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SUPPLEMENTARY CEMENTING MATERIALS FOR HIGH PERFORMANCE CONCRETE

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ABSTRACT

Supplementary cementing material is an important component of high performance concrete. In particular, the incorporation of supplementary cementing material is essential when the high strength and durability become the most desired properties of high performance concrete. The aim of this paper is to present several well known supplementary cementing materials such as silica fume, fly ash, ground granulated blast-furnace slag, rice husk ash and high reactivity metakaolin, which have been used extensively in the production of high performance concrete. This paper points at the sources, and briefly illustrates the physical properties and chemical composition of the aforementioned supplementary cementing materials. This paper also shows the major effects of the abovementioned supplementary cementing materials on fresh and hardened properties, and durability of high performance concretes.

Key words: Chemical composition; Durability; Fresh and hardened properties; High performance concrete; Supplementary cementing materials.

1. INTRODUCTION

Supplementary cementing materials are finely divided materials, which contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both [1]. They are used significantly in the production of high performance concrete. The shortage of cement in developing countries, the highly energy intensive process to manufacture cement, and the necessity to preserve natural resources are some of the main reasons for the need of supplementary cementing materials. Besides, supplementary cementing materials improve the properties and durability of concrete, and reduce the unit cost of concrete production. In a word, supplementary cementing materials greatly contribute to produce economic and durable concrete structures.

Supplementary cementing materials could be cementitious or pozzolanic, or both cementitious and pozzolanic based on their chemical composition [2]. They can be obtained as industrial by-products such as silica fume, fly ash, and ground granulated blast-furnace slag or from agricultural wastes such as rice husk ash [2-4]. Furthermore, several supplementary cementing materials can be obtained naturally such as volcanic tuffs, pumicite, calcined clay, opaline cherts, and shales [3-4]. In addition, supplementary cementing materials can be industrially manufactured such as high reactivity metakaolin [5].

Supplementary cementing materials has gained wide acceptance to produce high performance concrete. They are generally used as a partial replacement of cement, as an addition to cement, or as a component of blended cement in the production of high performance concrete [6]. The most widely used supplementary cementing materials for high performance concrete are industrial by-products. Silica fume is one of such elegant supplementary cementing materials. It has been used extensively to produce high performance concrete [7-8]. Other industrial by-products such as fly ash and ground granulated blast-furnace slag have also been used effectively as a supplementary cementing material to produce high performance concrete [7-10]. Besides, rice husk ash and high reactivity metakaolin have been used in the development of high performance concrete [11-13]. The present paper delineates the major supplementary cementing materials, and describes their sources, physical properties and chemical composition. Moreover, this paper highlights the principal effects of supplementary cementing materials on the fresh and hardened properties, and on various durability aspects of high performance concrete

2. SUPPLEMENTARY CEMENTING MATERIALS

Several well known supplementary cementing materials have been briefly depicted below along with their sources, physical properties and chemical composition.

2.1 Silica fume

Silica fume (SF) is a supplementary cementing material that possesses very high pozzolanic activity. It is obtained as a by-product during the manufacturing process of elemental silicon and ferrosilicon alloys [3]. Silica fume is gray in color. It is also known as microsilica or condensed silica fume. Silica fume particles are extremely fine with a spherical shape. The average silica fume particle is about 100 times finer than average cement particle [6]. Because of very small size, the particles of silica fume can occupy the spaces among cement particles. Silica fume usually contains 85% to 95% non-crystalline or amorphous silica (silicon dioxide) [4, 6]. Because of high content of silicon dioxide and extreme fineness, silica fume is a highly reactive supplementary cementing material. Some key physical properties and typical chemical composition of silica fume have been shown in Table 1 and Table 2, respectively.

Silica fume is used in high performance concrete to obtain high strength and high degree of impermeability. The content of silica fume in high performance concrete may vary from 5% to 30% by weight of cement [14, 15]. The optimum proportion of silica fume for obtaining high strength is theoretically about 30%, as this amount is needed to consume nearly the entire calcium hydroxide or portlandite liberated during cement hydration [4, 16]. However, the practical and economical optimum content is chosen toward 10% to 15% to reduce the high cost of silica fume and to eliminate the handling problem encountered in fresh concrete [17].

