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Engineering Properties of High Strength Blended Concrete Enhanced with Nano POFA

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Abstract. Global demand for cement in construction industry is expected to increase to 400% by year 2050 hence, contributes to the increasing global CO_2 emission. One of the alternative options that considered realistic to reduce usage of cement is using the blended concrete which replacing cement with other waste materials that contain cementitious properties. In this study, the engineering properties of high strength blended concrete such as workability, compressive, splitting tensile and flexural strengths were investigated. To achieve the aim, a total of 126 concrete specimens were produced that consist of concrete cubes, cylinders and prisms. Ten different mixes of blended concrete with the cement replacement of 0 to 30% of the 45-micron size of POFA and 1-3% of nano POFA. The hardened properties of blended concrete were determined at the age of 7, 28 and 90 days. The findings revealed that, the enhancement of the 2-3% of nano POFA improved the concrete workability with 5 to 10 mm increment of slump height. At all age of curing, the blended concrete consists of 10% of micro POFA and 1 to 3% of nano POFA showed a higher strength compared with the plain concrete. The highest enhancement strength of compressive, splitting tensile and flexural were 4%, 10% and 11% respectively at certain age of curing. These results showed the improvement of the engineering properties of the blended concrete with enhancement of the nano POFA.

Keywords: Blended concrete; nano POFA; engineering properties

1. Introduction

In the year of 2020, the cement production is expected to increase until the major growth in 2030 [1]. The rapid progress of the global cement consumption contributed about 5-8% of current global CO_2 emission under human activity category [2,3]. Hence, the urgency of finding the alternative options to support the sustainable development was raised by the International Energy Agency (IEA). There are several ways to reduce the impacts on the environment as reported by IEA and the realistic way is using 'blended cement'. Blended cement is the combination of the conventional cement with the supplementary cementitious materials such as fly ash, ground granulated blast slag, metakaolin and rice husk ash. These blended cements have been utilised to support this environmental issue and also can improve the engineering properties of concrete [4]. As one of the largest player in palm oil industry, Malaysia has the potential to help the cement industry by utilizing the palm oil biomass to produce blended cement. Furthermore, as reported by the National Innovation Agency Malaysia, the palm oil

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industry is now facing the difficulties in handling the waste product from the palm oil mills because the amount of the palm oil biomass is expected to increase of up to 100 million dry tons in the year of 2020. Plus, creating the negative effect on the environment due to the fact that the waste materials are dumped near the mill [5]. The potential material from the palm oil biomass to become supplementary cementitious materials is called palm oil fuel ash (POFA) that consists of 5% amount out of total palm oil biomass [6]. POFA is produced from the combustion process of palm fruit residues for generation of electricity. From the combustion process in the furnace, palm fruit fibres are conveyed to the chimney in the form of fly fuel-ash [7]. The first research on POFA started in 1990 and POFA was found to be a good SCM due to the pozzolanic reaction and hence, gives higher rate of hydration that makes the concrete denser [8,9]. The fineness effect of POFA also can vary the engineering properties due to the surface area of the particles and the nucleation site of the hydration products [10]. The micro size of POFA (45 micron) was found to give lower compressive strength at the early age and the workability of the fresh concrete also lower [8]. Therefore, to enhance the mechanical and durability properties thus, the nanoparticles was promoted [11-13]. The mechanism of improving the performance by filling the nano size pores of the cement paste, and nano silica reacts with the calcium hydroxide and generates additional C-S-H gel. The amorphous phase of C–S–H gel is the ‘‘glue” that holds concrete together and is itself a nanomaterial [14]. Nano POFA as supplementary cementitious material has been investigated by Johari et al. (2012) in producing high strength green concrete [11]. The inclusion of nano POFA showed the increase of compressive strength at the early age of water curing. However, the use of high replacement level (60%) of nano POFA was used with the loss on ignition value of 2.53%. From the review of the literature search, it is found that no study has been carried out to know the combined effect of nano and micro POFA on engineering properties of concrete. The enhancement of the low volume of nano POFA combined with the micro POFA is expected to improve the engineering properties of high strength concrete due to the cost and time consuming of producing nano POFA if the high volume is used. Therefore, the aim of this study was to determine the engineering properties of the high strength blended concrete.

