Structural performance of reinforced self-compacting concrete columns produced with palm oil fuel ash

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Abstract. Palm oil fuel ash (POFA) is an agricultural waste produced from the palm oil industries and disposed off into an open ground without any reprocessing or profitable return, has been established to enrich concrete durability as well as mechanical properties when used to replace cement. However the POFA used to partially substitute cement in self-compacting concrete (SCC) production were done on material properties by fabricating standard specimens such as cylinders, prisms and cubes. Moreover, the utilization of POFA to partially substitute cement to cast reinforced concrete structural members is not common compared to fly ash and ground granulated blast furnace slag. This study therefore focuses on structural performance of reinforced self-compacting concrete columns produced with palm oil fuel ash. Two mixes of SCC containing 0% and 15% of POFA were prepared to fabricate the columns. The main variables considered were percentage of POFA content, percentage of steel reinforcement ratio (2% and 3%) and thickness of concrete cover (25 mm and 35 mm). Eight columns were fabricated altogether and tested under axial compression load up to failure. The results of the test revealed that the ultimate axial capacity of reinforced SCC columns produced with POFA is higher than the columns produced without POFA by approximately 2.6% and 2.2% for 25 mm and 35 mm concrete covers, and 2.9% and 2.5% for 2% and 3% steel reinforcement ratios. It is also observed that the load-deflection pattern of reinforced SCC columns produced with and without POFA follow similar trends. However, columns produced with POFA showed slightly lower stiffness than the columns produced without POFA.

1. Introduction
The utilization of concrete is increasing day by day due to the increased in civil infrastructures such as buildings, tunnels, bridges, highways, and so on, and this make the concrete to become the second ever most extensively utilized material in the planet after water. The concrete usage will continue to increase as long as the population of the people continues to increase [1]. At present, the worldwide consumption rate of concrete per year is approximately 30 billion ton [2] compared to the year 2015 which was 25 billion ton [3]. The negative effect of concrete mostly derives from production of cement and this represents its main component. Presently, the worldwide production of cement per
year is approximately 4.4 billion tons and this number is predictable to increase to more than 5.5 billion tons by the year 2050, particularly in developing countries [4]. The production processes of cement alone are accountable for approximately 5 – 7% of the global CO₂ anthropogenic emissions and 3% of greenhouse gas global emissions [5]. Also, a higher energy consumption values between 3.2 – 6.3 GJ is used by the cement during the burning process [6]. The release of greenhouse gas and enormous consumption of natural resources associated with cement production cause considerable environmental effect.

Self-compacting concrete (SCC) has numerous merits over the conventional vibrated concrete (CVC), such as noise pollution reduction, removing the necessity for vibration, construction time and cost of labour reduction, enhancing the flowing ability of extremely congested structural elements, reducing the permeability as well as enhancing the concrete durability, easing constructability as well as ensuring better structural performance and enhancing interfacial transitional zone between aggregate and cement paste or steel reinforcement [7]. However, the production of SCC involves the use of chemical admixtures, which are costly. In addition, SCC requires a higher quantity of cement content than CVC and this in turn make the construction cost to be increased. Numerous studies have been executed in order to solve the negative effect associated with cement mentioned above by making use of supplementary cementitious materials (SCMs) to substitute cement in SCC production. The SCMs that have been used are fly ash [8], palm oil fuel ash [3], ground granulated blast furnace slag [9] and rice husk ash [10].

Palm oil fuel ash (POFA) is an agricultural waste produced from the palm oil industries and dispose of into an open grounds without any reprocessing or profitable return [3], has been established to enrich concrete durability as well as mechanical properties when used to replace cement [11,12]. A lot of research investigated on the utilization of POFA to partially substitute cement in SCC production were done on material properties by fabricating standard specimens such as cylinders, prisms and cubes. However, the utilization of POFA to partially substitute cement to cast reinforced concrete structural members is rare in the literatures compared to ground granulated blast furnace slag (GGBFS) [13–15] and fly ash [16–18]. It was only Andalib et al. [19] that used combination of POFA and fly ash to cast geo – polymer concrete beams.

