

# Influence of High Performance Hybrid Polyvinyl Alcohol-Polypropylene Fibres on Mechanical Properties of Oil Palm Shell Lightweight Concrete

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## ABSTRACT

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The mechanical properties of oil palm shell (OPS) lightweight concrete (LWC) reinforced with high performance of polyvinyl alcohol (PVA) fibre and polypropylene (PP) fibres were investigated in this study. The influence of single PVA fibre, single PP fibre and hybrid PVA-PP fibre with different volume fraction on the compressive strength, flexural load-extension curve and water absorption of OPS LWC were investigated. The test results indicate that, the strength of OPS LWC reinforced with single PVA fibre or PP fibre improved with the increase of fibre content. However, the compressive strength and water absorption enhances slightly, while the flexural strength improved significantly. When the two types of fibres are mixed into OPS LWC simultaneously, the results show positive and negative of synergy effects. The positive synergy effect of hybrid 0.25% PVA and 0.035% PP had showed the optimum results as compared to different volume fraction of mixes. It shows that, compressive strength and flexural strength increased by 5.5% and 22.1% respectively, while the water absorption decreased 23.1% compared with those of OPS LWC without fibres. Hence, the findings of this paper revealed that the combination with both high performance polymeric fibres can be used to develop more sustainable building materials.

### Keywords:

Lightweight concrete, polyvinyl alcohol fibre, polypropylene fibre, oil palm shell, mechanical properties, stress-strain relationship

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## 1. Introduction

Concrete is the most widely used construction material since it has the lowest ratio between strength to cost as compared to other available materials. It has been reported that, normal concrete exhibits poor tensile properties and low ductility [1,2]. Therefore, the inclusion of fibres to the plain concrete can significantly enhance the concrete mechanical properties especially for tensile strength [13,19]. Normal weight concrete (NWC) reinforced with fibres was developed for the requirements of high tensile strength, toughness and durability [6,9]. Yew *et al.*, [19] reported that, the inclusion

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of single micro fibre can only slightly improve the performance of a single aspect of concrete. In order to enhance the overall performance of concrete, it should be achieved by mixing with macro fibres or hybrid with different micro-macro fibres [16]. Different types or geometry of fibres are mixed into concrete by a certain amount of admixture to form a workable hybrid fibre concrete. Various types of fibre rationally combined in a concrete matrix in order to take advantage of each individual fibre properties at different levels of structure strength and time to form a positive hybrid influence. Apart from that, the overall cost can be reduced to make a positive impact to the concrete performance by using cheaper macro synthetic fibres instead of metal fibres. Mo *et al.*, [6] reported that oil palm shell concrete reinforced with hybrid steel-polypropylene showed the positive impact resistance and flexural toughness. However, most of the experimental results showed that the compressive strength of single or hybrid fibre reinforced concrete has decreased compared with plain concrete although tensile strength and flexural toughness enhanced significantly [3,10,15]. Moreover, the researchers [19] investigated the performance of concrete reinforced with 0.5% volume fraction of polypropylene fibres resulted in 96% reduction as compared with plain concrete in the slump value. Park *et al.*, [7] indicated that the utilization of different types of fibres can be used to compensate the disadvantages of concrete in tension, and prevent micro-crack and macro crack propagation in concrete. Many researchers investigated the positive results of flexural toughness, restrained shrinkage, modulus of elasticity and permeability of single [4] and hybrid fibre reinforced concrete.

Polyvinyl alcohol (PVA) fibre is a high performance polymeric fibre with high stiffness and excellent performance. It has been widely used in many areas of durability [9,21]. The elastic modulus of PVA fibre can reach up to 20 GPa, which can be used to enhance the compressive strength of concrete matrix. The elastic modulus of structural polypropylene fibre is slightly low. However, it can form complementary advantages with PVA fibre in the concrete matrix to fulfil requirements of high strength lightweight concrete. Hybrid of PVA fibre and PP fibre to replace of steel fibre into NWC matrix have attracted great interests to improve the defect of steel fibre NWC corrosion, which can be used to improve the mechanical properties of NWC at different levels. Hybrid fibre HSLWC can be used to combine the advantages of hybrid fibre concrete reinforced with LWC. According to the current statistic report, the research in this field is not particularly mature. In order to make LWC application more widely use, this research will be conducted individual and hybrid mixed PVA fibre and PP fibre into LWC. The influences of the individual and hybrid fibres on the mechanical properties were investigated.

