Engineering Science and Technology, an International Journal 45 (2023) 101492

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Review

Influence of palm oil fuel ash on the high strength and ultra-high performance concrete: A comprehensive review

Hussein Hamada [a], Farid Abed [a,*], Alyaa Alattar [b], Fadzil Yahaya [c], Bassam Tayeh [d], Yazan I. Abu Aisheh [e]

[a] Department of Civil Engineering, College of Engineering, American University of Sharjah, UAE
[b] Northern Technical University, Mosul, Iraq
[c] Faculty of Civil Engineering and Technology, University Malaysia Pahang, Malaysia
[d] Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, Gaza Strip, Palestine
[e] Department of Civil Engineering, Middle East University, Amman 11831, Jordan

A R T I C L E I N F O

Keywords:
High strength concrete
Ultra high-performance concrete
Palm oil fuel ash
Durability
Environment

A B S T R A C T

In recent days, the increase in significant infrastructure projects has led to urgent requirements for the use of high strength concrete (HSC) and ultra-high-performance concrete (UHPC). However, the use of cement and its derivative products, such as concrete, is associated with a high generation of carbon dioxide (CO2). The construction industry contributes about 8% of the total global CO2 production. Therefore, there is an urgent need to use agriculture-waste materials such as palm oil fuel ash (POFA) to help reduce environmental concerns associated with concrete. The accumulation of palm oil waste over an extended period of time causes environmental pollution. The use of these materials is expected to improve the environment by reducing the disposal of this waste in landfills and open areas. The chemical composition of POFA can vary depending on the source and processing methods. Elevated levels of impurities such as organic matter, unburned carbon, and chloride content in POFA can adversely affect the setting time, workability, and long-term durability of concrete. The optimal mix proportioning and replacement levels of POFA in concrete need to be carefully determined. Incorporating higher levels of POFA without proper adjustments to the mix design can result in detrimental effects on fresh and hardened concrete properties, including reduced compressive strength and decreased resistance to chemical attacks. This paper will highlight the impacts of POFA on the properties of HSC and UHPC in their fresh and hardened states. Durability and microstructure properties were also discussed. The use of ultrafine POFA helped in reducing the rapid chloride permeability and water absorption of HSC, thus improved its structure. Lastly, some recommendations for future studies are presented.

1. Introduction

Currently, the construction industry consumes large quantities of concrete that reach up to 10 billion tons annually [1]. It is expected that the demand for concrete will see a significant upsurge by 2050 and reaching up to 18 billion tons annually owing to the increase in the population worldwide [2,3]. A considerable quantity of this produced concrete, however, resulted in the significant production and release of CO_2, which damages the environment [4]. As reported earlier, many of the studies show that the cement industry contributes to about 8% of the total CO_2 emissions worldwide [5–8]. Numerous investigations have been carried out to discover industrial and agricultural waste that can be used as an alternative to cement and aggregates to reduce the disadvantages produced by the manufacturing of cement [9–18]. Consequently, academics have studied the feasibility of waste materials that have extreme pozzolanic reactions to be adopted as cementitious materials in concrete mixtures [9,19–22]. The utilization of palm oil fuel ash (POFA), a by-product material, can produce more eco-friendly and sustainable concrete [23–26]. This paper aims to clearly display the properties of HSC and UHPC produced with POFA utilized as cementitious material in production.

The concrete properties have been improved significantly over the decades due to ever-increasing demand to produce longer-than-ever long-span bridges, higher and higher high-rise buildings, and high

* Corresponding author.
E-mail address: fabed@aus.edu (F. Abed).

https://doi.org/10.1016/j.jestch.2023.101492
Received 11 March 2023; Received in revised form 20 June 2023; Accepted 18 July 2023
Available online 26 July 2023

earthquake-resistant structures [27,28]. To cater to these requirements, the properties of concrete in both states (fresh and hardened) had to be effective enough to produce high performance concrete. Presently, developments in the domain of concrete have been spearheaded by UHPC to answer the abovementioned requirements. UHPC has excellent performance as it regularly achieves a significant tensile strength and high compressive strength of 150 MPa and more with lower permeability and water absorption [29,30]. Therefore, UHPC has enhanced resistance against environmental pollution, considerably enhanced structural reliability, and outstanding service life.

In past decades, the concrete produced had durability limitations and poor microstructure [31]. These limitations were dealt with by utilizing some mineral admixtures and by-products of other industries such as silica fume, coal bottom ash, slag, waste glass, fly ash, and metakaolin as partial alternatives to cement in the concrete mixtures [32–35]. It was found that the use of these mineral admixtures with smaller particle sizes improves the chemical reaction. This is because of the increase in the surface area of the particles and the reduced water-cement ratio, which results in the production of a UHPC. Nevertheless, the concrete becomes more brittle with increasing compressive strength. In the last decades, the concrete characteristics have also significantly improved due to the implementation of steel fiber-reinforced concrete and slurry-infiltrated concrete (SIFCON) [36]. Moreover, a scientific improvement occurred with the introduction of reactive powder concrete (RPC), producing high compressive stress between 200 and 800 MPa [37–39]. Further development in RPC resulted in production of UHPC, that has high mechanical strength [40–42] and highly dense microstructure [43–46].

POFA is an alternative cementitious material that is utilized recently to deal with the economic and environmental issues surrounding concrete development [47]. POFA is a by-product (or a waste) that comes into existence as a result of burning leftover fruits and their shells, agricultural fibers, and kernels to produce electricity and other forms of energy for industries, especially palm oil mills [48,49]. Indonesia, Malaysia, and Thailand are the countries with the largest production of POFA, and the production is projected to grow every year [48,50]. Numerous investigators show that pozzolanic properties are prominent within POFA [51,52]. POFA when grinded into an ultrafine particle size (UPOFA), is known to enhance concrete when it comes to its engineering and transportation, essentially improving its mechanical properties [34,53] and producing HSC and UHPC [52]. Zeyad et al. [54] experimented with the use of UPOFA in concrete in hopes of improving concrete with significantly high strength. They concluded that the UPOFA has a substantial role in improving the workability, strength, and permeability of high-strength concrete (HSC). The reported compressive strength was about 108, 114, and 112 MPa, for HSC mixtures that contain 20, 40, and 60% of UPOFA, respectively. Modern studies illustrate that the latest use of UPOFA in producing HSC and UHPC still requires further investigation, as the current literature is incomplete.

This research was introduced to include analysis about the current problems related to the use of cement, associated problems because of generating harmful CO_2 emissions, and some literature related to using UPOFA as a sustainable and supplemental binder material to partially replace cement. The physical and chemical properties of UPOFA, as well as the effect of UPOFA on the mechanical, durability, and microstructure properties will be analyzed. Therefore, this research will investigate the results studied from previous research and further discuss the impact of UPOFA with and without other fibers and admixtures on the properties of HSC and UHPC.

2. Method and scope

This paper reviews different previous literature regarding the implementation of POFA as a cementitious material in the production of UHPC. Throughout this article, efforts have been made to study and report the investigation conducted by the previous researchers and to organize the data collected in a well-structured style for upcoming investigators. This paper focuses on the impact of using POFA on different properties accompanied by UHPC. Then, this paper also concentrates on potentially replacing cement with POFA by integrating different fiber volumes and admixture types. The paper, besides reviews of previous studies, focuses on the efforts made to obtain the highest values of compressive, flexural, and tensile strengths. Efforts to yield higher values of compressive, tensile, and flexural strengths will also be taken into consideration. Lastly, this study offers some recommendations for upcoming investigators about the extensive utilization POFA as cement replacement in producing HSC and UHPC.

Table 1
Physical properties of POFA by the last studies.

Ref.	Blaine fineness (m^2/g)	Specificgravity	Median particle size, d_{50} (μm)	Surface area (m^2/g)	Retained on sieve No. 325 (%)
[57]	1.136	2.59	2.06	1.775	
[54]	1.136	2.59	2.06	7.670	
[58]		2.33	10.1		1.5
[59]		2.33	10.1		1.5
[52]		2.50	2.99		

3. Properties of POFA in concrete

3.1. Physical properties of POFA

Table 1 provides an insight on the physical components of POFA. Certain factors, such as the temperature rate, burning duration, sourcing, and other environmental conditions authorize these components [9,26,55]. The raw POFA has a gray color and is converted into a darker complexion after the grounding process because of the presence of the significant amount of carbon that is of unburnt nature, the color again changes to gray after POFA is exposed to a higher temperature rate that results in burning of carbon particles. The size distribution of POFA is between (1.89 and 2.6). Image comparison between Ordinary Portland cement (OPC) and POFA is illustrated by Bashar et al. [56] as shown in Fig. 1.

