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Engineering Performance of Cement Mortar Cubes Containing Percentage of Date Palm Fibers and Leaf Ash

Mohammed Elhaj Alsoufi Mohammed Ahmed[1,*]

[1] Department of Civil Engineering, SIMAD University, Mogadishu, Somalia

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ABSTRACT

The problem of conventional cement mortar cubes is the requirement of cement to be used for their production. It is recognized that cement production involves a significant release of carbon dioxide to the atmosphere, which is detrimental to the quality of the environment. To adopt a sustainable development of building materials, date palm tree has been used by numerous researchers to partially replace the cement in the production of mortar cubes. The study aims: 1. To optimize the engineering properties of cement mortar cubes enhanced with date palm fibers and leaves ash. 2. To investigate the microstructures and chemical characteristics of the optimized cement mortar enhanced with waste date palm fibers and leaves ash. The design optimization in this study, mortar cubes were formulated in such a way that the trial mix designs were varied with date palm leaves ash (1% to 10% date palm leaves ash as partial substitute of cement) and date palm, fibers (1% to 5% as partial substitute of silica sand). The mechanism of reaction at early- and long characterization tests studied term period of curing on paste, including water absorption test, Ultrasonic Pulse Velocity (UPV) test, compression test, SEM test, energy dispersive X-ray (EDX) test, X-ray and Fluorescence tests (XRF). As the study's major finding, it was realized that the optimal mix ratio of the treated mortar cubes was noticed to have 4% date palm leaves ash as partial cement substitute and 2% date palm fibers as partial silica sand substitute. There was significant improvement in the treated mortar cubes' engineering properties compared to those of the control mortar cubes. The study outcomes proved that both date palm leaves ash and fibers can cause pozzolanic activity and reinforcing effect on the treated mortar cubes.

1. Introduction

For centuries, cement mortars have been widely applied as masonry units for building construction. As more and more buildings are constructed, cement usage for construction has increased tremendously. Therefore, it is important to research on the engineering performance of mortar cubes with respect to their admixtures to come out with suitable mix ratios that can be applied in the construction industry. With regard to that, natural resources can be fully exploited to

[*] *Corresponding author.*
E-mail address: mohammedelhajalsoufi2021@gmail.com

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enhance the engineering properties of mortar cubes. This will help to develop a resource-efficient strategy for producing sustainable mortar cubes [10]. Within the field of research in cement mortar cubes, there is an interest to partially replace cement with any material with cementation properties to reduce cement consumption and increase their long terms strength gain [10]. On the other hand, date palm fibers can be used to replace sand partially. Date palm leaves ash is rich of fine-grained silica particles that can bring filling impact on cement mortar cubes, thereby clogging their pore spaces and enhance the strength of the materials in long-term [20]. This study is concentrated on experimental investigation of the engineering performance of cement mortar cubes improved with date palm leaves ash and fibers [23]. The problem of conventional cement mortar cubes is the requirement of cement to be used for their production [20]. It is recognized that cement production involves a significant release of carbon dioxide to the atmosphere and this is detrimental to the quality of the environment [3]. Furthermore, the construction industry faces the challenge of sand depletion as a result of its massive usage as fine aggregates for producing construction materials [9]. In addition, waste date palm trees can be polluting to the environment when they undergo decomposition with time. As such, it is interesting to explore the viability of using these materials to optimize the performance of mortar cubes from their engineering aspects [12]. The strength performance of cement-sand mortar cubes enhanced with various types of ashes and fibers are reviewed under this section. Tulashie *et al.,* [23]. examined the development of compressive strength for sand-cement mortar prisms improved with various dosages of rice husk ash and curing durations. Overall, the longer the curing duration, the higher the mortar prisms' compressive strength. However, the strength development of the mortar prisms varied with the different dosages of the rice husk ash. The mortar prisms with the 50 g rice husk ash addition had the highest rate of compressive strength development. This is attributable to the pozzolanic reactivity and the rice husk ash's fineness at optimizing the mortar prisms' strength development.

Mo *et al.,* [16]. evaluated the effects of biomass ash and dregs on mortars. The study showed that by replacing 10% of the cement in the mortar cube with biomass ash, the highest compressive strength of 54.5 MPa could be achieved. The compressive strength value is 7.2 MPa higher than that of the mortar cube improved with 10% dregs as partial cement replacement. This proved that the biomass ash is more effective than the dregs at refining the pore spaces of the mortar cube, thereby enhancing its compressive strength [23]. Nasir and Al-Kutti [25] researched on the properties of mortars with fly ash as fine aggregate. The study managed to come out with a new approach to apply a large quantity of fly ash without downgrading the properties of mortars at a high ratio of 60 to 70%. High compressive strength of greater than 85.5 MPa could be achieved after testing the mortar cubes subjected to 28-day curing age.

Blaisi, [6] found the positive impacts concerning the inclusion of inertized municipal solid wastes fly ash on calcium aluminate cement mortars. The research work managed to yield a new outcome that there is a positive effect in developing calcium aluminate cement (CAC) mortars using treated fly ash as filler, assimilating 10% in weight of the aggregate and adding it into the mortar dosage. This is supported by the fineness in the treated fly ash which had the capability to clog the pore spaces of the mortars [13].

A study by Yousefi *et al.,* [26] on the compressive strength development of fly ash mortars yielded the result. It is seen that the peak 28-day compressive strength of the mortar with 30% partial replacement of coconut palm leaf ash (CPLA). Beyond the 10% partial replacement of cement with fly ash in the mortars, there was a steady decline in their compressive strength gain. This can be reasoned by the fact that the fly ash is very fine, and it further clogged the pore spaces of the mortar, thereby contributing to its robustness. However, the strength of the mortars declined with excessive amount of fly ash as partial cement replacement due to insufficient hydration reactions that can induce sufficient cementation on the mortars. Table 1 shows the improvement of adopting ash in the cement-sand mortar cubes by several researchers work

Several studies were carried out to assess the impacts of various types of fibers on the compressive strength development of mortar cubes. Yousefi *et al.,* [26] studied the influence of fiber Reinforced Mortar (FRM) to enhance the compressive strength of confined beam. It was evident from the study that FRM was successful in establishing the confining method for both masonry and concrete beam. However, the FRP's confining capability highly relies on the fibers' quality, and there was little effect from the mechanical parameters relevant to the polymetric matrix [24].

Orasutthikul *et al.,* [19] was discovered that recycled nylon from waste fishing net is effective at reinforcing mortars. The key discovery from the research finding is that inclusion of straight recycled nylon enhanced the flexural strength of mortars by 41% when compared to that of knotted recycled nylon, recycled PET, and PVA fibers. With an increase in loading application, it was found from the study that longer fibers tend to induce higher lateral tensile strength in the mortars when compared to that of the shorter ones.

Araya-Leterier *et al.,* [4] examined the effectiveness of new natural fibers on the damage-mechanical performance of mortar. The new natural fibers in the form of pig hair were proven to enhance the tensile and flexural properties of the mortars under the study. In fact, adding the animal fibers to cement-based mortars increased the tensile and flexural strength, fracture toughness and abrasion resistance. In addition, the animal fibers helped to delay cracks and decrease crack widths in the mortars.

Colombo *et al.,* [9] conducted a study on fiber reinforced mortar (FRM) application for out-of-plane strengthening of schist walls. The study revealed a significant influence of FRM to strengthen schist walls. The reinforcement system is novel as it involved applying a spraying thin layer of FRM fiber reinforced mortar to strengthen masonry walls exposed to out-of-plane load states.

Gupta *et al.,* [10] assessed the morphology of mortar improved with biochar-coated polypropylene (PP) fibers. The reinforcing effect of the fibers is clearly evident with the detachment of PP fibers from the mortar paste at various points. Similarly, the detachment of PP fiber coated with saturated biochar at various points can also be seen the microstructure of the hardened matrix of the mortar. The discovery affirmed the fact that fibers are robust reinforcing agents to improve the density and strength of mortar cubes. Table 2 demonstrates the improvement of utilizing ash in the mortar cubes by several researchers work.

Table 1
Review on the different types of ash for the making of mortar cubes

Study focus	Significance of the study
Nasir and Al-Kutti [19]	A novel method to utilize a high amount of fly ash without causing significant modification in the properties of mortars at a high ratio of 60 to 70%. The pozzolanic activity in high-volume fly ash mortars after 7 days of cement hydrolysis improved their compressive strength
Yousefi *et al.,* [26]	It was found that the pit sand-cement mortar prisms after 1, 2, 7 and 28 days achieved optimal strength at 11.11% and about 90% reduction in the permeability
Kappel *et al.,* [11]	Inclusion of sewage sludge ash modified the performance of mortars to the point that they have compatible compressive strength and workability with those of ordinary mortars
Mo *et al.,* [18]	It is viable to utilize waste from the paper industry in the form of biomass boiler ash and green liquor dreg to make mortars
Blaisi [6]	Development of Aluminum (Al) and iron (Fe) mortars using treated fly ash as filler, assimilating 10% in weight of the aggregate and adding it into the mortar dosage as a new formulation. No environmental risk to human health when used as cement replacement

Table 2
Summary review on the significance of various types of fibers for making mortar cubes

Study focus	Significance of the study
Yousefi *et al.,* [26]	The FRM has been proven to be a successful confining technique for concrete beam
Orasutthikul *et al.,* [25]	Inclusion of straight recycled nylon enhanced the flexural strength of mortars by 41% when compared to that of knotted recycled nylon, recycled PET, and PVA fibers
Araya-Leterier *et al.,* [2]	There is a positive impact of pig hair as animal fiber to improve the tensile and flexural properties of the mortars
Colombo *et al.,* [4]	There is a significant influence of FRM to strengthen schist walls

The literature review shows that a substantial researchers work has been conducted and researchers are still underway, in order to utilize the full benefit of date palm ash and fiber to enhance the performance of cement mortar cubes [1-3]. The knowledge gaps exist to optimize the engineering properties of cement mortar cubes enhanced with date palm fibers and leaves ash. Also, to investigate the microstructures and chemical characteristics of the optimized cement mortar enhanced with waste date palm fibers and leaves ash.

