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Mechanical properties of oil palm waste lightweight aggregate concrete with fly ash as fine aggregate replacement

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ABSTRACT

Environmental degradation posed by fly ash (FA) disposal from coal power plants and shell from the oil palm fruit processing trade is non-trivial. The destruction of flora and fauna resulting from the extraction of river sand and granite aggregate from the green hills in an uncontrolled fashion for the production of concrete that is widely used in the construction industry does also require a solution. Introducing oil palm shell (OPS) and fly ash as a mixing ingredient in zero granite lightweight aggregate concrete production is an appealing notion. Success in utilising the available solid waste would reduce dumping of these by-products and consumption of natural aggregates, thus ensuring the preservation of the environment for the future generation. Therefore, this research explores the influence of FA content as sand replacement towards the mechanical and durability properties of agro-based lightweight concrete. Five concrete mixes with FA quantity ranging from 0% to 40% were prepared. Two forms of curing procedure were practised viz. water and indoor air curing. All the mixes were tested for fresh and hardened characteristic as well as sulphate resistance. The test results demonstrated that a substitution of 10% sand with FA yielded better mechanical properties and denser concrete with more resistant to sulphate attack in comparison to the control mix. The utilisation of two industrial waste materials such as FA and OPS may address the issue of paucity of natural resources that is experienced in the construction industry, particularly in the case of natural granite and river sand.

1. Introduction

Concrete is extensively used in various building construction. Globally, the annual concrete consumption exceeds 25 billion tonnes [1]. The growth of this industry and the massive concrete production have led to the use of a considerable amount of natural resources and raw materials required as mixing materials. This material is formed using fine and coarse aggregate obtained from the river or ocean and hills, which comprises more than 50% of the total mixing ingredients. The estimated annual demand for this material is about 9 billion tonnes in 2050 [2]. As a result, the depletion of sand and aggregate, pollution, flora and fauna destruction are somewhat induced by the construction industry. The aggregate harvesting business without proper planning and concern towards environment tend to ruin the scenic beauty that is rich with plants and wildlife, transforming it into a desolate area exposed to erosion during the rainy seasons [3], pollutes the air, spoil the water quality and causes landslides amongst others [4]. It is essential to highlight that, the same industry is then again has to deal with the issues of exhaustion of natural assets and difficulty in obtaining them [5], that would inevitably result in the rising price of concrete, that in turn, affects the construction cost. In fact, it is worth noting that there are certain countries that are importing aggregates to mitigate the local natural aggregate supply shortage problem [6]. Thus, the extensive utilisation of aggregate in concrete, which has resulted in the substantial exhaustion of this non-renewable assets needs to be resolved for the sake of environmental sustainability [7]. The building industry must be

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Fig. 1. Collecting OPS.

Fig. 2. Processed OPS ready for use.

Table 1
Properties of processed OPS.

Properties	Value
Specific gravity	1.37
Fineness Modulus	6.53
Compacted Bulk Density (kg/m^3)	568
Water absorption (24 h)	12.47
Aggregate Abrasion Value (%)	7.6
Aggregate Impact Value (%)	18.18
Aggregate Crushing Value (%)	14.84

Table 2
Physical properties of sand and fly ash.

Types of Aggregate	Specific Gravity	Fineness Modulus	Particle Shape
River sand	2.7	2.72	Angular
Fly ash	2.3	2.51	Spherical

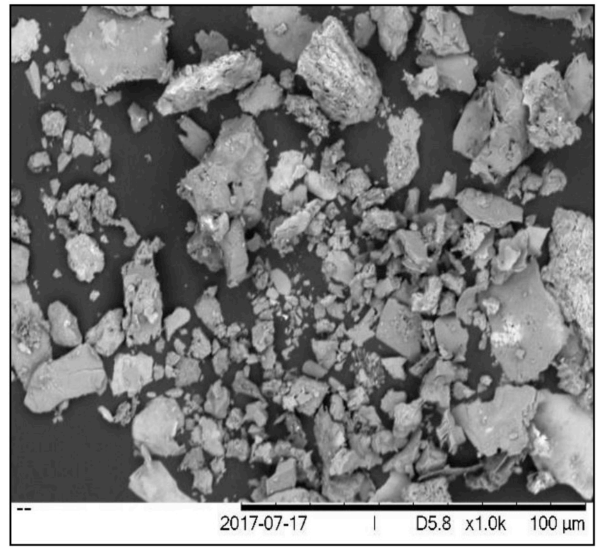

Fig. 3. SEM of sand at 100× magnification.

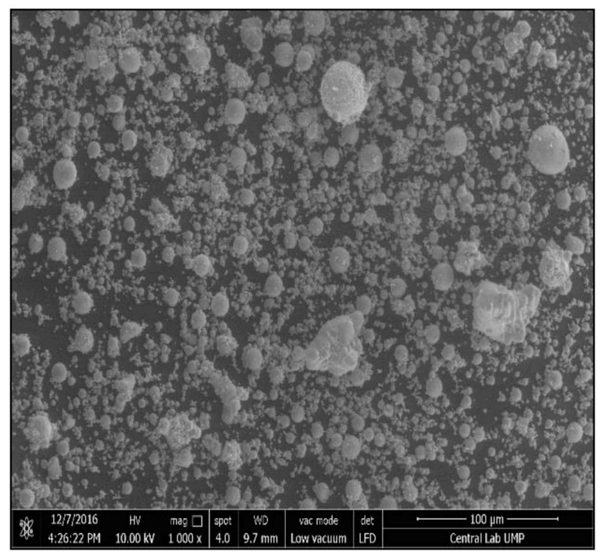

Fig. 4. SEM of fly ash at 100× magnification.

Table 3
Chemical composition of fly ash.

Chemical Composition	Percentage (%)
SiO_2	47.50
AL_2O_3	19.20
Fe_2O_3	5.18
CaO	4.47
MgO	1.15
P_2O_5	0.63
K_2O	1.33
Na_2O	1.07
SO_3	0.53

conscious of the resources reduction, conservation of natural resources and energy saving [4]. In order to minimise the environmental problems caused by the concrete production and nurture a sustainable environment, the utilisation of wastes from the industry as mixing materials is deemed as a viable option to prevent the excessive use of non-renewable assets of the earth. Also, the exploitation of solid wastes allow the construction industry to be more environmentally friendly and sustainable. Hitherto, a number of studies [8–22] examined the feasibility of integrating industrial leftover in concrete manufacturing. Success in integrating polished granite waste, fly ash, bottom ash, clinker, ferro-nickel slag, fruit shells and eggshell in production of sand and aggregate will be one of the steps towards the preservation of natural resources.

Sand supplying business is increasing in many parts of the world owing to escalating demand of expanding construction industry. To

Table 4
Mix proportions of concrete mixes (kg/m^3).

Mixes	Cement	Sand	OPS	FA	Superplasticizer	Water
MFA-0	450	650	310	0	1%	225
MFA-10	450	585	310	65	1%	225
MFA-20	450	520	310	130	1%	225
MFA-30	450	455	310	195	1%	225
MFA-40	450	390	310	260	1%	225

date, about 50 billion tonnes of sand is needed per year [23]. Many regions are blessed with rivers or sea, that offers plentiful sand supply which can easily be obtained through mining method. Regrettably, its utilisation is more than its natural renewal rate [23], whereby this situation tends to alter the river environment and harmful to aquatic lives in the river bed [18]. The mining activities at the river also causes detrimental impact such as the escalation of sediment interaction with the flow and the alteration of river morphology [24]. Uncontrolled river sand mining leads to the depletion of river beds, thus destroying the habitat of flora and fauna, interrupts the food chain in an ecosystem causing an ecological imbalance in future. Besides, the harmful effect of the industry on climate change occurrence [25], the mining activities also threatens the water source of local societies [26]. In addition, the reduction or the insufficient supply of sand to meet the growing demand from various trades also affect its pricing that in turn, renders to higher construction costs. In fact, there are already places in the world that are experiencing the depletion of natural sand for its usage in the construction industry [6,27]. Although, importing sands from other countries would solve this problem, nonetheless, the solution is rather temporarily and exposes the concrete industry to the risk of price increment due to the difficulties in getting supplies or higher trade price in future. Thus, the approach of substituting the use of natural sand with other alternative materials can reduce or avoid the negative impacts on the environment, communities [23] and construction industry.

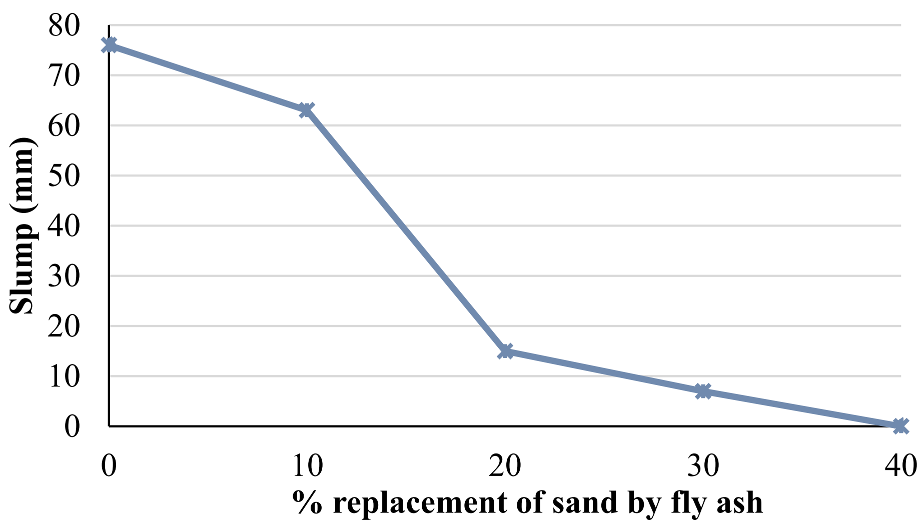

Fig. 5. The slump of OPS lightweight aggregate concrete mixes.

Fig. 6. Workability of OPS lightweight aggregate concrete mixes.

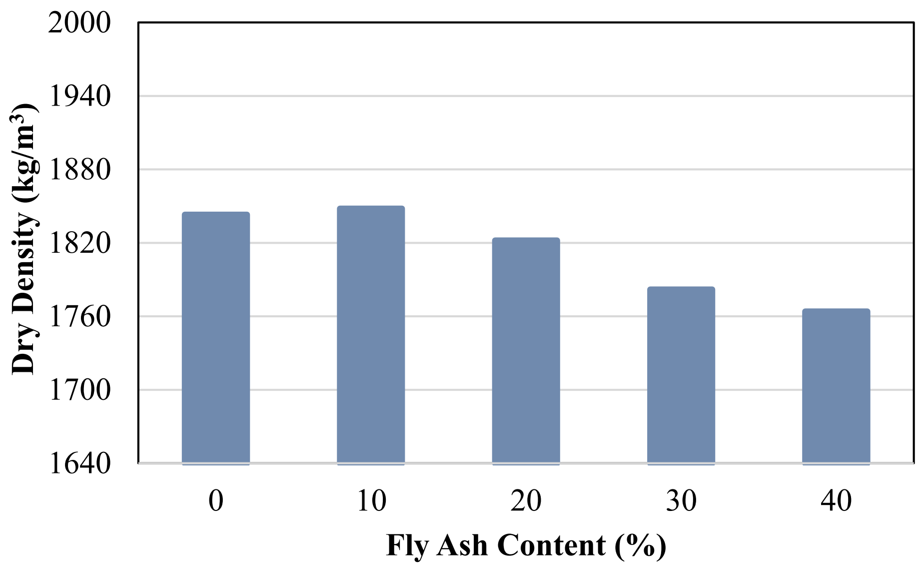

Fig. 7. Density of OPS concrete with various FA content.

