Eco-friendly GGBS Concrete: A State-of-The-Art Review

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Abstract. Concrete is the most commonly used material in the construction industry in which cement is its vital ingredient. Although the advantages of concrete are many, there are side effects leading to environmental issues. The manufacturing process of cement emits considerable amount of carbon dioxide (CO2). Therefore is an urgent need to reduce the usage of cement. Ground Granulated Blast furnace Slag (GGBS) is a by-product from steel industry. It has good structural and durable properties with less environmental effects. This paper critically reviews the literatures available on GGBS used in cement concrete. In this paper, the literature available on GGBS are grouped into engineering properties of GGBS concrete, hydraulic action of GGBS in concrete, durability properties of GGBS concrete, self-compacting GGBS concrete and ultrafine GGBS are highlighted. From the review of literature, it was found that the use of GGBS in concrete construction will be eco-friendly and economical. The optimum percentage of replacement of cement by GGBS lies between 40 - 45 % by weight. New materials that can be added in addition to GGBS for getting better strength and durability also highlighted.

1. Introduction

In cement production India stands next to china, which is the largest producer of cement in the world. Cement requirement will rise to 550-600 million tonnes per annum (MTPA) by 2025 in India [1]. Cement industries is one of the main cause for global warming as they are the main contributors of carbon dioxide. Hence there is an urgent need to reduce the usage of cement. This challenge can be addressed by using alternative materials which are less energy intensive and having lower carbon emissions like ground granulated blast furnace slag (GGBS), fly ash, silica fume, rice husk ash, wood ash, etc. Blast furnace slag is obtained as a by-product during manufacture of pig iron in steel plants. It is predicted that India will produce about 43.9 (MTPA) steel by 2020 [2]. About 0.45-0.50 tonne of blast furnace slag will be generated per tonne of steel. This will be a threat to the environment if it is disposed of as waste. Therefore, utilizing GGBS as a replacement to cement is a key to the environmental concerns of both the cement industry and steel industry.

GGBS is similar to Ordinary Portland Cement (OPC) in chemical composition. Since the advantages of GGBS are more, there is an urgent need to promote the usage of GGBS. The calcium content in GGBS is very small compared to cement therefore GGBS concrete will take more time attaining strength. The presence of lime stone powder or dolomite, or quick lime in GGBS may increase the number of Ca-OH bond which will enhance the early age strength without affecting pH of the concrete. Therefore replacement of cement by GGBS and other appropriate materials will give high early age strength and highly durable concrete.

2. Review of literatures

In 1889, Emil Langin of New York was discovered GGBS. United State started production of slag cement in 1896. The reaction of GGBS with water is a slow process. So an activator is necessary for GGBS for giving better strength properties. Nowadays 30-35% of GGBS is added in ready mix cement concrete plants because the calcium hydroxide released when portland cement reacts with water will act as an activator for GGBS. By 2000 itself, the researches started focused on the benefits
of usage of GGBS in concrete. In this paper the review of different literature divided is into three major groups such as properties of GGBS, types of GGBS concrete and chemical actions in GGBS concrete.

3. Studies focused on properties of GGBS
GGBS have advanced strength properties. In this section the review of literatures are grouped into engineering properties and durability properties of GGBS concrete.

3.1 Engineering properties of GGBS concrete
Oner et al [3] conducted experimental investigation for finding optimum percentage of GGBS for compressive strength in cement concrete. From the observation of thirty two mixtures, they concluded that more than 55% of GGBS replacement does not improve the compressive strength.

Chidiac and Panesar [4] carried out an investigation on concrete with GGBS as a replacement to cement. It was observed that the mechanical properties of concrete were influenced by the water content, quantity of GGBS and the curing period. The compressive strength improved as water binder ratio increased, due to better hydration. The increase in compressive strength was around 10% - 20% between 28 days to 120 days. It was also observed that the scaling resistance of GGBS concrete was inferior to that of OPC concrete.

