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Impact of Silica Fume and Palm Oil Fuel Ash on Workability, Strength, and Absorption of High Strength Mortars

Mohamed Alsnosi Karem[a], Megat Azmi Megat Johari[a], *Faesal Alatshan[b]

[a] School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Pulau Pinang, Malaysia;
[b] Civil engineering department, College of Engineering Technology, Houn, Libya;

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ABSTRACT

This study focused on the impact of adding silica fume (SF) and palm oil fuel ash (POFA) on the workability, compressive strength, and water absorption characteristics of high-strength mortar. The objective is to assess the impacts of different proportions of SF and POFA on mortar performance. Four types of mortar mixes were prepared: high strength mortar (HSM), high strength green mortar with 40% POFA (U40-HSGM), high strength green mortar with 5% SF (U40-SF5-HSGFM), and high strength green mortar with 15% SF (U40-SF15-HSGFM). The inclusion of 40% POFA improved workability, while adding SF slightly reduced it. The inclusion of silica fume improved compressive strength, with the highest obtained in U40-SF15-HSGFM. Further, water absorption increased with POFA substitution, but was decreased when SF was added instead. In summary, the combination of SF and POFA results in significant improvement in mechanical and durability characteristics in high-strength mortars.

تأثير دخان السيليكا ورماد وقود زيت النخيل على قابلية التشغيل، والمقاومة، وامتصاص المونة عالية المقاومة

محمد السنوسي كريم[1]و ميغات عزمي ميغات جوهري[1] و *فيصل العطشان[2]

[1]قسم الهندسة المدنية، جامعة العلوم الماليزية(USM) ،نيبونغ تيبال، بولاو بينانغ، ماليزيا
[2]قسم الهندسة المدنية، كلية التقنية الهندسية، هون، ليبيا

الكلمات المفتاحية:
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البناء المستدام
المونة عالية المقاومة

الملخص

ركزت هذه الدراسة على تأثير إضافة دخان السيليكا (SF) ورماد وقود زيت النخيل (POFA) على قابلية التشغيل، ومقاومة الضغط، وخصائص امتصاص الماء في المونة عالية المقاومة. وتهدف إلى تقييم تأثيرات نسب مختلفة من SF و POFAعلى أداء المونة. تم إعداد أربعة أنواع من الخلطات: المونة عالية المقاومة(HSM) ، والمونة الخضراء عالية المقاومة مع 40% من(POFA (U40-HSGM ، والمونة الخضراء عالية المقاومة مع 5% من SF (U40-SF5-HSGFM)، والمونة الخضراء عالية المقاومة مع 15% من SF (U40-SF15-HSGFM). أدى إضافة 40% من POFA إلى تحسين قابلية التشغيل، بينما أدى إضافة SF إلى تقليلها بشكل طفيف. وقد حسّن دخان السيليكا مقاومة الضغط، حيث كانت أعلى قيمة للمقاومة في الخلطة U40-SF15-HSGFM. علاوةً على ذلك، زاد امتصاص الماء مع استبدالPOFA ، لكنه انخفض عند إضافة SF بدلاً منه. وباختصار، يُسهم الجمع بين SF و POFAفي تحسين كبير في الخصائص الميكانيكية والمتانة في المونة عالية المقاومة.

1. Introduction

Recently, the construction sector has experienced a remarkable increase in demand for high-strength concrete (HSC) due to its ability to reduce the size of structural components and decrease the overall weight of buildings, thus lowering total construction costs. The use of mineral additives in concrete and mortar production can improve its mechanical and transport properties. However, these additives can also have negative environmental impacts due to the large amounts of carbon dioxide produced during cement manufacturing. Cement manufacture is thought to be responsible for roughly 7% of carbon dioxide emissions worldwide [1]. Therefore, it is crucial to explore partial substitutes for traditional cement to enhance environmental sustainability and reduce costs.

