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Sustainable and cost-effective cement-based composite utilizing calcined Iraqi date palm frond waste ash

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HIGHLIGHTS

- Iraqi palm frond waste ash used as a supplementary cementations material (SCM)
- PFWA showed pozzolanic and cementitious properties due to its elemental composition
- A 10% PFWA replacement improved the properties of cement-based mortar
- Caution is advised when increasing PFWA content in cement-based composites

Keywords:

Palm frond waste ash
Cost-effective mortar
Sustainable binders
Microanalysis
Supplementary cementitious materials

ABSTRACT

Ecological implications posed by the cement industry, biomass ashes, and agricultural waste are growing with emerging concerns. Hence, this paper analyzes and evaluates the characterization of Iraqi date palm frond waste ash (PFWA) and its potential impact on the performance of cement-based mortar. PFWA was utilized to substitute 10, 20, and 30% of the partial weight of cement. The experimental program consists of three main parts: Firstly, the preliminary physicochemical and microanalysis characterization of PFWA powder was investigated and corresponded with the limits of ASTMC-618. Secondly, the compressive and flexural strength, dry density, and water absorption capacity of the fabricated cement-based mortar with the adopted replacement percentages were observed. Finally, the cost analysis of the final products was conducted to obtain a cost-effective evaluation. Generally, the results proved that incorporating 10% PFWA boosts the hardened characteristics. Alternatively, further upgrading of the PFWA content adversely affects the investigated properties. After 28 and 90 days, 10% PFWA boosted the compressive strength by around 15% compared with the control mixture. The cost analysis proves a reduction in the total cost of the mortar by 8.1, 16.1, and 24.1% by replacing 10%, 20%, and 30% of OPC with PFWA. Therefore, using PFWA as SCM in cement-based composites could be a promoted alternative that would benefit the management, recycling, and reusing rate of agricultural waste and support the advancement of sustainability through the construction sector with cost-effective advantages.

1. Introduction

Global authorities impose strict ecological legislation on cement-based composite production processes, with principal branches of conventional cement (CC) industries. To cope with the crucial environmental threats regarding climatic changes and the consequences of global warming owing to the massive greenhouse gas (GHG) emissions and disproportionate energy consumed in its production process [1,2]. The growth of cement-based composites is expanding exponentially, resulting in an estimated consumption of around one cubic meter per capita, which uses a tremendous amount of CC, a primary binding substance in the composites [3,4]. One vital shortcoming of utilizing CC in various cement-based composites is that it significantly contributes to massive GHG emissions, mainly CO_2, into the environment. This accounts for about 5–8% of global CO_2 emissions [5], causing crucial ecological implications, pollution, global warming, and ozone depletion. According to some devoted studies, for each ton of CC produced, an equivalent of 0.9 [6] to 1.0 [7] tons of CO_2 are emitted to the environment. Hence, every ton of CC is estimated to emit nearly equal amounts of CO_2 into the atmosphere, whereas the chemical and fuel-burning processes in the CC industry emit around 50 and 40% of CO_2, respectively [8]. The cement industry in Iraq generates massive quantities of CO_2 annually, which is crucial in the augmentation of carbon footprint and the consequence of global warming. In the last 25 years, just the Kubaisa cement plant emitted about 7, 613, 605 tons of CO_2 [9].

In this regard, devoted studies have been conducted by enormous numbers of researchers and academics to boost CO_2 emission-diminution protocols. One of the most sustainable approaches encouraged by previous works of literature is the partial

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substituting of CC with supplementary cementitious materials (SCMs) that include silica fume (SF) [10,11], ground granulated blast furnace slag (GGBS) [12], fly ash (FA) [13, 14], and natural pozzolans [15]. Harnessing agricultural wastes to replace the CC partially seems to be a promising and sustainable approach to fabricating eco-friendly, low-CO_2 cement-based composites due to its economic and environmental benefits, as proved by previous studies [16,17]. Agricultural wastes require large areas of landfills and solid stockpiles, causing additional pollution and adversely affecting Mother Nature. Recycling them in cement-based productions demonstrated synergy benefits concerning managing their vast quantities, reducing CC consumption, CO_2 emissions, and overall construction costs [18,19]. However, massive quantities of agricultural waste accumulated in Iraq due to seasonal pruning processes, such as palm fronds, are challenging to reuse, and further research is needed to guide their recycling and reusing in cementitious composite fabrication.

The potential of agricultural waste ashes, particularly date palm leaf ash, has recently sparked interest as a promising, renewable, cost-effective source for cementitious substances. Date palm leaf ash, a by-product of agricultural biomass waste in hot, arid regions like the Middle East, is gaining attention [18]. While previous research has been limited, the potential of date palm leaf ash as a sustainable and renewable source for partial substitution of CC in producing various cement-based products is promising. Its use could significantly alleviate GHG emissions, lower energy consumption, and preserve the natural sources of raw materials used in the CC industry [20, 21], while being cost-effective and substantially affecting the future of the cement industry in Iraq. Furthermore, the use of this ash for replacing CC partially demonstrated its effectiveness in advancing behavior and long performance of the produced cementitious composites and their properties due to its pozzolanic reactivity [22, 23]. Due to the chemical composition of this ash with high summation of the principal pozzolanic oxides (i.e., SiO_2, Al_2O_3, and Fe_2O_3) that confirm the requirements of ASTM C-618 [24]. The oxides consume the weakest products from the cement hydration process (i.e., Ca $(OH)_2$). The reaction resulted in the formation of a supplemental hydration phase of calcium silicate hydrate (C-S-H) that boosts the characteristics of the fabricated cement-based composites by refining their microstructure and significantly contributes to the strength and durability [25]. Depending on the previous studies, the summation of the principal pozzolanic oxides varies depending on the region. In the study of Yousefi et al. [26], the summation was 83.28%, while it was 37.36% according to the study of Al-Kutti et al., [27].

The possibility of utilizing the palm leaf ash generated as a by-product waste from the industrial process of charcoal and firewood as SCM with replacement levels of (10, 20, and 30%) by weight of CC in cement-based products was studied by Al-Kutti et al., [27]. The findings revealed that the replacement of 10% of cement with palm leaf ash enhanced the compressive strength, water absorption capacity, rapid chloride permeability, and thermogravimetric analysis (TGA) performance of cement-based mortar and concrete due to the kinetics pozzolanic reaction and formation of an additional C-S-H that improved the general performance due to refining and strengthened the microstructure of the hardened cementitious matrices. These outcomes were aligned with those founded by Nasir and Al-Kutti [28]. In contrast, the optimum replacement percentage was 10%, which upgraded the mechanical strength, the microstructure of the hardened matrices, and durability. However, replacing 30% of cement with this ash produced a cementitious composite with reasonable behavior owing to the acceptable results obtained at all testing ages relative to the control mixture. Alrshoudi and Alshannag also emphasized the possibility of incorporating 30% date palm leaf ash without compromising the strength and durability of the examined cement-based mortars. The compressive strength contained 10% ash, lower than the control mortars. On the contrary, the compressive strength of mortars included by 20%, and 30% of the ash was higher than that of control mortar at later ages; meanwhile, the results of these mortars showed similar values after 90 days with an increasing rate of 14% in contrast with the control mixture. This is ascribed to the pozzolanic reaction between the ash and cement that consumed Ca $(OH)_2$ further and produced an additional amount of the higher-quality phase of C-S-H. In addition, it results in a denser microstructure with a high amount of fine ash and filling effect for the cementitious matrix in contrast with solely cement mortar. The potential impact of date palm leaf ash with replacement levels of (1, 3, 5, 10, and 15%) on the flexural behavior of normal and polypropylene fiber-reinforced concrete (PPFRC) beams was studied by Yousefi et al., [29].

