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Assessing the corrosion performance for concrete mixtures made of blended cements

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HIGHLIGHTS

- High slag cement (CEM III/A) significantly improves concrete corrosion protection.
- No significant protection advantage was achieved in case of replacing 20% (CEM III/A) with fly ash.
- Optimum, rather than the highest, cement content provides best corrosion protection.
- Protection improvement was more efficient for large cover and low water/binder.

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ABSTRACT

Although it has been used worldwide for decades, manufacturing of Blast Furnace Slag Cement (CEM III/A) has boomed since it was specified in the Egyptian Cement Standard ESS 4756 on 2006. However, corrosion protection efficiency of the Egyptian (CEM III/A) cement has rarely investigated. Therefore, in this research work corrosion performance was investigated for different concrete mixtures made of Egyptian manufactured (CEM III/A 42.5N), (CEM III/A 42.5N) partially replaced with fly ash and Ordinary Portland cement (CEM I). A total of 432 reinforced concrete (i.e. lollipop) specimens were exposed to impressed current accelerated corrosion technique. In addition to the cement types, the corrosion influence of the concrete mixture water/binder (w/b) ratio and cement content were assessed as well as the impact of reinforcement cover and exposure duration on reinforced concrete specimen's corrosion performance. The corrosion protection was assessed by the corrosion current and it was quantified by measuring the rebar diameter loss. The chloride ion penetrability, water permeability and measured corrosion current were significantly reduced by replacing (CEM I) with either (CEM III/A) or (CEM III/A + FA) cements specially for large reinforced concrete cover having optimum cement content and minimum w/b ratio with suitable workability.

1. Introduction

Generally, new cement types are being promoted with many objectives among them: cost saving, environmental protection; leading to reduction of the carbon dioxide emission and hence contributes to the global warming problem. Moreover, many new types of cement targeted conserving the resources, and decreasing the production energy [1–3]. Therefore, using mixture of cement clinker and cementious supplements – such as Ground Granulated Blast Furnace Slag (GGBS) or fly ash (FA) – in concrete production usually addresses deterioration, economic and environmental aspects corresponding to the use of cement clinker. It also improves some properties of both fresh concrete (e.g. enhance cohesion and workability) [2–5], and hardened concrete (e.g. improve durability long-term strength) [2–7]. Five main different cement groups were introduced to Egyptian standard specification for cement ESS 4756 on 2006 [8], providing a total of 27 new different cement types. With intentions to enhance the concrete performance and reduce the environmental impact of cement industry; the use of these five different cement groups was promoted. On the other hand, cement classification, provided in the Egyptian Standard, is very close to the European Standards EN 197-1 [9].

Corrosion of embedded steel rebars in concrete are one of the main and important causes of reinforced concrete deterioration. Corrosion of the embedded steel rebars in concrete plays a vital role in the determination of the durability and life time of the concrete structures [10]. Moreover, corrosion activity depends on the exposure conditions; such as the availability of moisture and

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chloride ions, in addition to some concrete; such as the electrical resistivity [11–13]. General (i.e. uniform) and pitting (i.e. localized) are the known types of corrosion. The most direct effect of corrosion is the reduction in reinforcement diameter and cross-sectional area. This may have a significant effect on the structural safety and integrity of the reinforced concrete element, if the loss of section is severe and the working stresses in the reinforcement are high. Additionally, Corrosion of steel produces an insoluble chemical by-product commonly known as rust products, which have a volume of 3–8-fold compared to the original metal volume [14,15]. This generates expansive stress around corroded embedded steel rebars causing cracking, spalling, and delamination of the concrete cover and bond loss between steel rebars and concrete, which further accelerates corrosion and thus reducing the serviceability of concrete structures. [3–16]. Most of researches divided the reasons of rebar corrosion into two main parts, the first contains the external condition such as exposure time, and surrounding environment [10]. Whereas, the second part is concerned with concrete mix and constituents such cement type, water/cement ratio, cement content, and percentage of mineral cementious supplement [2–17].

The impressed current method for lollipop samples is one of the most famous and reliable corrosion acceleration methods and it has many advantages, such as obvious saving in time and cost, providing different steel reinforcement exposure lengths and concrete covers. Additionally, it is considered as the easiest way of carrying and transporting the sample. One advantage over other techniques is the ability to control the rate of corrosion by changing the resistivity, oxygen concentration and temperature. The process of steel corrosion in both accelerated and normal corrosion techniques is similar [3–16].