2. Materials

2.1 Material properties

The cement used in the study was Type 1 Portland Cement from Cahya Mata Sarawak. The specific gravity of cement is 3.15. The chemical properties of the cement are complying with the requirements of ASTM C150-12 [15]. Palm oil fuel ash (POFA) was obtained from MJM Palm Oil Mill, Bekenu, Sarawak. The total content of oxide compounds from the silica, aluminum and iron is 69.7% and can be classified as Class C owing to the sum of silica, aluminum and iron oxide that is below 70% (ASTM C618-15 [16]. Crushed granite with size ranges from 9.5 mm to 12 mm was used. The grading of the aggregates conformed to ASTM C33-16 [17]. The aggregates used were in saturated surface dry condition. The fineness modulus, specific gravity and water absorption of the coarse aggregates used are 2.2, 2.69 and 0.5%, respectively. River sand from Miri was not in a good grading distribution. After conduction of the sieve analysis, the curve was not fall within the standard range according to ASTM C33-16 [17]. The fineness modulus was 0.99. Therefore, in this study the combination of river sand and quarry dust with weight ratio of 1:1 was used as fine aggregates. The superplasticizer used in present study was Master Glenium Ace 8538 obtained from Basf Petronas Chemicals. This type of superplasticizer contains polycarboxylate ether polymers and free of chloride that comply with the requirements of ASTM C494-16 [18].

2.1.1 Micro POFA

The raw POFA was dried for 24 hours at 100 °C to remove the moisture. The POFA was sieved through 150 μm and proceed with the first stage of grinding using high energy ball mill to produce micro POFA (45 μm). Ideally, the pot of the ball mill machine should be approx. 50% by volume full of grinding media and 25% by volume of product to be grounded [19]. The size of 45 μm POFA particles was verified until 90% of POFA passed 45 µm sieve according to ASTM C618-12 [20]. Then, the POFA was undergone the heat treatment in the furnace with the temperature at 500 °C for an hour. From the treatment, the LOI (Loss on Ignition) value was reduced from 10% to 1.8%. The test of LOI was in accordance with ASTM D7348-13 [21]. The morphology of the raw and micro POFA is shown in figure 1. It was found from the SEM analysis that the raw POFA exhibits larger particles, porous and irregular in shape (figure 1a) whereas micro POFA has spherical particles and irregular shapes and found to be more porous (figure 1b) compared with nano POFA (figure 1c).

2.1.2 Nano POFA
The micro POFA (45 µm) was ground for another 5 hours using high energy ball mill with the same ball to powder ratio [19]. To determine the fineness of the nano POFA, six samples of nano POFA were collected at different cycle of grinding. The images of nano POFA were captured using the transmission electron microscopy (TEM) as shown in figure 1.

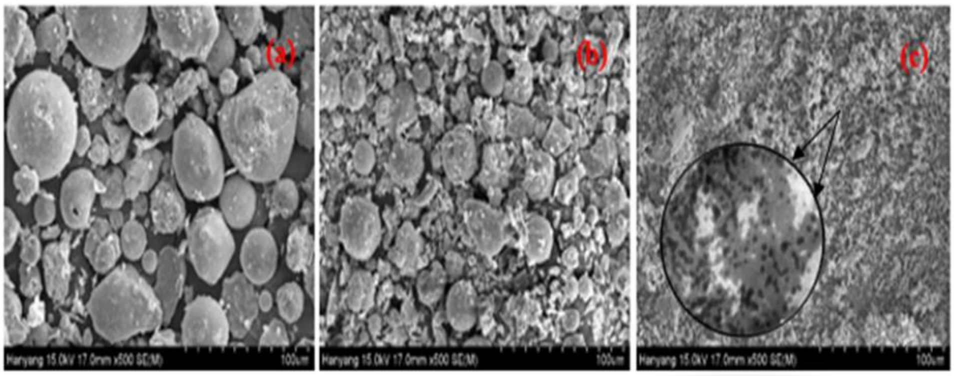

Figure 1. The morphology of (a) raw, (b) micro and (c) nano POFA.

2.2 Mix Proportion
The mix design for high strength blended concrete was designed based on ACI 211-4R guidelines [22]. From the guidelines, the mix proportion of high strength blended concrete is presented in table 1 with the percentage replacement of micro POFA (10-30%) and nano POFA (1-3%).

