Structural Performance of Precast Floor Panel Using Oil Palm Shell Solid Waste

Chee Hiong Ng1; M. A. Mannan2; and N. S. V. Kameswara Rao3

Abstract: The palm oil industry in countries such as Malaysia, Indonesia, and Colombia has been aggressively expanding over the years. Inevitably, the production of palm oil from fresh fruit bunches has generated solid waste, such as oil palm shell (OPS). Such exploitation of OPS when utilized as coarse aggregate in concrete can reduce the reliance of the local construction industry on the use of natural stone aggregates, which are depleting quantitatively. When and if huge amount of OPS can be effectively used, it will not only be a green solution but also a great advantage to both the local palm oil industry and the construction business. Particularly to highlight in typical modern buildings made of reinforced concrete, slab panels consume the most concrete compared to the rest of structural components because they occupy a large space in the floor. Precast floor panels cast with concrete made with OPS can comply with the Industrialized Building System (IBS) because they are innovative, involving the precast system. This paper reports the structural performance of precast floor panels made with OPS concrete under two-line load (TLL), both at the early age of 28 days and a later age of 400 days. Panels tested at an early age failed in a brittle manner, whereas the others, at the later age, failed in a flexural behavior. Results based on parameters, such as service and ultimate load capacity, moment capacity, deflection, cracking characteristics, and ductility, also revealed that the panels performed generally better at a later age compared to an early age. DOI: 10.1061/(ASCE)IS.1943-555X.0000317. © 2016 American Society of Civil Engineers.

Author keywords: Industrialized building system (IBS); Structural performance; Oil palm shell (OPS); Precast floor panel.

Introduction

Oil Palm Shell (OPS)

The palm oil industry in countries such as Malaysia, Indonesia, and Colombia has been aggressively expanding over the years. Inevitably, the production of palm oil from fresh fruit bunches has generated solid waste, such as oil palm shell (OPS) (Fig. 1). Currently in Malaysia, there are a total of 421 palm oil mills of which 124 are located in Sabah alone (BERNAMA 2011). This has made Sabah the largest producer of crude palm oil nationwide, accounting for 25% of the country’s total production (Daily Express 2010). Thus far, more than 4.0 million tons of OPS are produced annually.

Because OPS is the most difficult waste to decompose (Patumsawad 2002), the palm oil mills generally have excess unutilized OPS, which needs to be disposed separately (Subramaniam et al. 2008; Nurulain 2007; Graziani and Fornasiero 2006). Often, heaps of OPS are dumped, as shown in Fig. 2. Subramaniam et al. (2008) have even revealed that OPS is sometimes used as fuel in the boilers for steam generation at the palm oil mills or cement and brick factories; it would further produce boiler ash, which can adversely impact the environment if not disposed of properly.

The OPS as solid waste at palm oil mills, when not properly discharged or disposed, would emit methane to the atmosphere. In Malaysia, it is estimated that 2.23 million tons of methane emit annually; out of such, the methane emission from the palm oil industry has reached approximately 0.21 million tons (Shirai et al. 2003). They have further revealed that the greenhouse effect generated from palm oil industry is equivalent to 4.28 million tons of carbon dioxide (CO2) emission per annum because the greenhouse effect of methane is approximately 20 times higher than CO2.

One of the interesting uses of OPS as a coarse aggregate has been enormously reported in lightweight concrete (LWC) production (Jumaat et al. 2009; Alengaram et al. 2008; Teo et al. 2007; Olanipekun et al. 2006; Mannan and Ganapathy 2004; Okpara 1990; Okafor 1988; Uvisah, “Properties of palm kernel shells and fibre as aggregates for making concrete,” unpublished thesis, University of Benin, Benin, 1976). Unlike in the production of conventional normal weight concrete (NWC), such exploitation of OPS can reduce the reliance of the local construction industry on the use of natural stone aggregates, which are depleting quantitatively. It must be noted that nearly 80% of the aggregate resources used today in the construction industry are nonrenewable. It is now critical, therefore, to realize that the environmental impacts of crushed stone aggregate extraction have become a source of increasing concern in many parts of the country (Behera et al. 2004).
particularly for a framed building, representing some 60 floor construction is the most time-consuming and costly activity of OPS needed to cast floor slabs in housing projects. Also, the a large space in the floor. One can imagine the large quantity compared to the rest of structural components because it occupies the foundation. The floor slab thus consumes the most concrete for the beam, 6% for the column, 4% for the staircase, and 15% for the forced concrete, 44% of its total concrete is for the floor slab, 31%

Particularly to highlight in typical modern buildings made of rein-
terprises can represent a large percentage of the total cost of the building. This is especially true for the floor slab, which typically consumes the most concrete. The floor slab is a critical component of a building, and its cost and time required for construction can significantly impact the overall project budget.