SF and POFA are two materials that can be utilized as replacements for cement to enhance concrete characteristics. SF is a by-product of the silicon and ferrosilicon industry, characterized by its extremely

*Corresponding author:
E-mail addresses: f.alatshan@ceh.edu.ly ,(M. A. Karem) Mohamed_mota2000@yahoo.co.uk ,(M. A. Johari) cemamj@eng.usm.my
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fine particles and strong pozzolanic properties, that can remarkably develop the strength and durability of concrete [2, 3].

POFA, a by-product of the palm oil industry, is typically disposed of in landfills, causing environmental issues. POFA has similar pozzolanic properties to cement, and studies have shown that using it as a partial replacement can enhance concrete characteristics such as durability and resistance to chemical attacks [4]. The utilization of POFA in concrete can also help mitigate the environmental impact by decreasing the quantity of waste disposed of in landfills.

Previous investigations have explored the impact of SF and POFA on concrete and mortar properties. Research indicates that using silica fume (SF) in proportions up to 15% can enhance strength and durability, while POFA can improve workability and reduce shrinkage and creep effects [5-7]. The chemical composition of POFA, including its high SiO2 content, makes it a reactive pozzolanic material that can effectively replace cement in concrete mixtures [8].

The incorporation of SF into concrete mixes has shown to improve early age strength as a result of its pozzolanic reactivity and high surface area, which contribute to the formation of additional calcium silicate hydrate (C-S-H) gel, enhancing the microstructure and strength of the concrete [9]. However, the addition of SF can reduce the workability performance as a consequence of its fine particle size, necessitating the use of superplasticizers to maintain desired workability levels [10].

The aim of this paper is to assess the impacts of different proportions of SF and POFA on mortar performance. Four types of mortar mixes were prepared: high-strength mortar (HSM), high-strength green mortar with 40% POFA (U40-HSGM), high-strength green mortar with 5% SF (U40-SF5-HSGFM), and high-strength green mortar with 15% SF (U40-SF15-HSGFM). By understanding these effects, the construction industry can better utilize these materials to create more efficient, durable, and sustainable concrete structures. The findings of this paper could pave the way for wider adoption of green concrete technologies, contributing to both environmental conservation and advancements in construction materials science.

2. The experimental program

2.1. Materials

In this paper, high-strength mortar (HSM), high-strength green mortar (HSGM), and high-strength green SF mortar (HSGFM) were developed using various materials. The primary materials included Ordinary Portland Cement (OPC), Silica Fume (SF), Ultra-fine Palm Oil Fuel Ash (UPOFA), fine aggregates (sand), superplasticizer, and water. Detailed descriptions of these materials, their properties, and sources are provided below.

a. Ordinary Portland Cement (OPC): it was utilized as the main binder in all mortar mixes. OPC is a commonly used cement in construction, known for its high compressive strength and durability. The OPC employed in this study was supplied by Hume Cement, Malaysia (compatible with ASTM C150). It had a specific surface area of 0.785 m^2/g and specific gravity of 3.15. The median particle size of OPC was 6.77 µm. The chemical composition of OPC included 20.55% SiO_2, 5.63% Al_2O_3, 3.8% Fe_2O_3, 65.88% CaO, 0.86% MgO, 1.03% K_2O, and 3.76% SO_3, with a loss on ignition (LOI) of 2.51% .

b. Ultra-fine Palm Oil Fuel Ash (UPOFA): The material was derived from Palm Oil Fuel Ash (POFA), a by-product generated through the combustion of palm kernel shells, fibers, and empty fruit bunches in steam boilers. The POFA used in this study was sourced from a palm oil processing plant located in Nibong Tebal, Penang, Malaysia. To enhance its pozzolanic reactivity, POFA underwent a series of treatments as adopted by Megat Johari, Zeyad [11], N. Mohammed, Azmi Megat Johari [12] and Zeyad, Megat Johari [13]. The chemical composition of UPOFA included 64.81% SiO_2, 5.66% Al_2O_3, 4.73% Fe_2O_3, 8.24% CaO, 4.63% MgO, 6.37% K_2O, and 0.36% SO_3, with an LOI of 2.55%.