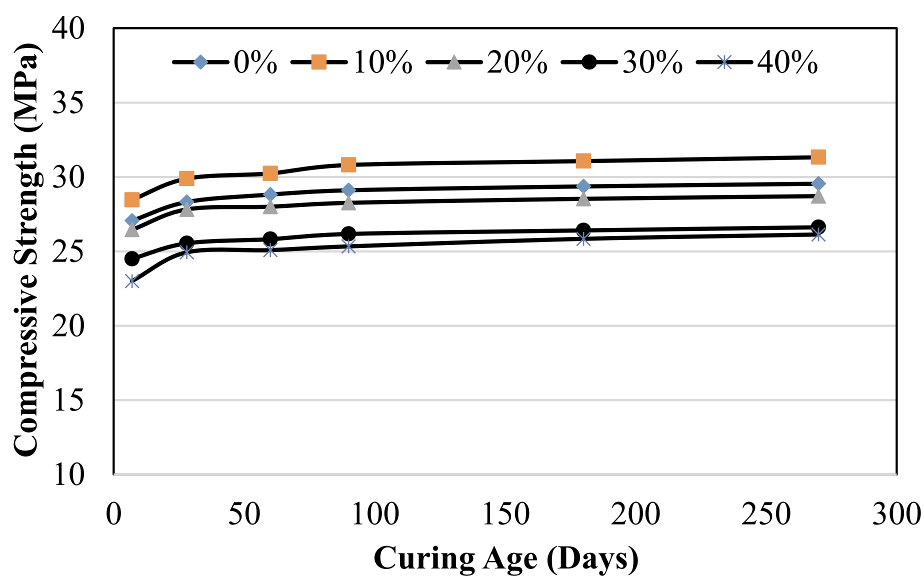

Fig. 8. Compressive strength of water cured concretes.

Therefore, one of the ways to mitigate these issues is to utilise local industrial excess to replace sand in concrete to a certain extent. As the production of concrete industry is vast, the measure opted-in enhancing the efficiency in resource utilisation has a substantial benefit to the environment [6]. It is also important to highlight that the use of wastes is in tandem with the United Nation's Sustainable Development Goals, particularly Goals 9 and 13 [28].

Coal is an important element for energy generation worldwide [29]. The increase in the world's population along with their need for better quality life, which in turn, calls for the increase in energy supply. As a result, coal and other resources are continuously explored and utilised to meet the ever growing demand. According to a published report by Ref. [30], the coal consumption in the world grows by 1.4% in 2018, which is the fastest growth since 2013. In Malaysia, coal consumption has been rising since 1996 from less than 10% to up to 42.5% in 2015 [31]. The growth in the quantity of coal subjected to combustion process at the plant also results in a large amount of a particular by-product known as fly ash, which inexorably needs to be managed. It consists of approximately 60–88% of the total combustion residues at the plant [32]. At present, the fly ash generation worldwide exceeded 800 million tonnes per year [33,34]. The annual production of ash reaches more than 300 million tonnes in China [35], about 200 million tonnes in India [36] and approximately 8.5 million tonnes in Malaysia [37]. The rising generation of fly ash by such industries has lead to the growth in its disposal at landfills or lagoons [38]. Currently, the primary technique used for fly ash waste management is by dumping it on open space [39]. It is noteworthy to mention, that the improper disposal method of fly ash can disrupt the soil quality [39], pollutes the environment as well as interrupting biological flow [40]. An individuals who continuously exposed to the air polluted with fly ash, which is easy to be carried by the wind may experience health problems [39]. Fly ash which contains heavy metals can also taint the groundwater [40,41]. These environmental degradations also may destroy habitats of certain animals, forcing them to migrate that in turn interrupts the existing ecosystem. In addition, the disposal of this by-product also arises other untoward concerns such as new terrestrial exploitation process for trash dumping, extra maintenance cost and undesirable environmental damages [30]. Channelling this waste to the factory as one of the mixing ingredient for

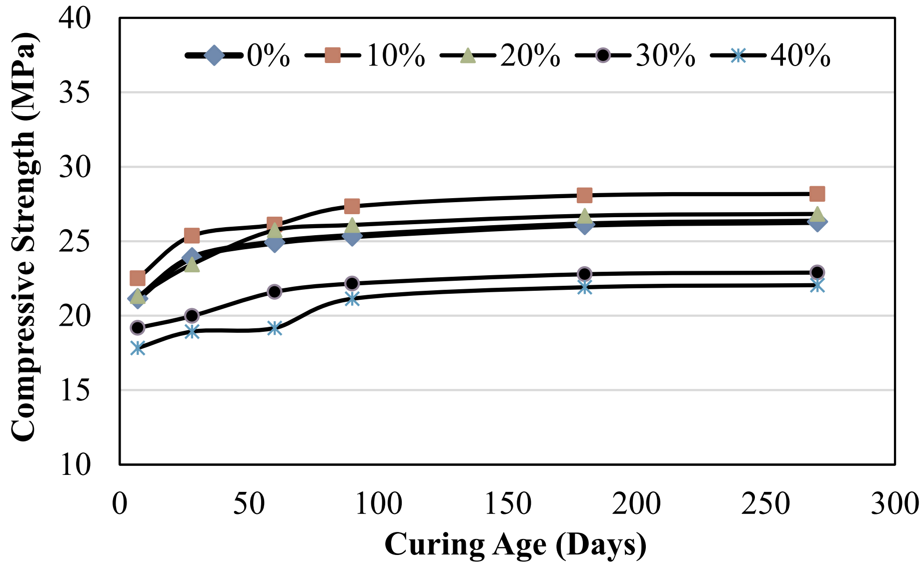

Fig. 9. Compressive strength of air-cured concretes.

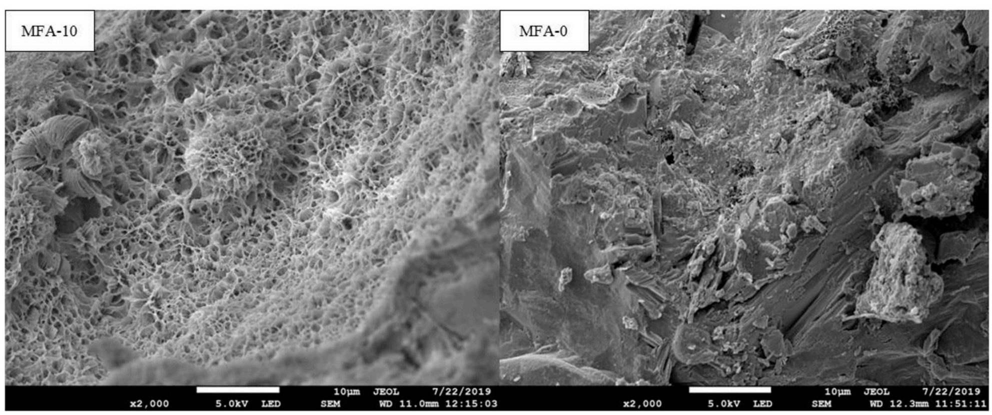

Fig. 10. MFA-10 rich in CSH gels in contrast with MFA-0 containing lesser CSH gel.

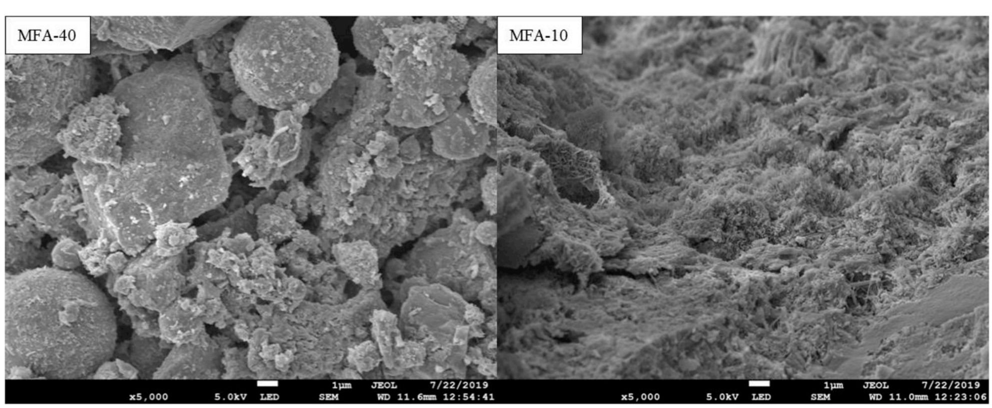

Fig. 11. MFA-40 with voids and unreacted fly ash in contrast with the densed structure of MFA-10.

product manufacturing would protect the valuable land from being turned into waste dumping sites apart from reducing waste management costs and promoting cleaner environment.

In view of environmental sustainability, these freely available ashes have been utilised for backfilling during earthwork, for pavement construction, cement and concrete manufacturing, and farming amongst others [33]. As concrete is one of the most widely used material in the world, good quality fly ash is used as supplementary cementitious material to reduce cement consumption. The well known pozzolanic effect of fly ash as mineral admixture in enhancing concrete properties which have been reported in past publications [42–46] makes it attractive to be used in concrete production. However, the biggest challenge is, that the concrete compressive strength varies when fly ash is used as supplementary cementitious material owing to its properties which differs

Table 5
Results of ANOVA for water cured concrete compressive strength.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	5.42	476.87	2.60×10^{-5}	0.9917	Yes
MFA-20	1	3.23	255.29	8.79×10^{-5}	0.9846	Yes
MFA-30	1	2.91	559.29	1.89×10^{-5}	0.9929	Yes
MFA-40	1	5.91	130.81	3.33×10^{-4}	0.9703	Yes

Table 6
Results of ANOVA for air-cured concrete compressive strength.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	22.62	265.31	8.31×10^{-5}	0.9852	Yes
MFA-20	1	23.23	111.98	4.51×10^{-4}	0.9655	Yes
MFA-30	1	10.61	40.09	0.003184	0.9092	Yes
MFA-40	1	12.66	17.70	0.013608	0.8157	Yes

significantly based on the coal category and combustion method at the power plant [47]. The variation in the silica and calcium content of fly ash influences the concrete performance, and hence may require the use of additional admixture to improve its performance. In other words, fly ash composition is one of the factors that determines the efficacy of ash on concrete properties [32,48]. Generally, fly ash which classified as Class C or Class F based on the total content of silica, alumina and iron oxide as stated in ASTM C618 is allowed to be utilised in cement production [33]. In Europe, the fly ash that is used in blended cement manufacturing must conform to the European Standard EN 450-1 [42]. As the coal consumption is growing in certain region, more fly ash would be generated in the future. Therefore, discovering other potential use of this solid waste would reduce the undesired environmental contaminations and health issues caused by the ash dumping. According to Ref. [41], initiatives in transforming this waste into a beneficial material for concrete industry is imperative as more fly ash is being generated.

