Effect of Water-Binder Ratio on Properties of Self-Compacting Concrete Containing Palm Oil Fuel Ash

Ahmad Nurfaidhi Rizalman1,*, Hii Yung Seng1, S.M. Iqbal S. Zainal1, Noor Sheena Herayani Harith1

1 Faculty of Engineering, Universiti Malaysia Sabah, Kota Kinabalu, Malaysia

*Corresponding Author: ahmadnurfaidhi@ums.edu.my

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Abstract: This paper presents experimental results of the fresh and hardened properties of self-compacting concrete (SCC) with palm oil fuel ash (POFA). In this study, four SCC mixes with 0% (control), 10%, 20% and 30% of POFA having different water-binder ratio (w/b) ratios of 0.45, 0.50, and 0.55 were prepared. The tests performed in the study include filling ability, passing ability, segregation resistance, and compressive strength of the SCC. The fresh properties of the concrete mixes fulfilled the acceptance criteria of the SCC by EGSCC (2005). Meanwhile, the w/b ratio had significant influence on the compressive strength of SCC containing POFA. Lastly, compressive strength of SCC decreases as the replacement level of POFA increases.

Keywords: self-compacting concrete, POFA, water-binder ratio

1. Introduction

Self-compacting concrete (SCC) is concrete that does not require compaction. It was developed in Japan to address the shortage of skilled labor and long construction time (Okamura and Ouchi, 2003). However, the production of SCC is quite expensive due to the use of chemical admixture and high amounts of cement. The latter also causes global warming because its production releases carbon dioxide into the atmosphere. Therefore, numerous efforts have been made to investigate the feasibility of sustainable waste materials as a replacement for cement in concrete. One of the highest waste sources in Malaysia is palm oil fuel ash (POFA) (Jokhio et. al., 2018). It consists of a large amount of silica which is seen as a threat to the health and environment. Thus, many studies have been conducted on POFA to investigate its potential use in other applications including construction materials.

Palm oil fuel ash (POFA) is ashes produced from husk fiber and shell of palm oil. It was burnt by a boiler to generate energy to be used in the palm oil mill. According to Amran et. al. (2021), POFA fulfills the pozzolanic property criterion due to the high content of silica oxide. Therefore, it can potentially be used as cement replacement in concrete. In Sabah, many studies have been conducted on the application of POFA in various cement-based products including normal concrete and geopolymer concrete (Arif et. al., 2019; Alias Tudin et. al., 2018). However, the effect of locally obtained POFA as cement replacement materials in SCC has not yet been explored.
One of the key differences between the SCC and other concrete is its enhanced fresh-state properties which include the flowability, passing ability (flow through congested reinforcement), and viscosity (measure of the speed of flow). These fresh-state properties are highly influenced by the water to binder ratio (w/b) ratio. For instance, the increase of w/b ratio increases flowability of the fresh SCC, but reduced the mechanical and durability properties of the hardened SCC (Rai, et.al. 2019).

It has been reported that the 5% to 15% of POFA replacing cement is the optimum amount to achieve high strength of concrete (Ode, 2019). However, the w/b ratio is also important factor that controls the workability and strength of concrete. Therefore, the present study reports the fresh state and compressive strength of SCC incorporating POFA at different water-binder ratio (0.45, 0.50, and 0.55), and replacement levels of POFA (0%, 10%, 20%, and 30%). There are four (4) tests conducted in this study which include slump flow, J-ring, segregation resistance, and compressive strength.

2. Research Methodology

2.1 Materials

This research used Ordinary Portland Cement (OPC) of ‘Cap Gajah’ brand from Cement Industries (Sabah) Sdn. Bhd. The OPC complies with the Malaysian Standard MS 522: Part I-2003. Meanwhile, the fine aggregate used for the SCC was the local river which passed through the 600 μm sieves. The coarse aggregate used for the SCC was sandstones which were sieved between 10 mm to 12.5 mm. For the superplasticizer, the ‘Darex Super’ brand was used as the chemical admixture. It is type A and F according to ASTM C494/ C494M-05.