Fig. 1. Various shapes and sizes of OPS (image by Chee Hiong Ng)

Fig. 2. Heaps of OPS solid waste being dumped at palm oil mill (image by Mannan M. A., republished with permission from Professor Walter)

a healthier indoor environment, better connectivity to public transport, adoption of recycling and greenery for projects, and reduction of our impact on the environment (The CSR Digest 2010).

Considering the previous information, it is strategic to radically exploit the OPS as far as possible to salvage, if not sustain, our environment. When and if a huge amount of OPS can be effectively used, it will not only be a green solution but also a great advantage to both the local palm oil industry and the construction business. Particularly to highlight in typical modern buildings made of reinforced concrete, 44% of its total concrete is for the floor slab, 31% for the beam, 6% for the column, 4% for the staircase, and 15% for the foundation. The floor slab thus consumes the most concrete compared to the rest of structural components because it occupies a large space in the floor. One can imagine the large quantity of OPS needed to cast floor slabs in housing projects. Also, the floor construction is the most time-consuming and costly activity particularly for a framed building, representing some 60–80% of the total in both cost and time (Goodchild 1997; Matthew and Bennett 1990).

Industrialized Building System (IBS)

Over the past years, the Malaysian Government has been promoting the use of precast components for buildings in line with the Industrialized Building System (IBS). According to Construction Industry Development Board (2003), the IBS is defined as a construction technique in which components are manufactured in a controlled environment (on- or offsite), transported, positioned, and assembled into a structure with minimal additional site works. The current IBS systems used in Malaysia housing projects are large panel systems, metal form systems, and modular systems (Kamar et al. 2009). Despite many attempts and initiatives taken by various authorities, there have been delays of IBS implementation and other issues related to IBS in Malaysia because of the low offsite manufacturing of construction components available in the market (Kamar et al. 2009). Innovative systems must be, therefore, obligatory to push IBS forward for greater accomplishment. It also appears that the most innovative system and components for using innovative materials are, however, based on imported technologies, which are obviously more expensive and difficult to purchase by local contractors [IBS Roadmap Review (Construction Industry Development Board 2007)]. Nevertheless, the IBS is still predicted to lead the Malaysian construction industry towards nation modernization and globalization (Hamid et al. 2008).

According to the Construction Industry Development Board (2007), the Construction Industry Master Plan (CIMP) is developed to provide guidance to the development of the Malaysian construction industry through the following decade (2006–2015). One of the seven strategic thrusts presented within the master plan is to innovate through research and development and adopt new construction methods. To gauge this success, the key performance indicator has been set for the use of the IBS/precast in construction industry to achieve above 80% by the year 2015.

Durability Aspect of OPS and OPS Concrete

The exploitation of OPS in LWC production will be credible when and if the durability of such concrete is satisfactory because the loss of durability reduces the life of the structure. Mannan et al. (2006) have conducted various types of pretreatment methods to improve the quality of OPS aggregates exposed to extreme conditions, incorporating alkaline (NaOH), acidic (H₂SO₄), and (MgSO₄) solutions. They have discovered that the most suitable method was by the use of 20% Polyaeryx (PVA), where the PVA solution fitted a thin layer on the OPS surface, preventing water infiltration. When using OPS pretreated with 20% PVA, the resulting concrete can achieve a higher compressive strength, revealing that the thin film of PVA gave good adhesion between the cement paste and OPS. Figs. 3(a and b) show the insight of the OPS concrete made with OPS aggregate compared to normal weight concrete with granite aggregate.

