Artificial lightweight aggregate from palm oil fuel ash (POFA) and water treatment waste

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Abstract. In concrete production, a large amount of cement and aggregate are consumed annually by the construction industry. There are approximately 10 million tonnes of natural aggregate consumption for the concrete since the aggregate occupy 70 % of the overall volume. To deal with the issue on the excessive of natural aggregate exploitation, an alternative and innovative solution is by developing energy efficient artificial aggregate that are incorporated with waste products. This study examines the properties of artificial aggregate containing palm oil fuel ash (POFA) and silt from water treatment sludge. A total of five mixes containing POFA at 10, 20, 30, 40 and 50% by weight of silt have been prepared for this study. An alkaline activator and lime were added to the mixes at a dosage of 5% and 25% to binder respectively. The physical and mechanical properties have been tested at the ages of 7, 14 and 28. The mechanical properties are investigated based on the individual crushing strength and impact value. The results shown that the lightweight aggregate made of silt and POFA as based material has a potential in replacing the natural aggregate in concrete production.

1. Introduction

Concrete is known as extraordinary structural construction material or as one of the composite material for construction used [1]. According to Brunauer and Copeland [2], concrete will be continued dominant as construction material with the civilization and development of countries. Annually, there is 8 to 12 million tonnes of natural aggregates consumption for the concrete since the aggregate occupy 70 % to the overall volume [3]. As the result, the high demand of natural aggregates have caused irreparable damage to the environment and reduced sharply for the resources of natural aggregate [4]. Therefore, new sustainable development solutions are required to minimise the general natural resources consumption, environmental pollution and the large amount of the industrial waste production from difference sectors [5]. According to Mo et al [6], investigation on the convection of recycled or waste product into potential construction materials has motivated and encouraged researchers to fulfil the sustainable development. There are researchers incorporated with industrial construction in investigation of the sustainable artificial aggregate production. Report on the performance of aggregate made from fly ash and clay as raw materials shows it has large potential use as coarse aggregate for concrete [7]. Bhatty and Reid [8] investigated the production of lightweight artificial aggregate from sewage sludge which sintered at difference temperature will result several of strength. Biernacki et al [9] determined the potential of coal fly ash as pellet in concrete based on the properties result.

According to Yap et al. [10], there is 0.06 million tonnes of palm oil fuel ash (POFA) is produced every year in Malaysia which generates the increasing trend for the wastage problem. The discharge of this high organic waste will cause negative impact to the environment. Furthermore, the rapid growth of population has increased the demand on the water supply. Typically, water treatment plant will produce almost hundred thousand tonnes of sludge per year [11]. In order to deal with the declination of natural resources and waste disposal problem, the construction industries figure out the methods of substituting recycled materials used as lightweight aggregates to replace the natural aggregate in concrete production. There are researches demonstrated that artificial aggregate made from municipal waste can provide the satisfactory result as the coarse aggregates in concrete [12].

The use of the lightweight artificial aggregate as the construction materials will provide functional and economic advantages in future. Furthermore, the properties of low density not only reduce its self-weight, but also the construction cost [13]. Therefore, this research aims to study the properties of POFA and silt as artificial aggregate. This study involves the primary study on the raw materials used and also the laboratory test according to standard method. The optimum mix for the artificial aggregate is defined to perform the high strength in replacing the natural aggregate in concrete.

2. Experimental Details

2.1 Raw materials

Production of artificial aggregates involves five materials such as silt, POFA, lime, alkaline activator and water. Silt is grained from dry sludge and sieved via 300μm. POFA is obtained from local palm oil mill sieved through a 300μm sieve to remove all the unwanted impurities particles and unburned bigger carbon. Both materials are stored in airtight container for used. The alkaline activator used for the artificial aggregate production in this research is the combination mixture of the sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).The NaOH with concentration of 14M is prepared by dissolving pellets in distilled water one day before mixing [14].

2.2 Charateristics of materials

The chemical compostion of silt and POFA are determined by X-ray fluorescence (XRF), whereas the crystalline phases are determined by X-ray diffraction (XRD) which operated at 40 kV and Cu-Kα wavelength and 2θ range from 10∘ to 70∘. Table 1 shows the highest percentage content present in both silt and POFA is silicate oxide which are 43.26% and 54.98% respectively. High content of SiO_2 will influence the pozzalanic reaction in the mixture when it reacts with the free lime in order to produce more calcium silicate hydrate gels and enhance the bond within mixture [15].