Table 1. Mix proportion of high performance concrete

Component	Weight
Cement	588 kg/m^3
Coarse Aggregates	1093 kg/m^3
Fine sand	268 kg/m^3
Quarry dust	268 kg/m^3
Water with superplasticizer	183 kg/m^3

3. Testing procedures

3.1 Slump test
ASTM C143-15 was followed to perform the slump test of concrete. Three layers of equal volume were filled and each layer was tamped with rod 600 mm long and 16 mm diameter [23].

3.2 Compressive strength test
ASTM C109-16 was followed to determine the compressive strength of concrete at the early age of 7, 28, and 90 days. A total of 42 cubes specimens of 100 x 100 x 100 mm in dimensions were prepared to conduct this test [24].

3.3 Indirect Tensile Strength
ASTM C496-11 was followed to determine the indirect tensile strength of concrete at the curing age of 7, 28, and 90 days. A total of 42 cylinder specimens of 100 mm diameter and 200 mm height were prepared with different percentage of micro and nano POFA [25].

3.4 Flexural Strength
ASTM C78-16 was followed to determine the flexural strength of concrete at the curing age of 7, 28, and 90 days. A total of 42 prisms specimens of 100 mm x 100 mm x 500 mm were prepared with different percentage of micro and nano POFA [26].

4. Results and Discussions

4.1 Workability
The workability of the concrete is important to ensure the ability of concrete flow during the process of pouring and placing the mix. This type of fresh properties can be obtained by performing a slump test. Based on previous studies, the workability was reported as one of the challenges faced by the researchers due to the reduction in the slump height [6,27,28]. In this study, investigation conducted on high strength blended concrete containing 10-30% of micro POFA and 1-3% inclusion of nano POFA. The slump height was obtained for all the 14 mixes as shown in figure 2. The most workable mix that provides the highest slump is M10N3. The improvement of the workability only can be seen in the concrete with 10% of micro POFA and 2-3% of nano POFA with the increment about 5 to 10 mm than that of mix 0 (plain concrete). The increase in workability can be explained from the morphology of the micro POFA that has spherical shape and porous structure. The addition of nano POFA might have filled in the porous part of the particles and provide the rolling effect during the mixing through presence of more lubricated water [29].

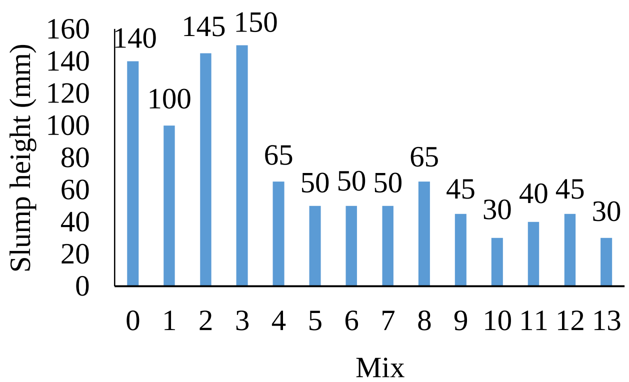

Figure 2. Slump height for each mix

4.2 Compressive strength
The compressive strength at the curing age of 7, 28 and 90 days containing 10% of micro POFA and 1 to 3% of nano POFA was observed higher than that of control concrete as presented in table 2. The incorporation of 1%, 2%, and 3% of nano POFA with 10% of micro POFA increased compressive strength by 4%, 2.9% and 0 % at 7 days, by 2.3%, 0.5 % and 3.6% at 28 days, and 3.2%, 3.2% and 3.7 % at 90 days, respectively. The increasing replacement of micro POFA was observed to decrease the

compressive strength at all ages. The decrease of the strength due to the high amount of micro POFA which contains porous particles resulting in more absorption of the water content which supposed needed for the cement hydration. The mix with the 10% of micro POFA and 1-2% of nano POFA showed the highest compressive strength at the early age. The improvement in the early age of curing can be well explained by the existence of the silica particles at the early age that make the process of generation of the C-S-H gels fast. Hence, the concrete gains the maturity earlier [30].

