

OIL PALM SHELL CONCRETE (OPSC): A SHORT REVIEW

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Abstract

With the increase of the world's population, industrial development and the construction of housebuilding and infrastructure activities, the demand for construction material is increasing. Disposals of agricultural waste have been making serious damages to the environment. Thus, by replacing the conventional raw materials used in concrete today by agricultural waste will intensely decrease unwanted impacts caused by the current concrete industry. A novel replacement for the conventional aggregate in the past 4 decades has been the utilization of oil palm shells (OPS) in concrete. This paper reviews published reports on OPS being used as aggregate for concrete in its current stand. Physical properties of OPS, fresh properties of OPSC, mechanical properties of OPSC, Structural behaviour and OPS with other materials have all been reviewed in this paper. Recently, however, development in high yield oil palm fruit has led to waning compressive strengths. This review also indicates the necessity for new investigations based on the new fruit breeding type of oil palm tree which is known as Tenera OPS.

Keywords: Agricultural waste; coarse aggregate; lightweight concrete; lightweight aggregate; oil palm shell; sustainability

Introduction

Environmental issues are becoming of vital importance around the world (Yusoff, 2006). One of the major issues in the world today is lack of sustainable development. Residential and industrial buildings are one of the increasing demands of human life to fulfil their basic requirements (Karim *et al.*, 2011). A report by the United Nations (UN, 1993) states in one of their principles that “*Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.*”

In the late 1950s, the Malaysian government shifted from rubber to the oil palm industry, which has now become one of Malaysia's largest exports, having grown substantially in recent decades among all its agricultural-

based industries. The growth of oil palm industries is also evident in neighbouring countries such as Thailand, Indonesia, and the Philippines (Awalludin *et al.*, 2015). Records show that Malaysia produced 18.5 million metric tons of palm oil in 2020, whereas Indonesia had the largest production of 42.5 million metric tons, respectively, 25.6% and 58.8% of the world's total 2020 production of 72.3 million metric tons (Shahbandeh, 2020) which increased to 75.5 million metric tons in 2022 (Shahbandeh, 2022). While the farming industry is the primary beneficiary of the production and export of palm oil, the resulting expansion of the oil palm industry has several downsides. When the oil is extracted from the fruits by the mills, large amounts of waste are produced,

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namely empty fruit bunches, mesocarp fruit fibres, and oil palm shells (OPS), creating the problem of biomass waste overload. This results in disposal difficulties for operators and increases the operation cost. The OPS is directly obtained by breaking the fruit exterior (and drawing out the oil palm) and is dumped in large quantities in local landfills as it serves no other purpose for the industry (Vincent, 2011). In the oil palm mill process, a total of 5.5% of OPS waste is produced (Abdullah and Sulaiman, 2013). This indicates that, in 2020, over 1 million metric tons of OPS waste were produced only in Malaysia, and a total of over 4.2 million metric tons of global OPS production in 2022, and it is expected to increase in the future. Therefore, it is necessary to tackle waste disposal issues caused by the oil palm industries in Malaysia and other oil palm-producing countries. OPS waste has significant potential in various renewable and sustainable applications, such as solid fuels for steam boilers in palm oil mills (Awalludin *et al.*, 2015). However, such a process is deemed to be non-environmentally friendly by causing emission problems, which are discouraged by the Malaysian government (Abdullah and Sulaiman, 2013). Another application that has been utilized for the last four decades is as coarse aggregate replacement in concrete. Abdullah *et al.* (1984) formulated the idea of utilizing OPS waste in concrete, and many other investigations have followed (Hamada *et al.*, 2020).

Concrete is a crucial construction material, composed of cement, water, and aggregates. Due to its high demand in industries and urban areas, large quantities of raw materials are required to produce concrete (Meyer, 2009; Pordesari *et al.*, 2016). One of the main reasons for its popularity is the ability to improve and develop the characteristics of each component (Swamy, 2007). However, the current concrete industry generates unwanted environmental impacts that can be reduced by substituting conventional raw materials with agricultural waste. This approach can minimize sourcing and transport costs while also reducing the amount of waste sent to landfills (Tavakolu and Hashempour, 2018). Regulations imposed by Departments of Environment over the world have tried different efforts to improve the recycling of these by-products (Corinaldesi, 2011). Concentrating on developing countries that have the highest demand for concrete, environmentally sustainable concrete structures can be built by using these agricultural wastes and industrial by-products (Shafigh *et al.*, 2010). This has economical and several practical advantages. Also, to assure an appropriate living atmosphere and safety for the coming generations, good coherence must be attained by engineers and scientists in the development of the construction industry. For such reasons, many countries in the world concentrate on sustainable concrete with main objectives such as developing low energy resources, decreasing carbon dioxide (CO₂) gas emissions and amount of pollution, efficient use of waste materials, increasing the serviceable age of the structures, flexible construction of buildings, and developing the thermal mass of concrete in a structure to reduce energy demand (Rodrigues *et al.*, 2013; Bravo *et al.*, 2015).

To achieve sustainable concrete structures, many countries are focusing on developing low-energy resources, decreasing CO₂ emissions and pollution, using waste materials efficiently, increasing the lifespan of structures, and reducing energy demand. With an estimated global population of 11 billion people by the 21st century, the demand for concrete and common goods is expected to increase significantly (Rosković and Bjegović, 2005). Ordinary concrete typically contains about 60-80% aggregate by mass (Mamlouk and Zaniewski, 2014). By the year 2050, it is estimated that around 18 billion tonnes of concrete are demanded (Mehta and Monteiro, 2006). Currently, the demand for conventional construction aggregates is around 11 billion tons per year (Golewski, 2019), valued at US\$559 billion (ReportLinker, 2021) as of 2021, whereas the total waste of OPS is around 4.2 million tons annually. Therefore, in terms of cost, up to US\$224 million of the conventional aggregate could be potentially saved annually by utilising OPS as aggregate in concrete. This paper reviews mechanical, structural and other properties of OPS in concrete from over the last 4 decades up to the most recent trends in OPSC. It also indicates the necessity for new investigations.

Oil Palm Tree

It is believed that the oil extracted from the tree was used at the time of the Pharaohs in Egypt around 5,000 years ago. It is said that the tree, also known as “*Elaeis guineensis*”, was originated in the jungle forest in East Africa (Cottrell, 1991). The tree is known to grow well in tropical climates (Loh *et al.*, 2013). The countries that produce these trees are to be found in Southeast Asia, South America, and Sub-Saharan (Mielke, 2000). The tree is mainly grown for its oil. It has a fruit which looks like a plum (Pantzaris and Ahmed, 2002). Today, oil palm tree has become a plantation-based industry. The main products are crude palm kernel oil and crude palm oil. The palm oil is extracted from the fresh fruit bunches by a machinal process. Within the mechanical process, the nuts (shells) are separated by means of “cracking” and are then separated (Figure 1). Some of the wastes (OPS and fibre) are used for burning to produce energy. However, not all wastes are burnt. This is because most of the waste has high water contents and thus serves as a poor fuel without cumbersome prior drying. Moreover, when burnt at high water content, it presents considerable emission problems which are discouraged by the Malaysian government. The wastes are therefore mostly left unused in open lands. This open disposal would eventually cause storage problems (Abdullah and Sulaiman, 2013).

Physical Properties of OPS as Aggregate

The importance of the physical properties of OPS is because it can alternate the mechanical properties of OPSC (Alengaram *et al.*, 2013a). In the below sub-sections physical properties of OPS are reviewed.

Types of OPS Fruits

The strength of aggregates used in concrete are one of the primary indicators of its strength as a building material. As such, physical properties of OPS are key indicators for their performance as aggregates in OPSC (Hamada *et al.*, 2020). One of the most important factors worth mentioning is that the oil palm tree produces different types of fruit species that have varying shell thicknesses. There are two known species of the oil palm tree family (Arecaceae), *Elaeis guineensis* and *Elaeis oleifera* (less cultivated species) (Baudouin *et al.*, 1997). The *E. guineensis*, which is predominantly planted in Malaysia, is a monoecious species, and mainly a hybrid between Dura and Pisifera, also known as the Tenera variety (Zulkifli *et al.*, 2010), see Figure 2. The Dura type is known to have a thick shell (2-8 mm) while the Pisifera (sterile tree) is known to be shell-less. The hybrid type variety Tenera produces a fruit with a very thin shell. The thinner shell of Tenera (0.5-4 mm) allows for 30% more extractable oil in the fruit part, called the Mesocarp/flesh/pulp compared to Dura (Lai *et al.*, 2012). The yielding and profit of the plantations of the Tenera type is known to be double compared to the Dura type (Woittiez, 2019). In 2021 it was reported that Malaysia started adapting the Tenera variety in the 1960s, and in 2017 the Tenera production has grown to 90.61% of the total oil palm tree harvest area compared to 8.09% for Dura and almost 2% for Pisifera (Singh, *et al.*, 2022). It is therefore believed that the Dura type shells will be outsourced in the future.

Specific Gravity

The normal range of OPS seems to be between 1.14-1.37. To add, Prusty and Patro (2015) mentioned that the specific gravity of OPS changes depending on the size variation of the OPS, this might have been the case with Anuar *et al.* (2017), which had the highest specific gravity of 1.6. This might be because of the different palm fruit, Dura and Tenera. Unfortunately, authors tend to not include the specific type of palm fruit. Some do have images where the reader could conclude by the thickness of the material by visual inspection, i.e., thicker means Dura OPS. To summarize, it is important to mention the type of fruit is used, Dura or Tenera, since this could affect the mechanical properties of the OPS.