Therefore, the evidence from the literature review can be used to justify the importance of the study that concentrated on the utilization of date palm Leaves ash and fibers to optimize the robustness of cement mortar cubes.

2. Methodology

Flowchart showing the research flow process for the study is depicted in Figure 1. As a first step, the research materials including Portland cement, silica sand, date palm leaves ash (DPLA) and fibers (DPF) were collected to make the mortar cubes. The type of Portland cement used is YTL cement. The silica sand applied in the research work is a typical river sand used for making construction materials. Both date palm leaves ash (DPLA) and fibers were sourced from the date palm trees found in the garden in Saudi Arabia as shown in Figure 2. The date palm leaves were burned into ashes in an incinerator and then cooled down to normal surrounding temperature. Next, both silica sand and DPLA were exposed to the procedure of sieving. The silica sand was passed through 2 mm sieve size. In a similar way, the DPLA was subjected to sieving process to pass through a sieve size of 300 µm. To do chemical characterization, Portland cement, silica sand and DPLA were sent for XRF. The date palm fibers were later examined for their microstructural characteristics by utilizing a scanning electron microscope. Designs of the mix ratios were later carried out to develop an organized approach of defining the material proportions for making the mortar cubes. The mortar cubes treated with DPLA and fibers were later formulated and cured for laboratory evaluation. For comparison purpose, the control mortar cubes were casted without DPLA and fibers. The mortar cubes were then tested in compression in order decide their optimal mix ratio at 28-day curing duration. On the basis of the highest average 28-day compressive strength for all the mortar cubes casted, the optimal mix design of the treated mortar cubes was justified. In order to examine the effect of curing age on the mechanical performance of the mortar cubes, curing of the mortar cubes were done for various curing periods of up to 90 days. For benchmarking, the compressive strength development with curing ages of the treated mortar cubes was compared to that of the control mortar cubes. By using the optimal mix ratio, mortar cubes were further produced for evaluation on their average flexural strength, ultrasonic pulse velocity (UPV) and water absorption. In chemical and morphology tests, samples of both control and treated mortar cubes were collected and assessed for their scanning electron micrographs and energy dispersive X-ray outcomes (EDX). These outcomes are very significant in quantifying the amount of cementation compounds and studying the packing pattern of particles in the matrices of the mortar cubes.

The raw materials under the study are Portland cement, silica sand, DPLA and fibers. The raw materials were selectively identified for the study after reviewing recent literature and establishing gaps for the research work. Detailed evaluation on these materials may provide insight into their suitability for manufacturing the mortar cubes under investigation. Figure 3 indicates a sample of the Portland cement under study. The essential Oxide compounds for the cement are lime, silica, alumina, iron (II) oxide, magnesium oxide and sulfur oxide. When manufacturing the cement, the raw materials with the appropriate proportions of the oxide compounds are crushed before exposure to firing in a kiln. The firing process leads to the chemical reaction that results in the making of clinker in solid form. Grinding of the clinker was later done to a very fine condition and adequately mixed with a small amount of gypsum to yield Portland cement.

The type of silica sand used as the aggregate for making mortar cubes is river sand. Figure 3 indicates the silica sand utilized as the aggregate for making the mortar cubes. Silica sand is the necessary ingredient for the making of construction materials due to its solidness and suitability to form aggregate. It is typically formulated as a result of segregation of quartzite due to the weathering process of non-foliated metamorphic rocks. Silicon oxide ($SiO2$) is recognized as the dominant mineral in silica sand. The primary function of silica sand is to form filler for the binding of the mortar cubes to take place. A sample of DPLA used for the research purpose is indicated in Figure 5. By incinerating dried date palm leaves in a muffle furnace, the DPLA was made. The muffle furnace used for incineration was available in the Civil Engineering Laboratory of SIMAD university. It must be noted that date palm leaves were sourced from date palm trees of the site and exposed to air-drying for a timeframe of 7 days. The dried date palm leaves were cut in small fractions before being subjected to incineration process in the muffle furnace for 4 hours. Cooling of the cogon grass ash was then done for 1 day before sieving to gather fine palm date leaves ash for the making of the mortar cubes.

Similarly, to that of date palm leaves, date palm fibers were collected from date palm trees (trunk surface). They are suitable to be applied as the reinforcing agents to strengthen the mortar cubes' tensile robustness. For the purpose of result consistency, each date palm fiber was cut to an approximate size of 5 mm before mixing as ingredient of the mortar cubes. Due to their eco-friendly nature, date palm fibers are attractive to be applied as partial replacement of silica sand in the mortar cubes. This is because date palm trees which were sourced for date palm fibers can be regrown due to their wide availability in the Middle East countries. A sample of the date palm fibers is shown in Figure 6. The corresponding scanning electron micrograph of the sample of date palm fibers. The photomicrograph of a coconut fiber. The diameter size of a typical date palm fiber was noticed to be 201. The date palm fibers readily available in thin-shaped size can enhance the flexural strength of the mortar cubes, which in turn can provide high resistance to cracks and deformation in the mortar cubes.

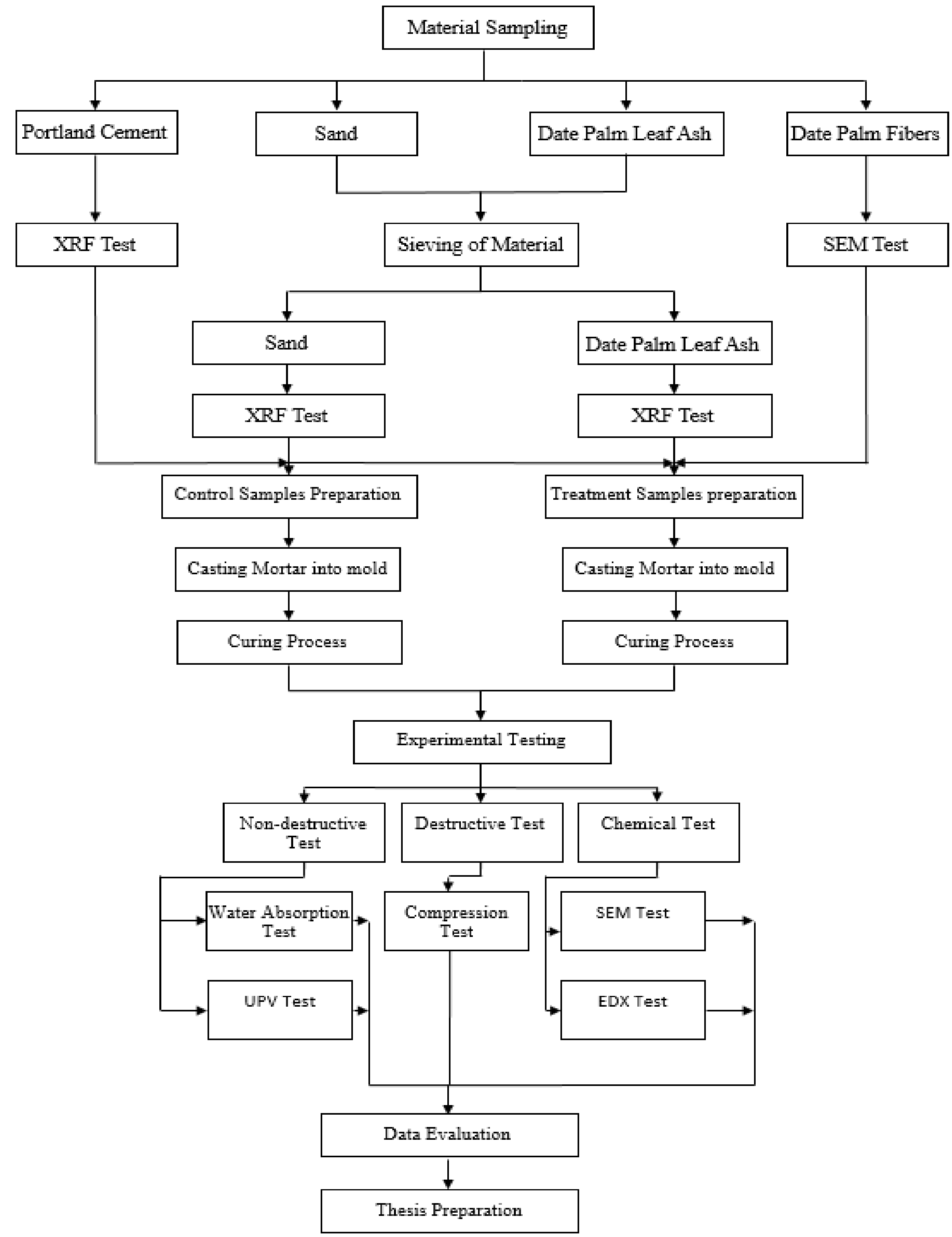

Fig. 1. Flowchart showing the research flow process for the study

Fig. 2. Date palm trees in Jeddah

Fig. 3. Silica sand

Fig. 4. Portland cement

Fig. 5. A sample of date palm Leaves ash

Fig. 6. A sample of date palm fibers

The process of sieving was needed to gather the raw materials with suitable particle sizes required for casting the mortar cubes. Figure 7 shows the sieves used to gather the required particle sizes of the raw materials. Two types of raw material under study that were sieved are silica sand and DPLA. For silica sand, it is important to ascertain that the sand particles were dried in an oven at 60°C for 24 hours before it could be cooled down. After oven drying and cooling, the sand was subjected to a sieving process such that only sand particles that passed through 2 mm sieve size were accepted. Each sieving process was done using a mechanical shaker for 20 minutes. Collection of the sieved sand particles was done using a pan.