Table 2. Compressive strength for each mix at different curing age

Mix	Compressive Strength (MPa)		
	7 days	28 days	90 days
0	47.3	61.9	64.8
1	49.2	63.3	66.9
2	48.7	62.2	66.9
3	47.3	64.1	67.2
4	44.8	53.0	59.9
5	42.3	54.3	60.4
6	42.8	54.7	60.4
7	42.2	54.3	60.0
8	42.7	54.7	60.0
9	42.7	54.7	60.0
10	48.0	55.0	64.3
11	34.7	43.3	52.2
12	37.0	45.5	52.4
13	39.5	50.0	56.0

4.3 Splitting Tensile Strength

For the splitting tensile strength test, the higher strength was observed from mixes 2 and 3 at the early age, mixes 3 and 5 to 9 at the age of 28 days and mix 2 at the later age. The results are given in table 3. In the early age of curing, the high strength blended concrete containing 10% of micro POFA with 2 to 3% of nano POFA increased the flexural strength by 10%. This shows the earlier maturity of the concrete due to the higher quantity of strengthening gel in the nano POFA hence, densely packed the concrete at the early age. At the later age, it showed the same pattern which the higher splitting tensile strength by 4.3%, 6.5% and 2.2% can be observed from the mix containing 10% of micro POFA and 1 to 3% of nano POFA, respectively. The increase amount of micro POFA was observed to reduce the splitting tensile strength. However, different patterns were observed in this test at the age of 28 days. The increment of splitting tensile strength compared with the plain concrete occurred also in the mix with the 20% of micro POFA and 2 to 3% of nano POFA. This increment about 10% could be related with the formation of the C-S-H gel that resulting in the packed microstructure of the concrete. Theoretically, the tensile strength development should provide the same pattern but much lower than the compressive strength. However, the different pattern of these results can be related to the relationship factors of both strengths such as age of concrete, type of aggregates, particle size distribution and curing process [31].

Table 3. Splitting tensile strength for each mix at different curing age

Mix	Splitting Tensile Strength (MPa)		
	7 days	28 days	90 days
0	2.9	3.1	4.6
1	2.9	3.2	4.8
2	3.2	3.3	4.9
3	3.2	3.4	4.7
4	2.8	3.1	4.0
5	2.9	3.4	4.5
6	2.9	3.4	4.4
7	2.9	3.4	4.5
8	2.9	3.4	4.5
9	2.9	3.4	4.4
10	2.9	3.2	4.6
11	2.7	2.8	4.0
12	2.4	2.9	4.3
13	2.1	3.0	4.5

4.4 Flexural Strength

The flexural strength at all ages of concrete are given in table 4. The increment strength of the flexural strength can be observed from the mix containing 10% of micro POFA with addition of 1%, 2%, 3% of nano POFA by 4.3%, 3.3%, 1% at 7 days, 8%, 5%, 1% at 28 days, 11%, 10%, 3% at 90 days, respectively. As presented from the previous results, the flexural strength also showed the same pattern from the decrement of the flexural strength as the micro POFA increases except at the later age (90 days). The concrete mix incorporating 20% of micro POFA and 1 to 3 % of nano POFA showed the higher strength with maximum 8% than plain concrete. The strength increment of the flexural strength could have attributed to the less porous microstructure of micro POFA particles in the concrete mix because only 10% of cement was replaced with micro POFA. In addition, the higher fineness of nano POFA also could enhance the reactivity of the bonding in the cement paste.

5. Conclusions

The incorporation of 10% of micro POFA with enhancement of 2 to 3% of nano POFA showed the best performance by improving the workability of the high strength concrete by increasing about 5-10 mm of slump height. The higher percentage of micro POFA incorporation with nano POFA weakened the workability of the concrete due to the higher amount of the porous micro POFA in the mix. The beneficiary effect of nano POFA also can be seen in enhancement of compressive, splitting tensile and flexural strengths. The replacement of 10% of micro POFA and 1 to 3% of nano POFA contributed to higher strength than that of plain concrete. The highest strength of compressive, splitting tensile and flexural were 4%, 10% and 11%, respectively at certain age of curing. The study revealed that lower volume of the nano POFA with combination of the micro POFA can advantageously affect the engineering properties of the high strength concrete.

Table 4. Flexural strength for each mix at different curing age

Mix	Flexural Strength (MPa)		
	7 days	28 days	90 days
0	9.2	9.9	10.1
1	9.6	10.7	11.3
2	9.5	10.4	11.1
3	9.3	10.0	10.4
4	9.2	9.3	10.8
5	9.1	9.5	10.9
6	9.1	9.5	10.8
7	9.2	9.5	10.9
8	9.2	9.5	10.9
9	9.1	9.4	10.9
10	9.1	9.6	10.9
11	8.5	8.7	10.0
12	8.5	8.7	10.1
13	8.3	8.9	10.1

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