Andalib et al. [19] carried out an investigation on the structural performance of maintainable waste from palm oil fuel ash and fly ash to produce geo – polymer concrete beams. They reported that the behaviour of reinforced concrete beams produced with POFA – fly ash was almost equal to control reinforced concrete beams because the ultimate moments and cracking patterns of the two types of columns were close together when tested in 90 days. Hawileh et al. [14] conducted a research on the performance of reinforced concrete beams cast with 0%, 50%, 70% and 90% of GGBS to replace cement. The results showed that the tensile and compressive strength of the various mixtures were fairly the same. Besides, the performance of RC beams produced with 70% GGBS is the same to the one with 0% GGBS. Lokeshwaran et al. [15] carried out a research on the flexural resistance of reinforced self-compacting concrete beams incorporating 0%, 10%, 20%, 30%, 40% and 50% of GGBS to replace cement. They concluded that the flexural behaviour of SCC beams produced with GGBS was improved and exhibits higher ductility than the SCC beams produced without GGBS.

Sunayana and Barai [16] carried out an investigation on the impact of fly ash in using 100% reused aggregate on the flexural performance of reinforced concrete beam. The results showed that the moment carrying capacity at ultimate limit state of beams produced with recycled coarse aggregate and fly ash is mostly similar with the beams produced with natural aggregate. The utilization of fly ash up to 30% and 100% reused coarse aggregate can be used to produce a concrete beam for potential application without compromising its performance in flexure. Sunayana and Barai [17] studied the impact of fly ash in using 100% reused aggregate on the axial compression of reinforced concrete column. They concluded that the results of load carrying capacity of columns cast with recycled coarse aggregate incorporating 20% fly ash and 30% fly ash are higher by about 4% and 9% respectively when compared with the columns cast with natural aggregate. Hashmi et al. [18] carried out a research on the effect of using 0%, 25%, 40% and 60% fly ash to replace cement on flexural
performance of reinforced concrete slab and beam. The results showed that the ultimate and yielding state of reinforced concrete with high volume of fly ash exhibit the same trend when compared to that of reinforced concrete without fly ash.

All the research carried out on the reinforced structural members are mostly on beams and only limited data are available on columns. At the same time, the majority of the researchers cast the structural members with the use of CVC while there is limited data on the structural members cast with SCC. Likewise, the 30% of the POFA used to produce geo– polymer concrete beams are mixed with 70% of fly ash. Up till now, the use of POFA to produce SCC structural members are scarce in the literatures to the best knowledge of the authors. To justify the use of POFA in the production of reinforced SCC structural members, more research should be carried out. In this study, an experimental investigation was performed on the structural performance of reinforced SCC columns produced with POFA. The parameters considered were the percentage of POFA (0% and 15%), thickness of concrete cover (25 mm and 35 mm) and percentage of steel reinforcement (2% and 3%). After curing for 28 days, axial loads were applied to all the columns up to failure. The results obtained are discussed in terms of failure patterns, ultimate load capacity, load- deflections and stiffness.

2. Experimental Methods

2.1 Materials
The materials utilized in the present study were dry river sand (fine aggregate), crushed granite (coarse aggregate), POFA, ordinary Portland cement (OPC), tap water and Super plasticizer (SP) of brand name Sika ViscoCrete – 1600. The POFA utilized was procured from the factory (Alif Palm Oil Mill) sited in Kota Tinggi, city of Johor in Malaysia. Details procedure used to process the POFA can be found in Mujedu et al. [20]. Table 1 displays the oxide compositions of OPC and POFA while Table 2 displays the physical properties of crushed granite and river sand. The POFA used was confirmed to be class – C type since the combined silica, alumina and iron oxide content is 53% which is above 50% according to ASTM C618 [21].

