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Influence of blended cements on corrosion rate of steel in reinforced concrete structures in a marine tidal zone – a review

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ABSTRACT

Reinforced concrete structures in the marine environment experience early deterioration problems due to chloride-induced steel corrosion. High chloride concentrations available and the waving action in exposure conditions such as the marine tidal zone makes the steel reinforcement vulnerable to corrosion. For this reason, modern procedures for reinforced concrete design are aimed at designing concrete that can resist weathering as well as corrosion to maintain quality and serviceability when exposed to the harsh marine environment. The use of blended cements in modern concrete production is notably increasing. This is because the introduction of supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBS), fly ash (FA), silica fume (SF), etc., to produce blended cements in concrete technology produces dense and impermeable concretes. However, SCMs show different characteristics and performance under different exposure conditions. The main aim of this paper is to critically review the influence of blended cements on the rate of corrosion in concrete exposed in a marine tidal zone. This paper also explores the suitability of the classification of exposure zone in the marine environment used in European standards (EN 206), adopted in South Africa.

Keywords: Blended cement, Reinforced concrete, Chloride-induced corrosion, Corrosion rate, Marine tidal zone.

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1. INTRODUCTION

Reinforced concrete (RC) structures in the marine environment experience premature deterioration problems due to chloride-induced steel corrosion. High chloride concentrations available and the waving action in exposure conditions such as the marine tidal zone make the steel reinforcement vulnerable to corrosion. Depending on the exposure conditions, chloride ions in seawater can penetrate the concrete by diffusion, convection, permeation, and wick action [1]. However, a combination of convection and diffusion is the dominant mode of chloride transport in a marine tidal exposure conditions.

For steel corrosion to be initiated, a certain amount of chlorides (referred to as chloride threshold) at the level of steel is required [2, 3, 4]. Consequently, the passive protective oxide layer around the steel reinforcement, which is formed as a result of high pH conditions (ranging from 12 – 13) in the concrete pore structure is disturbed and subsequently leading to corrosion initiation [5]. The corrosion initiation is followed by the formation of cracks, spalling of cover concrete, etc. in the propagation phase [6]. The propagation phase is mostly influenced by the availability of moisture and oxygen [1, 5].

Modern design procedures are aimed at designing RC structures that can resist weathering and corrosion to maintain quality and serviceability when exposed to the harsh marine environment. The use of blended cements incorporating supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBS), fly ash (FA) and silica fume (SF) in modern concrete production has therefore increased. This is because blended cements produce dense and impermeable concretes [7] that improve the durability of RC structures [9,10].

This paper critically reviews the influence of blended cements on steel corrosion in RC structures in a marine tidal zone. This will enable engineers with the knowledge to enhance the service life of reinforced concrete structures with blended cements. It also explores the suitability of the classification of exposure zone in the marine environment used in European standards [11], adopted in South Africa [12].

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2. SUPPLEMENTARY CEMENTITIOUS MATERIALS

Supplementary cementitious materials (SCMs) are used to partially replace a portion of plain Portland cement (PC). FA, GGBS, and SF are the most commonly used SCMs in South Africa. These materials are categorised as pozzolans and hydraulic materials [13]. The incorporation of SCMs in concrete improves its durability properties through pozzolanic or hydraulic activity, or a combination [13].

For example, low calcium FA, SF and other natural pozzolans such as metakaolin (calcined clay) and volcanic ash exhibit pozzolanic behaviour when used in concrete, whereas high calcium FA exhibits both pozzolanic and hydraulic reactions. In contrast, GGBS exhibits limited hydraulic behaviour due to its ability to form hydration products when in contact with only water [13]. For this reason, hydraulic SCMs can, independently of plain PC, harden or gain strength, however when jointly used with PC, chemical reactions are accelerated [13].

Guneyisi et al. [14] studied the properties of different SCMs and their durability performance when used in concrete. A performance variation in reinforcement corrosion and concrete resistivity was observed, where other SCMs yielded better resistance to reinforcement corrosion than others, based on their replacement levels. Further, they highlighted that the performance variation was attributed to SCM physical, chemical, and mineralogical composition as a result of their production and the properties of the raw material used. Other studies found that SCMs reduce the amount of calcium hydroxide in concrete due to the dilution effect and pozzolanic reaction [15, 16]. As a result, the reduction of calcium hydroxide weakens the passivity of the reinforcing steel [17]. Therefore, careful consideration of the type and the content of the SCM to be used in a particular concrete mixture is paramount because of the varying impact of SCM on concrete properties, which in turn influences their durability performance. The reader is referred to Thomas [13] for in-depth details on the origin of SCMs.

