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Mechanical properties and durability performance of reinforced concrete containing fly ash

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HIGHLIGHTS

- Marked improvement on long-term compressive strength of fly ash concrete.
- Significant reduction on porosity/sorptivity of fly ash concrete.
- Noticeable improvement of elastic modulus at 5% w/w addition of fly ash.

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ABSTRACT

This study presents the effect of Greek fly ash as a partial replacement of cement, on the durability and mechanical resistance of reinforced concrete immersed in sodium chloride (NaCl) solution. The aforementioned additive was used at 5% w.w and 10% w.w cement replacement. The compressive strength and static elastic modulus of the laboratory produced concrete specimens were measured after partial immersion in 3.5% w.w NaCl solution. Furthermore, the anticorrosive effect of fly ash was determined with measurements of open porosity and sorptivity, calculation of chloride concentration and mass loss of steel reinforcement embedded in cement mortars. The experimental results showed that the use of Greek fly ash improves the compressive strength and elastic modulus of concrete at all ages. Moreover, the porosity and sorptivity were decreased in the presence of the aforementioned additive. In addition, the theoretical mass loss of steel reinforcement embedded in cement mortars with 5% w.w fly ash addition was equal to that of reference concrete after 13 months of exposure in sodium chloride environment.

1. Introduction

Material deterioration and corrosion of steel reinforcement are the two most significant durability problems reinforced concrete structures are facing. A wide variety of protection methods such as corrosion inhibitors, galvanization, epoxy coating, re-alkalization of carbonated concrete, cathodic protection, and electrochemical chloride extraction, have been used to prevent the corrosion of steel reinforcement in polluted environments [1–4]. Moreover, the use of industrial wastes or by-products such as fly ash, blast-furnace slag and silica fume, has been shown to positively affect concrete hydration [5], thus reducing its porosity and the diffusion of chlorides and CO_2 [6]; hence the aforementioned additives also contribute toward the protection of steel reinforcement and the overall durability of reinforced concrete.

Another reason for using fly ash in the concrete industry is the reduction of cement use and subsequently of CO_2 emissions [7]. At the same time, many studies [8–13] have shown that the replacement of cement by fly ash improves the workability and durability of concrete, reduces hydration heat and helps in the development of long term compressive strength (at ages > 90 days). Furthermore, according to Uysal and Akyuncu [14], the use of fly ash leads to a decrease in chloride ion permeability. Nevertheless, fly ash concrete exhibits low strength and high porosity at early ages [15]. Furthermore, it is carbonated more than ordinary concrete [16].

The American standard ASTM C-618 [17] defines three classes of fly ash depending on its chemical composition and origin: (i) calcareous fly ash (Class C) with high content of CaO (>20%) produced from lignite or subbituminous coal, (ii) siliceous fly ash (Class F) with low amounts of CaO (<10%) produced from burning anthracite or bituminous coal and (iii) fly ash produced from raw or natural pozzolans (Class N). The properties of hardened fly ash concrete are affected from the chemical composition and burning conditions

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of fly ash. The European standard EN 450-1 [18] specifies requirements for the chemical and physical properties of fly ash for use as additive in the preparation of concrete conforming to EN 206-1 [19]. Greek fly ashes do not conform to any international standard. For this reason, National Technical Specifications [20] were adopted in April 2007. According to these, raw fly ash for use as additive in concrete should contain up to 5% SO_3 and 3% CaO_f.

In Northern Greece (Ptolemais area) there are four thermal power plants producing calcareous fly ash (FA). The annual production of FA in Greece reaches up to 10 million tones [21,22], while in Europe it is estimated at 100 million tones [23]. Despite the millions of tons of calcareous fly ash produced annually in Greece, only 10% of this industrial by-product is utilized by the local cement industry [24]. There is therefore an imminent need for research on the incorporation of Greek calcareous fly ash in the production of concrete. The pozzolanic activity of calcareous fly ash from the Ptolemais area can be improved either by adjusting its CaO_f content to acceptable levels or by grinding it [25] to granulometry levels below the fineness of cement. Additions of quicklime [26,27] or Na_2SiO_3, [28], can also improve the pozzolanic activity of the aforementioned fly ash, thereby increasing the alkalinity of concrete.

As demonstrated by a number of relevant studies found in the literature, the utilization of Ptolemais fly ash at percentages up to 20% w.w of cement, has no adverse effect on concrete resistance and expansion [29]. Based on the literature and the chemical composition (Table 1) of Ptolemais F.A, the latter has the following features:

- High SO_3 (7.56%) and CaO_f (11.5%) proportions.
- Higher SiO_2 content (27.05% total SiO_2 and 24.48% glass content) than CaO_f (11.50%). This increases the tendency for pozzolanic reaction between active Si (glass phase) and $Ca(OH)_2$ during the hydration of the mineral phases of clinker.
- Quick reaction with lime due to its fineness (560 m^2/kg) and high aluminum and amorphous silica contents [30]. It is should be noted that, the pozzolanic effect of FA and the improvement of concrete compressive strength at early ages is related with the FA fineness [31,32].
- Hydraulic behavior [33,34], as opposed to other Greek fly ashes (Megalopolis, Aliveri, etc.), which have only pozzolanic properties.