| Compound (%) | SiO₂ | Fe₂O₃ | Al₂O₃ | MgO | CaO | K₂O | MnO | SO₃ |
|--------------|------|-------|-------|-----|-----|-----|-----|-----|
| OPC          | 16.2 | 2.91  | 3.52  | 0.76| 70.9| 0.57| 0.13| 3.36|
| POFA         | 43.9 | 4.79  | 4.32  | 3.1 | 8.66| 10.8| 0.06| 1.04|

| Types of aggregates | Dmax (mm) | FM | Specific gravity |
|---------------------|-----------|----|------------------|
| Crushed granite     | 10        | 6.3| 2.56             |
| River sand          | 4.75      | 2.98| 2.55             |

Dmax : maximum aggregate
FM : modulus of fineness

2.2 Mix proportioning of SCC
The proportioning of different concrete constituents was prepared according to EFNARC guidelines and specifications for SCC [22]. Two different SCC mixes were produced with and without the POFA. The first mixes were prepared with POFA at substitution level of 15% by the cement weight while the second mixes were prepared with only OPC. 0.5 water cement – binder ratio was used to prepare all the two mixes. The details summary of the mix proportioning is shown in Table 3. To get the fresh properties in the SCC mixes, Super plasticizer (SP) of brand name Sika ViscoCrete – 1600
was utilized.

### Table 3. Mix proportions of SCC containing POFA.

| Mix Notation | POFA (% of B) | W/B Ratio | Coarse aggregate (kg/m³) | Fine aggregate (kg/m³) | Cement (kg/m³) | POFA (kg/m³) | Water (kg/m³) | SP (kg/m³) |
|--------------|---------------|-----------|--------------------------|------------------------|----------------|--------------|--------------|------------|
| SCC0         | 0             | 0.5       | 615                      | 750                    | 380            | 0            | 190          | 6.08       |
| SCC15        | 15            | 0.5       | 615                      | 750                    | 323            | 57           | 190          | 6.84       |

2.3 Design and casting of column specimens

Short columns of 150 mm x 150 mm square in cross-section and 600 mm height were designed as per Eurocode 2 [23]. All the eight columns had 12 mm diameter rebar as longitudinal steel reinforcement and 6 mm stirrup, spacing at 100 mm centre to centre, as transverse reinforcement. The longitudinal steel reinforcement as well as stirrups had yield strength of 538 MPa and 574 MPa respectively. The parameters considered for all the columns are percentage of POFA content of 0% and 15%, concrete covers of 25 mm and 35 mm and longitudinal steel reinforcement ratios of 2.0% and 3.0%. The cross-section of column and reinforcement provided are illustrated in Figure 1. The stirrups provided were bent at 135° with a length of 50 mm to the concrete core as illustrated in Figure 1.

![Figure 1. Column cross-section showing design details.](image)

The steel reinforcement cage already prepared was placed inside the steel formwork. Two batches of concrete containing 0% and 15% of POFA content were used for casting all the eight columns. However, the columns were cast one by one from the concrete batch while the casting was done horizontally. Three 100 x 100 x 100 mm cubes were also cast from the concrete batch to determine the compressive strength of concrete. In casting of the columns, the already prepared fresh SCC was poured into the column steel formwork in one layer without compaction. The columns were then levelled and finished on the open side of the formwork. After finishing the casting, the columns were later removed from the formwork after 24±4 hours, marked and stored at ambient condition inside the
laboratory. The columns cast were cured by wetting with water every day.

2.4 Instrumentation and test setup
Prior to testing on the machine, the bottom and top ends of all the columns were checked properly in order to make sure that they were all smoothed and levelled. Otherwise, electric grinding machine was used to smooth and level both ends. This is important for obtaining full contact between the ends of the column and loading platens of the testing machine. The column test setup and instrumentations is displayed in Figure 2 (a). Two linear variable differential transducers (LVDT) were installed to the mid-height of each column in horizontal and vertical direction. The LVDT measured the lateral and vertical displacement of the columns. Each column was tested to failure by applying concentric axial load gradually using SOP Tinius Olsen type universal testing machine at a rate of 0.5 kN per second as shown in Figure 2 (b). During the testing of the columns, the data generated was automatically recorded, using a data logger.

