, alkali content, fineness, and other chemical properties.

Key: ↓ reduced, ↓↓ significantly reduced, ↑ increased, ↑↑ significantly increased, ↔ no significant change, ↓ affect varies
Table 3. Effects of Supplementary Cementing Materials on Hardened Concrete Properties

<table>
<thead>
<tr>
<th></th>
<th>Fly ash</th>
<th>Natural pozzolans</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class F</td>
<td>Class C</td>
</tr>
<tr>
<td>Early strength</td>
<td>↓</td>
<td>↔</td>
</tr>
<tr>
<td>Long-term strength</td>
<td>↑↑</td>
<td>↑↑</td>
</tr>
<tr>
<td>Permeability</td>
<td>↓</td>
<td>↔</td>
</tr>
<tr>
<td>Chloride ingress</td>
<td>↓</td>
<td>↔</td>
</tr>
<tr>
<td>ASR</td>
<td>↓</td>
<td>↔</td>
</tr>
<tr>
<td>Sulfate resistance</td>
<td>↓</td>
<td>↔</td>
</tr>
<tr>
<td>Freezing and thawing</td>
<td>↔</td>
<td>↔</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>↔</td>
<td>↔</td>
</tr>
<tr>
<td>Drying shrinkage</td>
<td>↔</td>
<td>↔</td>
</tr>
</tbody>
</table>

Sources: Thomas and Wilson (2002b); Kosmatka, Kerkoff, and Panarese (2003)

Key: ↓ reduced
↓↓ significantly reduced
↑↑ increased
↑↑↑ significantly increased
↔ no significant change
↑↑↑↑ effect varies

It is important to test mixtures containing SCMs to ensure they are achieving the desired results, to verify the correct dosage, and to detect any unintended effects.

Blended cements are a manufactured blend of Portland cement and one or more supplementary Cementing Materials (SCMs) and, like Portland cement, are used in all aspects of concrete construction.

There are advantages to using a manufactured blended cement in a concrete mix instead of adding Portland cement and one or more SCMs separately to the mix at the concrete plant. By blending the cement and SCMs at the cement manufacturing plant, the chemical composition of the final product can be carefully and deliberately balanced, thereby reducing the risk of incompatibility problems. There is also less variability in the properties of manufactured blended cement compared to SCMs added at the concrete plant.

Blended Cement, which containing several main constituents appear very promising with regards to the strength development and durability of concrete, and contribute to climate protection by reducing CO2 emissions.
VI. References

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