3.2. Chemical composition of POFA

The individual constituents of POFA are shown in Table 2. Based on the table, POFA consists of mainly silica oxide. The POFA was examined in terms of chemical composition by many researchers, as presented in Table 2. A significant difference was detected in the chemical composition due to different conditions, for example quality of palm oil waste and temperature rate to the procedure of creating POFA [52,60,61]. Using the X-ray diffraction (XRD) analysis, it was shown that POFA generally contains a crystal phase of quartz and mullite. This analysis also showed crystalline silica peaks detected. A low quantity of $Ca(OH)_2$ was also detected. This low quantity is due to most of the $Ca(OH)_2$ being depleted in the pozzolanic reaction [62]. Additionally, the composition of POFA affects the heat of hydration of concrete during manufacturing [63]. POFA particles show significant development in concrete, as they allow for the production of UHPC [54]. Essentially, the main component in POFA that makes up 65 to 69% of its composition is Silica dioxide (SiO_2) which is responsible for the pozzolanic reactions in the HSC and UHPC.

3.3. Effect POFA on the HSC and UHPC

Numerous researchers have utilized POFA to produce HSCs by powdering the particles to a size of roughly 10 μm, replacing cement from 0 to 30% by total weight [66–68]. Sata et al. [58] reported compressive strengths with values 77.5, 81.3, 85.9, and 79.8 MPa for HSC at 28 days with partial replacement of 0, 10, 20, and 30% POFA,

Fig. 1. Images of OPC and POFA particles [56].

Table 2
Chemical properties of POFA presented by previous studies.

Ref.	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	SO_3	K_2O	LOI
[64]	65.2	2.6	2.0	3.1	6.4	0.3	0.5	5.7	10.1
[65]	69.02	3.9	4.33	5.18	5.01	0.18	0.41	6.9	1.8
[58]	65.30	2.60	2.00	3.10	6.40	0.30	0.50	5.70	10.10
[52]	65.01	5.72	4.41	4.58	8.19	0.07	0.33	6.48	2.53
[59]	65.3	2.5	1.9	3.0	6.4	0.3	0.4	5.7	10.0

respectively with 560 kg/m^3 as the total binder content and w/b of 0.28. Mohammed et al. [66] also analyzed the influence of UPOFA on the transport and strength qualities of UHPC with total binder content of 1128 kg/m^3. Tangchirapat et al.[59] analyzed the UHPC properties containing GPOFA with a total cement content of 560 kg/m^3 and a water-to-binder ratio of 0.32. The maximum stress achieved for concrete containing 20% POFA as a replacement to cement was 85.9 MPa.

Aldahdooh et al. [69] also utilized UPOFA as a cement replacement for preparing Ultra-High Performance Fiber Reinforced Cementitious Composites. They reported a compressive strength of 158.28 Mpa over the span of 90 days when 50% of cement was replaced by UPOFA. Zeyad et al. [70] used UPOFA to produce high-strength green concrete (HSGC) at different steam curing regimes. They added UPOFA in different concrete samples with replacement levels of 0, 20, 40, and 60% of the total weight of cement. To investigate the impact of curing temperatures, these samples of HSGC were also cured at different temperatures. They reported that at an earlier curing age, the compressive stress of the HSGC was reduced, while the long-term compressive strength i.e. at 360 days was reported to be enhanced by percentages of 5.4%, 10%, and 9.2%, respectively. These relativity increases were evaluated based on the control concrete specimens. The specimens possessing high compressive strength is due to the significant pozzolanic reactions that take place during the hydration process, as well as the utilization of fine particles that serve as fillers. These factors contribute to the optimal solution of filling voids and achieving a higher density, thereby enhancing the overall compressive strength.

Al-mulali et al. [71] mentioned that the replacement of 20 to 30 % of cement with 7.4 μm sized particles of UPOFA resulted in higher compressive strength, relative to the control concrete sample, and was associated with a higher pozzolanic reaction [48,72]. Rukzon and Chindaprasirt [73] reported that cement mortars combined using UPOFA as a replacement to cement with particle sizes less than 7 μm showed compressive strength higher than the relative control mortar sample due to the higher reactivity of POFA and its filler effect. The impacts of using UPOFA are better compared to the large particle size of between 22 and 55 μm of POFA. Consequently, the small particle size of POFA of up to 10.1 μm with 20% replacement cement achieved HSC with compressive strength of more than 70 MPa, demonstrating that fine particle size has a high pozzolanic reaction and can thus be utilized as an alternative mineral admixture in concrete production [59]. Kroehong et al. [74] also studied the influence of fine POFA on the particle packing and pozzolanic reactions of blended cement paste. They noted that the pastes containing POFA of particle size 2 μm and 10 to 30% replacement levels by total cement weight presented higher compressive strength between (105 and 111%) than the cement pastes.

Scholars have attempted to utilize and study different quantities to which POFA is added to a concrete mixture as a replacement to cement in order to produce UHPC. Most of them used admixtures or fibers to improve the UHPC properties, such as Nano Silica (NS), Metakaolin (MK), and silica fume (SF). These materials have been utilized owing to the highly absorbed water, and higher surface area that improves the performance of UHPC. Consequently, the water quantity required for lubrication decreased [75–77]. Because of the low specific gravity values of POFA, the workability of UHPC increases, especially at higher replacement levels. Moreover, due to the high surface area accompanied by UPOFA, an increase in the replacement level increases the viscosity of the HSC and UHPC. Khankhaje et al. [78] also investigated the impact of UPOFA on various properties of concrete. Results show that concrete samples with UPOFA replacing 20% of cement by weight exhibited superior durability properties than Ordinary Portland cement (OPC) concrete.

4. Fresh properties of HSC and UHPC containing POFA

4.1. Setting time

Mixing cement and water produces paste that progressively loses its plasticity, and ultimately changes into a solid form. The setting process is finished when the cement paste is adequately rigid to bear the required pressure. Therefore, the setting time is defined as the required time to reach the rigid or solid state. Zeyad et al. [57] determined the setting time of mixtures containing UPOFA according to the ASTM C403 [79]. The outcomes obtained showed a positive correlation between an increase in replacement levels of UPOFA and the initial and final setting times of the HSC samples. Similar outcomes were stated by Tangchirapat et al. [80] on the influence of various mineral admixtures with various

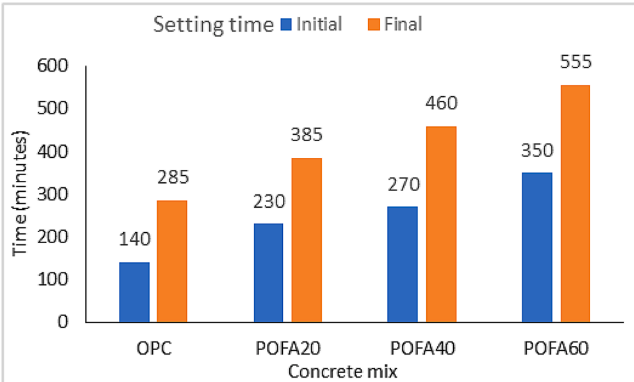

Fig. 2. Initial and final setting times in HSC and UHPC comprising UPOFA [84].

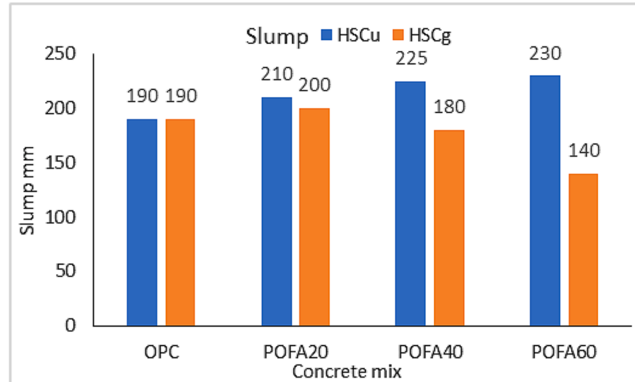

Fig. 3. Influence of UPOFA against the slump values [54].

Table 3
Effect of POFA on the setting time of UHPC.

Ref.	Replacement level	Cement content kg/m^3	Particle size of POFA μm	Effect of UPOFA on the setting time (min)	
				Initial setting time	Final setting time
[84]	0, 20, 4, and 60%	550	2.06	140, 230, 270, and 350	285, 385, 460, and 555
[66]	0, 17, 30, and 40%	1128	2.06	420, 450, 540, and 612	615, 669, 810, and 918
[52]	0, 20, 40, and 60%	550	2.06	140, 230, 270, and 350	285, 385, 460, and 555

Table 4
Effect of POFA on the workability of HSC and UHPC.