## 2. Materials and Methods

### 2.1 Cement

The cement used in the mixing was Ordinary Portland Cement (OPC) Type 1 which meets the ASTM: C150/C150M-12. The cement was manufactured by Tasek Corporation Berhard with a specific gravity of 3.14 g/cm<sup>3</sup>. The Blaine's specific surface area for this cement was 3510 cm<sup>2</sup>/g. The cement content was kept constant at 500 kg/m<sup>3</sup>.

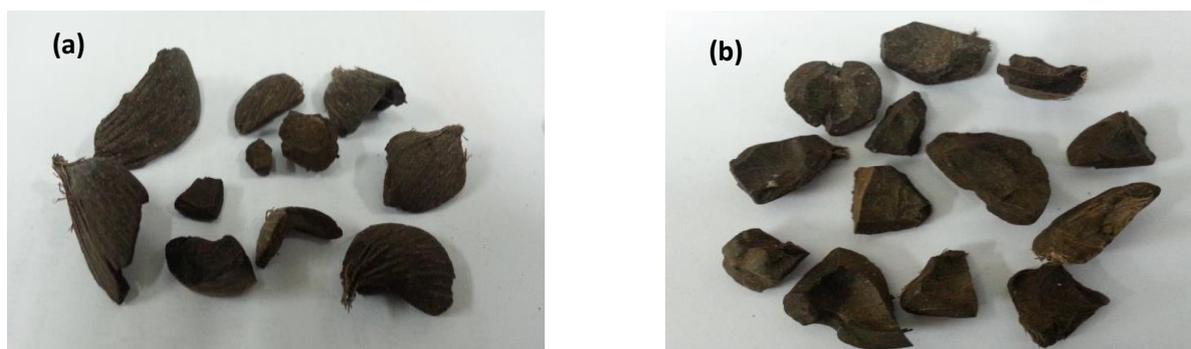
### 2.2 Water and Superplasticizer (SP)

Potable water with pH value of 6 was used for both mixing and curing. The water to cement ratio of 0.32 was used for all the mixes. The SP used in this study was polycarboxylic ether (PCE) supplied by BASF, which complies with [ASTM: C494/C494M-13](#). The SP was added in all the mixes at a constant amount of 1.2% of the cement weight in order to facilitate workability.

### 2.3 Fine and Coarse Aggregate

Local mining sand available from Hanson Quarry Selangor was used as the fine aggregate, having a specific gravity, fineness modulus, water absorption and maximum grain size of 2.68, 2.72, 0.97% and 4.75 mm, respectively. The fine aggregate was dried in an open air before use and was kept constant at  $865 \text{ kg/m}^3$  for all mixes.

In this study, crushed *dura* (Compared to *tenera* OPS) species was used as the coarse aggregate as shown in figure 1. The *dura* and *tenera* OPS were collected from local crude palm oil factory. The thickness of the OPS used throughout the research was 2.0 to 5.0 mm. Furthermore, OPS were washed and sieved using a 12.5 mm-sieve. The OPS aggregates that were retained in the sieve were crushed using a stone-crushing machine in the laboratory. The crushed *dura* OPS aggregates were sieved using a 9.5 mm-sieve to remove *dura* and *tenera* OPS aggregates with sizes more than 9.5 mm. For investigation of the size effect of OPS aggregate on compressive strength, crushed OPS aggregate sizes that were below 2.36 mm were removed and the sizes between 2.36 and 9.5 mm were used. The benefits of using crushed OPS aggregates in OPSC were reported by Yew *et al.*, [17]. In this study, OPS aggregates were heat-treated at  $130 \text{ }^\circ\text{C}$  over a period of 1 h using a temperature-controlled laboratory oven.



**Fig. 1.** Crushed (a) *dura* and (b) *tenera* OPS species between 2.36 and 9.5 mm

The heat-treated OPS will be rapidly cooling down by soaking under the water at  $22 \pm 2 \text{ }^\circ\text{C}$  as shown in figure 2. The OPS aggregates were subsequently air dried in the laboratory to attain an approximately saturated surface dry condition. A comparison between the physical properties of heat-treated and without heat-treated of crushed OPS aggregates is presented in Table 1, while the grading of *dura* and *tenera* OPS aggregates is presented in Table 2. The OPS content in all the mixes was kept constant at  $372 \text{ kg/m}^3$ .