Johari et al [5] discussed the effect of silica fume, metakaolin, fly ash, ground granulated blast-furnace slag and rice husk ash on flexural strength, compressive strength, elastic modulus, porosity and pore size distribution. The investigations revealed that with the addition of GGBS the workability of concrete increased. Early strength was found to be less particularly large amount of replacement levels due to the dilution effect. The GGBS specimens developed maximum strength between the ages of 28 and 90 days.

Babu and Kumar [6] stated that the reactivity of the slag is influenced by glass content and fineness of GGBS. They investigated the cementitious efficiency of GGBS at various replacement levels. They stated that the overall strength efficiency depends up on the age and percentage replacement of slag.

3.2 Durability properties of GGBS concrete
Bijen and Jan [7] described the effects of slag and fly ash on the mineralogy and microstructure of concrete. The advantages of addition of slag to the concrete in terms of durability were observed. GGBS and fly ash have finer pore size distribution than that of portland cement concrete. They concluded that slag concrete have increased resistance against chloride penetration also increases the resistance against sulphate attack and alkali silica reaction.

Osborne [8] conducted experiments to study the long-term durability of GGBS concrete. He made a comparative study on slag concrete based on the experiments conducted at site structures as well as laboratory specimens. It was concluded that structural concrete with 50% GGBS is suitable for ordinary or mild exposure conditions. Guidance towards the design, specification and application of slag concrete was provided for an economical ecofriendly concrete.

Koh et al [9] made ecofriendly prestressed concrete sleepers with concrete in which high-early-strength portland cement and fine aggregates was partially replaced by GGBF slag and rapid-cooling EAF oxidizing slag respectively. Through the testing in field, they concluded that the slag sleepers are eco-friendly prestressed sleepers having high mechanical and durability properties.

Yeau et al [10] analyzed the corrosion resistance of concrete containing ground granulated blast-furnace slag (GGBS) and ASTM Type I or ASTM Type V cement. The GGBS concrete specimens were subjected to Rapid Chloride Penetration (RCP) test, Accelerated Chloride Ion Diffusion (ACID) test, Accelerated Steel Corrosion (ASC) test and Half-cell Potential (HP) test to estimate the corrosion induced. The corroded area of the steel bars embedded in concrete was measured to confirm half-cell potential results. The test results revealed that the compressive strength of GGBS mixtures were stronger than that of control mixture after 28 days. It was concluded that the percentage of GGBS content, type of cement and concrete cover controlling the corrosion rate.
4. Studies focused on types of GGBS concrete

In this section the properties of concrete containing ultra-fine GGBS and the self-compacting concrete containing GGBS are discussed.

4.1 Ultrafine GGBS

Teng et al [11] conducted experiments with Ultrafine GGBS having surface area of 870 kg/m$^2$ and OPC of surface area 360 kg/m$^2$. They observed better workability and consistency for concrete with 30 % replacement of cement with UFGGBS. For UFGGBS the total surface area is more, therefore rate of hydration will increase. The rate of strength development of concrete increased and permeability of concrete is reduced due to reduced total pore volume. The UFGGBS concrete exhibited higher compressive strength, flexural strength, reduced porosity and chloride diffusion.

Lim et al [12] experimentally investigated the compressive strength, flexural strength, modulus of elasticity and chloride migration coefficient of UFGGBS concrete. Presence of UFGGBS in concrete will improve the rheology of concrete. The UFGGBS will reduce the permeability of concrete thus chloride penetration will reduce. Therefore UFGGBS have high resistance against corrosion.

4.2 Self-compacting GGBS concrete

Slag concretes are high performance concrete. Dinker and Sethy [13] proposed a new methodology for the mix design of GGBS self-compacting concrete. They fixed the percentage of slag by considering the strength requirements and efficiency. Experimental studies were conducted based on the proposed mix design and concluded that the high strength is only possible with optimum percentage of replacement. Higher percentage of replacement will create less strength concrete.

