Observations of Supplementary Cementitious Materials Effects on The Performance of Concrete Foundation

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Abstract. Concrete is the most consumed material after water, and it is responsible for 10% of total CO₂ emissions worldwide. Supplementary cementitious materials, including fly ash, silica fume, and granulated furnace slag, have been utilized to improve the mechanical and durability of concrete and reduce Portland cement consumptions. The paper aims to explore the effect of the supplementary cementitious materials' replacement on concrete foundation properties. It was found that fly ash significantly improved durability properties and workability. However, it delays the initial time setting and early compressive strength enhancements. At the same time, silica fume decreased concrete permeability and enhanced compressive strength. The incorporation of 15% silica fume can enhance the compressive by 21% compared to control concrete. On the other hand, silica fume can decrease workability remarkably.

Keywords: supplementary cementitious materials; concrete foundation; fly ash; silica fume; slag cement.

1. Introduction
The most common and widespread constructing material in the world is cement. However, one of the significant environmental problems in the world is the massive amount of cement used in construction activities since this activity results in carbon dioxide emission to the atmosphere [1,2]. Carbon dioxide emissions have been considerably increased as a result of cement fabrication. Consequently, alternative environmentally sustainable materials are necessary to reduce cement fabrication as one of the significant contributors to emission [2]. The use of environmentally sustainable materials in green concrete structures minimizes the effect of the concrete structures on the environment during their life cycle, including service life. Cement replacement is essential for sustainable structures since cement production emits a significant amount of carbon dioxide and uses massive energy [3]. Foundation is an essential part of concrete structural buildings. Generally, while a trench should be excavated, footings are made from concrete with reinforcement bars. The main reason for having a concrete footing in a structure is to support the building and prevent settlement [4]. The concrete foundation is the first member to be built, and it is in direct contact with soil.

Due to the direct exposure to surrounding environments and soil, concrete foundations are more susceptible to deterioration due to sulfate attacks, freeze-thaw cycles, and chloride penetrations. Compressive strength performance plays an integral part in the concrete foundation because it subjects
to the summation of applied load and superstructure weight. Therefore, several studies have focused on improving concrete structures’ performance regarding durability and mechanical properties using supplementary cementitious materials. Fly ash, silica fume (SF), and ground granulated blast-furnace slag (GGBFS) have been utilized as supplementary cementitious materials. Many studies showed that supplementary cementitious materials could improve concrete foundations’ mechanical and durability properties [5–8].

Fly ash has been used as a supplementary cementitious material in the production of Portland cement concrete. Generally, fly ash is used in concrete as a cement substitution 30% to 70% [9–11]. On the other hand, a greater amount of fly ash has been substituted up to 100% in high volume fly ash concrete as in geopolymer concrete [12,13]. Concrete incorporating fly ash must meet the requirements for strength and durability [14,15]. The effect of fly ash on the mechanical properties and durability of concrete depends on several factors such as replacement ratio, curing, and age [11,12,16]. The use of fly ash is considered an economical and efficient solution for partial cement replacement. The use of fly ash in concrete makes efficient use of the products of Portland cement hydration: (a) solutions of calcium and alkali hydroxide forming an additional calcium silicate hydrate (C-S-H) gel (cementing matrix), and (b) the heat produced by the hydration of Portland cement is a significant factor in initiating the reaction of the fly ash [17].

One of the primary supplementary materials that have been utilized to enhance durability and mechanical properties is silica fume. Silica fume (SF) is an ultrafine byproduct material with an average particle size of 0.10 µm to 0.30 µm [18,19]. Commercially, SF is also called condensed silica fume, micro silica, and volatilized silica [20]. SF is a highly reactive pozzolanic reaction because of its high surface area, as shown in Table 1. SF reacts with calcium hydroxide from the cement’s hydration to form new calcium silicate hydrates and consequently improves the mechanical properties and durability of concrete [21,22]. Additionally, SF can fill the voids between cement and aggregate particles and produce a dense matrix by enhancing the packing density of the concrete [23,24].