Sieve Analysis

The sizes can vary from 1.18 mm to 14 mm depending on if it is crushed or uncrushed. In Figure 3 it can be seen that most reporters had a good grading of OPS aggregate (Mannan and Ganapathy, 2002; Shafigh *et al.*, 2011a; 2011b; 2012; 2014 Kupaei *et al.*, 2013; Aslam *et al.*, 2015; Jumaat *et al.*, 2015; Farahani *et al.*, 2017). However, all seem to have exceed the upper limit in according with ASTM C33. A report by Shafigh *et al.* (2012) investigated crushed OPS with uncrushed OPS and highlighted that crushed OPS has better mechanical properties than uncrushed OPS. This concludes that the grading size of OPS aggregate can be important for the strength of the concrete mix. Similarly, (Yew *et al.*, 2014c) also studied the effects of crushed OPS with uncrushed OPS. The authors found an increase of 19% in compressive strength for crushed OPS compared to



Figure 1. Dura OPS solid waste (Mo *et al.*, 2015a)

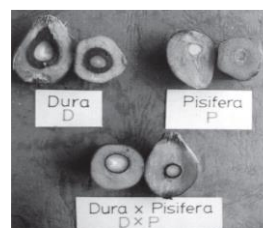


Figure 2. Commercial oil palm DxP hybrid seed production

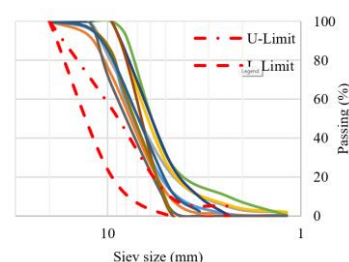


Figure 3. Grading of OPS from various researchers (limits from ASTM C33)

uncrushed, which is significantly lower compared to Shafigh *et al.* (2012). This might be since Yew *et al.* (2014c) studied the OPS at different age categories of 3-5, 6-9, and, 10-15 years old OPS, whereas (Shafigh *et al.*, 2012) did not mention the age of the OPS. Both authors theorized the increase in compressive strength of crushed OPS is due to a reduction of the smooth surface from both the interior and exterior of the OPS. Furthermore, the crushed OPS will have a different shape, especially at the jagged, rough edges, potentially creating a better area for bonding with the cement matrix.

Bulk Density

Table 1 shows the ranges of both loose and compacted bulk densities of OPS found by researchers. The table indicates that OPS is lighter than the conventional coarse aggregate. The bulk density variation is reported to be mainly affected due to the size of OPS (Alengaram *et al.*, 2010b; Shafigh, *et al.*, 2014).

Water Absorption

Another important factor that can alternate the mechanical properties of OPSC is the water absorption of OPS. When water is captured by the aggregate in the voids, it is not available for the cement to hydrate, or to improve the workability of plastic concrete (Mamlouk and

Table 1. Physical properties of OPS from various researchers

Reference	Water absorption (%) 24 h.	Specific Gravity	Fineness modulus	Aggregate impact value	Aggregate abrasion value (%)	Flakiness index (%)	Density range (kg/m ³)	
							Loose	Comp.
Okpala (1990)	21.3	1.14					500-600	512-740
Basri <i>et al.</i> (1999)	23.32	1.17	6.24	-	4.8			
Mannan and Ganapathy (2001)	23.32	1.17	6.24	7.86	4.8			
Mannan and Ganapathy (2002)	23.32	1.19	6.24	7.86	4.8	65.17		
Mannan and Ganapathy (2004)	23.3		6.24	7.86	4.8	65.17		
Teo <i>et al.</i> (2007)								
Teo <i>et al.</i> (2007)	33		6.08	7.51	4.9			
Teo <i>et al.</i> (2010)	33		6.08	7.51	4.9			
Gungat <i>et al.</i> (2013)	23.32		6.24	7.86	4.8			
Noor <i>et al.</i> (2017)	19.7		5.78					
Huda <i>et al.</i> (2016)	23.3		6.24	7.86	4.8	65.17		
Shafigh <i>et al.</i> (2011a)								
Ting <i>et al.</i> (2020)	18.11	1.19	5.31					
Shafigh <i>et al.</i> (2012)	18.73	1.22	5.72					
Shafigh <i>et al.</i> (2014)	18.7	1.22	5.98					
Ahmmad <i>et al.</i> (2014)	18.7	1.25				65		
Islam <i>et al.</i> (2016b)								
Alengaram <i>et al.</i> (2011b)	24.5	1.27	6.24	3.91				
Alengaram <i>et al.</i> (2013b)		1.27						
Gibigaye <i>et al.</i> (2017)	19.93	1.31			5.02			
Khankhaje <i>et al.</i> (2016)	25.6	1.3						
Foong <i>et al.</i> (2015)		1.33						
Okafor (1988)	27.3	1.37						
Alengaram <i>et al.</i> (2008a)	23.8	1.37						
Jumaat <i>et al.</i> (2009)	-	1.6						
Yap <i>et al.</i> (2013)	24.3		6.41	2.11	5	41		
Mo <i>et al.</i> (2014b)								
Yap <i>et al.</i> (2014)								
Yap <i>et al.</i> (2017)	24				5			
Anuar <i>et al.</i> (2017)								

Zaniewski, 2014). LWA's normally have higher water absorption than the conventional aggregate, as LWA are porous and absorb water into their interiors, whereas solid NWA adsorb water mostly on the surface (Chandra and Berntsson, 2002) and (Hossain, 2004). For NWA, the water absorption is normally between 0.5-1% (Neville, 1995). However, in the case of LWA, since the porosity differs depending on the material, the water absorption could be high compared to NWA. Since OPS is an organic aggregate, many pores are exhibited, with sizes of around 23 μm (Alengaram *et al.*, 2013a). The lowest water absorption is reported to be 18.7% and the highest 33% as seen in Table 1. While the main reason for high absorption rate is due to the porosity of OPS, the variance in water absorption between research may be owing to the different species type, age of samples, climate of area cultivated, dryness of samples, etc. Many researchers have treated the OPS by cleaning it with a detergent to remove dirt and other unwanted materials (such as loose fruit fibres), and used the OPS aggregate in a saturated surface dry (SSD) state in the mix to avoid the shells taking away the water required for the cement (Hamada *et al.*, 2020). However, no specific research has directly evaluated if such treatment is necessary or effective with regards to OPSC's mechanical properties. Having said that, by bringing OPS at SSD state, authors have observed better mechanical properties of OPSC. Furthermore, there have been no direct reported measurements to observe if water has been diverted from the cement hydration by the absorption of the OPS when used in dry state as well, which is not a simple endeavour. One issue important to mention regarding the range of water absorption values (18.7-33.3%) is that most researchers use the method by

weight, which can lead to a false similarity of experiment. As OPS is regularly used in SSD conditions, the exact water absorbed by the shell may vary depending on the shell characteristics (e.g., amount of pores, dryness) leading to a different proportion of volume mix, as well as free water content in the OPSC mix.

Fresh Properties of OPSC

Water Content of OPS

In many cases, LWA is saturated prior to mixing as not to absorb any amount of water that effects the w/c ratio content of the fresh concrete. However, one of the side effects of such procedure is that the LWA could deteriorate the concretes properties. Adding additional water to the cement above the required content, is not a solution. However, when LWA are let to absorb for a specific set of time and then used in the mix, it could enhance the adhesion of cement paste to the LWA and results in higher strengths of concrete and better durability (Domagala, 2015). Since OPS has high water absorption, (Mannan *et al.*, 2006) pre-treated OPS aggregates with different solutions such as polyvinyl alcohol (PVA), and exposed OPS to severe environmental conditions incorporating alkaline (NaOH), acidic (H_2SO_4), and sulphatic (MgSO_4) compounds, where OPS aggregates were soaked for 7 days in the respective solutions, specifically 1 mol of sodium hydroxide (NaOH), 0.1 mol of sulphuric acid (H_2SO_4), and 5.2% of magnesium sulphate (MgSO_4). The authors observed the possibility to decrease the water absorption of the OPS aggregate by 82% by pre-treating OPS with 20% PVA solution, which

Table 2. Mix ratio properties – Mineral Admixture Studies

Reference & Study	Mix number	(w/c)	Binder content (kg/m ³)	Slump (mm)	Density (kg/m ³)	Compressive strength (MPa)	Additional materials (%)	Admixtures (%)
Mannan and Ganapathy (2001)	E1	0.41	480	7	1890-1905	24.20	-	0
	E2		432	8		22.60		0.10
	E3		408	9		19.50		0.15
	E4		480	6		23.45		0.5
	E5		480	7		29.40		1.0
	E6		480	8		24.50		1.5
Kupaei <i>et al.</i> (2013)	B1	0.34	460	0-160	1766	28.14	-	6.0 (l/m ³)
	B2		460		1786	29.96		6.0 (l/m ³)
	B3		460		1790	30.81		6.0 (l/m ³)
	B4		480		1772	30.14		9.5 (l/m ³)
	B5		480		1792	32.63		9.5 (l/m ³)
	B6		480		1795	32.94		9.5 (l/m ³)
	B7		500		1836	20.08		9.0 (l/m ³)
	B8		500		1856	22.19		9.0 (l/m ³)
	B9		500		1860	22.87		9.0 (l/m ³)
Shafigh <i>et al.</i> (2013a)	F0	0.288	550	145	2,011	44.49	0	
	F10		495	140	1,984	46.08	10	
	F30	0.305	385	235	1,961	38.12	30	
	F50	0.320	275	240	1,886	30.04	50	
Mo <i>et al.</i> (2018)	M0	0.35	540	110	1,920	39.32	0	
	M5		540	86	1,983	45.00	5	
	M10		540	75	1,983	47.62	10	
	M15		540	65	1,989	47.13	15	
	M20		540	52	1,975	46.80	20	

may have resulted in stronger adhesion between the OPS and cement paste. However, the author did not further analyse the results via microscopic images to see the surface effect of the OPS after treatment. However, in a subsequent study by Traore *et al.* (2018), treatment experiments on OPS were done to find the effect on physical and mechanical properties of OPSC. The study focused on OPS treatment with lime (CH), sodium silicate (SS), polyvinyl alcohol (PVA), heat treatment (TH) and OPS as SSD state. Traore, *et al.* (2018) confirmed the same findings for PVA having the lowest water absorption on OPS as done by Mannan *et al.* (2006). The author mentioned that the PVA made a thick coating on the OPS, which explains the reduction in water absorption, evident in SEM images provide in their report. However, the author concluded that the CH treatment showed the highest improvements in mechanical properties compared to the control OPSC and other treatments. They mentioned that the CH treatment improved the adherence between the treated OPS and cement paste, verified by having the highest flexural strength result. A study by Nadh *et al.* (2021) used nano silane as a coating for OPS to reduce the water absorption. The nano coating reduced the water content from 23% to 8%. The nano coating made the pore diameter of OPS to be 0.5-1.5 micrometres compared 2-5 micrometres of conventional aggregates.

