Strength Performance of Oil Palm Shell Lightweight Aggregate Concrete

Zalipah Jamellodin1*, Lam Phooi Sim1, Huang Chai Qing1, Suraya Hani Adnan2, Norhafizah Salleh1 and Noor Azlina Abdul Hamid1

1 Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Johor.
2 Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Johor.
*Corresponding author: zalipah@uthm.edu.my

Abstract. The concrete consumption that is high in the construction industry had resulted in uncontrolled aggregates exploitation. The extraction of these natural resources has raised great environment concerns that the use of waste materials as replacement of aggregates is proposed. Oil palm shell lightweight aggregate concrete (OPS LWAC) is produced by full replacement of oil palm shell (OPS) to coarse aggregate. OPS is the lightweight aggregates that potentially produce lightweight aggregate concrete (LWAC). Palm oil fuel ash (POFA) is also the by-product of the palm oil industry that can be utilized to partially replace the fine aggregates. The objective of this study is to investigate the effect of POFA as partial fine aggregates replacement on density, compressive and tensile strength of OPS LWAC and to determine the optimum replacement percentage of fine aggregates with POFA. The control mixes were prepared with 100% OPC in the concrete while modified mixes contained various percentages of POFA, which were 5%, 10%, 15% and 20% as the replacement of fine aggregate. The specimens of cubes sizes 100 mm x 100 mm x 100 mm and cylindrical specimens with diameter of 100 mm and height of 200 mm were prepared and tested. The concrete mixtures were mixed according to the Department of Environment (DoE) method followed by the trial mixed. Mixes with 10% replacement of POFA to fine aggregate obtained the highest compressive strength and tensile splitting tensile strength which were 26.3 MPa and 2.37 MPa respectively. The property of POFA plays a role in the concrete strength determination. The higher replacement percentages resulted in lower density of OPS LWAC.

1. Introduction

Concrete is strong, hard building material that is commonly and widely used in field of construction industry. In the worldwide, the annual consumption of concrete exceeds 25 billion tones [1]. This heterogeneous consists aggregates which account for around 75% of concrete volume and cement which is in the range of 7-14% [2]. The uncontrolled natural fine aggregates mining had raised environment concerned [3]. The extraction of the earth nature by concrete production industry had transformed the beauty green hill land to a bared landscape, worsening the risk of soil erosion [4].

The application and adoption of the sustainable construction had become a major concerned in Malaysia recently which had been an issue under the Malaysian Construction Industry Master Plan (2005-2015). The concept of sustainable in building and construction stressed on the limited resources initially, together with the emphasizing of the way to minimize the impact on natural environment. The concept that namely environmental sustainability is related with the exploitation of natural resources [5]. The use of resources and building materials in an effective way, as well as reduce, reuse and recycle
materials is among the criteria of sustainable construction [6].

Oil palm shell concrete, which is one of the types of concrete, is formed when the coarse aggregates in the concrete is replaced with oil palm shell (OPS). OPS was considered as one of the possible lightweight aggregates (LWA) in the production of lightweight aggregate concrete (LWAC) [7]. Malaysia together with Indonesia is the producing countries of palm oil that contribute more than 80% of global supply of palm oil, which also take up 34% of vegetable oils global consumption in year 2018 [8]. Besides, palm oil fuel ash (POFA) is one of the solid wastes from palm oil mill industry that is created as by-products which is obtained from the burning of palm oil fibre, kernels, empty fruit bunches, and shells in electricity plant to produce energy [9].

The production of POFA has linked to the environmental issues with their effects on specific facets of life. The widespread of the solid waste materials from the field of agriculture and industrial had partially caused the occurrence of global warming [10]. The lightweight of the POFA allow the wind to blown them away and worsen the environment. There is a need to reduce the disposal of the wastes to the environment. It is a practicable alternative that utilize the industry waste as mixing ingredient, thus it can be utilized to partially replace fine aggregates in the production of concrete [11-12]. The integration of this by-products in concrete production reduce the waste being dumped in landfill. The availability of the natural river sand would be preserved too as the consumption had been greatly reduced if POFA is used as mixing ingredients to partially replace the natural sand in concrete production. Thus, this paper discussed the strength performance when the fine aggregates of the OPS LWAC is partially replaced by different percentages of POFA and the optimum percentage of the replacement.