Granulated blast furnace slag is a byproduct of supplementary materials, which is used to improve the long-term compressive strength and durability properties [25]. Yan et al. have investigated the effect of varied slag replacements on concrete sulfate resistance [26]. 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 [27]. However, once the percentage was increased by more than 20%, a rapid deterioration has occurred. As previously stated above, there are numerous studies have been conducted on supplementary materials to enhance the mechanical and durability properties of concrete in general. However, few works have explored these effects on concrete foundation performance. This paper aims to review the effect of fly ash and silica fume on concrete and concrete foundation performance particularly since these materials can reduce the permeability of the concrete. Besides, a summary of the best applications for the supplementary cementitious materials, including fly ash and silica fume will be drawn.

2. Effects of fly ash on durability and mechanical properties of concrete
To achieve green-friendly concrete, byproduct or waste materials should be used as an alternative or replacement material rather than cement [28]. There are million tons of industrial waste materials are annually produced worldwide. Billion tons of coal are annually burned, so vast amounts of coal ash are produced. Instead of sending this ash to landfills, some can be recycled for beneficial uses. Notably, the lighter ash (fly ash) has now been a common component in concrete, grout, acoustic ceiling tiles, and a myriad of other building materials. Fly ash (FA) is considered one of the most worldwide available byproduct materials from industrial processes [2]. Fly ash can be divided into ASTM class C, characterized by high calcium and produced from lignite or sub-bituminous coals; and ASTM class F: characterized by low calcium percentage and generally produced from bituminous coals [29]. In the world, fly ash has been produced about 750 million tons each year [30]. Moreover, the produced amount of fly ash has been expected to increase to 2100 million tons in 2031 [31]. On the other hand, the ACI-
limited the use of fly ash up to 25% of the total amount of binder for structural members that are subjected to freeze and thaw cycles [32].

3. Effect of fly ash on mechanical properties of fresh concrete

The use of fly ash as cement or an aggregate replacement affects the properties of fresh concrete. Concrete sets slowly when fly ash is used, so the thermal stresses produced from hydration reactions are reduced. High levels of high calcium, like Class C fly ash, may be used to control the temperature rise in mass concrete foundations [33]. The addition of fly ash to concrete improves workability by keeping the same water-cement ratio or effectively reducing the same workability [34]. This reduction in the water-cement ratio can improve the concrete strength and durability. Figure 1 shows the effect of using different fly ash ratios on the compressive strength at 7, 28, and 56 days [35]. It is noted that the percentage replacement 10% provided the greatest compressive strength. The compressive strength was increased by 4.8%, 9.6%, and 16.8% at 7, 28, and 56 days, respectively. Moreover, the addition of fly ash up to 20% as a supplementary cementitious material generally improved the concrete compressive strength at all ages, 7, 28, 56 days. The compressive strength was increased by 1.4%, 1.1%, and 7.5% at 7, 28, and 56 days, respectively. There are two reasons for this increment in strength. First, the fly ash being pozzolanic material, may react with free lime present in cement and produce C-S-H gel. The other reason is the low specific gravity of fly ash, so the finer particles are available for packing voids, which results in more dense concrete. However, when the percentage replacement was increased beyond 20%, the compressive strength was decreased at all ages. This reduction may be because fly ash volume is substantially more than that needed for packing voids in concrete [35]. Therefore, the compressive strength is reduced due to the increasing volumes needing more water for lubrication. On the other hand