**Table 1**

Comparison of the physical properties between heat-treated and without heat-treated *dura* and *tenera* OPS aggregates

Physical property	<i>dura</i> OPS	<i>dura</i> OPS*	<i>tenera</i> OPS	<i>tenera</i> OPS*
Maximum size (mm)	9.5	9.5	9.5	9.5
Specific gravity (saturated surface dry)	1.32	1.29	1.28	1.25
Finess modulus	5.70	5.76	5.78	5.90
Compacted bulk density (kg/m <sup>3</sup> )	623	617	628	620
Water absorption (1 and 24 h) (%)	12.10 and 19.61	10.02 and 17.15	12.06 and 19.55	9.96 and 17.08
Aggregate crushing value (%)	2.35	2.22	2.20	2.11

- Heat-treated

**Table 2**  
 Grading of OPS aggregates

Sieve size (mm)	Cumulative % by weight passing sieve size	
	Crushed <i>tenera</i> OPS (9.5 mm)	Crushed <i>dura</i> OPS* (9.5 mm)
19.05	100	100
12.5	100	100
9.5	100	100
8	93.55	93.40
4.75	21.46	20.38
3.35	8.37	8.26
2.36	4.78	4.28



**Fig. 2.** Microscopic images from the surface of OPS aggregates (a) heat treatment and (b) without heat treatment

**Table 3**  
 Physical properties of polyvinyl alcohol (PVA) and polypropylene (PP) fibre

Parameter	PVA fibre	polypropylene fibre
Length (mm)	30	25
Equivalent diameter (mm)	0.66	0.5
Aspect ratio (L/D)	45	50
Specific gravity (g/cm <sup>3</sup> )	1.3	0.91
Tensile Strength (MPa)	>800	>560
Elastic modulus (MPa)	>5000	> 3500
Melting Point (°C)	225	160-170
Ignition temperature (°C)	450	360
Water Absorption (%)	0	0
Alkali Resistance	Excellent	Strong

### 3. Mix Proportions

A total of four mixes were prepared. The mix proportions of all the concrete mixes used in this study are presented in Table 4. The dosage of water and superplasticizer were kept constant for all mixes.

**Table 4**  
Mixture proportion (kg/m<sup>3</sup>)

No.	Mix code	Cement	Water	W/C ratio	Fine Aggregate	OPS	Duration (h)	Temperature (°C)
						HT		
1	PVA0/PP0	500	160	0.32	865	372	1	130
2	PVA0.285/PP0	500	160	0.32	865	372	1	130
3	PVA0/PP0.285	500	160	0.32	865	372	1	130
4	PVA0.25/PP0.035	500	160	0.32	865	372	1	130

Note: HT = heat-treated

### 4. Testing Methods and Curing Regimes

The procedure adopted for mixing the heat-treated OPSC and heat-treated OPSFRC involves the following steps. Firstly, the sand and OPS were poured into a concrete mixer and dry mixed for 1 min. Secondly, the cement was spread and dry mixed for 1 min. This is followed by the addition of water and superplasticizer with a mixing time of 5 min. Slump test was performed on the mixture prior to sample casting. The concrete specimens were cast in 100-mm cube steel oiled moulds, and a poker vibrator was used to eliminate air bubbles in the mixture. The specimens were demoulded approximately 24 hours after casting and were cured in water at  $25 \pm 2$  °C until age of testing. The compression testing machine used was an ELE (Engineering Laboratory Equipment) with a load capacity of 3000 kN running at a pace rate of 3.0 kN/sec, in accordance to BS EN 12390-4:2000. To determine the mechanical properties for each mixture, 18 cubes (100 × 100 × 100 mm) are used to determine the compressive strength at 1, 7, 28 and 180 days. In addition, three cylinders (diameter: 100 mm, height: 200 mm) and three prisms (length: 500 mm, width: 100 mm, depth: 100 mm) are used to determine the indirect tensile strength and modulus of rupture (MOR) on the 28<sup>th</sup> day.