Fig. 7. Sieve analysis in the SIMAD lab

2.1 Laboratory Tests on the Mortar Cubes

All procedures of the laboratory tests on the mortar cubes are detailed in this section. The mechanical properties of the mortar cubes were characterized in compression, flexural, water absorption and ultrasonic pulse velocity (UPV) tests. The reference standard for testing the mortar cubes is BS EN 1015-11:1999 [7].

2.1.1 Tests of compression on the mortar cubes

The compression test machine used to test the mortar cubes. The type of model for the compression test machine is 51-8300. The manufacturer for the machine is KENCO and it has the precision of reading compressive force of 0.001 kN and its calibration was found to range from 600 to 2500 kN. The machine was designed to sustain a maximum compressive force of 2500 kN. Prior to the compression tests, the test machine must be checked and calibrated in such a way that it must be capable to operate in proper condition. All the necessary items required for the testing purpose were prepared. The dimension of the mortar cube was measured so that cross sectional area and then the volume of the mortar cube could be decided. Then, the necessary information with regard to the mortar cube dimension as well as the rate of compression were inputted in the display board of the compression test machine. The compression test started by constantly applied pressure through rotation of pressure valve in the direction of clockwise. The pressure exerted by the piston must be calibrated in such a manner that it matched with the value of compressive strength of the mortar cube. The test was stopped after the mortar cube was noticed to fail by cracks and shearing. The applied force was discontinued when the mortar cube was noticed to break. Therefore, the formula that represents the compressive strength of the mortar cube is given in Eq. (1).

$$\sigma_p = \frac{F}{A} \tag{1}$$

where
σ_p = Compressive strength of the mortar cube (MPa)
F = Compressive force on the mortar cube (N)
A = Cross sectional area of the mortar cube (mm^2)

2.1.2 Tests of flexural on the mortar beams

The flexural test machine for determining the flexural strength of the mortar beams. The aim of the flexural test is to assess the ability of the mortar beam to resist failure by bending. Flexural strength of the mortar beam can be used as an indirect indication of its tensile strength. It should be noted that the flexural test machine is of 51-8300 model and its manufacturer is KENCO. The test machine has a level of accuracy of flexural force reading of up to 0.001 kN and the machine calibration ranges from 30 to 150 kN. The modulus of rupture of flexural strength of the mortar beam could be obtained utilizing Eq. (2).

$$\sigma_r = \frac{3FL}{2bd^2} \tag{2}$$

where
σ_r = Modulus of rupture of flexural strength of the mortar beam (MPa)
F = Point force at the mid span of the mortar beam (N)
L = Length of the mortar beam (mm)
b = Width of the mortar beam (mm)
d = Thickness of the mortar beam (mm)

2.1.3 Tests of water absorption on the mortar cubes

The degree of intactness of the mortar cubes can be evaluated by conducting tests of water absorption on them. This can be reasoned by the fact that the more intact is the mortar cube, the lesser quantity of water that could be absorbed by it due to lower void ratio. On the basis of the related mix design, each mortar cube was made and cured in water for a duration of 28 days. The mortar cube was later subjected to a submersion under water in a steel tank for 1 day. Later, the mortar cube was removed from the steel tank and weighed again using an electronic balance. This was aimed to measure the quantity of water uptake by the mortar cube. The water absorption of the mortar cube can be expressed as in Eq. (3).

$$W(\%) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100 \tag{3}$$

where
W = Water absorption of the mortar cube (%)
M_{wet} = Mass of the wet mortar cube (kg)
M_{dry} = Mass of the dry mortar cube (kg)

2.1.4 Tests of ultrasonic pulse velocity (UPV) on the mortar cubes

The degree of uniformity and quality of the mortar cubes can be gaged through ultrasonic pulse velocity (UPV) tests. There are three components of UPV machine namely, electronic timing device, amplifier and electric pulse generator. As a starting point of testing in UPV, the ultrasonic pulse was generated by the electro-acoustical transducer. The ultrasonic pulse was then made to pass through the mortar cube and this induced reflections over the boundaries of different stages of materials in the mortar cube. The basic objective for evaluating the quality of the mortar cube in UPV is to achieve high pulse velocity which are indicative of the superior quality of the mortar cube from the aspects of porosity, uniformity and intact ability. Eq. (4) states the formula for defining the ultrasonic pulse velocity of the mortar cube.

Ultrasonic pulse velocity of the mortar cube = Width of the mortar cube / Time required for the pulse to travel through the mortar cube (4)

2.1.5 Tests for analysing the chemical and microstructural characteristics of the mortar cubes

The chemical properties of the mortar cube samples can be quantified by performing X-ray Fluorescence (XRF) and Energy Dispersive X-ray (EDX) tests. The morphology of the mortar cube samples was evaluated using a Scanning Electron Microscope (SEM). Tests of XRF were utilized to investigate the dictating oxide compounds of the raw materials for producing the mortar cubes. Sizes of particles in the date palm fibers were assessed on the basis of the micrograph captured by the SEM. The binding minerals as a result of the cementation process in the mortar cubes could also be observed in scanning electron micrographs. The corresponding chemical elements of the mortar cube samples were traceable from the outcomes of the EDX tests.

2.1.6 Tests of x-ray fluorescence (XRF) on the mortar cubes

XRF machine used for testing the raw materials for making the mortar cubes. Bruker S4 Explorer X-ray spectrometer was identified as the type of XRF machine utilized for the study. The intensity of fluorescent radiation caused by the excitement of electrons of oxide compounds by the X-ray beam can be measured by the X-ray spectrometer. Through best positioning of the X-ray detector at the optimal angle in relation to the crystal under analysis in the spectrometer, the intensity of the fluorescent radiation can be gaged. Raw materials for the mortar cubes in the form of Portland cement, silica sand and date palm leaves ash were prepared in 50 grams each for testing in XRF. The specific outcome of the XRF tests on the raw materials for making the mortar cubes is definitely to assure accurate measurement of their oxide compounds so that the minerals in the raw materials which were responsible to induce cementation in the mortar cubes could be traced.

2.1.7 Tests of scanning electron microscope (SEM) and energy dispersive x-ray (EDX) on the mortar cube samples

Both microstructural and chemical results on the samples of mortar cubes were obtained using Toshiba Model SU 1510 Scanning Electron Microscope (SEM) machine. Through careful testing, microstructural images with varying surface magnifications of the mortar cube samples could be captured. The captured images were used to illustrate the physical proofs of the binding interaction among the various sizes and shapes of particles in the mortar cubes. It must be highlighted that both control and treated samples of mortar cubes were prepared for the SEM and EDX tests. Each sample of the mortar cube was produced in 4 cm × 4 cm size in a careful manner to ensure that only sample with intact surface was chosen. The mortar cube sample was then placed in a sample disk before it was positioned in the machine for testing. The results of SEM and EDX with high precision were gathered and the relevant data were analysed and projected in a computer.

3. Results

3.1 Influence of Water to Cement Ratio on the Development Average Compressive Strength of the Control Mortar Cubes

The result about the influence of water to cement ratio on the 28-day average compressive strength of control mortar cubes is indicated in Figure 8. It is observed from Figure 8 there is a progressive increase in the 28-day average compressive strength of the control mortar cubes with water to cement ratio between 0.5 and 0.65 (Table 3 and Table 4 below).The 28-day average compressive strength of the control mortar cubes with a water to cement ratio of 0.5 was found to be 16.6 MPa. However, the average compressive strength increased to 29.6 MPa when the control mortar cubes were prepared and tested based on a water to cement ratio of 0.65 as it is shown in Table 4. Beyond a water to cement ratio of 0.65, the average compressive strength of the control mortar cubes continued to reduce with the increasing water to cement ratio of up to 1.0. At a water to cement ratio of 1.0, a very low 28-day average compressive strength of 15.7 MPa was of the mortar was observed. This can be rationalized by the fact that sufficient quantity of water is required to provide enough lubrication in the control mortar cubes so that cement hydrolysis could happen for initiating the binding mechanism. The low average compressive strength of the control mortar cubes with high water to cement ratio is due to the repelling action of particles in the cubes due to their excessive water during their tamping process. This is undesirable as the excessive water further weaken the strength performance of the control mortar cubes.

