DURABILITY PERFORMANCE OF HPC CONTAINING MK AND GGBS FOR MARINE ENVIRONMENT: A REVIEW

THOMAS GMAWLUE JR. and PANKAJ KUMAR

Dept of Civil Engineering, UIE, Chandigarh University, Mohali, India

High performance concrete (HPC) is designed to serve certain purpose and overcome certain environmental condition that normal concrete cannot achieve. Many supplementary materials in varieties of proportions have been incorporated to make HPC. This review study considered the partial replacement of cement by Metakaolin (MK) and Ground Granulated Blast-furnace Slag (GGBS). It provides information on the composition of marine environments and the mineral reactive admixtures as well as their usage while highlighting their behavior relating to chloride ion penetration, sulfate attacks and permeability. The scope of this study considers outstanding research articles, from 1980 to 2022, as well as major books on Marine Environment, Concrete Technology and Civil Engineering Handbooks as to reveal the various techniques that engineers and researchers have used to optimize concrete performance in marine environment. This study found out that the incorporation of MK and GGBS greatly improves HPC in marine environment but the pattern of their influence varies per the durability parameter; the increment in quantity of each mineral admixture incorporated in the concrete were found to have either progressive or retrogressive effect towards chloride ion diffusion and gas permeability but progressive enhancement trend when resisting sulfate attacks. Also, water to binder ratio greatly influence the HPC in relation to the admixtures. It is concluded that MK level from 10% to 15% and GGBS level from 40% to 60% have optimal performance in most harsh conditions of marine environment.

Keywords: Mineral admixture, Chloride ion penetration, Permeability, Sulfate.

1 INTRODUCTION

Ordinary concrete may fail to give the required quality performance or durability (Shetty 2000); in such cases, high performance concrete (HPC) that has substances and proportion of ingredients different from normal concrete is used. HPC is a concrete that is designed to meet special combination of uniformity and performance requirements that cannot always be achieved typically when conventional ingredients and regular mixing, placing and curing places are used (ACI 2018). For this reason, additional substances known as admixtures—materials other than cement, aggregates and water—have been added to produce HPC; there are many types of admixtures which are classified into chemical and mineral admixtures. Chemical admixtures intended to affect workability while mineral admixtures are intended to enhance the properties of hardened concrete.

In this light, this review paper is focused on HPC designed for better performance in marine environment. Researchers have used many admixtures and this study reviewed the usage of
Metakaolin (MK) and Ground Granulated Blast-furnace Slag (GGBS) because of their potential environmental and economic benefits. The prime aim of this review paper is to agglomerate the findings of other researchers in a systematic manner on how MK and GGBS are used to design HPC and their performance in regards to permeability, sulfate attacks and chloride ion penetration.  

2 DETERIORATION OF CONCRETE IN MARINE ENVIRONMENT  

Firstly, let us consider the ocean, the environment with saline water, which is the most severe one. According to Santhanam and Otieno (2016), there are three main exposure conditions for reinforced concrete structures which include the atmospheric, tidal and submerged zones. Table 1 concisely outline the transportation medium—means through which aggressive substances penetrate the concrete—and their deterioration mechanisms.  

The chemical composition of seawater clearly depicts the adversity of structures in or nearby such region as indicated by Santhanam and Otieno (2016). Their study reveals that chloride ions (Cl\(^{-}\)) are the most dominant with concentration reaching as high as 36.9 g/l. The sulfates are also high and they are contributed by magnesium sulfate (\(\text{MgSO}_4\)); structures in contact or in close proximity to such water will have to face high Cl\(^{-}\) concentration. When these ions react with the chemical composition of cement, they cause concrete phases to be altered. For example: calcium hydroxide in cement is altered into gypsum, brucite and aragonite; calcium silicate hydrate (CSH) is altered into decalcified CSH or magnesium silicate hydrate.

Table 1. Deterioration mechanisms of concrete at various zones in seawater (Santhanam and Otieno 2016).