POFA was collected from Beaufort palm oil mill, Sabah. It is the same material used by Alias Tudin et. al. (2018). After POFA was collected, it was oven dried at constant temperature of 100°C for 24 hours. Then, it was sieved at 212 μm to remove the impurities and unburned materials. Then, they were ground for 6 hours in the Los Angeles abrasion test machine.

The scanning electron micrograph (SEM) of OPC and ground POFA are presented in Figure 1 and 2, respectively. These micrograph images were captured at Biotechnology Research Institute, Universiti Malaysia Sabah. From these images, both materials have an angular and irregular particle shapes.

Table 1 tabulates the chemical composition of OPC and POFA which was retrieved from local researchers. The result shows that SiO₂ in POFA is higher than OPC with 47.44% and 14.4%, correspondingly. Meanwhile, the combination value SiO₂, Al₂O₃, and Fe₂O₃ in POFA was
59.09%. According to ASTM C61-91, the POFA used in this study is classified as Class C pozzolan material.

| Chemical Composition          | OPC  | POFA |
|------------------------------|------|------|
| Silicon dioxide (SiO₂)       | 14.4 | 47.44|
| Aluminium oxide (Al₂O₃)      | 3.60 | 1.63 |
| Iron Oxide (Fe₂O₃)           | 3.20 | 10.02|
| Calcium Oxide (CaO)          | 72.3 | 17.04|
| Magnesium (MgO)              | 1.70 | 3.76 |
| SiO₂ + Al₂O₃ + Fe₂O₃         | 21.2 | 59.09|

### 2.2. Mix Proportions and Mixing Method

This research consisted of twelve (12) specimens including the control specimen. There were three water-binder ratios investigated in this study which include 0.45, 0.50, and 0.55. Meanwhile, the cement was replaced at three (3) levels including 10%, 20% and 30%. The total concrete cubes prepared in this study was 96.

The summary of mix proportions for all the specimens are presented in Table 2. The proportions were designed based on the guidelines by EGSCC (2005). It suggested that the coarse aggregates should be within the range between 750 to 1000 kg/m³. After several trials, the coarse aggregates were set at 775 kg/m³ which was half of the total amount of aggregates in the SCC mixtures. In the table, the coding of the specimens is as follows: SXX-YY; XX indicates the water-binder ratio of the mixtures (45=0.45, 50=0.50, and 55=0.55), and YY indicates the cement replacement level (00=0%, 10=10%, 20=20%, and 30=30%).

The process of making SCC started with the mixing of fine and course aggregates mixer for 3 minutes. Then, the mixing continued for another 2 minutes after the OPC was added to the mixer. The water was added to the mix for two times, the first half was poured and mixed for 2 minutes, then the remaining was added after that.

### 2.3 Fresh Properties Tests

There were three (3) tests were conducted to examine the fresh properties of the SCC mixture, which include filling ability test, passing ability test, and segregation test. In this research, all tests were conducted according to apparatus required and standard procedures as stated in EFNARC Specification and Guidelines for Self-Compacting Concrete (EFNARC 2002; EGSCC, 2005).

For the filling ability test, the SCC mixtures were first poured into the Abrams cone without external compaction, as shown in Figure 3(a). Then, the cone was lifted vertically in one movement without interfering with the flow of SCC. After the flow spread stopped, the largest diameter of the flow spread was recorded.

The passing ability test was similar to slump test with the additional of J-Ring as obstacle for the slump, as shown in Figure 3(b). The step height was measured to obtain the passing ability of the SCC mixtures.

Lastly, the segregation test was conducted by pouring the SCC mixtures into the sieve, as shown in Figure 3(c). This allowed water, paste and mortar to flow into a sieve receiver. The amount of material that passed through the sieve was calculated as percentage of original
sample. The classification of SCC was based on EFNARC Specification and Guidelines for Self-Compacting Concrete (EFNARC 2002; EGSCC, 2005).