The objective of the present work is to assess the influence of local High Blast Furnace Slag Cement (CEM III/A) -separately or after partial replacement with fly ash- on reinforced concrete corrosion performance. In order to implement this program, the following parameters were considered:

1. Concrete constituents; specifically; binder type, binder content and w/b ratio according to the following scheme;
   a. Binder type: (CEM I 42.5N), (CEM III/A 42.5N) and (CEM III/A 42.5N + 20% FA).
   b. Binder content: 350, 400 and 450 kg/m^3.
   c. Water/binder (w/b) ratio: 0.45 and 0.55
   The investigated binder contents and w/b ratios are selected based on the commonly used values.
2. Reinforced concrete specimens cover and elapsed time under severe exposure.
   a. Specimen cover: 1.9, with exposure period 1, 3, and 7-day (168-h)
   b. Specimen cover: 4.4, with exposure period: 3, 7, and 20-day (480-h)

Impressed current accelerated corrosion technique was used to assess the corrosion performance of steel rebars embedded in different mixtures and sizes of concrete specimens (i.e. lollipop).

2. Materials and testing method

2.1. Materials

Three types of Egyptian manufactured cements, as different binding materials, were used in this experimental works; namely:

1. Ordinary Portland cement (CEM I 42.5N)
2. Blast Furnace Slag Cement (CEM III/A 42.5N)
3. Blast Furnace Slag Cement (CEM III/A 42.5N) partially replaced with 20% of locally available Fly ash (FA), Class-F according to ASTM C618 [18]. The 20% fly ash replacement was chosen as this ratio was recommended for durable concrete [19–24].

The specific surface area, specific gravity, and the compressive strength, for the investigated cementitious materials are showed in Table 1. On the other hand, the chemical analysis of cementitious materials showed in Table 2. Standard aggregates (i.e. coarse and fine), complied with ASTM C33 [25] and ES 1109/2002 [26] limits, were used for making concrete lollipop specimens. The used coarse aggregate was dolomite with maximum nominal size of 10 mm, where the specific gravity was 2.66 and 2.7 for coarse aggregate and sand respectively. The aggregate fineness modules were 2.47, and 6.53 for sand and coarse aggregate respectively while the combined aggregate was 5.27. The used aggregate was in saturated surface dry (SSD) condition and complying with ECP 203-2007 [27] limits. Super-plasticizer (SP) – type (G) was used with a specific gravity of 1.19, and pH value 8.3 to achieve the desired fairly constant workability in all concrete mixtures.

2.2. Concrete mixtures proportions

A total of eighteen mixtures were designed with two different w/b ratios of 0.45 and 0.55, and three different binder contents (350, 400, and 450 kg/m^3). Different percentage of (SP) was used, according to initial exploratory mixes, to achieve slump (i.e. 120–220 mm) suitable for easy compaction. Concrete mixtures were cast with the aforementioned different cementitious materials while the mixture's proportions are given in Table 3. The mixture's identifications were adopted to represent the main parameters. The letter (C) stands for control mixtures cast with ordinary Portland cement (CEM I 42.5N), the letter (S) stands for mixtures cast with (CEM III/A 42.5N) cement and the abbreviation (SFA) stands for mixtures containing (CEM III/A 42.5N + 20% FA). On the other hand, the numbers 35, 40, and 45 stand for binder contents 350, 400, and 450 kg/m^3; while the label A, and B stand for 0.45, and 0.55 w/b ratio respectively. The slump test was performed according to ECP 203-2007 [27] within 2 min after mixing.

2.3. Concrete specimen's preparation

Lollipop concrete specimens with 5 cm, and 10 cm diameter were designed to provide two different concrete cover thicknesses which were (1.9 cm, and 4.4 cm) with embedded rebar length of 15 cm. To assure corrosion initiation through the concrete cover of the lollipop specimen, 6 cm of the steel bar's length was zinc-rich coated such that 3 cm are on the embedded part and the other 3 cm are on the free part as shown in Fig. 1. Cubes with 15 × 15 × 15 cm dimensions were cast to determine the concrete compressive strength. On the other hand, 10x20cm cylinders were also cast to measure permeability and rapid chloride penetration. All the concrete specimens were water cured for 56-day as shown in Fig. 2.

2.4. Compressive strength test

Cube specimens were tested to determine the concrete compressive strength at the ages of (7, 28, and 56-day). Testing specimens at the ages of (7, and 56-day) was performed to investigate the strength gain for the different binder types.

Table 1
Specific surface area of different cementitious materials.

Cementitious Type	Specific surface area (cm^2/g)	Specific gravity	Compressive strength (MPa)
CEM I 42.5N	3218	3.13	46.2
CEM III/A 42.5N	4234	2.91	42.6
Fly Ash	4196	2.38	–
CEM III/A 42.5N + 20% FA	4215	2.78	40.1

Table 2
Chemical analysis of different cementitious materials.

Sample	CEM I 42.5N	CEM III/A 42.5N	Fly Ash
SiO_2	20.57	21.96	85.75
CaO	62.13	60.93	0.81
MgO	2.13	1.00	0.11
Fe_2O_3	3.45	3.22	2.66
Al_2O_3	5.02	4.70	6.70
Na_2O	0.4	0.42	0.53
K_2O	0.16	0.17	0.17
Cl	0.09	0.03	0.03
SO_3	3.05	2.69	0.02
L.O.I	1.95	2.74	2.74
Total	99.95	99.96	99.55