INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
VOL. 14 NO. 2 (2023) 31-40

IJSCET

http://publisher.uthm.edu.my/ojs/index.php/ijscet

ISSN : 2180-3242 e-ISSN : 2600-7959

International Journal of Sustainable Construction Engineering and Technology

Investigation on Mechanical Strengths and Carbon Foot Print of Modified Foamed Concrete

Koh Heng Boon[1*], Zainorizuan Mohd Jaini[1], Tan Tee How[2]

[1]Faculty of Civil Engineering and Built Environment
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA

[2]Faculty of Built Environment
Tunku Abdul Rahman University College, Jalan Genting Kelang, Setapak, 53300 Kuala Lumpur, MALAYSIA

*Corresponding Author

DOI: https://doi.org/10.30880/ijscet.2023.14.02.004
Received 30 January 2023; Accepted 07 February 2023; Available online 08 May 2023

Abstract: This paper describes the work of a study carried out to investigate the mechanical strengths and carbon foot print of foamed concrete incorporating with local industrial wastes. Experiments were performed to obtain a minimum 28 days compressive strength of 15 MPa modified foamed concretes by using palm oil fuel ash (POFA) and fly ash (FA) as partial cement replacement and unprocessed rush husk ash (RHA) as partial fine aggregate replacement. Carbon footprint analysis was carried out by determining the CO_2 emission for each constituent materials in the modified foamed concrete mixes. Although incorporation of POFA in the foamed concrete containing RHA fine aggregate gained lower mechanical strengths compared to the use of FA, the minimum compressive strength is still can be attained. In terms of the sustainability, modified foamed concrete with 30% POFA or 30% FA was found an encouraging reduction of carbon foot print up to about 30% compared to the control foamed concrete. Based on eco-strength indicator, the optimum foamed concrete mix with POFA was found to be at 22.5% cement replacement level. The eco-modified foamed concrete has good potential in civil engineering construction and environmentally friendly.

Keywords: Modified foamed concrete, mechanical strengths, low carbon foot print, environmentally friendly

1. Introduction

Foamed concrete is a lightweight and versatile construction material. Foamed concrete commonly exhibits low density with intermediate strength (Albiajawi, M. I, 2022) and excellent thermal insulation. The thermal conductivity of foamed concrete is only 5% to 30% to a normal concrete (ASTM International, 2014). Production of foamed concrete is similar as normal concrete, which requires ordinary Portland cement (OPC) as the main binding material. However, the cement content used in foamed concrete is generally higher than normal strength concrete. It is reported that to manufacture one ton of cement, there is approximately one ton of carbon dioxide (CO_2) emitted. Half of the emissions are due to the decarbonation process whereby limestone $CaCO_3$ is reduced to calcium oxide, CaO. The high operation temperature of rotary kiln is another contributor to the CO_2 emission. The CO_2 emission from cement production constitutes is up to 5 - 7% to the total worldwide CO_2 emission (Awal, A. A. & Hussin, M. W., 2011). Thus, the use of cement replacement material is necessary to reduce the emission of CO_2. Pozzolan from the agricultural and industrial is the most viable choices for the cement binder sustainable development (Awang, H. & Al-Mulali, M., 2016).

Corresponding author: koh@uthm.edu.my

Agricultural wastes such as rice husk ash (RHA) and palm oil fuel ash (POFA) were found to be exhibit pozzolanic activity and could be potential used as supplementary cementitious material in blended cement (Bayuaji, R., 2015).

POFA is a type of waste generated from palm oil mill through burning of the waste materials, such as empty fruit bunches (EFB), palm oil kernels, fibres and shells (Benhelal, E., 2013). Palm oil industry is one of the biggest and leading industry in Malaysia. It is estimated that about 10 million tons of total solid wastes per year have been generated by approximately two hundred palm oil mills in Malaysia (British Standards Institution, 2022). These wastes are usually burnt as biomass fuel in boiler, with high temperature ranging from 800ºC to 1000ºC to generate electricity. The residue that is left in the boiler is known as POFA. Due to pozzolanic characteristics and abundance of POFA, research of POFA incorporation in concrete has been studied and many advantageous properties had been discovered, such as improvement in mechanical strengths as well as durability properties with optimum amount of POFA. 90 days compressive and splitting tensile strengths of lightweight concrete were improved compared to control concrete when up to 20% of POFA was used as cement replacement (Bayuaji, R., 2015). Concrete with approximately 10 – 20% of POFA as cement replacement exhibited a higher splitting tensile strength (British Standards Institution, 2010). Experimental result showed that the compressive strength of foamed concrete was able to improve with up to 25% cement replacement with POFA (Deepak, T., 2014).