2.2 Fly ash

Fly ash (FA) is generally obtained as the finely divided residue during the combustion of ground or powdered coal in electric power-generating plants [1, 6]. It is collected from the exhaust gases released from the combustion chamber of a furnace. Fly ash is also known as pulverized fuel ash. It is gray or tan in color. Fly ash consists of mostly solid spheres; a small number of hollow spheres called cenospheres, and some combined tiny spheres known as plerospheres [4, 6]. Fly ash particles are not very small, as compared to silica fume. The particles of fly ash vary in the size range of 1 μm to 100 μm [6]. However, the majority of fly ash particles pass 45-μm sieve [18]. Fly ash particles are principally comprised of aluminosilicate glasses [4]. The spheres of fly ash have a skin of glassy or amorphous silicon dioxide. This glassy skin is the major reactive component of fly ash and basically responsible for the pozzolanic activity [19]. Fly ash also contains some crystalline materials, which can be reactive or non-reactive at ordinary temperature.

There are two classes of fly ash: Type C and Type F. Type C fly ash is produced by burning sub-bituminous coal or lignite while Type F fly ash is produced from burning anthracite or bituminous coal [1, 18]. They vary in physical properties and chemical composition. Some key physical properties and typical chemical composition of both Type C and Type F fly ash are shown in Table 1 and Table 2, respectively. Type C fly ash possesses a high amount of calcium oxide (15 to 35%) in comparison to Type F fly ash and therefore exhibits significant cementitious property [4, 20]. Conversely, Type F fly ash contains a very low amount of calcium oxide (less than 10%) but much higher proportions of silica and alumina [4, 18]. It shows little or no cementitious value but significant pozzolanic activity [19]. Because of higher pozzolanic activity, mostly Type F fly ash has been used in the production of high performance concrete.

Fly ash has been used in high performance concrete mainly to impart durability. The proportion of fly ash in concrete is usually larger than that of highly reactive supplementary cementing materials such as silica fume and rice husk ash. Fly ash can be used with a weight content above 50% of cement to produce high performance concrete [9, 21]. Nevertheless, it is generally recommended to keep the fly ash content limited to 15% to 30% to obtain high strength [22, 23].

2.3 Ground granulated blast-furnace slag

Ground granulated blast-furnace slag (GGBS) is produced from grinding granulated blast-furnace slag, which appears as a non-metallic by-product during the manufacturing process of iron [1, 24]. It is also known as slag cement or simply as slag. Ground granulated blast-furnace slag mostly consists of silicates and alumino-silicates of calcium and other bases [24]. It is white in color. Ground granulated blast-furnace slag possesses both cementitious and pozzolanic properties. In concrete production, it has been used as a chief supplementary cementing material for more than a century. Ground granulated blast-furnace slag consists of angular particles with smooth surfaces. The particles of ground granulated blast-furnace slag are not much finer than cement particles. However, more than 80% of ground granulated blast-furnace slag particles passes 45-μm sieve [3]. Several key physical properties and typical chemical composition of ground granulated blast-furnace slag have been shown in Table 1 and Table 2, respectively.

Ground granulated blast-furnace slag has been used in the production of high performance concrete as a partial replacement of cement or as a component of blended cement. The proportion of ground granulated blast-furnace slag usually varies from 25% to 70% of cement by weight [24]. However, ground granulated blast-furnace slag has been incorporated in high performance concrete mostly with a content in the range of 30% to 50% [7, 25].

2.4 Rice husk ash

Rice husk ash (RHA) is produced from incinerating the husks of rice paddy. Rice husk is a by-product of rice milling industry. Controlled incineration of rice husks with a temperature between 500^0C and 700^0C produces non-crystalline amorphous rice husk ash [4, 21]. Rice husk ash is whitish or gray in color. The particles of rice husk ash occur in cellular structure with a very high surface fineness [4]. They have a high content of amorphous silica (up to 90% to 95%), which originally comes from the surfaces of the husk [26, 27]. Due to high silica content, rice husk ash possesses excellent pozzolanic activity. Therefore, rice husk ash has been used effectively as a supplementary cementing material to produce high performance concrete [11, 28]. The key physical properties and typical chemical composition of rice husk ash have been showed in Table 1 and Table 2, respectively.

Rice husk ash has been used to produce high performance concrete with high strength and good durability. The content of rice husk ash generally varies from 5% to 30% by weight of cement [29, 30]. Nevertheless, the published works illustrate that the use of rice husk ash beyond 10% cannot impart significant additional improvement in properties and durability of concrete [11, 30-31].

