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Correlations Between Compressive, Flexural and Tensile Strengths of Foamed Concrete Strengthened with Oil Palm Biomass Wastes

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Abstract: ***Owing its superior features, such as low in density, excellent thermal properties and great fire resistance performance, foamed concrete is gaining acceptance in the construction industry. Nevertheless, foamed concrete is weak in tension. Foamed concrete reinforced with fibers has amplified due to its boosted properties after cracking of the cementitious matrix. Hence, fibers from spikelets and stalks from oil palm biomass wastes were used to scrutinize the correlations between compressive, flexural and tensile strengths of foamed concrete in this study. The fibers content was maintained to 0.45% of volume fraction for all mixes and the mixes were modified to different densities which were 600kg/m^3, 1200kg/m^3 and 1800kg/m^3. Then, the compressive, flexural and tensile strengths of the foamed concrete were measured at 7, 28, 60 and 180 day. The result showed a general trend that the engineering properties of foamed concrete increased as its density increased and the desirable result could be achieved with the inclusion of stalks and spikelets in the foamed concrete. Finally, the empirical equations were established and coefficient of determination (R^2) was obtained at different ages through the regression analysis. The comparison between the correlations of the engineering properties, made in terms of R^2 of the polynomial regression, showed that all of the relations were obtained high value which is in range 0.96-0.99.***

Keywords: foamed concrete, biomass waste, compressive, flexural, tensile, oil palm

I. INTRODUCTION

Malaysia is known as one of the major contributors of palm oil which has been exporting their productions that cover up to 80% of global palm oil. Despite of this vast production, the palm oil is found limited from the total wastes that has been produced. Subsequently, the present of these wastes can conceive disposal problems to the country which is a negative impact on environment when it is merely abandoned on the plantation fields [1].

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There is an immense amount of lignocellulosic biomass that not efficiently utilized are developed by trunk, frond and fruit bunch of oil palm tree. For example, Fig. 1 shows the oil palm empty fruit bunch (EFB) were left behind at the oil palm mills after the oil refining process. Therefore, these remaining wastes are a factor that turns a country into a crisis due to the inquisition of the oil palm sustainability [2].

Fig. 1. Oil palm EFB left at the oil palm mills after the oil refining process

Instead of that, previous researchers have discovered a wide range of application from the implementation of oil palm biomass wastes in the construction materials. Accordingly, there is a tendency to utilize the oil palm biomass wastes in manufacturing new products for sustainable construction materials [3]. Thus, the oil palm biomass wastes are considerable for this study as the wastes is classified as non-hazardous biodegradable materials where the application in the construction industry is in the quest for environmental importance. However, the efficiently utilization of the oil palm biomass wastes in the sustainable construction materials should not only solve a major disposal problem in order to reduce the environmental impact, but the advantages of the material properties can be used to modify the flaws in the construction materials. For example, microcracks that exist in the foamed concrete have limited its application in the construction industry [4].

In addition, the microcracks that will begin to propagate in the matrix when load is applied is caused by poor in tension resistance. Due to this situation, additional reinforcing elements in tensile zone are required to sustain the tensile stress from the applied forces.

Therefore, the use of foamed concrete strengthened with fibers such as steel, glass, synthetic and natural fiber has increased due to its enhanced properties after cracking of the cementitious matrix [5]. However, the inclusion of synthetic fiber is often inferred as an alternative because of the steel fiber are easily exposed to corrosion. Despite of that, high consumption of energy and expenses during the manufacturing of synthetic fiber has introduced the option to the exploitation of natural fiber in the foamed concrete [6].