Ramasamy et al. (2008) have also investigated the performance of OPS and OPS concrete under aggressive conditions. They have revealed that OPS aggregates are durable under potable water and deleterious solutions, such as salt and alkaline solutions of 3% sodium chloride (NaCl) and sodium hydroxide (NaOH with approximate 13 pH), respectively. It is, however, only severely affected by the corrosive effect of the acidic solution of 1% hydrochloric acid (HCl). As for OPS concrete, it is relatively durable in terms of compressive strength when exposed to the potable water and salt solution. Also, the water absorption of OPS concrete continues to decrease with age under all exposure environments.

Teo et al. (2007) have found that the durability of OPS concrete was very much affected by the curing condition, where it performs better under water curing. They have also concluded that the water absorption and water permeability of OPS concrete are comparable to other LWCs. To further access the performance of OPS concrete under different curing conditions, Teo et al. (2010) have investigated its durability properties, such as the volume of permeable voids (VPVs), sorptivity, water permeability, chloride diffusion
coefficient, and time to corrosion initiation from the 90-day salt ponding test and rapid chloride penetrability test (RCPT). It was found that the results compared reasonably well with those of others LWCs. To achieve better durability, especially at later ages, proper curing is essential for OPS concrete. They have recommended that the minimum duration of moist curing for OPS concrete should be given continuously for at least 7 days.

In May 2001, a 2.0-m span footbridge made with OPS concrete (Fig. 4) built at the campus of University Malaysia Sabah (UMS), Kota Kinabalu, Sabah has shown satisfactory performance until now. It was made with 4 precast reinforced concrete solid flat panels using OPS concrete. A thermally comfortable low-cost house using OPS concrete and OPS hollow blocks was also built at the UMS campus in 2003, as shown in Fig. 5.

The need to explore such a performance remains vital with respect to exploitation of OPS solid waste. In detail, this paper investigates both short-term and long-term performances of precast floor panels made with OPS concrete under two-line loads (TLL).

**Materials and Methods**

**Materials**

Prior to casting concrete made with OPS, the properties of OPS and river sand were determined as per relevant BS and ASTM Standards, as tabulated in Table 1. For OPS concrete production, Malaysian ordinary portland cement (ASTM Type I) was used as a binder, sand as a fine aggregate, and OPS as coarse aggregates. The OPS was supplied by a local palm oil mill in Sabah, Malaysia. The constituents of 1.0 m$^3$ of OPS LWC are presented in Table 2. Before the OPS was used as aggregate, it was sieved, and only the aggregate passing through the 12.5-mm sieve and retained on the 4.75-mm sieve was used. The OPS aggregate was used in a saturated surface dry (SSD) condition. The water/cement ratio ($w/c$) was 0.38. Darex Super 20, a superplasticizer formulated in an aqueous solution of a modified naphthalene sulfonate complied with specification as per ASTM Designation C-494 (ASTM 1999a), was incorporated in the mix to increase the workability. This admixture is also ideal for use in precast concrete because it

Fig. 3. (a) Insight of OPS concrete with OPS aggregate (LWC) (image by Chee Hiong Ng, republished from MCRJ, Vol. 9, No. 2, 2011, with permission); (b) insight of conventional NWC with granite aggregate (image by Chee Hiong Ng, republished from MCRJ, Vol. 9, No. 2, 2011, with permission)

Fig. 4. Footbridge made with precast reinforced concrete panels using OPS concrete in May 2001 at UMS campus (image by Mannan M. A.)

Fig. 5. Thermal comfort low-cost house (of about 59 m$^2$ floor area) made using 17 m$^3$ OPS concrete and 2,400 nos. of OPS hollow blocks at UMS campus (image by Mannan M. A.)
Table 1. Properties of OPS, Crushed Granite, and River Sand

<table>
<thead>
<tr>
<th>Number</th>
<th>Property of aggregates</th>
<th>Unit</th>
<th>Coarse aggregate (OPS)</th>
<th>Fine aggregate (river sand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum size</td>
<td>mm</td>
<td>12.50</td>
<td>1.18</td>
</tr>
<tr>
<td>2</td>
<td>Specific gravity (SSD)</td>
<td>–</td>
<td>1.34</td>
<td>2.43</td>
</tr>
<tr>
<td>3</td>
<td>Water absorption capacity (24 h)</td>
<td>%</td>
<td>21.30</td>
<td>3.89</td>
</tr>
<tr>
<td>4</td>
<td>Los Angeles abrasion value</td>
<td>%</td>
<td>2.90</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>Bulk density, compacted</td>
<td>kg/m³</td>
<td>646</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>Fineness modulus</td>
<td>–</td>
<td>6.30</td>
<td>1.33</td>
</tr>
<tr>
<td>7</td>
<td>Aggregate impact value, AIV</td>
<td>%</td>
<td>6.60</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>Aggregate crushing value, ACV</td>
<td>%</td>
<td>7.12</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2. Constituents of 1.0 m³ OPS LWC