| No. | Specimen | POFA (kg/m³) | Cement (kg/m³) | Water (kg/m³) | Fine aggregates (kg/m³) | Coarse Aggregates (kg/m³) | SP(%) |
|-----|----------|--------------|----------------|---------------|-------------------------|---------------------------|-------|
| 1   | S45-00   | 0.00         | 455.56         | 205.00        | 775                     | 775                        | 2.00  |
| 2   | S45-10   | 45.56        | 410.00         | 205.00        | 775                     | 775                        | 2.00  |
| 3   | S45-20   | 91.11        | 364.45         | 205.00        | 775                     | 775                        | 2.00  |
| 4   | S45-30   | 136.67       | 318.89         | 205.00        | 775                     | 775                        | 2.00  |
| 5   | S50-00   | 0.00         | 455.56         | 227.78        | 775                     | 775                        | 2.00  |
| 6   | S50-10   | 45.56        | 410.00         | 227.78        | 775                     | 775                        | 2.00  |
| 7   | S50-20   | 91.11        | 364.45         | 227.78        | 775                     | 775                        | 2.00  |
| 8   | S50-30   | 136.67       | 318.89         | 227.78        | 775                     | 775                        | 2.00  |
| 9   | S55-00   | 0.00         | 455.56         | 250.56        | 775                     | 775                        | 2.00  |
| 10  | S55-10   | 45.56        | 410.00         | 250.56        | 775                     | 775                        | 2.00  |
| 11  | S55-20   | 91.11        | 364.45         | 250.56        | 775                     | 775                        | 2.00  |
| 12  | S55-30   | 136.67       | 364.45         | 250.56        | 775                     | 775                        | 2.00  |

2.4 Compressive Strength Test
The specimens were casted into 150x150x150 mm cube mould and water cured for 7 and 28 days to obtain its compressive strength. Three (3) readings were captured for each test. The test was conducted according to apparatus required and standard procedures as stated in British Standard (2019). The specimens were subjected compressive load until failure, as shown in Figure 3(d). The strength was measured in MPa unit.
3. Results and Discussion

3.1 Fresh Properties of SCC
Table 3 shows the fresh properties of the specimens which were obtained from the flowing ability test, passing ability test, and segregation resistance test. The flowing ability of the specimen was measured based on its slump flow and T500 spread time. Meanwhile, the passing ability of the specimen was assessed based on the step height of the fresh mixtures. Lastly, the segregation resistance of the specimen was evaluated based on the ratio between coarse aggregate mass in the top part and bottom part of the sieve receiver.

From these results, it shows that the SCC mixtures fulfilled the acceptance criteria for self-compacting concrete by EFNARC (20020, as illustrated in Table 4. Based on the EGSCC (2005), the slump flow and J-ring results show that the SCC is classified as SF3 and SR2, respectively. This means that the SCC is suitable for vertical, highly congested reinforcement, and complex shape applications.

Table 3: Fresh properties of SCC POFA

| No. | Specimen  | Slump Flow (mm) | Spread Time (sec) | J-Ring Height (mm) | Sieve segregation (%) |
|-----|-----------|-----------------|-------------------|-------------------|-----------------------|
| 1   | S45-00    | 800             | 4.6               | 9                 | 8.6                   |
| 2   | S45-10    | 800             | 3.2               | 8                 | 10.6                  |
| 3   | S45-20    | 735             | 3.5               | 9                 | 5.5                   |
| 4   | S45-30    | 790             | 5.8               | 10                | 5.8                   |
| 5   | S50-00    | 765             | 5.0               | 10                | 4.7                   |
| 6   | S50-10    | 760             | 4.1               | 9                 | 1.7                   |
| 7   | S50-20    | 760             | 4.0               | 10                | 3.2                   |
| 8   | S50-30    | 805             | 2.3               | 7                 | 8.6                   |
| 9   | S55-00    | 750             | 2.4               | 9                 | 5.7                   |
| 10  | S55-10    | 760             | 4.1               | 10                | 15.0                  |
| 11  | S55-20    | 780             | 4.5               | 8                 | 13.7                  |
| 12  | S55-30    | 783             | 2.5               | 9                 | 11.2                  |