4. Effect of fly ash on durability properties of the concrete foundation

Concrete durability is considered the most important hardened property of concrete, along with strength. The use of fly ash enhances the concrete resistance to chloride ions since the denser microstructure improves the concrete permeability due to a filling effect by the ultrafine fly ash [36]. Moreover, the use of fly ash improves the acid resistance of concrete [37]. Figure 2 shows that the mass loss of concrete cubes immersion in the 10% sulfuric acid solution is enhanced by using fly ash with different water/cement ratios [38]. The higher the fly ash replacement proportion, the greater the apparent acid resistance. The mass losses of 0, 10, 20, 30, and 40% fly ash replacement are 11.4, 6.0, 6.9, 4.3, and 1.5%, for specimens having 0.42 water/cement ratio (w/c), 9.3, 6.7, 6.6, 3.5, and 0.4%, for specimens having 0.50 water/cement ratio (w/c), and 6.1, 4.4, 1.3, 0.8, and 0.4%, for specimens having 0.55
water/cement ratio \((w/c)\), respectively. It can be determined that fly ash decreases the mass loss from the concrete surface due to sulfuric acid exposure. Furthermore, the use of a higher water/cement ratio also reduces mass loss.

Figure 2. Effect of fly ash on mass losses [38].

Figure 3 shows that the mass loss of concrete cubes immersion in the 10% sulfuric acid solution is enhanced by using fly ash with different water/cement ratios [38]. It is noticeable that higher replacement with fly ash decreased the compressive strength losses of the concrete. The compressive strength losses of 0, 10, 20, 30, and 40% fly ash replacement are 61.2, 53.9, 40.8, 38.1, and 34.3% for, for specimens having 0.42 water/cement ratio \((w/c)\), 50.1, 36.9, 54.4, 45.7, and 40.1%, for specimens having 0.50 water/cement ratio \((w/c)\), and 48.5, 17.4, 22.8, 17.4, and 12.2%, for specimens having 0.55 water/cement ratio \((w/c)\), respectively. It can be concluded that the compressive strength loss is reduced when water/cement ratios are increased. For instance, the compressive strengths loss of concrete with 0% fly ash replacement are 61.2%, 50.1% and 48.5% for water/cement ratios of 0.42, 0.5 and 0.55, respectively. On the other hand, the compressive strength losses of concrete at 10% fly ash replacement are 53.9, 36.9, and 17.4% for water/cement ratios of 0.42, 0.50, and 0.55, respectively. Furthermore, at 20, 30, and 40% fly ash replacement, the compressive strength losses of concrete for water/cement ratio 0.50 are higher than that for water/cement ratios of 0.42 and 0.55.

Figure 3. Effect of fly ash on compressive strength loss [38].
5. Silica fume (SF)
Silica fume (SF) is an ultrafine byproduct material with an average particle size of 0.10 µm to 0.30 µm [18,19]. Commercially, SF is also called condensed silica fume, micro silica, and volatilized silica [20]. SF is a highly reactive pozzolanic reaction because of its high surface area. SF reacts with calcium hydroxide from the cement’s hydration to form new calcium silicate hydrates and consequently improves the mechanical properties and durability of concrete [21,22]. Additionally, SF can fill the voids between cement and aggregate particles and produce a dense matrix by enhancing the packing density of the concrete [24,39]. The following section discusses the effect of SF on the mechanical properties and durability of ordinary Portland cement concrete (OPCC).

5.1 Effect of silica fume on mechanical properties and durability of OPCC
When SF is incorporated in concrete, it yields a considerable enhancement in the mechanical properties and durability of concrete [40]. Typically, SF is incorporated as a partial replacement for ordinary Portland cement (OPC). The replacement ratio can reach up to 20% of the total weight of the binder content in the case of ultra-high performance concrete (UHPC) [24]. Figure 4 presents the development of compressive with age (7, 14, 28, 42, 90, 365, and 400 days). SF was incorporated in the mixture proportions at different percentages (0%, 6%, 10%, and 15%) of the total amount of OPC. It can be seen that compressive strength increased with time for all mixtures and regardless of the SF content. The incorporation of 15% SF resulted in the highest compressive strength at all ages. The enhancements of compressive strength at 7 days were 15%, 5%, 2% compared to 0% SF, 6% SF, and 10% SF, respectively. The high early strength improvements can be beneficial for different structural applications, such as casting concrete in cold weather. On the other hand, the compressive strength increments at 28 days were 21%, 8%, and 4% compared to 0% SF, 6% SF, and 10% SF, respectively.