2.5 High reactivity metakaolin

High reactivity metakaolin (HRM) is a highly reactive and thermally activated manufactured supplementary cementing material. It is obtained by calcining purified kaolinite within a specific temperature range (700^0C to 900^0C) [5, 32]. High reactivity metakaolin is essentially an amorphous material with a small quantity of crystalline phases that include anatase, cristobalite and quartz [33]. It is white in color. The particles of high reactivity metakaolin are angular with an average size greater than that of silica fume. However, they are much smaller than the particles of rice husk ash, fly ash, and ground granulated blast-furnace slag. The key physical properties and typical chemical composition of high reactivity metakaolin have been presented in Table 1 and Table 2, respectively.

High reactivity metakaolin can be used alone or in conjunction with other less reactive supplementary cementing material to produce high performance concrete [12-13]. Besides, high reactivity metakaolin produces high performance concrete without some typical drawbacks such as undesirable color, excessive stickiness and unfavorable finishing ability [12]. The content of high reactivity metakaolin is similar to that of silica fume and rice husk ash. It has been reported that 20% high reactivity metakaolin virtually consumed the entire calcium hydroxide liberated during cement hydration [32].

3. MAJOR EFFECTS OF SUPPLEMENTARY CEMENTING MATERIALS

Supplementary cementing materials improve the quality of fresh concrete, provide significant improvement in mechanical and transport properties, and greatly enhance the durability of high performance concrete. Indeed, the production of high performance concrete cannot be achieved without using any supplementary cementing materials, especially when high strength and good durability are the prime goal. The most important effects of supplementary cementing materials have been highlighted below.

3.1 Effects on properties of fresh concrete

The properties of fresh high performance concrete such as water demand, workability, slump loss, segregation and bleeding, plastic shrinkage, setting time, air content, unit weight or bulk density, and heat of hydration are influenced by supplementary cementing materials. In general, this is due to the physical characteristics of supplementary cementing materials.

Water demand. The water demand of high performance concrete is affected by supplementary cementing materials. Silica fume, rice husk ash and high reactivity metakaolin increase the water demand due to fine particle size and high surface fineness [3, 4, 33]. Owing to favorable particle size and shape, fly ash and ground granulated blast furnace slag generally decrease the water demand by about 1% to 10% for a given slump [6, 18]. However, the changes in water demand also depend on cement replacement level and water-binder ratio of concrete.

Workability. The presence of supplementary cementing materials increases the paste volume and, thus improves the workability of high performance concrete [34]. However, it greatly depends on particle characteristics, water-binder ratio, and extent of cement replacement. Silica fume, rice husk ash, and high reactivity metakaolin usually increase the cohesiveness, and thus make the concrete mixture more sticky and “gluey” that requires greater dosage of high-range water reducer to achieve a good workability [7, 11, 33]. On the other hand, fly ash and Ground granulated blast-furnace slag enhance the workability due to favorable particle characteristics, higher paste content and better particle dispersion [6, 18, 24]. They make the concrete mixtures cohesive but mobile, and therefore need relatively a lower dosage of high-range water reducer to obtain a good workability [7, 34].

Slump loss. The slump loss is a very common phenomenon in highly workable high performance concrete. It is generally decreased when supplementary cementing materials are used in high performance concrete. This. Fly ash and ground granulated blast-furnace slag were found to show relatively a low rate of slump loss [3, 18, 24]. Silica fume, high reactivity metakaolin, and rice husk ash are expected to reduce the slump loss significantly due to reduced rate of water movement or bleeding. Indeed, it has been reported already that silica fume significantly decreases the slump loss in high performance concrete [15].

Segregation and bleeding. Supplementary cementing materials prevent segregation and bleeding in high performance concrete. Fly ash and ground granulated blast-furnace slag were found to reduce segregation and bleeding [3, 18, 24]. However, the extent of reduction also depends on their fineness. Ground granulated blast-furnace slag coarser than portland cement may increase the rate and quantity of bleeding [6, 24]. Silica fume is very efficient to reduce both segregation and bleeding [6, 35]. Similar effects have been shown by rice husk ash and high reactivity metakaolin [27, 33].

Plastic shrinkage. Supplementary cementing materials generally make high performance concrete more vulnerable to plastic shrinkage due to reduced bleeding [6, 36]. The degree of plastic shrinkage greatly depends on the type of supplementary cementing materials. Compared to fly ash and ground granulated blast-furnace slag, silica fume may cause severe plastic shrinkage because it significantly reduces the bleeding of concrete [35]. Similar effect can be observed in case of rice husk ash and high reactivity metakaolin.

