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Review

Utilization of coal- and biomass-fired ash in the production of self-consolidating concrete: a literature review

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ABSTRACT

Both coal – and biomass-fired electric power plants have an enormous negative impact on the environments in which they are situated. However, there is potential to recycle waste such as coal ash and biomass ash for the production of high-performance concrete, i.e., self-consolidating concrete (SCC). This innovative high-performance concrete can flow and become compact under its own weight without segregation. Thus, the need for tamping and vibratory compaction is eliminated, which improves the production process and the performance of concrete structures. This article reviews SCC in terms of several aspects, including its history, the processes through which it is produced, and the mix designs used. The article also discusses the incorporation of four main by-products—fly ash (FA), bottom ash (BA), rice husk ash (RHA), and sugarcane bagasse ash (SBA)—into the production of SCC. Due to the rapid expansion of industrial and agricultural operations, the disposal of by-products such as ash has become the subject of increasing environmental concern, and their use in the production of SCC constitutes a new material recycling and sustainability effort. The by-products act as filler materials and can participate in the pozzolanic reaction associated with cement hydration, often resulting in improved SCC performance.

1. Introduction

Coal and biomass fuels are used in electric power plants worldwide, and the use of these fuels in this context is growing at a high rate year by year. Although these fuels are relatively inexpensive and readily available, demand is outstripping supply for both and prices are increasing. A sound fuel management strategy designed to maintain the required output power level of power plants means replacing the main fuels used (lignite, anthracite, and bituminous fuels) with biomass fuels (rice husk and sugarcane bagasse fuels). And, given the increasing demand for power, large quantities of by-products (hereafter referred to as ash) are being produced and must be properly collected and stored, disposed of, or used (Khan et al., 2012). Nevertheless, given the limited reach of environmental rules and regulations, ash is disposed of principally by dumping it in landfills and reusing it in agriculture. Disposing of ash in landfills means that heavy metals from the fly ash may leach into the ground, thus leading to a higher risk of contaminated ground water (Pedersen et al., 2008). Similarly, when incinerated, rice husk produces a great quantity of ash. Each ton of rice produces 200 kg of rice husks, which on complete combustion produces 40 kg of rice husk ash (RHA). Hence, an adequate handling method for disposal must be established in order to avoid a negative impact on the environment (Zerbino et al., 2011). Otherwise, huge quantities of RHA will be wasted and will pose a great threat to the environment because of the damage caused to the land and the surrounding areas in which it is dumped (Khan et al., 2012). Further, sugarcane bagasse ash (SBA) is also disposed of in landfills (Chusilp et al., 2009a, 2009b; Sua-iam and Makul, 2013a). Ash obtained from power plants is a highly porous material that tends to have low density. And, in high volume this material can contaminate adjacent soil and underground water. It can, therefore, cause significant health problems, which, in turn, give rise to serious social and environmental problems (Frías et al., 2011). In order to comprehensively address issues relating to sustainability and environmental impact, the 3R key principles pertaining to ash materials and the environment should be taken into consideration, i.e., reduce, reuse, and recycle. This approach also encompasses (a) reducing production costs in the electric power, cement, and concrete construction industries, (b) reserving an area for disposal, thus allowing more land to be put to other uses, (c) realizing benefits from the sale of by-products by offsetting processing and

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disposal costs, and (d) replacing some of the scarce and/or expensive natural resources used in the production of concrete (Ahmaruzzaman, 2010).

Self-consolidating concrete (SCC) is used widely in many kinds of construction projects and offers many advantages over standard concrete mixtures. For example, SCC reduces construction time, eliminates problems associated with the application of vibration, and reduces the noise level at construction sites (Okamura and Ouchi, 2003). According to a study by Zhu (2001), SCC is more self-leveling in regard to vibration than standard concrete is. In 1996, many European countries adopted this technology and set specifications and standards for SCC. The US, which has also established standards for the use of SCC, uses the material in areas such as the precast concrete industry (Ouchi et al., 2003). Further, the use of SCC, which is a high-performance concrete, entails a lower vibration level than does the use of other concretes: SCC is self-compactable and does not lead to either segregation or excessive bleeding. It should also be noted that the production of SCC consumes relatively little energy in the process of vibration.

It is widely accepted that the vibration used to compact fresh concrete into casing releases excess air bubbles and that the extent of the compaction has a direct influence on the initial and long-term properties of the concrete. The effect of inadequate vibration on the strength and durability of concrete structures has been studied by Hoffmann and Leemann (2003). Also, at present, in the compaction process, the vibrator creates a pressure wave, which controls the aggregate particles and thereby reduces and overcomes the friction between the cement paste and the aggregates.