Table 1. XRF analysis for major oxides in silt and POFA

Compound	Silt (%)	POFA (%)
SiO_2	43.26	54.98
TiO_2	0.61	0.19
Al_2O_3	28.50	3.27
Fe_2O_3 (t)	6.98	3.96
MnO	0.03	0.14
MgO	0.44	5.02
CaO	0.14	10.77
Na_2O	bdl[a]	0.40
K_2O	1.70	9.50
P_2O_5	0.22	5.64
SO_3	n.d.[b]	4.09
Cl	n.d.[b]	1.78

[a] below detection limit

[b] not detected

2.3 Preparation and manufacture of artificial aggregate
A total of 5 difference proportions of raw material mixtures for the artificial aggregate production are shown in Table 2, which contain POFA at 10, 20, 30, 40 and 50% by weight. The ratio of Na_2SiO_3/NaOH was kept constant at 2.5 for all the mixtures with additional of lime [16, 17]. The water is added into the mixtures to ensure there is homogenous and uniformly mix.

Table 2. Proportion mix for artificial aggregates

Mix	POFA (%)	Silt (%)	POFA (g)	Silt (g)	Lime (g)	Alkaline Activator (g)	
						Na_2SiO_3	NaOH (Solution)
S50P50	50	50	500	500	125	17.9	7.1
S60P40	40	60	400	600	100	14.3	5.7
S70P30	30	70	300	700	75	10.7	4.3
S80P20	20	80	200	800	50	7.1	2.9
S90P10	10	90	100	900	25	3.6	1.4

The round shaped of the manufactured artificial aggregate should be firmly compacted to avoid contain any voids. Fresh pellets produced are then allowed to air dry. The aggregates produced are vary in term of colour from dark grey to brown depends on the mix proportions as shown in Figure 1.
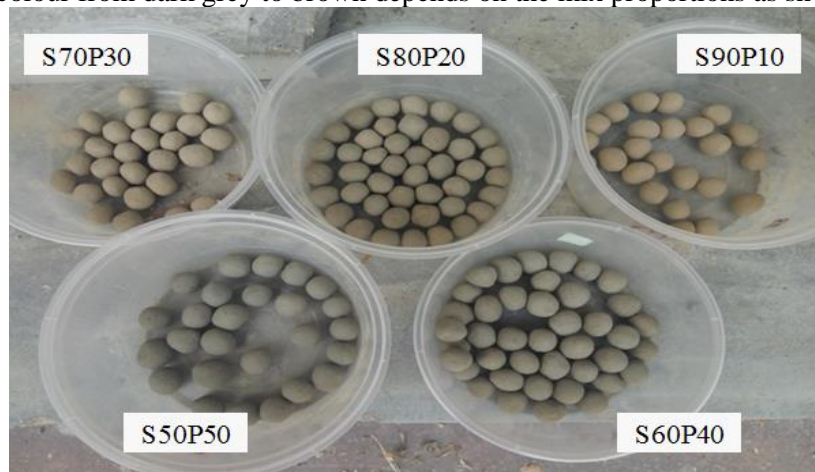

Figure 1: Colour intensity for artificial aggregate in difference mix proportion

2.4 Experimental Testing of artificial aggregate
Specific gravity (apparent, oven dry, saturated surface-dried mass) and water absorption of the artificial aggregates are determined based on the standard BS 812: Part 2 (1995) [13]. The water absorption was determined using the following equation:

$$\text{Water absorption capacity, AC} = (W_{SSD} - W_{OD}) / W_{OD} \text{ X } 100\% \tag{1}$$

Crushing strength of individual aggregates is determined using California Bearing Ratio test by placing the pellet for an average of 10 pellets between two parallel plates and force until it cracks. Strength index is calculated based on the formulae below [18]:

$$\sigma = 2.8 \, P/\pi X^2 \tag{2}$$

where σ is the individual crushing strength of pellet, P is the fracture load and X is the distance between loading points.