### 5. Results and Discussion

### 5.1 Properties of Fresh Concrete (Slump)

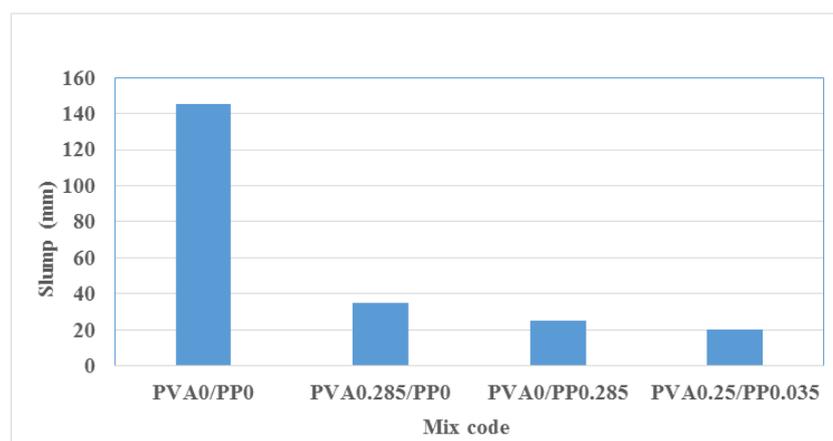
The workability of concrete determines the ease and homogeneity, with which it can be mixed, placed, consolidated and finished. It is a way to understand the behaviour of concrete and to recognize the requirements of workability on site. In this study, the slump test was carried out to determine the consistency of fresh concrete. The slump values of fresh control OPSC, single fibre OPSFRC and hybrid OPSFRC are presented in Figure 3.

The use of fibres is well known to affect the workability and flowability of plain concrete intrinsically [5,19]. Ramezaniapour *et al.*, [8] exhibited that plain lightweight concrete mixture without steel fibres the workability was controlled by the slump in the range 10 - 90 mm.

In this study, the quantity of water and SP were kept constant for all mixes in order to access the effects of different content of single and hybrid fibre on the workability of OPSFRC. From Figure, , it could be seen that the workability of fresh OPSC decreases due to an increase of fibre content.

The inclusion of fibres from 0% to 0.285% single-PVA, 0.285% single-PP and hybrid: 0.25% single-PVA + 0.035% single-PP reduced the slump value by approximately 75.9%, 82.8% and 86.2%, respectively. The ascending trend in slump value is attributed to the fact that the addition of fibres creates a network structure in the concrete, which in turn, increases the viscosity of the mixture from segregation and flow. The friction between the individual particles in the concrete and the mould increased with the addition of fibre due to the high content and large surface area of the fibres which resulted in a stronger interfacial fibre-matrix bond. Furthermore, the internal friction increase with fibre content and the amount of work done will eventually increase, hence, low workability were observed at higher volume fraction. It can be ascertained that the fibres will absorb more of the cement paste in order to 'wrap around' due to the high content and large surface area of the fibres, and the increase in viscosity of the mixture promotes a decrease in workability [15].

It can be concluded that the inclusion of hybrid fibre (PVA0.25+PP0.035% V<sub>f</sub>) significantly reduced the workability of OPSC. Furthermore, the twisted bundle geometry of PP fibres through the surface area had an impact on workability. Yap *et al.*, [14] reported that the fibrillated fibres produced higher slumps as compared to multi-filament fibres is mainly due to the fibre geometry.



**Fig. 3.** Slump versus control, single and hybrid OPSFRC with different percentage of volume fraction

### 5.2 Compressive Strength (Continuous Moist Curing)

The results of the compressive strength for all concrete mixes subject to moist curing up to 180 days are presented in table 5. It could be noted that all the compressive strength of OPSC and heat-treated OPSC increased at all ages, however marginal compressive strength gain at 180-days. Yew *et al.*, [18] reported that not all type of OPS species aggregates is suitable for production of HSLWC. Therefore, *dura* and *tenera* OPS have been selected in this study. Yew *et al.*, [17] also found that, the use of proper heat treatment method on crushed OPS aggregate caused notable surface quality improvement without compromising the strength of the OPSC.

Table 5 shows the compressive strength development for OPSC containing different volume fraction of fibres. As can be seen, there is notable difference between PVA0/PP0 and PVA0.25/PP0.035 with the increment of 5.5% compressive strength of OPSFRC at 28 days. The highest compressive strength was achieved for the PVA0.25/PP0.035 concrete mix, with a value of 42.2 and 44.5 MPa at 28-days and 180-days, respectively.