The OPS is classified as lightweight concrete in the production of structural LWAC [13]. The large amounts of OPS that produced ends up being stockpiled behind the oil palm mill, requires long time to degrade naturally. The issue then leads to environmental pollution and unpleasant sight of view. Thus, being a readily available and waste reused material that can be afforded by local contractors, the OPS is utilized as lightweight aggregates in the formation of OPS LWAC [14].

The preservation of the natural aggregate is achieved for a sustainable environment with the application of OPS LWAC. This type of concrete possesses normal compressive strength. However, the strength is enhanced when the oil palm shell with large sizes are segregated and crushed. This is due to the crushed state of OPS is strong and there is great bonding with hardened paste of cement. There are thus the chances for OPS LWAC to be developed into strengthened lightweight concrete [15].

According to Muthusamy et al. [16], the OPS aggregate determines the pattern of failure of concrete at early ages while at ages later, the bonding between the OPS and the paste is strengthened. The compressive strength of OPS concrete is observed in the range of 13-22 MPa. It is found in this research that the high incorporation level of OPS shows decreased compressive. The property of OPS aggregates with smooth texture of surface is the factor that causes weaker interfacial zone in the mix and reduce in strength.

According to Maghfouri, Shafigh and Aslam [17], the strength of compressive at maximum for the LWC containing OPS is about 25-35 MPa which satisfy the typical compressive strength of structural LWC that show the range of 20-35 MPa. The porous surface of the OPS results in the high waters absorption. The organic nature of this solid waste influence on the level of handling of the concrete and reduction in the slump value. The tensile strength of OPS concrete is in average of 8% of corresponding cube mould compressive strength and within the range of 1.1 to 2.4 MPa. POFA is the products from the burning of the waste products from palm oil industry to generation of electricity and to ensure the extraction events in the palm oil factory. These wastes then act as biomass fuel to boil the water and produce steam. POFA account five percent by weight from the solid wastes [18]. These greyish materials turn darker with greater amounts of unburnt carbon inside the content. POFA mostly appears as spherical size with its electron micrograph is shown in Figure 1 [19].
The properties of POFA enables it to be utilized for the purpose of construction. According to Mohammadhosseini, Awal and Sam [20], POFA has specific gravity in the range of 1.78 - 1.97. When the POFA is ground, the particle sizes of the POFA decrease, cause reduction in porosity and obtain specific gravity in the range of 2.22 - 2.78. Besides, fineness of POFA is a vital property that speed up the hydration process as well as assisting in pozzolanic reaction. The fineness is normally indicated through specific surface area in the units of m²/kg or through the percent of mass passing through 45 µm sieve. Furthermore, the carbon content in the POFA becomes low when the burning temperature is high, thus is light grey in colour. The chemical composition of the POFA allows the pozzolanic reaction, effect of nucleation and packing to occur [21]. When the cement reacts with water, hydration reaction starts and a by-product Calcium Hydroxide, Ca(OH)₂ is being produced. The POFA which high in the constituent of SiO₂ and Al₂O₃ then can react with Ca(OH)₂ to begin the pozzolanic reaction. The reaction produces a greater amount of calcium silicate hydrate gel (C-S-H). The continuous supply of moisture during pozzolanic reaction enables the production of secondary C-H-S gel. The gel then fills the pores of the concrete [11].

For the filling or packing effect, it is the densification process by the small particles to fill in the voids of the paste. The nucleation effect is the phenomenon of tiny particles are segregate in the cement paste to accelerate the reactions [22].