The findings demonstrated that incorporating ash positively impacted compressive and flexural strength, toughness, and ductility. The results proved that the optimum replacement level of cement with ash was 5% for boosting the compressive and splitting tensile strength for the normal and PPFRC; meanwhile, increments of 23.4 and 17.1% were exhibited by the compressive strength of the normal and PPFRC specimens, respectively. With the same replacement level, the splitting tensile strength increased by 11.11and 8.91%, respectively. In contrast, a 3% substitution of cement with ash enhanced the flexure behavior of both normal and PPFRC beams. Further upgrading in replacement levels beyond the optimum values negatively impacted the mechanical behavior of both types of concrete. Depending on the deliberated findings mentioned above, there was a remarkable discrepancy between the recorded results owing to the chemical composition and defining the optimum percentage of cement replacement with date palm leaf ash. Despite that, it seems to be an effective, renewable, and promising solution for recycling and harnessing date palm leaf ash as an SCM to replace cement at an appropriate level. This is beneficial in managing the vast amount of the generated date palm frond seasonally, exceptionally alleviating the emission of GHG owing to the lowering of the cement demand and consequently reducing the ecological implications.

Very few devoted studies have been carried out on the potential impact of Iraqi date palm frond waste ash (PFWA) on cement-based composites by partially replacing CC, and it has yet to be utilized as an SCM in cement-based mortar. Therefore, this research project aims to observe how to enable the harnessing of PFWA in cement-based products. In the context of cement-based mortar, the mechanical and durability indication parameters combined with PFWA are the most critical characteristics. Therefore, this study examines the preliminary characteristics of PFWA, its potential impact on the mechanical strengths, and indicators of the durability of cement-based mortars at varied replacement levels. This research was conducted to lower the amounts of ordinary Portland cement (OPC) and provide an appropriate mixing ratio reference for sustainable and cost-effective cement-based mortar.

2. Research methodology

2.1 Materials

2.1.1 Cement

Throughout the research, Type-I Portland cement (CEM I 32.5R) was used as a primary binder in the fabrication of each mixture evaluated, with a specific gravity of 3.15. The other properties correspond to the Iraqi standard specification (I.Q.S – No.5/19) [30]. The OPC was used at various levels, ranging from 100% to 70%, aligning with the prevailing trends in construction applications and previous literature. The chemical and physical properties of the used cement are listed in Table 1.

Table 1: Physical and chemical properties of used OPC

Chemical Oxides	Oxide Composition (%)	Physical parameter		I.Q.S – No.5 limits [30]
CaO	64.1	Initial setting time (Vicate), Min	115	≥ 45
Al_2O_3	4.8	Final setting time (Vicate), Min	155	≤ 600
SiO_2	20.4	Compressive Strength-2 days, MPa	17.4	≥ 10
Fe_2O_3	3.9	Compressive Strength-28 days, MPa	33.7	≥ 32.5
MgO	1.7	Blaine fineness, m^2/kg	321	≥ 250
SO_3	2.3			
Na_2O	0.7			
K_2O	0.3			
Free CaO	0.7			

2.1.2 Palm frond waste ash (PFWA)

The PFWA comprises palm fronds and leaves ash, which was used as a partial substitution for OPC. The frond wastes accumulated from the seasonal pruning process of date palm trees were collected from the nearby regimes of holy Karbala City – Iraq. The first step of the preparation process for PFWA consists of drying the collected frond waste by spreading it under the sun in atmospheric conditions to remove the inherent moisture. The second step was burned down in an open area under atmospheric conditions and left to cool to the average normal temperature. The resulting bottom ash was further grounded using a laboratory grinder; the grinding time was optimized to reach a particle fineness degree that confirmed the requirement of ASTM C-618 [24], depending on the grinder type and efficiency. The resulting ash was further calcined in a furnace at 600 °C for two hours; the calcined ash was allowed to cool down inside the waffle furnace to laboratory temperature. Figure 1 illustrates a graphical sketch for the calcination program.

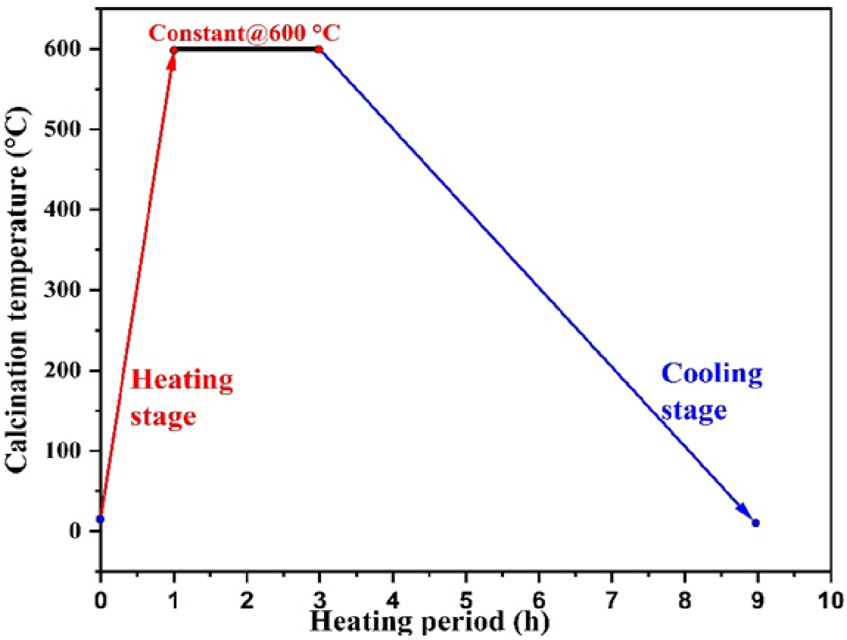
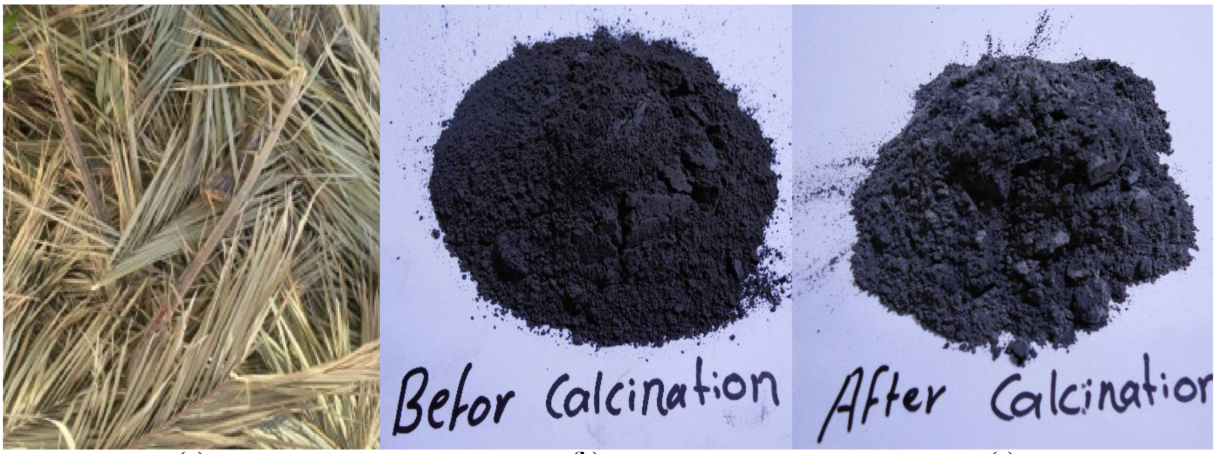


Figure 1: Schematics representation of calcination regime of PFWA

This preparation protocol was conducted depending on previous studies [31, 32]. The frond waste and the produced ash before and after calcination are illustrated in Figure 2. The collected raw date palm frond wastes are shown in Figure 2 a. After burning and grinding, they converted to a blackish powder, as presented in Figure 2 b. Calcination leads to substantial weight loss due to the combustion of organic materials present in the leaf ash due to the removal of volatile compounds and moisture [33]. The calcination temperature influences the particle size and morphology of DPLA. Higher temperatures generally produce finer particles, as seen in Figure 2 c, with increased surface area, which is beneficial for pozzolanic reactivity [34].