Workability

Several researchers have tried to increase OPSC strength by reducing the water content, which can lead to a practicality issue, namely low workability. To ensure a concrete mix can be handled with ease to properly fit the formwork, the workability of the mix must be controlled, thus the quantity of water present in the mix should be of proper ratio. However, the physical shape of the coarse aggregate also plays an important role (Neville, 1995). A slump of 50-75 mm is deemed adequate for structural

LWC compared to a slump of 100-125 mm for NWC (Mehta and Monteiro, 2006).

Employing OPS in an SSD-state prior to mixing allows for controlling mix workability, however an increase of OPS content decreases the mechanical strength of OPSC (Hamada *et al.*, 2020), while the low content of OPS in the mix does not significantly impact slump (Alengaram *et al.*, 2010b). Additionally, the size and proportion of OPS used in the mix did not cause any change in the workability reported by Alengaram *et al.* (2010b). A report by Yew *et al.* (2014a) mentioned when OPS is heat treated at 150°C for 1 h, the workability is improved by 20%. The author mentioned that the cause of this is because “heat treatment decreases the swelling-shrinkage of wood, which in turn increases its dimensional stability and durability, permeability, quality of surface treatment, as well as decrease equilibrium moisture content”. However, the author didn’t quantifiably confirm the shrinkage of OPS. Other authors increased the workability by pre-treating OPS with PVA solution (Mannan, *et al.*, 2006; Chai *et al.*, 2014; Traore, *et al.*, 2018).

Generally, good workability is seen with OPSC since OPS has a smooth surface (Shafigh *et al.*, 2010). Other investigators achieved higher slump values by incorporating admixtures (Alengaram *et al.*, 2010a). When adding different amounts of SP of 1-2% by weight of cement, the OPSC slump value was increased 14 times relative to control (Mannan and Ganapathy, 2004). Other investigators also studied the flexural strength of OPSC when adding fibres to the mix, and it has been shown that the workability decreases when adding steel fibres to the mix (Mo *et al.*, 2017a). In a later study by the same authors (Mo *et al.*, 2015a) a study was done on adding acrylic fibres and showed a reduction in the workability. This is the same when adding Polypropylene-fibre (PP-fibre) according to Yew *et al.* (2015b).

Table 3. Mix ratio properties – Super Plasticiser (SP) Studies

Reference & Study	Mix number	(w/c)	Binder content (kg/m ³)	Slump (mm)	Density (kg/m ³)	Compressive strength (MPa)	Additional materials (%)	Admixtures (%)
Mannan and Ganapathy (2002)	D-1	0.48	400	30	1,859	19.8		1
	D-2			90	1,868	20.8		2
	D-3	0.45		13	1,854	21.3		1
	D-4			17	1,851	21.0		2
	D-5	0.43	420	0	1,860	21.8		1
	D-6			10	1,863	16.3		2
	D-7	0.48		55	1,873	20.7		1
	D-8			65	1,884	19.9		2
	D-9	0.45	400	45	1,883	21.2		1
	D-10			50	1,894	19.8		2
	D-11	0.43		25	1,883	20.9		1
	D-12			45	1,890	20.7		2
	D-13	0.46	400	70	1,882	19.8		1
	D-14			5	1,801	17.6		0
Foong <i>et al.</i> (2015)	MS0		550	136	1,862	46.43	0	0.8
Manufactured sand + SP	MS1	0.351	550	147	1,933	48.53	50	0.8
	MS2		500	156	1,848	48.12	100	0.8
Manufactured sand and Rice husk ash+ SP	MSA1		550	106	1,813	48.14	50	1.2
	MSA2		550	85	1,766	51.49	100	1.2
Yap <i>et al.</i> (2015a)	NWC-0	0.3207	320	100	2,300	34.7	0	0
	OPSC-0		530	80	1,810	33.9	0	0.35
	OPSC-25		530	55	1,850	39.3	0.25	0.35
				50				
Steel fibers + SP	OPSC-50	0.3207	530		1,890	41.2	0.50	0.35
	OPSC-75		530	40	1,890	45.9	0.75	0.35
	OPSC-100		530	25	1,898	47.3	1.00	0.35
Aslam <i>et al.</i> (2015)	OPSC	0.36	480	55	1,790	36.90	100 (OPS)	1
OPS vs Palm Oil Palm Boiler + SP	OPBCC	0.36	480	100	1,860	42.60	50	0.90
Shafigh <i>et al.</i> (2016)	L	0.36	480	50±5	1,640	22	0	1.2
Expanded clay vs OPS + SP	L25		480	50±5	1,720	24	25	1.5
	L50		480	50±5	1,770	27	50	2.0

Table 4. Mix ratio properties – Aggregate Studies

Reference & Study	Mix number	(w/c)	Binder content (kg/m ³)	Slump (mm)	Density (kg/m ³)	Compressive strength (MPa)	Additional materials (%)	Admixtures (%)
Olanipekun <i>et al.</i> (2006)				62	2,400	35	0	
OPS vs conventional coarse aggregate (gravel)	1:1:2	0.50		25-50	2,300	24	25	
					2,000	21	50	
					1,800	17	75	
					1,700	-	100	
Control			-	37	2,400	28	0	-
OPS vs conventional coarse aggregate (gravel)	1:2:4	0.75		25-50	2,250	22	25	
					1,800	19	50	
					1,700	17	75	
					1,600	14	100	
Foong <i>et al.</i> (2015)	MS0		550	136	1,862	46.43	0	0.8
Manufactured sand + SP	MS1	0.351	550	147	1,933	48.53	50	0.8
	MS2		500	156	1,848	48.12	100	0.8
Manufactured sand and Rice husk ash+ SP	MSA1		550	106	1,813	48.14	50	1.2
	MSA2		550	85	1,766	51.49	100	1.2
Aslam <i>et al.</i> (2015)	OPSC	0.36	480	55	1,790	36.90	100 (OPS)	1
OPS vs Palm Oil Palm Boiler + SP	OPBCC	0.36	480	100	1,860	42.60	50	0.90
Shafigh <i>et al.</i> (2016)	L	0.36	480	50±5	1,640	22	0	1.2
Expanded clay vs OPS + SP	L25		480	50±5	1,720	24	25	1.5
	L50		480	50±5	1,770	27	50	2.0

Thus, there is no consensus on the effects of OPS on concrete workability. This may be owing to variations in the type of OPS used, resulting in varying volumes of added OPS (of same weight), along with different porosity and hence water absorption capabilities. However, the author of this present review cannot confirm this hypothesis, due to limited provided data on the specific characteristics of OPS that are suspected to affect workability.

Density of Hardened OPSC

As seen from Tables 2, 3, and 4, different mix ratio's effects the density of the OPSC when it is in its hardened state. From Tables 2-4, when filtering out the control specimens (without OPS), it can be seen that most of the OPSC's tested have a density of <2,000 kg/m³ which is confirmed as structural LWC by ACI Committee 213

(2009) (1,120-1,920 kg/m³) and by BS EN 206-1 (2000) (800-2000 kg/m³). It can be determined that the density of OPSC depends on factors such as specific gravity of OPS, w/c ratio, sand content, OPS content, water absorption of OPS, and cement content (Alengaram *et al.*, 2013a). Of note, researchers use the 'as received' or SSD state of the OPSC when measuring its density and use these results to specify whether it is considered as a lightweight concrete or not. However, both BS (BS EN 206, 2021) and ACI (ASTM C330M-17a., 2017), requires the oven-dry density to be less than 2,000 kg/m³ and 1,850 kg/m³ for lightweight concrete respectively.

Also, when using different binders, such as fly ash, the OPSC density decreases when increasing the binder replacement for cement (Mannan and Ganapathy, 2004; Shafigh *et al.*, 2013a). This was the same for slag content (Mo *et al.*, 2015c). However, when introducing 1% steel fibres, the OPSC density significantly increases by 170 kg/m³ (Mo *et al.*, 2014b). Although, when using Polypropylene (PP) fibres, the density of OPSC decreases when increasing PP fibres (Yap *et al.*, 2013). It can be concluded that when using OPS as a LWA in concrete, it reduces the density by 20-25% compared to NWC.