Aggregate impact value (AIV) represents the strength for aggregate. The AIV was determined according to BS 812: Part 112 (1990) [19]. The AIV was calculated using the following equation:

$$AVI = \frac{Weight\ of\ specimen\ pass\ through\ 2.36\ mm\ sieve}{Total\ weight\ of\ specimen} \ x100\% \qquad (3)$$

3. Result and Discussion

3.1 Specific gravity

Specific gravity is essential to define the property of aggregates used in concrete mix. The specific gravity is increasing gradually as the proportion of silt content in the mixture increases. Figure 2 shows the result of specific gravity for artificial aggregates. The highest specific gravity is S90P10 (1.51) where the lowest is S5P50 (1.42). This is because increase of the silt proportion in the mixture will enhance the densification of artificial aggregate since the specific gravity of the silt is 2.51 heavier than POFA which is 1.90. Overall, the specific gravity of artificial aggregates is low compared to natural aggregate (2.77) and the average is only about 55% to the coarse aggregates.
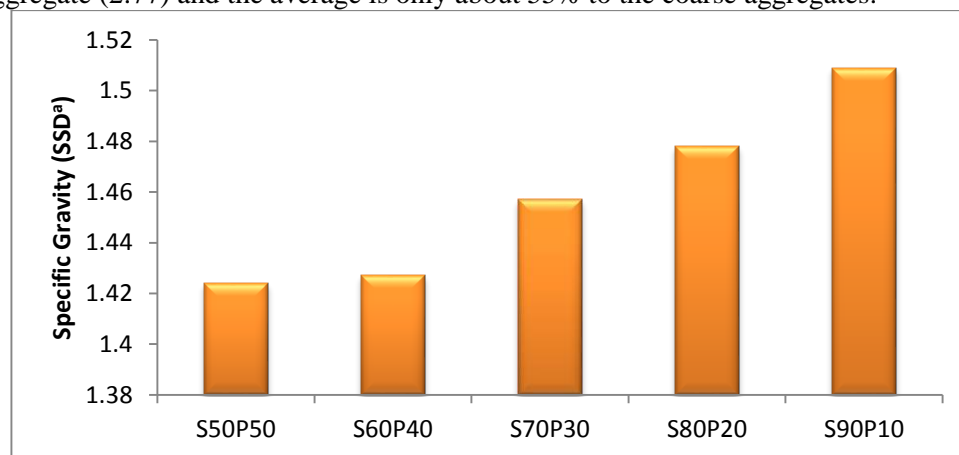
[a] Saturated Surface Dry

Figure 2. Specific gravity for difference proportion mix of artificial aggregates

3.2 Water absorption

Water absorption of artificial aggregate provide indicator to classify the open and close porosity property [20]. Figure 3 shows the water absorption of the artificial aggregates at various proportion mixes. It is clearly show that the artificial aggregate give higher percentage as the silt content increases. However, it is noted that the water absorption of S60P40 is 27.8% which is lower than S50P50 (28.0%). This is due to the high rate of the pozzolanic reaction of the optimum mix between the mixture and calcium hydroxide (present in water) which lead to further occurring of calcium silicate hydrate and make the structure more closely, less porous [21]. Sarkar [22] observed that some water absorption coefficient for artificial aggregate does not follow the order of aggregate.
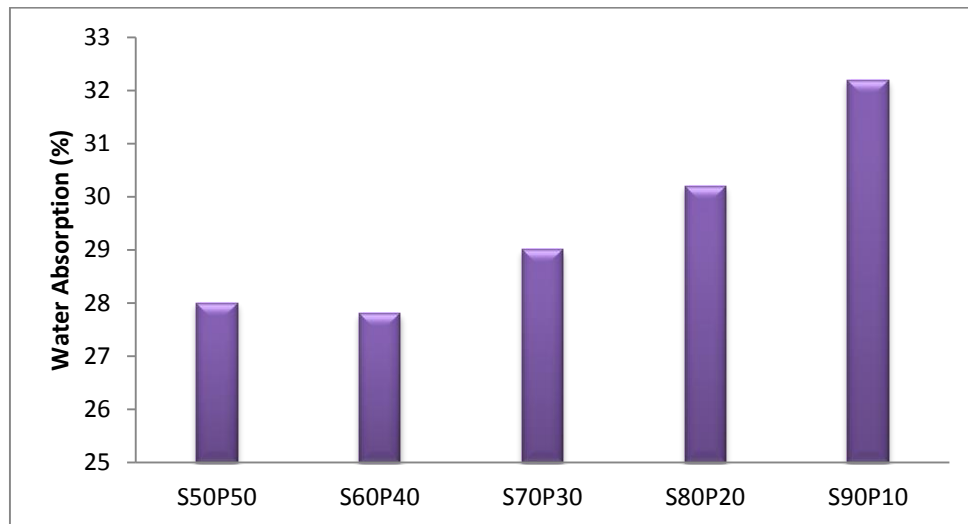
Figure 3. Water absorption for difference proportion mix of artificial aggregates