c. Silica Fume (SF): is an extremely reactive pozzolanic material, produced as a by-product of the smelting process in electric arc furnaces during the manufacturing of ferrosilicon alloys or silicon metal. The SF utilized in this paper had a specific gravity of 2.22 and a specific surface area of 29.2 m^2/g, with particle sizes ranging from 0.1 to 1 µm. Its high SiO_2 content (92.25%) significantly contributes to the pozzolanic reaction, enhancing the durability and strength of the mortar. The chemical composition of SF also included 0.88% Al_2O_3, 1.86% Fe_2O_3, 0.94% CaO, and 1.37% K_2O, with an LOI of 4.96% .

d. Fine Aggregates (Sand): Natural sand from a river in Nibong Tebal, Penang, Malaysia, was emloyed as the fine aggregate in this study. The sand was clean and dry, conforming to British Standards (BS 882). It was sieved to ensure a particle size distribution suitable for high-strength mortar, with particles retained on a 150 µm sieve and passing through a 5 mm sieve. The specific gravity and the fineness modulus of the fine aggregate were 2.63 and 2.87, respectively.

e. Superplasticizer: To increase the mortar workability without more water content, a superplasticizer named Sika ViscoCrete-2044 was employed in this paper. it is a high-range water reducing admixture (polycarboxylate based) complies with ASTM C494. The constant water-cement ratio of 0.22 was maintained for all the mixes to achieve the desired flow and strength.

f. Water: Potable water, free from impurities and contaminants, was utilized for mixing and curing the mortar specimens. The water-to-binder (w/b) ratio was carefully controlled to ensure the consistency and strength of the mortar. The water played a vital role in the hydration process of the cement and the pozzolanic reactions of UPOFA and SF, contributing to the overall strength and durability of the mortar.

2.2. Mix Proportions

The components of the high-strength mortars (HSM, HSGM, and HSGFM) were carefully designed based on the American Concrete Institute guidelines ACI 211.1-91. The experimental program included a control mix with 100% of OPC and several mixes incorporating UPOFA and SF at varying replacement levels. The w/b ratio was maintained at 0.26 for all mixes, and the sand-to-binder weight ratio (s/b) was kept at 1.5.

Table 1: Proportions of mortar mixtures

Mix ID	OPC (%)	UPOFA (%)	SF (%)	w/b	s/b
HSM	100	0	0	0.26	1.5
HSGM	60	40	0	0.26	1.5
HSGFM-5	55	40	5	0.26	1.5
HSGFM-10	50	40	10	0.26	1.5
HSGFM-15	45	40	15	0.26	1.5
HSGFM-20	40	40	20	0.26	1.5

2.3 Specimens' preparation

The mixing procedures were carefully followed to ensure the homogeneity and consistency of the mortar mixes. A Hobart mixer with a 4.73-liter capacity was used. Initially, the dry components (OPC, UPOFA, SF, and sand) were weighed and placed in the mixer, where they were mixed for five minutes to ensure uniform distribution. Next, half of the superplasticizer was mixed with the total water required and steadily added to the dry ingredients while mixing, continuing for additional five minutes. Finally, the remaining superplasticizer was slowly added to the premixed materials, and the mixture was homogenized for an additional five minutes until a thick paste consistency was achieved.

The casting and curing procedures were crucial for achieving the desired properties in the mortar samples.

Casting: 50mm steel cube molds were cleaned and oiled to prevent sticking. The mixed mortar was placed into molds in two layers, with each layer compacted on a vibrating table for 15 seconds to eliminate air bubbles and ensure adequate compaction. Once the molds were filled, they were left at room temperature for 24 hours.

Curing: After that, the cubes were demolded and submerged in a water tank kept at 25°C for continuous hydration. The samples underwent curing for specific periods, such as 7 and 28 days, to investigate the compressive strength, water absorption, and porosity under normal water curing conditions.

3. The results

3.1 The mortar workability

This section explores the impact of POFA on the workability of high-strength mortars (HSM), as measured by the flow table test before casting. As shown in figure 1, the results demonstrate significant variations in flow values, which provide insights into the influence of these additives on the fresh behavior of the mortar mixes.