The light weight of OPS, combined with its varying characteristics and its pre-treatments for OPSC, poses an interesting issue of how much space does it occupy in the hardened OPSC, and if that allows for different void ratios which could be contributing to the varying OPSC performances. This is further aggravated by the rough shapes of the OPS. For instance, using crushed OPS would logically reduce the voids in the OPSC mix, leading to a denser hardened structure. This may also be true for heat-treated OPS. As mentioned earlier, sieve analysis of Dura type OPS with similar dimensions to Tenera OPS will fail to account for the differing thicknesses of the shells, however the latter would undoubtedly weigh less due to its relative thinness. Therefore, if OPS is added by weight to the OPSC mix, greater volume of Tenera OPS would be added, which may significantly alter its mechanical contributions to the concrete. To the authors knowledge, specific research on this issue has not been performed for OPS/OPSC, however measuring strength per unit weight of OPSC may lead to some insight regarding the variations in mix designs and resulting strengths of OPSC. Another simple alternative would be to specify mix designs in terms of both weight and volume ratios to better conceptualize the effects this may have on the density and porosity of hardened OPSC.

Durability Properties of OPSC

The utilization of waste materials derived from palm oil residues requires careful treatment, including cleaning and heating, to enhance their properties. In a study conducted by Teo *et al.* (2010), the durability properties of OPSC were investigated and compared with those of traditional LWAC. The authors found that during the early stages of curing, cementitious hydration in OPSC was enhanced due to water absorption by the internal reservoir in the lightweight aggregate. Additionally, Teo *et al.* (2007) proposed that the permeability of OPSC is a crucial

factor affecting its durability and could be used for evaluating the concrete's durability. In another study by Teo *et al.* (2007), the authors demonstrated that curing conditions had a significant impact on the durability of OPSC, with water curing leading to better durability properties.

Water Absorption and Permeability

In a study by Teo *et al.* (2007), it was found that the water absorption of for air dry curing and full water curing of OPSC was 11.23% and 10.64%, respectively, which is higher than that of NWC. The higher water absorption of OPSC is explained by the high-water absorption of the OPS aggregate (Alengaram *et al.*, 2013b). Water permeability can serve as an indicator of concrete durability. It was found in a study by Mannan and Ganapathy (2002) that the permeability of OPSC reduces by 2.4 and 7 times for air dry curing and full water curing from 3 up to 90 days. Also, the fully cured specimens had one sixth the permeable of the air cured. (Teo *et al.*, 2007) reported that the cracking of the paste-aggregate interface in OPSC is due to internal stress, which contributes to its permeability.

Mechanical Properties of OPSC

Compressive Strength

OPS is reported to "perform satisfactorily" as an LWC for middle- and low-strength concrete, and the reported investigation reached a maximum of 24-30 MPa in 28-day compressive strength (Okafor, 1988). Subsequently, many other compressive strengths obtained by researchers (Table 5) are higher than C17/20 MPa and 18 MPa, which is confirmed to be a structural LWC as per ASTM C330M-17a. (2017), ACI 318M-08 (2008) and BS EN 206-1 (2000) respectively. As mentioned earlier, the compressive strength decreases when the percentage of OPS coarse aggregate is increased. It can also be observed from Table 5 that most researchers have shown an improvement in compressive strength by increasing the fine aggregate to OPS ratio. This was investigated and confirmed by Mahmud *et al.* (2009). This may lead some credence as to better packing of OPSC by fine aggregates, especially due to the irregular concave structure of the OPS, however no research has specially examined these interactions, although different strength grades have been reported with changes in the particle size of OPS (Alengaram *et al.*, 2010b). Additionally, strength also depends on the curing conditions of OPSC (Mannan *et al.*, 2002). Curing OPSC via full immersion in water showed the highest compressive strength compared to curing in partial water and full and partial covering with plastic (Mannan *et al.*, 2002). Curing OPSC via full immersion in water showed the highest compressive strength compared to curing in partial water and full and partial covering with plastic (Mannan *et al.*, 2002). This was also later confirmed by Alengaram *et al.* (2010b), Shafigh *et al.* (2012) and Maghfouri *et al.* (2021). However, Shafigh *et al.* (2012) found when OPSC is water cured more than 3 weeks, no difference in mechanical strengths is observed. Alengaram *et al.* (2010b) further recommended to use all particle sizes of

Table 5. Mechanical Properties of OPSC from Various Researchers

Reference	Investigation	Compressive strength (MPa)	Flexural strength (MPa)	Splitting tensile strength (MPa)	Young's modulus (GPa)
Okafor (1988)	OPS mix ratio	16-23	4.30-6.20	2.00-2.40	-
Okpala (1990)	OPS mix ratio	14.90-22.20	2.13-2.81	-	-
Mannan and Ganapathy (2002)	OPSC vs NWC	20.12-24.22	2.75-4.00	1.78-2.41	7.0-7.6
(Alengaram <i>et al.</i> , 2008b)	RC Beams	36.70-37.41	3.50-3.83	-	10.02-10.71
Mahmud <i>et al.</i> (2009)	Sand/Cement ratio	26.98-37.79	2.79-4.10	1.98-2.35	7.08-10.09
(Alengaram <i>et al.</i> , 2010b)	Agg. size + SF + FA	26	2.21-3.00	1.50-18.4	7.01-11.18
(Alengaram <i>et al.</i> , 2010c)	OPSC vs NWC	36.70-37.41	3.50-3.83	1.95-2.10	10.05-11.15
(Ahmed and Sobuz, 2011)	OPSC vs NWC	15.4-19.9	2.4-2.6	2.1-2.5	13.4-17.1
(Alengaram <i>et al.</i> , 2011a)	Shear - RC	32.6-33.7	4.0-4.2	2.4-2.6	10.9-13.8
Shafigh <i>et al.</i> (2011c)	Steel Fibers	39.34-44.95	5.42-7.09	2.83-5.55	5.50-7.10
Shafigh <i>et al.</i> (2012)	Curing condition + Crushed OPS	34-53	4.4-7.0	2.8-3.5	-
Yap <i>et al.</i> (2013)	Fibers PP Nylon	23.9-36.0 35.8-36.8	3.51-4.64 4.20-4.37	2.48-3.23 2.97-3.49	14.16-15.23 12.26-12.78
Shafigh <i>et al.</i> (2013a)	Fly Ash (FA)	30.04-46.08	3.65-4.94	1.98-2.59	-
Shafigh <i>et al.</i> (2014)	SP + OPBC sand	31.2-37.8	3.22-4.18	2.20-2.64	8.6-13.8
Mo <i>et al.</i> (2015)	GGBFS	33.4-45.1	4.03-5.71	2.31-3.51	12.6-17.6
Mo <i>et al.</i> (2014a)	Steel fibers Cube Cylinder Prism	33.51 36.78 43.57	4.73 5.91 6.88	2.49 4.80 5.80	9.71 10.65 14.79
Foong <i>et al.</i> (2015)	Rice husk ash + manufactured sand + SP	48.12-51.49	5.2-5.9	3.12-3.45	14.1-17.8
Islam <i>et al.</i> (2016cb)	POFA	36.0-42.4	3.0-6.5	2.6-4.0	12.7-15.4
Yap <i>et al.</i> (2015a)	Torsion RC + Steel fibers	33.9-47.3	3.26-8.16	-	13.87-16.29
Yap <i>et al.</i> (2015c)	PP Fibers	42.2-47.2	5.75-7.64	3.35-4.12	12.04-15.36
Yew <i>et al.</i> (2015c)	Steel fiber aspect ratio	32.8-37.0	3.81-6.04	2.83-3.91	13.25-15.48
Yap <i>et al.</i> (2015b)	PP twisted bundle fibers	50.6-54.6	5.98-6.46	3.52-3.98	17.4-15.9
Yap <i>et al.</i> (2015b)	Torsion Behave. + Steel fibers + Silica Fume	33.9-47.3	3.26-8.16	2.59-5.47	13.87-16.29
Mo <i>et al.</i> (2015c)	Polyvinyl Alcohol fibers	42.89-48.51	4.17-5.49	-	15.3-16.9
Khankhaje <i>et al.</i> (2016)	High volume slag	25.4-33.3	-	2.328-2.690	-
Shafigh <i>et al.</i> (2016)	Torsion Behave. + Steel fibers	33.9-47.3	3.26-8.16	-	13.87-16.29
Huda <i>et al.</i> (2016)	Pervious concrete	6-12	-	0.79-2.40	-
Mo <i>et al.</i> (2016ba)	Expanded clay	24-27	3.69-4.2	1.96-2.29	13.8-15.1
Mo <i>et al.</i> (2016ba)	OPS vs POC	38.28-46.47	3.93-6.00	2.90-3.37	6.80-10.38
Mo <i>et al.</i> (2016cb)	M/Ø approach - Prediction + GGBFS	19-26	-	2.3-2.5	5.5-8.3
Yap <i>et al.</i> (2017)	Bond stress-slip Cube	25.68-36.01	-	2.516-2.985	-
Noor <i>et al.</i> (2017)	behavior + GGBFS + SP Cylinder	17.93-27.84	-	2.516-2.985	-
Mo <i>et al.</i> (2017)	Steel fibers	34.8-56.7	4.84-18.48	3.22-10.99	13.53-16.35
Aslam <i>et al.</i> (2017a)	Palm oil Fiber	3.6-25.6	1.2-6.6	-	-
Traore <i>et al.</i> (2018)	Shear behave. + Steel fiber + Geo-polymer concrete + FA + AA	27.79-38.85	3.182-6.180	2.129-6.125	-
Mo <i>et al.</i> (2018)	OPSC + SP	37.2	5.38	3.29	7.9
Jagarapu and Eluru (2019)	OPBCC + SP	53.3	7.00	3.58	15.7
Yap <i>et al.</i> (2019)	OPS treatment	20.5-41.8	4.0-6.4	-	7.06-12.08
Fanijo <i>et al.</i> (2020)	Metakaolin-blended OPS	45-47.62	4.58-6.88	2.55-3.38	13.71-15.46
Ting <i>et al.</i> (2020)	GGBFS + POFA + FA + Glass fiber + SP	14-35	-	1.0-3.2	0.55-3.25
	Ductility behave. + Steel fibers + SF + SP	33.9-47.3	3.26-8.16	-	13.87-16.29
	Laterized concrete	20-38	-	3.7-4.8	-
	FA + SP	18.72-38.88	-	1.62-2.82	-

OPS in the mix, as removing small particles (less than 5 mm) would decrease the compressive strength. A study by Alengaram *et al.* (2010b) concluded that OPS with small particle sizes (accounting for about 65-70% of the total concrete mass) have higher relative density, which accumulates for 4% of the total density of OPSC. This would therefore make the concrete more packed and thus decrease the concrete water absorption. It has further been reported when OPSC has a low water absorption ranging between 3.12-6.2%, high concrete strengths are obtained (Shafigh *et al.*, 2011a), confirming the earlier study by Alengaram *et al.* (2010b).