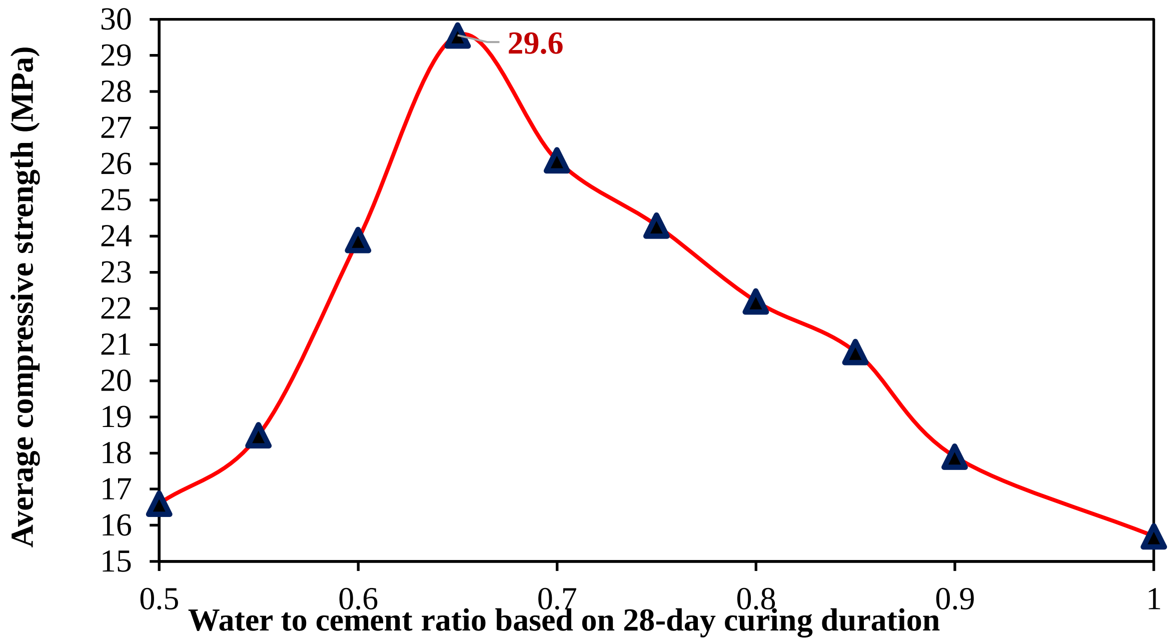

Fig. 8. The 28-day average compressive strength pattern of control mortar cubes with respect to varying water to cement-ratio

3.2 Influence of Date Palm Leaves Ash on the Average Compressive Strength Development of the Mortar Cubes

It is seen in Figure 9 that there exists a pattern of 28-day average compressive strength development of mortar cubes with varying percentages of date palm leaves ash as partial substitute of cement. The results of the 28-day average compressive strength of the mortar cubes were based on varying percentages of partial cement substitute of DPLA from 0 to 10%. The highest 28-day average compressive strength of 28.6 MPa was achieved from the results of the mortar cubes with 4% DPLA as partial substitute of silica sand. It is depicted in Figure 4.2 and Table 5 that at below 4% DPLA as partial substitute of cement, lower 28-day average compressive strength was observed for the mortar cubes. Similarly, above 4% DPLA as partial substitute of cement, reduced 28-day average compressive strength was also noted for the mortar cubes. The statement can explain this that below 4% DPLA as partial substitute of cement, there was insufficient filling impact that can be induced by the ash to trigger optimal cement reactivity in the mortar cubes. Similarly, above 4% DPLA as partial substitute of cement, the ash was excessive and cement was insufficient for the optimal hydration to take place although the filling effect was improved with more DPLA. This clearly implies that the amount of DPLA needs to be added at optimal level so as to optimize the filling of voids in the mortar cubes in order to maximize their 28-day average compressive strength. With the right quantity of the ash, the pore spaces of the mortar cubes can be decreased to the minimum, thereby optimizing their 28-day average compressive strength.

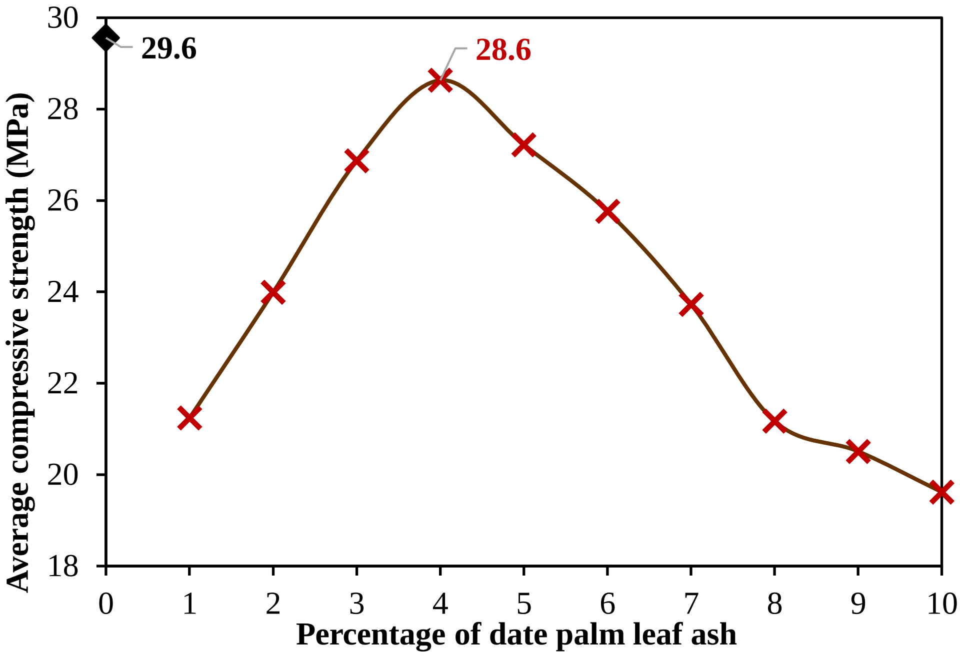

Fig. 9. The pattern of 28-day average compressive strength of mortar cubes with varying percentage of date palm leaves ash

3.3 Influence of Date Palm Leaves Ash and Fibers on the Average Compressive Strength and Density of the Mortar Cubes

By narrowing down the mix designs of the mortar cubes to 0.65 water to cement ratio and 4% DPLA as partial cement substitute as it declared in Table 4 and Table 5 below, further trial test results were examined by varying the date palm fibers in the mix designs from 0 to 5%. Figure 11 illustrates the pattern of the 28-day average compressive strength of the mortar cubes with 4% DPLA as partial cement substitute and variation from 0 to 5% date palm fibers as partial silica sand replacement as it shown in Table 3 below. At 1% date palm fibers as partial silica sand substitute, the 28-day average compressive strength of the mortar cubes was measured to be only 29.0 MPa only. Optimally, addition of 2% date palm fibers as partial silica sand substitute in the mortar cubes resulted in a 28-day average compressive strength of 31.3 MPa. Such value is 7.9% higher when compared to that of the mortar cubes with 1% date palm fibers as partial silica sand substitute. Beyond 2% date palm fibers as partial silica sand substitute of the mortar cubes in Figure 4.3, there was no significant increase in their 28-day average compressive strength. The average compressive strength of the mortar cubes was as low as 8.5 MPa with 5% date palm fibers as partial silica sand replacement. The results imply that it is important to quantify and test the right proportion of date palm fibers to maximize the mortar cubes' compressive strength. The role of the date palm fibers as reinforcing agent is equally important when compared to that of palm date leaves ash as filling agent in the mortar cubes. This justifies the need of extensive experimentation to obtain valid results of the mortar cubes enhanced with DPLA and fibers.

Figure 11 shows the results of the average density of the mortar cubes with 4% DPLA as partial cement replacement and varying date palm fibers as partial silica sand replacement. With 0% date palm fibers as partial cement substitute, the average density of the mortar cubes was found to be 2004 kg m-3. However, inclusion of 2% date palm fibers as partial cement substitute resulted in an average density of 1909 kg m-3 for the mortar cubes. Further increase in the quantity of date palm fibres in the mortar cubes resulted in lower average density. For instance, the average density of the mortar cubes was found to be 1783 kg m-3 when they were analyzed at 5% date palm fibers and 4% DPLA as it is declared in Table 5. Basically, this provides an indication that more date palm fibres is added to the admixture of the mortar cube, the lighter is the mortar cube. However, it must be cautiously clarified that lower density of the mortar cubes does not imply they are more robust. Although light mortar cubes are desirable, their densities need to be verified with their strength before their optimal mix design can be decided.

