Effect of supplementary cementitious materials on RC concrete piles

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Effect of Supplementary Cementitious Materials on RC Concrete Piles

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Abstract. Pile foundations are the elements of structures used to carry and transmit the structures loads to the bearing ground located at some depth below ground surface. The aim of this paper is to explore the improvement of reinforced concrete piles, subjected to harsh marine environment, because of including supplementary ce-mentitious materials, including fly ash and ground granulated furnace slag (GGFS). The overview showed that fly ash might be the optimum material to be included because it improved the workability, slump, hy-dration process, and it enhanced some mechanical properties such as compressive strength. The main im-provement was in the durability properties. For instance, the permeability and void ratio was significantly improved as well as the internal microcracks were decreased as a results of initial temperature reduction of hydration process. Fly ash replacement ratio should be within a limit, 10-30%. Having a ratio more than these can delay the hydration process; hence, delaying the initial and final setting times. Incorporating ground granulated blast furnace slag was enhanced durability properties such as resistance to chemical at-tacks, chloride attacks, carbonation and it decreased water permeability of concrete.

Keywords. Compressive strength; durability, fly ash, slag.

INTRODUCTION

One of the most common structural foundations are the concrete piles, which used to support offshore structures such as bridges and floating ports and airports (Valliappan and Khalili, 2001). Typically, it is precast and prestressed concrete. Based on constructability, there are three types of concrete piles, which are driven pile, cast-in-situ, and driven and cast-in-situ piles (Mishra, 2015). Concrete piles are one of the main solutions for making a foundation that is able to resist high applied load even though soil bearing capacity is low. Concrete piles provide an excellent durability in marine environments such as ports and shore structures (Pipinato, 2015).

Several studies have been conducted to investigate the concrete pile performance under harsh weather and high loads such as marine waves and saltwater effects. Zhuang et al. studied the cracking behavior of reinforced concrete piles subjected to harsh marine environment, bonded with carbon fiber (Zhuang et al., 2018). The study reported that crack width can be used in assessing the damage when fractal analysis is being used. Mather was found that concrete deterioration was due to chemical actions including chloride and sulphate attacks in the warm seawater (Mather, 2005). In cold seawater, chemical effects have less influence while the temperature changes play a prominent role. It was reported that the only remedy is to select an appropriate cement type and concrete mixture ingredient to avoid concrete deterioration due to harsh seawater environments.

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Shayan et al. (Shayan et al., 2010) investigated the effects of reactive and nonreactive aggregates with high or low alkali content on concrete samples subjected to seawater environments such as saltwater, and varied humidity and temperatures. It was shown that the alkali content and type of aggregate plays the dominant role in Alkali-Aggregate Reaction (AAR). The reviewed studied showed that reinforced concrete piles' resistance to chemical attacks and durability performance in marine environments are greatly depending on concrete mixtures and its constituents.

Supplementary cementitious materials, such as fly ash, blast furnace slag, and silica fume, have been utilized to improve some mechanical and durability properties of Portland cement concrete (Toutanji et al., 2004). Because supplementary cementitious materials replace 5-20% of Portland cement weight, they help to reduce CO2 emissions (Assi et al., 2018). Portland cement is responsible for 7-10% of CO2 emissions; hence, reducing the amount of consumed cement is an urgent goal.

Several projects and countries have incorporated fly ash as partial replacement for Portland cement. Fly ash incorporation in Portland cement concrete enhances several mechanical and durability properties (Berndt, 2009; Golewski, 2018a; Kareem et al., 2020a; Suleiman and Nehdi, 2017). The use of fly ash in concrete improve the hydration process by forming an additional calcium silicate hydrate (C-S-H) gel (cementing matrix) and it reduces the initial internal heat of the concrete (Belie et al., 2018). Portland cement hydration: (a) solutions of calcium and alkali hydroxide, and (b) the heat produced by the hydration of Portland cement is a significant factor in initiating the reaction of the fly ash.