(a) **(b)** **(c)**

Figure 2: (a) Raw date palm frond waste, (b) Date palm frond ash after burning and grinding, (c) Final PFWA powder

The specific gravity of the PFWA powder is 2.42, and its chemical is tabulated in Table 2, as well as other physical properties; it can be noticed that the summation of the principal oxides (SiO_2, Al_2O_3, and Fe_2O_3) is more than 50%. Therefore, the PFWA could be classified as good pozzolanic material with cementitious characteristics because of the considerable amount of CaO according to ASTM C-618 [24].

Table 2: Physical and chemical properties of the prepared PFWA

Chemical Oxides	Oxide Composition (%)	Physical parameter		ASTM C-618 limits [24]
CaO	38.5	Strength activity index-28 days, percent of control mix	107.8	≥ 75
SiO_2	47.7	Degree of fineness: Retained 45 µm (No. 325) sieve, %	11.2	≤34
Fe_2O_3	3.7			
MgO	0.3			
Na_2O	1.6			
K_2O	5.8			
SO_3	2.1			

2.1.3 Fine aggregate

Standard sand as the fine aggregate was used to produce all mixtures, which was graded and chemically treated by Al-Nawafith Co.LTD. It has a specific gravity of 2.61 and a density of 1462 kg/m^3, corresponding to the Iraqi standard specification (I.Q.S – No.2080) [35]. The particle size distribution of the used sand ranges between 600 µm and 850 µm as a maximum size with rounded particle shapes. It is free from clay and other fine materials, as it is chemically treated to remove as many harmful substances as possible. Distilled water was used as the mixing solution to prepare the specimens made, while potable water was used to cure hardened specimens until the testing age.

2.2 Mixtures proportion and mixing procedure

The mortar specimens were prepared by fabricating four mixtures in which the level of PFWA ranged between 0 and 30% (with intervals of 10%). The control mortar was designated as CM, while the sustainable mortars were designated as X-PFWA, where X expresses the level of PFWA to total cementitious binders. For instance, 10-PFWA means the cementitious materials comprising 10% PFWA plus 90% OPC by weight. A constant water-to-binders (W/B) ratio of 0.4 was adopted to prepare all mixtures and binders to the fine aggregate ratio 1:2.75. Figure 3 illustrates the mixture proportion of all mixtures.

It is worth mentioning that the intended replacement levels of OPC with PFWA were to reach 50% by weight to investigate the feasibility of replacing OPC with agriculture waste with a wide range of substitutions. However, with a 40% replacement level with the same W/B, the fresh mix was harsh and unworkable; hence, 30% was the highest level that could be reached, depending on the laboratory practice.

The laboratory mixing process consisted of several steps. Firstly, the cementitious binders (OPC and PFWA) were mixed for approximately one minute in a steel bowl of the laboratory mixer. Secondly, the standard sand was added and blended for another minute or until the dry mixture appeared homogenous. Finally, the distilled water was gradually added to ensure all ingredients were well mixed, and the mixing process was continuous until the mixture was homogeneous. The resulting fresh mixture was cast in the specified molds depending on the required specimen shapes and compacted using a high-frequency vibrating table. After the final leveling of the specimens' surfaces, they were covered with polyethylene sheets for approximately one day to prevent the evaporation of mixing water and loss of moisture, which is necessary for the early hydration kinetics of binders. The specimens were demoulded after 24 h and watery cured until the specified testing ages (i.e., 7, 28, 56, and 90 days).

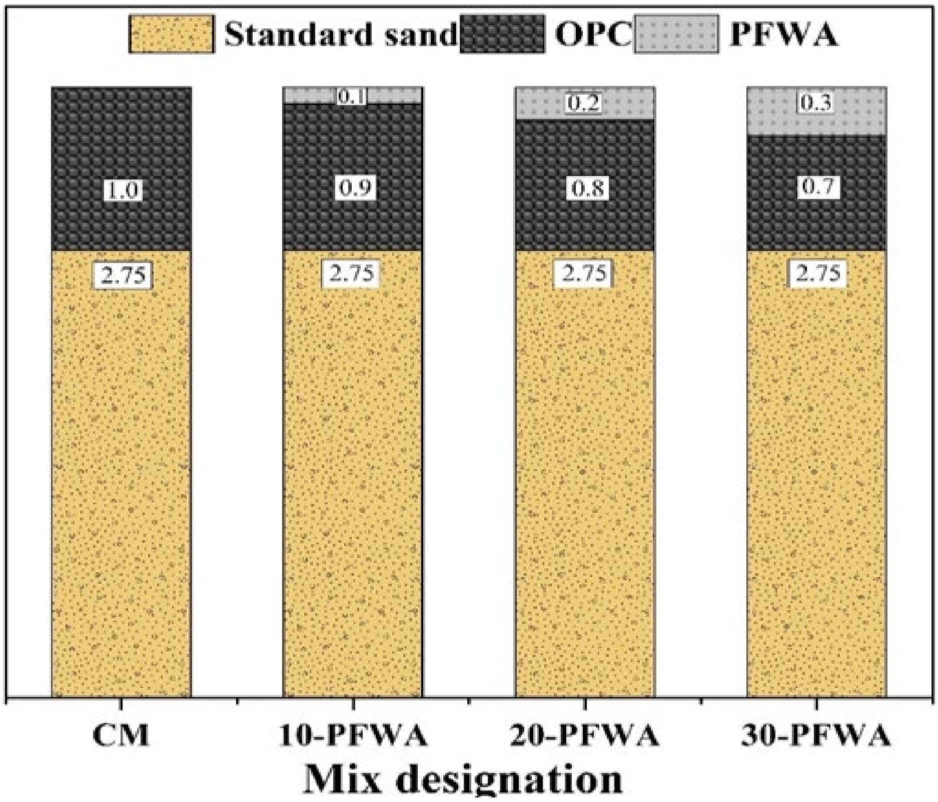


Figure 3: Mixture proportion of the prepared specimens

2.3 Methods and testing program

The preliminary characteristics of the prepared PFWA were assessed using strength activity index (SAI), fineness degree, X-ray Fluorescence (XRF), X-ray diffraction (XRD), field emission scanning electron microscope (FESEM), and Fourier-transform infrared spectroscopy (FTIR) tests. All test procedures were performed to obtain laboratory results under the Iraqi standard specification (I.Q.S) or ASTM. The amount of retained materials on sieve No. 325 using the wet sieving method and SAI of the PFWA were tested according to ASTM C-311 [36], at both testing ages (See Table 2).

The elemental chemical composition (i.e., XRF) was explored using the Spectrocube analytical instrument. The phase analysis and identification of the different crystalline phases present in PFWA were analyzed by XRD test utilizing (Shimadzu XRD-6000 powder) spectrometer. This is crucial because the performance of any SCM incorporated in a cement-based material significantly depends on its mineralogical composition and the phases it contains [37]. To provide more detailed insights into the chemical composition and identification of the functional groups in PFWA, the FTIR test was conducted using (Shimadzu-FTIR 8400) spectrometer. FTIR analysis can help to determine the purity of PFWA by identifying impurities or contaminants that may impact its performance in cementitious composites. For instance, unwanted substances can adversely affect the mechanical behavior and/or durability of final composites [38,39]. The microscopic morphology of the PFWA powder was observed by (FESEM Quattro) instrument. This is substantial in identifying the shapes and surface textures of the obtained particles of PFWA.

