The Effect of Palm Oil Fuel Ash (POFA) and Steel Fiber Addition to the Mechanical Properties of Ultra High Performance Concrete (UHPC)

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Abstract Over a period of time, Ultra High Performance Concrete (UHPC) has been innovated more and more. Since it has high performance and durability, thus it is deemed to be expensive due to the material used in the recipe. High cement content due to low water cement ratio and high production cost are a few of UHPC disadvantages. Therefore, a new innovation and alternative to this solution is needed. Incorporating waste material such as Palm Oil Fuel Ash (POFA) in UHPC could be the new innovation, since POFA is abundantly available. Other than that, POFA is proven to improve conventional concrete performance, hence it could also be used to enhance UHPC. Therefore, this paper emphasizes the effect of POFA and steel fiber inclusion to the mechanical properties of UHPC using modified cube method and four-point bending test. Non Destructive Testing (NDT) using Ultrasonic Pulse Velocity (UPV) method was also conducted. The POFA percentages used were 5, 10, and 15% whereas, steel fiber percentage was only 1% by weight of OPC cement. The Test specimen dimension used was 500 mm × 100 mm × 100 mm. The testing

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S. Belayutham et al. (eds.), *Proceedings of the 5th International Conference on Sustainable Civil Engineering Structures and Construction Materials*, Lecture Notes in Civil Engineering 215, https://doi.org/10.1007/978-981-16-7924-7_26

in this study was done at a concrete age of 28 days by following the standard of the American Society of Testing and Material (ASTM). Based on the result, the addition of 15% POFA gave the highest flexural strength, while 5% POFA plus 1% steel fiber gave the highest compressive strength. UPV highest value result was obtained from 15% POFA. It is recommended that the optimum addition level of POFA is 15% for good results of both flexural and compressive strength.

Keywords Palm oil fuel ash (POFA) · Steel fiber · Ultra high performance concrete (UHPC) · Compressive strength · Flexural strength · Ultrasonic pulse velocity (UPV)

1 Introduction

Structures constructed may be made of different concrete materials and each has a certain characteristic feature. Concrete is a vital material and is often used in construction as a part of building materials. Nowadays some modern functional technologies and some innovative application methodologies have been introduced. The usage of recycled material as an alternative for originally concrete components such as aggregates, fine, and cement has resulted in many innovative works.

Thereafter another new concrete material is also widely released to give more strength to the concrete mechanical properties. Because of this, a variety of concrete types have been created that have specific requirements in terms of origin and operation for each concrete. Ultra-High-Performance Concrete (UHPC) is typically one of its types, which can be accomplished by incorporating or replacing new materials from conventional concrete materials such as chemicals or waste products.

Ultra-High-Performance Concrete (UHPC) is one of the latest building materials. Compared to ordinary concrete it has superior mechanical strength, durability, and impact resistance as the name suggests. The extremely low porosity increases the uniformity of the mixture and helps the concrete to achieve extreme properties with a more homogeneous stress distribution [1]. Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) is a composite material based on cement with distinctive properties such as compressive and flexural strength ranging from 150 to 30 MPa [2].

On the other hand, palm oil ash is one of the choices for the re-use of palm oil goods. Palm oil is derived from soil materials used in the palm oil crop. After the extraction process, earlier lunches are scorched as biomass fuel into bubble water, e.g. palm oil filaments, shells, and void organic material, which produces steam for energy and extraction in palm oil plants. The result is heavy waste factor palm oil fuel debris (POFA), which by weight is around 5%. Calcium hydroxide ($Ca(OH)_2$) can degrade the silica oxide content of POFA to concrete, and pozzolanic reactions produce more calcium silicate hydrate (C–S–H), a gel compound that decreases the calcium hydroxide measurement. Thus, this contributes to the strength of the concrete thus producing stronger and denser concrete as well as enhancing the durability of the concrete [3].