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg)</td>
<td>450</td>
</tr>
<tr>
<td>Water (kg)</td>
<td>171</td>
</tr>
<tr>
<td>Sand (kg)</td>
<td>629</td>
</tr>
<tr>
<td>OPS (kg)</td>
<td>488</td>
</tr>
<tr>
<td>Admixture (L)</td>
<td>7.5</td>
</tr>
</tbody>
</table>

The panels were designed to carry the live load of 1.5 kN/m² as per residential dwellings [BS 6399-1 (BS 1996)]. Every panel was reinforced with welded wire mesh type A10 with 200-mm spacing c/f [BS 4483 (BS 1985) Ref. No. A393]. Welded wire mesh has been increasingly used for floor panels because of the ease of placing the fabric sheets, control of reinforcement spacing, and better bond. The yield strength of the welded wire mesh was approximately 485 N/mm². The concrete cover was 20 mm. Three nos. of 100-mm companion cubes were prepared for each panel according to BS 1881: Part 116 (BS 1983).

They were cast with OPS concrete and cured for 7 days under shed (temperature = 28 ± 5°C, relative humidity = 68–91%). After casting, they were immediately covered with plastic sheets for 7 days. Water was sprayed three times per day in the daytime from Day 2 until Day 7, after which formworks were stripped. The panels were lifted up by forklift so as to allow the removal of the bottom formworks. They were then left exposed under weather conditions at a temperature of 25.5–35.6°C and relative humidity of 64–94% until the age of the test. It is not practical to expect precast concrete products to be stored indoors or to be effectively protected from the environment (Precast Prestressed Concrete 1997). It is worth noting that steam curing is not required, even though such a curing practice is common in the precast construction industry. In Bangladesh, the construction industry adopts this method of curing because steam curing is expensive for precast as compared to cheap labor. Without the use of steam curing, the cost to manufacture precast floor panels made with OPS concrete becomes far lower than expected, and it can consequently encourage the involvement of small and medium entrepreneurs for IBS system. For such, Kamar et al. (2009) have reported on the monopoly of “big boys” in the construction industry, limiting opportunities to other contractors.

After casting, the precast floor panels were to be tested at the age of 28 days and 400 days, labeled as S-28 and S-400, respectively. Prior to testing, the side of panels were painted white so that all cracks, subjected to loading, could be easily detected using a crack-detecting pocket microscope with an optical magnification ×40. The panels were tested as simply supported panels under two-line loads (TLL) at load increments of 2 kN up to 10 kN and then 5 kN until failure. The actuator with 1,000 kN capacity was used to monitor the applied load. The distance between the loading points was kept constant at 1,000 mm. Linear variable displacement transducers (LVDTs) capable of measuring maximum displacements of 100 mm were used to monitor the deflection at midspan of the panel.

Table 3. Panel Details

<table>
<thead>
<tr>
<th>Panel number</th>
<th>Dimension</th>
<th>Age of testing (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effective span (m)</td>
<td>Width (mm)</td>
</tr>
<tr>
<td>S-28</td>
<td>3.0</td>
<td>1,000</td>
</tr>
<tr>
<td>S-400</td>
<td>3.0</td>
<td>1,000</td>
</tr>
</tbody>
</table>

Test Methods

The precast floor panels were in modular sections of 3-m span and 1-m width, with a thickness of 135 mm, as shown in Table 3. Based on these dimensions, approximately 19 million nos. of precast panels can be prefabricated from 4 million tons of OPS produced annually (approximately 0.21 tons of OPS per panel).