Ref.	Replacement level	Cement content kg/m^3	Particle size of POFA (μm)	Effect POFA on the workability (mm)
[54]	0, 20, 40, and 60%	550	2.06	190, 210, 225, and 230
[69]	0, 25, and 50%	720	2.06	167, 169, and 171
[70]	0, 20, 40, and 60%	550	2.06	180, 200, 220, and 230
[87]	0, 10, 20, 30, and 40%	588	45	95, 100, 80, 65, and 20
[88]	0, 10, 20, and 30%	588	30	140, 100, 65, and 40
[89]	0, 10, 20, 30, 40, 50, and 60%	550	2.06	190, 210, 210, 220, 255, 225, and 230.

particle sizes UPOFA on the HSC properties [81]. The benefit of delaying the setting time can be advantageous when producing concrete in hot weather to mitigate the effects of rapid setting caused by high temperatures. Also, the increase in compressive strength of concrete, which incorporates low replacement levels and ultrafine particle size of POFA, is attributed to the pozzolanic reactions that occur, particularly at later ages. These reactions align with the delayed setting time observed in concrete containing POFA.

Tay and Show [82] stated that adding POFA to the cement paste caused an increase in the setting time. (125 and 165 min) were the respective initial setting time ranges for the concrete specimens comprising POFA with replacement levels between (0 and 50) %. Additionally, the final setting time ranges between (185 and 250) minutes, within the acceptable ASTM standards. Tangchirapat et al. [80] reported the initial and final setting times for concrete that contained 40% of POFA as a replacement to cement in the mix to be 410 and 740 min, respectively. Likewise, Karim et al.[83] detected that using UPOFA lead to a rise in the initial and final setting times of cement paste. However, both times were equal to or less than 375 min. The delay in these setting times might be because more water absorption and a rougher POFA particle size caused delays in the hydration process. Zeyad et al. [84] also support this by reporting that using of UPOFA instead of cement results in a significant delay in the setting times, as shown in Fig. 2. Table 3 shows the relationship between POFA and the setting time of UHPC.

4.2. Workability

The workability of a concrete mix consisting of POFA replacing a portion of cement is calculated using the slump test. The slump values of the concrete mixtures are different due to the difference in the replacement levels of UPOFA. Numerous investigations have mentioned the influence of POFA on the workability of UHPC. Johari et al. [52] for instance, investigated the workability of HSC mixtures comprising UPOFA with fine particle size (2.06 μm) and replacement levels of 50, 60, and 70% of cement according to BS EN 12350–2 [85]. It was concluded that an increase in the replacement levels of UPOFA in a concrete mixture led to an increase in its slump values. This increase in workability can be because of the low specific gravity associated with POFA. The concrete workability can also improve by adding admixtures to the concrete mix. Generally, the viscosity of normal concrete is already lower than that of the UHPC [86]. Zeyad et al. [54] supported this by showing that increasing the percentage of UPOFA in a concrete mix results in an increase in the slump values as can be shown in Fig. 3. Whereas the HSCg and HSCu refer to the high strength concretes made of ground POFA (GPOFA) and ultrafine-POFA (UPOFA), respectively.

Superplasticizers are frequently employed in concrete to enhance its workability and fluidity by dispersing cement particles and reducing the necessary water content for a desired slump [87]. When GPOFA is incorporated into concrete mixes, it can have a beneficial effect on the fluidity of the mixture. The fine particles and pozzolanic characteristics of GPOFA can contribute to improved particle packing and lubrication, thereby enhancing the flowability and workability of the concrete mixture. The specific surface area and chemical composition of GPOFA can influence its capacity to adsorb superplasticizers. Muthusamy et al. [88] utilized ground POFA (GPOFA) in concrete mixtures, replacing portions of cement in various percentages (0 to 40%). Their results show that GPOFA has a major impact on the workability of HSC. Concrete mixtures with 10% cement replaced have a higher slump value relative to the other mixtures. This might be due to the characteristics of GPOFA, which can fill the internal pores because of its fine particle size, and the ability to obtain superior lubrication of the concrete mix. Table 4 displays the relationships between different replacement levels of POFA

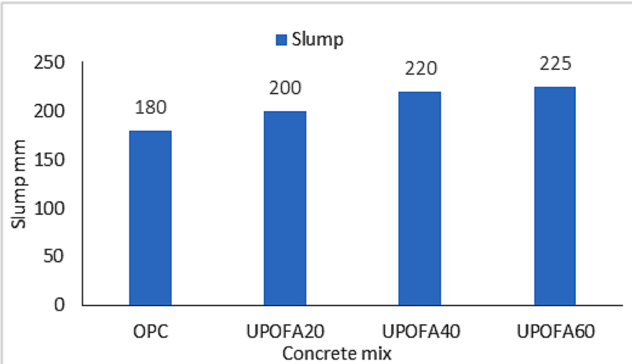

Fig. 4. Slump values against the UPOFA content in HSGC [70].

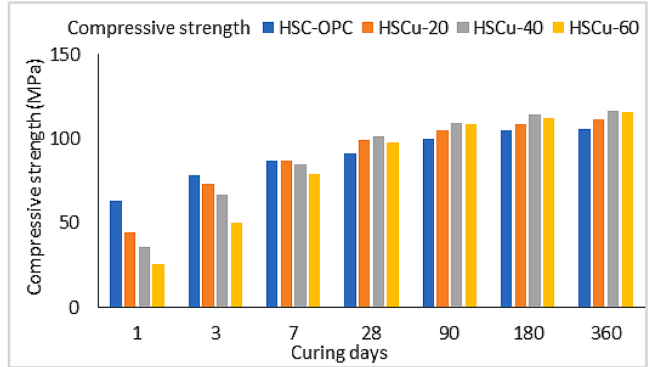

Fig. 5. Compressive strength values of HSC vs curing time in days [70].

and the workability of UHPC.

Many have also previously investigated the impact of using POFA in HSC and UHPC on the workability of the mix. These investigations yield that adding POFA enhances the workability of UHPC. This is because of the low specific gravity of POFA, as supported previously by other investigations. Furthermore, the workability may be improved by increasing the addition of binder paste. Moreover, the high surface area of UPOFA results in an increased viscosity of the UHPC, which is also directly proportional to the replacement levels of UPOFA [52,66,90]. Aldahdooh et al. [69] studied the influence of using high volumes of UPOFA on the UHPC in different replacement levels, up to 75%. They concluded that using UPOFA remarkably enhances the workability of UHPC. This is because the more workable a concrete mixture is, the lower its carbon content and loss of ignition (LOI),as examined by other studies [52]. Zeyad et al. [70] also examined the impact of UPOFA on the HSC at various percentage replacements to cement and different curing steam temperatures. They concluded using UPOFA increases the slump values of a mixture, as shown in Fig. 4.

5. Mechanical properties of UHPC and HSC

5.1. Compressive strength

UHPC, as the name suggests, has a significantly larger compressive strength relative to ordinary concrete, with values reaching up to 150 MPa. A large quantity of cement is generally required to produce UHPC [91]. Other physical conditions, like fine particle size of the mineral admixtures and their components, like high-strength steel fibers and superplasticizers for example, also play an important role in developing UHPC. This partially explains the impact of POFA in different replacement levels in addition to fibers and the impact of different admixtures, particularly regarding their influences on compressive strength. Muthusamy et al. [88] studied the long-term effect POFA has on the strength of HSC in a humid tropical environment after 360 days of curing. The highest strength value was in the sample that contained 10% replacement of cement with GPOFA. This value was significantly high because of the high pozzolanic reaction of GPOFA and packing of the internal pores, ultimately leading to a dense concrete structure that can retain larger value of loads. There is a correlation between GPOFA and the compressive strength of HSC. The addition of a certain amount of GPOFA, particularly at later ages, leads to an increase in the compressive strength of concrete. This is primarily attributed to the high pozzolanic reaction of GPOFA, which is due to its high silica content and the presence of other amorphous materials. These factors facilitate the reaction between GPOFA and calcium hydroxide during cement hydration, resulting in the production of additional calcium silicate hydrate (C-S-H) gels. Consequently, the density and compressive strength of the concrete are enhanced. Furthermore, icorporating GPOFA with a small particle size contributes to the refinement of the concrete's microstructure. The pozzolanic reaction between POFA and lime generates additional C-S-H gel, which fills gaps and forms a more uniform and refined microstructure. This denser microstructure improves the transfer of loads and interlocking of particles, thereby leading to enhanced compressive strength.

Table 5
Relationship between UPOFA and the compressive strength of HSC and UHPC.

Refe.	Replacement level	Cement content kg/m^3	Particle size µm	Effect POFA on the compressive strength MPa
[54]	0, 20, 40, and 60%	550	2.06	91.4, 99.5, 101.5, and 98.1
[69]	0, 25, and 50%	720	2.06	25, 38, and 73
[70]	0, 20, 40, and 60%	550	2.06	93.1, 99, 102.1, and 94.9
[88]	0, 10, 20, 30, and 40%	576	30	60, 65, 60, 58, and 56
[87]	0, 10, 20, and 30%	588	45	61.9, 63.3, 53.0, and 43.3

Zeyad et al. [70] have thus concluded that the increasing UPOFA as a replacement to cement in a concrete mixture has a substantial effect on the improvement of the compressive strength of UHPC, as presented in Fig. 5.