Another factor affecting the strength is the irregular shape and strength of OPS (Mannan and Ganapathy, 2004). The compressive strength depends on either the strength of the aggregate or the cement paste depending on which one fails first (Mannan and Ganapathy, 2002). However, the bond between the OPS aggregate and cement paste also plays an important role (Okpala, 1990). Because of the smooth surface of OPS, the cement binding

force is found to be inadequate (Shafigh *et al.*, 2011b) due to the low adhesion between the cement paste and OPS surface (Okpala, 1990) and (Mannan and Ganapathy, 2002).

A way to increase de-bond properties between OPS and cement paste has been done by adding silica fume (10%) (SF) and fly ash (5%) (FA) in the mix, showing an increase in the compressive strength by 30% (Alengaram *et al.*, 2011b). SEM images taken by Alengaram *et al.* (2011b) of OPS prior and after the mix as seen in Figure 4. The images reveal that the pores are uniformly filled when adding SF and FA compared to just cement, thus increasing the bond, and therefore increasing the compressive strength. Though, Mannan and Ganapathy (2001) showed a decrease in strength with the addition of FA (10 and 15%) as cement replacement by 7% and 19% respectively. This is also confirmed by Shafigh *et al.* (2013a), Ting *et al.* (2020), Maghfouri *et al.* (2021) and Muthusamy *et al.* (2021). It is possible that the increase in compressive strength reported by Alengaram *et al.*

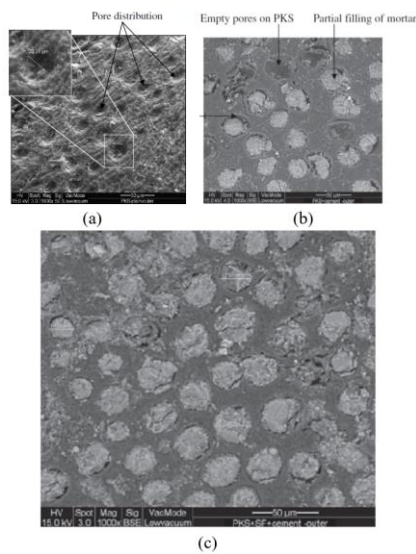


Figure 4. Filling of mortar in micro-pores of OPS with FA and SF (a) OPS shell prior to mixing, (b) OPS shell with only cement, (c) OPS shell with 5% FA and 10% SF cement replacement (Alengaram *et al.*, 2011a)

(2011b) was obtained solely due to the SF, also confirmed in a previous study by Mahmud *et al.* (2009).

Conversely, a decrease in compressive strength has been observed with ground granulated blast furnace slag (GGBFS) as cement replacement in OPSC (Mo *et al.*, 2015b), while the durability was not measured. Muthusamy *et al.* (2015) incorporated 20% palm oil fuel ash (POFA) with cement replacement in OPSC and presumed an enhancement of the bond between the cement paste and OPS, resulting in an increase in compressive strength by 15%. Higher content of POFA was not recommended, as it would decrease the compressive strength (Muthusamy *et al.*, 2015). Foong *et al.* (2015) found that rice husk ash (RHA) increases the compressive strength by 10% with 15% of RHA replacement with cement in OPSC. The author concluded that it might be because the RHA attributed to the strong bond at the interfacial transition zone (ITZ) cause by the pozzolanic reaction of RHA. However, no SEM images were included to confirm this hypothesis. To the authors' knowledge, no further studies investigating RHA in OPSC were available to corroborate these findings.

Other investigations have found an increase in bonding between OPS and cement by treating OPS with PVA solution which created a thin layer on the shells (Mannan *et al.*, 2006; Chai *et al.*, 2014; Traore *et al.*, 2018). One study Mannan *et al.* (2006) achieved to increase the compressive strength by 28% by treating OPS with 20% of PVA solution. However, Chai *et al.* (2014) could only increase the compressive strength by 13% with the same amount of PVA solution. The main reason for this could be because Mannan *et al.* (2006) exposed the OPS to very severe environment conditions by incorporating alkaline and acidic solution compared to Chai *et al.* (2014) who exposed the OPS to 1-2 weeks of

natural weathering. In contrast to Mannan *et al.* (2006) and Chai *et al.* (2014), the study by Traore *et al.* (2018) found that treatments of PVA decreased the compressive strength by 8%. This might be because Traore *et al.* (2018) only used 5% of PVA solution by covering the OPS for only 3 min and was then drained at room temperature. While Chai *et al.* (2014) did not mention their procedure, Mannan *et al.* (2006) followed a different procedure than Traore *et al.* (2018) for the treatment as described by Santos *et al.* (1999). However, Traore *et al.* (2018) found an increase in compressive strength (25.5 MPa) by 8% with lime solution treatment of OPS. The author concluded that the lime treatment improved the adherence of OPS with the cement matrix. A different treatment of OPS was done by hot and cold alkali treatment of OPS (Nabinejad *et al.*, 2014). It was found that hot alkali treatment improved the mechanical properties (tensile and flexural strength) of OPSC by 49% and 33% respectively at 28 days. However, no compressive strength tests were conducted. Nano coating OPS with siliceous material showed to improve the compressive strength by 53% (Nadh *et al.*, 2021). The authors mentioned that the interfacial transition zone of the nano coated OPS was reduces from 600 micrometres to 400 micrometres according to SEM images, thus creating a better bond. Another simple coating method was done by gun spraying grout formulation of 1.25 w/c on OPS prior to mixing (Yew *et al.*, 2021). This method proved to increase the compressive strength by 14%. However, the increase in strength might be due to the increase in cement content, i.e., addition of grout.

Tensile Strength

Most research on OPSC was done by Flexural and splitting tensile strength test, which is shown in the next sections.

Flexural and Splitting Tensile Strength

The flexural test measures the concrete's tensile strength in an indirect manner. Typically, the cement bonding matrix is the limiting factor for tensile strength of most concretes. Although the tensile strength of concrete in flexure is commonly neglected in strength design by engineers, it is still however important in deflection and cracking considerations at service loads (ACI 318M-08, 2008). In general, LWC has a lower flexural and splitting tensile strength compared to NWC. However, typically the cement bonding matrix is the limiting factor for tensile strength of most concretes.

However, in the case of OPSC, depending on the mix ratio and content of admixtures and or fibres, it can produce high tensile strength in comparison to NWC (Alengaram *et al.*, 2011a). The tensile failure mechanism in OPSC occurs because of failure of bond between the OPS surface aggregate and cement matrix, and not by the OPS aggregate (Alengaram *et al.*, 2010c). Table 5 reports the tensile strength of OPSC from various researchers. Because of low stiffness and strength of the OPS, a large difference is seen between OPSC and NWC in terms of flexural strength (Alengaram *et al.*, 2010a).

Increase in cement content (295, 314, up to 335 kg/m³) improved the flexural and splitting tensile strength of OPSC at 28 days by 14% and 16% respectively.

This was in parallel with decreasing the w/c (0.65, 0.54 to 0.48) (Okafor, 1988). Similar conclusions were drawn by Okpala (1990) with w/c's of 0.5, 0.6, 0.7, and 0.8 at mix ratios of 1:1:2 and 1:2:4 (cement: sand: OPS). The author also concluded that increasing the curing age, will also increase the flexural strength by 22%. Mannan and Ganapathy (2002) also confirmed when increasing the curing age from 7 to 28 days, the flexural strength increases by 46% and splitting tensile strength by 35%. However, the NWC control samples showed to have a higher flexural and splitting tensile strength by 55% and 93% respectively compared to OPSC. The author concluded that OPSC has a similar behaviour to NWC under curing conditions and that the main reason for weaker strength was influenced by the diffused moisture distribution on the OPS and the weak bonding between cement matrix and OPS. However, cement replacement with 10% SF and 5% FA showed a smaller difference to NWC in flexural and splitting tensile strength by 17% and 38% respectively (Alengaram *et al.*, 2010c).