The usage of POFA as building material could improve the performance of UHPC and reduce pollution to the environment at the same time. AS palm oil production increases, the amount of POFA also increases [4]. Since the wastage is abundant, POFA is disposed of in landfill. About 5% of ash is produced from solid waste, POFA due to limited application has been disposed of in landfill and could lead to environmental problems [5]. Therefore, this research aims to use POFA to be incorporated in building materials instead of disposing of it in the landfill. This can help to improve the performance of conventional UHPC to be more sustainable and greener, as well as saving the environment from pollution.

2 Methodology

2.1 Materials

Palm Oil Fuel Ash (POFA)

The POFA was dried up in the oven for 24 h during processing to reduce the moisture content. Then, the raw POFA collection is sieved passing 212 μm to remove the husk and shell of Palm Oil and the coarse and fine particles using a Sieve Shaker or by hand. Only POFA in the form of a filler was used to give effect to the compressive strength of the concrete. Alternatively, the sieved POFA was placed inside the container and stored in a dry, airtight humidity-controlled space within the laboratory. The POFA's chemical composition used in this research is tabulated in Table 1.

Table 1 Chemical composition

Chemical Composition	% in POFA
MgO	8.1241
Al_2O_3	3.2178
SiO_2	36.2926
P_2O_5	4.0987
SO_3	1.6632
K_2O	6.8238
CaO	36.3689
TiO_2	0.2677
MnO	0.2736
Fe_2O_3	2.8696

Cement

For this study, Ordinary Portland cement (OPC) obtained from Tasek Corporation Berhad was used with the cement strength category of 42.5 N.

Aggregate Preparation

The coarse and fine aggregate were sieved manually using a sieved tool device. Coarse aggregate was collected from the retained 2 mm sieve and 10 mm passing. While for fine aggregate was taken from passing 2 mm sieve.

Admixture

Master-Glenium ACE 8538 superplasticizer was used in this research to increase the strength and durability of concrete. This was also used to boost the early strength performance of the concrete. The flow and water reduction operation of the Master-Glenium ACE 8538 allows for the effective and direct formulation of self-compacting concrete. It can be put in without vibration. It was added after the water mixing process in the concrete.

Steel Fiber

The steel fiber form used in this research was a hooked end with a fiber length of 30 mm and a diameter of 0.5 mm. The fiber aspect ratio is the ratio of its length to its diameter and the aspect ratio usually varies from 30 to 150 and here the aspect ratio of the steel fiber is 60.

2.2 Mix Proportion and Specimens

Six different batches were examined in this study. In this research, only 5% POFA was added with the inclusion of steel fiber based on the previous study done in optimizing the results. Table 2 tabulates the mix proportion of UHPC with and without the addition of POFA and steel fiber. Since there is no specific design mix for a UHPC, the design mix used in this analysis was determined by comparison to previous research measurement and formula in a series of trial mixes [6].

The prism specimens' sizes are 100 mm × 100 mm × 500 mm. Numbers of prism specimens produce: 3 for each mix.

2.3 Testing

Flexural strength

Generally, the flexural strength is known as a material property that is defined as the stress experienced within a material just before it yields. It is also known as modulus of rupture. Knowledge of a material's flexural nature is very important to understand

Table 2 Mix proportion of UHPC with additions of POFA and steel fibers

Mixes material	OPC	5% POFA	10% POFA	15% POFA	OPC + 1% SF	5% POFA + 1% SF	Unit
Coarse aggregate (800 kg/m^3)	15.6	15.6	15.6	15.6	15.6	15.6	kg
Fine aggregate (433 kg/m^3)	8.44	8.44	8.44	8.44	8.44	8.44	kg
Cement (OPC) (800 kg/m^3)	15.6	15.6	15.6	15.6	15.6	15.6	kg
Water (160 kg/m^3)	3.12	3.12	3.12	3.12	3.12	3.12	kg
Admixture (16 kg/m^3)	0.31	0.31	0.31	0.31	0.31	0.31	kg
Steel fibers (V_f = 1%)					0.156	0.156	kg
POFA		0.78	1.56	2.34		0.78	kg

the quality of structural members under different loading conditions, which in turn depends on the deciding factors such as the materials used in the preparation, the mixed model adopted, and the fiber content [2].