As compared to the glass fiber, the natural fiber can be recyclable and not easily brittle during processing. Next, researchers such as Othuman Mydin and Wang [7] and Khalil *et al.* [8] found that the length of fiber is directly affect its tensile strength. Then, Norgaard and Othuman Mydin [9] verified this in a study which mentioned that the higher content of cellulose in the fiber prompts higher strength in tensile. As a consequence, the inclusion of oil palm biomass wastes in the foamed concrete is applied to study the behavior of engineering properties of cementitious matrix with natural fiber as the usage of other type of fibers are not completely suggested in the previous researches due to some drawbacks. The correlations between engineering properties of foamed concrete strengthened with oil palm biomass wastes is used as an extensive study. The foamed concrete that is lightweight and has capability to heat resistance are discovered can incorporate with other materials to control the engineering properties and its structural integrity [10]. Moreover, the EFB are preferred to be used as compared with other sources of fiber from oil palm tree. It has potential to be produced in large quantity which make it continually available thus low value in the market. However, there are two different component parts of EFB which are stalks and spikelets that need to be considered. From the previous study, spikelets is believed to be nominated as reinforcing fiber due to its higher tensile strength if compared to stalks [11]. In addition, based on the study conducted by Othuman Mydin *et al.* [12], the percentage of fibers between stalks and spikelets of EFB dry weight are in the range of 20–32% and 68–80% respectively. It is clearly indicated that there are more fibers in the spikelets then in the stalks from EFB thus make spikelets be a reliable resource in order to attain the need for new applications. Besides that, the attention in natural fiber has also grown in both of the academic and construction industry as natural fiber is increasingly viewed as a green alternative product. Hence, this study was conducted to scrutinize the correlations between compressive, flexural and tensile strengths of foamed concrete strengthened with oil palm biomass wastes. The finding will direct the future researchers to a clear interpretation on the engineering properties of foamed concrete when it incorporates with oil palm wastes. Then, increase the potential utilization of oil palm biomass wastes in the foamed concrete, minimize the disposal needed by one of the agricultural wastes and finally reduce the environmental deterioration that caused by pollutions.

II. METHODOLOGY

In this study, cement, fine aggregate, water and fiber were used to produce foamed concrete. The detail descriptions of the following materials were included below.

Ordinary Portland Cement (OPC)

OPC which complied to BS 12: 1996 was used as the main binder material.

Sand

Particle size of fine aggregate that suitable to be used for foamed concrete should be less than 4mm. In addition, specimens prepared with finer sand gradations obtained higher compressive and flexural strengths because the courser sand will settle in the cementitious matrix thus the foam will collapse during the process of mixing. Hence, additional sieved required to remove particles greater than 1.18 mm for this study. Acceptable strength was also possible to achieve for foamed concrete by using fine aggregate that having smaller particle size. Besides, the flow characteristics and stability of the foamed concrete can also be improved.

Water

Water is the most important agent used to fulfil the most important function of the concrete mixing. It enables the binder content undergo hydration process and helps in the workability. Furthermore, the low quality of water that used can also affect the foamed concrete that formed by using protein-based foaming agent. Therefore, clean and portable tap water has been used as accordance to BS 3148:1980 in this study.

Foaming agent

The most common foaming agents which have been used around the world are synthetic and protein based. The synthetic foaming agent is very stable for the formation of foamed concrete which having densities above 1000kg/m^3 while the protein foaming agent is more competent for the formation of 400-1600kg/m^3 of density of foamed concrete because the structure of bubbles that has been produced by this type of foaming agent will enable the large quantity of air to enter it and provide a stable network to air void. Besides, this study adopted the studies conducted by *Nafu et al.* [13] which used protein based foaming agent and it was diluted with water to a ratio of 1:40 and then aerated to a density of 65 kg/m^3. Portafoam TM-2 foam generator was used to produce the stable foam.

Fibers

Untreated raw stalks and spikelets were utilized as a supplementary material for foamed concrete in this study. Stalks and spikelets have about 2-4cm long and brown in color. The untreated raw stalks and spikelets fibers were shown in Fig. 2(a) and (b).

Fig. 2(a). Stalks

Fig. 2(b). Spikelets

Development of mix design

The desired properties of foamed concrete were obtained by trial and error method which by controlling the amount of cement, sand, water and foam as there is no specific mix proportion method. This method is acceptable as a technique to design foamed concrete. In this study, the target densities that need to be obtained were 600kg/m^3, 1200kg/m^3 and 1800kg/m^3.