The potential impact of PFWA was assessed and evaluated depending on the unconfined compressive strength, flexural strength, dry bulk density density, and water absorption capacity. The adopted testing ages for all tests were 7, 28, 56, and 90 days. The unconfined compression testing was determined using a compression machine brand ELE Int. with a maximum capacity of 2000 kN by loading cubic specimens with dimensions of 50×50×50 mm^3 according to ASTM C-109 [40]. The results are displayed directly in both ultimate load and stress. Three specimens were prepared for each mixture, and the average values were considered for each testing age. Three specimens with dimensions of 40×40×160 mm^3 were prepared for every blending level at each testing age. Each specimen was broken into two parts by three points loading test for the prismatic samples according to ASTM C-348 [41]. Cubical specimens with dimensions of 50×50×50 mm were used to measure the dry bulk density and water absorption capacity of all mixtures following ASTM C-642 [42]. Figure 4 illustrates all the details of the research methodology.

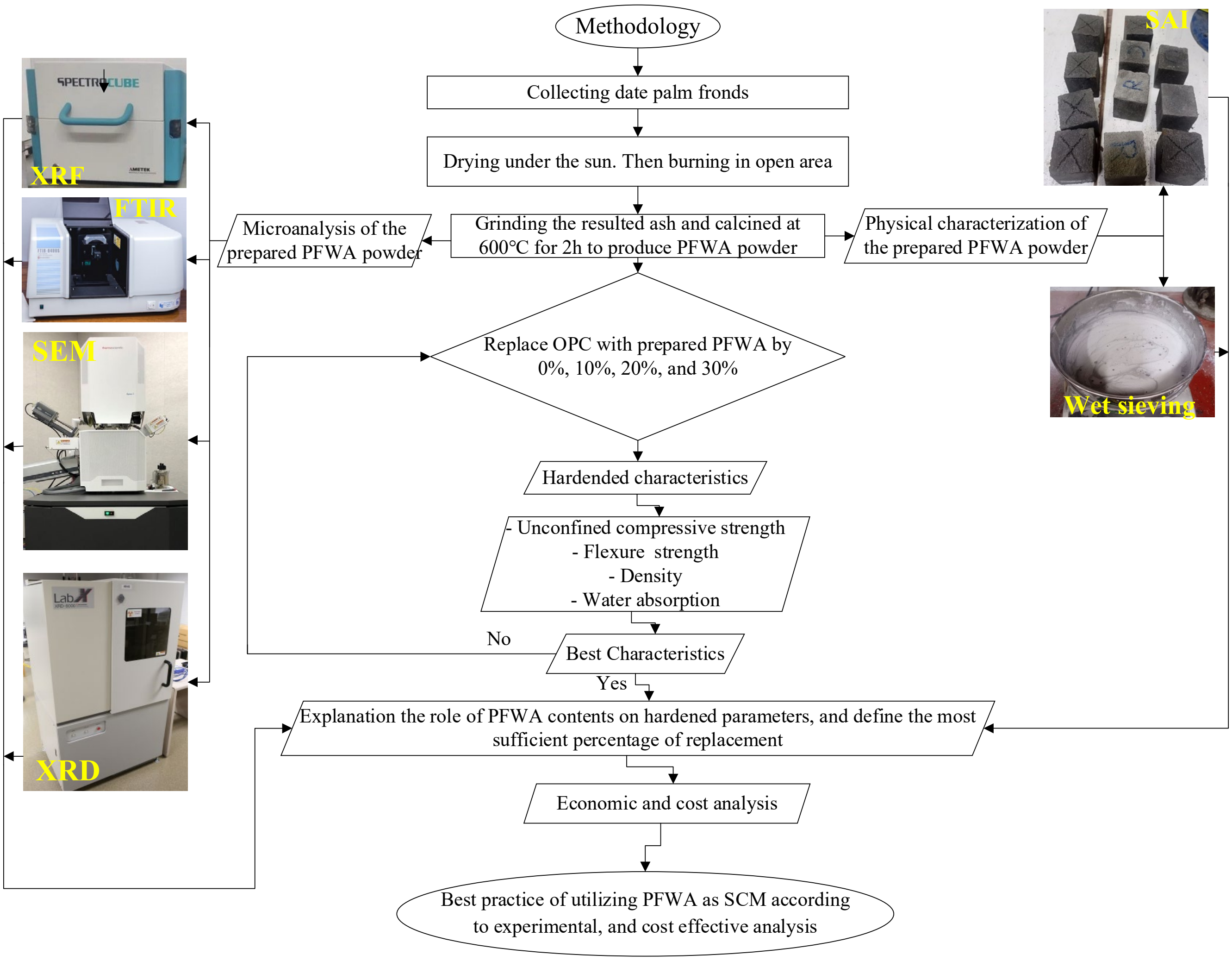


Figure 4: Diagrammatic flow chart of the research methodology

3. Results and discussion

3.1 Physicochemical characterization and microscopic morphology of PFWA

The fineness and SAI results of the prepared PFWA corresponded with the requirements of ASTM C-618 [24]. Meanwhile, the SAI values were 97.2 and 107.8% as a percentage of the control mixture at 7 and 28 days, respectively. The retained-on sieve No. 325 (45 µm) was 11.2%, lower than the maximum specified limit in the specification of about 67.1%. PFWA seems to have cementitious characteristics owing to the remarkable amount of CaO. It could also be classified as a good pozzolana because the summation of SiO_2, Al_2O_3 and Fe_2O_3 is more than 50% (See Table 2).

Figure 5 illustrates the XRD pattern of PFWA powder and mineralogical compositions. The XRD test was carried out to investigate the phase type within the prepared PFWA powder. The XRD patterns obtained the crystalline phases after calcination. The XRD showed several characteristic peaks for five crystalline phases: the calcium oxide (CaO) phase (marked with C), the characteristic peaks of silicon oxide (quartz) (SiO_2) phase (marked with Q) and the characteristic peaks of potassium oxide (K_2O) (marked with P), the detected peaks of iron oxide (Fe_2O_3) (marked with I) and the detected peaks of chlorine (marked with Cl).

The XRD pattern demonstrated that the CaO_2 and KO_2 are the dominant phases within the PFEA powder. The XRD results indicated that the characteristic peaks became sharper and more intense after the heat treatment. The detected peaks of calcium oxide CaO_2 attributed to the tetragonal-CaO_2 phase with space group (I4/mmm No.139) agreed well with the standard data (JCPDS 96-153-0293), the characteristic peaks of potassium oxide KO_2 assigned to tetragonal-KO_2 phase with space group (I4/mmm No.139) matched with the standard pattern (JCPDS 01-077-0211), the peaks of silicon oxide SiO_2 attributed to the cubic-SiO_2 phase with space group (Fd-3c No. 228) corresponded with standard pattern (JCPDS 98-017-0478), the peaks of iron oxide Fe_2O_3 attributed to the rhombohedral- Fe_2O_3 phase with space group (R-3c No.167) matched with standard pattern (JCPDS 01-073-0603), while the detected peaks of chlorine due to the tetragonal- Cl phase with space group (P4/mmm No.127) agreed with the standard data (JCPDS 96-590-0028). The XRD analysis demonstrated no impurities peaks that can be attributed to the high purity phases. The FTIR test determined the functional groups within the calcined PFWA powder; the FTIR spectra is presented in Figure 6. The detected FTIR vibration bands showed specific characteristic vibration bands of PFWA powder.