3.3 Crushing strength

The results by using California bearing ratio (CBR) test are shown in Figure 4. The average of the individual pellets is calculated to achieve the more reliable result. The type of the raw materials in mixture will significantly affect the crushing value [23]. Crushing strength of the artificial aggregates increases as the age of curing increase. From Figure 3, it is observed that there is not much significant variation in the crushing strength of each mix of artificial aggregate at each curing ages. However there are significant increasing for the crushing strength as the trend of curing time for artificial aggregates increasing.

The crushing value shows a dump bell shape for difference proportion mix of artificial aggregates. It can be noted that the highest crushing strength is 1.14 MPa for S60P40 at curing age of 28 (Figure 5). This indicates that the artificial aggregate is well manufactured with the optimum mix for S60P40. Despite the crushing strength of artificial aggregates is lower compared to natural aggregate (8.11MPa), but still comparable with the lightweight aggregates where all the mixes of aggregates are within the range of crushing value for lightweight aggregate (0.4-11.0MPa).
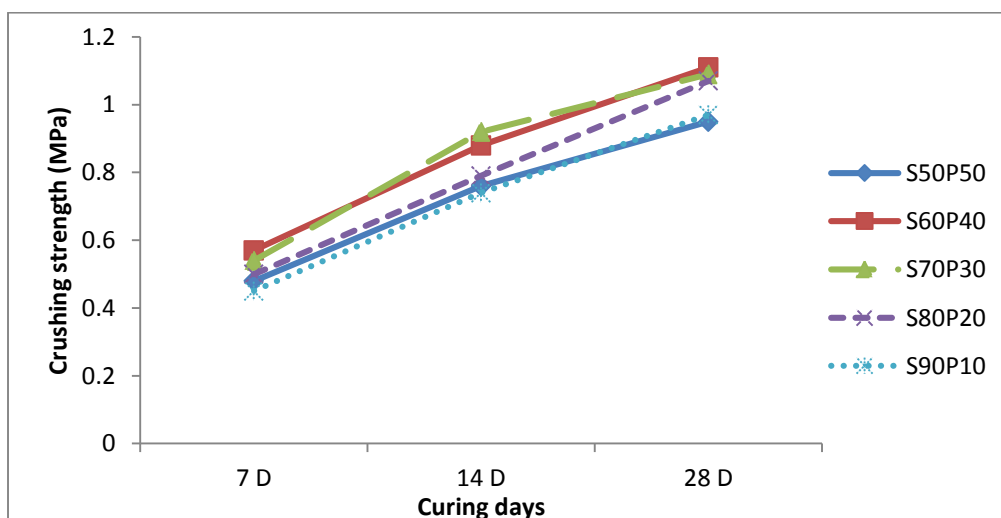

Figure 4. Crushing strength of aggregate for 3 ages of curing
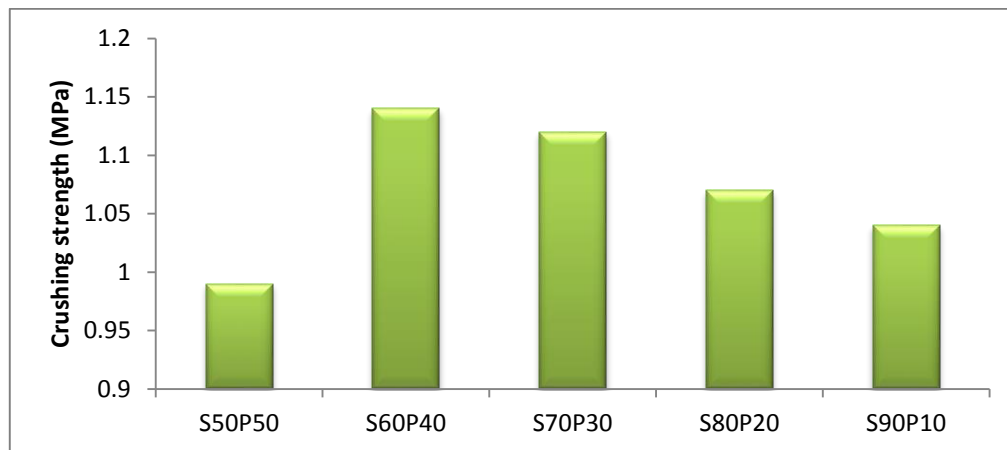
Figure 5. Crushing strength for difference proportion mix of artificial aggregates at 28 days