The main objective of this research is the theoretical and experimental investigation of the use of Greek fly ash from the Ptolemais area as a replacement of cement for the production of reinforced concrete, which will be resistant to exposure in sodium chloride environment.

Table 1
Chemical composition (%) of Ptolemais fly ash (FA) and cement.

Chemical compound	Ptolemais F.A (%)	CEM II A-M (%)
SiO_2	27.05	18.6
Al_2O_3	11.44	4.10
Fe_2O_3	4.84	2.90
CaO	37.30	60.50
MgO	3.90	2.00
K_2O	0.66	0.66
Na_2O	0.33	0.34
SO_3	7.56	3.60
LOI	3.45	<8.50
CaO_f	11.50	–
TIO_2	0.52	–
P_2O_5	0.30	–
Cl	0.07	0.05
Glass content	24.48	–

2. Experimental procedure

2.1. Materials, mix proportions and specimen preparation

The main raw materials used for this research consist of crushed limestone aggregates, CEM II 42.5N A-M and water from supply network. Fly ash (FA) from Ptolemais area (i.e. Agios Dimitrios power thermal station) was also used at 5% w.w and 10% w.w cement replacement. The chemical compositions of cement and FA are presented in Table 1, while their physical/mechanical properties are given in Table 2. Fig. 1 presents the mineralogical composition of fly ash obtained by X-ray diffraction method.

According to the chemical analysis, the fly ash contains high amounts of free lime; however, due to low burning temperatures it hydrates quickly and does not cause any expansion problems [9]. This fly ash, provides both pozzolanic and latent hydraulic activity, increases the *pH* value and decreases the corrosion rate of reinforcement against chlorides [9,35].

Three groups of mixtures were prepared in the lab: one group was designed without additive (reference), while the other two groups contained 5% w.w FA (5% FAPTOL) and 10% w.w FA (10% FAPTOL). In all categories of specimens, two kinds of coarse aggregates were used (fraction size of grains 4–10 mm and 8–20 mm), while the water:cement (w:c) ratio was 0.65 (see also Table 3 for mix designs). The choice of high w:c ratio was intentional to produce relatively weak (C20/25) concretes, which would highlight the effect of FA additive. It is also worth mentioning that such w:c ratios are not unusual in the building construction industry of Greece.

For the mechanical tests, cubic (dimensions $100 \times 100 \times 100$ mm^3) and cylindrical ($H = 300$ mm. $\varphi = 150$ mm) concrete specimens were prepared in accordance with EN 12390-2 [37]. The plastic molds were filled with fresh concrete and compacted on a vibrating table with frequency 3000 Hz for 15 s. The specimens were demolded after 24 h and were placed in a curing room (RH = 98%. $T = 20 \pm 1.5$ °C) for 7 days. After curing, the specimens were partially immersed in 3.5% w.w NaCl solution for a total period of 130 days.

For mass loss measurements and for the determination of total chloride concentration, cylindrical reinforced mortar specimens with dimensions $\varphi = 50$ mm and $H = 100$ mm were prepared (Fig. 2). The specimens were prepared by mixing CEM II 42.5N, crushed sand and water in the ratio 1:3:0.65. Steel rebars type B500C Tempcore [38] with diameter 10 mm and length 100 mm were used. The steel rebars were cleaned before insertion into the mortars according to ISO/DIS 8407.3 [39] and weighted to 0.1 mg accuracy. The specimens remained molded for 24 h; after removing the mold, they were fully immersed in water for 7 days under laboratory conditions ($RH_{average} = 63\%$, $T_{average} = 21$ °C).

2.2. Testing procedure

The effect of fly ash as a replacement of cement on the durability of reinforced concrete was evaluated with various physical, mechanical and electrochemical tests.

Compression tests were performed according to EN 12390-3 [40]. The test machine used was the model CONTROLS ADVANTEST 9 with maximum load capacity 5000 kN, while the loading rate adopted was 0.5 MPa/s. The tests were carried out at 7, 28, 70, 100 and 130 days.

Physical tests consisted of sorptivity and open porosity measurements. Sorptivity tests were performed at 28, 70, 100, 130 days using cubic specimens with dimensions $100 \times 100 \times 100$ mm^3, in accordance with ASTM C-1585 [41]. The specimens were initially dried in an oven at 105 °C for 3 days. After complete drying, they were weighed to ±0.1 mg accuracy and then, they were placed in a shallow container containing methanol. The bottom surface of the specimens rested on spacers, while the absorbing liquid was maintained at constant level throughout the test (3–5 mm above the bottom surface of the specimens). During the experiment, the temperature of methanol was recorded. Fig. 3 shows a schematic of the set-up used for measuring the sorptivity.

The open porosity was measured using vacuum saturation [42]. The specimens were dried completely in an oven at 105 °C, before being subjected to vacuum saturation with water for 24 h. The open porosity (*P*) was determined as follows:

Table 2
Physical and mechanical properties of cement and fly ash.

Physical properties		
	Cem II A-M	Fly ash
Blaine fineness	400 m^2/kg	560 m^2/kg
Specific gravity	3.15	2.56
Initial Setting Time (Vicat)	220 min	–
Compressive strength of cement		
2 days	23.0 N/mm^2	
7 days	38.0 N/mm^2	
28 days	51.0 N/mm^2	