Granulated blast furnace slag is a byproduct of supplementary materials, which is used to improve the long-term compressive strength and durability properties (Özbay et al., 2016a). Yan et al have investigated the effect of varied slag replacements on concrete sulfate resistance (Yan et al., 2019). It was found that increasing the slag replacement up to 70% has enhanced the sulfate attacks' resistance due to reducing the formation of ettringite. Ashish et al. investigated the effect of slag replacement on chloride attacks' resistance of concrete and it was found that replacement of Portland cement up 20% by slag showed the best performance of concrete against chloride attacks and acids (Ashish et al., 2016). However, once the percentage was increased by more than 20%, a rapid deterioration has occurred. Several afteromention papers have summrized the effect of supplementary cementitious materials on mechanical and durability properties of Portland cement concrete. However, few studies have focused on the effect of supplementary cementitious materials on reinforced concrete piles subjected to marine environments.

THE EFFECTS OF FLY ASH ON PILES FOUNDATIONS

Pile foundations are the elements of structures used to carry and transmit the structures loads to the bearing ground located at some depth below ground surface. The pile cap and the piles are considered the main components of the foundation. Beside steel and wood, the main material used for piles is concrete. However, the massive amount of cement used in construction activities is one of the significant environmental problems in the world due to the emission of carbon dioxide to atmosphere (Mo et al., 2015; Zabihi-Samani et al., 2018). Consequently, alternative environmentally sustainable materials are necessary to reduce the cement fabrication as one of the significant contributors to emission. Cement replacement is essential for sustainable structures since the production of cement not only emits a significant amount of carbon dioxide, but also uses a huge amount of energy (Zabihi-Samani et al., 2018; Mehta, n.d.). Therefore, by-product or waste materials should be used as alternative or replacement materials rather than cement (Lamine Zeggar et al., 2019). For instance, billion tons of coal are annually burned, so huge amounts of coal ash are produced. Fly ash (FA) is considered as one of the most worldwide available by-product materials from the industrial processes (Zabihi-Samani et al., 2018). Instead of sending this ash to landfills, some can be recycled for beneficial uses.

Effect of Incorporating Fly Ash on CO_2 Emissions and Economic Feasibility

The use of fly ash has been considered as an economical and efficient solution for partial cement replacement. There ae several advantages of using fly ash as a supplementary cementitious material, such as reduced carbon footprint, increased flowability, decreased hydration heat, enhanced long-term strength growth, reduced shrinkage, improved durability and lower cost (Hou et al., 2012). Usually, fly ash is used in concrete as a cement substitution 30% to 70% (Golewski, 2018b; Kareem et al., 2021, 2020b). Moreover, fly ash can be substituted up to 100% , such as geopolymer concrete (Assi et al., 2016; Karahan, 2017). The effect of fly ash on the mechanical and durability properties of concrete is dependent on numerous aspects such as, replacement ratio, curing, and age of the concrete (Assi et al., 2016; Ghanooni-Bagha et al., 2017; Kareem et al., 2021).

Effect of Fly Ash on Concrete Workability

The quality and workability of pile foundations concrete are required so that the concrete can be maintained for durable construction of pile foundations with needed strength. The workability of the mixture improves by using fly ash as supplementary cementitious material. The compacting factor improves by 4% when the percentage of fly ash is increased by 10% (Lamine Zeggar et al., 2019). Figure 1 shows the effect of fly ash replacement ratio with slump (Bharatkumaranaik et al., 2017). This figure shows that the concrete workability is improved by using fly ash as a supplementary cementitious material. When the replacement percentages are 10%, 20%, 40%, and 50%, the slump increases by 4%, 7%, 11%, and 13%, respectively. The circular shape and dispersive ability of the fly ash particles provide water reducing qualities and improving concrete slump (Ahirwar et al., 2015; Bharatkumaranaik et al., 2017).