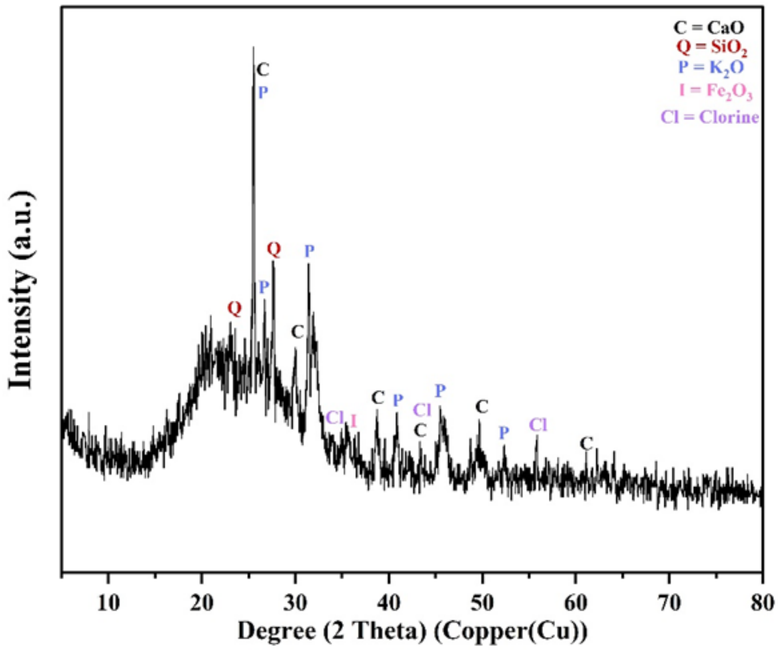


Figure 5: XRD pattern of calcined PFWA

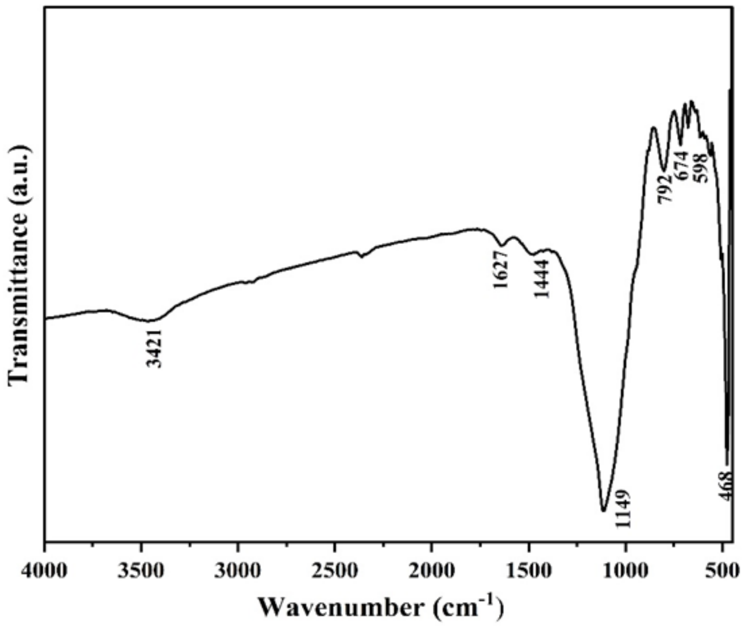
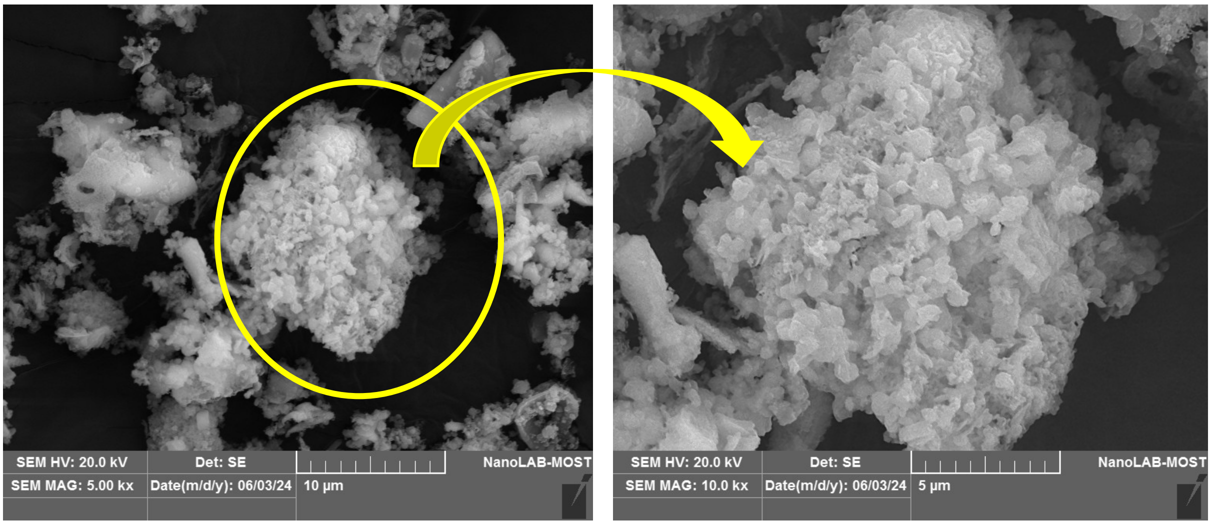


Figure 6: FTIR pattern of calcined PFWA

The broad vibrations band within the range (3000 - 3500 cm^{-1} centred at 3421 cm^{-1} attributed to the stretching vibrations of the OH bond. The detected band at 1627 cm^{-1} is assigned to stretching C–C bond vibrations in the aromatic compounds [43, 44]. The strong bands at 1149 cm^{-1} and 1444 cm^{-1} due to the symmetric and unsymmetrical glycosidic bonding C–O–C, stretching vibrations of C–C and C–O bonds, the bending vibrations of $–CH_2$ and the deformation vibrations CH_3, these bands indicated the presence of cellulose, hemicellulose and aliphatic skeletal [45]. The detected bands 468 cm^{-1}, 598 cm^{-1}, 674 cm^{-1} and 792 cm^{-1} located in the wavenumber range 400 – 800 cm^{-1} attributed to bending vibrations of metal – oxide bonds such as Si – O, Ca – O, K – O and Fe – O that presented in the PFWA [46, 47].

The obtained FTIR analysis proved that the ash's calcination with high temperature decreased most of the vibrations band's intensity; this change was attributed to the alteration and breakage of carboxylic groups connected to hemicelluloses. The low intensity of these vibration bands proves the deacetylation of hemicelluloses and their partial degradation due to heat treatment [48]. FESEM examination observed the microscopic morphology of the PFWA powder, which is a practical exam to characterize the surface morphology of various powders. The obtained FESEM images of PFWA powder with two scales of 10µm as shown in Figure 7a and 5 µm as illustrated in Figure 7b. The FESEM images generally designate clusters of angular and irregular shapes with rough surfaces and sharp edges of the PFWA particles with uneven and complex pore structures.



(a) (b)

Figure 7: The microscopic morphology of calcined PFWA powder, (a) 10µm, (b) 5µm

3.2 Unconfined compressive strength

The results of the unconfined compressive strength of mortar specimens of all mixtures subjected to different curing periods are depicted in Figure 8. The compressive strength trend was linear, with a curing age between 7 to 90 days due to the progression of the hydration of the cementitious binders with time. Generally, the increment in compressive strength was observed with an increase in PFWA to total cementitious binder ratio up to 10%, particularly at the later hydration stage. After that, a negative impact was noted. After 7 days of curing, which is considered the early testing age, the highest measured compressive strength for 10-PFWA was 30.6 MPa, which is around 23, 13, and 34% higher than CM, 20-PFWA, and 30-PFWA mixtures, respectively. At the governed age of 28 days, the highest compressive strength in 10-PFWA was 36.2 MPa, which is about 15, 12, and 27% higher than those at CM, 20-PFWA, and 30-PFWA, respectively.