3.4 Aggregate Impact value (AIV)

The AIV is known as the percentage of weight loss particles which sieving via 2.36 mm after 15 times hammers. The result of AIV is presented in Figure 6. The AIV limit for aggregates used for construction concrete structure must do not exceed 45% by weight of aggregate [24]. S60P40 is noted has the lowest AIV sample with 22.86% where the maximum AIV is 28.28% (S90P10). All of AIV is within the limit range, which indicates that the artificial aggregates are resistance towards the sudden impact.
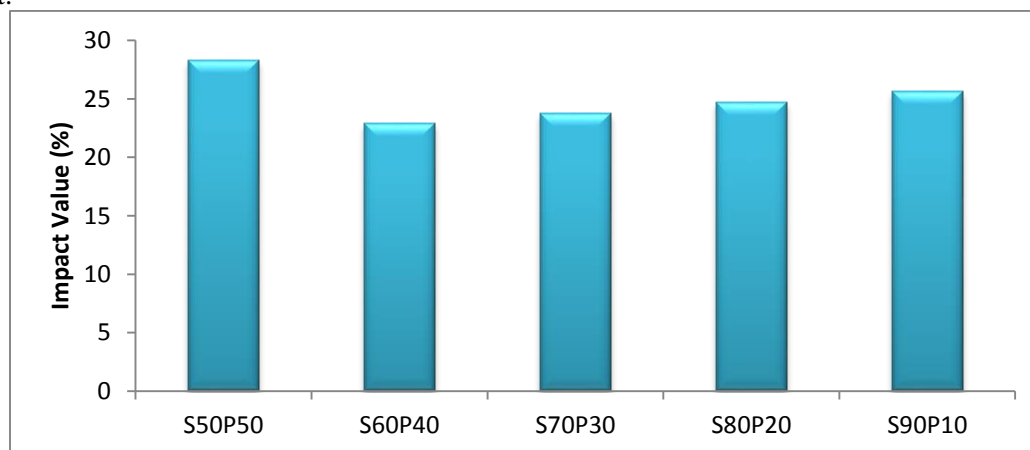

Figure 6. Impact value for difference proportion mix of artificial aggregates at 28 days curing

4. Conclusion

From the investigation and result analysis, the raw materials from silt and POFA with the addition of alkaline activator and lime can be used to manufacture artificial lightweight aggregates. The specific gravity of the artificial aggregates in the range of 1.42 to 1.51 are lighter than natural aggregate, which can be proved that it is the lightweight aggregates. Increasing the silt and decreasing POFA will decreased the crushing strength of artificial aggregate and increased the water absorption. Although the crushing strength of the artificial aggregates gives the result which is lower than the natural gravel (8.11MPa), but the artificial aggregates still comparable with the others lightweight aggregates that can replace as coarse aggregate. Besides, water absorption for the artificial aggregates is much higher compared to the natural aggregate (1.66%), which require more water ratio for the concrete mix. In addition, results also showed the AIV increased with the decreasing percentage proportion of POFA. The impact values of the artificial aggregates are lower than the allowable limit which is 45%. The lowest impact value is 22.86%, which still consider in high percentage compared to the natural aggregate (7.88%). The optimum lightweight artificial aggregates that suitable for the use in lightweight concrete is S60P40 due to its light specific gravity of 1.427 and high crushing strength of

1.14 MPa. The results showed that it is possible to utilize the unground POFA and silt from water treatment plant in the production of artificial aggregate.

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