Salam et al. [92] examined the impact of UPOFA on the self-consolidating high-strength concrete (SCHSC) and analyzed its properties. They reported a -compressive strength of ranges between (52.3 and 74.2) MPa after 28 days. After curing for 56 days, the value of the compressive strength was found to be ranging between (54.8 and 72.9) MPa. Moreover, Aldahdooh et al. [69] studied the effects of UPOFA on the compressive strength of UHPC. They used the densified micro-silica fume (DSF) with UPOFA and reported that the 28-day compressive strength of value 156.72 MPa was achieved with 50% (OPC-UPOFA) and 0.0% [DSF-UPOFA], while the concrete mix containing 25% UPOFA replacing cement has a compressive strength of 174.4 MPa. Table 5 showcases the influence of POFA on the compressive strength of HSC and UHPC produced by the last studies and shows the replacement levels for each study.

Table 6
Effect of POFA on the flexural strength of HSC and UHPC.

Refe.	Replacement level	Cement content kg/m^3	Particle size µm	Effect POFA on the flexural strength (MPa)
[93]	0, 25, 50, 60, and 75%	720	2.06	5, 7.5, 16, 20, and 24.5
[88]	0, 10, 20, 30, and 40%	576	30	11, 14.5, 11, 9.5, and 9
[87]	0, 10, 20, and 30%	588	45	9.89, 10.65, 9.33, and 8.65

Table 7
Effect of POFA on the splitting tensile strength of HSC and UHPC.

Ref.	Replacement level	Cement content kg/m^3	Particle size µm	Effect POFA on the tensile strength MPa
[87]	0, 10, 20, and 30%	588	45	3.14, 3.25, 3.14, and 2.84
[93]	0, 25, 50, 60, and 75%	720	2.06	2.1, 3, 5.9, and 8.3
[88]	0, 10, 20, 30, and 40%	576	30	4.5, 5.5, 3.6, 3.1, and 2.5

5.2. Flexural strength

The latest studies have discovered that the available information on the flexural strength of UHPC containing percentages of UPOFA is inadequate. The relationship between POFA percentage replacements and the flextural strength of the mix can be seen in Table 6. Aldahdooh et al. [93] analyzed the effect of high volume UPOFA up to 75% on the ultimate tensile and flexural strengths of ultra-high-performance fiber-reinforced concretes. They discovered that UPOFA improves fresh UHPC fiber reinforced interms of flexural strength. The 28 days-flexural strength was 42.38 MPa with a 50% replacement level, demonstrating the suitable use of UPOFA as an alternativepozzolanic material, as it has better engineering properties.

Aldahdooh et al. [69] adopted the Four-point bending tests to measure the flexural strength of HSC. The test was conducted with three specimens obtained from the optimum mixtures for different ages (7, 28, and 90) days. They mentioned that the respective flexural strength values were 39, 42, and 46.6 MPa for 7, 28, and 90 curing ages. Awal and Mohammad Hosseini [91] investigated the properties of HSC comprising carpet fibers and POFA and concluded that the flexural strength value was higher, relative to normal concrete. Bashar et al. [94] investigated the properties of HSC comprising 90% POFA that contains coarse aggregates in the form of oil palm shell (OPS), with the addition of steel fibers in three volumes(0.25, 0.50, and 0.75) %. The results show an increase in the flexural strength by 7 to 18% in comparison with the control concrete. GPOFA contains amorphous silica and other reactive materials that possess pozzolanic properties. When the finely ground particles of GPOFA react with the calcium hydroxide released during cement hydration, it results in the formation of additional calcium silicate hydrate (C-S-H) gel. This gel significantly contributes to the strength and durability of the concrete matrix, ultimately enhancing the flexural strength. The fine particles of GPOFA play a crucial role in filling the voids and spaces within the concrete structure, leading to a denser microstructure. This densification improves the contact between particles and enhances packing efficiency. As a result, the reduced porosity in the concrete limits the pathways for crack propagation, thereby increasing the flexural strength.

5.3. Splitting tensile strength

Aldahdooh et al. [69] notes the impact of adding UPOFA at different replacement levels starting at 0 to 75% on the splitting tensile strength of ultra-high-performance fiber-reinforced concretes. They concluded that an increase in UPOFA led to an improvement of the splitting tensile strength of fresh UHPC that contains fiber reinforcement. The 28 days-tensile strength was 13.35 MPa. Table 7 illustrates the relationship between adding POFA at different replacement levels and the splitting tensile strength of the concrete mixture.

Sata et al. [64] conducted a study on the split tensile strength of HSC mixtures containing UPOFA particles of sizes up to (10.1 µm) replacing 10, 20, and 30% of cement and containing a water binder ratio of 0.28. Their results showed that concrete mixtures prepared by replacing 10 to 20% of cement with fine POFA showed higher tensile strength relative to control mix samples at similar curing periods. This may be associated with a significant fineness of POFA particles that results in a higher likelihood of forming a pozzolanic reaction. However, Awal and Neguong [95] reported that higher percentages of POFA replacing cement in the concrete mixture reduce its tensile strength, relative to the normal concrete sample. Awal and Shehu [96] showed that the relationship between tensile strength and compressive strength development for POFA and OPC concrete is directly proportional. Altwair et al. [97] conducted a test for the split tensile strength of concrete specimens with replacement levels of 0%, 0.4%, and 1.2%, and a water/binder ratio of 0.33. The results showed that a value of 3.52 MPa was obtained for the splitting tensile strength for the concrete sample with a 0.4% of POFA replacing cement. This concrete sample had a 16% and 9% higher tensile strength than the sample of 1.2% replacement level and the normal concrete sample, respectively.

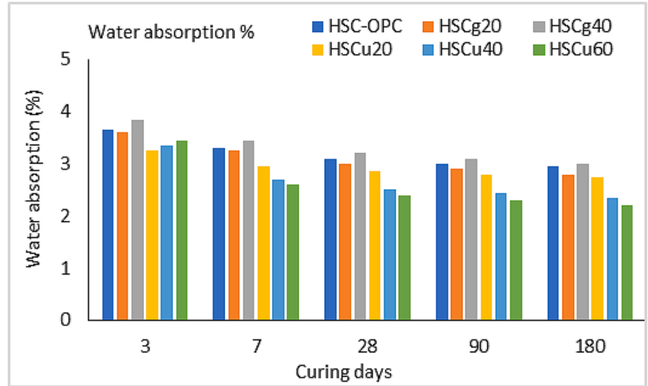

Fig. 6. Water absorption of hsc against time [54].

Table 8
Impact of adding POFA as a replacement on the water absorption of HSC and UHPC.

Refe.	Replacement level	Cement content kg/m^3	Particle size µm	Effect POFA on the water absorption
[54]	0, 20, 40, and 60%	550	2.06	Increasing the UPOFA led to a decrease in the water absorption rate.
[88]	0, 10, 20, 30, and 40%	576	30	Replacing 10% POFA led to reducing the water absorption rate.
[98]	0, 10, 20, 30, and 40%	751	9.51	The Fineness of UPOFA enhanced its pozzolanic reaction and micro-filling potential and enhance the hardened properties of HSC.
[92]	0, 10, 20, and 30%	706	11	The lowest value of water absorption was achieved by adding 20% POFA as cement replacement.
[99]	0, 20, 40, and 60%	550	2.06	The water absorption decreases with an increase in the UPOFA content in HSC mixtures.

6. Durability of HSC and UHPC

6.1. Water absorption

Zeyad et al. [54] analyzed the water absorption of HSC using UPOFA and GPOFA as a replacement for cement in different levels of (0, 20, and 40%). Fig. 6 displays the outcomes obtained for the water absorption of HSC comprising both GPOFA and UPOFA. They observed that the short and long-term water absorption periods were lower for concrete

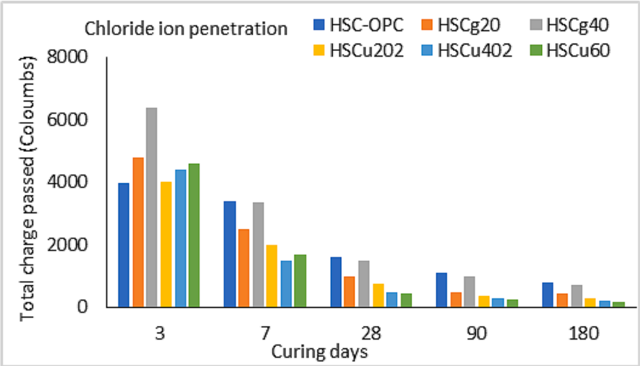

Fig. 7. Rapid chloride permeability of HSC against time [54].

mixtures containing UPOFA. Mixtures comprising GPOFA, however, showed an adverse influence on water absorption of the HSCs, owing to the existence of unburned carbon in their particles that leads to an increase in the rate of water absorption. Table 8 shows the influence of replacing cement in various percentages on the water absorption of HSC and UHPC.