In relation to that, sand is one of the principal constituents of concrete that is used in large volume in comparison with cement [49], has been partially replaced with fly ash in concrete production by Refs. [50–59]. Past researchers [52–54] have reported that the use of Class F fly ash as partial fine aggregate replacement enhances concrete strength. It was demonstrated that concrete produced with Class F fly ash as partial sand substitute exhibits better strength owing to the pozzolanic reaction of the ash [52,54]. Concrete strength enhancement was reported upon the incorporation of Class F fly ash up to 50% [52] and 30% [54], respectively. Nontheless, excessive use of fly ash would decrease concrete strength due to the absence of calcium hydroxide to be used in pozzolanic reaction [57]. Structural lightweight concrete can be produced by a suitable combination of fly ash as fine aggregate and the sintered fly ash lightweight aggregate as coarse aggregate [58]. The use of 10% fly ash has also been reported to be able to contribute to the increment of the lightweight aggregate concrete strength at 28 days [59]. Generally, investigation on the strength and durability performance concrete produced using fly ash as sand replacement is limited. Further findings on the potential use of fly ash in high performance concretes would expand its usage in the construction industry and reduce its quantity that is dumped as waste.

There is no doubt about the importance of palm oil production as major industry Malaysia and Indonesia primarily owing to its ability to be utilised as biofuels. Most importantly, elements such as sufficient rainfall, sunshine and perfect soil condition, further contribute to the optimal growth of oil palm plantation [60] that exist naturally in the aforesaid Asian countries, ensuring the growth of this industry throughout the years. Within 30 months after field planting of the oil palm trees; the matured tree produces fruit bunches throughout the year for up to a minimum of 25 years [61]. A publication in 2017 by Ref. [62] reported that both countries produce approximately 80% of the global total palm oil, with 90% of it is exported. In Malaysia, the relentless research and development in improving the yield of palm oil both in

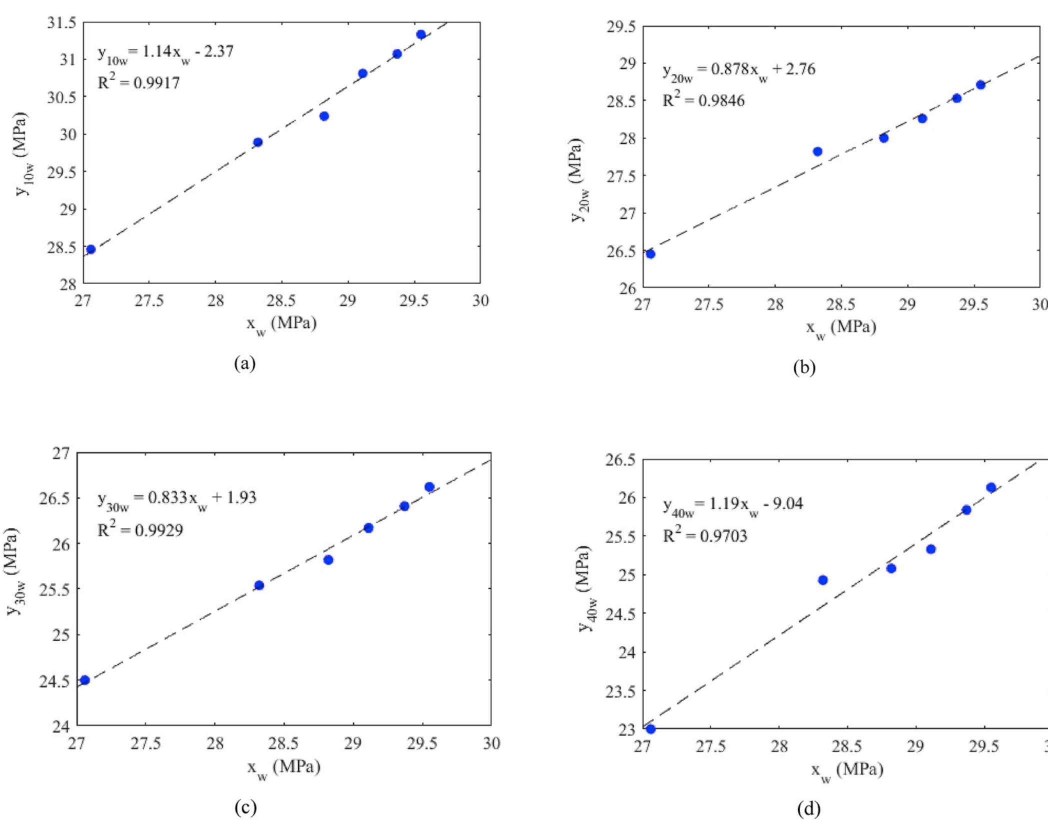

Fig. 12. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis of compressive results for water cured specimens against the control specimens.

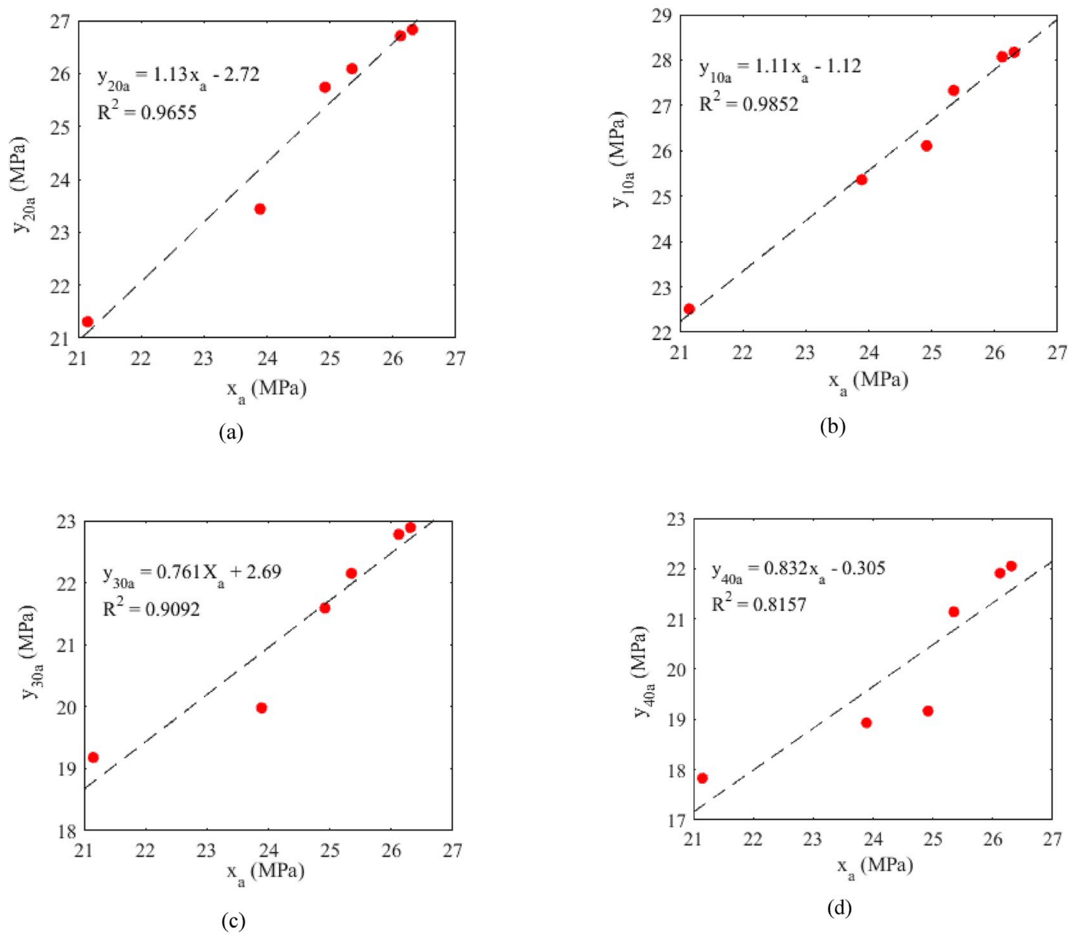

Fig. 13. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis of compressive strength for air-cured OPS concrete with changing FA replacement level against compressive strength of the control specimen.

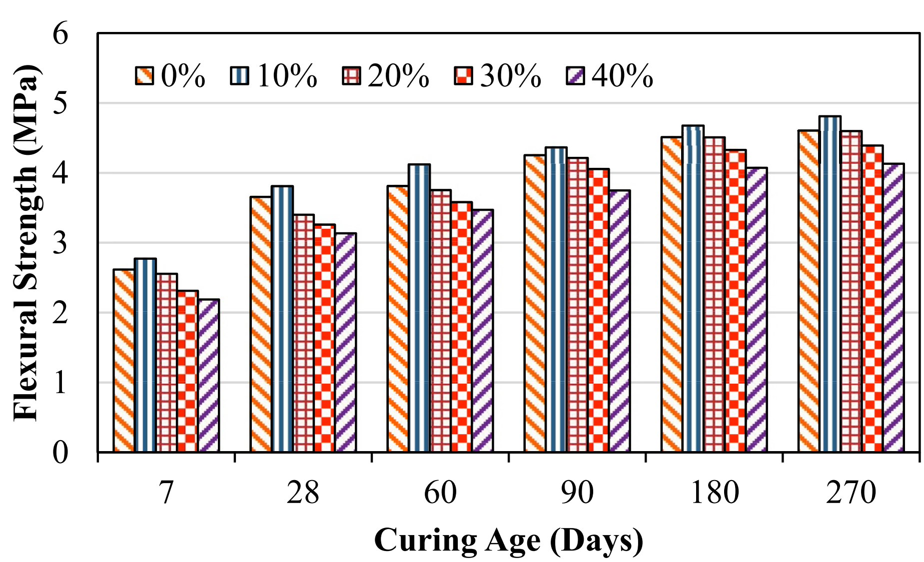

Fig. 14. Flexural strength of water cured concrete.

terms of quality and production capacity have ensured the trade continues to flourish. Based on the report by Ref. [63], the total oil palm plantation area in the country is increasing over the year, reaching up to 5,849,330 million hectares in 2018. Similar growing production trend was reported by Ref. [60] pointing out that the export of Malaysian oil palm product in 2018 surges about 3.5%–24.82 MT compared to the previous year. Approximately 39% of the world's palm oil production and 44% of global exports came from Malaysia [64]. The annual solid

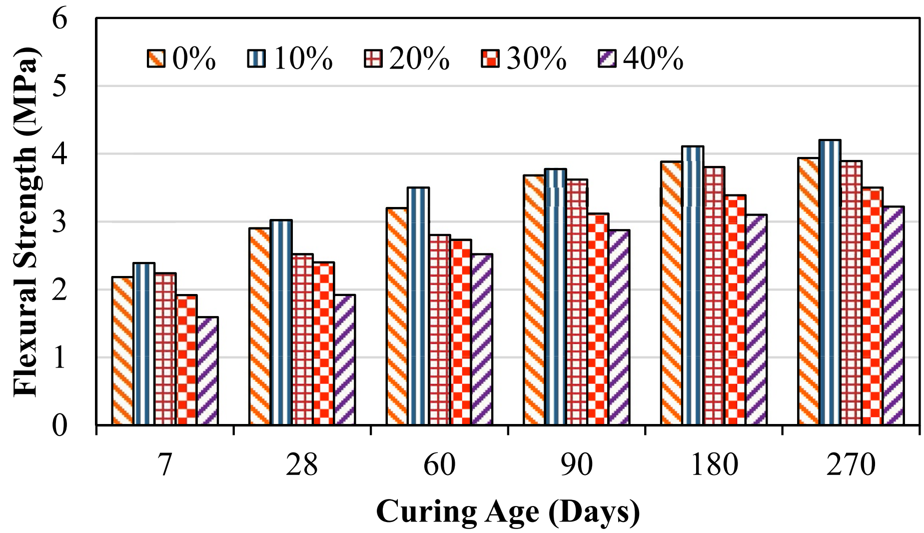

Fig. 15. Flexural strength of air-cured concrete.