However, 50kg/m^3 of tolerance was considered. The specimens were let in an oven for 24 hours at 110˚C after demoulding.

Then, the dry density of the foamed concrete was measured immediately after the specimens were cooled down for 2 hours after taking the specimens from the oven. Next, the fiber content was maintained to 0.45% of volume fraction for all mixes in this study because the water absorption characteristics that having by natural fiber will reduced the workability of fresh concrete if a higher amount of fiber was introduced as mentioned by previous researchers [14]. In addition, the ratio of water and cement for all mixes was adjusted to obtain a diameter measurement which in range 20-24mm for a flow table test.

Preparation techniques

This section presents the procedures to prepare the mixes. As the first step, the cement and sand were blended in a mixer. Then, the mixture was added with water and continued mixing. Afterward, the flow table test was performed and wet density of the mortar was checked to estimate the volume of foam that needed in order to produce the desired mix. Plastic moulds of 100mm cubes and 100mm diameter x 200mm height cylinders were used to evaluate the compressive and tensile strengths respectively.

Besides, steel moulds of 100x100x500mm prisms were used to evaluate the flexural strength. All the specimens were demould at 24 hours after casting. As the present of water can promote the hydration process of foamed concrete for strength development, the specimens were put in water before wrapping with plastic wrap. Then, the specimens were kept until 7, 28, 60 and 180 day for testing.

The compressive, flexural and tensile strengths of the specimens were evaluated based on the average of three specimens. The tests were conducted by using Universal Testing Machine (GOTECH GT-7001-BS300) as specified in the MS EN 12390-3:2012 and MS 26: Part 2:1991.

III. RESULTS

The results of compressive, flexural and tensile strengths of foamed concrete strengthened with oil palm biomass wastes which were stalks (ST) and spikelets (SP) with different densities and ages were presented in Table 1-3. The control (C) results also included for the comparison purposed. There was a general trend that could be seen from the Table 1 which indicated that the increment of density of foamed concrete could enhanced its compressive strength. However, the increment of compressive strength of foamed concrete were up to 52% and 87% for ST and SP respectively as compared with the control.

It demonstrated that the results were become more intense with the inclusion of fiber such as ST and SP in the foamed concrete. Therefore, density and incorporation of fiber were attributes to the strength characteristics of foamed concrete. This finding was also parallel with the previous researches conducted by Othuman Mydin *et al.* [15].

Table 1. Compressive strength results

Density (kg/m^3)	Specimen	Compressive Strength (N/mm^2)			
		7-day	28-day	60-day	180-day
600	C-600	0.96	1.36	1.44	1.60
	ST-600	1.12	1.68	2.01	2.32
	SP-600	1.36	1.92	2.24	2.72
1200	C-1200	3.95	4.88	5.12	5.35
	ST-1200	5.32	6.75	7.44	8.14
	SP-1200	6.89	7.79	8.99	9.99
1800	C-1800	10.22	11.26	11.46	11.65
	ST-1800	11.64	12.44	12.99	14.00
	SP-1800	12.47	13.61	14.36	15.01

The reduction of compressive strength of foamed concrete was due to the enlargement of void diameter existed in the foamed concrete especially for density lower then 1000 kg/m^3. Meanwhile, the compressive strength of foamed concrete for higher density was depended on spacing factor between the air voids. In conclusion, the air void system in foamed concrete was a major factor that contributes to the results of compressive strength. However, the present of fiber in the foamed concrete has filled the air voids in the foamed concrete. This finding was in agreement with [28] who found that the fiber inclusion was believed increased the solidity of physical structure of foamed concrete thus improved its compressive strength.