RHA is an agricultural waste generated from the process of burning rice husk. Rice husk is burnt as fuel to generate heat for rice drying purpose. It is usually burned under controlled temperature, which is below 800ºC. The colour of rice husk ash depends on the burning process, it is usually black, grey or pinkish-white (Department of Standards Malaysia, 2014). It is reported that incorporation of RHA in concrete reduces the permeability and heat of evolution of concrete (Fantilli, A. P. & Chiala, B., 2013). The incorporation of RHA as cement replacement less than 20% is able to improve the strength and workability of foamed concrete (Flower, D. J. M. & Sanjayan, J. G., 2007) (Hamada, H. M., 2018). RHA can be used as sand replacement up to 40% in foamed concrete (Jones, M. R. & McCarthy, A., 2005). The improvement in compressive strength was reported to be attributed to the pozzolanic reaction and reactive silica in the RHA.

Considering that foamed concrete is more commonly used for non-structural purposes, this provides a better avenue for incorporation of waste materials due to its more favourable acceptance compared to the use as structural concrete. Therefore, this study is aimed at investigating the effects of POFA and RHA as cement and sand replacement materials, respectively on foamed concrete. Additionally, the influence of POFA is compared with that of a more commercially available cement replacement material, i.e. fly ash (FA) in foamed concrete. The workability, compressive and splitting tensile strengths of the foamed concrete are assessed to evaluate the feasibility of incorporating these agricultural waste materials. In addition, as part of the sustainability study of the developed foamed concrete, the CO_2 emission factors of the foamed concrete mixes constituting of different amount of binder materials are estimated.

2. Experimental Programme

2.1 Materials

Ordinary Portland cement (OPC) conforming to the standard MS EN 197-1:2014 (Juma, A. & Sai, E. R., 2012). was used as the main binding material. POFA and FA are incorporated as partial cement replacement material for this investigation. POFA collected from local palm oil mill was oven dried at temperature of 105 °C ± 5 °C for 1 hour to remove the moisture, followed by grinding for 5 hours using a Los Angeles machine. Besides, the FA was obtained from Sejingkat Power Corporation Sdn. Bhd and it was used in as received condition.

The fine aggregate used to produce foamed concrete consists of a combination of river sand and RHA. The sand was dried until saturated surface dry (SSD) condition and then sieved through a 2.36 mm sieve. The particle size distribution of sand is shown in Figure 1. The RHA was collected locally and utilized in as-received condition without further processing.

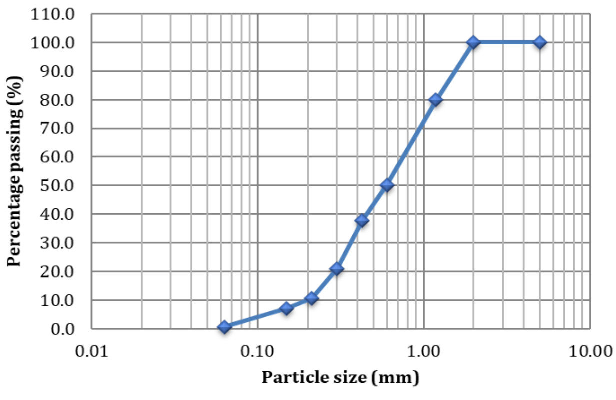

Fig. 1 - Particle size distribution of river sand

The chemical composition of RHA, POFA and FA was investigated through X-ray fluorescence (XRF) test and given in Table *1*. The SiO_2 content of RHA, POFA and FA was reported to be 76%, 44.7% and 61.29%, respectively. The RHA had the highest SiO_2 content, followed by FA and POFA. The silica content is important in strength improvement, particularly when used at finer fractions. The strength of concrete is increased as the silica content is increased (Kawabata, C. Y., 2012). This is due to pozzolanic reaction that occurs between silica dioxide and calcium hydroxide to produce calcium silicate hydrate (C-S-H), a gel compound that will contribute strength to the concrete. The FA could be classified as a class-F pozzolan as the total SiO_2, Al_2O_3 and Fe_2O_3 contents exceeded 70%. In order to produce the foamed concrete, the pre-forming method was adopted.