Table 7
Results of ANOVA for water cured OPS concrete flexural strength.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	2.73	473.62	2.64×10^{-5}	0.9916	Yes
MFA-20	1	2.97	319.16	5.77×10^{-5}	0.9876	Yes
MFA-30	1	3.09	616.44	1.56×10^{-5}	0.9936	Yes
MFA-40	1	2.61	518.50	2.20×10^{-5}	0.9923	Yes

Table 8
Results of ANOVA for air-cured OPS concrete flexural strength.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	2.37	287.58	7.09×10^{-5}	0.9863	yes
MFA-20	1	2.36	52.14	0.001951	0.9287	yes
MFA-30	1	1.85	283.2	7.30×10^{-5}	0.9861	Yes
MFA-40	1	2.08	99.55	0.000567	0.9614	Yes

waste produced by the Malaysian and Indonesian palm oil industry is about 47 and 40 million tonnes, respectively [65]. Owing to the nature of the industry, similar issues akin to the fly ash are reported with regards to the disposal of its by-product as well as its associated waste management costs. Approximately 80% volume of waste products are generated from the processing activities in mills [66]. Among the residues generated are oil palm shell (OPS), clinker, ashes and empty fruit bunches. It has also been reported that around 6.89 million tonnes OPS is produced from the palm oil industry annually [67]. These OPS are often disposed at the landfill area without any treatment [68]. This practice also may contribute to contamination of air, water and land [69]. In certain palm oil mills, a small portion of OPS is usually burned in the incinerator with other solid by-products to generate electricity for the mill operation and produces residual ashes. This approach is considered to be non-environmental friendly, as the burning produces smokes and dumping of the ash at open space pollutes the air [70]. As the palm oil trade is forecasted to continuously flourish, larger quantity of oil palm biomass would be generated [69], and oil palm shell is one of it. Failure to utilise this solid waste for product manufacturing may require the provision of larger space as dumping site, aggravates the environmental pollution problem and create surplus expenses for the waste management team of the mill.

In view of environmental sustainability, researchers in the construction material research area have been exploring the potential use of this solid waste as mixing ingredient in concrete. One of the early investigation conducted at the end of 20th century by Ref. [71] reported that compressive strength of concrete produced using oil palm shell as coarse aggregate falls in the range structural lightweight concrete. Further research has been carried out by Ref. [72] pointed out the potential application of this lightweight aggregate concrete as a structural member in low-cost housing project building. Concern on preserving the natural aggregate consumption for a greener environment has driven investigators [73–79] to examine the prospective use of oil palm shell as lightweight aggregate in high performance concretes. Owing to other environmental degradation issues, the inclusion of solid waste with pozzolanic properties as partial cement substitute in oil palm shell lightweight aggregate concrete research has also been investigated [80–84]. At present, the increase in sand mining that poses negative impact to the river environment and anxiety over sand depletion in the future has instigated research on discovering alternative waste materials to be used as partial sand replacement in oil palm lightweight aggregate concrete production. To date, very limited publication [85,86] discusses the performance of this agro-based lightweight concrete incorporating waste as sand replacement.

The aim of the present investigation is to develop a more environmental friendly OPS concrete with fly ash (FA) as sand replacement in concrete mixture. Therefore, in this study, the fine aggregate is replaced with various percentages of FA in an OPS concrete. The effects of different curing regimes on the mechanical and durability of this newly developed concrete were studied to ascertain the suitable curing method for this type of concrete.

2. Material and properties

2.1. Binder

Cement conforming to MS 522: Part 1 [87] from a single source is used as a sole binder.

2.2. Water

Tap water supplied by Pengurusan Air Pahang Berhad (PAIP) for mixing the concrete and specimens curing. Distilled water is used for preparing the solution for durability testing.

2.3. High range water reducing admixture

Sika Visco-Crete®-2199 supplied by Sika Kimia Sdn Bhd is used during concrete preparation to produce a concrete mix with good workability at a low water-cement ratio. This liquid form admixture is

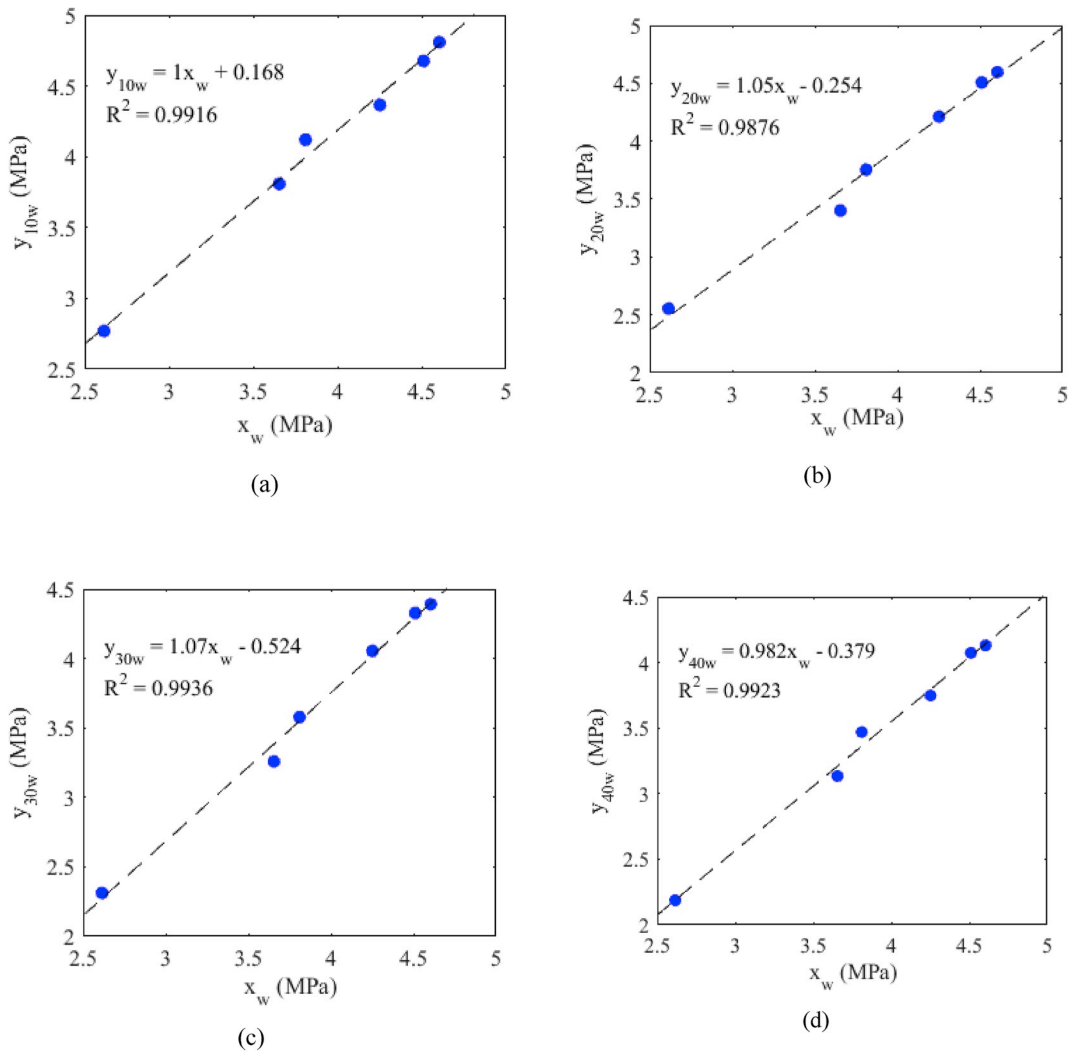

Fig. 16. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis of flexural strength for water cured OPS concretes with changing FA replacement level against the flexural strength of the control specimens.

water-reducing admixture of Type A as by ASTM C 494 [88] (see Table 1).

2.4. Processed OPS coarse lightweight aggregate

Oil palm shell (OPS) were gathered from oil palm mill in Pahang state, Malaysia, as illustrated in Fig. 1. Before the OPS is ready to be used in concrete preparation, the waste material washed by tap water to eliminate the dirt on the shells. Then, it is oven-dried before stored in a container. Fig. 2 depicts the processed OPS that is ready for concreting works. Table 1 presents the details of OPS used.

2.5. Fine aggregates

Two types of fine aggregate were included for concrete specimens production. The river's natural sand is obtained from a local supplier. The FA that is used as the fine aggregate replacement is supplied by a local coal power plant. Table 2 presents the properties of both types of fine aggregate the natural river sand and fly ash used in this research. Fig. 3 illustrates the physical appearance of sand, which is larger and angular in contrast with finer spherical shaped fly ash in Fig. 4. Fly ash is used to replace fine aggregate by 0%, 10%, 20%, 30% and 40% of the sand weight. Based on chemical properties of fly ash, as tabulated in Table 3, it is apparent that it could be categorised as Class C in compliance with ASTM C618-19 [89].

3. Mixture proportions and preparation

Five concrete mixes containing different percentages of fly ash (FA) replacing sand have been used in this experimental work. The quantities of other mixing ingredients, namely cement, water, superplasticizer and oil palm shell were fixed. A plain OPS concrete (MFA-0) of Grade 25 was designed using 100% normal sand as fine aggregate. Table 4 shows the mixes which were prepared by adding fly ash at various percentages by weight of the total fine aggregate.

Accurately measured mixing ingredients were added and mixed uniformly using a concrete mixer. After placed in a mould, the mixes were compacted and then covered for overnight by wet gunny sacks. 24 h later, the moulds were dismantled, and the specimens were cured. Investigating the effect of curing on the properties of concretes requires the specimens to undergo two different methods namely, water curing and indoor air curing until the testing date.