Table 2. Flexural strength results

Density (kg/m^3)	Specimen	Flexural Strength (N/mm^2)			
		7-day	28-day	60-day	180-day
600	C-600	0.16	0.25	0.28	0.31
	ST-600	0.25	0.38	0.48	0.55
	SP-600	0.36	0.48	0.56	0.72
1200	C-1200	0.73	0.85	0.90	0.95
	ST-1200	1.31	1.56	1.74	1.99
	SP-1200	1.77	2.05	2.37	2.66
1800	C-1800	1.84	2.03	2.06	2.10
	ST-1800	2.68	2.86	2.99	3.22
	SP-1800	3.24	3.54	3.73	3.90

Furthermore, the results of flexural strength were presented in Table 2. It was clear described that the results were also directly correlated to its density in such a way that flexural strength increased with increasing the foamed concrete density. By each 600kg/m^3 addition in density, the flexural strength increased by 2.5 to 4.5 times its value. It was due to the value of air bubbles and the interconnection of them have been decreased as the density of foamed concrete increased. Therefore, water vapor permeability decreased and it was led to increment in strength of the foamed concrete.

Meanwhile, the cellular solid structure was different in the foamed concrete with higher density because the cell walls were thicker and pore spaces were smaller and isolated, thus, more applied loads were required to fail the samples.

However, the flaw of flexural though in foamed concrete can be lessened by incorporating an appropriate volume fraction of fiber. Previous study conducted by [14] also concluded that utilization of natural fiber can decrease the development of cracks and improve the stiffness of foamed concrete and its toughness.

Foamed concrete was found good in compression however fairly brittle under flexural and it was tending to be fragile.

From the experimental data obtained, the ratio of flexural strength of foamed concrete strengthened with ST and SP increased up to 27% of its compressive strength as compared to only 17% of control specimens. Thus, the incorporation of ST and SP in the foamed concrete offered some degree of strengthening by restricting the progress of cracks [16] and improving the bonding between matrix that could increase the fracture toughness.

Table 3. Tensile strength results

Density (kg/m^3)	Specimen	Tensile Strength (N/mm^2)			
		7-day	28-day	60-day	180-day
600	C-600	0.10	0.15	0.17	0.18
	ST-600	0.16	0.26	0.30	0.34
	SP-600	0.23	0.32	0.38	0.46
1200	C-1200	0.38	0.44	0.50	0.51
	ST-1200	0.80	0.96	1.04	1.19
	SP-1200	1.14	1.32	1.55	1.73
1800	C-1800	0.98	1.07	1.09	1.11
	ST-1800	1.63	1.75	1.82	2.10
	SP-1800	2.10	2.37	2.50	2.61

Moreover, to investigate the tensile strength of foamed concrete, Table 3 presented the result of specimens that having different densities and ages. The results indicated that tensile strength was recorded 61% as the highest ratio from its flexural strength while 12% as the highest ratio from its compressive strength for the control specimens.

The incorporation of ST and SP in foamed concrete could increase the ratio to 68% from its flexural strength and 17% from its compressive strength. In conclusion, the fiber scattered throughout the foamed concrete developed the bonding between matrix which caused the specimens with oil palm biomass wastes resulted in 5-8% increment of the strengths. The engineering properties of the foamed concrete could be improved if adequate fiber was added.

IV. DISCUSSION

As shown in Fig. 3-14, the regression analysis was carried out on the series of data that taken at different densities from Table 1-3 to establish a general relationship between the engineering properties. Through the regression analysis, the prediction curves of the empirical relations and coefficient of determination (R^2) were obtained at different ages.

A. Compressive-Flexural Strengths Relationship

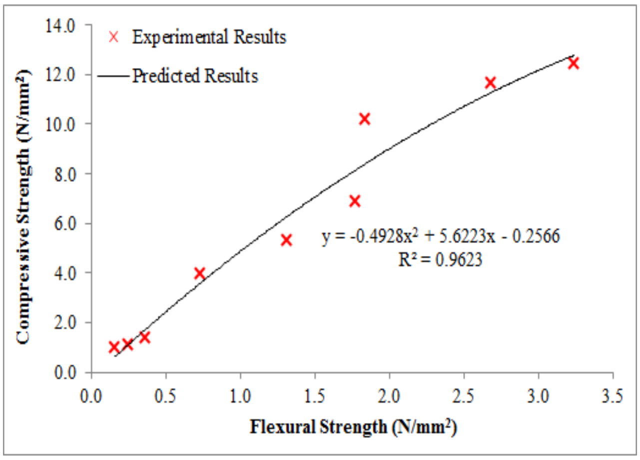

Fig. 3. Compressive vs Flexural Strength (7-day)