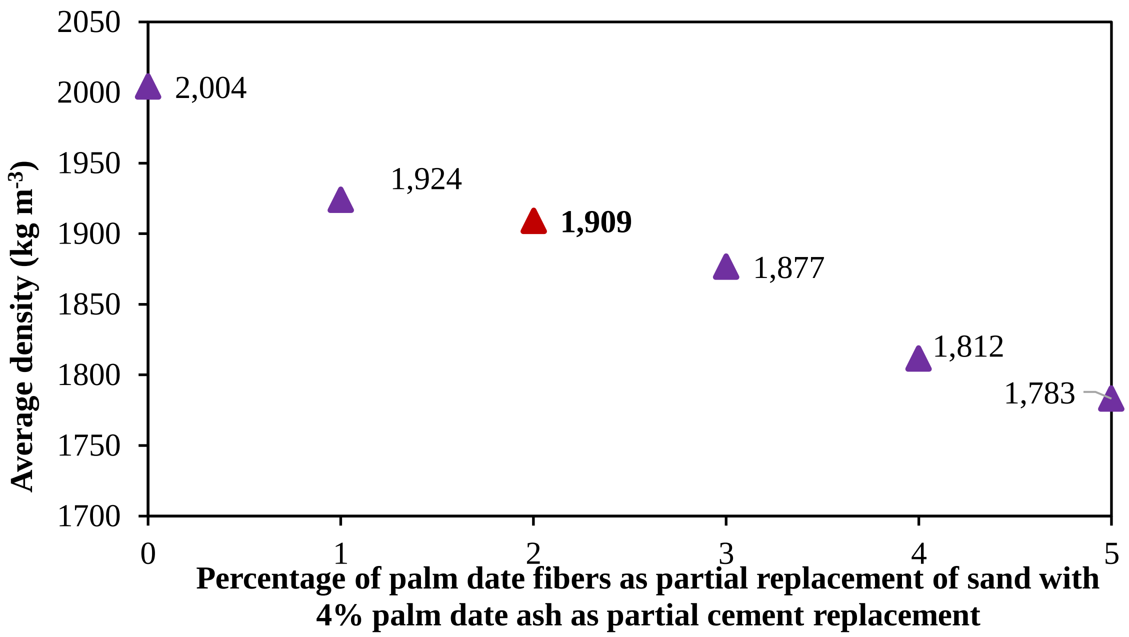

Fig. 10. The trend of 28-day compressive strength of mortar cubes improved with 4% date palm leaves ash and varying percentages of date palm fibers

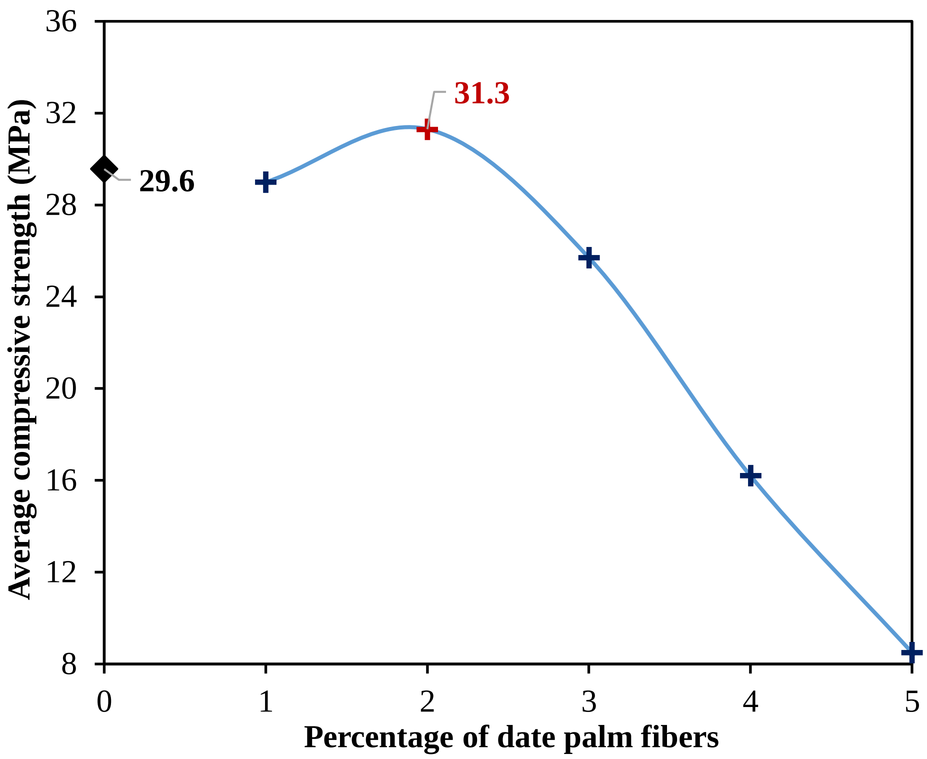

Fig. 11. The trend of density development of mortar cubes treated with 4% date palm leaves ash and varying percentages of date palm fibers

3.4 Effect of Curing Age on the Average 28-Day Compressive Strength Growth of the Mortar Cubes Optimized with Date Palm Leaves Ash and Fibers

The effect of curing age on the average 28-day compressive strength growth of the mortar cubes optimized with DPLA and fibers is illustrated in Figure 12. By expectation, there is a rapid growth of the average 28-day compressive strength from 0 to 7 days of curing age. After 7-day curing age, the average 28-day compressive strength development of the treated mortar cubes increased slower. The same pattern of compressive strength development of mortar cubes with curing age is also observable from the published work of López-Zaldívar *et al.,* [14]. The highest rate of average 28-day compressive strength development can be observed from the strength results of the treated mortar cubes with 4% DPLA and 2% date palm fibers as it is illustrated in Table 4 and Table 5 below respectively. The significant compressive strength growth of the treated mortar cubes is attributable to the continual hydrolysis process and pozzolanic activity that formed cementation products as well as the increased density and packed arrangement of the particles in them due to the addition of DPLA, fibers and silica sand. The results also indicate that curing age plays a very important role in ensuring continual compressive strength growth of the mortar cubes. Such results support justification on the optimal mix design of the treated mortar cubes to be further examined for their non-destructive and chemical properties in comparison to those of control mortar cubes.

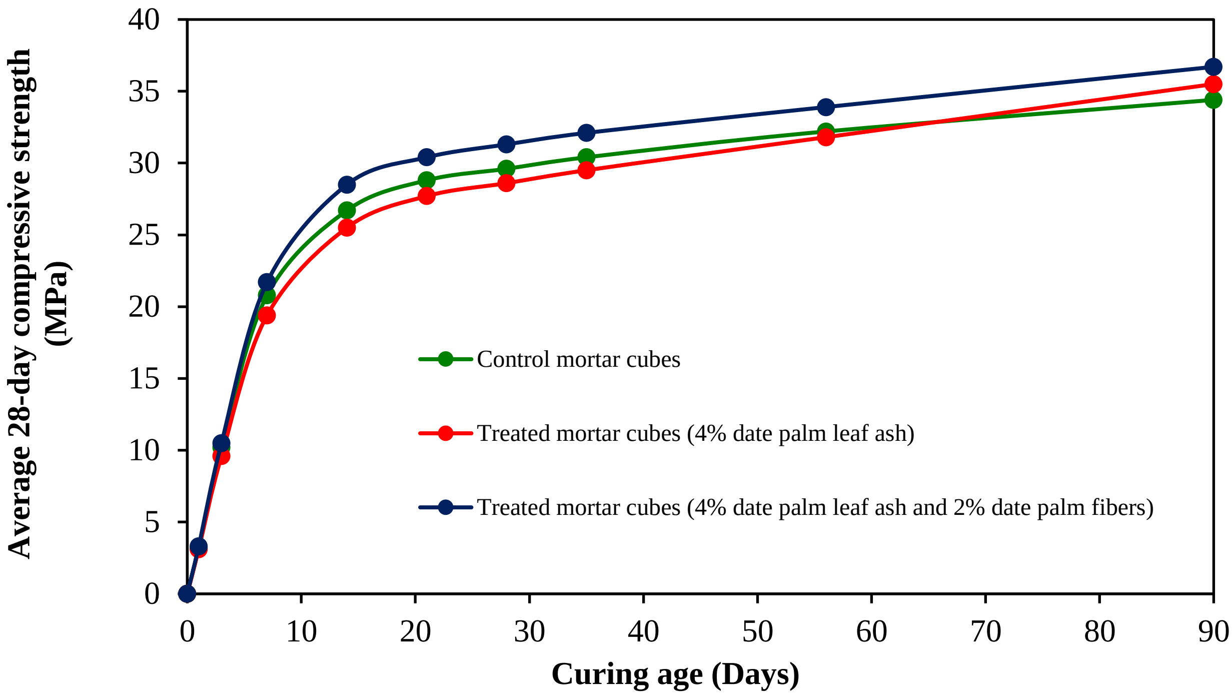

Fig. 12. Effect of curing age on the average compressive strength of the mortar cubes optimized with 4% date palm leaf ash and varying percentage of date palm fibers

3.5 Effect of Curing Age on the Average 28-Day Flexural Strength Growth of the Mortar Beams Optimized with Date Palm Leaves Ash and Fibers

Figure 13 shows the results relative to the effect of curing age on the average 28-day flexural strength growth of the mortar beams optimized with date palm leaves ash and fibers. to the average 28-day compressive strength growth, there is a drastic increase in the development of the average 28-day flexural strength from 0 to 7 days of curing age for the mortar beams under study. Slower rates of average 28-day flexural strength can be observed in the Figure for all the mortar beams subjected to more than 7 days of curing age. At 28-day curing age, the average flexural strength of the control mortar beams was discovered to be 3.03 MPa. By comparison, the average 28-day flexural strength of the treated mortar beams with 4% date palm leaves ash was realized to be 1.0% lower than that of the control mortar beams. However, with 4% and 2% date palm fibers in the mix design of the treated mortar beams; the highest 28-day average flexural strength of 3.22 MPa was achieved after testing. This is a reflection that the date palm fibers played an important role in enhancing the flexural strength of the treated mortar beams. This also indirectly indicates that date palm fibers can enhance the tensile strength of the treated mortar beams.