Table 1 - Major chemical compositions

Oxide	RHA (%)	POFA (%)	FA (%)
Silica Dioxide (SiO_2)	76.0	44.70	61.29
Aluminium Oxide (Al_2O_3)	0.2	16.10	24.41
Iron Oxide (Fe_2O_3)	0.2	3.61	5.84
Calcium Oxide (CaO)	0.7	3.41	1.84
Magnesium Oxide (MgO)	0.7	0.52	1.88
Sodium Oxide (Na_2O)	-	0.14	0.22

Synthetic based foaming agent (SikaAER®-50/50) was diluted with the tap water with the ratio of foaming agent to water of 1:20. The pre-formed foam was produced using a foam generator. Besides, superplasticizer (Estop Admix AP) was also added to facilitate workability.

2.2 Mix Proportion

Error! Reference source not found. shows the mix proportion of modified foamed concrete mixes with POFA or FA as partial cement replacement material and RHA as sand replacement material. The targeted wet density for all of the mixes is set at 1700 kg/m^3. For the fine aggregate, a fixed percentage of 40% RHA was used to replace the river sand by volume. The variable adopted is the POFA replacement level (by volume), namely 7.5%, 15.0%, 22.5% and 30.0%. In order to facilitate comparison, FA was used at equal content as POFA. In addition, the water binder (W/B) ratio in this study was fixed at 0.55 and a dosage of 0.55% superplasticizer by weight of binder was added to facilitate workability.

Table 2 - Mix proportion

Mix	Cement (kg/m^3)	POFA (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	RHA (kg/m^3)	Water (kg/m^3)
C	500	-	-	552	56	275
P7.5	462.5	30	-	552	56	275
P15	425	60	-	552	56	275
P22.5	387.5	90	-	552	56	275
P30	350	120	-	552	56	275
F7.5	462.5	-	30	552	56	275
F15	425	-	60	552	56	275
F22.5	387.5	-	90	552	56	275
F30	350	-	120	552	56	275

2.3 Mix Procedure and Testing

OPC, POFA, FA, RHA and river sand were weighed accordingly to the mix design and placed in a drum mixer. Water was added gradually into the dry mix followed by superplasticizer. Pre-formed foam extracted from the foam generator was added until the desired wet density was attained, i.e. at approximately 1700 kg/m^3. The fresh mix was then subjected to a slump flow test to determine the workability, as shown in Figure 2. Finally, the fresh foamed concrete mix was poured into moulds and left in the laboratory for 24 hours. The specimens were de-moulded after 24 hours and cured in ambient laboratory condition until the age of testing.

Fig. 2 - Spread of foamed concrete

The slump flow test on the foamed concrete was conducted according to ASTM C1611 (Khankhaje, E., 2016). In order to measure the slump flow, the fresh foamed concrete mix was placed into an inverted slump cone without compaction. The cone was then raised and the fresh mix was allowed to spread. Two diameters of the spreads were measured in approximately orthogonal directions and the average of measurements was reported as the slump flow for each mix. 100 mm cube specimens were used for the compressive strength test and the test was conducted in accordance to BS EN 12390-3 (Koh, H. B. et al., 2006). Meanwhile, cylinder specimens having diameter of 150 mm and 300 mm height were used for evaluating the splitting tensile strength of the foamed concrete. The splitting tensile test was conducted according to BS EN 12390-6 (Lawrence, C.D., 1998). Each test was conducted on the specimens at the age of 7, 14 and 28 days. Three specimens were tested for each case and the average value was reported.

3. Results and Discussions

3.1 Workability

Figure 3 shows the slump flow of modified foamed concrete with different percentages of POFA and FA as cement replacement material. It was observed that slump flow for the control mixture was 310 mm. Research done by Lim et al. (Lim, S. K. et al., 2013) investigated plain foamed concrete with different w/c ratio, namely 0.46 to 0.52, and the slump flow was reported within the range of 413 to 559 mm. The reason for having lower slump flow was possibly due to incorporation of RHA as replacement of fine aggregate. RHA is considered to be more porous compared to normal sand, and this increased the water demand of the fresh mix, hence reducing its workability. Another possible reason is the high surface area of RHA due to its internal pore surface. Greater amount of paste was required to coat the higher surface area of the RHA, and therefore reduced the lubricating effect of paste which decreased the flowability of the fresh mix. Nevertheless, all of the fresh foamed concrete mixtures could still exhibit adequate flowability.