The flexural strength was conducted on the prism with dimensions of 100 mm × 100 mm ✕ 500 mm in a four-point bending configuration. This test measured concrete flexural strength indirectly for the prism specimen at 28 days of age according to the UHPC flexural strength ASTM C1609 standard [7] using Universal Testing Machine (UTM). The speed rate of 0.20 kN/s was applied. For this experiment, the sample was located horizontally over two touch points or support points. Two loading points were the pressure to be applied on top of the specimen before the sample failed. The four-point flexural will yield greater tension. Three samples were prepared for each mixture and the experiment was carried out for 28 days. Figure 1 shows the setting up and testing of concrete prisms.

Compressive strength

The research protocol for Concrete Compressive Strength Using Portions of Broken Beams in Flexure for this compression test was carried out in accordance with the ASTM C116-90 standard [8] using Compression Testing Machine 3000 kN. The strength was recorded for 28 days of concrete age. The average reading of the tested broken beam was recorded as the concrete strength. The load was applied at the frequency of speeds 3.0 kN/s. The ultimate strength was then recorded.

In this study, concrete compressive strength determination and assessment were performed using portions of flexure-broken beams called the Modified Cube Method. Using standard concrete specimens and procedure, the results obtained from this test are approximately equal to, and on average may be up to five percent greater than those obtained by the compressive strength test. The Modified Cube Method is

Fig. 1 Flexural test setting up (left) and sample testing (right)

performed instead of normal compressive test for the reason that to minimize wastage. Figure 2 shows the modified cube method testing on a compression machine.

Ultrasonic Pulse Velocity

Non-destructive testing (NDT) is characterized as the process in which materials, parts, or assemblies are inspected, checked, or evaluated without compromising the part or system's serviceability. NDT seeks to determine the quality and reliability of materials, parts, or assemblies without compromising the ability to fulfill their

Fig. 2 Broken beam set up in compression machine

intended functions [9]. There are several NDT methods such as Ultra Pulse Velocity (UPV) and the Rebound Hammer (RH) techniques are two of the most widely used in in-situ applications. The UPV approach is based on the measurements of the velocity of an ultrasonic pulse that an electro-acoustic transducer produces through concrete. The concrete structure can be measured alongside its thickness and any cracks or faults based on the velocity measurements [10].

Ultrasonic Pulse Velocity (UPV) testing was done with the same flexural strength measurement prism. The UPV was calculated using ASTM C 597 standard [11]. A non-destructive test was conducted for checking or evaluating the quality of UHPC concrete with the addition of POFA and steel fiber. The ultrasonic pulse velocity (UPV) test using an indirect approach is the non-destructive test tool applied in this analysis. The purpose of this test was to determine the quality of the concrete without damaging the surface and the performance. Using a transducer, the ultrasonic pulse velocity passes through the concrete with a particular length was observed as the output.

In this study, the UPV method used was an indirect method on concrete prism samples. UPV calculations were done for each concrete sample at 4 locations which were at long surfaces, and the average values were determined. UPV was measured as the ratio of path length to flight time. Figure 3 shows the prism set up for the UPV test.

Fig. 3 Concrete prism marking (left) snd UPV device calibration (right)

3 Result and Analysis

3.1 Flexural Strength Test

In addition to the compressive strength, UHPC's flexural strength was also investigated in this research with a different percentage of additional Palm Oil Fuel Ash (POFA), which is 5, 10, and 15%, and inclusions of 1% of steel fibers. The results are given in Table 3.

The maximum flexural strength in UHPC was indicated from the results of 18.988 MPa for 5% POFA addition with 1% inclusion of steel fibers and 20.085 MPa for 15 percent POFA addition respectively. The flexural strength of concrete for beams with 1% steel fibers was observed to be slightly more than from the beam without steel fibers for UHPC with an addition of 5 and 10% of POFA. The percentage increase in flexural strength for beams with 5% POFA inclusion with 1% steel fibers compared to the 5% POFA without steel fibers beams is +8.58%.