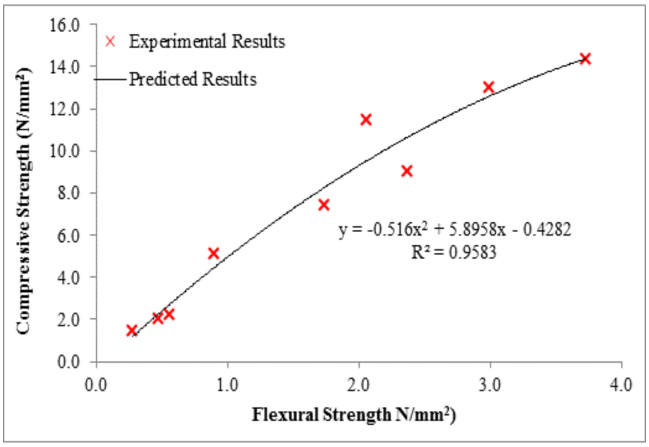

Fig. 4. Compressive vs Flexural Strength (28-day)

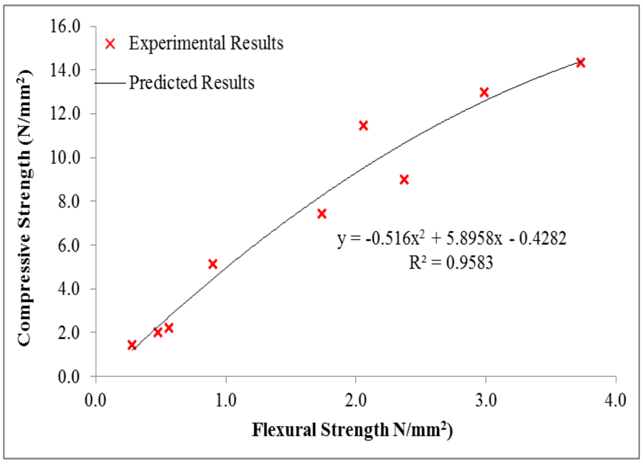

Fig. 5. Compressive vs Flexural Strength (60-day)

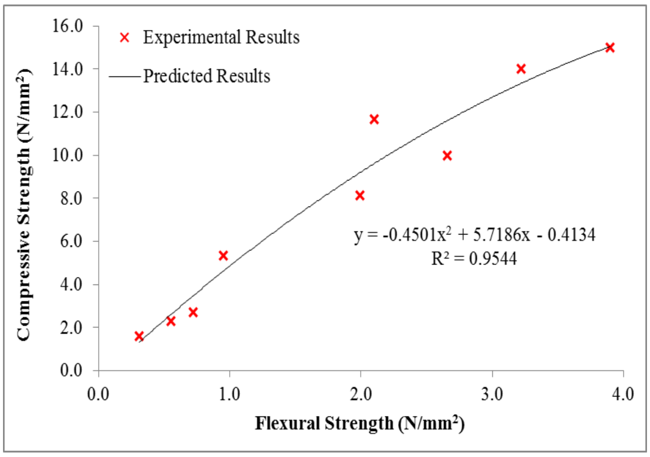

Fig. 6. Compressive vs Flexural Strength (180-day)

The correlation between flexural and tensile strengths was illustrated in Fig. 3-6 and the results were presented accordingly at 7, 28, 60 and 180 day. The polynomial relationship was used due to data fluctuating trend and it appeared to have 0.96 as the highest R^2 value among other trend line.

For 7-day, the empirical equation was:
f_{ck}=-0.4928$(f_f)^2$+5.6223(f_f)–0.2566 (R^2=0.96) (1)

For 28-day, the empirical equation was:
f_{ck}=-0.516$(f_f)^2$+5.8958(f_f)–0.4282 (R^2=0.96) (2)

For 60-day, the empirical equation was:
f_{ck}=-0.516$(f_f)^2$+5.8958(f_f)–0.4282 (R^2=0.96) (3)

For 180-day, the empirical equation was:
f_{ck}=-0.4501$(f_f)^2$+5.7186(f_f)–0.4134 (R^2=0.95) (4)

where f_t represents the flexural strength in N/mm^2 and f_{ck} the compressive strength in N/mm^2.