6.2. Rapid chloride permeability

HSC and UHPC containing POFA have been investigated and tested for rapid chloride by numerous researchers. Zeyad et al. [54] examined the effect of GPOFA and UPOFA containing replacement levels of 0, 20, 40, and 60% on rapid chloride penetration. They observed that the chloride charge passage reduces as the POFA content increases, as showcased in Fig. 7. Conversely, at 3 curing days, in HSCu, the charge passed decreased because of increasing the POFA content. Chindaprasirt et al. [100] tested the rapid chloride ion penetration on HCS prepared by replacing 10, 20, and 30% of cement with POFA particle sizes of 20.0 µm. All concrete mixtures were prepared with a 600 kg/m^3 of cement content, w/b of 0.3, and a superplasticizer amount that maintains an acceptable workability between (200 and 250 mm). The results obtained from this study indicate a decrease in the charge pass of POFA concrete samples as the replacement level of POFA increases, up to 30%. This outcome suggests that chloride ion penetration can be decreased by replacing cement with POFA. Lastly, the rapid chloride ion permeability test was conducted to evaluate the corrosion resistance of the concrete mixtures. The outcomes demonstrated that the total charge passed (TCP) considerably decreased if UPOFA were used in HSC samples. For further investigation, Zeyad et al. [101] used a large amount of UPOFA to replace cement to analyze the behavior of HSC against the rapid chloride permeability. They concluded that the UPOFA improves the properties of HSC by resisting the penetration of chloride ions.

Chindaprasirt et al. [100] tested the rapid chloride ion penetration on HCS prepared by replacing 10, 20, and 30% of cement with POFA particle sizes of 20.0 µm. All concrete mixtures were prepared with a 600 kg/m^3 of cement content, w/b of 0.3, and a superplasticizer amount that maintains an acceptable workability between (200 and 250 mm). The results obtained from this study indicate a decrease in the charge pass of POFA concrete samples as the replacement level of POFA increases, up to 30%. This outcome suggests that chloride ion penetration can be decreased by replacing cement with POFA. Lastly, the rapid chloride ion permeability test was conducted to evaluate the corrosion resistance of the concrete mixtures. The outcomes demonstrated that the total charge passed (TCP) considerably decreased if UPOFA were used in HSC samples. For further investigation, Zeyad et al. [101] used a large amount of UPOFA to replace cement to analyze the behavior of HSC against the rapid chloride permeability. They concluded that the UPOFA improves the properties of HSC by resisting the penetration of chloride ions.

Fig. 8. Resistance to carbonation [102].

6.3. Resistance to carbonation

Carbon dioxide (CO_2) can react with the alkaline component through penetrating the concrete surface to form $Ca(OH)_2$ as shown in Fig. 8 [102]. This carbonation (reaction) can minimize the pH solution within the concrete to less than 9. Therefore, the corrosion in steel reinforcement may increase. Similarly, other concrete properties, such as its strength, shrinkage, resistance to carbonation, are also be influenced.

Chindaprasirt and Rukzon [103] reported that, after exposing cement paste that contains UPOFA to CO_2 for a period of 28 days, the porosity and specific area of the paste decreased. Salih [104] performed an enhanced carbonation test in 50% relative humidity with 5% CO_2 to examine the carbonation of concrete containing UPOFA. To prepare mixes for the experiment, OPC was substituted with POFA in replacements of 20 and 40 % of total weight. The particle size of POFA ranged from fine to medium and coarse. They mentioned that concrete specimens consisting of fine particle size of POFA showed lower carbonation when compared with concrete specimens comprising medium and coarse particle sizes.

6.4. Resistance to acid attacks

Dissolution is one of the major durability problems that affect the service life of concrete structures. This phenomenon occurs when concrete is subjected to an aggressive environment composed of sulfuric acid. This durability problem also increases the maintenance costs of concrete structures. The existence of sulfuric acid in groundwater and waste materials can be the main reason for this durability problem. In an industrial sector, concrete corrosion can happen due to the prominence of sulfuric acid that results from acid rains. Ariffin et al. [105] tested the performance of concrete prepared with pulverized fuel ash (PFA) and UPOFA. These samples were submerged in a solution consisting of sulfuric acid for 540 days. The visual examination of control samples made

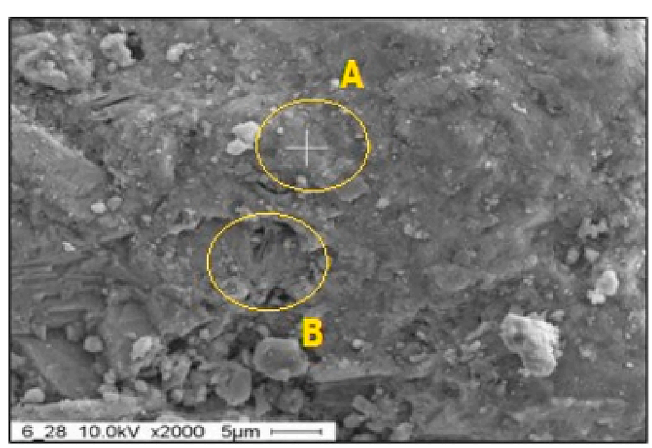

Fig. 9. Microstructure image of normal curing OPC paste [70].

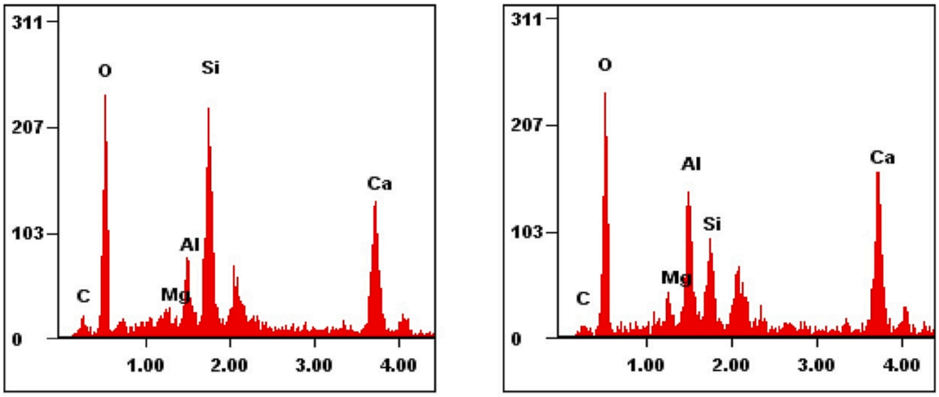

Fig. 10. EDX of normal curing cement paste; (a) point A and (b) point B [70].

of cement only exhibited simple decay that later developed with time, while the concrete consisting of PFA and UPOFA looks undamaged or hinged. For the control concrete sample, a 68% loss in the compressive strength was detected over the entire duration period, whereas the compressive strength of the UPOFA and POFA sample lost only 35% of its original value. Alsubari et al. [65] stated as a result, concrete samples containing UPOFA have high-resistance to acid attacks.

7. Scanning electron microscopy of HSC and UHPC

Zeyad et al. [70] performed a study to analyze the scanning electron micrograph (SEM) using Energy Dispersive X-Ray Analysis (EDX) of cement paste with and without steam curing. Using UPOFA as a replacement for cement achieved a denser microstructure relative to the ordinary cement pastes. This is due to the pozzolanic reaction of UPOFA that made extra hydration products. SEM/EDX of HSGC can be seen in Figs. 9 and 10. The cement paste specimens produced from UPOFA showed a denser microstructure at later ages compared with 3 days because of the hydration reactions and the pozzolanic progress over time.

Another study by Zeyad et al. [54] highlighted the role of the unburned carbon in HSC in the density of HSC by changing the poor density and interconnectivity of pores within the concrete microstructure, which influences fluid mobility. UHPC is considered to be used for its ability to act as pozzolanic mineral admixtures and closely pack density. Consequently, it has lower water absorption and porosity. UHPC mixtures contain a water cement ratio of 0.20 [106]. The pore size in UHPC generally ranges from 2 to 3 nm, with a porosity of around2.23%, and the pore diameter of about (2 nm) [107]. Scanning Electron Microscope (SEM) showed that the hardened paste structure was denser than normal concrete because of the decrease in water binder ratio, pozzolanic effect, and the cement hydration of GGBS and SF [108,109].