4. Fresh and hardened concrete properties testing

The workability of this new mixture is determined through slump

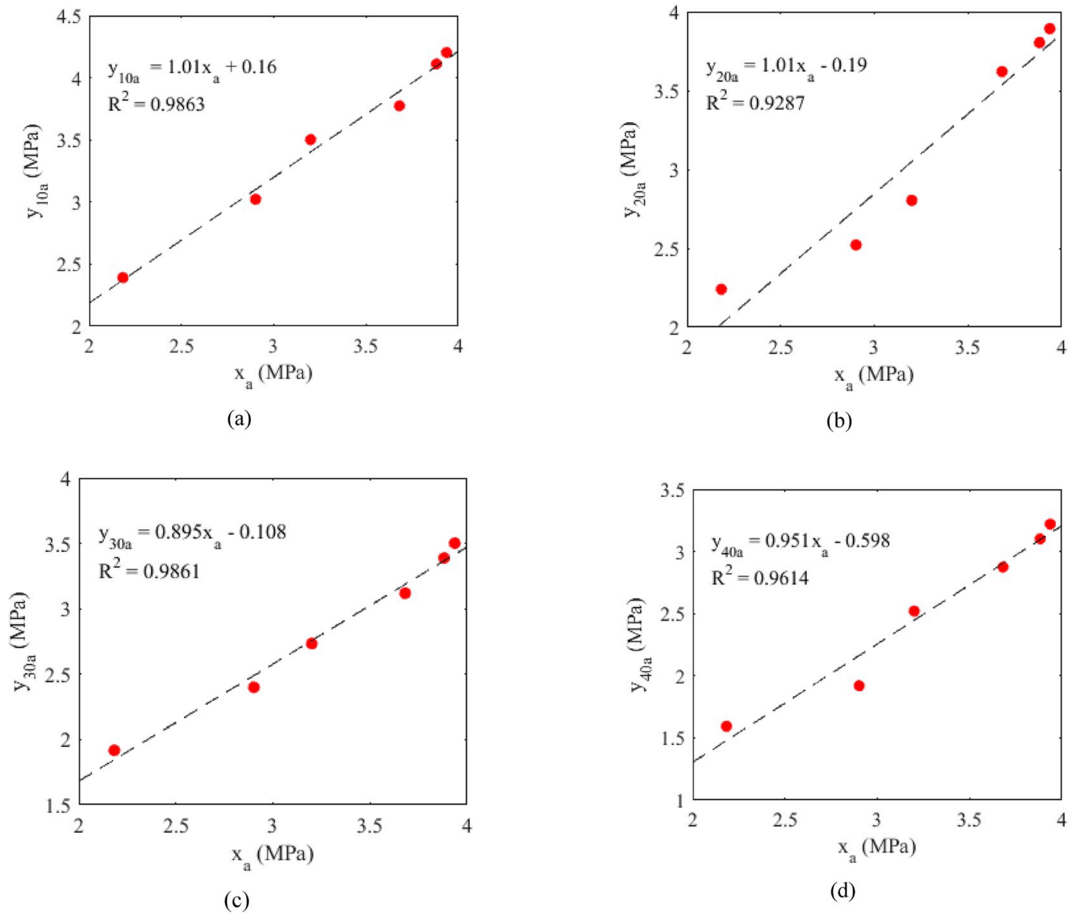

Fig. 17. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis of flexural strength for air-cured OPS concretes with changing FA replacement level against the flexural strength of the control specimens.

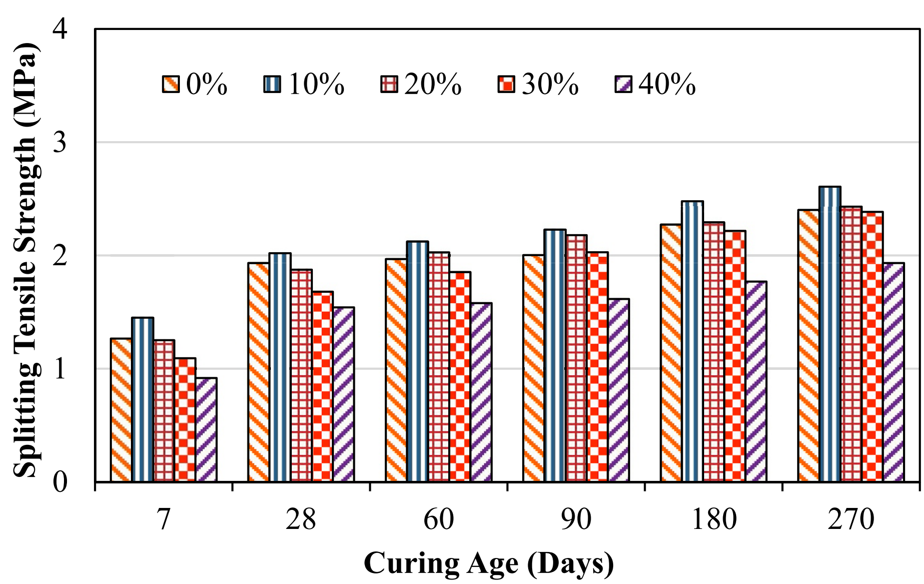

Fig. 18. Tensile strength of water cured concretes.

test adhering to BS EN 12350-2 standard [90]. All the hardened concrete properties testing were carried out after the specimens were cured at 7, 28, 60, 90, 180 and 270 days. The mechanical properties testing were carried out in accordance with standards [91–94]. The water absorption and sulphate resistance test were conducted adhering to the procedures outlined in BS 1881: Part 122 [95] and Murthy et al. [96].

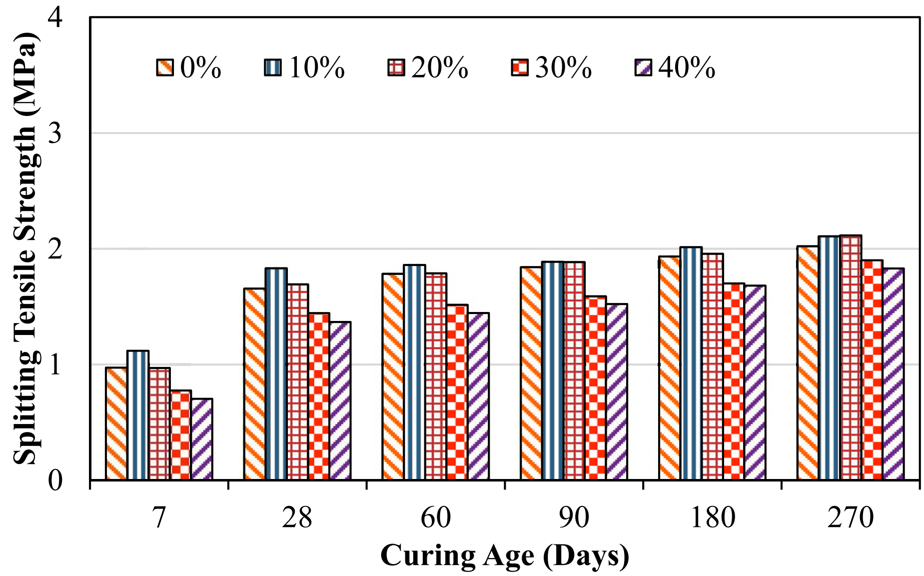

Fig. 19. Tensile strength of air-cured concretes.

Table 9
Results of ANOVA for water cured OPS concrete tensile strength.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	0.82	273.50	7.83×10^{-5}	0.9856	Yes
MFA-20	1	0.85	112.39	4.48×10^{-4}	0.9656	Yes
MFA-30	1	1.10	107.77	4.86×10^{-4}	0.9642	Yes
MFA-40	1	0.59	470.75	2.67×10^{-5}	0.9916	Yes

Table 10
Results of ANOVA for air-cured OPS concrete tensile strength.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	0.61	318.15	5.81×10^{-5}	0.9876	yes
MFA-20	1	0.80	913.80	7.13×10^{-6}	0.9956	yes
MFA-30	1	0.72	214.85	1.26×10^{-4}	0.9817	yes
MFA-40	1	0.75	228.20	1.12×10^{-4}	0.9828	yes

5. Results and discussion

5.1. Workability

Fig. 5 presents slump values of OPS lightweight aggregate concrete with a diverse portion of ash. The concretes slump becomes lower as the proportion of fly ash increases, as illustrated in Fig. 6. The workability of control specimen and the one containing 10% fly ash is within the targeted range and can be categorised as true slump. The utilisation of fly ash replacement of 20%, 30%, and 40% resulted in a substantial reduction of the slump value. The mix becomes more difficult to be mixed as larger quantity FA are integrated as partial sand replacement. Increasing the amount of fly ash, which is finer than river sand requires a more substantial amount of water to cover a larger surface area. Similarly, the workability of cold-bonded fly ash aggregate concrete reduced when sand is replaced partially with fly ash of higher surface area [97]. Thus, the inadequate water available to coat the particles results in lowering the adhesion of the concrete matrix, which, in turn, causes lower workability. The effect of the alternative aggregate material, which is finer than sand in reducing mix workability has been reported in past studies [98,99].

5.2. Density

Fig. 7 demonstrates the impact of different levels of ash (FA) substitution on the density of OPS LWAC at the age 28 days. It is observed that the dry density of specimen's with FA content is lower than 1850 kg/m^3 enabling it to be classified as lightweight aggregate concrete. To classify concrete as LWAC, the average oven-dried density of several samples should not exceed the value 2000 kg/m^3 [100]. The effect of adding fly ash, whereby its particles are lighter resulted in lower density concrete specimens as observed in past investigations [101]. The formation of concrete with lower density when pozzolanic ash replaces fine aggregate has also been noted in another research [102].

5.3. Compressive strength

The compressive strength result of lightweight concrete with fly ash content as partial sand replacement are shown in Figs. 8 and 9. The concrete's strength of specimens having 10% fly ash is higher than other mixes in all types of curing throughout the curing age. Submerging the concrete in water at all time, ensure uninterrupted hydration and pozzolanic reaction by fly ash which contributes towards strengthening of the transition zone as the concrete become denser owing to amplification of CSH gels quantity. Fig. 10 illustrates the presence of crowded CSH gel in the internal structure of the 1-year water cured MFA-10 as compared to MFA-0 control specimen with larger quantity of unused calcium hydroxide and lesser CSH gel. It is known that the pozzolanic reaction owing to the presence of pozzolanic ash as partial cement replacement decreases calcium hydroxide quantity in concrete [103]. In addition, the filler effect of the ash also improves the compactness of concrete's internal structure empowering the strength to be the highest of all. According to Ref. [46], fly ash being fine particle also fill in the cavities of concrete. Basically, the pozzolanic effect leads to the formation of better quality CSH gels and pore refinement that strengthen the interfacial transition zone of concrete microstructure resulting in strength increment [47]. The remarkable role of fine pozzolanic ash in concrete strength improvement has also been highlighted in the past [104].