3.THE INCLUSION OF BLENDED CEMENTS IN CONCRETE

3.1 Influence of blended cements on corrosion rate

Lopez-Calvo et al. [18] studied the influence of cover depth on the corrosion of steel in high-performance concrete (HPC) against the concrete quality and specimen crack width in laboratory simulated tidal conditions. The concrete contained corrosion inhibitors and 20% fly ash. A reduction in corrosion rate was observed in concrete specimens containing fly ash, regardless of the concrete cover and crack width. Similarly, Otieno et al. [19] conducted an experimental study on chloride-induced corrosion of steel in an accelerated (cyclic wetting and drying) and natural marine environment. A variation in cover depth of 20 mm and 40 mm was employed. The concrete specimens were made of 100% PC and a partial replacement of the Portland cement with SCMs (30% FA or 50% GGBS). They observed that the inclusion of SCMs results in a significant decrease in corrosion rate at a given cover depth.

In a recent study, Baten et al. [20], checked the corrosion vulnerability of RC structures using different blended cements and a variation in cover depth. In concrete mixes containing “30 - 40%” of GGBS, the results yielded moderate resistance to corrosion. The study further pointed out that the performance of GGBS concretes improved with the increase in cover thickness and higher compressive strength values. Whereas concrete mixed with “30 - 40%” FA yielded higher corrosion resistance even at lower cover depths but with slow strength development. The high corrosion resistance may be attributed as a result of higher silica content and a larger amount of calcium-silicate-hydrate (C-S-H) in FA concretes, with the latter leading to a more refined pore structure, hence stifled corrosion [21].

Further, Otieno [10] showed that the diffusion coefficient values of GGBS concrete, at different water to cement (w/c) ratios, were lower than those of FA concretes. This indicated that, based on the replacement levels used in that study, GGBS concrete had better durability performance than FA concrete concerning the ingress of chlorides, moisture and oxygen, hence lower corrosion risk. The better performance of GGBS than the other SCMs was also observed in a review by Yi et al. [22]. These studies reveal that SCMs show different characteristics and performance. Hence, it is important to provide engineers with enhanced knowledge to specifically select binder types suitable for a particular exposure zone, consequently assisting in improving the service life predictions of structures in the tidal zone of the marine environment.

Scott and Alexander [23] studied the influence of binder type, cracking and concrete cover on the rate of corrosion and resistivity in chloride-contaminated concrete. The specimens were exposed to cyclic wetting and drying. The results showed that SCM concretes (incorporating FA, GGB and SF) had higher resistivity compared to PC concrete, thus reducing the rate of corrosion of reinforcement. Therefore, they concluded that in blended concretes, concrete resistivity governs the occurrence of corrosion and results in low oxygen diffusion. Also, the results of Chang et al. [24] concur with these findings. Where the incorporation of GGBS resulted in low oxygen diffusion due to a denser microstructure exhibited by blended concrete. Therefore, an understanding of the influence of oxygen and moisture content on the corrosion rate is significant, especially for structures in a marine tidal zone, taking into account the influence of drying and wetting durations and SCMs under varied cover depths.

3.2 Influence of blended cements on chloride ingress

Chloride ingress is the primary cause of corrosion of reinforcement in chloride contaminated reinforced concrete structures. The concrete pore solution, concrete quality, exposure conditions, curing regime, cement composition, etc. influence chloride penetration into concrete [25].

Simcic et al. [26] investigated the chloride penetration profiles for mixtures exposed to cyclic wetting and drying conditions for 21, 42, 84, 105, and 126 days. The concrete mixtures incorporated unmodified and modified (with fly ash) cement. From their results, modified concrete showed lower chloride concentrations compared to the unmodified concrete in each observation. This was as a result of the dense microstructure in modified concrete. Also, Thomas and Moffatt [27] reached similar conclusions, where concretes incorporating SCMs (such as GGBS, FA and SF) yielded lower chloride penetrations than the PC concrete for structures exposed to different marine conditions (including tidal zone) for 25 years.