8. Conclusions

This review study aims to examine the effects of POFA on the properties of HSC and UHPC. UPOFA was utilized as a substitute for cement at various replacement levels to produce HSC and UHPC. Based on the findings of previous studies, the following conclusions have been drawn:

1. HSC and UHPC exhibit improved mechanical performance, achieving compressive strength values of 150 MPa and higher, as well as lower permeability and water absorption.
2. The use of POFA with a fine particle size enhances the workability of HSC and UHPC mixtures. The fine particles, due to their fineness and lower specific gravity, act as lubricates and fillers, effectively reducing gaps among the cement and aggregates.
3. The fine particle size of POFA contributes to increased compressive strength in HSC and UHPC, particularly when combined with certain admixtures, resulting in strengths of up to 115 MPa.
4. With a curing period of 360 days, the compressive strength of UHPC improves as the percentage of UPOFA replacement increases, surpassing the strength values obtained from normal concrete samples.
5. The addition of mineral admixtures and steel fibers, along with POFA at different replacement levels, can enhance the compressive, flexural, and split tensile strengths of concrete, making it suitable for high-importance infrastructure projects. However, these materials may have an impact on fluidity and other concrete properties.
6. Incorporating UPOFA helps reduce water absorption and rapid chloride permeability, thus improving the structural properties of HSC and UHPC.
7. SEM/EDX images of HSC and UHPC reveal a denser microstructure when UPOFA is included, compared to ordinary concrete without POFA. This denser microstructure is a result of the pozzolanic reaction of UPOFA, which forms additional hydration products.

Finally, further extensive studies are needed to examine the inclusion and impact of UPOFA and Nano-POFA in HSC and UHPC, considering different curing regimes, a wide range of replacement levels, and various aggressive environments. Additionally, the use of UPOFA in combination with steel fiber at different volumes is recommended, as it can facilitate the production of ultra-high-performance self-compacted concrete.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This paper represents the opinions of the authors and does not mean to represent the position or opinions of the American University of Sharjah. The work in this paper was supported, in part, by the Open Access Program from the American University of Sharjah.

References

[1] C. Meyer, The greening of the concrete industry, Cement and Concrete Composites 31 (8) (2009) 601–605.
[2] A. Favier, C. De Wolf, K. Scrivener, and G. Habert, “A sustainable future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050,” ETH Zurich2018.

[3] P. Monteiro, Concrete: microstructure, properties, and materials, McGraw-Hill Publishing, 2006.
[4] F. Colangelo, I. Farina, M. Travaglioni, C. Salzano, R. Cioffi, A. Petrillo, Innovative materials in Italy for eco-friendly and sustainable buildings, Materials 14 (2021) 2048.
[5] N. Mahasenan, S. Smith, and K. Humphreys, "The cement industry and global climate change: current and potential future cement industry CO2 emissions," in Greenhouse gas control technologies-6th international conference, 2003, pp. 995-1000.
[6] E. Benhelal, G. Zahedi, E. Shamsaei, A. Bahadori, Global strategies and potentials to curb CO2 emissions in cement industry, J. Clean. Prod. 51 (2013) 142–161.
[7] N. S Ismael and M. N Ghanim, "The Effects of Lime Addition and Fineness of Grinded Clinker on Properties of Portland Cement," Tikrit Journal of Engineering Sciences, vol. 23, 2016.
[8] I. York, I. Europe, Concrete needs to lose its colossal carbon footprint, Nature 597 (2021) 593–594.
[9] H.M. Hamada, G.A. Jokhio, F.M. Yahaya, A.M. Humada, Y. Gul, The present state of the use of palm oil fuel ash (POFA) in concrete, Constr. Build. Mater. 175 (2018) 26–40.
[10] H.M. Hamada, B.A. Tayeh, A. Al-Attar, F.M. Yahaya, K. Muthusamy, A. M. Humada, The present state of the use of eggshell powder in concrete: a review, Journal of Building Engineering 32 (2020), 101583.
[11] A.J. Zedan, R.A. Hummadi, S.A. Hussein, Effect of adding mixture of (concrete waste and asphalt waste) on the properties of gypseous soil, Tikrit J. Eng. Sci. 26 (2019) 20–25.
[12] A.S. Al-Luhybi, Mechanical properties of recycled aggregate concrete with steel fiber: a review, Tikrit J. Eng. Sci. 26 (2019) 37–42.
[13] A.D. Almuhmdi, A.A. Muhmood, A.O. Salih, Effects of crushed glass waste as a fine aggregate on properties of hot asphalt mixture, Tikrit J. Eng. Sci. 28 (2021) 129–145.
[14] T. Kareem Ibraheem, A. A.M.AL- Taei, Effect of Low-Density Polyethylene on the Stripping Properties under Fatigue Loading of Binder Layer of HMA Mixtures, Tikrit J. Eng. Sci. 27 (4) (2020) 102–113.
[15] H.M. Hamada, B.S. Thomas, B. Tayeh, F.M. Yahaya, K. Muthusamy, J. Yang, Use of oil palm shell as an aggregate in cement concrete: a review, Constr. Build. Mater. 265 (2020), 120357.
[16] H.M. Hamada, G.A. Jokhio, A.A. Al-Attar, F.M. Yahaya, K. Muthusamy, A. M. Humada, et al., The use of palm oil clinker as a sustainable construction material: a review, Cem. Concr. Compos. 106 (2020), 103447.
[17] H. Hamada, A. Alattar, F. Yahaya, K. Muthusamy, B.A. Tayeh, Mechanical properties of semi-lightweight concrete containing nano-palm oil clinker powder, Physics and Chemistry of the Earth, Parts a/b/c 121 (2021), 102977.
[18] B.S. Thomas, J. Yang, A. Bahurudeen, S. Chinnu, J.A. Abdalla, R.A. Hawileh, et al., Geopolymer concrete incorporating recycled aggregates: A comprehensive review, Cleaner Materials (2022), 100056.
[19] H. Hamada, B. Tayeh, F. Yahaya, K. Muthusamy, A. Al-Attar, Effects of nano-palm oil fuel ash and nano-eggshell powder on concrete, Constr. Build. Mater. 261 (2020), 119790.
[20] M. Abdul-Rahman, A.A. Al-Attar, H.M. Hamada, B. Tayeh, Microstructure and structural analysis of polypropylene fibre reinforced reactive powder concrete beams exposed to elevated temperature, Journal of Building Engineering 29 (2020), 101167.
[21] H. M. Hamada, A. Alya'a, F. M. Yahaya, K. Muthusamy, B. A. Tayeh, and A. M. Humada, "Effect of high-volume ultrafine palm oil fuel ash on the engineering and transport properties of concrete," Case Studies in Construction Materials, vol. 12, p. e00318, 2020.
[22] A.-A. Alyaa A., A. Mazin B., H. Hussein M., T. Bassam A., Investigating the behaviour of hybrid fibre-reinforced reactive powder concrete beams after exposure to elevated temperatures, J. Mater. Res. Technol. 9 (2) (2020) 1966–1977.
[23] G.A. Jokhio, H.M. Hamada, A.M. Humada, Y. Gul, A. Abu-Tair, E. Baltrėnaitė-Gedienė, C. Iticescu, Environmental benefits of incorporating palm oil fuel ash in cement concrete and cement mortar, E3S Web Conf. 158 (2020) 03005.