When using crushed OPS, OPSC is shown to have similar flexural and splitting tensile strengths compared to NWC with similar compressive strengths ranging from 34.8-53 MPa. Also, OPSC with higher compressive strengths have a higher flexural and splitting tensile strength (Shafigh *et al.*, 2012). Alengaram *et al.* (2010b) studied the OPS size and proportion in OPSC and showed that OPS sized between 2-10 mm (at 100% proportion) showed higher tensile strengths compared to 2-15, 5-10, 5-15, and 0-15 mm by 2%, 8%, 23%, and 12% at 28 days curing. The authors mentioned the smaller sizes had more flaky and angular surfaces which caused a better bonding with the cement matrix compared to the larger sizes, however they concluded that OPS particles of all sizes were the best performers in both compressive and tensile strengths. Interestingly, they did not provide the particle size distribution for the 2-10 mm OPS aggregates. When increasing the sand-cement ratio in OPSC (s/c: 1, 1.2, and 1.6), the flexural strength is increased by 17% and 49% respectively and splitting tensile strengths is increased by 5% and 24% respectively at 28 days. Though, the densities with s/c: 1, 1.2, and 1.6 did increase by 1% and 4% respectively. Nevertheless, it was still below the LWC requirement ($<2,000 \text{ kg/m}^3$) (Mahmud *et al.*, 2009). Traora *et al.* (2018) found that by treating OPS with lime, sodium silicate and heat treatments, improvements in flexural strengths were 8%, 5%, and 6% compared to the control, with strength varying from 4-5 MPa. PVA showed no significant increase or decrease in flexural strength, although as mentioned earlier, the treatment was quite brief and caused a decrease in compressive strength performance. Of note, despite the filling of pores by PVA, the adhesion of cement paste was not improved.

When FA is used as cement replacement in increments of 30%, 40%, and 50%, a decrease in splitting tensile strength is observed by 10%, 27%, and 58% compared to control specimen at 28 days, respectively. However, in the long term at 90 days, the decrease was 3%, 18%, and 27% respectively. The authors mentioned that the FA at 28 days were still smooth and spherical and is thus still at the early age of hydration, whereas at 90 days, the smooth and rounded shape of FA were not

easily noticeable, which explains the higher strength in 90 days compared to 28 days (Ting *et al.*, 2020). Comparable results for splitting tensile strength are observed with GGBFS as cement replacement where 20% and 60% have shown a decrease of 6% and 14% respectively compared to control specimen at 28 days (Mo *et al.*, 2015c). An earlier study Mo *et al.* (2015b) showed equivalent results, but studied GGBFS replacements at 20%, 30%, 40%, 50%, 60%, and 70% showing a decrease in splitting tensile strength by 4%, 5%, 4%, 13%, 15%, and 34% and for flexural strength by 4%, 13%, 16%, 19%, and 29% respectively at 28 days. In both studies by Mo *et al.* (2015c) and Mo *et al.* (2015b), the main reason for strength reduction stated was because of the delayed hydration compared to cement. Other studies by Mo *et al.* (2016b) and Mo *et al.* (2016c) observed similar tensile strength behaviours with GGBFS replacement in OPSC. Also, by using POFA as cement replacement at 5%, 10%, 15%, 20%, and 25% the flexural strength decreased by 0.5%, 5%, 12%, 28%, and 39% and for splitting tensile strength by 0.5%, 10%, 17%, 18%, and 26% respectively (Islam *et al.*, 2016c).

However, by using metakaolin as cement replacement at 10%, the flexural and splitting tensile strengths were found to be improved by 44% and 50% respectively at 28 days. The authors claimed to have increased the bonding in the ITZ between cement and OPS, though no SEM images were taken (Mo *et al.*, 2018). An increase was also seen when replacing 15% of RHA with cement by 15% and 28% for flexural and splitting tensile strength, respectively. The authors achieved this by also using 100% of manufactured sand. They mentioned the cause for increase in strength was due to the higher packing ability of the RHA particles (Foong *et al.*, 2015).

Fibres like polypropylene, nylon, steel, and other agricultural fibres have shown to improve the flexural and tensile strength, which proves to behave like NWC. In summary, as flexural and splitting tensile strength is incumbent on the adhesion of cement paste to the aggregates, including OPS, results between OPSC, LWC, and NWC show similar trends with or without addition of admixtures and/or additives. Also as expected, the addition of pozzolanic materials did not increase 28-day strengths significantly but showed improvements at the 90-day stage.

Modulus of Elasticity

Generally, the modulus of elasticity of NWC is higher than that of LWC because modulus of elasticity of NWA is higher than that of LWA (Holm and Bremmer, 2000). Table 6 shows results of the modulus of elasticity of OPSC from various researchers which concluded that the value of modulus of elasticity for OPSC is influenced by the coarse aggregate and OPS quantity, type of cement, w/c ratio of the mix, curing period and bond between the OPS and the cement matrix. Also, most researchers have achieved a modulus of elasticity of higher than 10 GPa to be recommended as a structural LWC according to (FIP, 1983).

As with NWC, it has been observed that the compressive strength of OPSC is related to the modulus

Table 6. Fibre investigations on OPSC

Reference	Type of Fiber	Advised fiber content
Shafigh <i>et al.</i> (2011c)	Steel	1%
Yap <i>et al.</i> (2013)	Polypropylene and nylon	0.5% (multi-filament)
Mo <i>et al.</i> (2014b)	Steel-polypropylene hybrid	0.9% steel, 0.1% PP hybrid
Yap <i>et al.</i> (2014)	Steel-polypropylene hybrid	0.9% steel, 0.1% PP hybrid
Mo <i>et al.</i> (2014a)	Steel	1%
Yap <i>et al.</i> (2015c)	Steel: Aspect ratio 80	0.5%
Yew <i>et al.</i> (2015a)	Monofilament-Polypropylene twisted bundle	0.5%
Yew <i>et al.</i> (2015c)	Polypropylene twisted bundle	0.25%
Yew <i>et al.</i> (2015b)	Polyvinyl Alcohol	0.375%
Yap <i>et al.</i> (2015b)	Steel	1%
Noor <i>et al.</i> (2017)	Palm oil	0.25%
Yap <i>et al.</i> (2017)	Steel	3%
Mo <i>et al.</i> (2017)	Steel	1%
Yap <i>et al.</i> (2019)	Steel	1%

of elasticity. As the compressive strength increases, the modulus of elasticity also increases (Aslam *et al.*, 2017b). As explained earlier, by reducing the OPS content, the compressive strength increases and thus leading to a higher modulus of elasticity (Shafigh *et al.*, 2016). This is similar when the fine aggregates are increased as shown by Mahmud, *et al.* (2009) and confirmed by Alengaram *et al.* (2011b). Though larger size particles of OPS (10 mm and above) decrease the compressive strength, it has been shown to increase the modulus of elasticity by 31% compared to OPSC with smaller sizes (Alengaram, *et al.*, 2010b). Moist curing compared to air curing of OPSC have shown higher modulus of elasticity (Islam *et al.*, 2016b), whereas curing for longer than 28 days up to 90 days have shown 8% and 6% increase in modulus of elasticity respectively (Mannan and Ganapathy, 2002). Similar results have been shown by Alengaram *et al.* (2010b). Nevertheless, this might be related to the increase in compressive strength. Other authors have used cement replacement agents such as SF, GGBFS, RHA, POFA, and metakaolin to study the modulus of elasticity. SF (Mahmud *et al.*, 2009; Alengaram *et al.*, 2010c), RHA (Foong *et al.*, 2015), and metakaolin (Mo *et al.*, 2018) have all shown increments in the modulus of elasticity. All authors claimed the agents have filled the OPS pores resulting in a better interfacial transition zone between the cement matrix and OPS. In contrast, GGBFS (Mo *et al.*, 2015b), and POFA (Islam *et al.*, 2016b) have shown a decrease in modulus of elasticity. Mo *et al.* (2015b) and Islam *et al.* (2016b) have concluded that GGBFS and POFA, respectively, contribute to the weak bond at the interfacial transition zone of OPS and cement matrix. Mo *et al.* (2015b) mentioned that it might be attributed to the fact that, as pozzolans, GGBS undergoes a slower hydration process compared to the cement. Islam *et al.* (2016b) drew a similar conclusion for POFA. This concludes that OPSC behaves in a similar matter to NWC i.e., increase in compressive strength increases the modulus of elasticity and vice versa. In another study mentioned in the earlier sections by Traore *et al.* (2018), the authors have shown that lime treatment of OPS increases the modulus of elasticity significantly by more than 64% compared to

the control OPSC. However, both the compressive strengths and modulus of elasticity values were far behind normal control concrete (41.8 MPa vs 25.5 MPa, 21.6 GPa vs 12.6 GPa, respectively). An investigation on predicting the modulus of elasticity of OPSC by using CEB/FIP model code formula was investigated by Alengaram *et al.* (2011b). The authors suggested modifying the formula because it overestimated the value from 65% to 120%. The modified formula is shown in Equation (1).

$$E_{s(pre)} = \left[\frac{\rho}{2400} \right]^2 \times (f_{cu})^{1/3} \times 5.0 \quad (1)$$

With the above formula it predicted Alengaram's modulus of elasticity with the experimental values with an error of ± 1.5 GPa. This was later confirmed in a study by Foong *et al.* (2015) who had a comparable error value of ± 1.5 GPa.

Drying Shrinkage

The ability of a material to maintain its size, shape, or dimension over time is referred to as dimensional stability. A dimensionally stable material's long-term volumetric change should be so negligible as to not affect the material's structural integrity. Shrinkage is one of the main phenomena that compromises the dimensional stability issue for concrete (Li, 2011).

According to FIP (1983), the shrinkage value of LWC is normally around 50% greater than that of NWC and is greatly affected by the properties of the LWA and its content (Chandra and Berntsson, 2002). A study by Maghfouri *et al.* (2019) found that OPSC showed a 60% higher drying shrinkage compared to NWC and prediction models from both ACI 209.2R-92 (2008) and BS EN 1992-1-1 (2014). Higher shrinkage value occurs when the LWC contains aggregates that have high rates of absorption, low modulus, high proportion of fineness, and/or require high cement contents to obtain the specified strength (Washa, 1956). However, when the LWA is saturated, internal curing occurs which could result in decrease of shrinkage (Geiker *et al.*, 2004).