<table>
<thead>
<tr>
<th>No.</th>
<th>Zones</th>
<th>Transport Mechanisms</th>
<th>Deterioration Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Atmospheric</td>
<td>Gaseous and water vapor diffusion</td>
<td>Carbonation-induced</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chloride-induced corrosion (most severe)</td>
</tr>
<tr>
<td>2</td>
<td>Tidal</td>
<td>Wick action, diffusion, sorption and permeability</td>
<td>Mechanical actions of waves cause erosion and abrasion; drying cycles caused salt crystallization</td>
</tr>
<tr>
<td>3</td>
<td>Submerged</td>
<td>Permeation and diffusion</td>
<td>Sulfate attack and chloride-induced corrosion</td>
</tr>
</tbody>
</table>

3 COMPOSITION OF MK AND GGBS  

Metakaolin is processed from a high-purity kaolin clay by calcining the clay in temperature range of 700 °C to 800 °C and grounding it into a fine powder with particle size between 1µm to 2µm. It has a white or cream color; a specific gravity of approximately 2.5 and surface area of approximately 20 m\(^2\)/g (Nawy 2008). The particle size and specific gravity are smaller when compare to ordinary Portland cement (OPC) which has 15 µm and 3.15, respectively. Although MK can have some pozzolanic properties, it becomes highly reactive when unreactive impurities are removed by water processing; such high reactive MK reveals high pozzolanic reactivity and reduces calcium hydroxide as early as one day and it makes cementitious material denser (Shetty 2000). In order to give insight of these properties range, Table 2 presents the most dominant chemical properties of MK and GGBS that were investigated by three different researchers (Buchwald et al. 2009, Al-Oran et al. 2022, Chen et al. 2021) at different localities. Silicon dioxide (\(\text{SiO}_2\)) and aluminum oxide (\(\text{Al}_2\text{O}_3\)) in MK are higher than GGBS while the ferric oxide (\(\text{Fe}_2\text{O}_3\)), calcium oxide (CaO), and magnesium oxide (MgO) in GGBS are higher than MK.
### Table 2. Chemical composition of MK and GGBS.

<table>
<thead>
<tr>
<th></th>
<th>Chen et al. Findings</th>
<th>Al-Oran et al. (2022) Findings</th>
<th>Buchwald et al. (2009) Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MK (%)</td>
<td>GGBS (%)</td>
<td>MK (%)</td>
</tr>
<tr>
<td>SiO₂</td>
<td>53.65</td>
<td>31.57</td>
<td>52</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>43.12</td>
<td>15.27</td>
<td>46</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.76</td>
<td>0.23</td>
<td>0.4</td>
</tr>
<tr>
<td>CaO</td>
<td>0.17</td>
<td>43.18</td>
<td>1.2</td>
</tr>
<tr>
<td>MgO</td>
<td>0.06</td>
<td>6.68</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Ground granulated blast-furnace slag (GGBS) is a by-product of the iron industry created when the molten slag melted from iron ore is rapidly quenched and grounded into fine powder (Anand et al. 2017); its specific gravity ranges from 2.85 to 2.95; an average particle size of 9.2μm (Divsholi et al. 2014). Most slags naturally possess pozzolanic properties while others become pozzolan when mixed with activators such as Portland cement and calcium sulfate.

## 4 INFLUENCE OF MK AND GGBS

MK influences the concrete by reducing the porosity, water absorption and resistance to acid attacks (Douamba et al. 2018); this is due to its smaller particle size and larger surface area that were discussed in the previous chapter. Wherever MK is incorporated, researchers have also observed that water to cementitious material (w/cm) ratio plays major role in the durability performance. W/cm ratio in the range of 0.33 to 0.5 have been successful for HPC incorporating MK (Curcio et al. 1998, Al-Akhras 2006, Elavarasan et al. 2021).

Like MK, the partial replacement of cement with GGBS influences the concrete by reducing the pore structure of the concrete pastes (Malhotra 2008, Qu et al. 2021); thereby, reducing penetration rate of deleterious substances of the marine environment. It is worth noting that the porosity of GGBS-induced HPC decreases with age (Qu et al. 2021). Another cardinal factor that researchers have considered is the w/cm ratio which ranges from 0.28 to 0.6 (Brooks et al. 2000, Elavarasan et al. 2021); however, this ratio is highly dependent on the magnitude of GGBS incorporated in the concrete.