Nevertheless, replacement of fly ash beyond 10% produces stiffer mix due to lack of mixing water for a larger surface area of fly ash. This condition disrupts the CSH gel formation process, which causes a weaker bond between the aggregates results in concrete strength reduction. The strength continues to drop as the quantity of fly ash used increases. MFA-

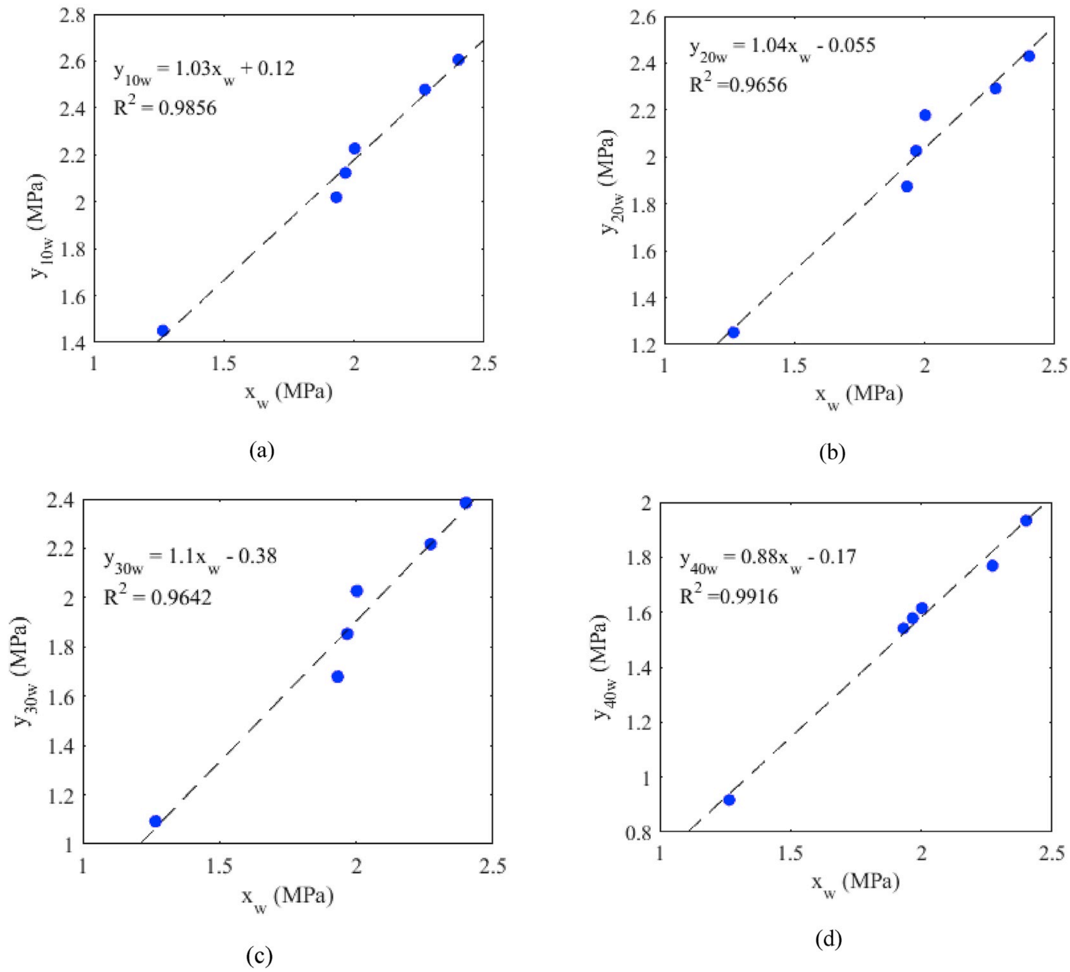

Fig. 20. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis for the water cured tensile strength of the OPS concretes with diverse FA content replacement against control specimen.

40 exhibits the lowest strength possess less compact internal structure with presence pores and some unreacted fly ashes unlike the densed structure of MFA-10 as illustrated in Fig. 11. Unlike the previous investigation by Siddique [105], the present research fixed the quantity of cement, water, coarse aggregate and superplasticizer for all mixes and integrated fly ash as fine aggregate replacement by weight of sand producing diverse result yet similar conclusion. Siddique [105] reported that 30% fly ash is the optimum replacement in plain concrete strength and decline at 40% replacement. Whereas the present research discovers that the optimum fly ash replacement for OPS lightweight aggregate concrete is 10%, and evidently the strength significant declination occurs at 30 and 40% substitution. The adverse effect on concrete compressive strength with the addition of waste material as fine aggregate replacement beyond its optimum amount has been reported elsewhere [26]. However, all concrete mixes containing fly ash exhibit compressive strength more than 17 MPa, enabling it to be classified as structural lightweight aggregate concrete. Past researcher [106], remarked that the strength requirement for structural lightweight aggregate concrete should be equal to or more than 17 MPa.

Additionally, analysis of variance (ANOVA) was also performed to investigate the consequences of including FA towards the compressive strength OPS concrete as demonstrated in Refs. [3,14]. A linear regression line was fitted against the control specimen (independent variable) and the variation of the FA replacements (dependent variable). The probability value (p-value) of less than 0.05 at 95% confidence level was employed in this case, i.e., in the event that the p-value is less than 0.05, the contribution of FA towards the properties of the OPS-FA concrete is considered to be significant. The ANOVA outcomes for compressive strength of both water and air curing methods are provided in Tables 5 and 6. The governing regression equations for various FA levels are shown within Figs. 12 and 13 and it may be expressed as shown in Eq. (1)

$$y_{\gamma\delta} = Cx_{\delta} + D \tag{1}$$

where y = compressive strength of the FA mixture, C is gradient constant, and D is y-axis intercept. The subscripts γ and δ corresponds to the mix percentage and form of curing. On the other hand, air denoted as a and water as w, while x symbolises the compressive strength of the control specimen (MFA-0). Apparently, ANOVA tables revealed that introduction of FA into the concrete mix does somewhat influence (increase or decrease) the compressive strength statistically as the resulting p-value are lower than that of 0.05.

5.4. Flexural strength

Figs. 14 and 15 illustrate the flexural strength result of lightweight concrete with various percentage of fly ash content. All specimens especially the containing fly ash exhibit strength increment as the curing age become longer, similar to observation by Siddique [52]. The flexural strength pattern shows a comparable pattern as the compressive strength results. The ratios of flexural strength to the compressive

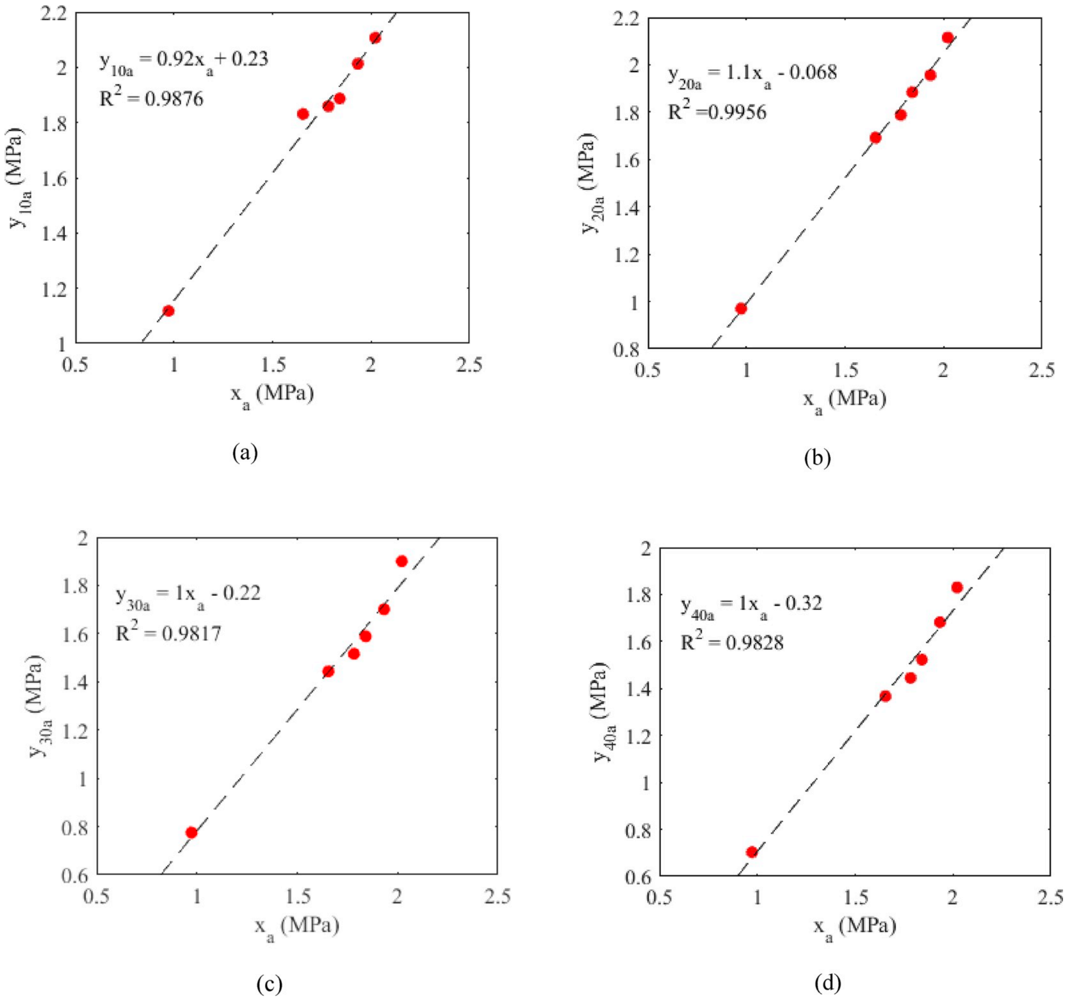

Fig. 21. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis for the air-cured tensile strength of the OPS concrete with diverse FA content against the control specimen.

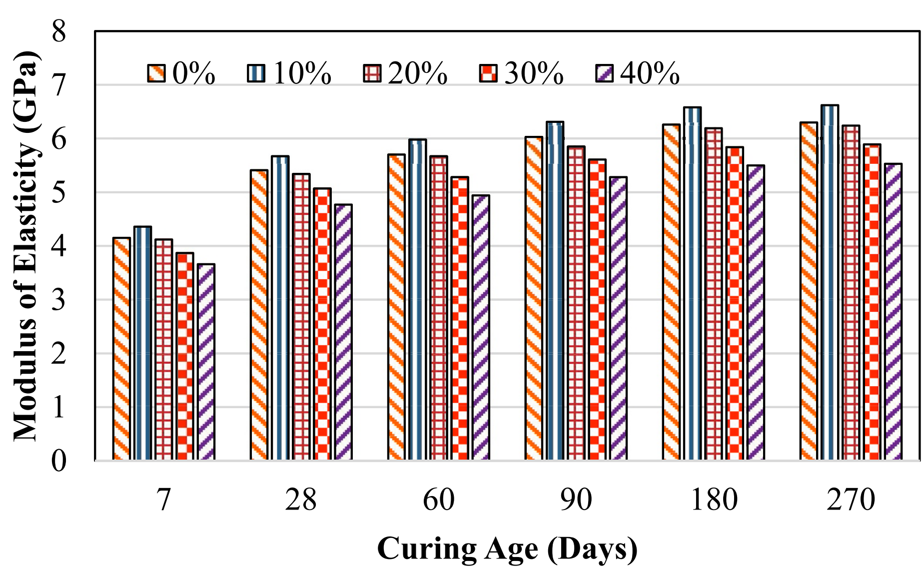

Fig. 22. Modulus of elasticity of water cured concrete.

strength of OPS LWAC with fly ash are between 0.11 and 0.13 which does not deviate far from the findings in Ref. [106], where a ratio between 0.07 and 0.10 for sintered fly ash LWAC was reported. It is worth noting that, OPS lightweight aggregate concrete with 10% fly ash exhibit the higher flexural strength value, when cured in water compared to air, cured one. Only with the presence of moisture, SiO_2 in

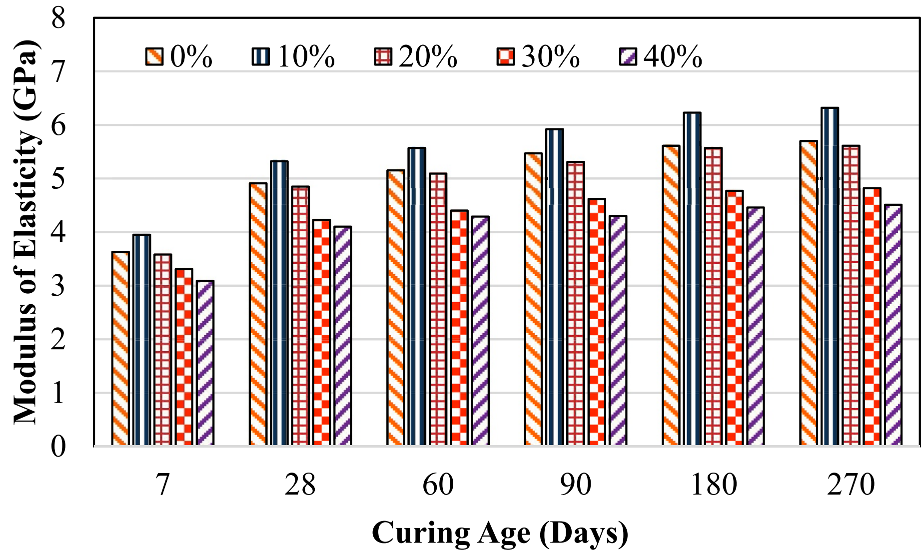

Fig. 23. Modulus of elasticity of air-cured concrete.