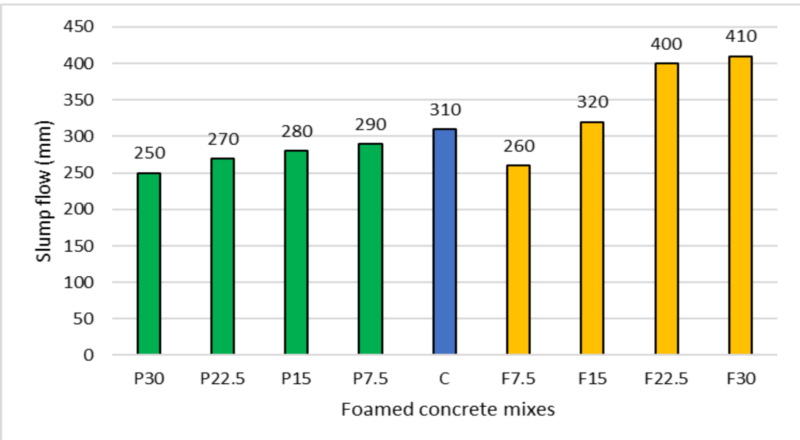

Fig. 3 - Slump flow of foamed concrete with incorporation of POFA and FA

In terms of the influence of POFA on the workability of foamed concrete, a trend of reduction in slump flow with increasing amount of POFA was observed. This finding was similar to those reported by Lim, S. K. et al., 2013. As shown in Figure 3, up to about 19% of reduction in slump flow was found when up to 30% POFA was incorporated as cement replacement. The reduction in workability was largely due to the inherent characteristics of POFA (Deepak, T. et al., 2014). The porous nature of POFA resulted in greater free water absorption from the slurry during mixing process. Besides that, the irregular and angular shape of POFA increases the water demand of the mix to lubricate the surface of the POFA particles. Hamada et al. (Lim, S. K. et al., 2013) revealed that the reason for workability of concrete incorporated with POFA to decrease was due to the high unburnt carbon content in POFA. On the other hand, the trend of slump flow in the foamed concrete due to the use of FA was found to be different than that observed for POFA. It was generally observed that, at higher replacement levels exceeding 15%, the slump flow of the foamed concrete increased. This was attributed to the spherical shape of fly ash which provided 'ball bearing' and lubrication effects, and thus enhanced the slump flow (Mo, K. H. et al., 2014)

3.2 Compressive Strength

Figure 4 shows the compressive strength of modified foamed concrete with different POFA contents over curing periods of 7, 14 and 28 days. It is generally observed that compressive strength of foamed concrete at all ages was decreased as the percentage of POFA used to replace cement increased. The reduction in compressive strength could be due to dilution effect caused by the reduce cement content. The lower amount of cement, the lesser amount of hydration products would be formed. Moreover, it was reported that concrete incorporated with POFA would release lower heat of hydration (Neville, A. M., (1995). The lower heat of hydration could have cause slower reaction and hydration of cement, resulting in lower strength, particularly at early ages. Nevertheless, the reduction in compressive strength of the foamed concrete was little, as only up to only about 20% reduction was observed when the POFA was used at 30%. On the other hand, Awang and Al-Mulali (Deepak, T. et al., 2014) reported that the compressive strength of foamed concrete was increased when the replacement of cement with POFA was up to 25%. The difference in the influence of POFA could be possibly due to the different source of POFA used in the study, since the SiO_2 content of POFA used in this study was lower at 44.7% compared to that of 66.6% reported by Awang and Al-Mulali (Deepak, T. et al., 2014). The lower SiO_2 content could have resulted in a lower pozzolanic reactivity of the POFA and eventually led to a lower compressive strength of the foamed concrete. Another possible reason may be due to incorporation of RHA as sand replacement. Even though RHA possesses pozzolanic characteristics, however, water absorption by both the RHA and POFA particles may result in reduction of the overall free water. This lower water content could have slowed down the cement hydration process, resulting in the lesser amount of calcium hydroxide being produced. Hence, due to the limited availability of calcium hydroxide, the pozzolanic reaction could have been limited and therefore affect the development of strength in the foamed concrete.