The use of supplementary cementitious materials as a partial replacement for Portland cement in concrete applications shows a high chloride binding capacity and great resistance to chloride penetration to the level of reinforcing steel [25, 26, 27, 28,29], thereby limiting the rate of corrosion in blended concretes. Furthermore, Chalhoub et al. [30] investigated the critical chloride threshold values as a function of cement type and steel surface. It was found that a low w/c ratio increased the chloride threshold value. Furthermore, blended concretes also exhibited higher chloride threshold values for the same low w/c ratio. These findings support the conclusion by Angst et al. [31] that concrete quality (which is affected by w/c ratio and cement type) influences the transport mechanism of aggressive fluids and gasses in concrete in aggressive environments such as the marine tidal zone, hence the significance of concrete quality in concrete durability assessments as well as service life predictions.

Moradllo et al. [32] quantified the convection zone depth and its influence on chloride profiles and service life prediction of concrete structures in a marine tidal zone for five years. The convection zone is generally known to consist of high chloride concentrations. Two w/c ratios (0.35 and 0.5) and silica fume were used in the mix. The concrete with low w/c ratio of 0.35 yielded a 50% decrease in the convection zone depth compared to a w/c ratio of 0.5 due to the high permeability of the latter.

Guneyisi [33] examined the effect of initial curing on chloride ingress and corrosion resistance using different binders. The results showed that initial curing had an influence on chloride penetration for all concretes. Nevertheless, the rate of chloride ingress and corrosion was found to be dependent on the w/c ratio as well as the cement type. Similarly, the influence of w/c ratio as well as cement type on chloride diffusion and corrosion rate was also noted by van der Wegen et al. [34].

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4. REVIEW OF EXPOSURE CLASSIFICATION IN SANS 10100-2: 2013

This section explores the suitability of the classification of exposure zones in the marine environment used in European standards (EN 206-1), adopted in South Africa (SANS 10100-2) [35]. The standard classifies the marine tidal zone and splash and spray zone as the most severe exposure conditions. However, the results from the field observations presented in Moore [1] challenge this classification because of a notable difference in corrosion severity, with the tidal zone exhibiting little or no signs of corrosion. Furthermore, findings from laboratory investigations of the same study, suggest an adjustment of the tidal zone to the submerged category based on the thickness of concrete cover (greater than 30 mm). However, it should be noted that the study only focussed on the use of PC in concrete, and due to the difference in concrete resistivity, concrete pore solution, oxygen diffusion rate, etc., when using blended cements, the results may differ. Hence, there is a need for further research when using SCMs.

Therefore, the classification of exposure classes indicating the severity of corrosion damage need to be refined taking into account the type of cement used and cover depth adopted. This will enable more precise durability design specifications depending on the exposure classes, leading towards sustainable design practice.

5. CONCLUSIONS

In this study, a review of the influence of blended cements on the corrosion rate of reinforced structures is presented. The study also explores the suitability of the exposure zone classification in the marine environment as per the adopted standard in South Africa. The following conclusions can be drawn:

- The inclusion of SCMs such as fly ash, ground granulated blast-furnace slag and silica fume, as partial replacement for PC, results in a more refined concrete microstructure and high concrete resistivity. Consequently, it leads to a reduction in the corrosion rate. Notably, GGBS concretes are reported to exhibit better durability performance than other SCMs from the reviewed studies.
- SCMs as a partial replacement for Portland cement in concrete applications show a high chloride binding capacity and great resistance to chloride penetration. Furthermore, the reviewed literature also reveals that the w/c ratio is influenced by the performance of SCMs to inhibit chloride penetration, where chloride ingress was inhibited even at relatively high w/c ratios. In addition, the concrete cover was shown to influence the reduction of diffusion of oxygen to the level of the reinforcement.
- Studies from the literature suggest that the current exposure zone classification of the marine tidal zone must be adjusted to the submerge category taking into account the influence of cover depth. However, more research, based on more field investigations and the incorporation of SCMs, is needed to support this notion.

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