The improvement came principally from the fibres interacting with the advancing cracks and showed the higher values of compressive strength compared to PVA0/PP0 concrete. When withstanding an increasing compression load, several distinct stages can be defined. During the first stage, micro-crack kinks develop randomly throughout the specimen. Due to the heterogeneity of the specimen, the hardened cement paste and OPS aggregates may have a different stiffness, and, thus, to develop local tensile stresses and further micro cracking occurs. As the advancing crack reaches the interface, micro-cracks join together forming macro-cracks that run parallel to the direction of the applied stress, thus blocking the forward propagation of the crack. The blunting, blocking, and even diverting of the crack allowed the fibrous concrete cubes to withstand additional compressive load, thus upgrading its compressive strength over the non-fibrous control OPSC. This process is attributed to the ability of the fibres to arrest cracks or bridging effect in concrete [3,10, 15].

**Table 5**

Development of compressive strength of control and OPSFRC under continuous moist curing

Mix code	Compressive strength (MPa)			
	1d	7d	28d	180d
PVA0/PP0	33.82 (0.6)	36.42 (0.4)	39.88 (0.5)	40.58 (0.4)
PVA0.285/PP0	33.15 (0.4)	38.25 (0.2)	40.76 (0.3)	42.35 (0.4)
PVA0/PP0.285	33.12 (0.5)	36.35 (0.3)	38.18 (0.5)	40.65 (0.3)
PVA0.25/PP0.035	38.62 (0.3)	42.31 (0.2)	42.15 (0.3)	44.50 (0.5)

The data in parentheses are standard deviation (in MPa) of the corresponding compressive strength.

### 5.3 Modulus of Rupture (MOR)

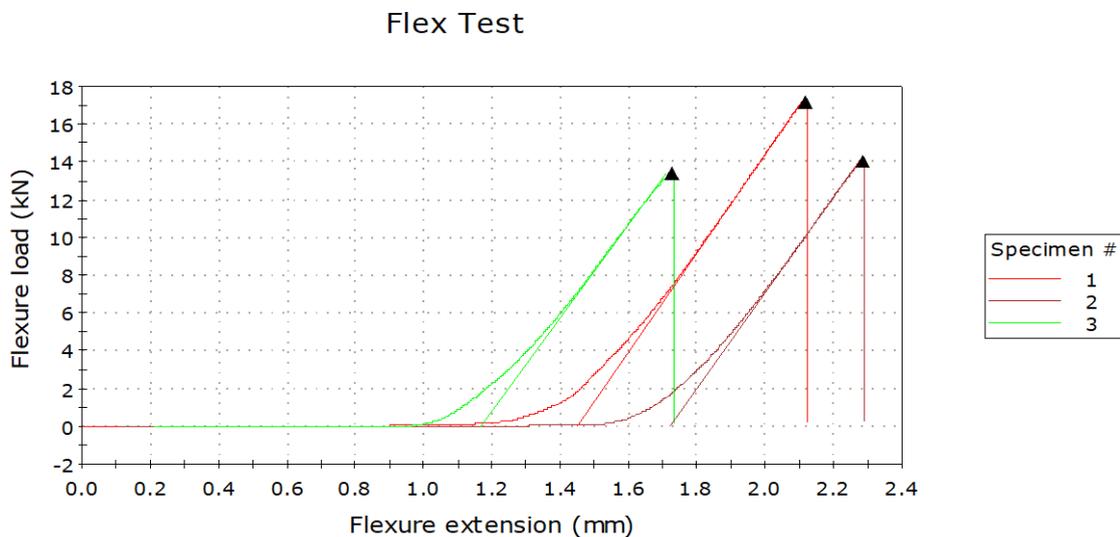
Flexural tests are the most important tests for fibre-reinforced concrete (FRC). These generate flexure load vs. flexure extension curves of the material in flexure which will in turn indicate the efficiency of the fibres as reinforcement. The ability of FRC composites to absorb energy has long been recognized as one of the most important benefits of the incorporation of fibres in plain concrete. Improvements in the fracture, impact and fatigue performance of FRC are among the consequent benefits.