Several authors have investigated the drying shrinkage of OPSC at different curing regimes and curing time, different mix proportions, and with different supplementary cementitious materials like FA, GGBFS, POFA and RH. As for the testing method, mainly two types were used: the free drying shrinkage test and the bar type test. However, it is difficult to relate and compare their results, since each author has used a different specimen size, different type of test, different mix proportions and different room temperature and RH. However, some indications can be related like the increase in shrinkage qualitatively. Results have shown a decrease in shrinkage from 735 to 855 micrometres when lower content of OPS (425-365 kg/m³, respectively) is used by 14% at 150 days, though with low water content (Mo *et al.*, 2015d). This is most probably because the moisture from the OPS assisted in internal hydration, since mixed in SSD state. This was also concluded by Aslam *et al.* (2016). When OPSC was compared to NWC, it has shown that the shrinkage value is five times that of NWC which decreased after 60 days (Abdullah, 1996). However, Mannan and Ganapathy (2002) mentioned that

the drying shrinkage of OPSC was 6, 27, and 14% higher than the NWC at 28, 56, and 90 days, respectively. The author further mentioned that the reason for a higher drying shrinkage at 56 days of curing was because of the loss of water at the early age when it was in the plastic stage and the surface irregularity of the OPS. This was also confirmed in a similar study by Mo *et al.* (2015d). The authors probably resulted in less shrinkage compared to Abdullah (1996) since they used a higher fine aggregate content (sand /cement: 1.71 vs sand /cement:1).

Other studies have investigated the drying shrinkage effect when incorporating supplementary cementitious materials such as FA (Maghfouri *et al.*, 2021), POFA (Islam *et al.*, 2016a), GGBFS (Mo *et al.*, 2016a), and RH+FA (Farahani *et al.*, 2017). Maghfouri *et al.* (2021) incorporated 20% FA in OPSC and compared it to OPSC without FA at different curing ages of 0, 7, and 28 days. It was observed that OPSC with FA content increases the long-term shrinkage (365 days) with higher curing age with 35% whereas without FA only 23%. While up to 7 days, no significant difference in shrinkage was observed for all specimen types. Shafigh *et al.* (2013b) mentioned when OPSC is mixed with 10% of fly ash, no difference in drying shrinkage was observed. However, only an insignificant increase was observed when higher levels were used (30% and 50%) by 17% and 8% greater than the control specimen, respectively. An increase of drying shrinkage of OPSC was found with higher levels of POFA (10%, 30%, and 50%) with a w/c ratio of 0.3 cured with 28 days by 53%, 66% and 126% respectively after 64 days. However, with a higher w/c of 0.4, OPSC with 70% of POFA was found to be similar to 0% of POFA (Islam *et al.*, 2016a). In a long-term study of 365 days by Mo *et al.* (2016a), it was found that OPSC without GGBFS replacement had a comparable drying shrinkage value to OPSC with 40% of GGBFS. However, when the GGBFS was increased to 60%, the drying shrinkage also increased by 20%. Mo *et al.* (2016a) mentioned the reason for this might be because the free water could escape from the pores caused by the low hydration with the presence of high GGBFS content. An increase in drying shrinkage was also found when using RH and RH+FA in OPSC, especially of RH and RH+FA in OPSC at 20% and 30% replacement by 26% and 79% compared to the control, respectively. However, no significant difference was seen with 10% RH and 15% RH+FA. The author further recommended when OPSC is incorporated with 30% of RH and or RH+FA, it is not recommended to be used for constructing structural elements due to its high shrinkage value (Farahani *et al.*, 2017).

OPS as Partial Replacement with Other Aggregates

A paper by Fanijo *et al.* (2020) investigated OPS with granite but also tested laterite sand replacement. Partial replacements of OPS showed better workability when compared to both control and mixture containing laterites. The mechanical properties decreased when OPS content increased. The optimum design was concluded to use 20% of both OPS and laterite replacements in concrete.

An investigation was done on using crushed granular coconut and OPS as a combination in concrete. It showed that the compressive strength decreased when the percentage of both shells increases. However, when OPSC was compared to coconut-concrete, the coconut-concrete showed a higher compressive strength. The author further concluded that both were “fairly-equal” in terms of water absorption performance (Olanipekun *et al.*, 2006). Most researchers conducted investigations of OPS with palm oil clinker (POC). A structural LWC was aimed to make by using POC and OPS as aggregate replacements by Aslam *et al.* (2015). Two mixes were compared, one with 100% OPS and the other with 60% OPS and 40% POC. When both LWA were used, an increase in compressive strength was observed compared to 100% OPS. The author mentioned that the quality of the concrete improved by using both LWA's. The density did increase by adding POC to OPS but was still in the limit of structural LWC. Also, the long-term drying shrinkage is improved by replacing 50% POC to OPSC (Aslam *et al.*, 2016). By using POC and OPS, structural lightweight geo-polymer concrete can be produced (Kabir *et al.*, 2017). Kabir further mentioned the compressive toughness was improved when using both OPS and POC compared to OPS alone. The author further claimed it was because of the porous POC aggregate that increased both the stiffness and the bond with the cement paste. A singly RC beam was produced by using OPS and POC to present the structural performance by Huda *et al.* (2016) with mix proportions of 60% and 40%, 70% and 30%, and 40% and 60% (OPS and POC). When 40% of POC was used, the highest compressive strength was achieved of 46 MPa (just within the limits of LWC).

Enhancing OPSC with Fibres

An adequate number research has been done on the addition of fibres to OPSC. In Table 6, investigations on fibres in OPSC can be seen. According to most investigators mentioned in Table 6, when incorporating OPSC with fibres, the shrinkage can be reduced through the reduction of micro-cracks. Though steel fibres increase tensile strength and perform better than synthetic fibres, it reduces the workability of OPSC because of the friction volumes of the steel fibres. Thus, decrease in slump values were noticed. However, with the addition of SP, the workability can be treated. In the case of synthetic fibres, no significant increase in density is noticed while improving the mechanical properties in contrast to steel fibres.

Structural Behaviour of OPSC

Flexural Behaviour

It was found that flexural behaviour of OPSC beams is comparable to other LWC beams and the results from the experiments showed to be “reasonably well” when compared to current codes of practices (Teo *et al.*, 2006b). All the serviceability requirements as per BS 8110-1 (1997) were met by the low reinforcement ratio beams.

Also, the following points of OPSC beams were observed under flexural behaviour. Also, it was observed when OPSC beams were under flexural behaviour, it has a typical structural behaviour, steel yielding occurred before concrete crushing, ultimate moment and deflection prediction from BS 8110-1 (1997) provided a good estimate for reinforcement ratios of up to 3.14% and single reinforced OPSC beam respectively. For doubly reinforced OPSC beams, the limit was exceeded by the deflections at service loads; beam depths should be increased, good ductility behaviour and crack widths were within the limits as per BS 8110-1 (1997). The flexural behaviour, which was among the structural behaviour study by Alengaram *et al.* (2008b) was investigated to compare NWC with OPSC beams. Same grade concrete (grade 30), both under reinforced and silica fume and Class-F fly ash was used. The overall flexural behaviour of OPSC beams were comparable to the NWC beams. The moment capacity of OPSC beams were higher than NWC beams by around 3%. A ductile failure was observed in OPSC beams while brittle failure was found in the NWC beams. Higher deflections occurred in the OPSC beam. Many small crack spacing's were observed in OPSC beams which in return prevented large crack openings which were within the requirements of BS 8110-1 (1997). The author finally reported that the OPSC beams in their investigation had better flexural behaviours than earlier reports. This might be because silica fume and Class-F fly ash were incorporated. In a later study by Huda *et al.* (2016), OPS and POC were used in singly reinforced beams and similar results were found as the above-mentioned authors. Experimental and theoretical investigations were compared on OPSC beams by Ahmed and Sobuz (2011) based on structural performances. From both experimental and theoretical analysis, brittle behaviour was found when un-cracked and ductile behaviour when cracked. When factors affecting the long-term performance of OPSC beams are provided, the theoretical approach gives an acceptable estimate of its deflection. The author concluded that close agreements have been met between the theoretical and experimental results. A "segmental moment-rotation (M/θ)" approach has been studied to predict flexural behaviour of OPSC beams at all load levels by Mo *et al.* (2016b). The approach has proven to be able to predict the full range of flexural behaviours (load-deflection and crack width) of OPSC beams at all load levels and to be used as a basis for developing design guidelines of LWC. Besides investigating the approach on the authors own experiments, good comparisons were also found by comparing it to earlier reports. The author further concluded that the addition of GGBFS showed no effect, high tension ratio beams had higher flexural capacity, lower ductility and smaller crack openings and serviceability mid-span deflection was well-predicted by the approach on flexural behaviour of OPSC beams.

Shear Behaviour

Shear behaviour on OPS foamed concrete (OPSFC) was investigated with and without shear reinforcement and compared to NWC with shear reinforcement by Jumaat *et al.* (2009). Higher shear capacity, more flexural and shear cracks occurred in the shear reinforced OPSFC

compared to the NWC. Using equations from ACI and numerical analysis using DIANA standard showed more predictable results than the BS equations for OPSFC. The shear strength was enhanced because of good aggregate interlock of OPSFC and was 10% higher than the NWC. A similar investigation was done by Alengaram *et al.* (2011a) with similar results given by Jumaat *et al.* (2009). However, Alengaram used OPSC instead of foamed concrete. Shear strength of OPSC was found to be 24% higher than that of NWC. Alengaram also used the DIANA software for analytical analysis and predicted the shear strength of OPSC with an error of 20%. Shear strengths of OPSC were also predicted using ACI, BS and EC 2 codes and according to the author, were underestimating the experimental results. Even though the elastic modulus of OPSC was lower than the NWC by 45%, OPSC fulfils the requirements of deflection criteria by BS 8110-1 (1997). Shear behaviour of OPSC beams was experimented by Mo *et al.* (2017b) with cement-based compared to OPSC with geo-polymer with steel fibres ranging from 0-1% and 0-0.5% respectively. For both types, the inclusion of steel fibres enhanced the shear resistance, however the cement based OPSC showed higher values. The author also concluded that codes from ACI, BS, and EC 2 underestimated the experimental values. However, modified equations, based on the codes, were used from other reporters mentioned by Mo *et al.* (2017b) proved it could be used "conservatively" to determine shear resistance of OPSC beams.