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Results and Discussions

General Behavior

In this investigation, the general behavior of the precast floor panels made with OPS concrete is very much different subjected to the age of testing. When tested on Day 28, the panel S-28 had failed in a brittle manner initiated by fracture of one or more of longitudinal tensile reinforcements, within the pure bending zone where the panels collapsed into 2 halves, as shown in Fig. 6. This panel S-28 only reached the ultimate load of 29.94 kN. Typically, reinforced concrete panels have relatively small tensile reinforcement ratios and are generally regarded as very ductile structural elements. However, this was not for the case of the panels reinforced with...
low-ductility welded wire fabric. The cold-drawing process significantly decreases the ductility of the welded wire fabric (Xuan et al. 1988). Similar observation was reported on normal weight concrete (NWC) panels by Sakka and Gilbert (2008), Gilbert and Sakka (2007) and Ayyub et al. (1996). Hence, the use of a significant amount of welded wire fabric should exhibit adequate ductility to ensure the overall ductility of the member. Minimum shear reinforcement can be provided as an alternative to improve the ductility.

On the other hand, the panel S-400 failed in flexural behavior a higher load of 36.12 kN, as shown in Fig. 7. Such failure mode is critically desirable because it provides sufficient warning to inhabitants.

**Compressive Strength**

From Table 4, it can be seen that the compressive strength of companion cubes continued to increase after the age of 28 days, from 27.60 to 29.90 MPa. These compressive strengths are far more than 17 MPa, as required for structural LWC [ASTM C330 (ASTM 1999b)]. Therefore, OPS concrete can be used as structural LWC.

In general, the strength development of concrete is very much influenced by the interparticle bond, porosity and strength of the paste, and strength of the aggregates (Popovics 1998). A close observation on the crushed surface of the companion concrete cubes of panel S-28 revealed the compression failure has taken place in the bond between OPS and the cement paste. In this bond failure, the crack path went around the OPS aggregates, as shown in Fig. 8(a). Teo et al. (2007) have disclosed that the interparticle bond between the OPS and cement matrix plays a less important role in the strength development because of the relatively smooth surface of the OPS aggregate. In the later ages, as for the companion cubes of panel S-400, however, the mortar-aggregate bond became stronger, and thus the crack traveled through the OPS aggregates, as depicted in Fig. 8(b). The porous surface of OPS, as reported by (Ramasamy et al. 2008; Jia and Lua 2008), improved the interfacial bond between the OPS and cement paste where the cement paste infiltrates the surface pores of the OPS aggregate. Lo and Cui (2004) have also reported a similar observation when the lightweight synthetic aggregate manufactured from expanded clay, which is filled with pores, is used. Nevertheless, the orientation of OPS aggregate within the cement matrix also influences the fracture path because the shape of the OPS is elongated and flaky. The shell is thinnest about its middle along the longitudinal axis. This feature causes the shell to be weakest along the transverse axis, as highlighted by Koya and Faborode (2005). Bremner and Holm (1986) mentioned that lightweight coarse aggregates are relatively weak and that the splitting of the particles in a direction normal to the applied load takes place.

**Service Load Capacity**

The load carrying capacity is of paramount importance to predict the safety, stability, and durability of a structural element. Hence, structural members are always designed with a capacity for load that is significantly greater than that required to support expected service loads.

The design live loads are usually expressed as uniform loads on the floor area in most building codes (Macgregor and Wight 2005). As the panel specimens investigated through TLL in the laboratory condition, there is a need to convert imposed TLL to equivalent uniform distributed load (UDL) so as to correlate the test loading with the real load application. Also, in common practice, floor panels are always designed with UDL.

From Table 5, the safety factor for panels S-28 and S-400 are 3.79 and 4.57, respectively. Clearly, it signifies that the panel S-400 reaches almost a 21% higher service load capacity compared to that
of panel S-28 at the age of more than one year. It is suggested that the increment in compressive strength, as a result of a stronger mortar-aggregate bond, has contributed to a higher load capacity. It must be remembered that the floor slab, which is normally laterally restrained, develops high axial compressive forces, which result in a significant increase in flexural stiffness and load-carrying capacity of the floor slab by approximately 30–40% compared to an unrestrained floor slab (Vecchio and Tang 1990).

At a later age, the panel can be therefore used for residential housing at palm oil plantations or even rural areas where the transportation cost of conventional coarse aggregates is high.