[24] H.M. Hamada, F. Yahaya, K. Muthusamy, A. Humada, Comparison study between POFA and POCP in terms of chemical composition and physical properties-review paper, IOP Conf. Ser.: Earth Environ. Sci. 365 (1) (2019) 012004.
[25] H. Hamada, F. Yahaya, K. Muthusamy, and A. Humada, "Effect of incorporation POFA in cement mortar and desired benefits: a review," in IOP Conference Series: Earth and Environmental Science, 2019, p. 012060.
[26] H.M. Hamada, B.S. Thomas, F.M. Yahaya, K. Muthusamy, J. Yang, J.A. Abdalla, et al., Sustainable use of palm oil fuel ash as a supplementary cementitious material: a comprehensive review, Journal of Building Engineering 40 (2021), 102286.
[27] M.B. Abdulrahman, S.M. Mahmood, Strength of reinforced reactive powder concrete hollow beams, Tikrit J. Eng. Sci. 26 (2019) 15–22.
[28] A.H. Majeed, Enforcement of epoxy with silica fume and carbon fiber, Tikrit J. Eng. Sci. 25 (2018) 74–77.
[29] D. Wang, C. Shi, Z. Wu, J. Xiao, Z. Huang, Z. Fang, A review on ultra high performance concrete: Part II. Hydration, microstructure and properties, Constr. Build. Mater. 96 (2015) 368–377.
[30] P. Rougeau and B. Borys, "Ultra high performance concrete with ultrafine particles other than silica fume," in Proceedings of the International Symposium on Ultra High Performance Concrete, 2004, pp. 213-225.
[31] M. Behera, S. Bhattacharyya, A. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete–a breakthrough towards sustainability in construction sector: a review, Constr. Build. Mater. 68 (2014) 501–516.
[32] H. Yazıcı, H. Yiğiter, A.Ş. Karabulut, B. Baradan, Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete, Fuel 87 (2008) 2401–2407.
[33] A.A. Al-Attar, H.M. Hamada, B.A. Tayeh, P.O. Awoyera, Exploring engineering properties of waste tire rubber for construction applications-a review of recent advances, Mater. Today:. Proc. 53 (2022) A1–A17.
[34] H. Hamada, A. Alattar, B. Tayeh, F. Yahaya, and A. Adesina, "Sustainable Application of Coal Bottom Ash as Fine Aggregates in Concrete: A Comprehensive Review," Case Studies in Construction Materials, p. e01109, 2022.
[35] B.S. Thomas, J. Yang, A. Bahurudeen, J.A. Abdalla, R. Hawileh, H.M. Hamada, et al., Sugarcane bagasse ash as supplementary cementitious material in concrete–a review, Materials Today Sustainability 15 (2021), 100086.
[36] K. Wille, A.E. Naaman, S. El-Tawil, G.J. Parra-Montesinos, Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing, Mater. Struct. 45 (3) (2012) 309–324.
[37] C. Marcel, M. Vincent, F. Laurent, Microstructural analysis of RPC (reactive powder concrete), Cem. Concr. Res. 25 (1995) 1491–1500.
[38] P. Richard and M. H. Cheyrezy, "Reactive powder concretes with high ductility and 200-800 MPa compressive strength," Special Publication, vol. 144, pp. 507-518, 1994.
[39] A.-a.-S. Al-Hazragi, A. Lateef, Behaviour of Uniaxial Reinforced Concrete Columns Strengthened with Ultra-High Performance Concrete and Fiber Reinforced Polymers, Tikrit J. Eng. Sci. 28 (2) (2021) 54–72.
[40] H. Zhou, Y. Liu, Y. Lu, P. Dong, B. Guo, W. Ding, F. Xing, T. Liu, B. Dong, In-situ crack propagation monitoring in mortar embedded with cement-based piezoelectric ceramic sensors, Constr. Build. Mater. 126 (2016) 361–368.
[41] R. Xiao, Z.-C. Deng, C. Shen, Properties of ultra high performance concrete containing superfine cement and without silica fume, J. Adv. Concr. Technol. 12 (2) (2014) 73–81.
[42] S. Park, S. Wu, Z. Liu, S. Pyo, "The Role of Supplementary Cementitious Materials (SCMs) in Ultra High Performance Concrete (UHPC) A Review, Materials 14 (2021) 1472.
[43] M.M. Reda, N.G. Shrive, J.E. Gillott, Microstructural investigation of innovative UHPC, Cem. Concr. Res. 29 (3) (1999) 323–329.
[44] B. A. Graybeal, "Material property characterization of ultra-high performance concrete," United States. Federal Highway Administration. Office of Infrastructure …2006.
[45] L. Sorelli, G. Constantinides, F.-J. Ulm, F. Toutlemonde, The nano-mechanical signature of ultra high performance concrete by statistical nanoindentation techniques, Cem. Concr. Res. 38 (2008) 1447–1456.
[46] J. Justs, D. Bajare, A. Korjakins, G. Mezinskis, J. Locs, Microstructural investigations of ultra-high performance concrete obtained by pressure application within the first 24 hours of hardening, Rigas Tehniskas Universitates Zinatniskie Raksti 14 (2013) 50.
[47] N.M. Altwair, M.M. Johari, S.S. Hashim, Flexural performance of green engineered cementitious composites containing high volume of palm oil fuel ash, Constr. Build. Mater. 37 (2012) 518–525.
[48] C. Jaturapitakkul, K. Kiattikomol, W. Tangchirapat, T. Saeting, Evaluation of the sulfate resistance of concrete containing palm oil fuel ash, Constr. Build. Mater. 21 (2007) 1399–1405.
[49] H.M. Hamada, A.A. Al-Attar, B. Tayeh, F.B.M. Yahaya, Optimizing the concrete strength of lightweight concrete containing nano palm oil fuel ash and palm oil clinker using response surface method, Case Stud. Constr. Mater. 16 (2022) e01061.
[50] P. Shafigh, H.B. Mahmud, M.Z. Jumaat, Oil palm shell lightweight concrete as a ductile material, Mater. Des. 1980–2015 (36) (2012) 650–654.
[51] S. Rukzon, P. Chindaprasirt, An experimental investigation of the carbonation of blended portland cement palm oil fuel ash mortar in an indoor environment, Indoor Built Environ. 18 (4) (2009) 313–318.
[52] M.M. Johari, A. Zeyad, N.M. Bunnori, K. Ariffin, Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash, Constr. Build. Mater. 30 (2012) 281–288.
[53] R. Karim, M. Zain, M. Jamil, N. Islam, Strength of concrete as influenced by palm oil fuel ash, Aust. J. Basic Appl. Sci. 5 (2011) 990–997.
[54] A.M. Zeyad, M.M. Johari, B.A. Tayeh, M.O. Yusuf, Efficiency of treated and untreated palm oil fuel ash as a supplementary binder on engineering and fluid transport properties of high-strength concrete, Constr. Build. Mater. 125 (2016) 1066–1079.
[55] E. Aprianti, P. Shafigh, S. Bahri, J.N. Farahani, Supplementary cementitious materials origin from agricultural wastes–A review, Constr. Build. Mater. 74 (2015) 176–187.
[56] I.I. Bashar, U.J. Alengaram, M.Z. Jumaat, A. Islam, The effect of variation of molarity of alkali activator and fine aggregate content on the compressive strength of the fly ash: palm oil fuel ash based geopolymer mortar, Adv. Mater. Sci. Eng. 2014 (2014) 1–13.
[57] A.M. Zeyad, M.A.M. Johari, B.A. Tayeh, M.O. Yusuf, Pozzolanic reactivity of ultrafine palm oil fuel ash waste on strength and durability performances of high strength concrete, J. Clean. Prod. 144 (2017) 511–522.
[58] V. Sata, C. Jaturapitakkul, K. Kiattikomol, Utilization of palm oil fuel ash in high-strength concrete, J. Mater. Civ. Eng. 16 (6) (2004) 623–628.
[59] W. Tangchirapat, C. Jaturapitakkul, P. Chindaprasirt, Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete, Constr. Build. Mater. 23 (2009) 2641–2646.
[60] M. Ismail, M.E. Ismail, B. Muhammad, Influence of elevated temperatures on physical and compressive strength properties of concrete containing palm oil fuel ash, Constr. Build. Mater. 25 (2011) 2358–2364.