Based on the analysis, the regression analysis indicated that the empirical equations showed in (1)-(4) were applicable to determine the value for flexural strength with corresponding compressive strength. In addition, the correlations of these proposed relations were in range 95-96% which indicated a strong correlation between both engineering properties.

B. Flexural-Tensile Strengths Relationship

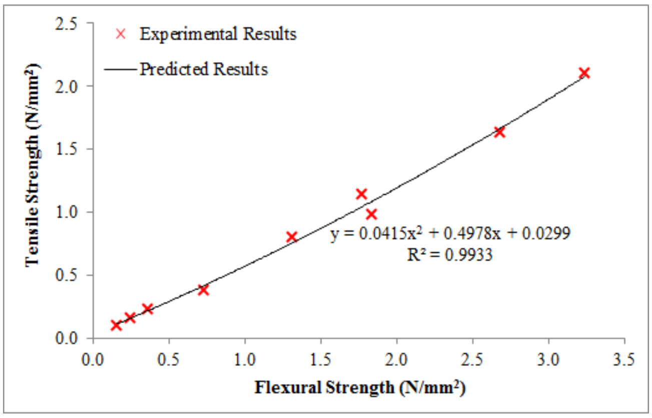

Fig. 7. Flexural vs Tensile Strength (7-day)

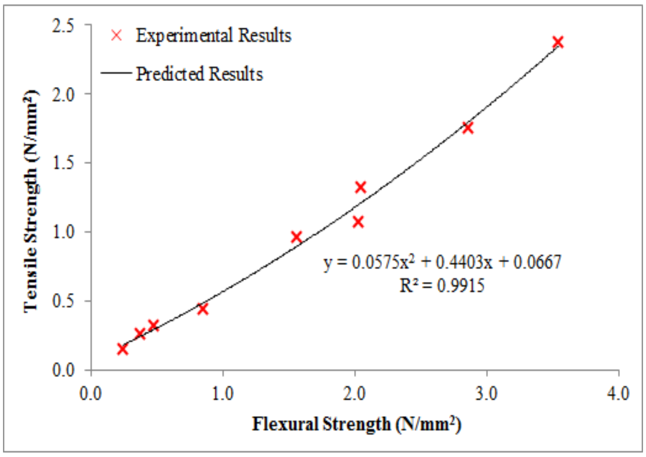

Fig. 8. Flexural vs Tensile Strength (28-day)

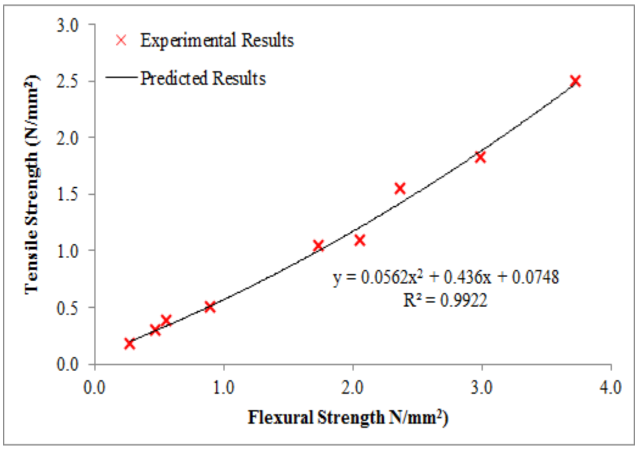

Fig. 9. Flexural vs Tensile Strength (60-day)