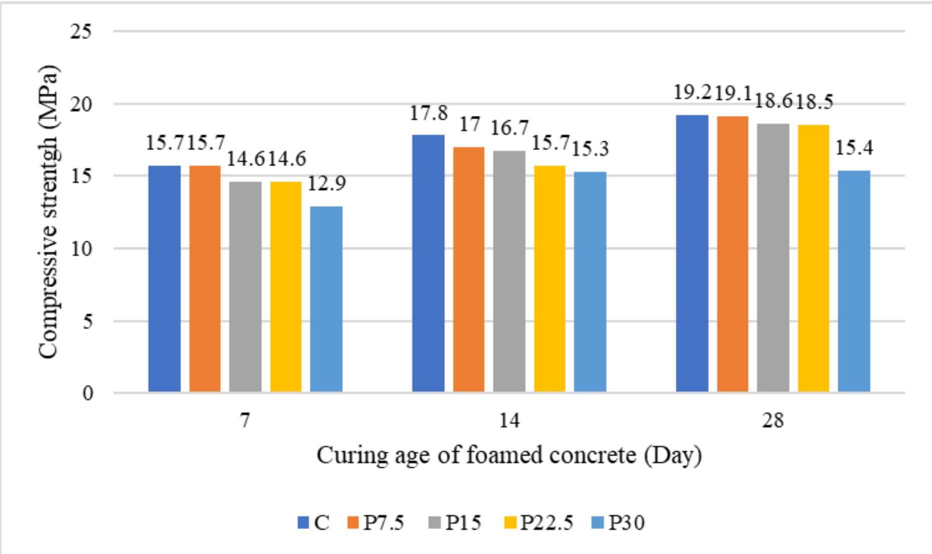

Fig. 4 - Compressive strength of modified foamed concrete containing POFA

Although the compressive strength of the foamed concrete was decreased when amount of POFA was increased, the reduction in strength for the P7.5, P15, and P22.5 mixes was not very significant, and only differed by a maximum of about 4% compared to the control mix without POFA. It is noteworthy that for all of these foamed concrete mixes containing POFA (up to 22.5%), the compressive strength was more than 17 MPa, which exceeded the minimum compressive strength requirement for structural lightweight concrete (Ramamurthy, K. et al., 2009).

In the case of foamed concrete containing FA, it was found that the inclusion of FA increased the 28-day compressive strength. Referring to Figure 4, the highest compressive strength was observed for the mix F15, which recorded an approximately 23% of increment compared to the control mix. However, higher FA contents would gradually reduce the compressive strength although the mixes could still exhibit higher strength than the control foamed concrete mix. The outcome corresponds well with the findings reported by Wang (Ramezanianpour, A. & Ahmadibeni, G., 2009). When lower amount of FA incorporated, the pozzolanic reaction could be more prevailing, as the FA could react with the available calcium hydroxides to impart strength to the foamed concrete. However, when higher amount of fly ash is incorporated, the dilution effect is more critical, resulting in lesser calcium hydroxide available for fly ash to react with, thereby slightly affecting the strength gain. Besides that, it should be noted that the 7-day compressive strength of foamed concrete was decreased when all levels of FA was incorporated. This occurrence is primarily due to the commencement of pozzolanic reaction only at later ages and the dilution effect was more prevailing at this early age. Similarly, Thomas (Rum, R. H. M. et al., 2017) revealed that incorporation of FA in concrete will develop a lower early age compressive strength due to the lower heat of hydration.