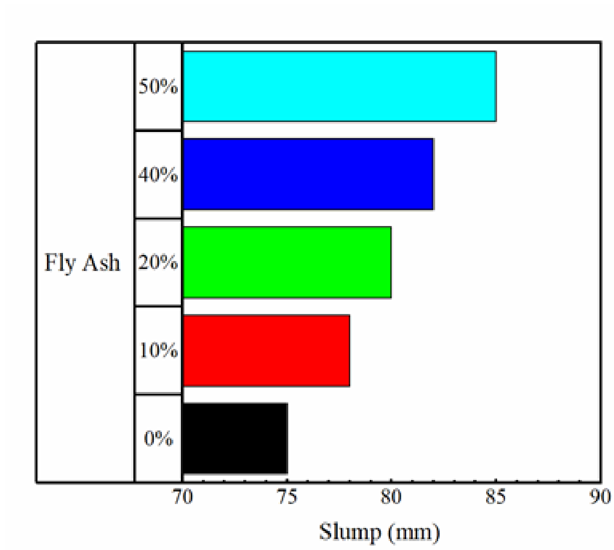

FIGURE 1. Effect of fly ash on slump

Effect of Fly Ash on Hydration Process

High levels of high-calcium, like Class C fly ash, can control the temperature rise in mass concrete foundations (Lamine Zeggar et al., 2019). Furthermore, the use of fly ash as a cement or an aggregate replacement affects the other properties of fresh concrete. Concrete sets slowly when fly ash is used, so the thermal stresses produced from hydration reactions are reduced. Fig. 2 shows effect of the percentage of fly ash replacement on the hydration heat of cement paste (Hou et al., 2012). It determines that fly ash replacement reduces the hydration peak temperature. The hydration heat was reduced by 12.8% and 20.5% when the percentages of fly ash replacement were 20% and 40%, respectively. Moreover, the hydration peak is also delayed with using fly ash. The hydration peak can be delayed up to 3 hours.

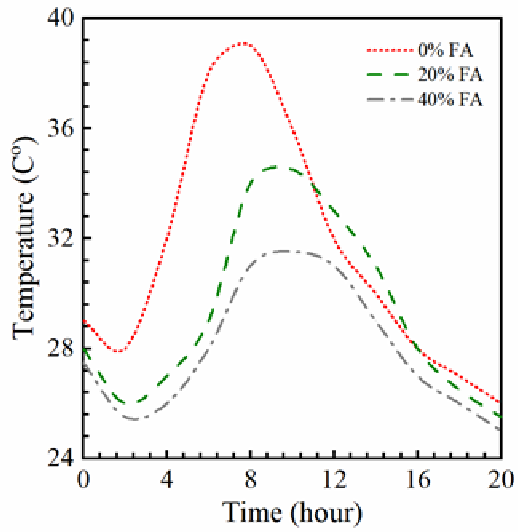

FIGURE 2. Effect of fly ash on hydration heat

Effect of Fly Ash on Compressive Strength

Pile foundations are generally needed when near surface soil conditions are not satisfied for the axial compression, axial tension, lateral load demand or a combination of the above. Therefore, the piles foundations require concrete having enough strength to transfer the applied loads. The use of fly ash can efficiently lower water cement ratio for same workability (Raut and Deo, 2015). This reduction in water cement ratio can enhance the concrete strength. Fig. 3 shows the effect of using different ratios of fly ash on the compressive strength at 7 and 28 days (Reddy and Reddy, 2013). It is indicated that when the replacement percentages of fly ash were 5%, 10%, 15%, and 20%, the compressive strength was improved by 6%, 15%, 33%, and 39% at 7 days and 7%, 17%, 29%, and 36% at 28 days, respectively. This improvement in strength can be due to that the fly ash being pozzolanic material may react with free lime present in cement and produce C-S-H gel (Kara De Maeijer et al., 2020; Kipkemboi et al., 2020). On the other hand, this improvement in strength can be also due to that the specific gravity of fly ash is less, so the finer particles are available for packing of voids which results more dense concrete (Hino Junior et al., 2021; Kara De Maeijer et al., 2020).