From the observations, it can be seen that the application of POFA and steel fibers can improve the flexural strength of concrete or its mechanical properties. This can be because of the steel fibers' presence by contributing its tensile strength by effectively holding the concrete mass. The steel fibers also act as anchorage between the coarse aggregate. When the binders harden, it will also enhance the anchorage points of the overall concrete structure, hence improve the flexural strength. Other than that, for specimens without steel fibers, as the POFA percentage increases, the flexural strength also increases. This is probably due to the pozzolanic reaction of POFA react with water and superplasticizer. This pozzolanic reaction could improve the bondage between aggregates since it can produce Calcium Silicate Hydrate (CSH) gel from calcium hydroxide (CaOH) produced by cement powder reaction with water.

It is therefore recommended to use steel fibers by concrete volume to get the maximum benefit in enhancing flexural strength. Since the purpose of this study is to assess the effect addition of UHPC POFA using a 4-point bending test, it can be observed that with additional POFA in cement content, the flexural strength of concrete also increases.

Table 3 Flexural strength test result (4-point bending) at 28 days age

Concrete mix	Pace rate (kN/s)	Flexural strength (MPa)
OPC	0.2	16.798
5% POFA	0.2	15.988
10% POFA	0.2	17.382
15% POFA	0.2	20.085
OPC + 1% SF	0.2	17.598
5% POFA + 1% SF	0.2	18.988

3.2 Compressive Strength Test

The findings obtained from the test performed are shown below in Table 4. The compressive strength was investigated using portion of broken beam in flexure. The compressive strength was observed for all mixes at 28 days of water curing since all tests showed a compressive strength value above 120 MPa.

The result indicates that the compressive strength appears to decrease with the addition of 10% POFA relative to other tests with additional POFA for 5 and 15% as well as the result for a concrete mix for control 1% steel fiber and additional 5% POFA with 1% steel fiber. This is probably due to the agglomeration of POFA particles in the mix. Agglomerate POFA particles happen when the mix is not blended well during preparation. Hence, this will affect the strength of the concrete produced. Agglomerate POFA will not be able to react completely since only the outer layer of the agglomerate POFA can react to produce the CSH gel. This resulted in the inner layer to be intact, hence no reaction occurs leaving the POFA to be as it is. This will influence the overall concrete strength since there will be void due the unreacted POFA powder in the structure.

The maximum compressive strength was recorded at 224.35 and 234.45 MPa with a 1% inclusion of steel fibers. The highest compressive strength value is UHPC 's concrete mixture with 5% POFA plus 1% steel fiber applied. The addition of POFA and the inclusion of steel fiber in UHPC mixes have, therefore, increased the compressive strength values over the control mix. It showed that the strength of UHPC mixes increased as the POFA percentage increased by comparing the control specimen of UHPC with the addition of 5% POFA as well as with the inclusion of steel fiber. The inclusion of steel fiber does not only improve flexural strength but also the compressive strength of concrete. This is because when applied to compressive loading, UHPC tends to burst when failing. With the steel fiber inclusion, there is some resistance to the bursting failure effect.

Table 4 Compressive strength test results at age 28 days

Concrete mix	Pace rate (kN/s)	Compressive strength (MPa)
OPC	3.0	134.50
5% POFA	3.0	184.15
10% POFA	3.0	158.30
15% POFA	3.0	189.25
OPC + 1% SF	3.0	224.35
5% POFA + 1% SF	3.0	234.45

Table 5 UPV test result (indirect method) at 28 days age

Concrete mix	Path length (m)	Ultrasonic pulse velocity (m/s)
OPC	0.2	3601.34
5% POFA	0.2	3809.67
10% POFA	0.2	3727.48
15% POFA	0.2	3830.43
OPC + 1% SF	0.2	3520.74
5% POFA + 1% SF	0.2	3563.12

3.3 Ultrasonic Pulse Velocity (UPV)

The results obtained from the test done are shown in Table 5. The results of the UPV test conducted in the laboratory, shows that there is a different value for the concrete mixtures that have POFA and steel fibers added.