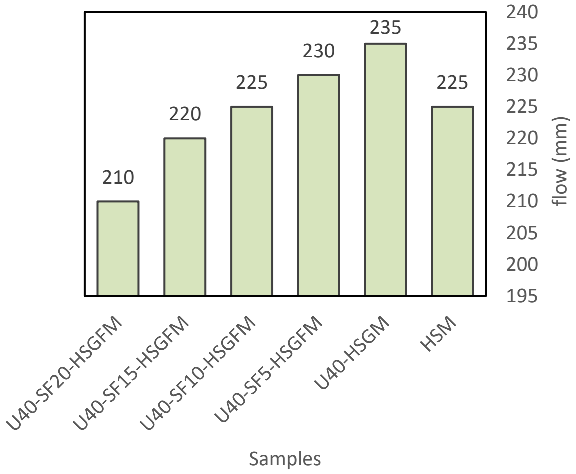


Fig. 1: mortar workability results

The control mix (HSM) exhibited a flow value of 225 mm. This serves as the baseline for comparison with the modified mixes containing varying percentages of POFA and SF. The mixture with 40% POFA (U40-HSGM) showed an increased flow value of 235 mm, indicating increased workability compared to the reference mix. The enhanced flowability can be attributed to the lower specific gravity of POFA in comparison to OPC, which increases the paste volume, thereby improving the mortar's overall flow characteristics.

Incorporating SF alongside POFA had a noticeable impact on the flow values. The U40-SF5-HSGFM mix, containing 5% SF, exhibited a flow value of 230 mm. This slight decrease compared to the U40-HSGM mix suggests that while the addition of SF enhances the pozzolanic activity and micro-filling effect, it also increases the water demand due to the fine particle size and large surface area of SF. Consequently, this results in a reduction in flow value.

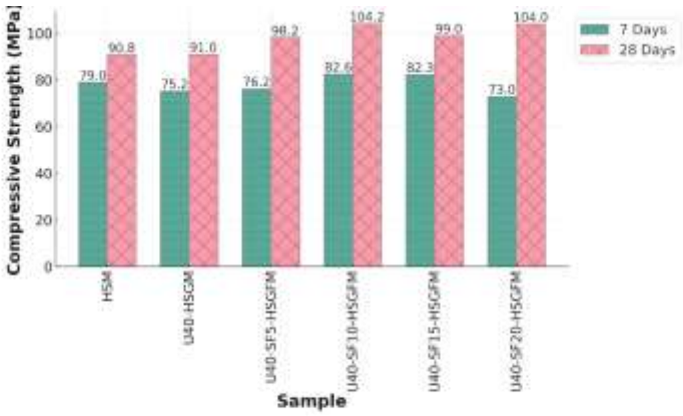
Further increasing the SF content to 10% in the U40-SF10-HSGFM mix resulted in a flow value of 225 mm, identical to the control mix. This balance suggests that 10% SF offers an optimal combination, where the benefits of enhanced pozzolanic activity and micro-filling are offset by the increased water demand, maintaining workability similar to that of the control mix.

However, as the SF content increased to 15% and 20% in the U40-SF15-HSGFM and U40-SF20-HSGFM mixtures, the flow values further reduced to 220 mm and 210 mm, respectively. These results indicate that higher percentages of SF significantly reduce workability. The high-water demand associated with the increased fine particles of SF outweighs the benefits of improved microstructure, leading to lower flow values. This trend aligns with findings from previous studies, which have shown that the inclusion of SF, despite its positive effects on strength and durability, can adversely affect the workability of cementitious mixes as a result of its high surface area and water absorption capacity.

In summary, the flow table test results highlight the delicate balance between workability and the inclusion of SF and POFA in high-strength mortars. While POFA significantly enhances flowability, the addition of SF, particularly at higher percentages, reduces workability due to increased water demand. The optimal performance, in terms of maintaining adequate workability, is observed with 10% SF in combination with 40% POFA.