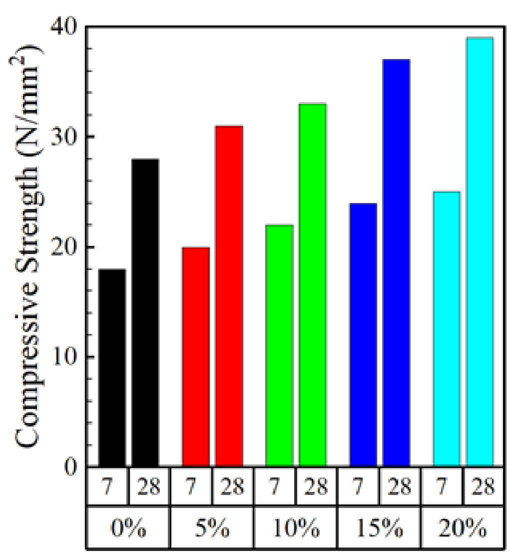

FIGURE 3. Effect of fly ash on compressive strength

Effect of Fly Ash on Durability

The durability of concrete is considered as the most important hardened property of concrete. Concrete piles embedded in permeable soils may be damaged by groundwater saturated by either acids, alkalies, or chemical salts (Grand, n.d.). Moreover, concrete piles extending above the surface of a water body are subject to damage from the abrasive action of floating objects, from ice where such exists, and from sand scouring (Grand, n.d.). Fig. 4 shows the relationship between the fly ash content using different ratios and concrete permeability at 28 and 180 days of curing (Saha, 2018). The concrete permeability was assessed by the volume of permeable voids test. It can be seen that after 180 days of curing, the permeable voids significantly reduced. This decline in permeable voids is as a result of the reduction of capillary and gel pores of the concrete paste due to the hydration of the binder. Furthermore, with the addition of fly ash, the permeable voids reduced up to 1.08% at 28 days curing and 0.95% at 180 days curing. The use of fly ash decreases concrete pores due to the higher fineness and ball bearing effect of fly ash particles.

Furthermore, the use of fly ash enhances the concrete resistance to chloride ion. Fig. 5 shows the mass loss of concrete cubes immersion in the 10% sulfuric acid solution (Nguyen et al., 2019). The use of fly ash improves the mass loss of concrete due to sulfuric acid. The greater fly ash replacement proportion, the more the apparent acid resistance. The mass losses of 0%, 10%, 20%, 30% and 40% fly ash replacement were 5.9%, 4.2%, 1.8%, 1.5% and 1.3%, for specimens having 0.55 water/cement ratio (W/C), respectively. It can be stated that fly ash decreases the mass loss from the concrete surface due to sulfuric acid exposure up to 77%. The concrete permeability is improved by the denser microstructure as a results of a filling effect by the ultrafine fly ash (Feng et al., 2015).