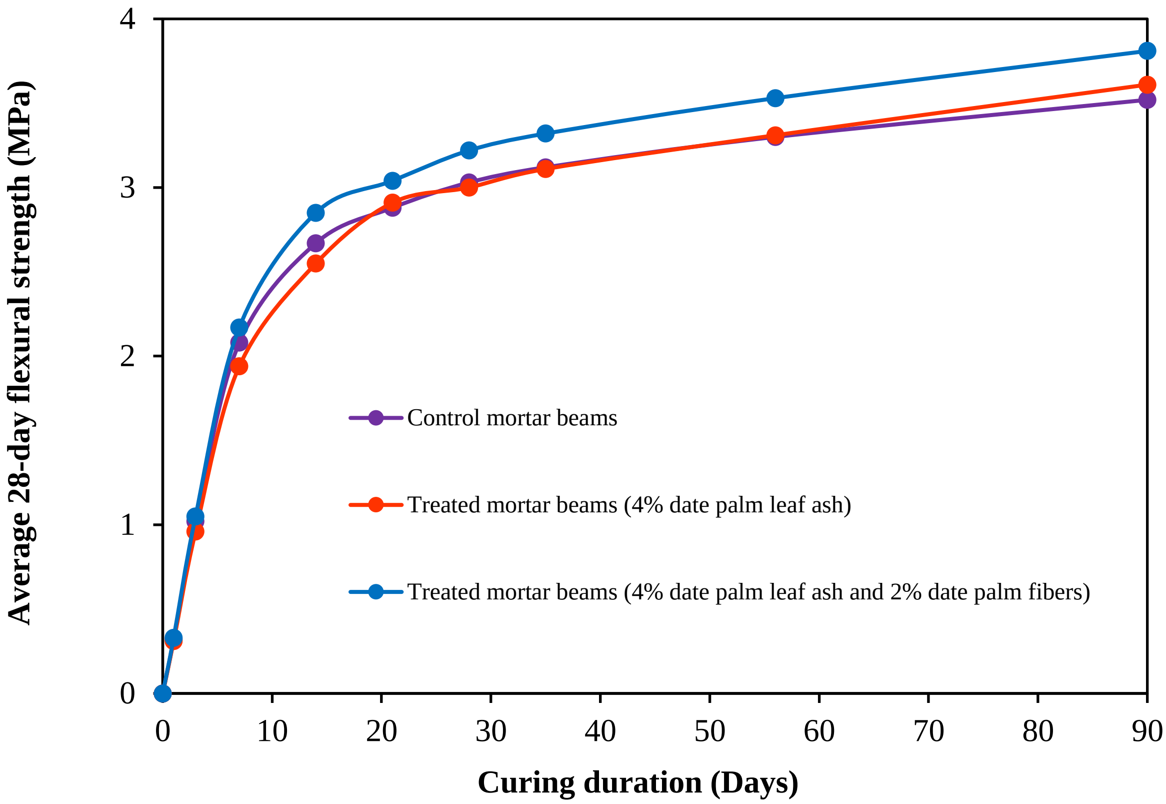

Fig. 13. Effect of curing age on the average flexural strength of the mortar beams optimized with 4% date palm leaves ash and varying percentage of date palm fibers

3.6 UPV Test Evaluation of Mortar Cubes Optimized with Date Palm Leaves Ash and Fibers

Figure 14 indicates the findings on the UPV of the treated mortar cubes improved with 4% DPLA date palm leaves ash and varying content of date palm fibers at 28-day curing duration. There is a progressive increase in the average values of UPV of the treated mortar cubes when the content of the date palm fibers was varied from 0 to 2%. The average UPV values for the treated mortar cubes were discovered to be 3999, 4037 and 4048 m s-1 with respect to the date palm fibers contents of 0, 1 and 2%. However, there is a drastic decrease in the average UPV values of the treated mortar cubes when the date palm fibers content was varied from 2 to 5%. The average values of UPV for the treated mortar cubes were found to be 3826, 3605 and 3502 m s-1 respectively for the date palm fibers contents of 3, 4 and 5%. It can be interpreted from the peak average UPV value of 4048 m s-1 for the treated mortar cubes improved with 4% date palm leaves ash and 2% date palm fibers that the mortar cubes achieved the best endurance in term of their quality performance. The peak average UPV value of the treated mortar cubes was noticed to be 1.38% higher when compared to that of mortar cubes optimally improved with dried marble slurry in the research work of [6-27]. The highest average value of the UPV for the treated mortar cubes reflects that they possess the minimal pore spaces, which indicates that their quality is the highest when compared to those of other mortar cubes tested in the present research work. The UPV finding also indicates that with the content of the palm date fibers exceeds 2% as partial sand replacement in the treated mortar cubes, the pore spaces are wider in the treated mortar cubes due to the low average values of UPV as a result of the shorter travel paths with time of the pulse over the mortar cubes. The UPV results provide reliable evidence that the mortar cubes treated with 4% DPLA and 2% date palm fibers are the most robust ones as compared to all the mortar cubes tested under the study.

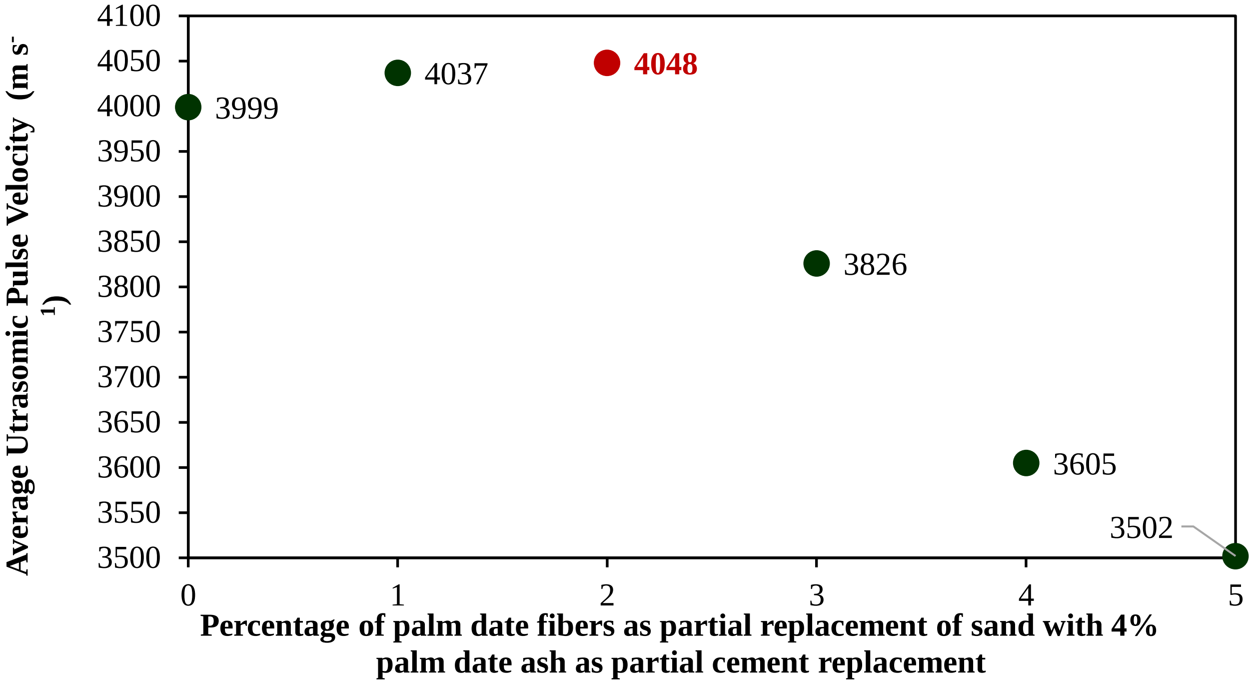

Fig. 14. Ultrasonic Pulse Velocity (UPV) test results of the mortar cubes optimized with 4% date palm leaf ash and varying percentage of date palm fibers

3.7 Water Absorptivity of Mortar Cubes Optimized with Date Palm Leaves Ash and Fibers

The average percentages of water absorbed by the mortar cubes treated with 4% DPLA and varying percentages of date palm fibers are shown in Figure 15. There is a continual slow increase in the average water absorption of the treated mortar cubes when the date palm fibers content was increased from 0 to 2%. The 0average water absorptions of the treated mortar cubes were found to be 2.23, 2.65 and 2.96% with the respective contents of date palm fibers of 0, 1 and 2%. Beyond 2% date palm fibers content, there is a drastic increase in average water absorption in the treated mortar cubes. The average water absorptions of the treated mortar cubes were found to be 8.58, 11.63 and 13.89% at 3, 4 and 5% date palm fibers contents respectively. This proves that the average water absorptions of the mortar cubes are directly related to their strength and porosity. The least porosity is the mortar cube, the minimal is its water absorptivity. Anyway, the average water absorption of the mortar cubes optimized with 4% DPLA and 2% date palm fibers was realized to be much lower as compared to 9% water absorption of mortar cubes optimally improved with dried marble slurry in the research work of [6]. The significant test results are solid evidence that shows positive clogging impact induced by the optimal combination of DPLA and fibers in minimizing the pore spaces of the treated mortar cubes.