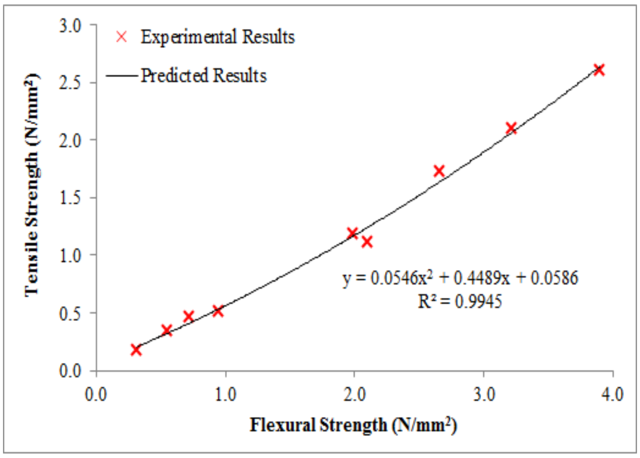

Fig. 10. Flexural vs Tensile Strength (180-day)

The correlations between flexural and tensile strengths were illustrated in Fig. 7-10 and the results were presented accordingly at 7, 28, 60 and 180 day. The polynomial relationship was used due to data fluctuating trend and it appeared to have 0.99 as the highest R^2 value for all trend line.

For 7-day, the empirical equation was:
f_t=0.0415$(f_f)^2$+0.4978(f_f)–0.0299 (R^2=0.99) (5)

For 28-day, the empirical equation was:

$f_t = 0.0575(f_f)^2 + 0.4403(f_f) – 0.0667 \quad (R^2 = 0.99) \qquad (6)$

For 60-day, the empirical equation was:

$f_t = 0.0562(f_f)^2 + 0.436(f_f) – 0.0748 \quad (R^2 = 0.99) \qquad (7)$

For 180-day, the empirical equation was:

$f_t = 0.0546(f_f)^2 + 0.4489(f_f) – 0.0586 \quad (R^2 = 0.99) \qquad (8)$

where f_f represents the flexural strength in N/mm^2 and f_t the tensile strength in N/mm^2.

Based on the regression analysis, the value of flexural strength could be applied in the empirical equations that showed in (5)-(8) in order to determine its tensile strength. The correlations of these proposed relations were 99% which indicated that there is strong correlation.

C. Compressive-Tensile Strengths Relationship

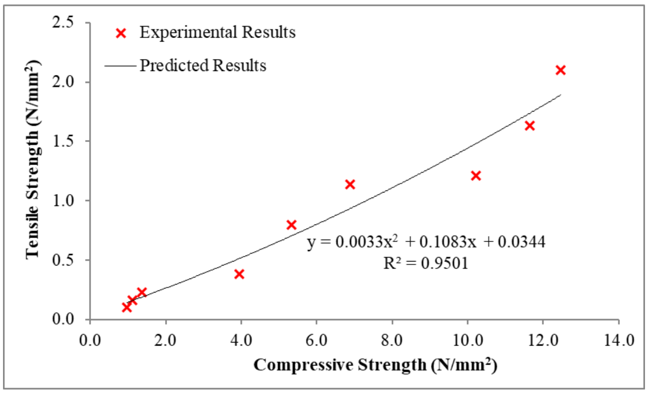

Fig. 11. Compressive vs Tensile Strength (7-day)

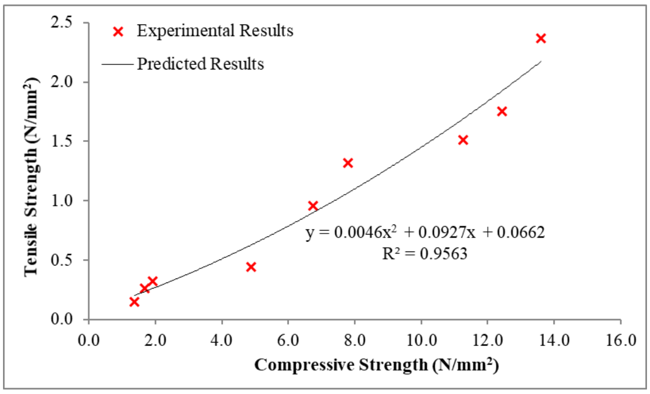

Fig. 12. Compressive vs Tensile Strength (28-day)