Table 11
Results of ANOVA for water cured OPS concrete modulus of elasticity.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	3.47	1083.66	5.08×10^{-6}	0.9963	Yes
MFA-20	1	2.78	9414.13	6.77×10^{-8}	0.9996	Yes
MFA-30	1	2.59	4576.93	2.86×10^{-7}	0.9991	Yes
MFA-40	1	1.89	494.62	2.42×10^{-5}	0.9919	Yes

Table 12
Results of ANOVA for air-cured OPS concrete modulus of elasticity.

Source	DF	MS	F-Value	p-Value	R^2	Significance
MFA-10	1	3.78	665.99	1.34×10^{-5}	0.9940	yes
MFA-20	1	2.83	1341.08	3.32×10^{-6}	0.9970	yes
MFA-30	1	1.57	4415.67	3.07×10^{-7}	0.9991	yes
MFA-40	1	1.36	157.24	2.33×10^{-4}	0.9752	yes

fly ash consumes hydrated lime and yields cementitious binder phase which increases concrete strength. Evidently, the absence of water during the application of air curing, disrupt the chemical reactions resulting in a lower amount of CSH gel generated producing concrete with lower strength. Moreover, it has been reported in Refs. [15,101,107] that curing specimens in the air demonstrates lower strength than the ones water-cured. Furthermore, ANOVA analysis performed indicates the impact of FA to flexural strength of the OPS concrete (Tables 7 and 8). The variables *y* and *x* in Figs. 16 and 17, respectively resemble the flexural strength.

5.5. Tensile strength

The tensile strength results of OPS LWAC exposed to water and air curing is demonstrated in Figs. 18 and 19 correspondingly. The ratios of splitting strength to compressive strength OPS LWAC with fly ash in this study are 0.07. It is observed that the application of water curing fuels chemical reaction of cement and pozzolanic material resulting in the formation of primary and second CSH gel respectively. This condition boosts the bonding between aggregates resulting in higher strength of the lightweight concrete. Mix produced using 10% fly ash which outshines the rest recorded 2.01 MPa, making it fit for structural application which is in accordance with the condition stipulated in ASTM C330 [108]. The contribution of FA towards the splitting tensile strength is demonstrated statistically via the ANOVA test as tabulated in Tables 9 and 10. The splitting tensile strength of both air and water cured mixes, as well as its control specimen, is denoted by *y* and *x*, respectively (see Figs. 20 and 21).

5.6. Modulus of elasticity

Both Figs. 22 and 23 depict the effects of different percentages of fly ash on the stiffness of OPS lightweight aggregate concrete. The modulus of elasticity value of water cured OPS LWAC is higher than air curing. It is similar to the trend displayed in compressive strength, flexural strength and tensile strength result. The high humidity condition and the optimum amount of fly ash used ensures enhanced chemical response resulting in the generation of more CSH gel contributing to voids reduction thus increasing concrete stiffness. Modulus of elasticity for concrete records improvement when water curing is applied instead of air curing [83], and optimum pozzolanic ash is added as a mixing ingredient [3]. Tables 11 and 12 tabulates the ANOVA tests that were performed on both water and air-cured specimens. It is apparent from the p-value statistics that FA affect the elastic modulus of concrete. Figs. 24 and 25 represent the association between the control specimen as well as the FA-based specimens. The variables *y* and *x* in the figures are associated with the modulus of elasticity.

5.7. Water absorption

Fig. 26 shows the water absorption of OPS LWAC with fly ash is in the range of 3.06–6.91%. All these concrete are in the range of high-quality concrete as the amount of water absorbed is lower than 10% as stated by Ref. [105]. Evidently, the integration of 10% fly ash as sand replacement contributes to the lowest water absorption. The use of water curing also enhances the concrete impermeability. The resistance towards water infiltration is due to the secondary CSH gel that forms during the pozzolanic reaction that fills in the voids inside OPS LWAC structure creating denser and higher impermeable concrete. However, too much fly ash replacement or more than the optimum amount produces a stiffer concrete mix which is hard to compact. This produces concrete with higher voids thus ease the water penetration into the concrete. It is apparent that the use of a suitable quantity of fly ash diminishes the concrete pores but excessive use creates vice versa condition as illustrated in Fig. 27. Thus, it can be concluded that the presence of moisture in curing conditions and percentage of fly ash used effect the water absorption of OPS concrete.

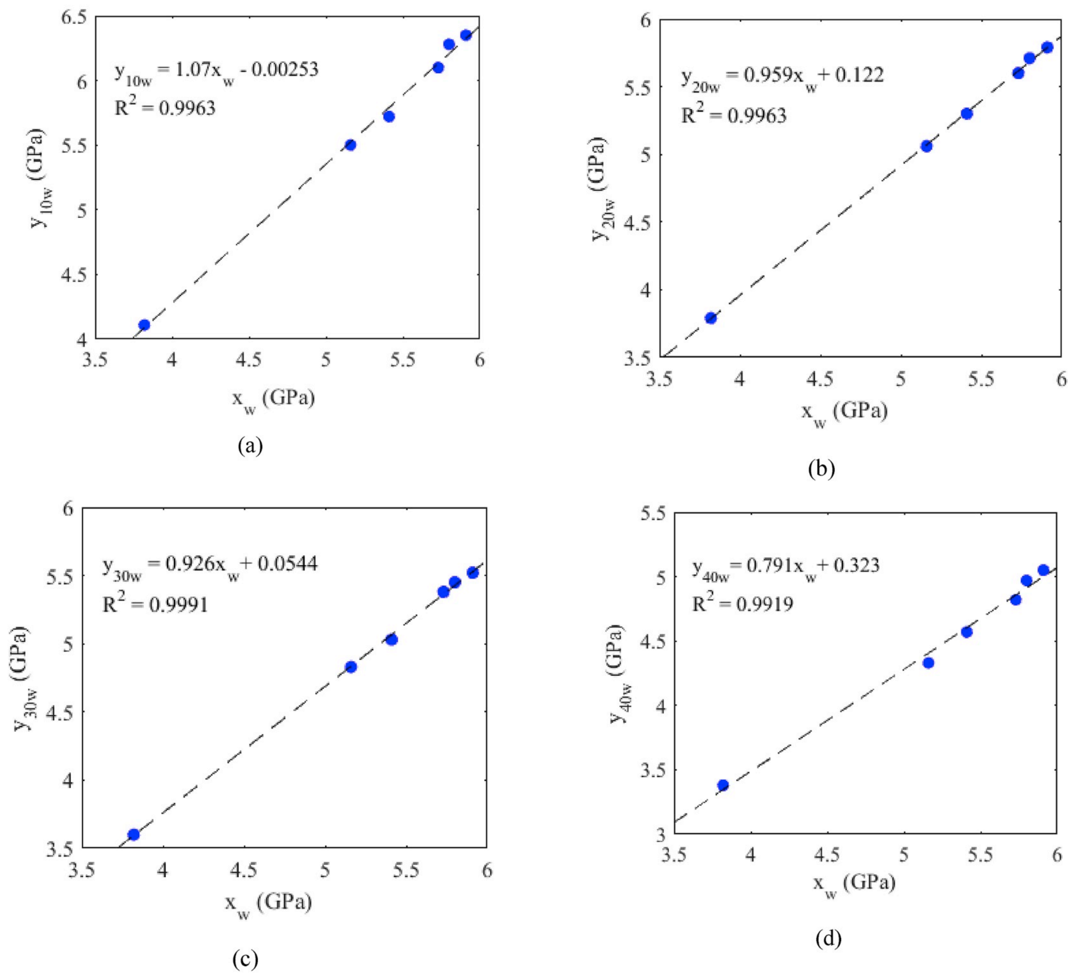

Fig. 24. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis for the water cured elastic modulus of the OPS concrete with various FA percentage replacement against the control specimen.

5.8. Sulphate resistance

Figs. 28 and 29 show the mass change of water cured and air-cured OPS concrete specimens immersed in sulphate solution up to 9 months, respectively. Specimen subjected to air curing is more affected by sulphate attack and losses more strength than water cured specimen, as shown in Fig. 30. Throughout the testing duration, highest mass change value was recorded by air-cured specimens with 40% FA followed by other specimens containing 30%, 20% FA and 0% FA. The trend remains constant until the end of the experimental work. Specimen containing 10% FA is the least affected and 40% is the most damaged with evident aggregate chippings and fine cracks on the concrete surface as illustrated in Fig. 31. Integration of 40% of fine FA in the concrete mix results in the driest mix of all, thus making it harder to compact, thus producing voids upon hardening. As a result, the sulphate ion easily penetrates the concrete then reacts with calcium hydroxide forming expansive gel known as ettringite, forcing physical changes in the hardened internal structure and further deterioration.

Water cured OPS LWAC with 10% FA is the most durable owing to the pozzolanic action of fly ash that consumes the vulnerable calcium hydroxide and produces secondary CSH gel. Obviously, the mix containing FA 10% experience the lowest strength deterioration value of all mixes. Concrete formed using optimum pozzolan content, performs better in sulphate solutions as the quantity of the calcium hydroxide is reduced, and the internal structure is densified through the increment of binding gel resulting from pozzolanic action. The enhanced durability of concrete containing pozzolanic material as a mixing ingredient has been reported by other researchers [109]. Conclusively, substituting an ideal amount of FA with sand, results in OPS LWAC that has better durability aspects than control specimens.

6. Conclusions

The concluding remarks of this study's results are:

1. Oil palm shell lightweight aggregate concrete with 10% fly ash as partial sand replacement exhibits the highest compressive, flexural, and splitting tensile strengths, and modulus of elasticity as compared to the control specimens.
2. The water curing regime has proven its suitability for oil palm shell lightweight aggregate with fly ash as it gives an adequate quantity of water to enhance the chemical reactions by cement and pozzolanic material to form CSH gel as a vital binding agent.
3. The moisture provided by curing conditions has its impact on water absorption of OPS LWAC with fly ash as it produces denser concrete with lowest water absorption value.
4. The integration of 10% fly ash to take the place of fine aggregate improves the durability of OPS LWAC by compacting further the concrete's internal structure, making it having a lower water absorption characteristic.