### 4.1 Resistance to Chloride-ion Penetration

Cement has been partially replaced (5% to 20%) by MK when designing HPC. Watanabe et al. (2004) did a durability study on bridge piers and found out that maintaining w/cm ratio of 0.44 and maximum coarse aggregate of 25mm, partially replacing cement with 10% MK reduced the Coulomb charge penetrating the concrete from 4978 to 2274; thereby making the MK-induced concrete pier to perform two times better than the normal concrete pier in regards to chloride ion penetration. In fact, as the percentage of MK increases, the opposition to chloride ion increases even if the w/cm ratio is held constant. Li et al. (2015) used freshwater and seawater for mixing separately while keeping the w/cm ratio at 0.45; however, resistance of the mixture to chloride ion penetration was still highly influenced by the MK content.
The partial replacement of cement by GGBS improves the concrete resistance to chloride ion penetration; however, the performance greatly relies on the w/cm ratio and the duration of exposure; it has been found that the increment of GGBS is inversely proportional to the increment in w/cm ratio. Basha et al. (2020) use the ponding test to predict the chloride ion penetration of reinforced concrete structures and found out that at 0.3 w/cm ratio, 70% GGBS content had better resistance to chloride ingress and at 0.5 w/cm ratio, 50% GGBS content had better resistance to chloride ingress as seen in Figures 1 and 2. Research has also revealed that the increase in GGBS level negatively affects the concrete when the calcium hydroxide provided by cement is not sufficient for the total pozzolanic reaction due to high GGBS content (Qu et al. 2021).

4.2 Resistance to Sulfate Attack

The incorporation of MK is one of the effective ways in which concrete structures can have better performance in regions that are prone to sulfate attacks. Al-Akhras (2006) experimentally studied the influence of MK on durability of concrete against sulfate attack and concluded that the sulfate resistance improves with increase in the MK levels; the study also noted that lower w/cm and autoclave curing method could give further resistance; MK replacement levels at 10% and 15% give better performance; Siddique and Klaus (2009) review on MK influence on the properties of mortar and concrete also attests to this. When air-entrainment is used, concrete tends to have poor resistance to sulfate attack but the incorporation of MK will compensate for such deficit and improve the concrete resistance to the sulfate attacks (Al-Akhras 2006).

The incorporation of GGBS gives concrete high performance against sulfate attacks. It has been reported that the higher the GGBS content, the better the concrete will resist sulfate attacks when exposed to sulfate prone environment; 40% to 65% significantly enhance sulfate resistance (Hogan and Meusel 1981). Even mortars containing GGBS up to 70% has shown superior performance than the ones containing only sulfate-resisting cement; the concretes with low GGBS content is inferior to the ones with high content (Frearson 1986).

4.3 Resistance to Permeability

The rate at which water and other liquid penetrate concrete can be reduced by partially replacing cement with MK. McCarter and Watson (1997) carried out a study on the influence of wetting and drying on cover zone by partially replacing OPC with MK, GGBS, FA and Micro Silica (MS); concretes which contained MS and MK produced the lowest sorptivity—the ability to absorb and transmit liquid—even under poor curing conditions. While studying the transport
mechanisms of MK blended concrete, Shekarchi et al. (2010) found out that concrete incorporating 15% highly reactive MK improves water penetration as well as gas permeability up to 50%.

The performance of GGBS-induced concrete towards permeability varies with the percentage of GGBS content in the concrete. Research has shown that higher GGBS percentage in concrete gives concrete denser structure and prevent water permeability (Manmohan and Mehta 1981). On the other hand, it has been discovered that the decrease in porosity of GGBS-induced concrete does not solely correspond with the decrease in permeability. Aghaeipour and Madhkhan (2017) investigation found out that at 60% GGBS, permeability increased even though porosity decreased. Likewise, Shi et al. (2009) revealed that gas permeability slightly increases with GGBS content up to 60% and w/cm ratio held at 0.3; however, when the w/cm ratio was increased to 3.5 and GGBS content decreased to 30%, the gas permeability was a bit lower than concrete without mineral admixtures. Although the physical property of GGBS refines the pore structures, the influence of the chemical composition on pozzolanic activities could be responsible for this inverse reaction.

5 RESULTS AND DISCUSSION

This review study has revealed that the pattern of influence per the environmental exposure characteristics varies. The increase in MK level leads to improvement in resistance to chloride ion penetration while increase in GGBS level will influence the concrete depending on whether the w/cm ratio is sufficient to accommodate such GGBS content. As for the resistance to sulfate attacks, the increase in MK and GGBS incorporation into concrete lead to continuous improvement. The incorporation of MK and GGBS improves water permeability; however, GGBS may have positive or negative influence on gas permeability due to the w/cm ratio.

6 CONCLUSION

This research review study concludes that the incorporation of MK and GGBS surely improves the durability performance of concrete when resisting Cl– penetration, sulphate attacks and permeability in marine environment. It is recommended that serious care be taken when incorporating high GGBS content because it may have negative effect on Cl– penetration and gas permeability as mentioned in previous paragraphs. Furthermore, this study recommends that MK level from 10 to 15% and GGBS level from 40 to 60% should be used as ideal cement replacement levels in HPC as they have shown good durability performance for marine environment.

References