POFA is beneficial to be utilized by increasing the concrete properties, potentially acting as a pozzolanic material [23]. Safiuddin, Salam and Jumaat [21] had proposed that 20-30% of replacement level of POFA is the optimum level. Fineness of POFA allows it has the great ability of micro filling and improved pozzolanic reactions, thus assists and strengthened the concrete compressive strength. The high fineness of POFA is later confirmed in the studied Sata, Jaturapitakkul and Rattanashotinunt [19] that fine ground POFA is suitable to be the replacement materials for cement at 10% level to obtain favourable compressive strength. The cementitious property of POFA with replacement of cement at 20% had improved the compressive strength of the concrete when it is comparing to the specimen with no composition of POFA [24].

The enhancement of concrete not only showed in the replacement with cement but also fine aggregates. The research outlined by Ahmad et al. [25] showed that with 6% replacement level of POFA with fine aggregates, the strength is enhanced as the filling effect plays its role in filling the pores which existed on the internal concrete structure [25]. When the POFA is incorporating in the aerated concrete at the rate of 30% as to replace partially to fine aggregates, the increment in the concrete strength showed that the properties of the materials are suitable to be used in the production of concrete [11]. The replacement of POFA with sand at the ratio of 10% showed increased in the concrete strength [12, 26].

The application of POFA had caused effects to the workability of concrete in fresh state. Muthusamy et al [16] discovered in their research that the best portion of POFA used in OPS LWAC is in the range of 20-30% for cement replacement. The 50% of percentage replacement produced driest mix with greatest slump value. However, the porous property of POFA causes the larger water absorption which leads to concrete segregation when using more than the optimum portion of POFA. This is due to the low cohesion of the mixture which then results in the collapse of slump [16]. Besides, the research
proposed Saffuan et al. [26] stated that unground POFA with replacement for river sand at the level of 8% does not change the workability much but when the level reached 10%, the workability is reduced as the porosity of the POFA that requires higher amount of water in the mixtures.

Density is the parameter that shows the mass of concrete per unit volume. It is a physical property for the verification of the category of concrete whether to be categorized as lightweight concrete. As the fine aggregates of OPS concrete are partially substituted by these waste products produced from burning of oil palm products, the density of concrete is further reduced. The waste materials content which is lighter in weight is increased for the use of OPS and POFA in the production of concrete. The usage of 0% to 50% of POFA results in the reduction of density to about 21% to 27% than other concrete type [27].

2. Materials and Methods
The mixing materials used in the production of oil palm shell lightweight aggregate concrete (OPS LWAC) are ordinary Portland cement (OPC), water, fine aggregates, palm oil fuel ash (POFA) and oil palm shell (OPS). The OPS and POFA used in this research were obtained from Ban Dung Palm Oil Industries Sdn. Bhd, which is in Pagoh, Johor. At the laboratory, the foreign particles in the POFA were removed and to be used as partial fine aggregate replacement in OPS LWAC.

The two types of mixes used included the control specimen of Grade 25 prepared by using full proportion of fine aggregates and the modified specimen by varying the content of POFA to replace the fine aggregates from 5% until 20% with interval 5%. While 100% coarse aggregate is replaced with OPS depending on its volume. The designed concrete mix was calculated by Design of Experiment (DOE) method and optimized by using trial mixes. The mix proportion used in the production of OPS LWAC containing POFA as partial fine aggregate replacement is shown in Table 1.

| Specimen | Percentage of POFA (%) | POFA (kg) | Fine Aggregate (kg) | OPC (kg) | Water (kg or litre) | OPS (kg) |
|----------|------------------------|-----------|---------------------|----------|------------------|----------|
| CP0      | 0                      | 0         | 11.00               | 7.4      | 3.48             | 3.3      |
| CP5      | 5                      | 0.37      | 10.45               | 7.4      | 3.48             | 3.3      |
| CP10     | 10                     | 0.73      | 9.90                | 7.4      | 3.48             | 3.3      |
| CP15     | 15                     | 1.10      | 9.35                | 7.4      | 3.48             | 3.3      |
| CP20     | 20                     | 1.46      | 8.80                | 7.4      | 3.48             | 3.3      |