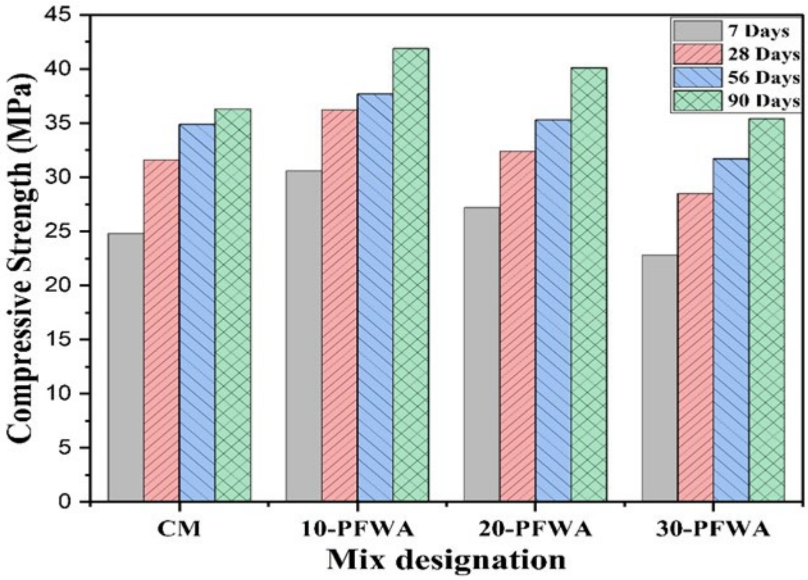


Figure 8: Compressive strength of OPC and OPC-PFWA mortars at different ages

Another significant observation from the obtained data is that the measured compressive strength in 20-PFWA is lower than that of 10-PFWA but higher than that of CM; it is about 10 and 11% higher than CM at ages 7 and 90 days, respectively. Likewise, after 90 days of curing, which is considered the later testing age, the highest determined compressive strength in 10-PFWA was 41.9 MPa, which is around 15, 5, and 18% higher than those at CM, 20-PFWA, and 30-PFWA, respectively. The advancement in compressive strength with the substitution of OPC with the optimum percentage of PFWA can be attributed to the densification of the microstructure of the hardened mortar resulting from the filler effect associated with the incorporation of PFWA; the fine particles of PFWA fill additional pores through the hardened matrix, and high packing density was achieved, enhancing the compressive strength of the mixture [23]. Moreover, this rise in compressive strength may be due to the pozzolanic reaction between SiO_2 and Al_2O_3 from PFWA and $Ca(OH)_2$ from OPC, resulting in a continuous formation of a higher quality hydration phase of calcium silicates hydrates gel (C-S-H) [32,49]. This additional reaction product refines the microstructure and increases the compressive strength of the cementitious composites [25].

The rise in compressive strength with the incorporation of 10% PFWA in mortar specimens aligned with the findings of Nasir et al., [20]. On the other hand, the results obtained through the current experimental works showed a decrease in compressive strength with further upgrading of the PFWA level. However, the compressive strength of the 20-PFWA mixture was still higher than that of CM. This mentioned observation contrasts with that found by Nasir et al., [20]. Whereas the reported results by the authors demonstrated that the compressive strength of specimens containing 20% date palm frond ash was lower than that of the control specimens (i.e., 100%-OPC). This conflict owing to the effect of the percentage of replacement of OPC with PFWA on the compressive strength of a cement-based composite may be attributed to variations in the chemical composition of the used date palm frond ash in these studies, differentiation in particle size distribution, or dissimilar mixing and testing conditions. Therefore, preliminary investigations are crucial to define the most appropriate percentage of replacement of OPC with PFWA before fabricating the final cement-based composites intended to be incorporated with PFWA. The improvement in the compressive strength of the control mixture and mixture included with 10% date palm frond ash by weight of OPC relative to the mixtures containing higher percentages of the ash (i.e., 20 and 30%) could be ascribed to the approximate similar ratio of Mg/Si, Al/Si, and Ca/Si depending on the chemical composition. The higher Ca/Si ratio might cause a combined impact of calcium ions and silicate chains through the microstructure, resulting in the formation of an additional amount of C-S-H that inherently improves the compressive strength of the hardened matrix. On the contrary, the proportional decline of the compressive strength by increasing the PFWA level could be attributed to the slow pozzolanic reaction between PFWA and OPC [50].

3.3 Flexural strength

Figure 9 shows the flexural strength development in CM, 10-PFWA, 20-PFWA, and 30-PFWA prismatic mortar specimens at all testing ages. The flexural strength gain with a curing period between 7 and 90 days was similar to that of compressive strength and linear and increasing the age of specimens. Depending on the plotted data, it can be observed that the incorporation of PFWA into cement-based mortar has been shown to influence flexural strength positively if used with an appropriate percentage; however, the effects can vary based on the replacement level used.

The flexural strength of specimens containing 10% PFWA by weight of OPC increased by around 11, 21, and 28% compared with CM, 20-PFWA, and 30-PFWA, respectively, in the early stage of hydration (i.e., 7 days). After 28 days of curing, considered the most important age, the highest flexural strength in 10-PFWA was 5.7 MPa, which is around 19, 24, and 33% higher than those at CM, 20-PFWA, and 30-PFWA, respectively. The same behavior was also exhibited at the later age of 90 days, whereas the highest flexural strength in 10-PFWA was 6.9 MPa, which is higher than those shown by CM, 20-PFWA, and 30-PFWA by about 21, 33, and 38%, respectively.

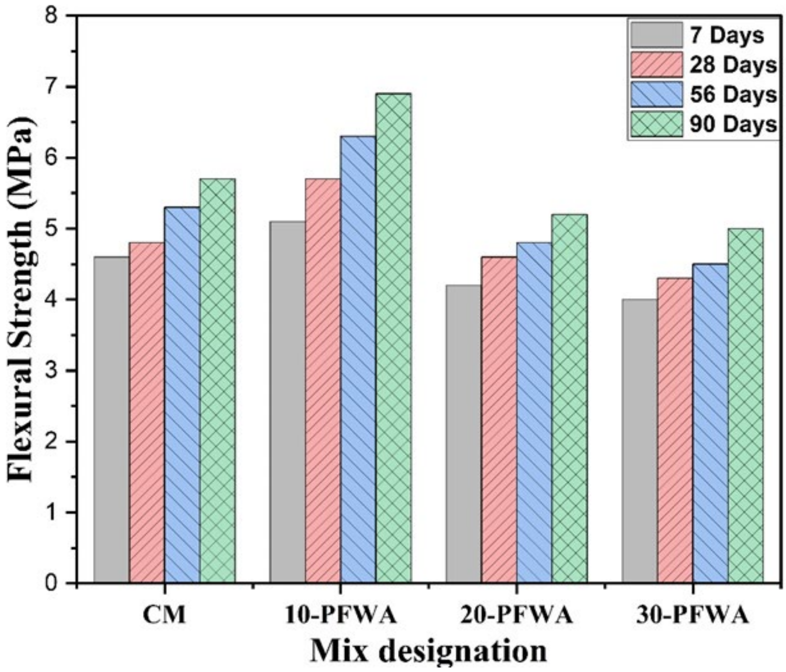


Figure 9: Flexural strength of OPC and OPC-PFWA mortars at different ages

The results analysis demonstrates that further upgrading the substitution level of PFWA to more than 10% resulted in a continuous decline in the flexural strength of the mortar specimen at all testing ages compared with CM. This reduction could be attributed to the presence of interconnected micropores through the hardened binders matrix; these micropores could have more effect on flexural strength than the unconfined compressive strength [23]. Despite the variation in the mixing ingredients, mixing and testing conditions, and sample sizes. The obtained trend of the flexural strength of mortars incorporated with different levels of PFWA was reasonably aligned with that founded by Islam et al., [51]. Meanwhile, the flexural strength of concrete was reduced by incorporating a 25% palm oil fuel shell as a cement substitute.