Torsional Behaviour

Only one author had studied the torsional behaviour of OPSC and published a total of two papers. The first investigation was in the paper (Yap *et al.*, 2015a) where OPSC was studied for the torsional and cracking behaviours with steel fibres introduced and compared to NWC. It was found that the OPSC beam had a post-cracking behaviour compared to a brittle and sudden failure of the NWC. The addition of steel fibre with 1% of volume of the OPSC provided enhancement in the ultimate torque by 60%, torsional toughness by 1,000%, and twist at failure by 550% and improved the crack resistance. All OPSC specimens were within the limits of LWC. The second investigation by Yap *et al.* (2015c), the fibre aspect ratio (55, 65, and 80) was studied under torsional behaviour with 0.5% fibre volume. The aspect ratio of 80 produced the highest torsional toughness, ultimate torque, and twist at failure. It was further added that OPSC with fibre was more ductile in torsion when compared to NWC. In this article, for the ultimate torque and cracking, the author proposed a modified prediction equation, which was from previous studies, with an error of $\pm 8\%$ for OPSC and $\pm 6\%$ for OPSC with steel fibres.

Dynamic Behaviour

The only type of dynamic behaviour test on OPSC was done by using the drop-weight impact method.

Impact Loads

An investigation by Mo *et al.* (2014b) used the drop-weight impact method on OPSC reinforced with steel fibres and with PP fibres with different contents of fibres.

Crushed and uncrushed OPS was also compared. The specimens with the uncrushed OPS had higher impact resistance than the crushed OPS with the inclusion of fibres. The author further concluded that a specimen with a combination of 0.9% steel +0.1% PP had the highest impact energy of 17 kJ. A similar investigation was done on the impact resistance of OPS reinforced with only PP fibres by Yahaghi *et al.* (2016). It was observed that with the increase of slab thickness (40 mm) and PP fibre content (0.3%), the impact resistance increased.

OPSC Exposed to Elevated Temperatures

Just in Malaysia, there has been reported a total of 50,720 fire incidents in 2019, which increased by 24.1% compared to 2015 (Mahidin, 2020). This indicates a need to study concrete structures under elevated temperatures. A method was proposed by Jumaat *et al.* (2015) to find out if there would be any effect in the concrete's enhancement if OPS was replaced with POC at elevated temperatures. Replacements were from 25%-100% with 25% increments and exposed to temperatures up to 500°C for 30 and 60 min. When POC content increased in OPSC when subjected to 500°C at 60 min, cracks decreased, and compressive strength increased. By using a Thermo-gravimetric analysis, it was noticed that samples with higher content of POC lost less weight when exposed to higher temperatures. This study was reinvestigated by Hama *et al.* (2022) and found similar results by using Tenera type OPS, though with lower compressive strengths.

Application of OPSC

Though with so much research in OPSC in the last four decades, very few applications have been made so far. Universiti Malaysia Sabah (UMS) had taken an initiative to construct a small footbridge in 2001 and later in 2003 a low-cost house as seen in Figure 5. However, 20 and 18 years later, no information has been published on both applications today.



Figure 5. Structures made from OPS concrete. (Left) Footbridge and (Right) Low-cost house (Teo *et al.*, 2006a)

Conclusions

Significant research has been undertaken to incorporate OPS in concrete, with varying success. Mix designs of OPSC appear to follow typical LWC trends, and addition of pozzolanic additives or plasticizing admixtures also

work as intended, making OPS use as a coarse aggregate viable in concrete. Furthermore, OPS do not affect workability significantly, which adds to the practicality of OPSC. However, the low density and high porosity of the shell is known to cause bleeding issues in the mix, alleviated by heat treatment, PVA coating or treatment with lime. Additionally, the high porosity of OPS and possibly its prolonged sterilization in the milling process may significantly increase its water absorption capacity. As a mitigative measure, it is recommended to have OPS in an SSD state prior to mixing. The adhesion of hydrated cement paste with the surface of OPS has also been investigated, mitigated by cleaning with detergent or lime/PVA treatment. Research literature has deduced that OPS's smooth surface could be resulting in poor bonding with hydrated cement, however flexural and tensile strength results of OPSC are more comparable to LWC, with compressive strength showing greater reductions and variabilities. This leads into some significant research omissions, which the author of the present review hypothesizes to be primary reasons behind the discrepancy in OPSC mechanical performance throughout the researched literature.

Unlike typical mineral LWA such as expanded shale, clay, or lime, the palm oil fruit is organic, and its growth is incumbent upon the environmental conditions, such as exposure to sunlight, age of ripening, etc. This also affects the palm oil kernel, also called the OPS. Research of the palm oil fruit showed that the genus of the plant bearing the fruit (*dura*, *tenera*, or *pisifera*) can significantly affect the OPS thickness, hardness, and porosity. With conventional LWA, high variance between coarse aggregates is not expected due to their crystalline origins, but most research on OPSC seemed to hold similar expectations with the OPS. As a result, there are glaring omissions of any mechanical tests performed on the OPS, and almost no information conveyed on mechanical properties of the shell aggregates being incorporated in OPSC. Furthermore, most literature did not specify the variety of OPS, age of the shell, storage conditions, and even the source where OPS was collected from, all of which are key parameters needed to better understand the characteristics of the aggregate being incorporated. Conversely, OPS is mostly subjected to conventional aggregate tests such as sieve analysis or crushing, which research as early as 1990 had deemed inappropriate for this aggregate.

The consequence of this approach is high variable in strength results, and low precision that often fails to validate the conclusions made by research authors. Often these results are non-replicable, with similar mix designs of OPSC giving 28-day compressive strengths in the range of 9 to 50 MPa. The absence of OPS characteristics then makes any detailed critique impossible. There is also an over-reliance on standard testing methods such as ASTM, which are not intended for LWA such as OPS and often give results that are inconsequential at best and misleading at worst, such as performing sieve analysis for OPS which fails to account for the thickness of the shells, a key mechanical property. Furthermore, more specific research such as the effects of admixtures, pozzolans, and additives on OPSC is also still open for critique, as presumptions of the smoothness of OPS surface and

its adhesion to the hydrated cement matrix in the ITZ remains unverified if the surface roughness and profile of OPS has not been quantified.

Over the last decade, developments in breeding of oil palm trees have resulted in considerably thinner shells, which would drastically alter the OPS mechanical properties. However, this change has not been reflected even in current OPSC research.

Furthermore, the following points highlight the key conclusions from this review:

- Many reports have investigated different kinds of design mix ratios for OPSC with and without other aggregates, admixtures, and fibres. Most mix designs are in the allowable limit of LWC ($\leq 2,000 \text{ kg/m}^3$). As a results, high mechanical strengths have been achieved with different mix ratios. A compressive strength of 54.6 MPa and flexural strength of 18.48 MPa has been achieved.
- Pre-saturating OPS is important to avoid high drying shrinkage values. However, additional studies are necessary for comparing OPS in dry and SSD state.
- When OPS is combined with other types of (none)-agricultural aggregates, good properties can be achieved. OPSC can be used in LWA-structural concrete production and for low-cost housings. Though only one low-cost housing has been made, no information has yet been released on the structure.
- Most structural behaviours of OPSC are comparable to NWC. OPSC is more ductile than NWC in flexural behaviour and has smaller crack thicknesses. Formulas have been found to predict the structural behaviour of OPSC. Further studies must be done to verify the prediction models.
- Many studies have been done on using fibres to enhance OPSC. Authors have concluded, depending on the type of fibre, to use a fibre volume content of 0.2-1% to reduce shrinkage and increase tensile strength.
- OPSC is good to use when exposed to extreme temperatures under 350°C .
- Many studies have been done on NWC by using Nano materials to improve its properties. However, no study has been found on OPSC by using Nano materials.

Other practical recommendations are as follows:

- Reporting mix designs by both weight and volume of OPSC constituents to account for the variability in density of OPS.
- Textural analysis and/or surface roughness and abrasion tests conducted on OPS, based on more reliable mechanical tests from the fruits or palm oil research industry.
- Mean thickness measurements of the OPS to consider its potential toughness and or strength.
- Detailed information on the variety of palm oil fruit, age of parent plants, and time elapsed since extraction and sterilization of said fruit from which the OPS originates.
- Crushing of OPS for improved strength performance.

- Exploration of the use of OPS as fine aggregate, as results showed improved strength with finer OPS particles.
- By following the abovementioned recommendations will allow for much more precise data regarding the mix design of OPSC, which could greatly accelerate OPSC research, as more predictable performances of OPS can allow for practical implementations of the product, which would address the sustainable and environmental issues surrounding OPS waste production.
- All reports have only been investigated on Dura OPS type in concrete, while little investigations have been done on the new Tenera OPS type. Since it is predicted that most farmers will breed the Tenera oil palm tree, it is there vital to restudy the new breeding type shell in concrete since it has different physical properties that could affect the properties of concrete.

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