**Bending Moment**

When subjecting to load application, the bending moment takes place over the reinforced concrete members, causing the members to deflect and crack. For panels designed as simply-supported one-way slabs subjected to equal line loads at third points, the middle third of the span undergoes maximum bending moment but zero shear. On the other hand, the remaining sections experience maximum shear force and varying bending moments.

The theoretical ultimate moment according to BS 8110 (BS 1997) and ACI 318 (ACI 2008) can be computed in Eqs. (1)–(3) where $M_{BS} =$ ultimate moment based as per BS 8110 (kNm); $d =$ effective depth (mm); $S =$ depth of equivalent rectangular stress block (mm); $f_{cu} =$ characteristic concrete cube strength (N/mm²); and $f_r =$ characteristic strength of reinforcement, N/mm²; $M_{ACI} =$ ultimate moment based as per ACI 318 (kNm); and $f_{ct} =$ characteristic concrete cylinder strength (taken as 0.8$f_{cu}$)

$$M_{BS} = 0.95f_{c}A_{d}(d - S/2)$$  \(1\)

$$M_{ACI} = f_{c}A_{d}(d - S/2)$$  \(2\)

$$S = A_{d}f_{ct}/0.8f_{ct}b$$  \(3\)

Based on Table 6, it is seen that both BS 8110 and ACI 318 can be used to obtain a conservative estimate of the ultimate moment capacity of the precast floor panels made with OPS concrete. The $M_{Exp}/M_{BS}$ and $M_{Exp}/M_{ACI}$ were found to be 1.09 and 1.32 and 0.87 to 1.06, respectively. Such ratios for panel S-400 are approximately 22% higher than that of panel S-28.

**Deflection Behavior**

Floor panels are slender elements with the dimension in the direction of the action far less than the spans, and this characteristic makes them sensitive to deflection.

Table 8 presents the comparison of experimental and theoretical deflections of the panels S-28 and S-400 at the service moment. The experimental service moment was derived from the estimated service load, which is equivalent to the experimental ultimate load divided by a factor of 1.7 (Rashid and Mansur 2005). It can be seen that the BS 8110 predicted the deflection of such panels much more conservatively compared to that of ACI 318. As the applied service moment was found greater than the experimental cracking moment (Table 7), the use of the effective moment of inertia adopted in the

**Table 5. Safety Factors at Serviceability**

<table>
<thead>
<tr>
<th>Panel number</th>
<th>Self-weight (kN/m²)</th>
<th>Design live load (kN/m²)</th>
<th>Total service load (kN/m²)</th>
<th>Equivalent UDL at serviceability (kN/m²)</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-28</td>
<td>2.44</td>
<td>1.5</td>
<td>1.5</td>
<td>5.68</td>
<td>2.7</td>
</tr>
<tr>
<td>S-400</td>
<td>2.44</td>
<td>1.5</td>
<td>1.5</td>
<td>6.85</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Note: UDL = uniform distributed load.

**Table 6. Experimental and Theoretical Moments of Various Types of Panels**

<table>
<thead>
<tr>
<th>Panel number</th>
<th>Experimental, Ultimate moment (kNm)</th>
<th>Theoretical Ultimate moment (kNm)</th>
<th>$M_{Exp}/M_{BS}$</th>
<th>$M_{Exp}/M_{ACI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-28</td>
<td>14.97</td>
<td>13.67</td>
<td>1.09</td>
<td>0.87</td>
</tr>
<tr>
<td>S-400</td>
<td>18.06</td>
<td>13.67</td>
<td>1.32</td>
<td>1.06</td>
</tr>
</tbody>
</table>

**Table 7. Safety Factors of Different Types of Panels at Service Load**

<table>
<thead>
<tr>
<th>Panel number</th>
<th>Cracking moment (kNm)</th>
<th>$M_{cr(Exp)}$</th>
<th>$M_{cr(Theo)}$</th>
<th>Ratio $M_{cr(Exp)}/M_{cr(Theo)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-28</td>
<td>3.10</td>
<td>11.54</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>S-400</td>
<td>3.75</td>
<td>11.54</td>
<td>0.32</td>
<td></td>
</tr>
</tbody>
</table>

**Cracking Moment**

The cracking moment, $M_{cr}$, refers to the moment that produces a tensile stress equal to the modulus of rupture of the concrete. When the applied service moment is less than the cracking moment, the concrete cross section is uncracked, and the moment of inertia is based on the gross area. On the other hand, in the regions where the moment exceeds the cracking moment, then the concrete is cracked, and the properties of the cross section rely on the properties of the cracked section.