The experimental results on the MOR of the hybrid fibre-reinforced OPS LWC and the non-fibrous control concrete appear in Table 6 and Table 7. Following the Figure 4 and Figure 5, the comparison of MOR of control OPS LWC, single OPSFRC and hybrid OPSFRC tests were showed. As can be seen in Figure 4 (28-days), plain concrete specimens failed right at the peak load with no post-crack response. It shows that the plain concrete is brittle. After failure the concrete is unable to carry load. The load carrying capacity has dropped abruptly.

**Table 5**

Plain concrete of flexural test at 28 days

	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Stress (Nmm-2)	Extension at Max Flex Load (mm)
1	PVA0/PP0-1	102.740	100.690	16.190	4.852	2.116
2	PVA0/PP0-2	101.230	100.570	12.999	4.102	2.178
3	PVA0/PP0-3	105.450	100.640	12.443	3.772	1.517
	Average			<b>13.877</b>	4.275	1.937

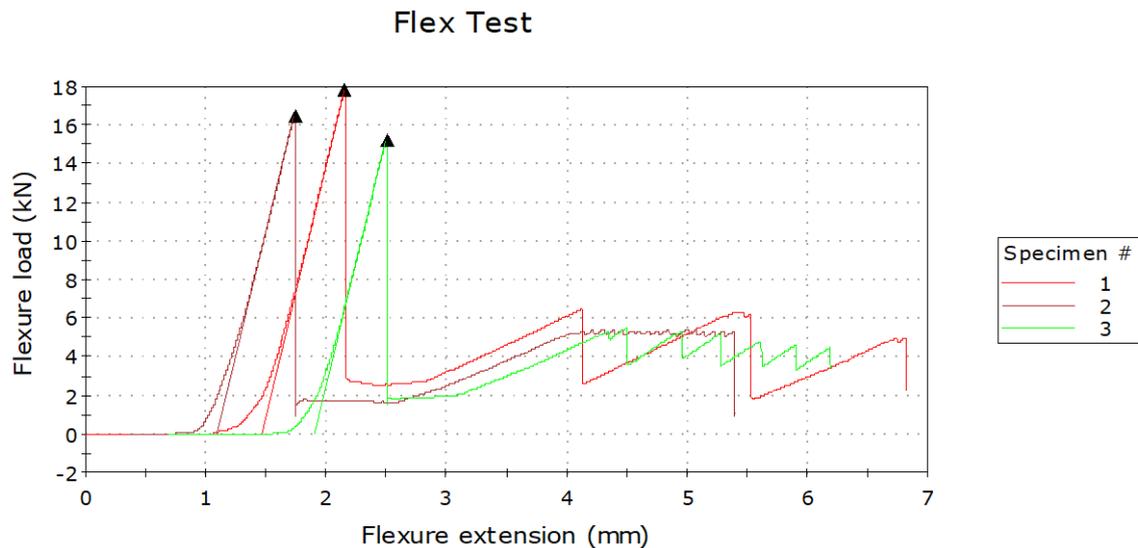


**Fig. 4.** Plain concrete of flexural test at 28 days

**Table 7**

OPS fibre-reinforced lightweight concrete of MOR test at 28 days

Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Stress (Nmm <sup>-2</sup> )	Extension at Max Flex Load (mm)	
1	PVA0.25/PP0.035-1	100.690	101.270	17.810	5.174	2.158
2	PVA0.285/PP0-2	101.140	101.560	16.447	4.739	1.405
3	PVA0/PP0.285-3	100.420	100.530	15.200	4.493	1.825
Average			<b>16.495</b>	4.802	1.796	