3.2 The compressive strength

This section explores the impact of SF and POFA on the compressive strength of high-strength mortars (HSM) at 7 and 28 days. The results indicate a complex interplay between the additives and the curing process, revealing critical insights into the optimal formulation for enhanced mechanical properties. Figure 2 shows a comparison of the resulted compressive strength for the different concrete samples at 7 and 28 days.



Fig, 2: Comparison of compressive strength development Over 7 and 28 Days

At 7 days, the HSM reference mixture showed a compressive strength of 79 MPa, which increased to 90.8 MPa at 28 days. This baseline performance underscores the efficacy of traditional Portland cement in developing early and long-term strength. However, the inclusion of 40% POFA (U40-HSGM) slightly reduced the 7-day strength to 75.2 MPa (−4.8%) but recovered to 91 MPa at 28 days (+0.2%). This recovery can be due to the pozzolanic reactions that enhance the microstructural development over time, compensating for the early strength loss.

The incorporation of SF alongside POFA significantly impacted the strength development. The U40-SF5-HSGFM mix, containing 5% SF, showed a moderate improvement at 7 days with a compressive strength of 76.2 MPa (−3.5%), and a notable increase to 98.2 MPa at 28 days (+8.2%). This enhancement is likely due to the micro-filling effect of SF and its high pozzolanic activity, which promotes the formation of additional calcium silicate hydrate (C-S-H) gel, thereby densifying the mortar matrix.

The optimal performance was observed in the U40-SF10-HSGFM mix, where 10% SF was used. This mix achieved a compressive strength of 82.6 MPa at 7 days (+4.6%), the highest among all tested mixes, and further improved to 104.2 MPa at 28 days (+14.8%). The results suggest that 10% SF provides a balanced enhancement of both early and long-term strength. The fine particles of SF not only act as nucleation sites for C-S-H gel formation but also improve the packing density of the mortar, reducing porosity and enhancing strength.

However, increasing the SF content beyond 10% did not yield proportional benefits. The U40-SF15-HSGFM and U40-SF20-HSGFM mixes exhibited compressive strengths of 82.3 MPa (+4.2%) and 73 MPa (−7.6%) at 7 days, respectively, with long-term strengths of 99 MPa (+9%) and 104 MPa (+14.5%) at 28 days. The diminished early strength in these mixes can be attributed to the higher water demand of SF, which may not be fully compensated by the available mixing water, leading to suboptimal hydration of the cementitious components.

In summary, the study demonstrates that while POFA can enhance long-term strength through pozzolanic reactions, the optimal behavior in terms of both early and long-term compressive strength is achieved with a 10% replacement of SF. This formulation balances the benefits of micro-filling and pozzolanic activity, resulting in a dense, strong mortar matrix. Future research should explore the precise mechanisms through which these additives interact and the potential for further optimizing mix proportions to achieve even greater performance enhancements.

3.3 The water absorption

The investigation into the influence of SF and POFA on the water absorption performance of high-strength mortars (HSM) reveals significant findings. Figure 3 shows a comparison of the resulted water absorption for the different concrete samples at 7 and 28 days.

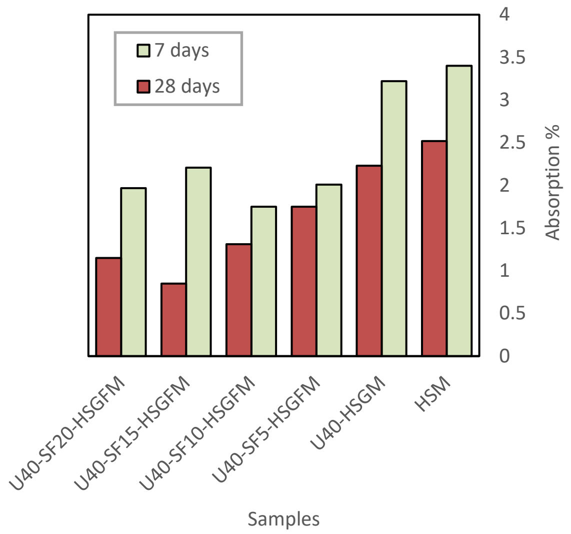


Fig 3: Comparison of water absorption development Over 7 and 28 Days

At 7 days, the control mix (HSM) demonstrated a water absorption rate of 3.4%, which decreased to 2.52% by 28 days. This reduction is indicative of the typical hydration process in traditional Portland cement, where continued hydration leads to a denser microstructure and reduced porosity over time. In contrast, the mix containing 40% POFA (U40-HSGM) showed a water absorption rate of 3.22% at 7 days, further reducing to 2.23% at 28 days. This improvement can be attributed to the filler impact of POFA particles, that enhance the packing density and reduce the pore connectivity within the mortar matrix.