![Figure 4: The development of compressive strength with age for different replacement ratios of silica fume](image)

After 28 days, the achievements in strength were minimal. As the incorporation of SF increased, the ratio between 28 days and 400 days compressive strength increased; the ratios of 28 days to 400 days strengths were 78%, 89%, 92%, and 92% for % SF, 6% SF, 10% SF, 15% SF, respectively. This indicates that the mixture with 100% OPC keeps the strength development over time. However, the ultimate strength is still less than the strength of 15% SF. In other words, the incorporation of SF accelerates the attaining of ultimate strength while increasing the early strength [41]. A similar trend
was concluded by [42], who investigated the effect of SF on concrete performance at different ages. SF was incorporated at 0%, 5%, 10, and 15% by the weight of the total binder (total binder = 500 kg/m³). Also, they included the effect of water to binder ratio (w/b): 0.27, 0.30, and 0.33 were used. It was reported that for a w/b ratio of 0.27 and 0.30, the 15% SF achieved the highest strength at 28 days. The increase in strength was 20% and 18% for 0.27 and 0.30 w/b ratios compared to 0% SF concrete. On the other hand, for w/b of 0.33, the 10% SF attained the greatest compressive strength; the increase in strength was 19% compared to 0% SF.

Four replacements ratios [43] (0, 10, 15, and 20%) and investigated their effect up to 182 days, as shown in Figure 5. It was reported that the incorporation of 10% and 15% increased the splitting tensile strength at 28 days. The enhancement was 21% and 19% of 10% SF and 15% SF, respectively, compared to the 0% SF. On the other hand, the incorporation of 20% SF decreased the strength by 12% compared to 0% SF. At later ages (91 days and 183 days), SF negatively influenced the splitting tensile of the tested concrete. The effect of SF on the tensile strength of high-performance concrete was examined by [44] at 28 days of age. Results indicated the very high replacements of SF (up to 25%) did not affect the strength noticeably; the enhancement in strength was minimal beyond 15% replacement of SF.

![Figure 5](image)

**Figure 5.** Effect of Silica fume on the splitting tensile strength of concrete at different ages; data were collected from [43].

Flexural strength, which is an indirect way to estimate the tensile strength of the concrete, was evaluated [45]. The results are presented in Figure 6. It can be seen that as the SF% increased, the flexural strength increased. The 5% SF, 10% SF, and 15% SF increased the flexural strength by 7%, 42%, and 64%, respectively compared to 0% SF mixture. It was found that as the SF content increased, the flexural strength increased up to a replacement level of 15% SF by the weight of the total binder [44].
Figure 6. The effect of silica fume replacement level at 28 days flexural strength of high strength concrete; data were collected from [45].

The effect of SF on the modulus of elasticity, which is the measurement of the stiffness of the concrete, was evaluated [41]. Figure 7 shows the benefit of using SF on the modulus of elasticity. As the SF% increased, the modulus of elasticity increased. The increase in modulus of elasticity was 8%, 8%, and 9% for 6% SF, 10% SF, and 15% SF compared to 0% SF at seven days of age. The enhancements for the 28 days were 3%, 8%, and 11% for 6% SF, 10% SF, and 15% SF, respectively compared to 0% SF. The enhancement can be associated with improvement in the concrete's packing density as SF is ultra-fine material that can fill the voids and create a denser matrix [39].

Figure 7. Effect of silica fume replacement level on the modulus of elasticity of concrete at 7 and 28 days; data were collected from [41].