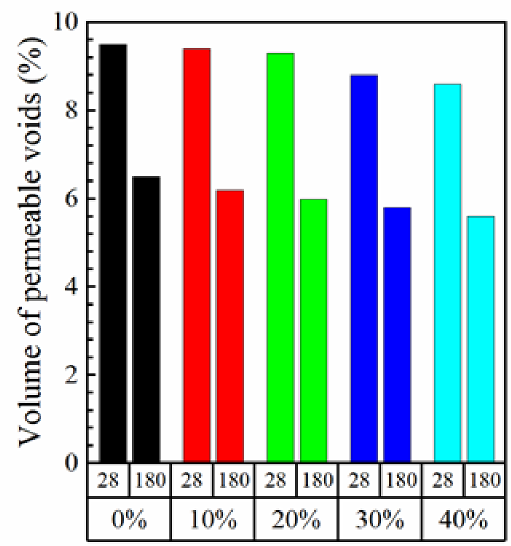

FIGURE 4. The effect of fly ash on permeable void ratio

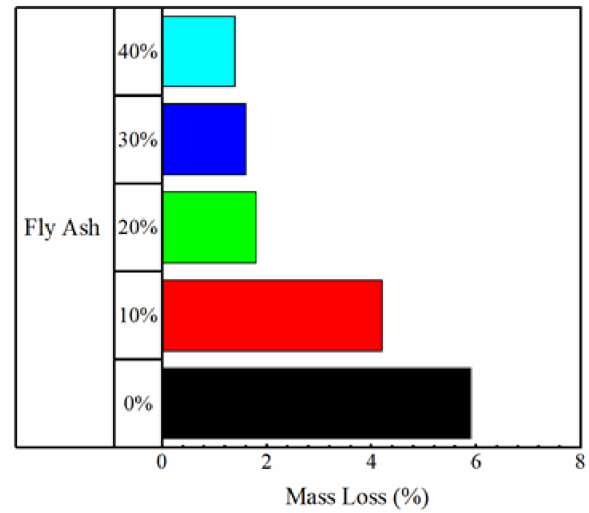

FIGURE 5. Effect of fly ash on mass losses

EFFECT OF GROUND GRANULATED BLAST FURNACE SLAG (GGBFS) OR SLAG CEMENT ON PILE FOUNDATION

Slag cement is a by-product that is obtained from blast furnaces that are used to make iron. Typically, slag occurs when iron, iron scrap, coal, coke, and fluxes are melted together (Assi et al., 2020; Thomas, 2017). Table 1 presents the chemical and physical properties of slag.

TABLE 1. Chemical and physical properties of silica fume

Chemical Composition		**References**
CaO (%)	29.0 – 43.7	(De Belie et al., 2018; Özbay et al., 2016b; Wu and Ye, 2017)
SiO_2 (%)	30.0 – 40.0	
SO_3 (%)	1.0 – 4.0	
Al_2O_3 (%)	6.0 – 19.30	
Fe_2O_3 (%)	0.1 – 2.5	
MgO (%)	0 – 19.0	
K_2O (%)	0.3 – 0.5	
Na_2O (%)	0 – 1.2	
LOI (%)	0.1 – 1.7	
Physical Properties		**References**
Shape	angular	(Jiao et al., 2017; Thomas, 2013; Wu and Ye, 2017)
Particle size (µm)	13.8 – 22.2	
Surface area (m^2/kg)	350 – 650	
Specific gravity	2.85 – 2.95	

Effect of Slag (GGBFS) on Mechanical Properties and Durability OPCC

When GGBFS is added to the concrete mixture as a partial replacement, two major reactions take place. The first reaction is between the GGBFS and the sodium and potassium alkali hydroxides. The second reaction is with the calcium hydroxide that is released from the hydration process of OPC; this pozzolanic reaction leads to the formation of additional calcium silicate hydrates. The effectiveness of GGBFS on the mechanical properties of OPCC may vary depending on several factors such as w/b ratio, the chemical composition of GGBFS, replacement level, and reactivity index of the slag (Panesar, 2019).

Figure 6 illustrates the effect of GGBFS on the 28 days compressive strength. The 25% GGBFS experienced the highest strength; the enhancement in strength was 21% compared to 0% GGBFS. On the other hand, 50% of GGBFS showed approximately similar strength compared to the 0%GGBFS. Finally, the 75% GGBFS decreased the strength significantly; the reduction in strength was 44%.

The effect of high volume GGBFS on the mechanical properties of concrete was investigated (Güneyisi and Gesoğlu, 2008). Fig. 6 demonstrates the effect on compressive strength and splitting tensile strength. It can be seen that all replacement levels of GGBFS decreased compressive strength and splitting tensile strength at 28 days as shown in Fig. 7 (a) and Fig. 7 (b), respectively. This is attributed to the slower rate of hydration process compared to 0% GGBFS. However, at 90 days, both strengths were enhanced. 50% replacement of GGBFS showed the highest compressive and splitting tensile strengths. The increase was 5% and 2% for compressive and splitting tensile strengths, respectively, compared to 0% GGBFS.

Incorporating ground granulated blast furnace slag was enhanced durability properties such as resistance to chemical attacks, chloride attacks, carbonation and it decreased water permeability of concrete (Guo et al., 2014). In addition, the initial and final setting time was increased as well as the slump was lower. The Properties of Portland cement concrete with GGBFS had low heat evolution and high resistance to sulfate attacks and alkali silica formations; however, particular attention should be paid during the early curing to avoid carbonation deposits on concrete surface and frost attacks (Osborne, 1999).