This paper presents a literature review of SCC covering a discussion of applications for some important by-products produced by other industrial processes. The materials—principally fly ash (FA), bottom ash (BA), rice husk ash (RHA), and sugarcane bagasse ash (SBA)—are used as filler materials and/or for the pozzolanic reaction and hydration reaction in order to improve the mechanical properties and durability of SCC.

2. Characteristics of self-consolidating concrete (SCC)

SCC has three main characteristics: (a) the ability to flow under its own weight without vibration, (b) the ability to flow through heavily congested reinforcement under its own weight, (c) and the ability to become homogeneous without the aggregates becoming segregated. The difference between conventional and self-consolidating concrete lies in the much greater flowability of the latter. Conventional concrete has a high level of bleeding, which can be seen from the slump test under ASTM C 143 (American Society for Testing and Material, 2011a); i.e., the bleeding exceeds 200 mm. SCC has a slump flow under ASTM C 1611 (American Society for Testing and Material, 2011b) that exceeds 600 mm, which results in a high level of cohesion and means that the concrete can flow into casing without the application of vibration. In addition, the viscosity of SCC is sufficient to overcome the friction between coarse aggregates. This property helps prevent the aggregates from becoming segregated and obstructing flow of the concrete when poured into the casing. The coarse aggregates and mortar should not become segregated in SCC.

2.1. *Filling ability*

According to both the **E**uropean **F**ederation of **N**ational **A**ssociations **R**epresenting Producers and Applicators of Specialist Building Products for **C**oncrete (EFNARC) (EFNARC, 2002) and the American Concrete Institute (ACI) (ACI, 2007), SCC has the ability to flow through heavily congested reinforcement under its own weight and the ability to become homogeneous without the aggregates becoming segregated (Skarendahl, 2000). Thus, fresh SCC has the ability to both flow under its own weight and through heavily congested reinforcement. Other important parameters include the effect on deformability, which refers to the reduction of internal friction between particles by reducing either the surface tension via a superplasticizer and/or the volume of coarse and fine aggregates, and by increasing the paste volume in order to improve filling ability (Gaimster and Dixon, 2003; Khayat, 1999; Sonebi and Bartos, 2002). Well-graded cement and powder can maintain a high water–cement ratio, thereby reducing inter-particle friction and rendering the paste less viscuous, both of which lead to less segregation and mitigate against excessive bleeding (Sonebi and Bartos, 2002). Some of the resulting bleed water (Beaupré et al., 1999) reaches the upper concrete surface, whereas some remains in bleed channels and under various obstacles such as aggregate and reinforcement. The effects of bleeding and the water–cement ratio, the latter of which is very high in this case, relate to the compressive strength and durability of concrete (Bartos, 1992). Ensuring adequate stability is especially critical in deep structural elements such as walls, where highly flowable concrete is necessary for adequate filling to occur. Such stability can be ensured by using a superplasticizer, which not only reduces the friction between particles but also maintains the concrete's deforming ability and viscosity (Chandra and Björnström, 2002; Björnström and Chandra, 2003). An increase in the water–cement ratio has a greater effect on the rigid concrete property than the amount of superplasticizer does.

The use of fine filler can enhance many aspects of cement-based systems through physical or chemical effects. Some physical effects are associated with the small size of the particles, which can improve the packing density of powder and reduce interstitial voids, thus decreasing the amount of entrapped water in the system. The use of a continuously graded skeleton of powder is reported to reduce the powder volume required to ensure that the concrete has adequate deformability. However, excessive fine particles can result in a considerable increase in the specific surface area of the powder, such that more water is needed to achieve the required consistency (Yahia et al., 2005). The use of mineral additives is important in binary and ternary systems. The advantages of a given material, however, can compensate for its disadvantages. For example, although a material that causes a high water-absorption effect negatively affects concrete, such a material would also develop the compact strength and durability of the concrete (Belaidi et al., 2012). The respective filling ability of each of the samples is shown in Table 1.

2.2. *Passing ability*

The ability to flow through reinforced concreted in the mold relates to the flowability of concrete in restricted areas such as complex reinforcement structures that are close together (Gaimster and Dixon, 2003). The important parameters are the space and arrangement of the reinforced structure, which must be considered in order to select the size and shape of the coarse aggregates in and the mortar volume of the concrete (Okamura and Ouchi, 2003). If the arrangement of the reinforcement structures is very dense, the amount of paste included in the concrete must be increased proportionally to the coarse aggregates. As defined by the Reunion Internationale des Laboratoireset Experts des Materiaux, Systemes de Construction et Ouvrages (RILEM) Technical Committee (Skarendahl, 2000; EFNARC, 2002; ACI, 2007), flowability refers to the ability to flow through tight openings such as spaces between steel reinforcing bars without segregation/blocking and the ability to pass among various obstacles and narrow sections in formwork