Setting time. Most supplementary cementing materials affect the setting time of high performance concrete. Fly ash and ground granulated blast-furnace slag generally exhibit set retardation, and thus give higher setting time [3, 6, 37]. In contrast, silica fume and high reactivity metakaolin results in lower setting time [7, 33, 35]. Nevertheless, it also depends on the extent of cement replacement. Hence, 5% and 10% silica fume showed negligible effect on setting time but 15% silica fume noticeably increased the setting time of concrete [35]. Rice husk ash does not follow the same trend as silica fume and high reactivity metakaolin. It has been found that rice husk ash gives longer setting time than cement and silica fume [11].

Air content. Generally, the air content of high performance concrete tends to remain same or decrease in presence of supplementary cementing materials. Ground granulated blast-furnace slag and portland cement exhibit similar air retention characteristics, and thus need comparable dosages of air-entraining admixture [6]. Fly ash requires greater dosages of air-entraining admixture than portland cement [6, 34]. Also, silica fume, rice husk ash and high reactivity metakaolin cause marked reduction in volume of air voids and therefore need a high dosage of air entraining admixture for a given air content [3, 11, 33].

Unit weight. Usually, the incorporation of supplementary cementing materials decreases the unit weight or bulk density of high performance concrete because they are much lighter than portland cement [34]. However, the reduction in unit weight can be insignificant since the densification or compactness of concrete is also improved in presence of supplementary cementing materials.

Heat of hydration. The use of supplementary cementing materials affects the heat of hydration. Ground granulated blast-furnace slag and fly ash produce lower heat of hydration than portland cement [18, 24]. In contrast, silica fume, rice husk ash and high reactivity metakaolin create greater heat of hydration than portland cement due to high reactivity [11, 33, 35].

3.2 Effects on properties of hardened concrete

The physical properties such as various strengths, elastic modulus, pulse velocity and porosity as well as the transport properties of high performance concrete are improved in presence of supplementary cementing materials. This is because supplementary cementing materials strengthen the microstructure of concrete, and produce a dense mass with finer pore structure.

Compressive strength. Most supplementary cementing materials improve the compressive strength of high performance concrete [7, 8, 38]. Silica fume, rice husk ash and high reactivity metakaolin produce high strength at both early and later ages [4, 27, 33]. But fly ash and ground granulated blast-furnace slag mainly contribute to later-age strength [3, 20].

Splitting tensile and flexural strengths. The splitting tensile and flexural strengths of concrete are generally increased in presence of supplementary cementing materials [5, 7, 20, 11-12, 29, 33]. However, it depends on level of cement replacement too. At greater cement replacement level (≥15%), these strengths could be same or less [35].

Bond strength. Most supplementary cementing materials improve the bond strength of concrete at the paste-aggregate and paste-steel reinforcement interfaces due to increased area of contact surface [3, 35, 39]. In particular, it was found that silica fume significantly increases the bond strength of concrete [39]. Similar effect can be shown by rice husk ash and high reactivity metakaolin.

Table 1: Key physical properties of various supplementary cementing materials

Property	SF	FA (Type C)	FA (Type F)	GGBS	RHA	HRM
Relative density	2.20	2.78	2.31	2.90	2.06	2.50
Fineness, % passing 45-μm sieve	98.9	81.4	93.7	---	99	99.8
Specific surface area (m^2/kg)	26,100 (Nitrogen adsorption)	263 (Blaine)	386 (Blaine)	500 (Blaine)	38,900 (Nitrogen adsorption)	16,800 (Nitrogen adsorption)
Mean particle size (μm)	0.1	10-20	10-20	10-20	7	1.5

* From references 3-5, 7, 11, 23, 33, 39, 47, 55.