The specimens were prepared with 30 pcs in cube size and 15 pcs in cylinder. Then all the casted specimens were demoulded in the next day. All specimens are cured in water for 7 and 28 days. Before the test is conducted. Specimens were weighed before testing was conducted for density according to the procedure in BS EN 12390-7:2019 [28]. The compressive strength test was conducted for the cube specimens with curing age of 7 and 28 days according to BS EN 12390-3: 2019 [29] while tensile splitting strength test was conducted for the cylinder specimens according to BS 12390-6: 2009 [30]. Figure 2 shows the tensile splitting test for control specimen CPO for 28 days curing.
3. Results and Discussions

3.1 Concrete Density

Figure 3 shows the graph of density of OPS LWAC when the fine aggregates were partially replaced by POFA at different replacement levels, which are 0%, 5%, 10%, 15% and 20%. The density was determined at the curing age of concrete at 7 days and 28 days. From the chart, the range of density at curing age of 7 days lies from 1660-1880 kg/m$^3$ while at the curing age of 28 days, the density is in the range of 1730-1920 kg/m$^3$. The concrete is classified as lightweight concrete when the freshly mixed concrete having the density not more than 2000 kg/m$^3$ [13]. Since the density is not more than 2000kg/m$^3$, thus it can be categorized as lightweight concrete.

As the replacement level of POFA increased, which the highest level of replacement reached 20%, the density of concrete shows decreased trend. This is because the density of POFA, which is 966 kg/m$^3$ is less than the density of fine aggregate, which is 1464 kg/m$^3$. Thus, the higher the replacement level of POFA to fine aggregates, the lesser density of the OPS LWAC obtained.

The utilization of OPS and POFA in the mixing of concrete enables the concretes to have lower density which aligns with the concept of mostly structural designs, that is, to be as lightweight as
possible. The lightweight of concrete helps reduces dead weight and this can lead to high ratio of strength to weight, improved sound and heat insulation and better fire resistance. However, the adverse side of using lightweight concrete is, it has restricted mechanical properties and higher usage of cement to achieve the concrete strength [17].

3.2 Compressive Strength

Figure 4 shows the graph that presents the compressive strength of various replacement level of mix design of OPS LWAC at the curing age of 7 days and 28 days. The concrete strength can be almost fully achieved at the curing age of 28 days. The testing was conducted according to the standard and the design characteristics strength for the concrete is specified as 25 MPa. Since the average compressive strength of control specimen, that is, the specimen with 0% replacement level of POFA to fine aggregates is 25.3 MPa, thus the design strength of 25 MPa is achieved.

![Compressive Strength Graph](image.png)

Figure 4. Compressive strength for various mix design of OPS LWAC at curing age of 7 days and 28 days.

The utilization of POFA to replace the fine aggregate in OPS LWAC shows various compressive strengths. The strength for 7 days and 28 days both show a trend that the strength increases for 5% and 10% replacement percentage and drops at 15% and 20% replacement percentage. The strengths achieved at replacement of fine aggregate at 15% and 20% at 28 days curing age are lower than the characteristics design strength, which are 24.7 MPa and 22.3 MPa respectively.

The highest compressive strength achieved is at the replacement percentage of 10%, which is 26.3 MPa at 28 days curing age. The results probably due to the physical property of the POFA. The POFA which as the fine particles, act as filler that occupied the voids that exists between the aggregates so that the internal surface of concrete becomes more packed and eventually enhances the strength without the reaction with chemicals. The replacement of POFA increases the packing density that cause in the densification of microstructure of the concrete [11].