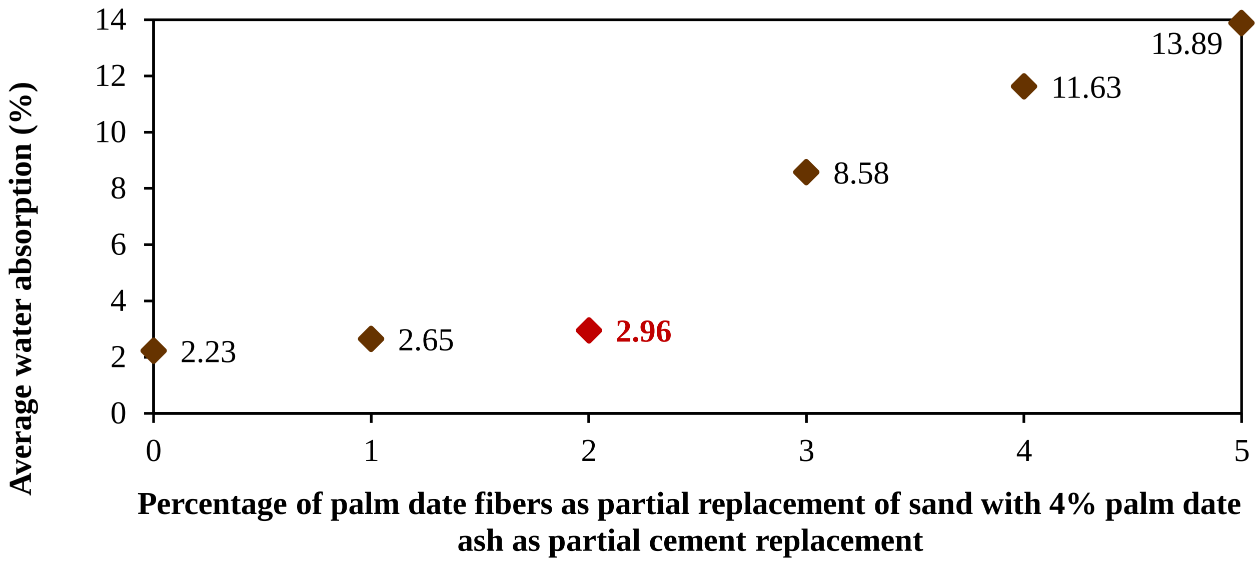

Fig. 15. Average water absorption of the mortar cubes optimized with 4% date palm leaves ash and varying percentage of date palm fibers

Table 3
Trial mix designs for deciding the suitable water to cement ratio for the control mortar cubes

Set of Mortar cubes	Number of mortar cubes	Water to cement ratio	Date palm leaves ash (%)	Date palm fibers (%)	Cement (g)	Silica sand (g)	Water content (g)	Date palm leaves ash (g)	Date palm fibers (g)
1	9	0.50	-	-	500	1500	250	-	-
2	9	0.55	-	-	500	1500	275	-	-
3	9	0.60	-	-	500	1500	300	-	-
4	9	0.65	-	-	500	1500	325	-	-
5	9	0.70	-	-	500	1500	350	-	-
6	9	0.75	-	-	500	1500	375	-	-
7	9	0.80	-	-	500	1500	400	-	-
8	9	0.85	-	-	500	1500	425	-	-
9	9	0.90	-	-	500	1500	450	-	-
10	9	1.00	-	-	500	1500	500	-	-

Table 4
Trial mix designs for deciding the suitable water to cement ratio for the control mortar cubes

Set of Mortar cubes	Number of mortar cubes	Water to cement ratio	Date palm leaves ash (%)	Date palm fibers (%)	Cement (g)	Silica sand (g)	Water content (g)	Date palm leaves ash (g)	Date palm fibers (g)
1	9	0.50	-	-	500	1500	250	-	-
2	9	0.55	-	-	500	1500	275	-	-
3	9	0.60	-	-	500	1500	300	-	-
4	9	0.65	-	-	500	1500	325	-	-
5	9	0.70	-	-	500	1500	350	-	-
6	9	0.75	-	-	500	1500	375	-	-
7	9	0.80	-	-	500	1500	400	-	-
8	9	0.85	-	-	500	1500	425	-	-
9	9	0.90	-	-	500	1500	450	-	-
10	9	1.00	-	-	500	1500	500	-	-

Table 5
Trial mix designs for optimizing the strength of the mortar cubes enhanced with date palm leaves ash and fibers

Set of mortar cubes	Number of mortar cubes	Water to cement ratio	Date palm leaves ash (%)	Date palm leaves fibers (%)	Cement (g)	Silica sand (g)	Water content (g)	Date palm leaves ash (g)	Date palm fibers (g)
1	9	0.65	4	1	480	1485	325	20	15
2	9	0.65	4	2	480	1470	325	20	30
3	9	0.65	4	3	480	1455	325	20	45
4	9	0.65	4	4	480	1440	325	20	60
5	9	0.65	4	5	480	1425	325	20	75

3.8 Morphological and Chemical Evaluation of the Mortar Cubes Optimized with Date Palm Leaves Ash and Fibers

Characterization on the morphology of a sample of control mortar cube is depicted in the scanning electron micrograph of Figure 16. It is noticeable in the figure that the control mortar cube sample is characterized by needle shaped particles which reflect the presence of calcium Silicate Hydrates (C-S-H) crystals. C-S-H crystals are recognized as the cement hydration. The C-S-H crystals are observed to be closely packed to each other as shown in the scanning electron micrograph of the Figure. These crystals were responsible for the binding of the control mortar cube. A typical C-S-H crystal of 3.51 µm size of the control mortar cube sample is observed in Figure 16. The evidence on the existence of the C-S-H crystals can be further seen from the outcome of the energy dispersive X-ray (EDX) on the control mortar cube sample, as shown in Table 4.1 and Figure 19. There are significant peaks of calcium (Ca) elements from the observation of the EDX finding on the control mortar cube sample as shown in Figure 19. With reference to 0.5 and 3.5 keV, the sum of the elemental weights of Ca for the control mortar cube sample was discovered to be 20.50% as indicated in Table 18. In the same manner, the chemical quantifications for all the other elements of the control mortar cube sample were determined in order to calculate the total elemental percentage of the mortar cube sample as illustrated in Table 18. In total, the accumulation of the elemental weights from the EDX analysis for the elements of calcium (Ca), Silicon (Si), Aluminum (Al) and oxide (O) was realized to be 86.94% which predominated the elemental sum of the control mortar cube sample. It must be stressed that these elements are necessary form Calcium Silicate and Calcium Aluminate Hydrates, the primary cementation minerals produced from the cement hydrolysis. The cementation products are also analyzed and discussed from the morphological discoveries of the published works on mortar cubes from [19,24,25].

Different from the chemical microstructure of the control mortar cube sample, the mortar cube sample treated with date palm leaves ash and fibers is characterized by the morphological surface with a denser cementation matrix as indicated in Figure 19. The formation of the C-S-H crystals coupled with the reinforcing impact from the date palm fibers increased the degree of denseness of the treated mortar cube. The high packing effectiveness of the particles in the treated mortar cube is attributed to the combination of the cementing effect, date palm leaves ash and fibers that helped the void spaces of the treated mortar cube to be reduced significantly. A typical C-S-H crystal from of 3.93 µm in size of the treated mortar cube sample can be observed in Figure 19. The EDX finding on the treated mortar cube sample can be examined in Table 7 and Figure 18. The cumulative elemental percentage for Ca, Si, Al and O for the treated mortar cube sample was found to be 85.83% which is just slightly lower than that of the control mortar cube sample (Table 7). The high peaks of these elements of the treated mortar cube sample is evident in Figure 18. The results reflect the impact of cementation binding in the treated mortar cube due to the addition of date palm leaves ash and fibers.