Table 7 presents the experimental and theoretical cracking moment of the precast floor panels made with OPS concrete. The experimental cracking moment is taken at the point of change from the initial slope of the moment-deflection curve. The theoretical cracking moment, $M_{cr(Theo)}$, of the panels was determined using Eq. (4) recommended by ACI 318, where $f_r =$ modulus of rupture of concrete (MPa), $I_g =$ second moment of inertia of gross area ignoring reinforcement (mm⁴), and $y_i =$ distance from the extreme tension fiber to the neutral axis (mm)

$$M_{cr(Theo)} = (f_r x I_g)/y_i$$  \(4\)

For panels S-28 and S-400, it is found that the experimental cracking moments are approximately 27 and 32% of the theoretical cracking moments, respectively. The prediction by the code through Eq. (4) is very much conservative. A similar observation is reported by Teo et al. (2007) in their investigation on OPS concrete beams that the experimental cracking moments were approximately 35 to 80% of the theoretical values. They have further recommended using a reduced value of approximately 55% of $f_r$ for better prediction of the cracking moments.
ACI code takes into the account of the fully cracked section, resulting in the actual curvature. The deflection ratio of $\Delta_{\text{Exp}}/\Delta_{\text{ACI}}$ for the panels S-28 and S-400 is found to be 1.51 and 1.18, respectively.

Nevertheless, it also seems that both theoretical methods can predict the deflection more accurately at a later age.

### Cracking Characteristics

Cracking contributes to the corrosion of the reinforcement, surface deterioration, and its long-term detrimental effects. According to Nayw (2008), the major factors influencing the development and characteristics of cracks are reinforcement ratio, bond characteristics and size of bar, concrete cover, and concrete area in tension. However, for a concrete member to be both efficient and economical, flexural cracks are necessary in order to activate the reinforcement, utilizing the tensile strength of the steel to achieve equilibrium in the composite section.

Table 9 presents the cracking characteristics of the panels S-28 and S-400 at failure load. The average crack spacing of panels S-28 and S-400 are found to be 92.86 and 84.43 mm, respectively. Smaller crack spacing as observed in panel S-400 could be the result of a stronger bond between OPS concrete and reinforcement at a later age. The lesser number of cracks between loading points for panel S-400 compared to panel S-28 may provide further explanation. The goal of the reinforced concrete design is to keep the spacing between the cracks small in order to limit the crack width.

### Ductility

The ability of a concrete section to crack and undergo a finite amount of rotation prior to failure is a reflection of the section’s ductility. This further implies that the slab sections should be ductile enough to allow rotation to occur at the critical sections. In order to mobilize the assumed load paths and redistribute the load resistance in a flexural member, particularly like floor slab, the slab must possess certain ductility. This capability prevents total structural collapse and provides protection to occupants of buildings. It is defined as the ratio of deflection at ultimate load, $\Delta_u$, to the deflection at yield load, $\Delta_y$, of the slab specimens. In general, high-ductility ratios indicate that a structural member is capable of undergoing large deformations prior to failure. Ashour (2000) mentioned that members with a ductility ratio in the range of 3 to 5 have adequate ductility and can withstand large displacements because of sudden forces, such as an earthquake.

Table 10 tabulates the ductility ratio of the panels S-28 and S-400. The ductility ratio for panel S-28, which collapsed abruptly, cannot be computed because its ultimate deflection could not be recorded. It is also noted that the ductility ratio of panel S-400 was very low. When the high-strength reinforcement is used, a lower steel ratio will be necessary to obtain appropriate ductility (Park and Gamble 2000). Thus, careful attention has to be taken when designing floor panels with such low-ductility reinforcement.