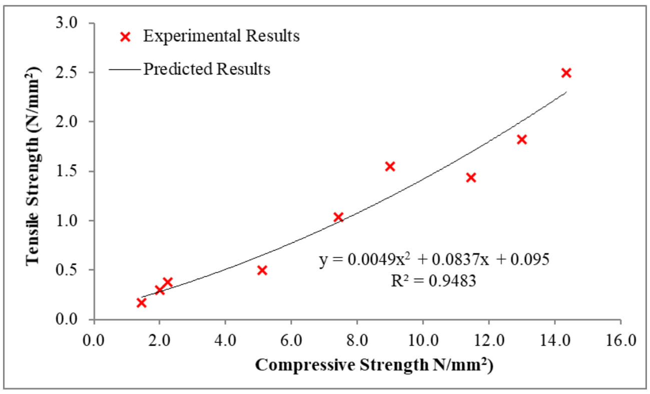

Fig. 13. Compressive vs Tensile Strength (60-day)

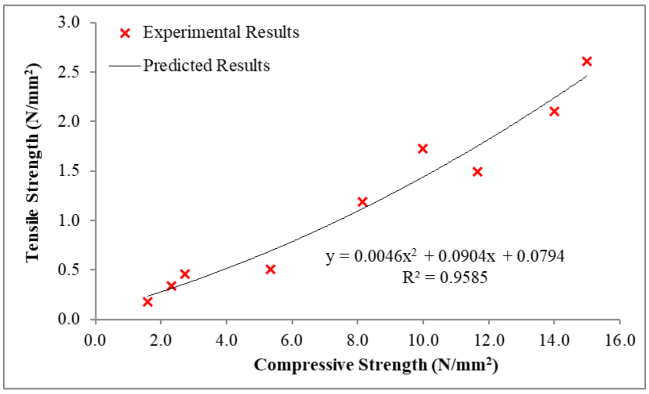

Fig. 14. Compressive vs Tensile Strength (180-day)

The correlation between compressive and tensile strengths were illustrated in Fig. 11-14 and results were presented accordingly at 7, 28, 60 and 180 day. The polynomial relationship was used due to data fluctuating trend and it appeared to have 0.96 as the highest R^2 value among other trend line.

For 7-day, the empirical equation was:

$f_{ck} = 0.0033(f_t)^2 + 0.1083(f_t) – 0.0344 \quad (R^2 = 0.95) \qquad (9)$

For 28-day, the empirical equation was:

$f_{ck} = 0.0046(f_t)^2 + 0.0927(f_t) – 0.0662 \quad (R^2 = 0.96) \qquad (10)$

For 60-day, the empirical equation was:

$f_{ck} = 0.0049(f_t)^2 + 0.0837(f_t) – 0.095 \quad (R^2 = 0.95) \qquad (11)$

For 180-day, the empirical equation was:

$f_{ck} = 0.0046(f_t)^2 + 0.0904(f_t) – 0.0794 \quad (R^2 = 0.96) \qquad (12)$

where f_t represents the tensile strength in N/mm^2 and f_{ck} the compressive strength in N/mm^2.

Based on the analysis, the regression analysis indicated that the empirical equations shown in (9)-(12) were applicable to determine tensile strength with corresponding compressive strength. In addition, the correlations of these proposed relations were in range of 95%-96% which indicated strong correlation.

V. CONCLUSIONS

This study was performed to dissect the correlations between compressive, flexural and tensile strengths of foamed concrete with the addition of spikelets and stalks from oil palm biomass wastes. The drawn conclusions can be summarized as follows:

1. Based from the statistical analysis on the experimental data obtained, general relationship between the engineering properties that have been established showed in (1)-(12) were applicable for the foamed concrete strengthens with oil palm biomass wastes which are stalk and spikelets.
2. Although the relationship between the engineering properties was empirical, the R^2 value of equations which range between 0.95-0.99 was an indication that there was strong correlation between the parameters.
3. The value of compressive strength was sufficient to determine the corresponding flexural and tensile strengths of the mix with an acceptable degree of accuracy from the empirical equations that have been obtained.

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