Table 2: Typical chemical composition of various supplementary cementing materials

Constituent	Mass Content (%)				
	SF	FA (Type C)	FA (Type F)	GGBS	RHA
Silicon dioxide (SiO_2)	90.00	32.5	49.02	38.35	87.2
Aluminum oxide (Al_2O_3)	1.21	21.9	26.69	8.76	0.15
Ferric oxide (Fe_2O_3)	3.87	5.1	12.31	0.61	0.16
Calcium oxide (CaO)	0.34	27.4	2.37	32.34	0.55
Magnesium oxide (MgO)	1.43	4.8	0.95	18.64	0.35
Sodium oxide (Na_2O)	0.46	1.1	0.21	0.22	1.12
Potassium oxide (K_2O)	1.49	---	2.34	0.71	3.68
Manganese oxide (MnO)	----	---	----	1.41	----
Phosphorous oxide (P_2O_5)		---	----	----	0.50
Titanium oxide (TiO_2)		---	----	0.36	0.01
Sulfur trioxide (SO_3)	0.31	2.8	0.77	----	0.24
Chloride (Cl)	----	---	---	----	0.45
Carbon (C)	----	---	---	----	5.91
Sulfur (S)	----	---	---	0.95	----
Loss on ignition	2.17	1.2	2.78	----	8.55
HRM: Silicon dioxide (SiO_2) + Aluminum oxide (Al_2O_3) + Ferric oxide (Fe_2O_3) $\rightarrow$ 97% (minimum)					

* From references 5, 8-12, 19.

Modulus of elasticity. Usually, supplementary cementing materials result in similar or higher modulus of elasticity, as compared to portland cement [5, 18, 24, 29, 35]. Ground granulated blast furnace slag results in essentially the same elastic modulus, as given by portland cement alone [24]. Fly ash provides elastic modulus slightly lower at early ages but a little higher at later ages [18]. In contrast, silica fume, rice husk ash, and high reactivity metakaolin provide higher elastic modulus than portland cement [5, 29, 35].

Pulse velocity. Most supplementary cementing materials increase the pulse velocity, as they improve the microstructure and pore structure in bulk paste and transition zone of high performance concrete. Silica fume, rice husk ash, fly ash, and ground granulated blast-furnace slag were found to provide good pulse velocity [29, 40, 41]. Similar effect is also expected for high reactivity metakaolin.

Drying shrinkage. Supplementary cementing materials perform inconsistently with regard to drying shrinkage. A number of research publications reported that silica fume, rice husk ash and high reactivity metakaolin decrease the drying shrinkage of high performance concrete [5, 7, 11-13]. Conversely, fly ash and ground granulated blast-furnace slag exhibited lower or greater drying shrinkage depending on the replacement level of cement [7, 9, 23]. Therefore, the inconsistent performance of supplementary cementing materials points at the need for further research in this ground.

Creep. Supplementary cementing materials improve the creep characteristic of high performance concrete. Creep is not adversely affected by fly ash and ground granulated blast-furnace slag [3]. When the strength of the concrete is same, fly ash produces lower creep than portland cement [18]. Silica fume was also found to reduce the creep in high performance concrete [7, 39, 42]. Similar effect is expected in case of rice husk ash and high reactivity metakaolin.

Porosity. Supplementary cementing materials generally refine the pore structure and decrease the porosity [8, 11, 41, 43-45]. It has been reported that silica fume and rice husk ash significantly reduce the porosity of concrete, particularly in interfacial transition zone [44, 45]. Fly ash and ground granulated blast-furnace slag were also found to reduce the porosity of concrete [41, 43]. Similar effect can be produced by high reactivity metakaolin.

<u>Transport properties</u>. Most supplementary cementing materials competently improve the transport properties of concrete because of pore refinement and porosity reduction. They significantly reduce water absorption, water permeability, chloride penetration, air or oxygen permeability, and oxygen diffusion in high performance concrete [8-13, 40, 43, 46]. In particular, high reactivity metakaolin, rice husk ash and silica fume are very efficient in reducing the transport properties of concrete [4, 8, 11, 13].

3.3 Effects on durability of concrete

Supplementary cementing materials usually make high performance concrete greatly resistant to aggressive environments and thereby contribute to create excellent durability. In fact, the enhanced durability of high performance concrete is attributed to the improved transport properties and refined pore structure produced by supplementary cementing materials.

<u>Freeze-thaw resistance</u>. Most supplementary cementing materials provide very good resistance to repeated cycles of freezing and thawing [3, 8-9, 11-12, 23, 33, 47-49]. Ground granulated blast-furnace slag may or may not have any beneficial effect with respect to freezing and thawing [3, 24]. Both Type C and Type F fly ash, rice husk ash, high reactivity metakaolin and silica fume exhibit good resistance to freezing and thawing [3, 11-12, 33, 48-49]. However, it has been emphasized that the performance of silica fume with respect to freezing and thawing resistance depends on the cement replacement level, air void spacing, and densification of hydrated binder paste [3].