Table 4: Comparison of fresh properties between EFNARC and experimental results

| No. | Criteria                          | Unit   | EFNARC’s criteria | Experimental results | Evaluation |
|-----|-----------------------------------|--------|-------------------|----------------------|------------|
| 1   | Slump Flow by Abrams cone         | mm     | 650 to 800        | 735 to 800           | Fulfilled  |
| 2   | T500 Slump Flow                   | sec    | 2 to 5            | 2.3 to 5             | Fulfilled  |
| 3   | J-Ring                            | mm     | 0 to 10           | 7 to 10              | Fulfilled  |
| 4   | Segregation Resistance            | %      | 0 to 15           | 1.72 to 15           | Fulfilled  |

4.2 Compressive Strength of SCC
Table 5 shows the compressive strength of SCC at the 7th and 28th day of curing. At 0% replacement level of POFA, the strength of SCC at 28th day with 0.45 w/b ratio had the highest strength with 53.0 MPa, followed by the SCC with 0.50 and 0.55 w/b ratio with the strength of 44.5 MPa and 40.9, respectively. Similar trend was also observed for the 10%, 20%, and 30% replacement level of POFA. This shows that the increasing w/b ratio reduces the compressive strength of SCC which agrees with Moghadam and Khoshbin (2012) that increasing the water-binder ratio of the SCC reduced the compressive strength of SCC.

The results also show that there is huge difference between the strength of SCC containing POFA with 0.45 ratio and 0.50 to 0.55 ratio. For instance, the strength difference between the SCC containing 20% of POFA with 0.45 and 0.50 w/b ratio is 7.6 MPa. Meanwhile, the
strength difference between the SCC containing 20% of POFA with 0.50 and 0.55 w/b ratio is 2.7 MPa. This finding agrees with Safiuddin et. al. and Mohammadhosseini et. al. who discovered that the effect of POFA as cement replacement was more significant if lower w/b ratio, such as 0.40 and 0.45, was used. But, when higher w/b ratio was used, such as 0.50 and 0.60, the effect of POFA as cement replacement was not effective.

The effect of replacement level of POFA on the 28th day strength of SCC is illustrated in Figure 4. At 0.45 w/b ratio, the compressive strength of SCC is reduced for every 10% increment of POFA replacement. Similar trend was observed for SCC at 0.50 and 0.55 w/b ratio. It is also observed that, as the w/b ratio increases, the difference in the strength of SCC as the replacement level of POFA become smaller.

### Table 5: Compressive Strength of SCC at the 7th and 28th Day

| No. | Specimen | Water-binder ratio | 7th Day Strength | 28th Day Strength |
|-----|----------|--------------------|------------------|-------------------|
| 1   | S45-00   | 0.45               | 38.1             | 53.0              |
| 2   | S45-10   | 0.45               | 38.5             | 48.1              |
| 3   | S45-20   | 0.45               | 33.3             | 45.9              |
| 4   | S45-30   | 0.50               | 28.7             | 42.0              |
| 5   | S50-00   | 0.50               | 35.4             | 44.5              |
| 6   | S50-10   | 0.50               | 32.6             | 40.4              |
| 7   | S50-20   | 0.50               | 28.6             | 38.3              |
| 8   | S50-30   | 0.50               | 27.3             | 39.2              |
| 9   | S55-00   | 0.55               | 33.2             | 40.9              |
| 10  | S55-10   | 0.55               | 33.3             | 35.6              |
| 11  | S55-20   | 0.55               | 28.6             | 35.6              |
| 12  | S55-30   | 0.55               | 25.2             | 35.8              |

The effect of replacement level of POFA on the 28th day strength of SCC is illustrated in Figure 4. At 0.45 w/b ratio, the compressive strength of SCC is reduced for every 10% increment of POFA replacement. Similar trend was observed for SCC at 0.50 and 0.55 w/b ratio. It is also observed that, as the w/b ratio increases, the difference in the strength of SCC as the replacement level of POFA becomes smaller.

**Figure 4: Compressive strength of SCC at different w/b ratio**

### 5. Conclusion

The conclusion of the research are as follows:

1. The SCC containing POFA satisfies all the fresh properties criteria including filling ability, passing ability, and segregation resistance.
2. W/b ratio had significant influence on the strength of SCC, where lower w/b ratio is preferred for higher compressive strength of SCC containing POFA.
(3) Compressive strength of SCC decreases as the replacement level of POFA increases.

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