[61] A. Zeyad, M. Johari, N.M. Bunnori, K. Ariffin, N.M. Altwair, Characteristics of treated palm oil fuel ash and its effects on properties of high strength concrete, Adv. Mat. Res. (2013) 152–156.
[62] B.S. Thomas, S. Kumar, H.S. Arel, Sustainable concrete containing palm oil fuel ash as a supplementary cementitious material–a review, Renew. Sustain. Energy Rev. 80 (2017) 550–561.
[63] A.S.M. Abdul Awal, M. Warid Hussin, Effect of palm oil fuel ash in controlling heat of hydration of concrete, Procedia Eng. 14 (2011) 2650–2657.
[64] V. Sata, C. Jaturapitakkul, K. Kiattikomol, Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete, Constr. Build. Mater. 21 (2007) 1589–1598.
[65] B. Alsubari, P. Shafigh, M.Z. Jumaat, Development of self-consolidating high strength concrete incorporating treated palm oil fuel ash, Materials 8 (2015) 2154–2173.
[66] A. N. Mohammed, M. Azmi Megat Johari, A. M. Zeyad, B. A. Tayeh, M. O. Yusuf, Improving the engineering and fluid transport properties of ultra-high strength concrete utilizing ultrafine palm oil fuel ash, J. Adv. Concr. Technol. 12 (4) (2014) 127–137.
[67] N.H.A.S. Lim, M.A. Ismail, H.S. Lee, M.W. Hussin, A.R.M. Sam, M. Samadi, The effects of high volume nano palm oil fuel ash on microstructure properties and hydration temperature of mortar, Constr. Build. Mater. 93 (2015) 29–34.
[68] M.O. Yusuf, M.A. Megat Johari, Z.A. Ahmad, M. Maslehuddin, Impacts of silica modulus on the early strength of alkaline activated ground slag/ultrafine palm oil fuel ash based concrete, Mater. Struct. 48 (3) (2015) 733–741.
[69] M. Aldahdooh, N.M. Bunnori, M.M. Johari, Development of green ultra-high performance fiber reinforced concrete containing ultrafine palm oil fuel ash, Constr. Build. Mater. 48 (2013) 379–389.
[70] A.M. Zeyad, M.A.M. Johari, Y.R. Alharbi, A.A. Abadel, Y.M. Amran, B.A. Tayeh, et al., Influence of steam curing regimes on the properties of ultrafine POFA-based high-strength green concrete, Journal of Building Engineering 38 (2021), 102204.
[71] M.Z. Al-mulali, H. Awang, H.A. Khalil, Z.S. Aljoumaily, The incorporation of oil palm ash in concrete as a means of recycling: A review, Cem. Concr. Compos. 55 (2015) 129–138.
[72] C. Jaturapitakkul, J. Tangpagasit, S. Songmue, K. Kiattikomol, Filler effect and pozzolanic reaction of ground palm oil fuel ash, Constr. Build. Mater. 25 (2011) 4287–4293.
[73] S. Rukzon, P. Chindaprasirt, Strength and chloride resistance of blended Portland cement mortar containing palm oil fuel ash and fly ash, Int. J. Miner. Metall. Mater. 16 (4) (2009) 475–481.
[74] W. Kroehong, T. Sinsiri, C. Jaturapitakkul, Effect of palm oil fuel ash fineness on packing effect and pozzolanic reaction of blended cement paste, Procedia Eng. 14 (2011) 361–369.
[75] E. Ghafari, H. Costa, E. Júlio, A. Portugal, L. Durães, The effect of nanosilica addition on flowability, strength and transport properties of ultra high performance concrete, Mater. Des. 59 (2014) 1–9.
[76] N. Van Tuan, G. Ye, K. Van Breugel, O. Copuroglu, Hydration and microstructure of ultra high performance concrete incorporating rice husk ash, Cem. Concr. Res. 41 (2011) 1104–1111.
[77] A. Korpa and R. Trettin, "Ultra high performance cement-based composites with advanced properties containing nanoscale pozzolans," in Ultra High Performance Concrete (UHPC): Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008, p. 391.
[78] E. Khankhaje, M.W. Hussin, J. Mirza, M. Rafieizonooz, M.R. Salim, H.C. Siong, M. N.M. Warid, On blended cement and geopolymer concretes containing palm oil fuel ash, Mater. Des. 89 (2016) 385–398.
[79] C. Astm, Standard test method for time of setting of concrete mixture by penetration resistance, ASTM C403/C 403/M (2016) 217–221.
[80] W. Tangchirapat, T. Saeting, C. Jaturapitakkul, K. Kiattikomol, A. Siripanichgorn, Use of waste ash from palm oil industry in concrete, Waste Manag. 27 (1) (2007) 81–88.
[81] J.J. Brooks, M.A. Megat Johari, M. Mazloom, Effect of admixtures on the setting times of high-strength concrete, Cem. Concr. Compos. 22 (4) (2000) 293–301.
[82] J.-H. Tay, K.-Y. Show, Use of ash derived from oil-palm waste incineration as a cement replacement material, Resour. Conserv. Recycl. 13 (1) (1995) 27–36.
[83] M. Karim, M. Zain, M. Jamil, F. Lai, Fabrication of a non-cement binder using slag, palm oil fuel ash and rice husk ash with sodium hydroxide, Constr. Build. Mater. 49 (2013) 894–902.
[84] A.M. Zeyad, B.A. Tayeh, A.M. Saba, M.A.M. Johari, Workability, Setting Time and Strength of High-Strength Concrete Containing High Volume of Palm Oil Fuel Ash, TOCIEJ 12 (1) (2018) 35–46.
[85] B. EN, "12350-2 (2009) Testing fresh concrete. Slump-test," British standards, 2009.
[86] A. Sadrmomtazi, S. Tajasosi, B. Tahmouresi, Effect of materials proportion on rheology and mechanical strength and microstructure of ultra-high performance concrete (UHPC), Constr. Build. Mater. 187 (2018) 1103–1112.
[87] W.N.F.W. Hassan, M.A. Ismail, H.-S. Lee, M.S. Meddah, J.K. Singh, M.W. Hussin, et al., Mixture optimization of high-strength blended concrete using central composite design, Constr. Build. Mater. 243 (2020), 118251.
[88] K. Muthusamy, J. Mirza, N.A. Zamri, M.W. Hussin, A.P.P. Abdul Majeed, A. Kusbiantoro, A.M. Albshir Budiea, Properties of high strength palm oil clinker lightweight concrete containing palm oil fuel ash in tropical climate, Constr. Build. Mater. 199 (2019) 163–177.
[89] A. M. Zeyad, M. Johari, B. A. Tayeh, and I. M. Alshaikh, "Influence of palm oil fuel ash on properties of high-strength green concrete," Sci. J. King Faisal Univ: Basic Appl. Sci., vol. 20, 2019.
[90] A.H. Alani, N.M. Bunnori, A.T. Noaman, T.A. Majid, Mechanical characteristics of PET fibre-reinforced green ultra-high performance composite concrete, Eur. J. Environ. Civ. Eng. 26 (7) (2022) 2797–2818.
[91] A.A. Awal, H. Mohammadhosseini, Green concrete production incorporating waste carpet fiber and palm oil fuel ash, J. Clean. Prod. 137 (2016) 157–166.
[92] M. Salam, M. Safiuddin, M. Jumaat, Durability indicators for sustainable self-consolidating high-strength concrete incorporating palm oil fuel ash, Sustainability 10 (2018) 2345.
[93] M. Aldahdooh, N.M. Bunnori, M.M. Johari, Influence of palm oil fuel ash on ultimate flexural and uniaxial tensile strength of green ultra-high performance fiber reinforced cementitious composites, Mater. Des. 1980–2015 (54) (2014) 694–701.
[94] I.I. Bashar, U.J. Alengaram, M.Z. Jumaat, A. Islam, H. Santhi, A. Sharmin, Engineering properties and fracture behaviour of high volume palm oil fuel ash based fibre reinforced geopolymer concrete, Constr. Build. Mater. 111 (2016) 286–297.
[95] A. Awal, S.K. Nguong, A short-term investigation on high volume palm oil fuel ash (POFA) concrete, in: Proceedings of the 35th Conferenece on Our World in Concrete and Structure, 2010, pp. 185–192.
[96] A. Awal, S.I. Abubakar, Properties of concrete containing high volume palm oil fuel ash: ashort-term investigation, Malaysian Journal of Civil Engineering 23 (2011) 164–176.
[97] N.M. Altwair, M.A.M. Johari, S.F.S. Hashim, Influence of treated palm oil fuel ash on compressive properties and chloride resistance of engineered cementitious composites, Mater. Struct. 47 (4) (2014) 667–682.
[98] M. Safiuddin, M. Jumaat, M. Salam, M. Rahman, Effects of palm oil fuel ash on the permeable porosity and water absorption of high-strength concrete, in: In ProceedIngs of the First AustralAsia and South-East Asia Structural EngIneerIng and Construction Conference, 2012, pp. 457–462.
[99] A. M. Zeyad, M. A. Megat Johari, B. A. Tayeh, and M. O. Yusuf, "Pozzolanic reactivity of ultrafine palm oil fuel ash waste on strength and durability performances of high strength concrete," Journal of Cleaner Production, vol. 144, pp. 511-522, 2017/02/15/ 2017.
[100] P. Chindaprasirt, C. Chotetanorm, S. Rukzon, Use of palm oil fuel ash to improve chloride and corrosion resistance of high-strength and high-workability concrete, J. Mater. Civ. Eng. 23 (4) (2011) 499–503.
[101] A.M. Zeyad, M.A.M. Johari, A. Abutaleb, B.A. Tayeh, The effect of steam curing regimes on the chloride resistance and pore size of high–strength green concrete, Constr. Build. Mater. 280 (2021), 122409.
[102] B.S. Thomas, R.C. Gupta, A comprehensive review on the applications of waste tire rubber in cement concrete, Renew. Sustain. Energy Rev. 54 (2016) 1323–1333.
[103] P. Chindaprasirt, S. Rukzon, Pore structure changes of blended cement pastes containing fly ash, rice husk ash, and palm oil fuel ash caused by carbonation, J. Mater. Civ. Eng. 21 (11) (2009) 666–671.
[104] M.A. Salih, N. Farzadnia, A.A.A. Ali, R. Demirboga, Effect of different curing temperatures on alkali activated palm oil fuel ash paste, Constr. Build. Mater. 94 (2015) 116–125.
[105] M. Ariffin, M. Bhutta, M. Hussin, M.M. Tahir, N. Aziah, Sulfuric acid resistance of blended ash geopolymer concrete, Constr. Build. Mater. 43 (2013) 80–86.
[106] O. Bonneau, C. Vernet, M. Moranville, P.-C. Aïtcin,, Characterization of the granular packing and percolation threshold of reactive powder concrete, Cem. Concr. Res. 30 (2000) 1861–1867.
[107] G. Long, The composites, structures, and properties of reactive powder concrete, Tongji University, China, 2003. Ph. D. Thesis.
[108] F. J. Alaee, "Retrofitting of concrete structures using high performance fibre reinforced cementitious composite (HPFRCC)," Cardiff University, 2002.
[109] C. Wang, C. Yang, F. Liu, C. Wan, X. Pu, Preparation of ultra-high performance concrete with common technology and materials, Cem. Concr. Compos. 34 (4) (2012) 538–544.