<u>Corrosion resistance</u>. Usually, supplementary cementing materials exhibit very good resistance to reinforcement corrosion due to reduced permeability of water, air and chloride ions [23-24, 41, 49-50] though they slightly reduce the alkalinity of the concrete. In particular, they significantly decrease chloride ion penetration, increase electrical resistance of concrete, and hence reduce the electrochemical reaction of corrosion. Silica fume, rice husk ash, fly ash and ground granulated blast-furnace slag have shown very good resistance to reinforcement corrosion [11, 33, 41, 49-51]. Similar performance is expected in presence of high reactivity metakaolin.

<u>Resistance to sulfate attack</u>. The incorporation of supplementary cementing materials makes high performance concrete more resistant to sulfate attack. Silica fume and rice husk ash provide good resistance to sulfate attack [39, 48]. Similar performance is likely in case of high reactivity metakaolin. Moreover, ground granulated blast-furnace slag improves the resistance to sulfate attack [10, 21, 24, 43]. Also, Type F fly ash is more suitable than Type C fly ash to improve the sulfate resistance of concrete [4, 9, 18].

<u>Resistance to alkali-silica reactivity</u>. Usually, supplementary cementing materials impart excellent resistance in high performance concrete to cope with alkali-silica reactivity. Especially, silica fume and rice husk ash are very effective in controlling expansive alkali-silica reaction [3, 4, 27]. Similar effect has been shown by high reactivity metakaolin [13, 52]. Fly ash (Type F) and ground granulated blast furnace slag also reduce alkali-silica reaction [9, 21, 49].

<u>Deicing salt scaling resistance</u>. Supplementary cementing materials have shown conflicted results for salt scaling resistance. Some studies reported that silica fume, rice husk ash and high reactivity metakaolin exhibit high deicing salt scaling resistance for high performance concrete [12, 53] whereas several other studies have presented similar or marginally inferior results for the above-stated supplementary cementing materials [11, 33, 39]. Also, several studies have reported that both Type C and Type F fly ash exhibit poor resistance to deicing salt scaling when used in large proportions [9, 18, 32]. In contrast, an earlier study has showed that a large volume of Type F fly ash provides very good salt scaling resistance [23]. Also, few studies have showed that ground granulated blast-furnace slag produces no considerable improvement in deicing salt scaling resistance [24]. Therefore, further investigation is essential in this field.

<u>Resistance to acid attack</u>. Most supplementary cementing materials induce good resistance to acid attack. Silica fume, rice husk ash, high reactivity metakaolin and fly ash have showed good resistance to acid attack [14, 48]. Similar effect is also expected in presence of ground granulated blast-furnace slag.

<u>Resistance to carbonation</u>. The presence of supplementary cementing materials is not

conducive to increase concrete's resistance to carbonation. Fly ash and ground granulated blast-furnace slag increase carbonation [3]. In addition, it has been reported that silica fume does not improve the resistance to carbonation [54]. Similar performance is expected in case of rice husk ash and high reactivity metakaolin. However, the degree of carbonation also depends on the cement replacement level and permeability of concrete. At low permeability and when the cement replacement level is not very high, the carbonation depth in concrete becomes insignificant [3, 54].

<u>*Resistance to abrasion*</u>. Most supplementary cementing materials improve the abrasion resistance of concrete since they increase the compressive strength of concrete. Silica fume offers excellent resistance to abrasion [3]. Both Type C and Type F fly ash provide similar or improved abrasion resistance [3, 18]. Similar performance is expected in presence of rice husk ash, high reactivity metakaolin, and ground granulated blast-furnace slag.

4. Concluding Remarks

The following conclusions can be drawn based on the performance of the supplementary cementing materials depicted previously:

a. Supplementary cementing materials are very useful to produce high performance concrete with high strength and good durability.
b. Supplementary cementing materials improve the fresh properties of high performance concrete due to their favorable particle characteristics.
c. Supplementary cementing materials improve the key properties of hardened high performance concrete due to densification and strengthening of the microstructure.
d. Supplementary cementing materials improve the transport properties of high performance concrete due to pore refinement and porosity reduction.
e. Supplementary cementing materials enhance the durability of high performance concrete due to improved transport properties.
f. Further research is needed to clarify the effect of supplementary cementing materials on drying shrinkage and deicing salt scaling resistance.

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