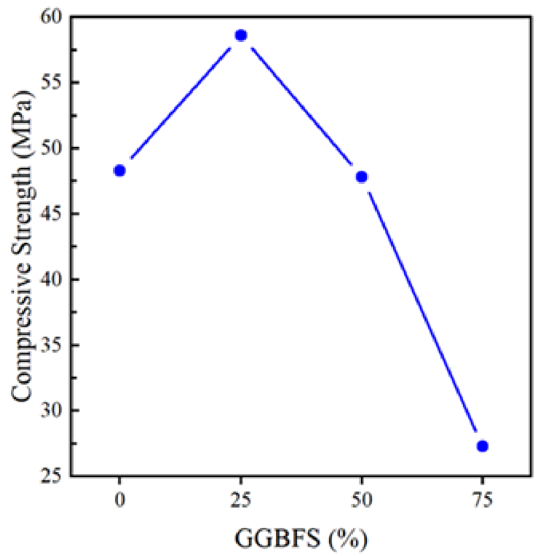

FIGURE 6. Effect of slag replacement level on compressive strength
Note: GGBFS = ground granulated blast furnace slag; data were collected from (Aldea et al., 2000)

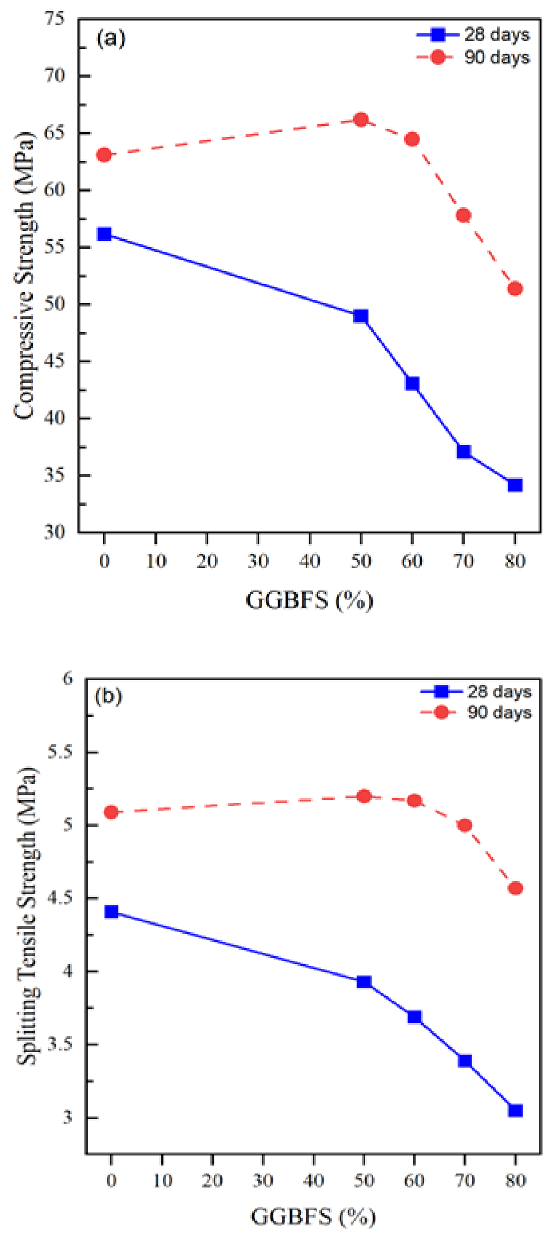

FIGURE 7. Effect of slag replacement level on (a) compressive strength and (b) splitting tensile strength

Note: GGBFS = ground granulated blast furnace slag; data were collected from (Aldea et al., 2000)

CONCLUSION

The overview of the previous studies of effect of incorporating supplementary cementitious materials was concluded the followings:

- Fly ash was the best option because it enhances several mechanical and durability properties.
- The workability and slump were improved due to incorporating fly ash in the mixture.
- The compressive strength and other mechanical properties were enhanced.
- Durability properties of concrete was improved by reducing permeability and void ratio.
- Incorporating ground granulated blast furnace slag was enhanced durability properties such as resistance to chemical attacks, chloride attacks, carbonation and it decreased water permeability of concrete.

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