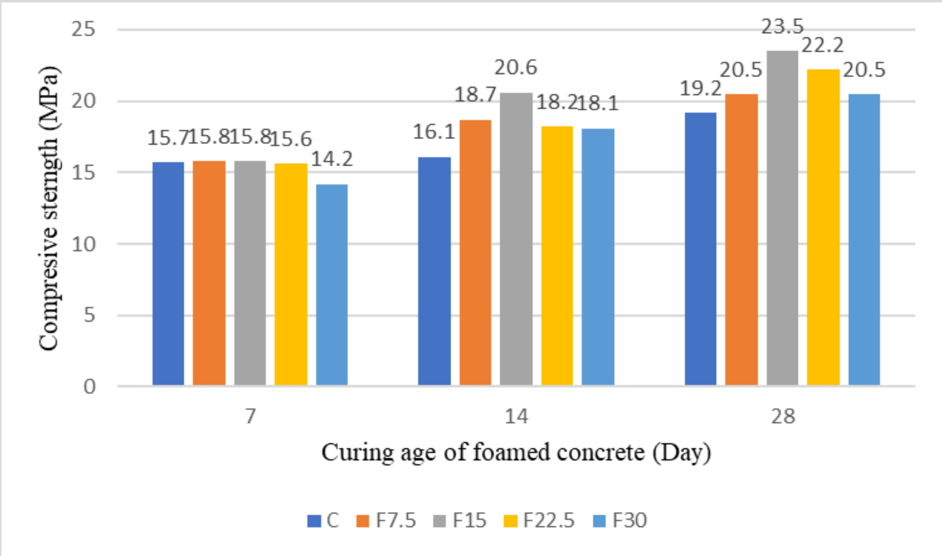

Fig. 5 - Compressive strength of modified foamed concrete containing FA

When comparing the 7-day compressive strength of foamed concrete containing POFA and FA, there was minimal difference between the two, as only a difference of 1 - 10% was found. As such, the use of POFA in place of commercially available supplementary cementitious material is possible when adequate early strength is required and the ultimate strength is not the prime consideration. When the 28-day compressive strength is considered, the compressive strength of foamed concrete with POFA as cement replacement was about 23 – 33% lower compared to the foamed concrete produced with FA. This is because of the higher SiO_2 content of FA than POFA, which contributed to better pozzolanic reactivity for the former, hence achieving higher ultimate compressive strength.

3.3 Splitting Tensile Strength

Splitting tensile strength of foamed concrete containing different percentages of POFA as cement replacement is shown in Figure 6. It is observed that the splitting tensile strength was increased when the percentage of POFA used to replace cement increased up to 22.5%. Beyond that, the splitting tensile strength starts to decrease. P22.5 showed the highest splitting tensile strength at 28 days, which is 1.87 MPa while the control mix exhibited the lowest 28-day splitting tensile strength, which was only 1.57 MPa.

On the other hand, it is observed that the effect of FA on splitting tensile strength of foamed concrete was almost similar to POFA, in which the splitting tensile strength was increased when the amount of FA increased. Figure 7 shows the splitting tensile strength of foamed concrete with FA as cement replacement. However, a lower strength development was noticed. At day 7, the splitting tensile strength showed an increment up to F15. Beyond that, the splitting tensile strength was decreased. This is possibly due to incorporation of high amount of FA retarded the early strength development. Nevertheless, after 28 days, all of the foamed concrete containing FA demonstrated strength gain and exceeded the splitting tensile strength of the control mix. The compressive strength of the F30 mix was found to be

2.15 MPa, which represents a 15% increment compared to control mix. The improvement is likely due to the continuous pozzolanic reaction of FA as the curing age increased.