To highlight the connection between the compressive and flexural strength of the fabricated mortar samples, including 10, 20, and 30% PFWA, in addition to the control mortar, the relationships between these two strengths have been displayed in

Figure 10 at the ages of 28 and 90 days. Such an investigation is important for acquiring insights into the relationship between the compressive and flexural strength of green mortars incorporated with different levels of PFWA, which can have repercussions for determining and evaluating flexural strength that progresses with an increase in the curing period and can be estimated by using compressive strength values measured at 28 or 90 days. The generated statistical models suggest a better understanding of the integrity between the mechanical parameters of the sustainable cement-based products containing PFWA as OPC replacing material. A strong connection provides reliable predictions of flexural strength regarding compressive strength. The obtained equations to calculate the flexural strength using compressive strength at 28 and 90 days have R^2 values of 0.8482 and 0.6974, respectively, indicating a stronger correlation between [52], these two strengths at 28 days.

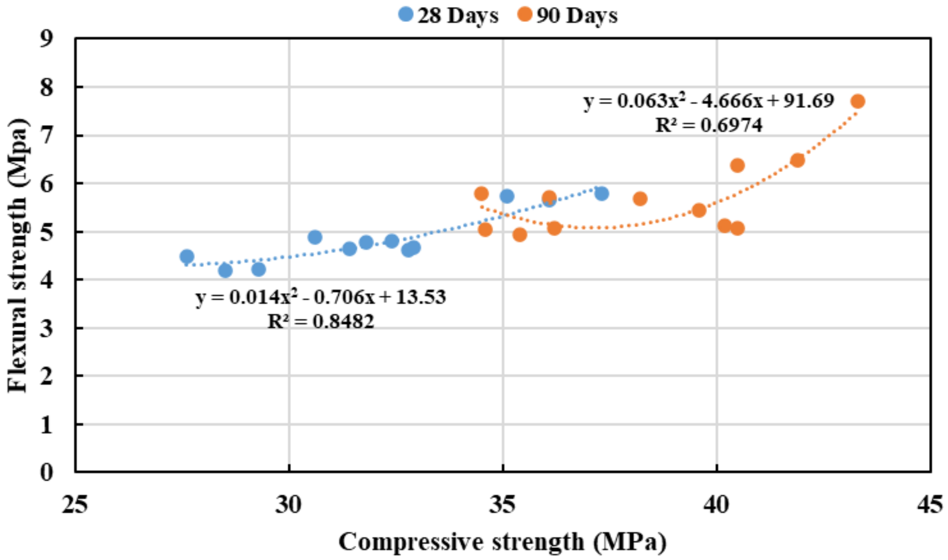


Figure 10: Relationship between the compressive and flexural strength of the produced mixture at 28 and 90 days

3.4 Dry bulk density

The results of the dry bulk density of mortar specimens of all mixtures after different curing periods are plotted in Figure 11. These parameters play vital roles in the mechanical and long-term performance of cementitious composites owing to their inherent effect on water penetration and the ingression of deterioration agents like acidic solutions, sulphate and/or chloride ions, and others [53]. Generally, the tendencies of the measured density values of OPC and OPC-PFWA mortars were comparable; only a slight increment was recognizable over time. Hence, the measured values of all mixtures increased with the prolongation of the curing period to 90 days due to ongoing hydration processes and microstructural changes. As the specimens cured, the formation of hydration products as solid phases fill voids and enhance compactness, leading to a denser structure of the hardened matrices that mainly contribute to increasing the dry bulk density over time [54].

Meanwhile, the dry bulk density values for 10-PFWA were still higher than CM. Furthermore, it can also be seen that upgrading the PFWA level reduced the dry density of hardened mortar. After 28 days of curing, the density value of 10-PFWA is around 0.5, 1.9, and 4.3% higher than that of CM, 20-PFWA, and 30-PFWA mixtures, respectively. At the later age of 90 days, the density of 10-PFWA is higher than that of CM, 20-PFWA, and 30-PFWA mixtures by about 0.9, 1.9, and 4.2%, respectively; this exhibition could be attributed to the pozzolanic reaction between OPC and PFWA. The other reason is that the fineness of the PFWA plays a significant role in its effectiveness as a filler; thus, the fine particles of PFWA can fill voids between larger particles in the cement-based composites, leading to providing better filling capabilities and denser packing microstructure [23, 55].

It is worth mentioning that further increasing PFWA content by 30% resulted in lower-density values in contrast with the control mixtures. The densities of 30-PFWA were lower than that of CM by about 3.3, 3.6, 3.4, and 3.1% at 7, 28, 56, and 90 days, respectively. These calculated percentages demonstrate that the escalation of the substitution rate of OPC with PFWA will reduce the density of the hardened mortar; however, it can be increased with the prolongation of the curing period for the hardened mortar. The linear decreasing of density with a high amount of PFWA could correspond to the reduction of the pozzolanic reaction kinetics when PFWA partially replaced a large amount of OPC. This hinders the formation of additional solid hydration phases, resulting in a higher content of the hydration products in the produced cementitious matrix [32]. The other reason for lowering the density of mortar incorporated with DPLA might be the lower specific gravity of PFWA compared with OPC. As the percentage of PFWA increases, the overall density of the mixture decreases due to the lighter nature of this ash [22]. The decrease in the OPC content, which has a high density compared with PFWA, resulted in a decline in the dry density of the mortar [56].

Despite the variation in the mixture materials and the type of cementitious composites, laboratory conditions, and sample dimensions. The observed decrease in the dry density of mortars incorporated with different levels of PFWA was reasonably aligned with the findings of Ranjbar et al., [57]. Meanwhile, the highest reduction of 5.75% in the density of self-compacting concrete was determined in comparison with the control mixture, owing to including 20% palm oil fuel shell as cement-replacement material. The researchers ascribed this behavior to the lower specific gravity of this ash and its potential effect in trapping air bubbles that cause a subsequent reduction in density.

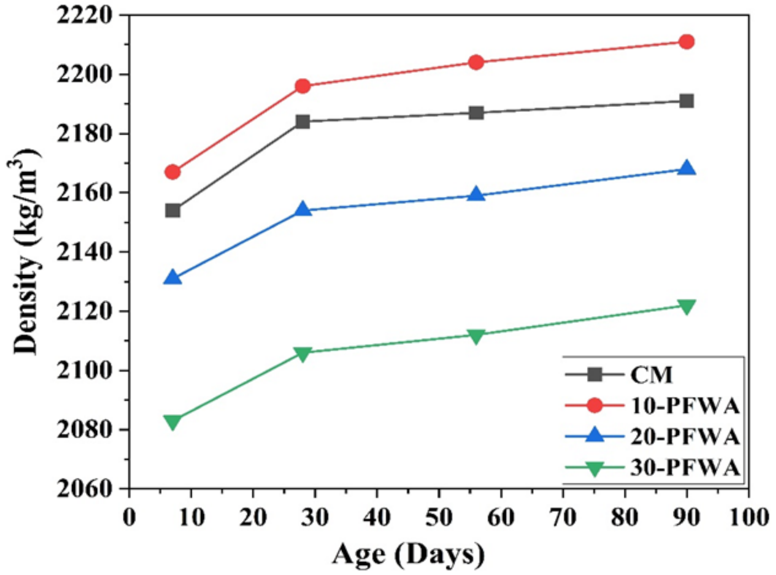


Figure 11: Density of OPC and OPC-PFWA mortars at different ages

3.5 Water absorption

Figure 12 depicts the water absorption values of OPC and OPC-PFWA mortar specimens after the adopted curing ages. Water absorption testing is indeed a critical protocol to assess the durability of mortar and other cementitious composites. The relationship between water absorption and durability plays a crucial role; higher water absorption typically indicates lower durability. This is because as mortar absorbs more water, it becomes more susceptible to damage from freeze-thaw cycles, chemical attacks, and other environmental factors [58,59].