### Ultimate Load Capacity

To determine the ultimate load capacity of a structure element, it is usually tested to destruction. Mayr (1992) has recommended the use of a load test to check proposed maximum loadings and to ensure that structural elements are able to take the designed working load with safety. For tests carried out on new precast units for acceptance purposes, BS 8110: Part 2 requires the ultimate strength should be at least 5% greater than the theoretical ultimate load.

Table 11 tabulates the experimental and theoretical ultimate load of panels S-28 and S-400. It is clearly seen that the experimental ultimate load, $U_{\text{Exp}}$, was greater than their respective theoretical ultimate load, $U_{\text{Theo}}$. The ratio of $U_{\text{Exp}}/U_{\text{Theo}}$ was found to be 1.68 and 2.03 for panels S-28 and S-400, respectively. Similarly, the ultimate load capacity of panel S-400 at a later age is approximately 21% higher than that of panel S-28. Nevertheless, the use of welded wire fabric influences the ultimate capacity of the floor panels (Xuan et al. 1988).

### Conclusions

In the last few years, the ever-growing palm oil industry in Malaysia has inevitably produced a large yet significant amount of OPS solid waste that, when not disposed properly, can bring negative impacts to the environment. Unless the local construction industry can largely exploit OPS as a coarse aggregate in concrete production, particularly in precast modular floor panels, it will not provide a green solution to the environment. The innovative use of OPS in the prefabrication of such precast building products can help to quicken the wider implementation of IBS among the construction industry players in a direct yet specific measure. Based on this pilot investigation on precast modular floor panels tested at different ages, the following conclusions have been drawn:

1. The precast modular floor panel tested at the early age of Day 28 failed in a brittle manner, whereas the other at the later age
of Day 400 failed in flexible behaviors. The latter failure mode is critically desirable because it provides sufficient warning to inhabitants.

2. The compressive strength of companion cubes continued to increase after the age of 28 days, from 27.60 to 29.90 MPa, as a result of stronger mortar-OPS aggregate bond developed at a later age. Hence, the suitability of OPS as coarse aggregate in concrete production is established.

3. The safety factor for panels S-28 and S-400 are 3.79 and 4.57, respectively, where the panel S-400 reaches almost a 21% higher service load capacity compared to that of panel S-28. It is suggested that the increment in compressive strength, as a result of stronger mortar-aggregate bond, has contributed to higher load capacity.

4. Both BS 8110 and ACI 318 can be used to obtain a conservative estimate of the ultimate moment capacity of the precast floor panels made with OPS concrete. The $M_{\text{Exp}}/M_{\text{BS}}$ and $M_{\text{Exp}}/M_{\text{ACI}}$ were found to be 1.09 to 1.32 and 0.87 to 1.06, respectively. Such ratios for panel S-400 are approximately 22% higher than that of panel S-28.

5. For panels S-28 and S-400, it is found that the experimental cracking moments are approximately 27 and 32% of the theoretical cracking moments, respectively. The prediction recommended by ACI 318 is very much conservative.

6. With respect to deflection, ACI 318 can predict a better result compared to BS 8110 because the ACI code takes into account the fully cracked section resulting in the actual curvature. The deflection ratio of $\Delta_{\text{Exp}}/\Delta_{\text{ACI}}$ for the panels S-28 and S-400 is found to be 1.51 and 1.18, respectively.

7. The average crack spacing of panels S-28 and S-400 is found to be 92.86 and 84.43 mm, respectively. Smaller crack spacing, as observed in panel S-400, could be the result of a stronger bond between the OPS concrete and reinforcement at a later age.

8. The ductility ratio for panel S-400 was very low. For panel S-28, which collapsed abruptly, the ratio cannot be computed because its ultimate deflection could not be recorded. Careful attention has to be taken when designing floor panels with such low-ductility reinforcement.

9. The ratio of the experimental ultimate load/theoretical ultimate load ($U_{\text{Exp}}/U_{\text{Theo}}$) was found to be 1.68 and 2.03 for panels S-28 and S-400, respectively. Similarly, the ultimate load capacity of panel S-400 at later age is approximately 21% higher than that of panel S-28.

10. It is seen that, with appropriate use of welded wire mesh, the precast modular floor panels made with OPS concrete have generally performed better at a later age than an early age. They can be, therefore, used for residential housing at palm oil plantations or even rural areas where the transportation cost of conventional coarse aggregates is high.

References


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