SF can influence the dimensional stability of the concrete considerably (creep and shrinkage). Several studies have concluded that as the SF increased, the shrinkage of the concrete increased [41,46,47]. The high replacement level of SF (e.g., 10% and 15%) can increase the autogenous shrinkage by 33% and 50%, respectively. This is associated with the fact that SF examines minimal or no bleeding, which leads to the probability of cracking. Due to the pozzolanic reaction, SF consumes the mixing water, and consequently, the shrinkage is accelerated [48]. Figure 8 is a clear illustration of the effect of SF on the shrinkage of the concrete samples.
On the other hand, SF can reduce the strain due to creep compared to the concrete with 0% SF. It was found that as the replacement level of SF increased to 15%, the creep of the concrete decreased by 20-30% [41]. The porosity of concrete can be an indication of the permeability of the concrete. Permeability plays an essential role in resisting the sulfate attack from the soil in the case of foundations subjected to severe sulfate attack. Typically, when the attack is moderate, OPC type V with low C3A (max of 5%) is used. However, in severe cases (sulfate content > 2% in soil), supplementary cementitious materials must be incorporated [21]. Figure 9 (a and b) presents the effect of SF on the porosity and pore size of the tested concrete. It can be seen from Figure 10 that both the porosity and pore size decreased with age the age of concrete as the hydration process evolves. The use of 10% SF resulted in the lowest porosity at 7, 28, and 90 days. The porosity enhancement was 27%, 29%, and 27% at 7, 28, and 90 days, respectively, compared to 0% SF. On the other hand, the use of 10% SF yielded the lowest average pore size at all ages as shown in Figure 9 (b). This attributed to the reaction of SF with calcium hydroxide which led to producing a denser matrix and, therefore, the porosity was reduced.

Figure 8. Effect of silica fume replacement level on plastic shrinkage strain; data were collected from [49].

Figure 9. Effect of silica fume replacement level on (a) porosity of the concrete and (b) the average pore size of the concrete (Note: MIP = mercury intrusion porosimetry); data were collected from [50].
6. Summary of the best practices of supplementary cementitious materials
The review showed that fly ash would enhance the durability properties of the concrete. However, these improvements come with some cons regarding the early age properties of concrete. Using high fly ash replacement percentage will significantly affect early age compressive strength development, which will delay removing the forms. Because fly ash's average particle size is finer than Portland cement, it will reduce the permeability of the concrete, which is preferred in foundation concrete because it reduces the potential attacks of acid and sulfate. Fly ash can decrease the internal temperature, leading to a decrease in microcracks. Including silica fume (SF) in foundation concrete will almost have only advantages. Because silica fume is of ultra-fine particles, it will reduce the permeability of concrete, which will significantly improve durability. The review showed that silica fume increased the compressive strength by more than 20% in comparison with plain concrete. The potential ettringite reaction will decrease. As the SF% increased, the modulus of elasticity increased. The increase in modulus of elasticity was 8 and 9% for 6% SF, 10% SF, and 15% SF compared to 0% SF at seven days. The enhancements for the 28 days were 3, 8, and 11% for 6% SF, 10% SF, and 15% SF, respectively compared to 0% SF. However, using silica fume by more than 10% will reduce the concrete workability because silica fume has a high surface area, which results in high water demand. Therefore, special care should be taken to avoid stiff mixture by increasing the water/cement (w/c) ratio or using a high range of water reducer (superplasticizer).

7. Conclusions
Based on the conducted review, the following conclusions are drawn:

- Fly ash replacement will have several advantages, such as reducing the internal temperature, reducing concrete permeability, and enhancing short-term concrete properties. However, special attention should be paid to the delayed early reaction, increasing the initial time setting.
- Silica fume will have remarkable effects on the long-term concrete foundation. Silica fume will densify the concrete matrix and reduce the permeable void ratio because it has very fine particles. Silica fume will significantly reduce workability; therefore, the percentage should be limited to no more than 10%, and it should be combined with a high range water reducer.
- Several factors can influence the performance of supplementary cementitious materials. Cement content is one of the significant factors; if the cement content was not sufficient, then no calcium hydroxide can react with the supplementary cementitious. Also, the fineness of these materials can affect their degree of reactivity; finer material increases the surface area and, consequently, affects performance.

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