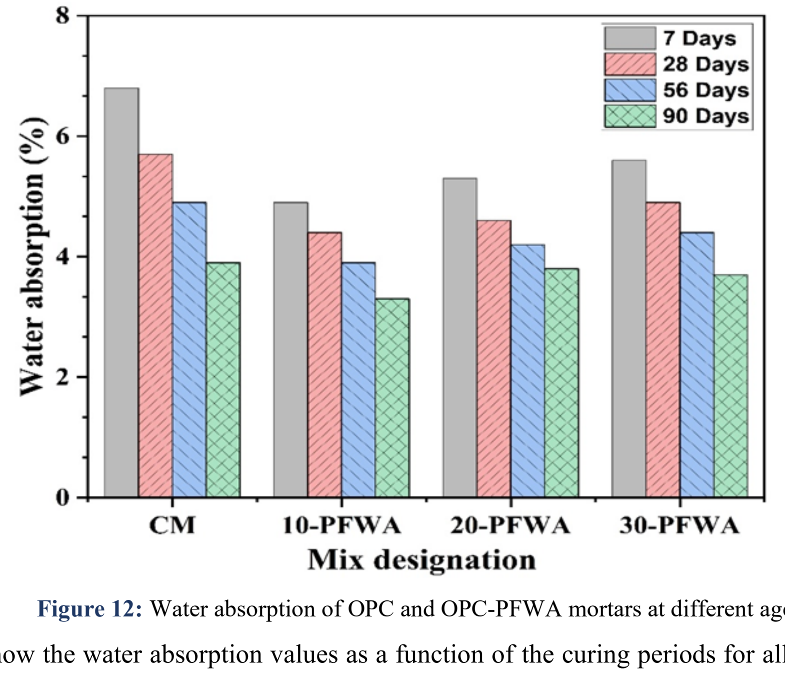


Figure 12: Water absorption of OPC and OPC-PFWA mortars at different ages

The result diagrams show the water absorption values as a function of the curing periods for all the investigated mixtures. In general, the trend of the water absorption capacities of OPC and OPC-PFWA specimens is similar. In addition, the water absorption of all mixtures rises proportionally with the increasing curing age owing to ongoing kinetic reactions of the binders over time and microstructural advancement through the hardened cementitious matrix. This highlighted observation indicates a further restriction on the external water ingression into both conventional OPC mortar and the produced sustainable mortars, including PFWA with various levels, because of the prolongation of the curing period. Moreover, replacing OPC with different PFWA rates significantly impacts the water absorption percentages of the mortars produced. After 28 days of curing, the water absorption capacity value of 10-PFWA is around 23.4, 5.6, and 10.9% lower than that of CM, 20-PFWA, and 30-PFWA mixtures, respectively. At the later age of 90 days, the water absorption capacity of 10-PFWA is lower than that of CM, 20-PFWA, and 30-PFWA mixtures by about 14.8, 11.6, and 13.2%, respectively; this behavior could be attributed to the pozzolanic reaction between OPC and PFWA that produces an additional amount of hydrate phases that refine the microstructure of the hardened matrices.

These findings align with those claimed by Mlinarik et al., [60]. They ascribed the reduction of the water absorption capacity resulting from the partial replacement of OPC with other SCMs to the better-filling ability of the pores due to their smaller particle size, which can produce a more compact structure through the hardening stage. Moreover, the fine particles of PFWA act as an effective filler that fills the voids between the cementitious composite ingredients, resulting in a denser microstructure [55]. Further analysis of the plotter result indicates that a further increase in the PFWA level increases the water absorption capacity. However, the 30-PFWA mixture exhibited lower water absorption percentages than CM. This trend of results is consistent with the outcome of Al-Kutti et al. [49], and Nasir and Al-Kutti [28].

3.6 Cost analysis

The total cost was analyzed for all adopted cement-based mortars examined through the experimental program. The mixture proportions explained in Figure 3 were combined with the cost of each ingredient to calculate the cost of production in the laboratory, depending on their current cost in local Iraqi markets. A notable cost-saving aspect was the use of PFWA, which had no cost as it was collected from the nearby regimes of holy Karbala City – Iraq (see section 2.1). The costs of the used ingredients for each 1 kg and the total cost of each 1 m^3 of the OPC and OPC-PFWA mortars are presented in Table 3.

Table 3: Cost for each (kg) of used ingredients and total cost for OPC and OPC-PFWA mortars

Ingredient	OPC	PFWA	Fine aggregate		
Cost ($)	0.093	0.0021*	0.0074		
Cost (ID)	125	3	10		
Mixture Code	**Quantities (kg/m^3)**			**Total Cost ($/m^3)**	**Total Cost (ID/m^3)**
	OPC	***PFWA***	***Fine aggregate***		
CM	660	-	1820	74.8	101,000
10-PFWA	594	66	1820	68.8	93,000
20-PFWA	528	132	1820	62.8	84,750
30-PFWA	462	198	1820	56.8	76,750

* Estimated depending on the current conditions

The total cost of producing 1 m^3 OPC mortar is 74.8 $/m^3. The OPC solely contributed around 61.4$/m^3, accounting for about 92% of the total cost required to produce each 1 m^3 of conventional OPC mortar. In contrast, including PFWA for partial OPC substituting material is a crucial key advantage in reducing the total cost of mortar production. The substitution of 10, 20, and 30% of OPC with PFWA brings down the total cost by around 8.1, 16.1, and 24.1% relative to CM without PFWA. Hence, harnessing PFWA to replace a partial weight of OPC is a cost-saving and sustainable approach to fabricating cost-effective and eco-friendly green cement-based composites.

4. Conclusion

Based on the outcomes of the laboratory examinations and results analysis, the following conclusions were drawn:

1) The multiscale testing and cost analysis conducted through the current research offers further insights into utilizing agriculture, biomass waste, and ashes to produce cost-effective, sustainable cement-based mortar. In contrast, the findings encourage awareness of the limitations of upgrading PFWA levels for various applications that should be taken. Meanwhile, the utilization of PFWA presents numerous benefits; it is crucial to balance the incorporating level to avoid excessive deterioration of the overall performance of the fabricated cementitious products.
2) The preliminary investigations prove the feasibility of harnessing Iraqi PFWA as SCM because it satisfies the requirements of ASTM C-618.
3) At all testing ages (7, 28, 56, and 90 days). Including 10% PFWA, the unconfined compressive and flexural strength of the cement-based mortar is positively improved. The compressive strength enhanced by 15% at 28 and 90 days, owing to the replacement of 10% OPC with PFWA. On the contrary, further increasing the PFWA amount reduces the measured strength.
4) Harnessing PFWA as SCM proves a key advantage in reducing the total estimated cost of the proposed mixtures, which can substantially contribute to decreasing the cost of building materials. For instance, the estimated cost of the OPC mortar reduces from 74.8 $/m^3 to 68.8 $/m^3, 62.8 $/m^3, and 56.8 $/m^3 with the replacement of 10, 20, and 30% OPC with PFWA, respectively.
5) Regarding all arguments deliberated through the current study, replacing 10% OPC with Iraqi PFWA is recommended to advance the characteristics of cement-based mortar. Further upgrading in the PFWA level adversely impacts the behavior of the final product. Despite this drawback in mortar characteristics and performance, the obtained outcomes of mortars, including higher amounts of PFWA, provide acceptable characteristics. Hence, harnessing Iraqi PFWA to replace a partial weight of OPC is a cost-saving and sustainable approach to fabricating cost-effective and green cement-based composites.

Author contributions

Conceptualization, **L. Mahmmod** and **W. Abbas**; data curation, **L. Mahmmod**; formal analysis, **L. Mahmmod**; investigation, **L. Mahmmod**; methodology, **L. Mahmmod** and **W. Abbas**; project administration, **W. Abbas**; resources, **L. Mahmmod**; software, **L. Mahmmod**; supervision, **W. Abbas**; validation, **L. Mahmmod** and **W. Abbas**; visualization, **L. Mahmmod** and **W. Abbas**; writing—original draft preparation, **L. Mahmmod**; writing—review and editing, **L. Mahmmod** and **W. Abbas**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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