3. Results and discussions

3.1 Compressive strength
Compressive strength test was carried out on SCC cubes cast along with columns as per BS 1881: Part 116 [24]. Compressive strength of SCC cubes produced with 15% POFA (SCC 15) and the one produced without POFA (SCC 0) cured for 28 days is given in Table 4. It can be observed from Table 4 that compressive strength of SCC 15 was 4.9% higher than SCC 0. The increment values of compressive strength noticed for SCC 15 is ascribed to pozzolanic reaction of POFA which reacts with calcium hydroxide that liberated from the cement hydration and thus formed additional calcium silicate hydrate gel which is the major strength provider [11].
Table 4. Compressive strength of test cubes cast with SCC columns produced with and without POFA.

| Specimen identification | Compressive strength (MPa) | Average compressive strength (MPa) |
|-------------------------|---------------------------|-----------------------------------|
| SCC 15 - 1              | 40.75                     |                                   |
| SCC 15 - 2              | 41.01                     |                                   |
| SCC 15 - 3              | 40.13                     | 40.63                             |
| SCC 15 - 11             | 41.13                     |                                   |
| SCC 15 - 22             | 40.08                     |                                   |
| SCC 15 - 33             | 40.68                     |                                   |
| SCC 0 - 1               | 39.26                     |                                   |
| SCC 0 - 2               | 38.82                     |                                   |
| SCC 0 - 3               | 38.17                     | 38.75                             |
| SCC 0 - 11              | 38.69                     |                                   |
| SCC 0 - 22              | 38.42                     |                                   |
| SCC 0 - 33              | 39.14                     |                                   |

3.2 Failure patterns

Failure patterns of reinforced SCC columns after carrying out compression test are discussed under this section. There is longitudinal cracks and crushing of concrete on the surface of all the columns. There is also spalling of concrete cover along the height of the columns. However, the cracks, crushing of concrete and spalling of concrete covers that observed are more noticeable on the columns produced without POFA. Mostly, in all the columns, the failure was brittle, explosive and abrupt.

3.3 Ultimate axial capacity

The ultimate axial capacity of all reinforced SCC columns produced with and without POFA is shown in Table 5. It can be seen from the Table 5 that the ultimate axial capacity of columns produced with POFA is higher than the columns produced without POFA by approximately 2.6%, 2.9%, 2.5% and 2.2%, respectively, for 25 mm and 35 mm concrete covers, and 2% and 3% percentage of steel reinforcements. PCOL1, PCOL2, PCOL3 and PCOL4 stand for columns produced with POFA while CCOL1, CCOL2, CCOL3 and CCOL4 stand for columns produced without POFA. The higher values of ultimate axial capacity observed for columns produced with POFA is ascribed to the pozzolanic reaction of POFA which reacts with the portlandite that released from hydration of cement, and liberated extra calcium silicate hydrate gel which is the major strength provider [11].

The ultimate axial capacity of the columns increased by approximately 12.4%, 11.8% and 12.6%, 12.6% when the percentage of steel reinforcement ratio changed from 2% to 3% for columns produced with and without POFA for 25 mm and 35 mm concrete covers. The increase in ultimate axial capacity of the columns when percentage of steel reinforcement ratio changed from 2% to 3% could be attributed to the large cross-sectional area covered by 3% steel reinforcement ratio. Thus, allow the compressive load coming on to it to spread well compared to 2% steel reinforcement ratio which has small cross-sectional area to contain the spread load.

When the concrete cover changed from 25 mm to 35 mm, the ultimate axial capacity of the columns increased by approximately 1.9%, 1.3% and 1.6%, 1.6% for columns produced with and without POFA for 2% and 3% steel reinforcement ratios. The increase in ultimate axial capacity of the
columns when concrete cover changed from 25 mm to 35 mm could be attributed to the reduction in the buckling of steel reinforcements.