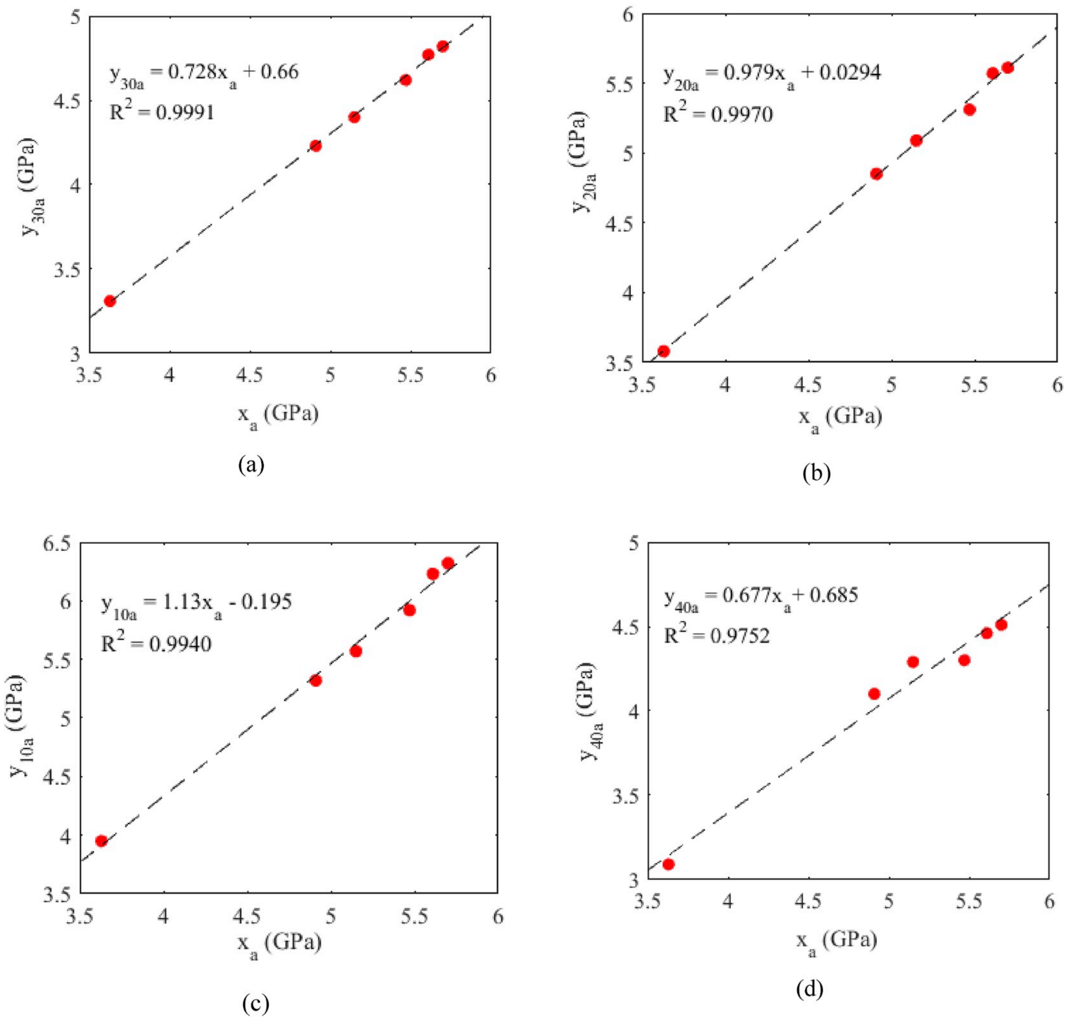

Fig. 25. (a) MFA-10, (b) MFA-20, (c) MFA-30 and (d) MFA-40 are regression analysis for the air-cured elastic modulus of the OPS concrete with different FA percentage against the control specimen.

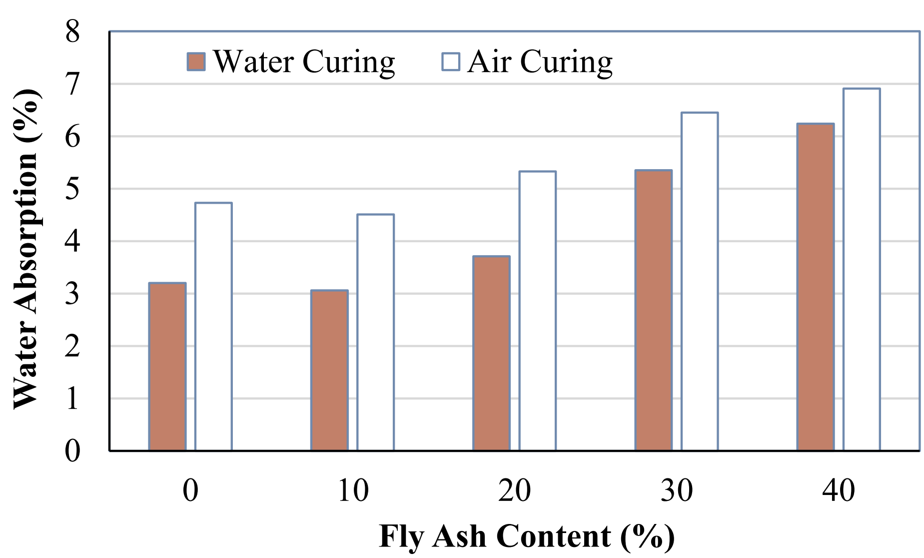

Fig. 26. Water absorption result.

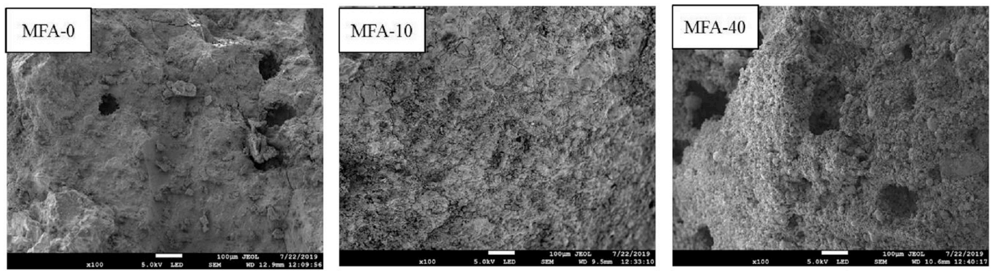

Fig. 27. Presence of voids in water cured concrete containing different fly ash content.

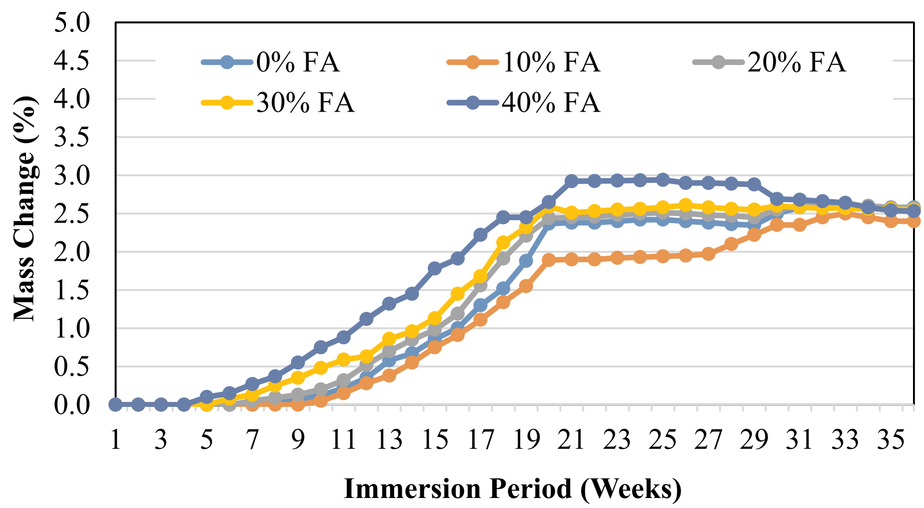

Fig. 28. Mass change of OPS LWAC with FA for water curing.

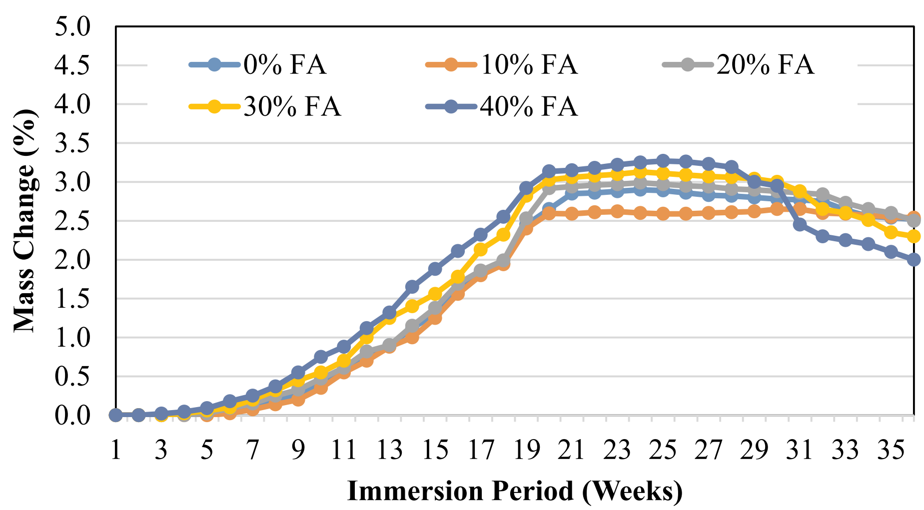

Fig. 29. Mass change of OPS LWAC with FA for air curing.

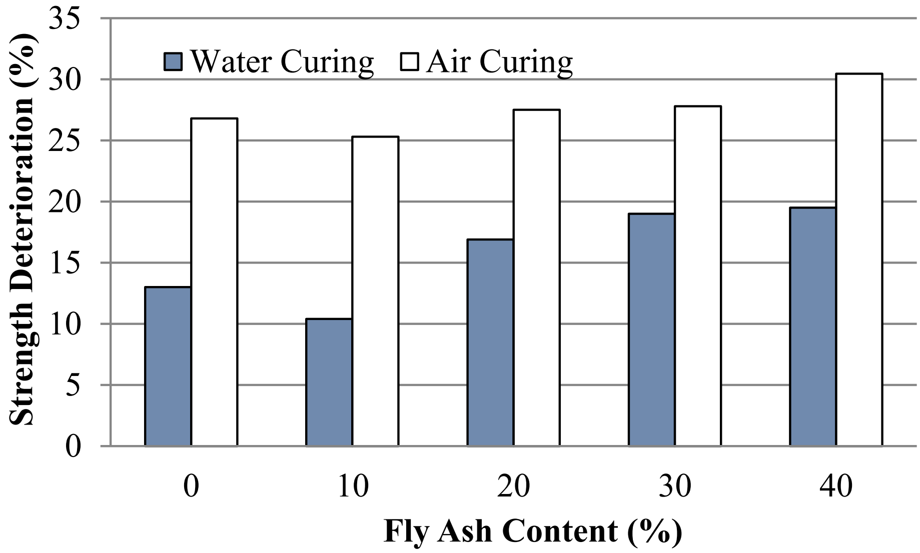

Fig. 30. Strength deterioration of water cured and air-cured OPS LWAC with FA after exposure to sulphate solution.

Fig. 31. Physical damage on air-cured concrete with various FA content after immersed in sodium sulphate solution.

5. During the exposure period to sulphate solution, OPS LWAC, which cured in water has experienced the lowest mass change with the least strength deterioration value of all specimens.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2019.100924.

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