Othmane et al [14] found out that the replacement of cement with slag on self-compacting concrete is beneficial with the presence of polycarboxylate based superplasticizer through experimental investigation. The addition of slag in concrete will give more workability and strength. The early age strength was less for slag concrete. The yield stress and plastic viscosity decreases with increase of slag content.

5. Studies focused on hydraulic action of GGBS in concrete

Cement can be classified as hydraulic or non-hydraulic, based up on its ability to set with water. Hydraulic materials are set in wet conditions. Non hydraulic materials set as it dries and reacts with CO$_2$ in the air.

Barger et al [15] discussed the use of raw or processed natural pozzolans (ACI Committee 232). They have explained about the selection of natural pozzolans and its reactions with water. The hydraulic characteristic of GGBS are due to the chemical reactions involving Calcium, Silica and Aluminium constituents which react with water to form Calcium Silicate and Calcium Aluminate Hydrates. They concluded that the slow reaction of GGBS can be improved by the calcium hydroxide.

Whittaker et al [16] focused on the relation between changes in hydrate phase with mechanical performance of cement-slag mix. The effect of aluminium content on the hydration and microstructure of OPC-slag blends also discussed. Two slags with varying Alumina content were employed in the study. The XRD analysis showed that slag altered the chemistry of the hydration products. Slag exhibited slower hydration but the performance of slag was better at later stages due to changes in the composition of the hydrate. He proposed that addition of sulphate improved the early strength of the slag composites.

Siddique et al [17] investigated the hydration reaction of GGBS in the cement paste. The GGBS particles get activated by the alkali present in the cement and form their own hydration products. Some of the hydration products of GGBS react with Portland cement again to form hydrates which tend to block the pores. This results in a cement paste with very fine gel pores. The hardened cement paste is more stable due to lesser free lime content. GGBS does not contain any Tri Calcium Aluminate (C3A) and its inclusion in concrete reduces the overall proportion of C3A in the concrete mix and increases the sulphate resistance.
6. Discussion
GGBS have glassy and crystalline phases. Glassy phase consist of alumina-silicates of calcium, which are responsible for the cementitious properties in GGBS. Activation of GGBS is necessary for the hydration reaction in GGBS concrete. Activation of GGBS is possible with other alkali materials or ordinary portland cement. Therefore complete replacement of cement with GGBS is not possible. The formation of hydrates leads to pore blocking effect. Pore blocking effect is the main reason for chemically stable and hardened concrete.

Pozzolanic reaction occurs only in the presence of lime materials and water in GGBS. In Ca(OH)$_2$ saturated solution, the hydraulic reaction consumes Ca(OH)$_2$ and also produces Ca(OH)$_2$. Quantity of Ca(OH)$_2$ crystals depends on its formation itself. GGBS reduces the size of Ca(OH)$_2$ crystals[18]. Formation rate should be more than reaction rate for better reaction. The presence of other pozzolanic materials which contains calcium can improve the formation rate. The early age strength is possible with the addition of other pozzolanic materials in GGBS concrete.

The fineness of GGBS increases the strength and durability properties by providing lower permeability. The absence of C$_3$A made the GGBS less reactive to sulphate. These properties enhance the usage of GGBS in high performance concrete.

7. Summary
This paper highlights the review of research works conducted on GGBS. From the available literature, it is observed that,

- The inclusion of GGBS in concrete has several advantages like reduced heat of hydration, adequate ductility, reduction in the size of the concrete pores, improved strength at later stages, reduced primary energy usage and carbon emissions, lighter colour and better aesthetics etc.
- The concrete in which the cement is replaced 35-40% by GGBS have advanced durability properties such as increased resistance to sulphate attack, increased resistance to alkali silica reaction, reduced chloride ion ingress which enhances corrosion resistance
- The ultrafine GGBS have improved strength and durability properties. Calcium oxide which formed during the reaction between Portland cement and water can activate the reaction of GGBS which can improve the strength properties.
- Applications of optimum percentage of cement replacement by GGBS can be extend up to all structural elements of a building, bridges, prestressed elements etc.

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