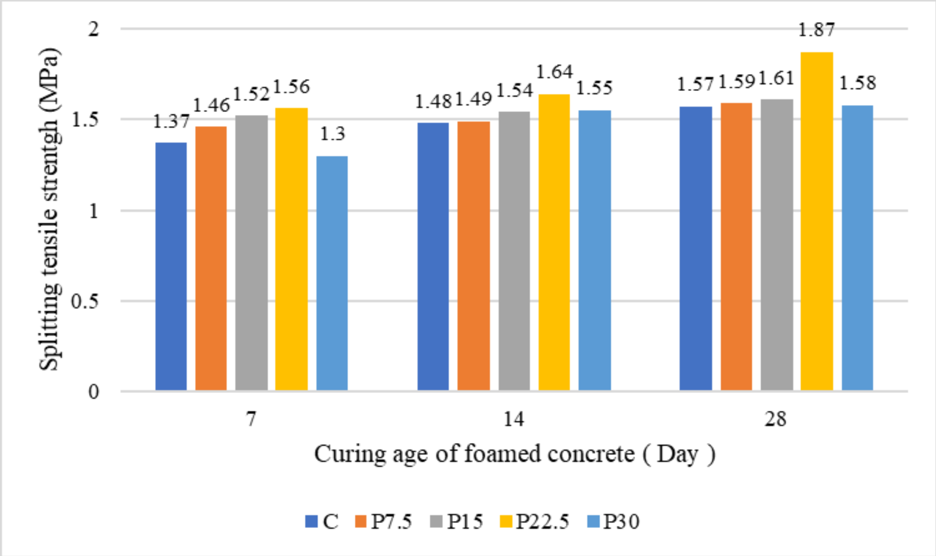

Fig. 6 - Splitting tensile strength of modified foamed concrete containing POFA

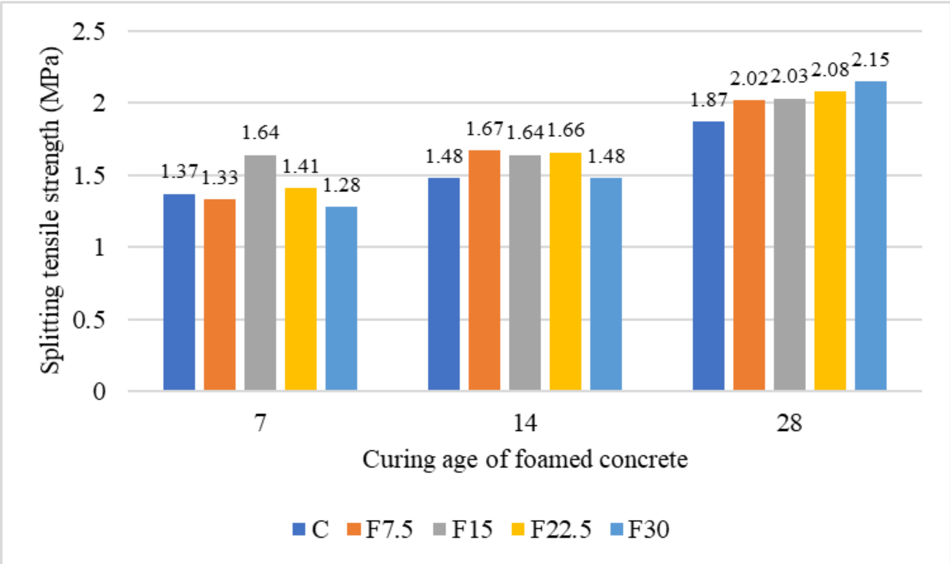

Fig. 7 - Splitting tensile strength of modified foamed concrete containing FA

Similar to the observation from the compressive strength results, the 7-day splitting tensile strength of foamed concrete with POFA as cement replacement did not show much difference compared to the corresponding concrete containing FA. Only a minimal difference of about 2 – 5% was observed. However, a higher difference between foamed concrete containing POFA and FA was noticed for the case of splitting tensile strength after 28 days. The difference was approximately 12 – 28 % as this was thought to be primarily caused by the difference in SiO_2 content and hence pozzolanic activity between the two different types of materials, as explained in the earlier section.

3.4 Carbon Footprint

As this study was to explore the feasibility and sustainability of incorporating the agriculture wastes of POFA and RHA into foamed concrete, a carbon footprint analysis was carried out. This was done via determining the CO_2 emission for each of the constituent materials for the developed foamed concrete mixes. The amount of CO_2 emission for each particular component was calculated, based on 1 m^3 of foamed concrete. The emission value for OPC was taken as 0.82 t CO_2-e/tonne, which took into account the process of decomposition of lime, grinding and heating kiln and also transportation. For river sand, the CO_2 emission value was reported at 0.0139 t CO_2-e/tonne (Sata, V. et al., 2007). Since RHA and POFA are essentially wastes from the agriculture industry, therefore the CO_2 emission was considered as null for the calculation. FA, however, is no longer considered as waste and the CO_2 emission value was taken into account, which was reported to be 0.0270 t CO_2-e/tonne (Sata, V. et al., 2007). Due to the relatively low amount of chemical admixtures used (superplasticizer and foaming agent), these are not considered in the CO_2 emission analysis. The analysis which was done is presented in Table 3.

Table 3 - Estimated carbon dioxide emission for 1 m^3

Mix	Binder content (kg/m^3)			CO_2-e for binder (t)	Fine aggregate (kg/m^3)		CO_2-e for fine aggregate (t)	Total CO_2-e of foamed concrete (t/m^3)
	OPC	POFA	FA		River sand	RHA		
C	500	-	-	0.4100	552	56	0.0077	0.4177
P7.5	462.5	30	-	0.3793	552	56	0.0077	0.3869
P15	425	60	-	0.3485	552	56	0.0077	0.3562
P22.5	387.5	90	-	0.3178	552	56	0.0077	0.3254
P30	350	120	-	0.2870	552	56	0.0077	0.2947
F7.5	462.5	-	30	0.3801	552	56	0.0077	0.3877
F15	425	-	60	0.3501	552	56	0.0077	0.3578
F22.5	387.5	-	90	0.3202	552	56	0.0077	0.3279
F30	350	-	120	0.2902	552	56	0.0077	0.2979

It can be observed that the CO_2 emission of all of the mixes containing cement replacement was lower than control mix and the reduction is significant; a reduction as high as 30% and 29% were noticed for P30 and FA30 compared to control mix. This is attributed to the reduction of cement content in the mix considering that cement is the major contributor of CO_2 emission. The overall CO_2 emission was also lower for the foamed concrete containing POFA compared to FA, though the difference was only slight.