The results indicate that the control sample, which is without the addition of POFA and steel fibers, has the lowest UPV value, followed by 10, 5 and 15%. Such findings showed that UHPC's compressive strength can be improved with the addition of POFA due to the POFA's fineness which can serve as a filler to close the voids. When POFA pozzolanic reactions improve filler and binder effect, it improves the concrete quality altogether. This in turn makes the concrete denser, therefore less defects such as voids. As observed in a compressive strength test where 10% addition has slightly lower strength compared to 5% addition due to the effect of POFA agglomeration. This also affects the quality of concrete as shown by the UPV test. The quality is shown to have a slight defect since there is void due to the POFA agglomeration effect during mixing.

On the other hand, the inclusion of steel fibers tends to further decrease the UPV reading as shown in the figure. Although it is proven in flexural tests and compressive tests that the inclusion of steel fiber increases the performance of concrete, UPV shows the opposite result. This is probably due to the steel fibers reflecting the ultrasonic pulse when emitted through the structure itself, hence reducing the UPV reading. However, steel fiber specimens showed an increasing result in the 5% POFA plus 1% steel fiber specimen compared to the OPC plus 1% steel fiber. This shows that the POFA once again improves the quality although the UPV reading is interfered by the presence of steel fibers.

All the specimens tested at 28 days of curing are classified in a good category using the indirect method. The classification of concrete quality can be referred to in Table 6. From the results obtained, it can be concluded that UHPC has the highest pulse velocity value with a percentage of 15% addition of POFA. The UHPC control specimen showing the lowest value of OPC.

Table 6 Classification of concrete quality [8]

Ultrasonic pulse velocity (m/s)	Quality of concrete
Above 4500	Excellent
3500–4500	Good
3000–3500	Medium
Below 3000	Poor

4 Conclusion

This study emphasizes the performance of UHPC when cement is partially replaced by POFA and the inclusion of steel fibers. The performance is measured by conducting flexural test, compressive test and ultrasonic pulse velocity test. Based on the test conducted, here are the findings.

1. In flexural tests, addition of POFA indeed improves the flexural strength of UHPC beam. The inclusion of steel fiber will further enhance the performance of UHPC with POFA.
2. In the compressive strength test, the addition of POFA does improve the compressive strength of UHPC. With the inclusion of steel fibers, the performance is improved up to 127%. However, the agglomeration of POFA particles could affect the compressive strength of UHPC since it resulted in voids inside the structure.
3. In ultrasonic pulse velocity, it is seen that POFA does improve the quality of concrete by its pozzolanic reaction, which resulted in higher pulse reading. However, the inclusion of steel fiber tends to interfere with the pulse velocity reading resulting in lower pulse reading. On the other hand, the effect of POFA agglomeration can also be seen on the UPV test since it can indicate there are defects such as voids inside the specimen.

Overall, the addition of POFA and steel fiber in this study shows promising results in increment of flexural and compressive strength as compared to conventional concrete mixture. The pozzolanic reaction of POFA plays a vital role in affecting these mechanical properties. Thus, it is recommended that the optimum addition level of POFA is 15% for good results of both flexural and compressive strength. Whereas, inclusion of steel fiber should be studied further.

Acknowledgements The authors would like to acknowledge the financial support for this study from Ministry of Higher Education—Fundamental Research Grant Scheme of 600-IRMI/FRGS 5/3 (178/2019) and other supports from Institute of Research Management & Innovation (IRMI), Institute for Infrastructure Engineering and Sustainable Management (IIESM) and School of Civil Engineering, UiTM Shah Alam, Selangor. The authors would also like to acknowledge industrial support from United Palm Oil Sdn Bhd Penang for providing POFA in this study. These supports are gratefully acknowledged.

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