The inclusion of SF in combination with POFA significantly impacted the water absorption characteristics. The U40-SF5-HSGFM mix, which includes 5% SF, exhibited an absorption rate of 2.01% at 7 days and 1.75% at 28 days. This improvement is mainly because of the high pozzolanic reactivity of SF, which enhances the formation of additional calcium silicate hydrate (C-S-H) gel, thus reducing the pore size and connectivity.

The optimal performance in terms of water absorption was observed in the U40-SF10-HSGFM mix, where 10% SF was used. This mix exhibited an absorption rate of 1.75% at 7 days and 1.31% at 28 days. The results suggest that 10% SF provides the best balance for enhancing water resistance because of its fine particle size and high reactivity, which significantly densifies the mortar matrix and blocks water penetration.

However, increasing the SF content beyond 10% did not proportionally enhance the water absorption properties. The U40-SF15-HSGFM and U40-SF20-HSGFM mixes showed absorption rates of 2.21% and 1.97% at 7 days, respectively, and 0.85% and 1.15% at 28 days. These results indicate that higher SF content increases the demand for mixing water due to its fine particle size, which may not be fully compensated by the available water, leading to higher residual porosity and increased absorption rates compared to the 10% SF mix.

In summary, the study demonstrates that while POFA significantly enhances water resistance by filling voids and reducing porosity, the addition of SF at an optimal level (10%) further improves these properties by enhancing the microstructure density and reducing water permeability. This combination of POFA and SF offers a balanced approach to developing high-strength mortars with superior durability and reduced water absorption. Future research should explore the precise mechanisms and interactions of these additives to optimize mix designs for various environmental conditions and applications.

4. Conclusion

This study has demonstrated the significant effects of incorporating SF and POFA on the workability, strength, and absorption characteristics of high-strength mortars (HSM). The investigation revealed that while POFA increase the workability and long-term strength of the mortars, SF contributes significantly to improving the microstructure and reducing the water absorption of the mixtures.

The results of the flow table test indicated that the addition of 40% POFA increased the flow value, thereby improving the workability of the mortar compared to the reference mixture. However, the inclusion of SF, particularly at higher percentages, resulted in decreased workability because of the increased water demand of the fine particles. The optimal workability was observed in the mix with 10% SF and 40% POFA, which maintained a flow value similar to the reference mix.

In terms of compressive strength, the mortars containing both POFA and SF exhibited superior performance. The optimal mix, containing 10% SF and 40% POFA, achieved the highest compressive strength at both 7 and 28 days, demonstrating the synergistic effect of these additives in developing the mechanical properties of the mortar. Higher percentages of SF, however, did not proportionally improved the strength and instead led to diminished workability.

The water absorption tests highlighted the beneficial impact of SF and POFA in reducing porosity and enhancing the water resistance of the mortars. The mix with 10% silica fume and 40% POFA showed the lowest absorption rates, underscoring the effectiveness of this combination in producing a dense and durable mortar matrix.

In conclusion, the findings of this study suggest that the optimal performance in high-strength mortars can be achieved by incorporating 10% silica fume and 40% POFA. This combination strikes a balance between improved workability, enhanced compressive strength, and reduced water absorption. Future research should investigate the effects of different levels of UPOFA replacement under ambient curing conditions, the efficiency of using locally available industrial and agricultural wastes in Libya, such as palm and olive waste, as well as by-products from the iron and steel industries, under various curing regimes such as air curing and steam curing. Additionally, examining the performance of these mortars in marine environments will further optimize and expand their applications.

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