In order to effectively evaluate the influence of POFA in terms of the strength and carbon footprint of the foamed concrete, an eco-strength indicator was adopted based on the performance index done by the previous researchers (Thomas, M., 2007) (Wang, X. Y., 2014). The eco-strength indicator was determined by the ratio of amount of CO_2 emission to the 28-day compressive strength of foamed concrete, which is denoted as I_{es}. Figure 8 presents the eco-strength indicators for all of the mixes. A lower value of I_{es} indicates a better optimization in terms of the strength and carbon footprint for the concrete. All of the mixes were found to exhibit a lower I_{es} value compared to the control mix, and were in the range of 15 – 22 kg/MPa.

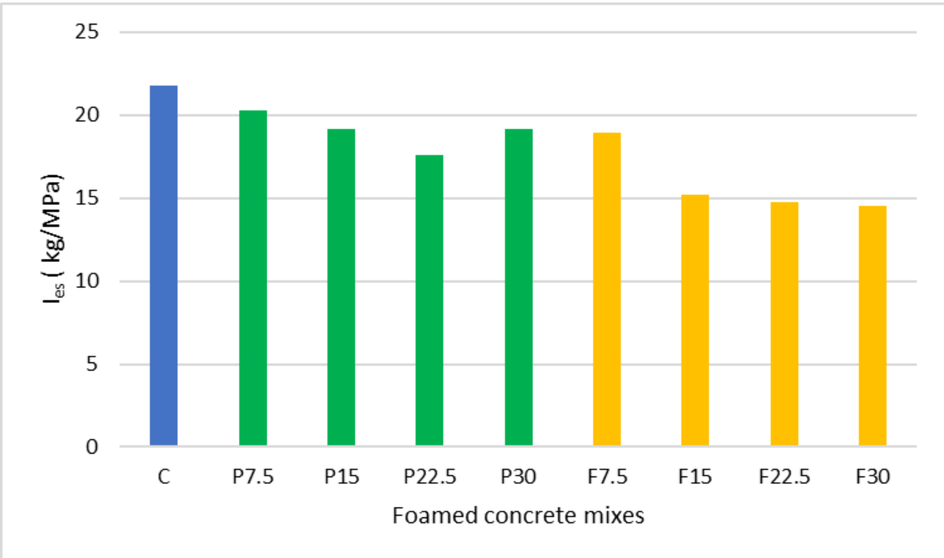

Fig. 8 - Eco-strength indicators for foamed concrete mixes

It can be observed that eco-efficiency of the foamed concrete improved in the presence of up to 30% POFA. This meant that in the presence of POFA, despite the reduction in compressive strength, the reduction in CO_2 emission was more significant. However, the best eco-efficiency among the POFA mixes was observed to be the mix with 22.5% POFA. At 30% POFA, the I_{es} was higher than the P22.5 mix as the reduction in compressive strength had a more prevailing effect over the reduction in CO_2 emission. Besides that, it was observed that for foamed concrete incorporated with FA, the I_{es} was lower than the corresponding concrete mixes with POFA. Therefore, in terms of the sustainability consideration, for foamed concrete containing POFA, P22.5 is recommended whereas F30 is recommended for foamed concrete containing FA.

4. Conclusions

This study investigated the mechanical strengths and carbon footprint of foamed concrete incorporating industry wastes namely fly ash (FA), palm oil fuel ash (POFA) and rice husk ash (RHA). The properties of the foamed concrete were focused on the workability, compressive strength and splitting tensile strength. Meanwhile, the carbon footprint for the foamed concrete mixes was estimated by calculating the amount of CO_2 emission for each of the constituent materials.

It was observed from the experimental work that, workability of foamed concrete was decreased when amount of POFA was increased while incorporation of FA in foamed concrete the workability was improved. The increase in POFA content reduced the compressive strength whereas the use of FA at all levels increased the compressive strength of foamed concrete. The splitting tensile strength of foamed concrete of all mixes containing POFA and FA were increased compared to control mix. Regarding the carbon footprint analysis, all mixes showed a lower CO_2 liberation compared to the control mix. An approximately of 30% of reduction in CO_2 emission were noticed for the modified foamed concrete incorporating 30% POFA or 30% FA. By considering the performance of compressive strength and emission of CO_2, the optimum amount of POFA and FA as the cement replacement in foamed concrete is 22.5% and 30%, respectively.

Acknowledgement

Communication of this research is made possible through monetary assistance by Universiti Tun Hussein Onn Malaysia and the UTHM Publisher’s Office via Publication Fund E15216.

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