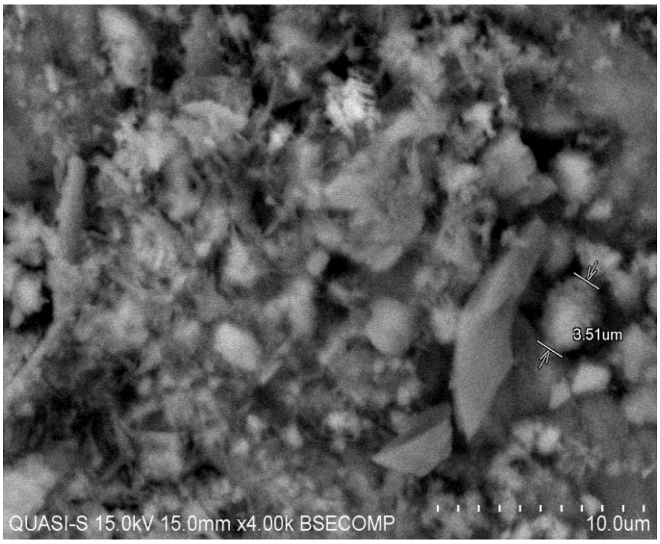

Fig. 16. Microstructure of the control mortar cube sample

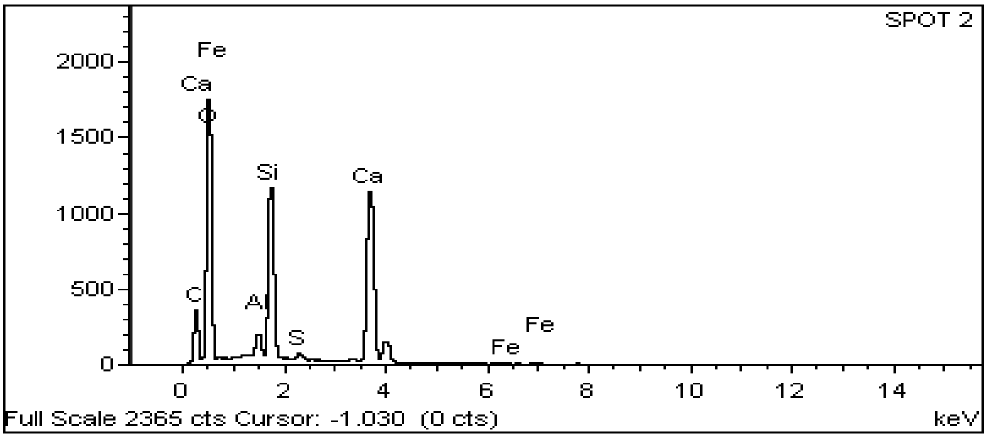

Fig. 17. Energy dispersive X-ray (EDX) result of the control mortar cube sample

Table 6
Elemental weight percentage for the chemical composition of the control mortar cube sample from energy dispersive X-ray (EDX) test

Element	Weight (%)
C	11.98
O	55.32
Al	1.23
Si	9.89
S	0.44
Ca	20.50
Fe	0.65
Total	100.00

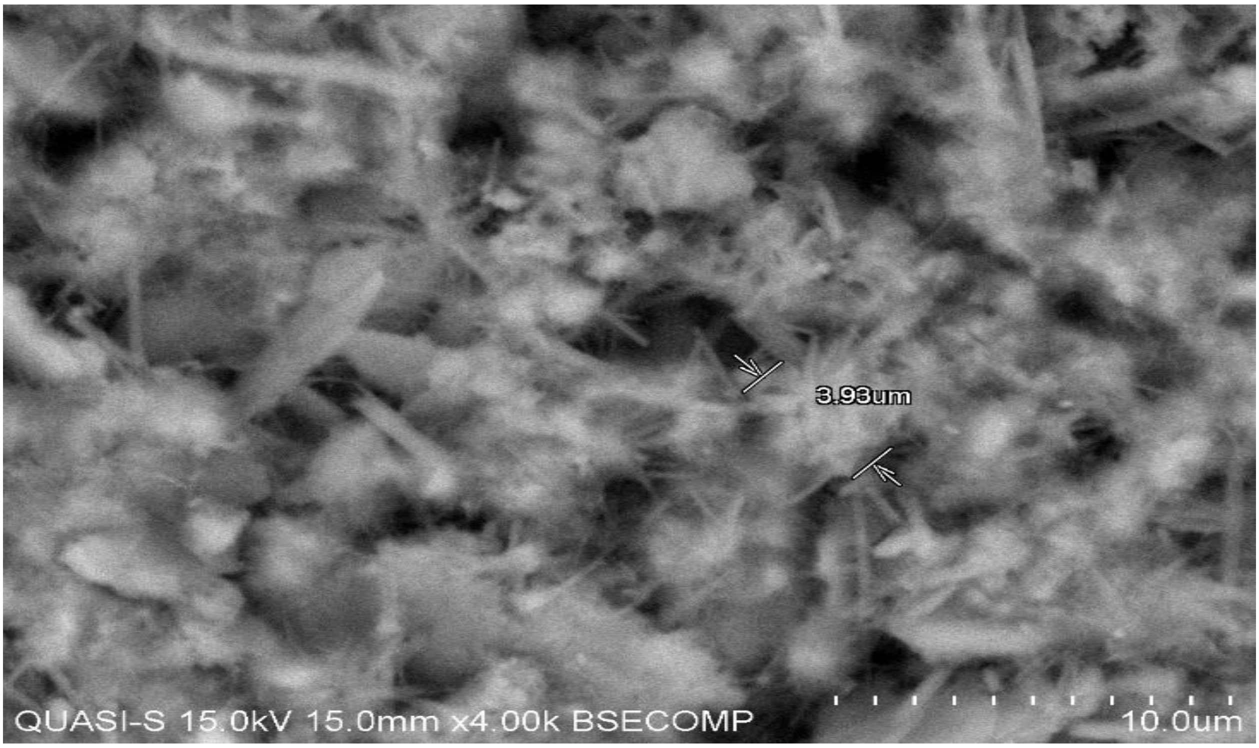

Fig. 18. Microstructure of the mortar cube sample treated with date palm leaves ash and fibers

Table 7
Sample with date palm leaves ash and fibers from energy dispersive X-ray (EDX) test

Element	Weight (%)
C	9.03
O	53.98
Mg	0.24
Al	2.69
Si	6.68
S	3.17
K	0.74
Ca	22.48
Fe	0.99
Total	100.00

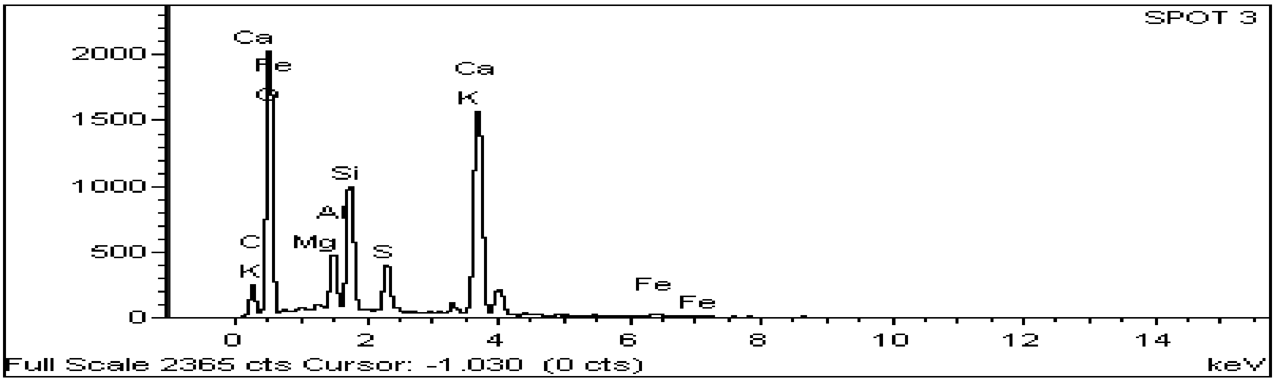

Fig. 19. Energy dispersive X-ray (EDX) result of the treated mortar cube sample with date palm leaves ash and fibers

4. Conclusions

The primary objective is to investigated application of date palm tree wastes in the form of leaf ash as SCM and date palm fibers on the mechanical properties of cement mortars. For this purpose, different mix design containing different ratios of mentioned ash and fibers are designed and experimental tests are performed on the curved specimens. Based on the experimental outcomes, the following conclusions can be drawn

i. The optimum values of 4% date palm leaf ash and 2% date palm fibers improve the engineering properties of cement, resulting in a 28-day average compressive strength of 31.3 MPa.
ii. The results showed the average UPV values for the treated mortar cubes were discovered to be 3999, 4037 and 4048 m s-1 with respect to the date palm fibers contents of 0, 1 and 2%. However, there is a drastic decrease in the average UPV values of the treated mortar cubes when the date palm fibers content was varied from 2 to 5%. The average values of UPV for the treated mortar cubes were found to be 3826, 3605 and 3502 m s-1 respectively for the date palm fibers contents of 3, 4 and 5%.
iii. The mortar cubes optimized with the DPLA date palm leaves ash and fibers were experimented to have an average 28-day compressive strength of 31.3 MPa, an average density of 1909 kg m-3, an average UPV of 4048 m s-1 and an average water absorption of 2.96%. The treated mortar beams based on the optimal mix design were discovered to have an average 28-day flexural strength of 3.32 MPa.
iv. With reference to the optimal mix design, the sample of mortar cube treated with DPLA and fibers were found to consist of 85.83% elemental weights of calcium (Ca), silicon (Si), Aluminium (Al) and oxide (O) from the outcomes of the EDX. The existence of cementation compounds inclusive of calcium trisilicate, calcium bisilicate, calcium aluminate and calcium carbonate were the reason for such a high percentage of the elements. These cementation compounds played predominant roles in the binding process, hardening mortar cubes. Proofs of the C-S-H crystals which played significant role in the binding process can be seen in the scanning electron micrograph of the sample of mortar cube optimized with DPLA date palm leaves ash and fibers.

It is recommended to extend this work to be done on mix ratios of mortars treated with other types of leaves ash such as banana leaves ash, mango leaves ash as well as guava leaves ash. This is because the leaves of those plants are widely available in natural environments and it is very resourceful to transform them into ashes for partial substitutes of cement in mortar cubes. Also, in order to improve the tensile characteristic of the mortar cubes, it is suggested for their mix ratios to incorporate other types of plant fibres such as pineapple, bamboo and oil palm fibres.

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