Besides, one of the reasons that the occurrence of 10% of POFA that exhibits 3.95% higher compressive strength than control specimens, is probably due to the pozzolanic property of POFA. When the content of Silica from POFA reacts with the Calcium Hydroxide, the by-product from hydration process of cement, the secondary calcium silicate hydrate gels (C-S-H) is produced, which helps in the development and improvement of concrete strength. The reaction occurred that reduces the calcium hydroxide content also assists to increase durability and strength of concrete [26]. Furthermore, the curing process that took place in water tank ensured the continuous hydration that enables the higher production of C-S-H gel [11].

The decreased in the compressive strength occurred when the replacement percentages of fine aggregates by POFA were at 15% and 20%, might due to the insufficient amount of sand that results the
concrete mixtures becomes harsh and leads to segregation. Besides, the increasing uses of POFA increases the fineness physically, as well as the surface area of the particles, this will cause the concrete mixtures to require higher water demand. However, the constant water-cement ratio will result in the deficiency of water for completion of cement hydration process. As a result, the amount of Calcium Hydroxide produced become less, thus lesser secondary C-S-H gels will be produced in the strength development of concrete [26].

3.3 Splitting Tensile Strength
Figures 5 shows the splitting tensile strength achieved at curing age of 28 days for each percentage of replacement of fine aggregates by POFA. The control specimen achieved the average strength of 2.30 MPa, and the strength continues to increase for 5% and 10% replacement level, which are 2.33 MPa and 2.37 MPa respectively. The strength drops when the percentages of replacement reach 15% and 20%, which are 2.27 MPa and 2.13 MPa respectively. The optimum mix design is CP10, which is when the 10% of fine aggregates are replaced by POFA.

![Figure 5. Splitting tensile strength for various mix design of OPS LWAC at curing age of 28 days.](image)

The graph shows similar trend as the compressive strength achieved. The results for splitting tensile test are also almost aligned with the equation proposed for the relationship of splitting tensile strength from cube compressive strength when LWAC composting of pozzolanic substances. The equation is shown below while $F_t$ represents splitting tensile strength while $f_{cu}$ represents cube compressive strength [17].

$$F_t = 0.27(f_{cu})^{1/3}$$  \hspace{1cm} (1)

4. Conclusions
OPS and palm oil fuel ash POFA are the wastes that can be utilized as the replacement materials in the production of OPS LWAC. The application of the concrete enables the sustainable construction to be achieved meanwhile to satisfy and fulfil the need of concrete in construction. The depletion of fine and coarse aggregates can be reduced by using these alternative materials. The use of POFA as replacement of fine aggregates reduces the environmental issue caused. Thus, it is necessary to determine the density, as well as the compressive and tensile splitting strength of OPS LWAC when POFA partially replace the fine aggregates.

The density of OPS LWAC at curing age of 28 days with different mix design proposed range about 1730-1920 kg/m$^3$, thus it is categorized as LWAC. The control specimen of concrete meet the target strength of 25 MPa in compressive strength test, thus it can be utilised as the structural lightweight concrete. The partially replacement of fine aggregates with POFA shows increased compressive and
splitting tensile strength of concrete in the percentage replacement of 5% and 10%. The replacement level shows optimum at 10%, the further 15% and 20% of replacement result in the decreased of compressive and splitting tensile strength.

It is recommended to conduct the curing process in water to provide continuous hydration of process to take place. The hydration rate and the reactions of pozzolanic can be improved when higher fineness of particles used. Besides, the porosity property of the POFA can be reduced as well. The absorption capacity of OPS and POFA is larger than coarse aggregate and fine aggregates, the increment of water should be provided in the concrete mixes to allow complete hydration of cement in all mixes. The OPS LWAC should be evaluated thoroughly in terms of the long-term behaviour and durability performance. The optimum percentage of replacement in the OPS LWAC that is tested in small scales in the laboratory should be evaluated in large scales tests on field to investigate the performance.

5. References

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