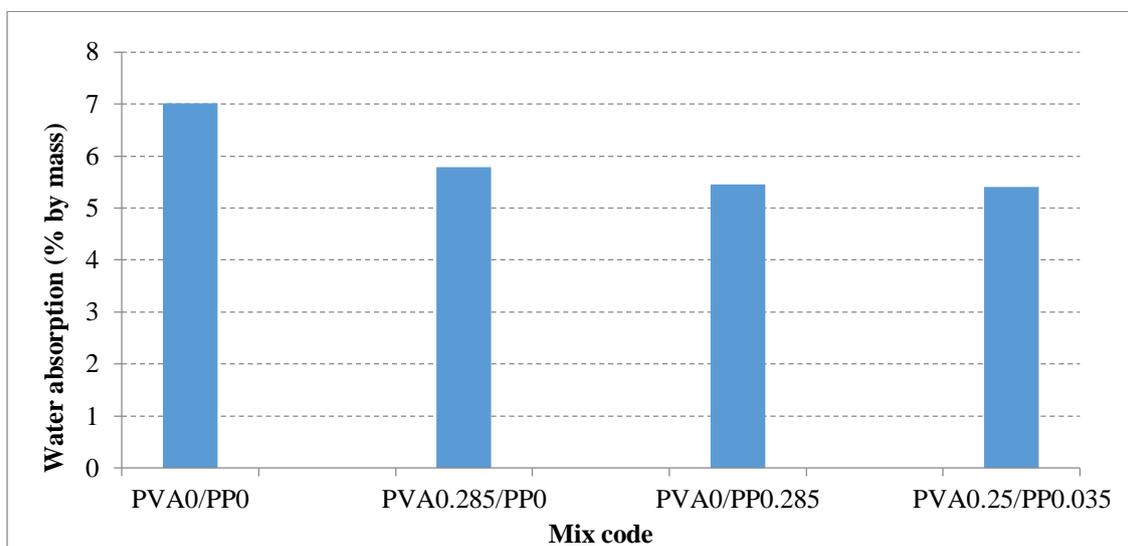
**Fig. 5.** OPS fibre-reinforced lightweight concrete of MOR test at 28 days

In contrary single-OPSFRC and hybrid-OPSFRC has performed well. After crack the concrete still performed its ductility. As shown in Figure 5 (28-days). Each of the results was the average of 3 test specimens. The MOR of the OPS fibre-reinforced lightweight concrete posted 18.1% (PVA0/PP0.285), 15.6% (PVA0.285/PP0) and 22.1% (PVA0.25/PP0.035) increase over the non-fibrous control concrete respectively. The increase resulted primarily from the fibres intersecting the cracks in the tension of the reinforced beam. These fibres accommodated the crack face separation by stretching themselves, thus providing an additional energy-absorbing mechanism and also stress relaxing the micro-cracked region neighbouring the crack-tip.

#### 5.4 Water Absorption

Figure 6 shows the water absorption for all mixes. It can be seen that PVA0/PP0 had the highest water absorption value at about 7.02% while PVA0.25/PP0.035 with hybrid OPSFRC achieved the lowest water absorption of about 5.40%. Moreover, it can be observed that the water absorption for tenera heat-treated OPSC is lower compared to dura OPSC without heat-treated. This may be due to the low equilibrium moisture content in OPS when dried wood is subjected to heat treatment and therefore the heat-treated OPS aggregates tend to reduce the water absorption as compared to OPS without heat-treated. In addition, the inclusion of PVA and PP fibre had a positive effect to reduce flow rate and lead to lower water absorption, which can be related to the pore blocking effect of fibres with zero water absorption. Yew *et al.*, [17] also reported that for high strength (40 – 54 MPa)

OPSC the water absorption fall within the range of 3.04 – 6.30%. For OPSC with conventional compressive strength (15 – 29 MPa), the water absorption was in the range between 10.64% and 11.23% [11].



**Fig. 6.** Water absorption versus control, single and hybrid OPSFRC with different percentage of volume fraction

## 6. Conclusion

Based on the experimental results of this study, it can be concluded that:

- (1) The workability decreased by increasing the content of fibre into OPS LWC. The slump value for PVA0.25/PP0.035 mix had exhibited the lowest workability with a value of 20 mm.
- (2) The compressive strength of plain OPS LWC and OPSFRC (single and hybrid) increased at all ages. Moreover, the compressive strength increased slightly with the combination of hybrid PVA0.25/PP0.035 into OPS LWC.
- (3) The results of MOR test clarify that, by incorporating hybrid PVA0.25/PP0.035 into OPS LWC had outperformed its non-fibrous control OPS concrete companion in the upgrading of MOR strengths. The outperforming arose from the higher tensile strength of hybrid fibre reinforced concrete compared to non-fibrous control concrete.
- (4) The water absorption of control OPSC and OPSFRC value varies from 5.40 to 7.02% for all mixes, which falls within the range of good concrete.

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