**Table 5. Test results of reinforced SCC columns produced with and without POFA.**

| Column No | % of steel reinforcement | Concrete cover (mm) | Ultimate axial capacity (kN) | Secant stiffness (kN/mm) |
|-----------|--------------------------|---------------------|------------------------------|-------------------------|
| PCOL 1    | 2                        | 25                  | 835.1                        | 355.4                   |
| CCOL 1    | 2                        | 25                  | 813.6                        | 360.0                   |
| PCOL 2    | 2                        | 35                  | 850.6                        | 322.2                   |
| CCOL 2    | 2                        | 35                  | 826.6                        | 324.2                   |
| PCOL 3    | 3                        | 25                  | 938.6                        | 430.6                   |
| CCOL 3    | 3                        | 25                  | 916.1                        | 436.2                   |
| PCOL 4    | 3                        | 35                  | 951.1                        | 393.0                   |
| CCOL 4    | 3                        | 35                  | 930.6                        | 404.6                   |

3.4 *Load-deflection pattern*

The relationship of applied load with axial displacement of the columns produced with POFA and without POFA is shown in Figure 3. It can be seen from the Figure 3 that when the same load level was applied to the columns, the columns produced with POFA showed slightly smaller rigidity than the columns produced without POFA and that is why the values of axial displacement displayed by the columns produced with POFA were slightly higher than the columns produced without POFA. The slightly higher values of axial displacement displayed by the columns produced with POFA are attributed to its self-weight which is slightly less than the columns produced without POFA.

![Figure 3. Applied load – axial displacement relationship of reinforced SCC columns produced with and without POFA](image)

3.5 *Stiffness*

The stiffness of the columns produced with and without POFA is illustrated in Table 5. The secant stiffness of all the columns produced was determined by dividing the ultimate axial capacity by the maximum axial displacement recorded during the testing. Though the value may not signify the total actual stiffness of all the columns produced [25]. However, it offers a valuable criterion to compare the stiffness of columns produced with and without POFA. It can be observed from the Table 5 that the stiffness of columns produced with POFA is slightly lower than the one produced without POFA.
This is accredited to its self-weight which is slightly less than the columns produced without POFA. For the two types of column produced, the stiffness is reduced as the concrete cover increased. However, the stiffness is increased as the percentage of steel reinforcement increased.

4. Conclusions
The structural performance of reinforced self-compacting concrete columns produced with 15% POFA was investigated. The findings from the experiment carried out are as follows:

- The compressive strength of cubes produced with POFA is higher than the cubes produced without POFA by approximately 4.9%.
- The cracks, crushing of concrete and spalling of concrete covers that observed are more noticeable on the columns produced without POFA.
- The ultimate axial capacity of columns produced with POFA is higher than the columns produced without POFA by approximately 2.6%, 2.9%, 2.5% and 2.2%, respectively, for 25 mm and 35 mm concrete covers, and 2% and 3% of steel reinforcements.
- The ultimate axial capacity of columns increased by approximately 12.4%, 11.8% and 12.6%, 12.6% when the percentage of steel reinforcement ratio changed from 2% to 3% for columns produced with and without POFA for 25 mm and 35 mm concrete covers.
- When the concrete cover changed from 25 mm to 35 mm, the ultimate axial capacity of columns increased by approximately 1.9%, 1.3% and 1.6%, 1.6% for columns produced with and without POFA for 2% and 3% steel reinforcement ratios.
- The stiffness of columns produced with POFA is slightly lower than the one produced without POFA.

Acknowledgments
The authors honestly appreciate the support provided by the Research Management Centre (RMC) through Grant No: 16H94 and the Technical staff of Structure and Materials unit, Universiti Teknologi Malaysia (UTM). The financial supports given by the Federal Government of Nigeria through TETFund are thankfully appreciated by the first author. Many thanks are also extending to authority of Alif Palm Oil Mill, Malaysia for providing the palm oil fuel ash.

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